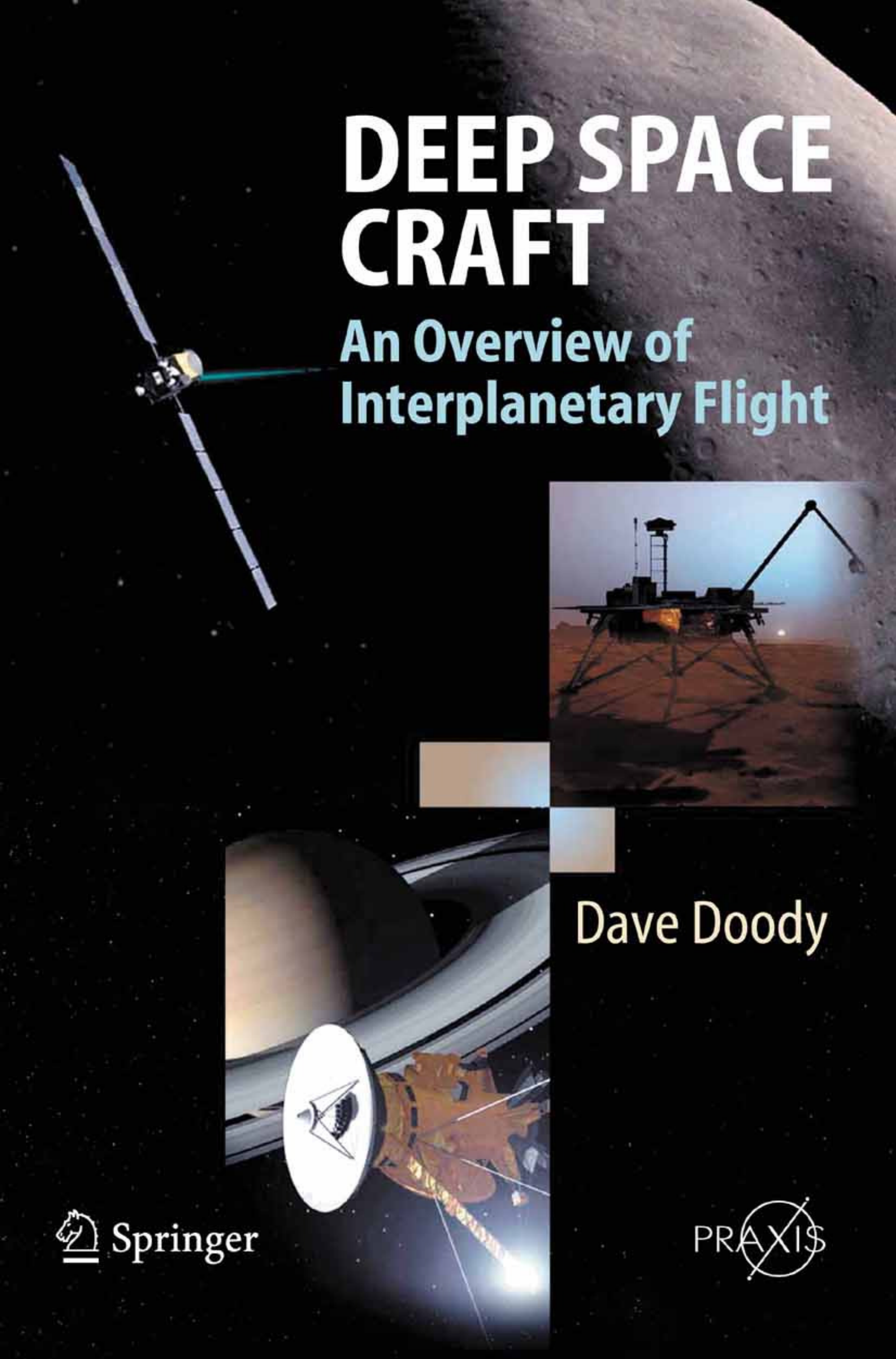
DEEP SPACE CRAFT

An Overview of Interplanetary Flight

Dave Doody



Springer

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Published in association with
Praxis Publishing
Chichester, UK

PRAXIS

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California
USA

Front cover illustrations: (Upper) Artist's rendition of the *Dawn* spacecraft operating its ion propulsion system upon arrival at the main-belt asteroid Vesta in 2011. Image courtesy McRel, Mid-continent Research for Education and Learning. (Next lower) Artist's concept of the *Phoenix* lander operating in the Martian Arctic, as it did from May to November 2008. Image courtesy University of Arizona. (Lower left) Artist's concept of the *Cassini* spacecraft as it operates in Saturn orbit July 2004 through the present day.

Back cover illustrations: (Left) A near-duplicate of the Mars *Phoenix* lander used in developing command sequences before being sent to the spacecraft. Here, members of the Robotic Arm Engineering Team test the arm's motorized raft in the Payload Interoperability Testbed at the University of Arizona, Tucson in July 2008. Image courtesy University of Arizona. (Right) Rob Manning, Chief Engineer of NASA's Mars Exploration Program, cheers along with other team members as the first images from rover *Spirit* come back from Mars. Courtesy NASA/Bill Ingalls.

SPRINGER–PRAXIS BOOKS IN ASTRONAUTICAL ENGINEERING
SUBJECT *ADVISORY EDITOR*: John Mason M.B.E., B.Sc., M.Sc., Ph.D.

ISBN 978-3-540-89509-1 Springer Berlin Heidelberg New York

Springer is part of Springer-Science + Business Media (springer.com)

Library of Congress Control Number: 2008943657

Cover design: Jim Wilkie
Project copy editor: Michael McMurtrey, Carrollton, Texas, USA
Author-generated LaTex, processed by EDV-Beratung, Germany

Printed in Germany on acid-free paper

Table of Contents

List of Figures

Introduction

We might not realize it, but we are living under astonishing circumstances as we go about the business of our lives. We take for granted our planet's immense value as a home, unconscious of the fact that the very nature of the world and the solar system in which we find ourselves sustains and protects us from minute to minute. Throughout the millennia of history and pre-history we have never been able to know the character of another planet or another solar system, but that has changed dramatically in recent decades. Interplanetary flight, an adventure long dreamt of and only recently achieved, has returned more knowledge about our place in the universe than any human has ever possessed in all the centuries preceding.

Interplanetary missions of today are unencumbered by the need for complicated life-support arrangements that were, in previous ages, thought necessary for making the journey across the vast oceans of interplanetary space to the other worlds. Unmanned spacecraft preceded humans to the Moon, and today they operate at a small fraction of the cost of our ventures into the low Earth orbits explored by astronauts.[1] Robot explorers go far beyond that distance. They travel a hundred thousand times — a hundred *million* times — as far, all the while extending and expanding our limited human senses. They are doing this right now, without a lot of public attention, without much danger to life or limb, as a footnote to our busy earthbound lives.

For the reader occupied in any field unrelated to interplanetary flight — artist or zoologist — who is curious about it, here is a snapshot of the craft of deep-space exploration. Examine the section and subsection headings, stopping to pick up any details that might be of interest along the way. By design, the book's content is more broad than deep, though references will take you as far as you like into any subject. A few times, we will look in on a specific project in deep space — *deep space* being defined as the distance to Earth's Moon and farther. We'll follow it through an event in its mission and check out its implications, eventually to explore how all the major pieces of a deep-space mission work.

In the process, *Deep Space Craft* hopes to offer some of the pleasure of finding things out, in the spirited way for which the American physicist Richard Feynman

[1] This is not meant to disparage human space flight. The author's greatest admiration goes to the NASA Apollo team and the twelve who set foot on the Moon, and to those who carry out great work in Earth orbit. It's been a while, though, since humans have left Earth's gravitational bond.

(1918–1988) was well known.[2] Readers will have a framework for placing in context virtually any interplanetary discovery, mission, or instrument to be encountered in the news or other media, and will be better prepared to communicate with friends, family, and colleagues who work in the disciplines described.

For the young student deciding on a career path, this book spotlights all the related disciplines involved in interplanetary flight, identifying and explaining some of the essentials of each. You will see names of the sometimes familiar giants in engineering and science on whose original work interplanetary flight is based: the shoulders we stand on to reach deep into space and time.

Over and above references to the literature, the Internet presents such rich opportunities for locating further information, and information more current than printed herein, that some hints for effective searching may be warranted, especially for the reader who may not have much experience with the Internet. One should pass two or three words to a good search engine, carefully selected from the text, to narrow down the topic of interest. One more hint: Many of the figures and references in this book mention an image identification, such as, "Image ID: PIA08329." If you simply search on the ID alone most engines will immediately give you the catalog page so you can view or download the image at full resolution and in full color, and read its original caption.

[2] The book, *The Pleasure of Finding Things Out* by Jeffrey Robbins (Basic Books, 2000) contains some of Feynman's essays, and edited transcripts of some of his addresses and interviews, including one for BBC television shown in 1981.

Author's Preface

It was my immense good fortune to be part of the *Voyager* flight team when late one August night in 1989 we watched images building up line-by-line on the monitors from *Voyager 2*'s very remote eyes. We were in touch with this craft while it dove over Neptune's cold northern cloud decks and flew right through the gravitational corridor that would take it close by the big, retrograde, captured moon Triton. We had a few hours to catch a nap. Then, thanks to newly programmed image motion compensation tactics running perfectly aboard the spacecraft, clear images revealed a cold alien landscape. Later analysis of these revealed active nitrogen geysers issuing from beneath Triton's icy, nitrogen-snowy surface. This was the last encounter. *Voyager 2* was on a hyperbolic trajectory leaving the Sun behind forever.

Days later, while Neptune was a thin, ever-receding crescent on television monitors suspended from the high ceilings in the cafeterias, Carl Sagan (1934–1996), one of the imaging-team scientists, threw the whole flight team quite the party. Chuck Berry (1926–)[3] was rocking and duck-walking his electric guitar across the wide concrete steps out in front of JPL's administration building, helping us properly celebrate a fine solar-system exit.

Welcome to the craft — the art, or trade — of interplanetary flight. Let's explore how it works.

Dave Doody
Altadena, California, March 10, 2009

[3]See biography online at wikipedia.org/wiki/Chuck_Berry.

Acknowledgments

Many individuals have helped by contributing ideas and answering questions regarding specific parts of chapters, but any errors in interpreting their input are strictly the author's, who would welcome feedback.[4] Thank you to Jim Taylor, Laura Sakamoto Burke, and Julie Webster for sharing telecommunications expertise, Thanks to Jitu Mehta for sharing knowledge of attitude control, Todd Barber for advice on propulsion, Mary Beth Murill for technical review of electrical power issues, Pam Chadbourne, Ken Fujii, and Charles Kohlhase for help with mission architecture and mission planning. Thanks to Jim Hodder for DSN advice, to Bill Owen for navigation help, and to Michael Minovitch for personal communications and for kindly supplying a great deal of background material on the gravity-assist technique. Thanks to Scott Maxwell for comments on MER, to Brent Ware for a gravitational radiation sanity check and to Sooz Kurtik for plentiful, informative emails. Thanks to Rob Smith, Arden Accord, Kuei Shen, Vicki Ryan, and Kathy Lynn for reviewing the manuscript, to Roger Lighty for help with that process, and to Mitch Scaff for scrutinizing technical quality throughout. Thanks to Ray Sabersky for the encouraging words, and to Dolores Simpson for some good initial advice.

Thank you to artists Don Davis, Don Dixon, and Gordon Morrison for kindly being so willing to share their visionary work, and to all the persons whose "artists conceptions" in the book are credited to NASA and other institutions. Thanks to JAXA, NASA, ESA, and ASI for making images and information widely and easily available.

Thanks to Clive Horwood for the thoughtful suggestion from Praxis, to John Mason, and to editor Michael McMurtrey, who made my weak sentences strong and clear.

Thanks, Rosaly Lopes, for the inspiration.

D, the rocket ship worked.

[4] *Via www.linkedin.com.*

Foreword

The Space Age was born barely half a century ago, when a basketball-sized satellite named *Sputnik* was lofted into the skies over the Soviet Union, the first object built by humans ever to orbit the Earth. *Sputnik* carried no scientific instrumentation. Instead, its payload was a simple radio, sending out an easily detected beeping signal. *Sputnik*'s job was not to explore, it was simply to prove to the world that it was there, where nothing had gone before.

It did so with great success, and the effect was electrifying. The Space Age was underway. The United States, the Soviet Union, and ultimately many other nations began to hurl vehicles, both robotic and with human crews, into Earth orbit and beyond at a dizzying rate.

Among these vehicles, few have captured the imagination more than the deep space probes that have flown far beyond the Earth's orbit. In the few decades since *Sputnik*, spacecraft have flown by all the planets save one. (I'm an old-timer, and to me Pluto is still a planet, recent scientific debates over what to call it notwithstanding.) They have orbited Venus, Mars, Jupiter, and Saturn. They have landed on Venus, Mars, and, astonishingly, Saturn's moon Titan. In a remarkably short period of time, the planets in our solar system have gone from points of light in telescopes to real worlds that we can puzzle over and try to understand, with their own weather, mountains, canyons, and plains. One even has wheel tracks winding for kilometers across its surface.

None of this came easily. Behind the spectacular images and the new scientific understanding lies the complex business of building spacecraft, navigating them to the planets, and operating them once they get there. In *Deep Space Craft,* Dave Doody shows how it's done. In clear language, Dave explains how a planetary mission is conceived, formulated, and executed. For every thinking person who has ever looked at a spectacular image of the rings of Saturn or a sunset on Mars and wondered "How did they do that?", here is the answer.

Those of us who are fortunate enough to work in this business know that being part of a deep space mission is, in the very literal sense of the phrase, the adventure of a lifetime. This book shares that adventure. Better yet, I'm sure it will encourage a few lucky readers to become part of the adventure themselves.

Steve Squyres
Goldwin Smith Professor of Astronomy, Cornell University
Principal Investigator, Mars Exploration Rover Project

Dedicated to the Solar System Ambassadors: the hundreds of women and men who formally participate in the NASA program of that name, and also to everyone who shares with others the high adventure to be found in traveling among the planets.

1 Telepresence

1.1 On Location

It is September 10, 2007. The *Cassini* spacecraft is moving at a relatively slow 4,400 kilometers per hour with respect to Saturn, nearing the high point in its orbit some 3,600,000 kilometers above the equator of the gas giant, itself 1,500,000,000 kilometers from us here on Earth. *Cassini*'s purpose, like that of many interplanetary craft operating in the solar system and beyond, is to extend the human presence to distant realms, bearing instruments that augment the ranges and capabilities of the human senses, and to add to the scientific knowledge and understanding of our local corner of the universe.

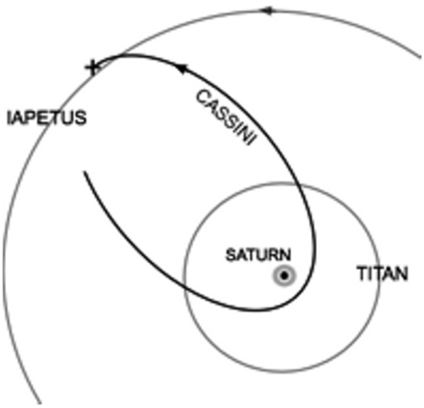

Fig. 1.1. *Cassini*'s orbits are more highly elliptical than those of Saturn's moons. The + mark shows *Cassini* at apoapsis after Iapetus encounter. Titan orbits 1.22×10^6 kilometers from Saturn, Iapetus at 3.56×10^6 kilometers.

Despite such vast distances, communications with unmanned machines in the depths of the outer solar system is nearly as reliable and routine as exchanging email messages with a coworker, thanks to the telecommunications capabilities designed into the spacecraft on the one hand, and NASA's worldwide Deep Space Network (DSN) on the other. But there's a constant reminder of the vast distance: It can take hours for messages to propagate at the speed of light across interplanetary space between Earth and the spacecraft.

This is the fiftieth orbit *Cassini* has flown about its ringed host since arriving on the first of July 2004. Mission planners and operations teams have intentionally raised this apoapsis (high point) in *Cassini*'s highly elliptical orbit, using gravity assists from Saturn's massive moon Titan during previous months.[1] Finally, at this increased height, the spacecraft will be able to rendezvous with a perplexing object: 1,436 kilometer-diameter Iapetus. This icy moon's 79.33-day nearly circular orbit around Saturn is bringing it into position for a historic meeting. *Cassini* will pass only 1,229 kilometers above its surface.

Cassini's on-board computers are executing a sequence of commands radioed to the spacecraft's memory a month before to control the robot's every move. This particular sequence of commands, called "S33" (the "S" for Saturn-tour, "33" an integer count of these command sequences), turns and twists the craft, pointing its attached optical instruments with sub-milliradian precision toward carefully selected terrain on the puzzling target. At times these commands rotate the whole spacecraft slowly to compensate for Iapetus's relative motion in the instruments' fields of view; tracking the object keeps the cameras' close-up views motionless and free of blur as the spacecraft speeds by.

Iapetus has been puzzling scientists for more than 300 years, and it also figures prominently in science fiction [1]. The Italian-French astronomer Giovanni Domenico (Jean-Dominique) Cassini (1625–1712), for whom the spacecraft is named, discovered Iapetus from the Paris Observatory on October 25, 1671. He noted that he could only detect Iapetus when it was on the west side of Saturn; the object was never visible when it was on Saturn's east side. He deduced that Iapetus is locked in synchronous rotation about Saturn, as is our own Moon, keeping the same face toward the planet as it moves in its orbit. He also concluded that one side of Iapetus must be darker than the other. These conclusions were confirmed when striking images came back from the two *Voyager* spacecraft in 1980 and 1981 revealing that Iapetus's leading hemisphere is indeed as dark as asphalt and the hemisphere that trails as the moon proceeds in Saturn orbit is almost as bright as snow. The dark hemisphere is named *Cassini Regio* in honor of the astronomer.

Fig. 1.2. *Voyager 1* captured this view of Iapetus in November 1980 from a distance of 2.5 million kilometers showing the remarkable layout of its bright and dark hemispheres. Even with the bright side overexposed, the dark surface is barely visible. Image courtesy JPL/NASA (Image ID: PIA02291).

Cassini's mission plan includes only this one close encounter with Iapetus over its entire four-year prime mission in orbit, while many of Saturn's other moons enjoy repeated close-up visits. They offer more opportunities for encounters because they orbit closer to the planet and have shorter periods than Iapetus. Nearly every one of *Cassini*'s orbits includes a close flyby of Titan, for instance, which orbits Saturn every sixteen days. Given the uniqueness of this Iapetus encounter and the puzzling nature of the icy Saturnian moon, the images and other data being written to *Cassini*'s solid-state memory during the encounter will be highly valued. Scientists eagerly anticipate receiving them.

In a few days, the craft will begin to fall back toward the ringed planet in a dive that will take sixteen days and reach a Saturn-relative speed of 57,188 kilometers per hour passing periapsis, its closest point to Saturn. Right now, though, *Cassini* must pause in its Iapetus observations while receding from the encounter to establish communications with Earth for a couple of hours. First, the spacecraft orients itself to point its dish-shaped radio antenna squarely toward a bright, bluish planet near the Sun. The commands in the S33 sequence will keep the spacecraft in this orientation for 2.25 hours. The signal radiating from *Cassini*'s 19-watt transmitter, which is always powered on and transmitting, is now on its way to Earth.

Moments after *Cassini* stabilizes in its Earth-pointing attitude, a radio signal arrives at the spacecraft. It was radiated by an 18 kilowatt transmitter from a station in California's Mojave Desert, part of the Goldstone Deep Space Communications Complex, which is one of the three worldwide DSN antenna complexes. Obviously, the signal from Station 25 at Goldstone had to have started out much earlier. Propagating at the speed of light, Station 25's uplink took 1 hour, 24 minutes, and 41 seconds to arrive.

Riding on the stable-frequency uplink signal from Earth are navigation tones for measuring distance and, at five hundred bits[2] per second, a couple of routine commands for the spacecraft's computers to execute. The arrangements that brought the Earth-based signal to *Cassini* just as it finished turning started more than three months ago in negotiations among representatives of some of the Deep Space Network's users — the ones whose spacecraft occupy the same quadrant of sky as *Cassini*. Later a team of engineers created the S33 sequence of commands and installed it aboard the spacecraft.

A minute after pointing toward home, another timed command in the S33 sequence steps *Cassini*'s downlink data rate up to 99,541 bits per second, and then another command begins relaying some of the Iapetus data acquired prior to closest approach from the on-board solid state memory. *Cassini*'s telecommunications system sends the data off toward Earth as symbols — wiggles in its radio signal's phase — which the Deep Space Network will decode into 1s and 0s to faithfully reconstruct digital images and spectra from the Iapetus observations, and other telemetry (digital data) such as magnetometer readings and measurements of plasma and dust in Iapetus's neighborhood.

Aside from the digital data, the exact frequency of the radio signal from *Cassini* is also prized. Since the spacecraft is still very close to Iapetus, the moon's gravity, which caused it to speed up slightly on approach, is now slowing it down slightly on departure. Calculating these gravitational accelerations from the shift seen in *Cassini*'s frequency due to the Doppler effect enables a measurement of Iapetus's mass — an important quantity to know because it enables computation of the body's density, which is an essential clue for deducing its internal composition.

After the flawless two-and-a-quarter-hour communications session, *Cassini* steps down its data rate, suspends its data playback, and begins another turn, all under control of the S33 commands. The craft's transmitted radio beam sweeps away from the distant Earth. *Cassini* is still in the mystery-moon's vicinity, and there are many more observations to carry out. For the next six and a half hours *Cassini* will operate its eleven scientific instruments in response to the S33 "list of things to do while visiting Iapetus," adding the new data to the solid-state recorder. As *Cassini* carries all its optical instruments bolted to a fixed pallet on its side, the whole vehicle will again be twisting and turning to precisely aim the instruments' apertures.

At the appointed time, *Cassini* finishes up all its Iapetus observations and turns its big ear toward Earth, but no signal from home is to be found this time. This is the usual way of doing business. The previous communications session used an extra allocation of time from the Deep Space Network to provide an early uplink to Saturn.[3] This time, *Cassini* starts transmitting its messages to Earth fully three hours before a signal carrying navigation tones and more command data will arrive at the spacecraft.

1.1.1 A Busy Realtime Night

At the same time Iapetus data is leaving *Cassini,* John Tullius is showing up for work on the third floor of JPL's Space Flight Operations building and awakening the computers on his *Cassini* Realtime Operations console. It's just after 10:30 P.M. Pacific Daylight Time, and he has plenty of time to prepare. The data from *Cassini,* while traveling at the speed of light, won't arrive until 11:55 P.M.

At 11:00 P.M. PDT, John is in voice contact with the Deep Space Network staff in Madrid, Spain, where it is 8:00 A.M. They are preparing Deep Space Station 63 for an all-day session with *Cassini.* Station 63 is one of the Network's three behemoth 70-meter-diameter radio telescopes. There is also one in Canberra, Australia, and another at Goldstone. John gives Station 63's operator a two-minute-long briefing over the voice net, reviewing expected events and providing updates. The station acknowledges and informs John that the sky is clear, the winds are light and variable, and all their equipment is "green," meaning all the systems at the station are in working order.

At 11:55 P.M. PDT, thanks again to previous months' planning and negotiations, just as Station 63 finishes moving its 2.7 million-kilogram antenna to point precisely toward Saturn, which is rising above the Sun on Madrid's eastern horizon, there is the faint signal from *Cassini* completing its interplanetary crossing right on schedule.

"*Cassini* Ace, this is station six three. We have receiver in lock."

The pass is in progress. The period for which a DSN station is scheduled, formally called a *space-link session,* is commonly known as a pass or a tracking pass: the spacecraft is passing through the sky, and the DSN station is tracking it. Unlike earth-orbiting spacecraft that pass overhead in a matter of minutes, a craft in deep space spends all day or all night passing across the sky at about the same rate as a planet or a star.

John, whose call sign on the voice net is "Ace"[4] acknowledges the voice-net call from the Spanish station and types an entry in his online log. The data rate is 110,601 bits per second. This is the eagerly anticipated Iapetus data playback that includes all the observations taken during closest approach. Hundreds of close-up and wide-angle images are now pouring in, showing the enigmatic surface on the dark leading side of Iapetus, the bright trailing side, and the boundary between them. Spectra from the ultraviolet spectrograph and the visual and infrared mapping spectrometer, as well as data from all the other instruments will report on compositions and properties of the surface and the local environment. Interleaved with the science telemetry data are thousands of engineering telemetry measurements including voltages, pressures, temperatures, and computer states detailing the spacecraft's own status and health. In a few minutes the playback is expected to increase in data rate to 124,426 bits per second and then continue for another fifteen hours. Saturn will set on Madrid's western horizon and rise before the Sun in California where Goldstone's 70-meter-diameter "Station 14" is scheduled to take over from Madrid. The Iapetus data playback should complete late in the afternoon Pacific time. John checks some of the engineering data from *Cassini*, now showing up on his computers. All is fine aboard the distant craft.

"Six-three, this is *Cassini* Ace. I see your telemetry, and it looks good."

Station 63 acknowledges John's report, glad to know their end of the long-distance communications link is operating smoothly. Ten minutes later, still tracking *Cassini*'s signal as Saturn rises in the morning sky, the Spanish station energizes its 18-kilowatt transmitter to carry navigation tones, plus a command John will send from one of his computers, all right on time:

"Cassini Ace, six-three. We have transmitter drive on."

1.1.2 Realtime as Middle Ground

Realtime normally refers to the actual time that events occur. Of course, it is impossible to command a spacecraft and expect immediate response because radio signals take a while to travel, so we can define realtime as *as close as we can come to immediate interaction, given the speed of light.* John's realtime operations team, working closely with the DSN, has its role situated right in the middle of a flight project's landscape between previous planning and future data analysis. We'll take advantage of this unique point of view again a few times in subsequent chapters. The Ace's realtime tasks include overseeing the data streams and processors, watching for anything out of the ordinary as all the planned events unfold, and publishing a log of everything that happens. A realtime computer program parses all the spacecraft's engineering measurements and sets off an alarm for the Ace to heed if any parameters are found exceeding normal limits.

Years in advance of realtime, working one floor below the Ace console, the mission planning team coordinated with science planners and navigators to determine which trajectories and orbits the spacecraft will fly, and how its expendable resources such as propellant will be utilized, all the while minding the guidelines and constraints which these and other planners had established prior to launch. They also established high-level requests for time on antennas, receivers, transmitters, and related equipment and submitted them to the DSN resource allocation team for ongoing negotiation among all the DSN's users.

A few months prior to realtime, science planners, navigators, and spacecraft engineers, led by members of the science planning team, pulled together the observations that the science investigation teams have decided they wish to carry out. They made room for any brief propulsive maneuvers the navigators need for orbit maintenance and engineering activities the spacecraft team needs to do, such as routine housekeeping and software updates. All these activities are based on negotiations, determining who gets to point the spacecraft in which direction, and how the onboard expendable resources are to be allocated.

Several weeks before realtime, engineers on the sequencing team translated the finalized plans into sequences of commands that will be sent aboard the craft, and they negotiated the final DSN schedule to mesh seamlessly with the spacecraft's activities to be commanded.

Downstream in the process post-realtime, data that the DSN has captured will make its way to the navigators who make new iterations of their models of the spacecraft's flight path. Data will also go to the spacecraft engineers who will use the latest on-board engineering measurements to analyze the spacecraft systems' current health, long-term trends, and the state of expendables. Finally, the volumes of science data representing the mission's results will be delivered to the science investigation teams worldwide. In many cases these are the same teams that had originally designed and supplied the spacecraft's instruments. The scientists, working with their institutions and their graduate students, will analyze their data, publish results in the peer-reviewed science literature,[5] and present their discoveries in person at heavily attended meetings of the various scientific institutions. They will also work to update their models and theories associated with the physical targets of *Cassini*'s observations and the related scientific fields.

1.1.3 Wake-up Calls

John knows his command will take nearly an hour and twenty-five minutes to reach the spacecraft and another hour and twenty-five minutes before he sees confirmation that *Cassini* has received and acted upon it. He settles in to his routine of checking *Cassini*'s data, making log entries, sending commands, watching the ground system, and keeping alert during the morning's wee hours. But ten minutes later, his night is interrupted. Instead of a fifteen-hour playback of unique data from Iapetus, the data stream ends abruptly and unexpectedly after only twenty minutes. The DSN receiver status, "OUT OF LOCK," lights up in orange-colored blocks of reversed text on his computers.

"*Cassini* Ace, six-three. Receiver out of lock."

An experienced Ace, John recognizes the condition immediately. He has been watching the signal levels, numbers indicating the strength of *Cassini*'s signal in Spain, and he noticed it drop off over the span of a few seconds. A sudden rainstorm in Madrid might cause a loss of signal, because too many water molecules near the antenna would give off so much radio noise of their own that they can drown out a spacecraft's signal. But the noise indication John sees, 21 kelvins, isn't high enough to indicate rain. Station six-three confirms over the voice net that the sky is still clear, and that there are no obvious system problems.

Just to be sure the loss of signal wasn't caused by some unseen problem in the ground system, John calls over the voice net to the DSN Operations Chief who works downstairs on the first floor in front of the public viewing gallery. He requests a second antenna, if any are available, to look independently for a signal from Saturn. Within minutes, Deep Space Station 55, a 34-meter diameter machine also in Madrid, turns to train its huge steel ear on Saturn, still fairly low on the Spanish eastern horizon. Five-five cannot detect a signal.

John starts making phone calls. The experts he contacts within minutes of initiating his well-rehearsed "anomalous loss of downlink" procedure all agree with his initial assessment: there is no Earth-based problem, the ground system is fine.

The spacecraft has either quit transmitting or has turned its High-Gain Antenna (HGA) dish away from Earth unexpectedly. There is nothing more he can do to re-establish contact, so the Ace continues with his procedure and calls up members of the *Cassini* Anomaly Team, waking them and advising them to come in to JPL for a meeting at 1 A.M. Prime among them is Julie Webster (1953–), manager of the forty-five engineers who are responsible for all the spacecraft's systems and subsystems. Julie is used to receiving calls from the Ace at all hours to discuss minor problems, but a midnight call to come in to an anomaly meeting is unusual.

Meanwhile back near apoapsis in Saturn orbit, *Cassini* has indeed turned away from Earth. It is executing a set of emergency instructions that was stored in its memory years before, and never used while in Saturn orbit until now. To do this, the spacecraft has had to quit executing any more of the commands in its S33 stored sequence. Of the many "fault protection monitor" programs that are always running in *Cassini*'s systems, one sensed a failure on the spacecraft, and requested the main computer to execute a "safing" response that would take the HGA away from direct Earth-point.

Fifteen hundred million kilometers away, the *Cassini* Anomaly Team is meeting to discuss the situation in a first-floor conference room. At the realtime console upstairs, John knows that if *Cassini*'s fault protection had called for "safing" it would have switched to a different on-board transmitting antenna. The Low-Gain Antenna (LGA) has a nearly omnidirectional pattern of transmission and reception, so its signal can be received on Earth, although very weakly, even if *Cassini* is not pointing its HGA directly toward the planet. *Cassini*'s normal HGA signal usually registers about −147 dBm on Station six-three, but the low-gain signal should be closer to −171 dBm.[6] He asks Station 63 to look for it in that much weaker range of signal strength.

There it is! The weak signal is probably carrying telemetry, but at such a low rate — five bits per second is the "safing" rate — it would be of little use because it would take hours to collect the minimum number of bits, just over ten thousand, for the ground system computers to even begin any processing. But the signal's presence confirms that the spacecraft is indeed under control of the safing routine. The Ace's next step is to wait an hour and then have Station 63 configure for the next event.

If there is no problem with the spacecraft's attitude control system, and *Cassini* still knows where to find Earth in the sky, the safing routine will command the vehicle to rotate and point the HGA to Earth once again after an hour. At the same time, the routine will also step up the data rate from five to 1,896 bits per second, enough to provide a complete picture of the on-board situation over the space of just a few minutes. If on the other hand the spacecraft has lost its attitude knowledge for some reason, then the team would be stuck with having to process the painfully slow five bits per second telemetry[7] from the LGA to find out what went wrong.

While waiting, another member of John's team looks for periods in the schedule when DSN antennas might be borrowed from other flight projects, or from scheduled maintenance, in order to continue communications throughout the next

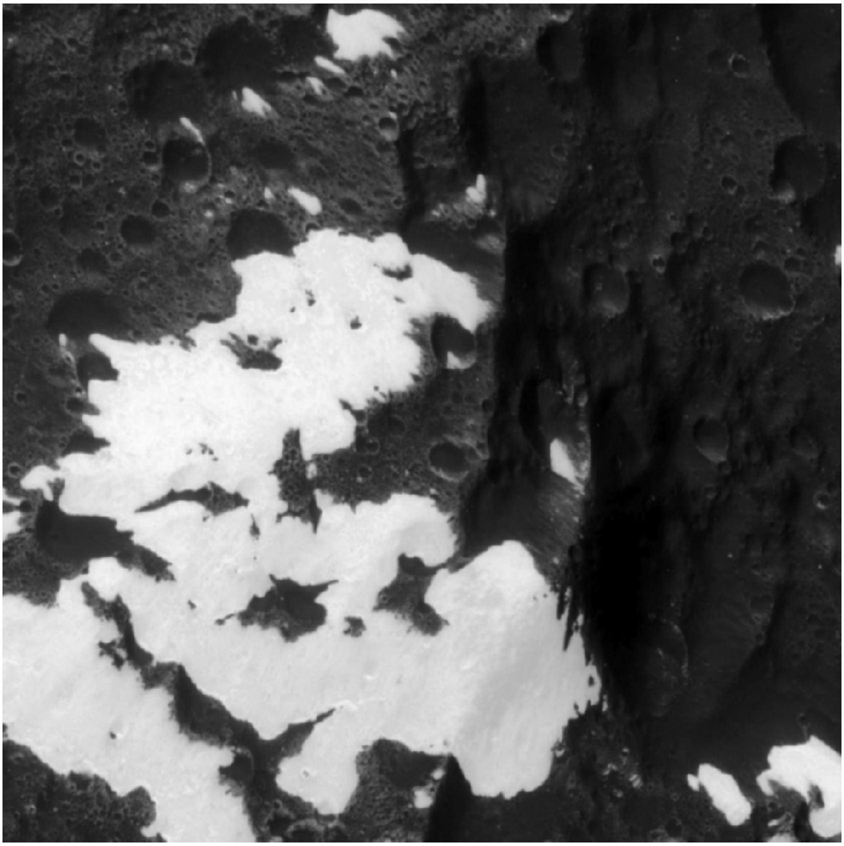

Fig. 1.3. Among the data recovered after *Cassini*'s safing was this close-up image of Iapetus's patchy, bright and dark mountains originally identified in images *Voyager* had returned at low resolution more than twenty-five years earlier. This square patch of terrain, 56 kilometers on a side, is on the equator at approximately 199° west longitude, in the transition region between the bright and dark hemispheres. Dark matter is now understood to be overlying Iapetus's bright icy terrain (rather than the reverse) and is thought to have come from a source exterior to Iapetus. This image was taken on September 10, 2007, with the *Cassini* spacecraft's narrow-angle camera at a distance of approximately 9,240 kilometers from Iapetus. Image ID: PIA08375, Courtesy *Cassini* Imaging Team and NASA/JPL/Space Science Institute.

day or two. Since execution of the S33 command sequence has been interrupted, the spacecraft will do nothing but stare HGA-to-Earth until commands sent from John's computer in real time instruct it to do otherwise.

1.1.4 Resolution

Fortunately, the relatively strong signal from *Cassini*'s HGA came in loud and clear after the hour-long delay, and Station 63 was soon sending *Cassini*'s 1,896-bps telemetry to the team. Within twenty minutes, Julie's spacecraft systems and subsystems engineers were able to characterize the problem. Electrical power to *Cassini*'s main transmitter, called the X-band Traveling Wave Tube Amplifier, had been shut off because a cosmic ray — an energetic proton from a stellar explosion somewhere in the galaxy, most likely — hit the solid state power switch. This happens to the multi-circuit switch an average of two or three times per year, but such impacts usually have benign results. Often, the switch that happened to be struck was already in its "off" state. Sometimes the affected circuit was one of a redundant pair. The onboard "Radio Frequency Loss" fault protection monitor program was the one that had sensed tonight's event, and requested safing.

Julie's engineers, working with other members of the flight team, prepared commands that would read out additional sections of *Cassini*'s memory and confirm the diagnosis. They transferred the commands to a database where John retrieved them, and after careful checking and approval by the team, up they went. In the three hours before the commanded readouts would return, participants in the ongoing anomaly team meetings would work on determining the next strategy.

The whole recovery process benefited from an operations-readiness training exercise Julie had put the team through a year before. By eerie coincidence, she had selected for training the very fault that actually occurred tonight. According to Julie, she had picked this specific fault "precisely because it was so onerous, with many decisions to be made, hardware swaps to entertain. It took five days of meetings last year just to develop the [recovery] strategy."

There would be little disagreement on what to do next. The top priority was to continue playing back the Iapetus data before re-starting the S33 sequence of commands, which would have the spacecraft take new observations and overwrite the Iapetus data on the recorder. The team spent the remainder of the sleepless hours working toward that goal, commanding and confirming each step across the 1.5 trillion-meter gulf of space. Over the following days, all the high-value Iapetus science data bits were successfully recovered. The on-board computers were commanded to resume executing the S33 sequence at an appropriate point, and the team returned to business as usual while the spacecraft gathered speed plunging toward periapsis number fifty, 217,180 kilometers above Saturn's hazy upper atmosphere.

A press conference had previously been scheduled for the morning of September 11, 2007, in which the science team had intended to present a first-look analysis of Iapetus to reporters and members of the community, based on at least a few hours spent studying freshly received images. But these were delayed somewhat, given the safing incident. Bob Mitchell (1940–), manager of the *Cassini-Huygens* Program, took the podium first: "We flew by Iapetus yesterday morning. The data coming down right now, I haven't seen. More importantly, the scientists sitting down here who are going to comment on it for you, have not seen it either." Following a good laugh, the science team members proceeded to make off-the-cuff analyses as the stunning new images lit up Von Kármán Auditorium.

Present on-screen via video link from Sri Lanka was British author Sir Arthur C. Clarke (1917–2008), who remarked, "I have always had a strange fascination for Saturn and its family of Moons. By the way, that 'family' has been growing at a very impressive rate. When *Cassini* was launched, we knew of only eighteen moons. I understand it is now sixty — and counting. I can't resist the temptation to say: 'My God, it's full of moons!'"

1.2 The Link With Earth

Operating and navigating a distant spacecraft depends upon a having system of extremely reliable communications across interplanetary space serving three basic functions, usually at the same time:

1. Returning the irreplaceable science data a spacecraft's instruments collect, while monitoring the craft's health and status. This function is *telemetry.*
2. Controlling the spacecraft's activities and installing software updates onboard. This function is *command.*
3. Measuring the spacecraft's trajectory. This is *tracking.*

This extensive section explores the principles and the many components which make up this three-fold fundamental link between spacecraft and Earth, and touches upon some additional uses beyond its three essential functions, such as when the radio science team uses the radio link itself to probe a phenomenon of interest. One example of this was Iapetus's mass determination mentioned on page 3, and examined again in Chapter 6. Chapter 2 will look more closely at the broader aspects of tracking and navigating a spacecraft.

The interested reader is invited to compare the content of this section with the succinct 9-page account of *Voyager*'s telecommunications with the DSN in reference [2]. The article is freely available for viewing online.

1.2.1 Spacecraft and the Deep Space Network

Interplanetary spacecraft are lightweight, compact, and highly capable self-contained machines. In flight they are physically untouchable. But every one of these esteemed craft would be inoperable and incomplete were it not for its titanic steel and concrete and electronic counterpart. The DSN is as massive and gritty as it is refined and sensitive. It is cranes and jackhammers and ironwork as much as it is computers and mathematics and ultra-precision. Steelworkers, scientists, hydraulics technicians, engineers, theorists, programmers, operators, administrators, and team members of every description animate an awesome and powerful machine that is nothing less than a fundamental component of every deep-space faring craft. No matter that its greatest beams are invisible and have no mass, it is the root system of every interplanetary tendril.

The DSN is the largest and most capable scientific telecommunications and radio navigation network in history. It came into being gradually in 1957 through 1961 to support the *Pioneer* missions to the Moon, the Earth-orbiting *Echo* balloon communications-reflection experiment, and Venus radar experiments. It then grew along with NASA, improving its capabilities in response to new demands from evolving spacecraft designs, as more missions ensued to the Moon and then to the planets. Reference [3] provides the complete history.

Today, the DSN's principal responsibilities are to support interplanetary spacecraft communications and radio and radar astronomy in the exploration of the solar system and the universe. The network consists of three deep-space communications complexes, located on three continents: at Goldstone, in southern California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. Reference [4] describes the modern DSN. An interplanetary spacecraft is always in view of at least one DSN complex as the Earth rotates. Each of the three complexes consists of multiple deep-space stations equipped with high-power transmitters, ultra-sensitive receiving systems, and colossal parabolic dishes. At each complex there are multiple 34-meter diameter antennas and one 70-meter antenna. Operators in a centralized signal processing center at each complex remotely control the 34- and 70-meter antennas — the ones routinely used for interplanetary communications — and they support data throughput.

All three complexes' signal processing centers connect with the operations control center in the Space Flight Operations Facility[8] at JPL in California, via the NASA Integrated Services Network, NISN. This network employs ground-based and Earth-orbiting communications resources to convey data, video, and voice, using commercial capabilities wherever possible. Modern data transport protocols ensure practically 100% fidelity. The operations center in turn links with each flight project, such as *Cassini* or *Voyager*, where a realtime operations team, or an associated team on each project, then typically manages data repositories from which the project's other teams — spacecraft engineering, navigation, and science — obtain their data in real time or post real time.

1.2.2 Microwaves

Interplanetary craft connect with the stations of the Deep Space Network via beams of radio signals in the band of the electromagnetic spectrum called *microwave.* The wavelengths of gigahertz-range[9] frequency emissions are much smaller than previously used in terrestrial broadcasting and are measured in centimeters. Microwave systems, originally employed in military radar, find use not only in spacecraft communication, but also in radio astronomy, Earth- and space-based radar systems, passive remote sensing, weather observation, fixed and mobile land based communications, and, of course, cooking.

Fig. 1.4. Radio *frequency* describes how often the cycles of an electromagnetic wave repeat, as the strength of its magnetic or its orthogonal electrical field component increases, decreases, then increases back again. *Wavelength* is the distance between crests of the wave as it propagates through space.

The nomenclature can be appreciated in view of the development of communications technology during the twentieth century, with radio frequency capability increasing past "high-frequency" (HF), which includes up to 30 MHz (3×10^7 hertz, also known as "short-wave"), into "very high frequency" (VHF), up to 300 MHz. Additional superlatives needed to be invoked, as "ultra high frequency" (UHF), up to 3 GHz, penetrated into the so-called microwave range. Next comes "super high frequency" (SHF), up to 30 GHz, and "extremely high frequency" (EFH), up to 300 GHz (3×10^{11} Hz). SHF wavelengths approach one millimeter, so the name "millimeter-wave" also applies. Sub-millimeter wave radio, at higher frequencies, then merges into the far infrared region of the spectrum. Appendix D further describes the electromagnetic spectrum.

Both the International Electrotechnical Commission, IEC, and the IEEE[10] define microwave frequencies as starting at 1 GHz (30 cm wavelength). Microwave frequencies are then functionally grouped into nine different letter-designated bands, of which four are significant to interplanetary flight: S-band (2 to 4 GHz) and X-band (8 to 12 GHz) are both currently in use for command, telemetry and radio science. Ku-band (12 to 18 GHz) is used by some spacecraft with on-board radar instruments. Ka-band (26.5 to 40 GHz), currently used in radio science, is earmarked to support telemetry for upcoming missions such as the *Lunar Reconnaissance Orbiter* and the *James Webb Space Telescope*. Specific segments of these three bands are allocated for use in deep space by the International Telecommunication Union.

Microwaves' physical properties drive their application. The same equations of electromagnetic theory apply at all frequencies whether radio, light, or x-ray. Oscillating electromagnetic waves pass through the air and the vacuum of space at the speed of light, without requiring any medium of transport. When they encounter an electrical conductor, such as a wire, the oscillating fields induce an alternating current in the conductor, which can be detected and then amplified.

Radio waves can be used to carry information if we systematically change, or modulate, some property of the radiated waves, such as their amplitude, their frequency, or their phase. The latter is the most common practice in microwave communications. Since the capacity to carry information generally increases with the frequency, microwave communications are well suited to the need to transfer thousands or millions of binary digits (bits) of data per second between spacecraft and Earth.

As wavelengths approach the physical size of electronic components, practical circuit designs become subject to different rules. Coaxial transmission wires, which work at lower frequencies, give way to pipe-like waveguides. Circuits that employ resistors, capacitors, and chokes are replaced by cavity resonators or resonant lines to better handle microwave frequencies. The effects of reflection, polarization, scattering, diffraction, and atmospheric absorption that are usually associated with visible light become significant in the microwave realm. A microwave receiving antenna, for example, is designed to intercept and reflect the radio waves toward a focal point much the way a reflecting optical telescope does with light.

The parabolic reflector of a microwave antenna dish is a familiar component of spacecraft and ground station alike. References [5] and [6] offer technical background on these antennas. The satellite television receiving antennas in common residential use, as well as their space-based transmitting counterparts, typically use a paraboloid reflector and an offset focal point feed that sits clear of the incoming signal's path. Antenna dishes may be designed with an additional reflector that increases its performance by "folding" a long focal length into a short space (see Figure 1.5). All DSN antennas employ a two-reflector system that was invented in 1672 for telescopes by Nicolas Cassegrain (1625-1712). The DSN system is essentially the same as that of the Cassegrain optical telescope and its variations that commonly find use in amateur and professional astronomy. Each DSN antenna dish surface comprises precision-shaped perforated aluminum panels whose surface accuracy is maintained within millimeters of the ideal reflector shape, fastened to an open steel framework. These reflecting antennas not only capture incoming signals, but they can also focus energy from the station's transmitter into a narrow beam toward a spacecraft. Transmitting and receiving can normally take place simultaneously. Page 331 in Appendix B illustrates a DSN antenna.

1.2.3 Antenna Gain

The advantage of reflecting and focusing is providing *gain,* either by making an existing transmitter appear more powerful than it is (but only along a narrow beam), or collecting a weak incoming weak signal over a wide area and concentrating its power at a smaller focal point where it can be put to work. Gain in a microwave antenna is therefore analogous to *leverage* that redistributes force in a mechanical system. The most common high-gain antenna is a passive reflector.[11] It cannot add any energy to a signal, it merely redistributes it in a desired direction.

As an example, if a spacecraft's HGA were to make a 1-watt transmitter look as though it were a 100 watt transmitter in a specific direction, this would represent a gain of 100. Gain, like many telecommunications parameters, is expressed in *decibels,* dB, a logarithmic measure. A number of decibels represents the number of tenths to which the power of ten is raised. If the use of dB is unfamiliar, one can use this as a key to its meaning:

$$\boxed{n \text{ dB} = 10^{n/10} \text{ therefore: } 20 \text{ dB} = 10^{20/10} = 100}$$

We would in this case invoke a theoretical construct and assume the 1-W transmitter radiates *isotropically,* meaning evenly in all directions. Actual transmitters cannot achieve perfectly isotropic radiation, but this is convenient for reference. To make this assumption explicit we express the ratio of actual to apparent power as 20 dBi, where the "i" means it is in reference to an isotropic radiator — the 1-watt transmitter. A ratio of 20 dBi equals 100 times the isotropic radiator's intensity. Its beam can cover at most 1/100 of the sky.

The HGA is often the largest component of an interplanetary spacecraft, because its size directly affects the amount of gain it can provide. Gain G (a dimensionless ratio) is proportional to the reflector's effective aperture A_e for a given radio wavelength λ:

$$G = \frac{4\pi A_e}{\lambda^2} \tag{1.1}$$

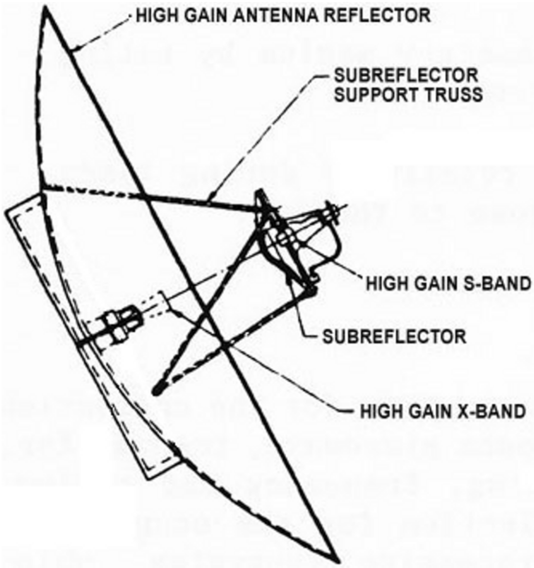

Fig. 1.5. The 3.7 meter diameter High-Gain Antenna on *Voyager* collects incoming radio energy with a parabolic main reflector. S-band achieves focus at a waveguide behind an X-band-opaque- and S-band transparent-surface subreflector, and propagates via waveguides to receiving equipment in the spacecraft electronics housing (not shown). The HGA also concentrates the spacecraft's transmitter power into a narrow beam. The X-band transmitter supplies a feed horn at the center of the main reflector dish. Employing the Cassegrain design, its output reflects off the subreflector, illuminating the main reflector for propagation to Earth. The S-band transmitter's feed is behind the S-band-transparent subreflector. From there, it directly illuminates the main reflector. Gain is 48 dB at X-band, 36 dB at S-band. Also visible in the drawing is an S-band low-gain antenna (not labeled) mounted atop the subreflector, which was available for emergency communications at distances less than Earth to Saturn. The LGA's gain is about 1 dB. Courtesy NASA/JPL/Caltech.

where the effective aperture A_e equals the actual aperture (dish diameter) multiplied by a factor μ representing the antenna's efficiency, which depends on such factors as the accuracy of its reflectors' shape, the radio reflectivity of any painted coatings, and the area blocked by structures such as the subreflector. In many cases, μ can be as low as 50%.[12] Nevertheless, a spacecraft's HGA makes a world of difference. At X-band, the *Voyager* HGA's 48.2 dB gain means a multiplier of 6.6×10^4 for its transmitter's effective power. An antenna's gain would be the same for both transmitted signals and received signals, except that each typically uses a slightly different frequency, so gain values differ accordingly for uplink and downlink.

1.2.4 Power in the Link

The microwave signal starts out from a lightweight transmitter on the spacecraft whose power output is necessarily modest due to the need to keep mass and power consumption at a minimum. This basic radio-frequency signal is called the carrier signal, because it can be used to carry information such as telemetry. Sometimes the carrier is used in its pure form, for example to carry out various kinds of radio science experiments.

The loss of power that the carrier appears to suffer across the interplanetary distances it travels can be quite substantial.[13] If the spacecraft's transmitter were radiating isotropically, that is in all directions without the benefit of a columnizing HGA, then the received power flux density[14] at a point on Earth would simply be the transmitted power divided by the area of a sphere whose radius is equal to the distance to Earth, since the signal expands in spherical wave-fronts during propagation.

Voyager 2's X-band transmitter radiates at 12 watts, and the HGA concentrates this into a narrow cone-shaped beam of nearly 800,000 watts effective isotropic radiated power (EIRP) with respect to our theoretical omnidirectional radiator. This cone of concentrated power expands at the same rate nonetheless, with the result that an antenna of finite area on Earth only intercepts a tiny portion of *Voyager*'s expanding spherical wave-fronts. The signal usually suffers no significant attenuation from anything except the Earth's atmosphere, and at X-band and S-band frequencies the air is largely transparent unless there happens to be precipitation occurring in front of the ground-based antenna. So the distance itself is the major contributor to signal weakening, and its effect on the received signal is called the free-space path loss, or space loss, L_S:

$$L_S = \left(\frac{4\pi r}{\lambda}\right)^2 \tag{1.2}$$

where $4\pi r$ accounts for the area of the expanding wave-front of radius r, which is the distance to Earth. λ is the radio signal's wavelength. Why would wavelength affect space loss? Well, it does not, directly. It is part of the equation only because we must intercept the small sector of the signal arriving at Earth using an antenna of finite size, and antennas *are* dependent on wavelength (see Equation 1.1).

1.2.5 All Things Considered

Prior to considering any scheme of modulating information onto the carrier, let's visit the complete list of factors that effect the carrier's level of power received in a line-of-sight deep space communication link from a distant spacecraft. Most of the terms in the list are seen as losses which diminish the signal. There are only two gain factors that provide an increase. Since each of the terms is expressed here in the logarithmic unit dB, adding algebraically will determine received power (alternatively, the terms could be expressed as factors to be multiplied). Often called a "link budget," the factors are:

$$P_R = P_T - L_T + G_T - L_{TP} - L_S - L_A - L_P - L_{RP} + G_R - L_R \tag{1.3}$$

where

P_R is the power in milliwatts of the pure carrier received on Earth from the spacecraft's transmitter, as seen at the input to the DSN receiving electronics (a low-noise amplifier). Expressed in dB for convenience; "m" indicates the reference is to a milliwatt (n dBm equals $10^{(n/10)}$ mW).

P_T is the spacecraft's transmitter power, a quantity usually on the order of tens of watts, which can also be expressed in dBm. For example, 10 watts of transmitter power equals 10,000 milliwatts, which can be expressed as 40 dBm.

L_T represents the sum of losses in the transmitter's cable and/or waveguide "plumbing." This is usually a small loss, on the order of 1 dB. Here, we use dB as a unitless ratio; 1 dB is equal to a factor of about 1.26.

G_T is the transmitting gain that the spacecraft's antenna supplies. An HGA can boost the signal tens of thousands of times, measured along the resulting narrow beam. It is determined by the antenna's area, efficiency, and the radio wavelength as discussed with equation 1.1. Unitless ratio.

L_{TP} is the transmitter pointing loss. This term will only be non-zero if the Earth is not within the spacecraft antenna's optimal radiation pattern, for example a spacecraft using an HGA that is not pointing squarely toward Earth. In the worst case, L_{TP} can rise to infinity. For spacecraft such as *Voyager* which fire thrusters to maintain HGA pointing, L_{TP} will vary continuously, though typically only a fraction of 1 dB, within limits imposed by the spacecraft's attitude dead-band (discussed in Chapter 3). Unitless ratio.

L_S is the big one — space loss. The signal power that we can capture with an antenna of any given size diminishes by factors including the square of the interplanetary distance, as we saw in equation 1.2. In some literature, this factor appears as L_P for "path loss" in free space. The path through "free space" is typical of deep-space communications in contrast to some land-based systems which may involve obstructions or reflections from buildings, etc. in the signal path. Unitless ratio.

L_A is atmospheric loss, attenuation when the signal passes through an atmosphere. For example, a spacecraft's signal passing a minimum distance through Earth's usually benign clear air might suffer less than 1 dB. The effect can become more significant when the spacecraft appears low in the Earth's sky while rising or setting, or when there is precipitation along the path to the antenna. Note this term can also include the effects of an atmosphere in which the spacecraft is immersed, such as that of Mars or Titan. Unitless ratio.

L_P is the polarization[15] loss, caused if there happens to be a mismatch between the spacecraft transmitter's polarization and the polarization settings for the Earth-based receiver. Typically, this loss is zero or near zero, but a mismatch might cause it to be tens of dB. Unitless ratio.

L_{RP} is the receiving antenna pointing loss, caused if the DSN station is not aimed squarely toward the spacecraft's location in the sky. Note that near the horizon, the antenna pointing must accommodate atmospheric refraction which makes the spacecraft appear higher in the sky than it really is. Typically, L_{RP} is zero or near zero during normal operations. Sometimes high winds at the station may interfere with accurate pointing, and cause this value to fluctuate. Unitless ratio.

G_R is the largest gain in the link budget, that of the receiving DSN station's Cassegrain antenna system. In the example of a 34-meter aperture or a 70-meter aperture DSN antenna, the X-band gain can typically be near 68 or 74 dB respectively (note the latter figure means a 25 million-fold increase), although it will vary depending on frequency. Unitless ratio.

L_R is receiver loss, by which the signal is diminished in the waveguides, cables, and other hardware leading up to the receiver input. This is usually a small loss, on the order of 1 dB. Unitless ratio.

Table 1.1 compares operational values for some of these parameters among three interplanetary spacecraft.

To increase the amount of received power P_R, two significant components of a link budget can be varied during spacecraft design and fabrication, and a third can be varied at any time:

1. Increasing the spacecraft's transmitting power P_T. A more powerful transmitter may have more mass, and will probably require more electrical power from the spacecraft's power supply, thus it impacts the spacecraft's mass and its power system design. The electrical power supplying a transmitter is substantially greater than its radiated output. *Voyager*'s X-band transmitter, which is typical, consumes 48 W of DC power to put out 12 W at X-band.
2. Increasing the size and efficiency of the spacecraft's antenna gain G_T. This mostly means increasing the diameter of the HGA, and therefore probably its mass. The antenna's diameter may run into constraints imposed by dimensions of the launch vehicle's aerodynamic shroud. Some spacecraft, such as the Tracking and Data Relay Satellite System, TDRSS,[16] have overcome such limits by deploying folded antenna reflectors after launch. A notable case is *Galileo*'s 4.8-meter aperture HGA, whose deployment failed en route to Jupiter in 1991, requiring that the mission be carried out using the spacecraft's low-gain antenna. Reference [7] provides the complete details of this failure and the success in recovering *Galileo*'s mission.
3. Finally, there is one thing that can be done to improve link performance even after a spacecraft has been designed, built, and launched. The Earth-based receiving antenna gain G_R can be improved by adjusting or replacing its reflecting surfaces to increase efficiency, or by increasing aperture to intercept a larger portion of the incoming spherical wave-front from the spacecraft. This can require building new, larger antennas, engineering improvements to existing antennas, or combining signals from multiple antennas in a technique called *arraying.*

Increasing the efficiency and aperture of Earth-based stations was indeed accomplished in 1978, when three of the DSN's 26-meter aperture antennas worldwide were modified to increase their main reflectors to 34 meters in diameter. Again in 1988, re-engineering the DSN's three 64-meter aperture antennas was completed, increasing their apertures to 70 meters and improving their efficiencies in several ways (see reference [8]) in anticipation of the *Voyager 2* encounter with Neptune.

Table 1.1. A comparison of parameters in the routine downlink communications between Earth and three interplanetary spacecraft. Refer to equation 1.3 for parameter definitions. Adapted and updated from [9–11].

Spacecraft	*Galileo*[a]	*Cassini*	*Voyager 1*
Location	Jupiter	Saturn	Outer solar system
Distance	7.41×10^8 km	1.52×10^9 km	1.57×10^{10} km
Epoch	March 2002	September 2007	January 2008
Frequency Band	S	X	X
Frequency, GHz	2.3	8.4	8.4
Basic link budget:			
$P_T - L_T$, dBm	+40.8	+41.7	+40.9
Antenna, G_T, dBi	LGA, +8.1	HGA, +47.2	HGA,[b] +48.2
L_S, dB	–276.9	–294.5	–314.8
70 m antenna / G_R, dBi	+63.3	+73.7	+73.7
= P_R, dBm	–164.7	–131.9	–152.0
= P_R, mW	3.39×10^{-17}	6.46×10^{-14}	6.31×10^{-16}

[a] *Galileo*'s mission ended September 21, 2003 after orbiting Jupiter for nearly 8 years.

[b] It may seem odd to realize *Voyager*'s smaller (3.66-meter) HGA provides better gain than *Cassini*'s 4-meter diameter dish. *Cassini*'s HGA is optimized for performance of radio science experiments at Ka-band, for which it provides a 56.4 dB gain.)

During that encounter in 1989, the Voyager project instantiated an array of its 70-meter and 34-meter antennas with twenty-seven additional 25-meter antennas of the Very Large Array (VLA) near Socorro, New Mexico, which had been modified to capture Voyager's signals.

Using more than one antenna and electronically combining their individually collected signals can provide a healthy boost to G_R. Arraying a number of separate antennas in this way of course requires pointing them all toward the same spacecraft. Four 34-meter aperture antennas can provide a collecting area and signal gain approaching the equivalent of one 70-meter antenna. While this is rarely done, it is not uncommon to use one 70-meter antenna and one 34-meter antenna to improve link performance on occasion. It is even possible to array two 70-meter antennas on different continents. While the arraying technique can improve the Earth-based receiving situation substantially, it is subject to new categories of minor losses related to the process of electronically combining the separate inputs. Probably the largest drawback to the arraying technique, though, is logistical: it is often difficult to schedule multiple antennas for use by one project, because there are usually many users competing for the DSN's limited resources.

While considering that widely separated antennas may be arrayed to augment a spacecraft's received signal power, we should note that the goal here is to increase the total aperture: the area of incoming signal actually collected. This is a goal different from the astronomer's goal in using widely separated microwave antennas or optical telescopes trained on one source. Using apertures separated by distance r, the astronomer can apply the technique of interferometry (which we will visit in Chapter 2) to obtain the spacial resolution (not the collecting ability, though) of a single aperture of diameter r. Examples of this application of interferometry include the Keck Telescope Interferometer [12] and the Very Large Array.[17]

1.2.6 Signal-to-Noise Ratio: SNR

Compare, if you will, the task of receiving a faint spacecraft signal across the solar system to the task of hearing a person whisper across a soccer field. Success will depend greatly on the level of audio-frequency noise present on the field, which might range from that of a still, quiet dawn when you can hear a bird calling a kilometer away, to mid-game when a thousand fans are screaming. The ratio of the signal power to the ambient noise power in the frequencies of interest is all-important. It's known as *signal-to-noise ratio (SNR).*

Fortunately, there's little microwave noise in deep space. What pervasive noise there is, though, is the feeble residual from a powerful event in our deep past, the "Big Bang," when space-time and energy came into being and simple forms of matter and antimatter initially condensed and largely annihilated one another. The fossil radiation from this event can be measured as a background noise spanning microwave frequencies, with a peak around 160 GHz. For the purpose of telecommunications, we can assume this background noise to be isotropic — the same intensity in all directions. Measuring miniscule variations, or anisotropy, in this cosmic background radiation by the way, is the subject of scientific investigations, some of which use spacecraft to study the universe's origins, for example, the *COsmic Background Explorer* (COBE),[18] the *Wilkinson Microwave Anisotropy Probe* (WMAP),[19] and the *Planck Surveyor*.[20]

We typically express microwave noise as a temperature on the Kelvin scale. Absolute zero, a theoretical point at 0 K, represents the total absence of noise-making atomic or molecular motion. Anything warmer than that, i.e. everything, will be radiating some electromagnetic energy (noise) at frequencies spanning all the way from radio and infrared wavelengths, for cool objects, to frequencies of visible light from objects heated to incandescence, and to higher frequencies for objects at even higher temperatures. Matter being crushed as it falls into a black hole in the center of a galaxy can reach a hundred million kelvins and radiate at frequencies up through X-ray. Measurements show the cosmic microwave background noise to have a temperature of 2.73 K. By comparison, the microwave noise emitted from a warm patch of terrain here on Earth[21] can be close to 300 K. The Sun's noise temperature is about 5,780 K.

An Example of X-Band SNR

In the soccer-field example cited above, if instead of yelling, the fans were all blowing dog-whistles with frequencies well above the range of human hearing, there

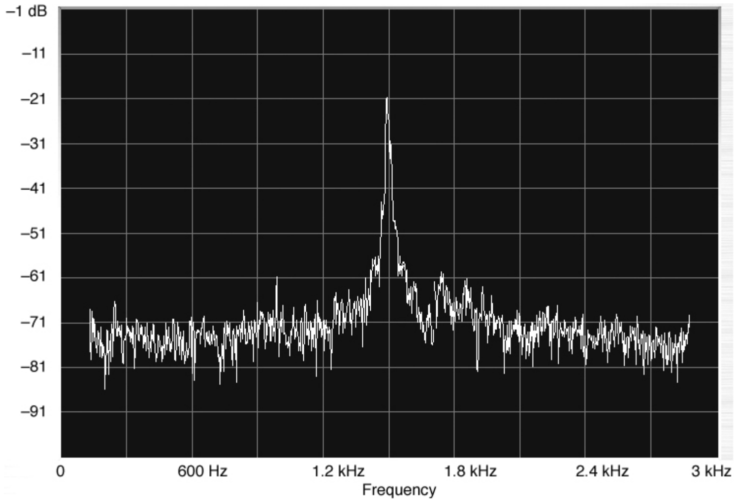

Fig. 1.6. As an illustration of the signal and noise from more familiar phenomena, this display shows the results of a fast Fourier transform (FFT) algorithm, known for the French mathematician and physicist Jean Baptiste Joseph Fourier (1768–1830), applied to the audio received by a laptop computer's built-in microphone. These audio frequencies are quite low compared to microwave radio frequencies and represent acoustic rather than electromagnetic waves, but they serve nonetheless to illustrate the relationship between noise and signal. The display indicates on its vertical scale the power measurement of each of 1,024 discrete frequencies that the algorithm sampled, starting near zero on the left and extending toward 3 kHz at right. Much of the display shows the power of ambient noise at a level between −71 dB and −81 dB generated by the computer's internal fan. The peak, up to −21 dB near 1.5 kHz, represents the sound of a whistle blowing, a signal standing out from the noise by roughly 50 dB — a factor of a hundred thousand. Such FFT graphic displays conveniently show the power of each of many specific frequencies, including noise and signal, and are widely used in radio communications operations and analysis. Compare with Figure 1.11 on page 44.

would be no impact on the ability to hear the person whispering. Noise only concerns us when it is present within the band of frequencies being used for communication. Let's consider an example with an antenna looking through Earth's atmosphere into deep space with no terrain or Sun in view, and see what component of noise is important. On a clear dry day, tracking at an elevation well above the horizon, the noise that Station 63 reported to the Ace (on page 6) had a value of 21 K. We know the spacecraft signal's power in watts, so we'll convert the noise temperature from kelvins to noise power *spectral density,* the power of noise per unit frequency — that is, the amount of noise present in one-hertz samples of signal. We can use one of the equations formulated by the Austrian physicist Ludwig Boltzmann (1844–1906):

$$N_0 = kT \tag{1.4}$$

where

N_0 is the noise (power) spectral density in watts per hertz,
k is the Boltzmann constant 1.38×10^{-23} joules per kelvin, and
T represents the noise temperature in kelvins, the units reported by DSN.

The constant k is given in units of J/K. Since the joule is a measure of energy equivalent to watts (power) times seconds, our desired result in watts per hertz — cycles per second — will be consistent. For our example,

$$N_0 = 1.38 \times 10^{-23}\ x\ 21 = 2.90 \times 10^{-22}\ W/Hz \tag{1.5}$$

For convenience, we'll convert the value in watts per hertz on a calculator to −185.4 dBm/Hz (note the change to milliwatts). Dividing the received total power P_R from *Cassini* at Saturn from Table 1.1 on page 18 by this noise level (subtracting the dB values since they are logarithmic) gives the ratio of the spacecraft's received power to the noise spectral density, P_t/N_0:

$$P_t/N_0 = \frac{-131.9\ dBm}{-185.4\ dBm/Hz} = 53.5\ dB/Hz \tag{1.6}$$

The result means that wave-for-wave, *Cassini*'s signal is over 223,000 times more powerful than the noise presented to the receiver. It is still a whisper of a signal, but it will be clearly detectable among the much softer whispers of noise.

Receiving systems, though, often have sensitivity across a range of frequencies, rather than tuning in to only one specific frequency. This range of frequencies is called the receiver's *bandwidth.* For example, if a receiver can accept frequencies in the range from 8.3 GHz to 8.5 GHz, we would say its bandwidth is 0.2 GHz, or 200 MHz. As we'll later see, it is useful to consider the total noise power within the bandwidth. As long as we can assume the noise is pretty evenly distributed, its total power can be determined by multiplying bandwidth B by the noise spectral density N_0 from equation 1.4. In this case, the total noise power N across bandwidth B is:

$$N = BN_0 \tag{1.7}$$

where N is expressed in dBm, B is given in hertz, and N_0 in dB/Hz. What is important here is that increasing a receiver's bandwidth exposes it to more noise. Thus when it is necessary to achieve a high signal-to-noise ratio, SNR, one strategy is to design a system in which the receiver's bandwidth can be made as small as possible.

Usually, we're talking about the spacecraft's total radio-frequency signal received by the DSN including the carrier and the data. We'll visit N_0 again later in evaluating ratios of the information a carrier signal can convey relative to the background noise. But first, there are more sources of noise to consider.

1.2.7 Amplification

Although the spacecraft's signal stands out against the noise, it is of extremely low power, and to be of use it must be amplified. An *amplifier* is a device that takes in a weak electronic signal and sends out a stronger one that faithfully replicates certain characteristics of the input such as phase and amplitude changes. It actively generates signal *gain* at the expense of power from an electrical power supply.

We know that all objects radiate electromagnetic noise as they are warmer than absolute zero, and the higher the temperature the more noise they emit. As electronic signals pass through discreet electronic components such as transistors inside receiving equipment, they will be subjected to additional sources of noise. You can imagine electronic noise being generated when flowing electrons knock into the atoms that make up a transistor. Imagine a brook flowing rapidly along a channel full of large rocks, babbling as the water encounters obstacles. The warmer the atoms in the transistor are, the higher the level of noise they contribute, almost as though rocks in the brook were rapidly moving about on their own, even as the current of water rushes by them. An important challenge, then, especially while our incoming signal is very weak, is to use electronic components that contribute little additional noise.

Having been collected and focused by a DSN antenna's main reflector and its subreflector the way a reflecting telescope manipulates light, a spacecraft's tiny signal beams into a feed-cone in the center of the dish, then propagates down along a system of pipe-like waveguides, through filters and polarizers, to the Low-Noise Amplifier (LNA), which is mounted either within the moveable antenna structure, or in its basement. To minimize the LNA's contribution of noise from vibrating atoms and molecules, liquid helium refrigerates it to temperatures of 7 K or lower. Furthermore, the LNA's design employs some highly evolved physics that minimizes noisy collisions between its cold, nearly motionless, atoms and molecules and the flowing electrons.

Early Amplifiers

In 1906 the American inventor Lee DeForest (1873–1961) devised the first electronic amplifier, which he called the "Audion." Two years earlier, the British physicist Sir John Ambrose Fleming (1849–1945) had developed the first electronic vacuum tube, which became known as the "Fleming valve." We'll briefly trace the workings of these first vacuum tubes so we can compare them to the functions of modern low-noise microwave amplifying devices that are crucial to sustaining the link between spacecraft and human.

Fashioned after the experiments Thomas Alva Edison (1847–1931) conducted with incandescent light bulbs, Fleming's revolutionary device also had a metal component, called a cathode, that was electrically heated to incandescence. The heated cathode is shown schematically in Figure 1.7 as the $\wedge$ at the bottom of each circular vacuum tube symbol. The small battery symbols in the figure, with + and – polarity indications on their left and right below each vacuum tube, represent the electrical supply used solely for heating the cathode. When the larger, higher-voltage battery is connected with its negative polarity to the cathode, a direct current[22] of electrons flows across the vacuum to another metal component, called the anode or plate, completing the circuit to the battery's positive terminal. This flow is illustrated with three arrows inside the tube going from cathode to plate. Ammeter "A" in the plate circuit would register the current flowing. From previous employment with Edison, Fleming understood this phenomenon as the Edison effect,[23] and he put it to use detecting (but not amplifying) radio signals.

In his work with the British Wireless Telegraphy Company, Fleming wanted to observe the arrival of "wireless" (radio) waves using a galvanometer, a device which did not respond well to the alternating electric current that incoming electromagnetic waves set up in a receiving antenna wire. The indicator needle of his galvanometer, an instrument that today we would call an analog DC voltmeter, would have tried to vibrate too rapidly to even notice, instead of showing some net deflection in one direction when a wireless signal arrived. He applied the antenna's signal to the cathode of the "valve," which then conducted the radio signal's current only when its wave was cycling through its positive polarity. His device thus acted as a rectifier, filtering out the waves' excursions into its other polarity. Since the needle of his galvanometer was no longer being driven rapidly in two conflicting directions, it indeed was able to register the small incoming radio signal. (Around the same time, radio enthusiasts were fitting lumps of mineral crystals — "semiconductors" in today's language — with delicate, moveable pointed wires called "cat's whiskers" to detect signals, though somewhat unreliably.)

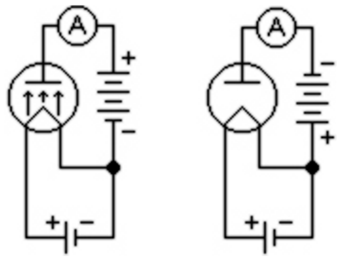

Fig. 1.7. Thermionic emission, known as "the Edison effect" and "cathode rays" prior to discovery of the electron in 1897 by British physicist J. J. Thomson (1856–1940), is seen as a current (arrows on left) flowing through a vacuum from a heated cathode to an anode, or "plate," but only when the plate is given a more positive potential than the cathode. Note the absence of current when polarity of the large battery is reversed in the diagram on the right.

Since the Fleming valve had two components, a cathode and a plate, he called it a "diode."[24] Small solid-state components in wide use today bear the same name because they have two wires, and they serve to let electric current pass only in one direction, as did Fleming's vacuum tube. While Fleming's diode could be used to detect radio signals, it could not increase, or amplify, their strength. This is the breakthrough DeForest achieved.

Knowing that a Fleming valve would only conduct current when the cathode "saw" a more positive electrical charge than its own, DeForest inserted a third component — the grid — in his vacuum tube, in between the cathode and anode, creating the first "triode." When the grid was given even a small negative charge, it reduced or prevented current flowing to the anode. In this way, his Audion allowed detected radio waves to exercise *control* over a flowing electric current that was powerful enough to drive an audio transducer — headphones or a loudspeaker. The triode's amplified output formed a powerful duplicate of the miniscule input signal. This revolutionary technique, electronic amplification, ushered in the age of electronics.

1.2.8 The HEMT Low-Noise Amplifier

Today, the most common component used in the DSN as the first stage of amplification for a received microwave signal also involves controlling the flow of electrons in a relatively strong current. It does this in the solid state by applying a varying electric field — part of the incoming microwave electromagnetic signal — physically near the main current flow, much like the Audion does in vacuum. The device is a type of field-effect transistor (FET)[25] called a high-electron mobility transistor (HEMT).

How HEMTS Work

A very thin layer of highly concentrated electrons, sometimes called a two-dimensional electron gas, is made to move across a specially layered very pure semiconductor material, typically either gallium arsenide layered atop aluminum gallium arsenide, or alternatively indium phosphide on indium phosphide antimonide. It is also called a heterostructure FET (HFET). The electrons flow through this device largely unimpeded, with very low resistivity and thus very little noise, between source and drain components which we might call the equivalent of a vacuum tube's cathode and anode. The third component of this solid-state device is the gate, analogous to the triode's grid, where the microwave signal is introduced straight from the DSN antenna dish. The microwave signal presents a minute varying voltage on the gate, which alters the conductivity of the layer of high-mobility electrons, producing amplification not unlike in DeForest's Audion, but much more quietly.

Recall that the cathode in a vacuum tube amplifier is intentionally *heated* until it glows and emits electrons by virtue of its hot, agitating atoms. At microwave frequencies, this elevated T in equation 1.4 would spell troublesome quantities of noise. In DSN applications the HEMT and its adjacent waveguide are instead *cooled* cryogenically to within several kelvins of absolute zero. Two aspects are at work here to minimize noise. First the quantum physics of a HEMT's thin free-flowing electron layer permits electrons to glide with few noisy collisions across the pure semiconductor. And second, the cooled thermal state means the HEMT's and waveguide's atoms and molecules themselves contribute little vibrational noise.[26]

HEMTs are also employed in many other microwave receivers in common use, such as residential television systems that receive signals directly from spacecraft in geostationary orbits. These, and many other applications, enjoy higher power levels of incoming microwave signals from nearer, stronger spacecraft transmitters, so they can forego the complicated and expensive cryogenic cooling systems that are found in the DSN.[27]

1.2.9 The Maser Low-Noise Amplifier

Maser LNAs offer lower noise contributions than HEMT LNAs and better rejection of unwanted signals. Maser stands for "*M*icrowave *A*mplification by *S*imulated *E*mission of *R*adiation" (a *laser* applies the same principle to light). This kind of amplification differs from the way a triode or a transistor works by controlling a strong potential current using a weak input signal. The maser principle, proposed in 1917 by German-born physicist Albert Einstein (1879–1955), is based on the ability of matter to absorb and then emit radiation at microwave frequencies (and at light frequencies in the case of the laser). The American physicist Charles Hard Townes (1915–) and his colleagues built the first maser in 1954 using ammonia molecules in a resonant cavity. He shared the 1964 Nobel Prize in physics for his work on masers and lasers.

How Masers Work

Emission and radiation are everyday occurrences. Household electricity heats a cathode at the ends of a residential-style fluorescent tube or compact fluorescent lamp. The cathode gives off electrons via thermionic emission, some of which collide with atoms of mercury vapor or other gasses inside the tube. In turn, the gas soon ionizes and conducts electrical current freely along the length of the tube, adding more electrons to the mix (at which point the lamp's external electrical ballast serves to reduce the current flow). Every time a fast-moving electron hits an atom of gas inside the tube, it causes one of the atom's own electrons to jump to a higher energy level, absorbing some or all of the energy delivered by the collision. The atom's new energy state is unstable, so the atom soon reverts to a lower, more stable, energy level. In doing so, the atom *emits a photon.* This process repeats as long as electrical current is supplied. (The photons emitted from the atoms of gas within the tube typically have wavelengths in the ultraviolet part of the electromagnetic spectrum, which excite a chemical coating on the inside of the tube, making it fluoresce, radiating photons at longer, visible wavelengths, and lighting up the room.)

In a DSN maser LNA, a ruby, which is an aluminum oxide crystal, harnesses a process similar to the fluorescent tube's gas, but the result is amplification instead of illumination. Masers' internal configurations are highly complex and varied, incorporating crystals, resonating cavities, and magnetic fields, but here's the concept: atoms or molecules in the ruby are "pumped" with an input of relatively strong microwave energy at the right resonant frequency, vaguely analogous to household electricity "pumping" atoms of the gas in a fluorescent tube up to a higher energy level. The ruby's atoms' new, higher energy state is also unstable — on a "hair trigger," if you will — so that interaction with a weak incoming signal from a spacecraft is all it takes to stimulate them to drop en masse to their lower-energy stable states. In doing so, the trillions of atoms in the crystal emit their "photons" of microwave energy coherent with the incoming signal. This all happens billions of times a second, in resonance with the microwave signal's frequency. The result of this stimulated radiation is a powerful amplification of the incoming microwave signal. The amplified signal is directed to the maser's output waveguide. A DSN maser can achieve a gain of 50 dB or more, while introducing very little noise of its own.

1.2.10 LNA Bandwidth

Whether the first amplifier that a spacecraft signal encounters is a HEMT or a maser, the LNA must be sensitive to a fairly large bandwidth of frequencies for a couple of reasons. First, the DSN antennas where the LNAs are physically located serve many different spacecraft, each of which transmits on its own frequency. Second, relative motions between the Earth and the spacecraft induce substantial changes in the received frequency because of the Doppler shift, which we'll examine more closely in the next chapter. These factors make it impractical for a DSN LNA to have a very narrow bandwidth, despite the potential improvement in signal-to-noise ratio this would mean per equation 1.7. As a trade-off, LNAs in the DSN typically have a bandwidth near the order of 100 MHz. Separate LNAs are, however, provided in DSN antennas for the widely separated microwave frequency *bands* they serve, including S-band, X-band, and Ka-band. It is physically impossible for one LNA to cover all these bands, and it would be undesirable anyway due to the unfavorable effect of large bandwidths on SNR. Instead, it will be the next stage, the receiver, which selects a very narrow band of frequencies from among those that the LNA outputs, to further amplify and process.

1.2.11 Microwave Signals To Go

Up until the LNA has amplified it, the infinitesimal signal from a distant spacecraft has required extraordinary handling including precisely configured antenna reflectors and waveguides, and cryogenically cooled components. After it has been boosted by the LNA, whether maser or HEMT, the signal is strong enough now to be delivered to the Signal Processing Center a number of kilometers from the antenna. This is accomplished by representing the microwave signal as light, and sending it via fiber optic cable to the SPC. Here's how that works:

In the antenna system near the LNA, there is a laser that serves as a source of spectrally pure light with an output power around 25 milliwatts. The output from the LNA, which contains the amplified spacecraft's radio signal, feeds into an optical modulator. This device varies the intensity of the laser light to replicate the microwave signal: when the radio energy reaches the crest of each of its waves, the modulator becomes most transparent to the laser light, and allows most of its intensity to pass into the fiber optic cable. As the radio energy decreases toward the bottom of each wave, the modulator becomes more opaque until a minimum of light goes into the cable. All this happens more than 8×10^9 times per second for an X-band microwave system, and over four times that rate in the Ka-band system.

1.2.12 The Closed-Loop Receiver

Upon arrival in the SPC the signal from the LNA is fed to a receiver. In your automobile, the radio receiver selects incoming radio waves of a desired frequency, locks onto them, separates off the audio signal, which it amplifies and sends to the speakers. The receiver the DSN typically uses is called the Block-V (Roman numeral five) Receiver (BVR). The BVR works basically the same way as your audio receiver does, but it accomplishes several additional tasks. This software-based intelligent device has evolved over the years to meet the most stringent requirements of the missions the DSN serves.

While the DSN station is preparing to track a spacecraft, the BVR is directed to configure itself. It pulls information from a local database that enables it to select the proper antenna, identify the spacecraft whose signal it will be receiving, tune to the proper frequency, select a desired bandwidth (typically less than 10 Hz), and prepare to output its signals to the correct equipment. When the antenna is pointed at the spacecraft as it rises above the horizon, the BVR initiates an acquisition process that includes executing a fast Fourier transform to locate the exact frequency of the spacecraft's signal. When it finds the signal it locks onto it. After acquisition, its sensitive bandwidth is typically narrowed to just a few hertz to increase its signal-to-noise performance. As the spacecraft's signal changes frequency gradually because of Doppler shift, the BVR remains firmly locked, following it for hours.

Receiver In Lock

What does it mean when a receiver "locks" onto a signal? When you listen to an FM radio station in your home, after you have set your dial to the desired carrier frequency, the receiver stays in tune even if its frequency changes, or drifts by some small amount as FM transmissions tend to do. The receiver accomplishes this by using an electronic circuit known as the phase-locked-loop (PLL). It generates an internal error-signal voltage when the incoming signal changes its phase or its frequency. This error signal forces the receiver to change its own tuning slightly, away from the exact frequency you set the dial to. Because of this, the PLL is an example of a control system using negative feedback in a closed loop (see page 94). Suffice it to say that the PLL in your FM radio "watches" every wave of the signal, around a hundred million of them every second, and adjusts its own tuning in response to any small changes it sees. A signal being followed by a receiver's PLL in this way is said to be "in lock." Any large change in the signal's frequency, though, will cause the receiver's PLL to lose lock, resulting in loss of signal in the receiver. This doesn't normally happen with your FM radio station, but it can happen with spacecraft.

The BVR processes the incoming signal to make sense of the information it has carried from the spacecraft. It measures the Doppler shift that will reveal the craft's line-of-sight velocity by counting all of the incoming carrier-signal waves per unit time. It also demodulates the signal. Demodulation means taking the information-bearing signal out of the higher-frequency carrier signal that transported it through space. The BVR demodulates range data to reveal the spacecraft's distance (we will examine Doppler and range in the next chapter). Finally, the BVR demodulates telemetry symbols which the telemetry system will decode later to reconstruct the binary digits "1" and "0" relaying results from the spacecraft's science instruments, and the vehicle's health and status, to scientists and engineers on the flight project.

As if these tasks were not enough, the BVR also manufactures the signal that will be sent up to the spacecraft. The circuitry within the BVR that does this is called the "exciter" because its output will be used to excite a very powerful amplifier, called a *klystron*,[28] which will replicate it as a multi-kilowatt microwave uplink to the spacecraft, funneled through the same DSN station's massive reflectors while they are gathering the faint incoming signal. Signals to be uplinked that comprise input to the BVR's exciter include a stable reference frequency that will become the carrier, and signals carrying commands and ranging tones that will modulate this uplink carrier.

Finally, the BVR and all its associated equipment provide complete data on how they themselves are performing. This *monitor* data is used by station operating personnel as well as flight project team members, and is eventually archived along with all the spacecraft's data. Not only the BVR, but also virtually all equipment in the DSN, generates monitor data during use.

1.2.13 The Open-Loop Receiver

There's another receiver system that can be useful for some processes such as very long baseline interferometry (VLBI) and radio science, each of which we'll examine later. Open-loop receivers, also called full-spectrum receivers, capture the signal and noise over a fairly wide band of frequencies and record it by sampling it at high rates. They can display and analyze the bandwidth they observe using fast Fourier transforms (see Figure 1.6) and other methods. The receivers that serve this purpose do not select one frequency from among many and lock onto it in closed-loop fashion the way the BVR does. Instead, they simply observe everything that is present in their bandwidth, capturing precise measurements of frequency, phase, and amplitude across a given range. Open loop receivers take their input from the LNA via fiber optics, as do the closed-loop receivers, and their output goes directly to the users for storage and further processing. Figure 1.11 on page 44 is an example of an open-loop receiver's display.

1.2.14 Transporting Information

On the spacecraft, information from its subsystems and from its scientific instruments to be transported to Earth consists of the binary digits one and zero. This is the type of data known as *telemetry,* from the Greek prefix *tele*, "distant," and *metron*, "measure." The microwave signal propagating through space is known as the "channel" through which this information is to be sent.[29]

As an example of information, consider the black-and-white image that registered on the detector in *Cassini*'s 1-megapixel narrow-angle camera on September 10, 2007, which we see on page 8. The camera's electronics can use a mode in which the brightness of each pixel (picture element, a single dot) in the image is represented by twelve binary digits, representing 2,048 different levels of grey. There are 1,024 pixels on each side of the image on page 8. In this mode, an image would consist of about 1.26×10^7 bits for the telecommunications system to send home to Earth. Once received, the imaging science team's software re-creates each pixel to its specified brightness, and arrays all million-plus pixels into an exact replica of the image that registered on the camera's image detector. Natural color renditions typically require three images to be taken, each through a different color filter, later to be combined on Earth into a single color image (more on this process in Chapter 6).

1.2.15 Modulation Schemes

There are various ways to send information via a radio beam, but since many of today's distant interplanetary spacecraft use a method called Binary Phase Shift Keying (BPSK), we'll focus on that scheme. To explore how BPSK works in deep space applications, let's take the microwave radio sine wave illustrated in Figure 1.4 back on page 11, and assume it represents the spacecraft's downlink. The wave would repeat at a frequency in the neighborhood of 8,400 MHz, which gives it a wavelength of about 4 centimeters from crest to crest as it propagates through space. To create a symbol for carrying information, the spacecraft's BPSK encoding scheme causes the wave to jump to the right of its nominal position a little, so its crests and troughs occur a little later in time, and it maintains this state for a predetermined duration, then shifts its phase back to normal. See Figure 1.8. Each period of shifted phase and each period of absence of a shift is called a "symbol."

Symbols and Bits

We could imagine a convention of using symbols in which each shift to the right and back would convey a "1," and each period without such a shift would convey a "0." This illustrates the fundamentals of BPSK modulation. The convention used in actual operations does basically this, but the relationship between the original number of bits and their corresponding phase-shift symbols is not so simple. The actual symbols are determined by special algorithms, within the spacecraft's telecommunications subsystem, designed to overcome noise and maximize the communication rate.

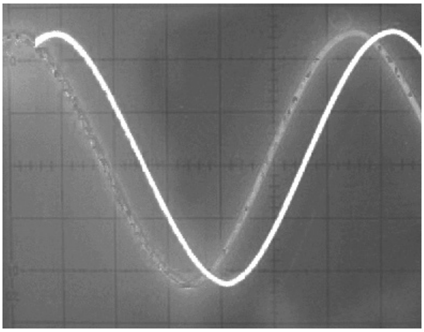

Fig. 1.8. Binary Phase Shift Keying (BPSK) conveys information by shifting the carrier signal's phase between two possible states.

The *modulation index* describes how much the carrier signal's phase varies around its unmodulated state. The specific value for a modulation index is selected to optimize performance in the telecommunications system. Figure 1.8 illustrates a symbol shifted to a modulation index of perhaps 40° out of phase with the unmodulated wave, which appears as the lower-contrast "ghost" wave in this artist's conception. For reference, a value of 180° out of phase would mean the peak occurs when the wave's trough would otherwise have occurred.

By way of comparison, another scheme for sending information is Quadrature Phase Shift Keying (QPSK), which has four possible phase-shift-keyed symbols, each using a different amount of phase shift. QPSK is often used in local area network communications between computers and peripherals over wire, fiber optics, or short-distance microwave radio channels. To digress even further, there are methods that use even more symbols. Known as 64QAM and 128QAM (also called QAM64 and QAM128), these quadrature amplitude modulation methods vary the carrier waves' amplitude, or height, instead of their phase, to modulate the information they carry using 64 or 128 recognizable steps. Even more densely packed with information, 256QAM is commonly used for high-definition television delivered by cable in the U.S. If noise were not a concern, a system could be designed in which every wave could in theory carry an *infinite* number of symbol-steps. This is because every possible infinitesimal variation of a wave could represent a different information symbol, if such a noiseless channel could exist.

Returning to the topic of BPSK-modulated signals from spacecraft, information can be placed either directly on the carrier or alternatively a carrier can be modulated by a high-frequency tone, called a subcarrier, which itself is then modulated with information symbols. This scheme can be useful for transporting multiple kinds of information, such as navigation ranging signals on a subcarrier, and telemetry on another subcarrier or directly on the carrier. In a more familiar application, use of a subcarrier makes the two audio signals in stereophonic sound available in FM radio broadcasts.

No matter which scheme is employed for modulating symbols and reckoning bits, we must be sure the telemetry data has been allocated enough power that it can be wrung from amid the noise in its communications channel, and its bits can be extracted and used.

1.2.16 Power in the Data

Recall from the bottom lines in Table 1.1 (page 18) that *Cassini*'s total received power P_R had a value of -131.9 dBm when collected with a 70-meter aperture DSN facility such as Station 63 in Spain. This measure of total power *includes* the carrier, but the act of modulating the carrier with data symbols decreases, or suppresses, the carrier power. Under conditions such as the Iapetus playback pass mentioned earlier, the *Cassini* telecommunications subsystem suppresses the carrier with data by about 15.5 dB (unitless), leaving the residual carrier power, called P_c at -147.4 dBm. Recall that in Subsection 1.2.6 we characterized the channel's noise spectral density N_0 as -185.4 dBHz, and we found that the spacecraft's received power is typically strong in relation to this noise. Suppressed by data modulation, carrier power P_c/N_0 is reduced accordingly. In our example:

$$P_c/N_0 = \frac{-147.4\ dBm}{-185.4\ dBm/Hz} = 38\ dBHz \tag{1.8}$$

The carrier is important for keeping the closed-loop receiver in lock and measuring the Doppler shift, which will be used for navigation. Additional carrier power may be needed for some radio science experiments, so the spacecraft's data modulation can be turned off temporarily, sacrificing data altogether but bringing carrier power up to the full P_R value. On the other hand, suppressing the carrier puts power into the data, P_d. Against the noise, data power is stronger than the partially suppressed carrier. A typical value for data power over noise for Cassini using a 70-meter station is:

$$P_d/N_0 = 53.6\ dBHz$$

The bottom line in a spacecraft's ability to convey telemetry is the measure of power invested *in each bit* of the data once we have accounted for the total power collected with a DSN station's aperture, the modulation scheme in use, and noise in the channel. The power in each bit, commonly called E_b (bit-energy) compared to noise N_0 serves as a useful *figure of merit* for evaluating a communications system's end-to-end performance and comparing it to similar systems and capabilities. To determine E_b/N_0 we can divide the ratio of data power to noise P_d/N_0 by the data rate in bits per second:

$$E_b/N_0 = \frac{P_d/N_0}{Data\ rate} \tag{1.9}$$

In the beginning of this chapter, *Cassini*'s telemetry data rate was 110,601 bits per second when the Iapetus data playback had started (see page 4). We can express this value in dB for convenience: 110,601 bps ≈ 50.4 dBHz. The power in each of those bits is:

$$E_b/N_0 = \frac{53.6\ dBHz}{50.4\ dBHz} = 3.2\ dB \tag{1.10}$$

This is indeed the value John entered into his log in the early morning of September 11, 2007 one minute before the signal disappeared from Station 63: "MCD SNR +3.21 dB at 110,601 bps."

What's an MCD? It's the hardware device in the DSN that recovers bits from symbols in the downlink from spacecraft such as *Voyager*, *Cassini*, and many others. We'll define it in the next subsection, and find how it plays an important role in the following topic:

1.2.17 Error Detection and Correction

If a spacecraft were to use the simplest possible method to convey its data using BPSK, we could imagine the on-board telecommunications system might bring in a stream of digital data, a long series of 1's and 0's, directly from the science instruments or from the data storage device. It might then impose one symbol on the downlink radio signal corresponding to each bit in the series. The DSN telemetry system then would watch all the waves in the downlink signal being received, and observe any changes in phase. It would output a 1 when it saw a period of shifted phase and a 0 for a period of non-shift, resulting in a string of binary digits corresponding to the spacecraft's data transmission.

In practice, this simple scheme of original-bit to final-symbol correspondence would manifest a high rate of error due to noise. Unwanted phase shifts can be introduced into the signal as it propagates across interplanetary space, through the Earth's ionosphere, atmosphere and weather, into the antenna, and through the low-noise amplifier and the receiver. The result would be that some 1's are incorrectly interpreted as 0's and vice-versa. So the challenge is to shift the downlink radio signal's phase in such a way that minimizes the incidence of error. As is true in so many aspects of the craft of deep space operations, this challenge invokes an entire field of technology.

Theoretical Limit First

Many human endeavors begin with clever inventions, with the limits of what can be achieved becoming apparent only as technology evolves. The opposite is true with coding theory. The American engineer and mathematician Claude Shannon (1916–2001) showed that there was an upper limit to the amount of error-free information that a channel such as a microwave radio signal can carry amid any given noise level. It then remained for researchers to devise high-order systems over the decades that could approach that limit. If you send information at a higher rate than the channel can support, the message won't get past the noise. This maximum is commonly known as the "Shannon limit." His classic article in 1948 analyzing electronic communications[30] shows how this limit is determined.

In his fundamental work, Shannon brought the ideas of British mathematician George Boole (1779–1848), who originated what is widely known today as Boolean algebra, into the field of communications. Shannon considered ways of encoding[31] information onto a communications channel, modifying the data to make it robust against errors. He used tools found in probability theory [15], introducing the concept of *information entropy* as a measure of uncertainty in a message, in effect inventing the field of information theory [16]. Today the science of error detection and correction (EDAC), has evolved so far that deep space communications performance can closely approach the Shannon limit.

Forward Error Correction

There are two main branches of EDAC protocols. Interplanetary spacecraft are too distant to make practical use of the first of these, automatic repeat-request (ARQ), which involves instantly acknowledging correctly received data and automatically re-transmitting the same data in the absence of an acknowledgment after a predetermined amount of time. The ARQ protocol is common among computer networks wherein propagation time is measured in microseconds. But instead of ARQ, to make best use of a spacecraft's substantial round-trip-light time and its limited opportunities to communicate, deep-space communication employs the second type of protocol, *forward error-correction,* (FEC). This is also known as error-control coding (ECC). Bits are manipulated on the spacecraft in logic operations and somewhat increased in number before transmission, typically in two sequential processes, resulting in a new stream of bits that can be decoded on Earth to reproduce the spacecraft's original data to a high degree of fidelity.

Reed-Solomon coding is typically the first of the two FEC process to be applied. Blocks of data in the spacecraft's computer are first rendered into polynomials whose evaluation at various points become the data to be transmitted. If some of these values become corrupted in the interplanetary transmission channel, the receiver can still deduce the original polynomial and decode it into the original data. Irving Reed (1923–) and Gustave Solomon (1930–1996) of the Lincoln Laboratory at MIT invented the concept in 1960. Reed-Solomon coding is also used in a wide range of familiar applications including postal bar codes, compact disc (CD) audio players, digital versatile disc (DVD) video players, computer data storage, transmission technologies such as digital subscriber line (DSL), and various radio and television broadcast systems.

Next the data encounters an FEC coding scheme which produces the symbols that will be leaving the spacecraft. *Convolutional coding* improves channel performance by adding some carefully designed redundant information to the data being transmitted. This scheme involves carrying out logic operations on strings of k quantity of bits, known as the constraint length, and outputting symbols for modulating the carrier at rate r symbols per bit. The constraint lengths and rates are typically small numbers. *Voyager* uses a constraint $k = 7$ bits and a rate $r = 1/2$, which means there are two symbols (phase shifts) for each transmitted bit. *Cassini*'s $k = 15$, $r = 1/6$ coding takes in fifteen bits at a time, and wiggles the downlink signal's phase six times for every bit.

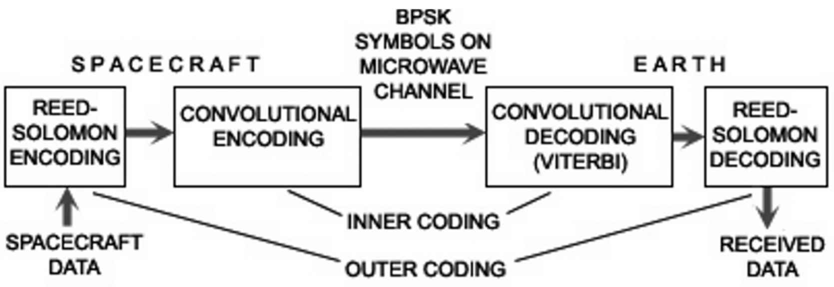

Fig. 1.9. Telemetry from the spacecraft is processed through concatenated data encoding, symbol transmission and reception, and data decoding.

The MCD

Once received on Earth, convolutional coding is decoded in the DSN. The system is designed so that it would take an extraordinary amount of noise to result in erroneous decoding, therefore the most likely result is the accurate one. This principle is reflected in the decoder's name: Maximum-likelihood Convolutional Decoder (MCD). The Viterbi algorithm it runs — in hardware, for high-speed performance — is named for its inventor, the Italian-American electrical engineer Andrew J. Viterbi (1935–). The DSN decoder accepts symbols directly from the Block-V Receiver on a fiber-optic interface at a maximum rate of over 26 million symbols per second. Leaving the MCD, the radio symbols from deep space have become digital data — bits — once again.

Aside from deep space communications, Viterbi decoding applications can be found in systems ranging from cellular telephony to speech recognition.

Bit Flipping

One might imagine that the DSN's decoder could misinterpret the phase shifts it sees on the downlink, and be unable to distinguish between shifted and non-shifted states. Should the DSN's decoding system mistake the distinction between shifted and non-shifted waves, all the data would be complemented; 1's would appear when there should be 0's and vice-versa. This does occur, and it is acceptable. In downstream ground processing, another system will recognize the complemented state based on its search for a known pattern of bits embedded in the data, and would invert it back to its original sense.

Perfect Data

The operational result of EDAC coding and decoding in a deep-space communications link is remarkable. The output of the MCD will usually exhibit a bit error rate, BER, on the order of 5×10^{-6} meaning roughly only five bits out of a million do not correspond to bits the spacecraft originally sent. While this may sound like pretty good performance, such a rate can be unacceptable, especially when some of the data has been compressed (compression is discussed in Subsection 1.2.19 below). A single erroneous bit can cause decompression of a block of thousands of bits to fail, resulting for example in an anomalous black band across an image. But the presence of Reed-Solomon coding before convolutional, and R-S decoding of the MCD output, can achieve virtually *perfect* performance. Reed-Solomon does sometimes fail to correct errors, but in such cases the uncorrected data is discarded, or at least flagged as error-ridden and stored off-line. The bottom line is that one can rest assured that if data is flowing, then it represents an exact copy of the data the spacecraft originally sent. If you've got data, it's perfect data. This applies not only with deep space communications, but also with digital television broadcasting, cellular telephony, the Internet, audio and video consumer electronics, and many other fields.

1.2.18 Telemetry in Lock

Following the LNA and the receiver, the DSN's MCD is the first component in the telemetry system. Next comes the Reed-Solomon decoder. Once Reed-Solomon decoding has produced error-corrected digital data, the bit stream is passed to the telemetry system which examines the data for a familiar tag. Each spacecraft injects its own unique pattern of bits at regular intervals into its data stream to serve as a marker. When the telemetry system recognizes the marker it interprets it as indicating the start of a unit of data volume called a *transfer frame. Cassini* places its 32-bit marker, called a pseudo-noise code or PN code, once every 10,112 bits to indicate the start of a new transfer frame. Adjacent to the PN code is a group of bits constituting a descriptive frame header, followed by data bits, and then Reed-Solomon check bits that comprise a little over 10% of the frame's volume.

The component in the telemetry system that looks for the PN code is called the *frame synchronizer.* It works by filling up a section of memory with incoming data, and it then searches through the data for the PN code, or the complement of the PN code's bits, in case the 1's and 0's were inverted. Once it has found it, it looks again precisely 10,112 bits (in *Cassini*'s case; other spacecraft may have different size transfer frames) into the next batch of data where it should find it again. If it is indeed there, the frame synchronizer can safely assume the first PN code it encountered was not just a random pattern in the data, and it can treat the second occurrence as confirmation (or the n^{th} occurrence; the number of attempts is a selectable parameter). The frame synchronizer therefore reports that telemetry is in lock. As long as it keeps finding the PN code at the right place, it will continue to churn out transfer frames to relay across the Earth-based communications system to the flight project's realtime team to be checked and stored, distributed to the engineers who operate the spacecraft, and to the teams of scientists for analysis.

Two terse reports are expected at the beginning of every period of DSN tracking. The first, "receiver in lock," is the welcome news that the spacecraft is still running its sequence of commands and has successfully pointed its antenna toward Earth. Its faint signal has arrived at the DSN and has been teased out of the background noise. It means the DSN antenna is operating correctly, pointing its massive reflectors in precisely the correct direction and tracking the spacecraft as it slowly moves across the sky. It means the LNA is cold enough and the BVR is performing its tasks, and it means every one of the link-budget parameters (see equation 1.3) is within limits.

The second report, "telemetry in lock," then heralds the fact that the spacecraft and ground system are configured and operating properly, the decoder has reconstituted the spacecraft's binary digits and the frame synchronizer has recognized telemetry from the spacecraft, that any bit errors have been corrected via Reed-Solomon decoding, and that the data has proven not to be garbage. The Ace checks the telemetry's content, especially the engineering data, and runs programs that compare the telemetered values to previously established limits to confirm that the spacecraft's systems are all operating as expected. Finally, "telemetry in lock" means scientist teams are receiving eagerly anticipated data from their distant instruments and experiments.

The telemetry system can be expected to remain in lock until the spacecraft makes a change, such as increasing its data rate, and then it will take only a few seconds to achieve telemetry lock again after the change. The BVR itself will remain in lock but for a brief Doppler mode change (discussed in the next chapter, page 66) until the end of the tracking period when the spacecraft turns away to continue about its business of exploring and collecting data for the next communications session.

1.2.19 Data Compression

The channel capacity Shannon theorized applies to information that appears as random bits using error-correction coding. Sometimes bits are not random in appearance; for example, you may need to transmit a string of a hundred 1's followed by a hundred 0's. Shannon's limit would no longer represent the actual maximum limit, since you could gain efficiency "compressing" the data by transmitting an indication of the quantity of each of these bits, instead of the bits themselves, and then uncompressing the data to the original bit pattern upon receipt. Data compression is an important branch of information theory that goes far beyond this crude example, and it can apply to all kinds of data including images, audio, video, and executable computer programs. Reference [20] discusses data compression schemes. No matter what variety of compression schemes may be used, the basic premise of data compression is to remove redundancy from the original data before transmission, and then restore it upon receipt, either without any loss of quality, or via a scheme that permits an acceptable level of loss to occur.

1.2.20 Pushing the Shannon Limit

Algorithms don't have mass, of course. But efficient error-correction coding schemes can indeed reduce the mass of a spacecraft. Improving an ECC's correcting power means that a spacecraft's telecommunications system may need a smaller antenna, or a smaller and less massive transmitter to do its job. Reducing spacecraft mass spells a reduction in the launch vehicle's required energy, relating directly to cost. It may also have a favorable impact on the craft's power supply, perhaps reducing the mass of solar panels or batteries required.

The result of concatenating Reed-Solomon and convolutional coding is performance within about 2 dB of the Shannon limit — good, but still far from ideal efficiency. In 1993, the French engineers Claude Berrou (1951–) and Alain Glavieux (1949–2004) and Thai engineer Punya Thitimajshima (1955–2006) working together devised an ECC system they called *turbo code* in which encoding occurs in parallel. At the receiving end, each of two decoders is given a different encoded version of the original data. The algorithms collaborate to decode the message, iterating several times and comparing notes to reach a consensus on a correctly decoded result. On initial publication, these researchers' codes promised to come so close to the Shannon limit that many others in the field assumed their assumptions were incorrect. But their efficiency held up to scrutiny, and turbo code gained enthusiastic acceptance. It is currently in use with the *Mars Reconnaissance Orbiter* which returns telemetry at rates up to 6×10^6 bits per second to Earth. The *Messenger* mission to Mercury also uses turbo code, as do many Earth-orbiting satellites.

Another class of ECC, called low-density parity-check (LDPC), was first described in 1960 by the American graduate student Robert Gallager (1931–). This was long before computers were efficient enough to implement his computationally-intensive scheme, so his work was shelved for decades. Now that computers are powerful and ubiquitous, Gallager's work has finally come into its own. LDPC uses a decoder for each bit in the message, so depending on the size of data segments being processed, the system can employ thousands or tens of thousands of decoders working together. Gallager codes, used today in digital satellite television, compete with turbo codes in reaching to within a fraction of a dB of the Shannon limit.

1.2.21 Data Structure

An early, widely accepted data structure specification is the Open Systems Interconnection (OSI) Basic Reference Model, which is described in reference [23]. Under this model the transfer frame, discussed in Subsection 1.2.18, constitutes the highest level of structure in a spacecraft's downlinked telemetry data. Lower-level structure will be in one of two forms, both of which serve to identify the content of data being transmitted and received at a given moment. How, for example, do you know whether a handful of bits represents part of an image, the temperature of a propellant tank, or data from an ultraviolet spectrometer? Communicating a variety of telemetry measurements is called multiplexing.

Time-Division Multiplexing

Consider the multiplexing scheme the *Voyager 1* and *Voyager 2* spacecraft use, as well as previous *Mariner*-class robots have used, to sort out their various measurements: *time-division multiplex* (TDM). In this older scheme, each transfer frame, or group of transfer frames, starts out by conveying a specific number of bits from one source, say an image from a camera, then a specific number of bits from another source, say from a thermal sensor, and so on until all the necessary kinds of data have been transmitted. The time-slots then recur in a fixed order, conveying groups of bits divided among a set of pre-determined sources of data on the spacecraft. As long as the Earth-based idea of what to expect maps to the spacecraft's schedule of what it is sending at any moment, an imaging scientist will receive images, and a thermal engineer will receive temperature data. These divisions are dictated by programmable "maps" in the spacecraft's computer that control the outbound TDM, and by corresponding maps in the receiving system. The spacecraft's map is called a *commutation* map, and on the ground, a *de-commutation*, or decom map. The PN code in each transfer frame serves to synchronize the data with the maps.

If you've ever been in the audience of an IMAX 3-D film, or other high-quality three-dimensional imaging presentation, the goggles you wear offer an interesting demonstration of TDM. At one instant, the left lens switches to a transparent mode, while the image on the screen is showing the scene intended for the left eye. The next instant, the left lens turns opaque and the right one admits the image, which has switched to the scene intended for the right-eye. This repeats on the order of thirty times per second, synchronized by control signals from an infrared transmitter in the theater, for an impressive 3-D experience. Mars Exploration Rover realtime operations team members use a similar display system in their support area when viewing images returned from the stereoscopic navigation cameras. The 3-D view helps them plan commands to control the rovers' movements across the alien surface.

Packets

The alternate to TDM is *packet-mode* communication, which most modern spacecraft use. A packet is a variable-length series of bits. The first set of bits in a packet, called the packet header, has information defining the length of the current packet:

how many bits it comprises in total. This information alone tells the receiving telemetry system where to look for the start of the next packet, amid a continuous stream of bits. The header also identifies the source of the data, including the spacecraft's designation, the instrument or subsystem, and other information such as the time the packet was created, and how it is to be routed. Following the header is the data itself, for example the bits making up an image or part of an image. Since packet lengths are variable, the relationship between packets and transfer frames can go either way: many packets can make up one frame, or it can take many frames to convey one packet.

One advantage of packet-mode communication is that each packet is self-identifying. Packets can be created by many instruments or subsystems on the spacecraft, stored on board, downlinked, and stored again on the ground conveniently. They can be retrieved out of storage according to their types or sources, their creation times, or any other header-related attributes. Once an imaging science team has received their packets, the image data can be stripped away from the headers, and recombined into the original image taken by the spacecraft's camera — all automatically of course, at a low level in the processing software.

Packets repeat a lot of information in their header "overhead," and this is the disadvantage of the packet-mode system. Millions of times, the spacecraft sends its own identification as part of the header of packets it creates. Millions of times, every instrument "wastes" bits by including administrative information in its packets. But the overhead is easily accommodated in today's environment of high-speed communications and high-volume storage, so the packet-mode's convenience outweighs the disadvantage of its redundant information content.

Another advantage of packets is that each can be designed to carry its own error detection and correction (EDAC) bits so that processing systems can recover errors that may have been introduced during storage, transmission and processing. And the data content of a packet is flexible. All the data in one packet might come from only one source, such as image data from an imaging instrument, or a packet's data might come from multiple sources and require a decom map to correctly distribute it to the various user-destinations. This is more common a practice with engineering measurements rather than science data.

Today, packets not only convey data to and from spacecraft, they underlie many familiar applications. The Internet is full of packets, conveying web pages, email, data files, music, and software of every description. Modern telephone systems, including cellular and voice-over-Internet-protocol (VOIP), carry voice data in packets that are processed and converted to audio in such quick fashion that the sound they convey seems seamless to the ear.

1.2.22 Channelized Engineering data and Science data

One final data-structure concept to identify is *channels*. This is a different use of the word from its treatment in the beginning of this Section (page 28), where "channel" referred to microwave radio energy propagating through space. We've already seen that various measurements repeat. Whether conveyed via TDM or in packets, a temperature sensor on the top left side of a propellant tank will send its measurement repeatedly, so engineers can monitor the sensor's temperature data over periods of minutes, days or years. The voltage of an electrical supply needs to be monitored in the same way. A spacecraft can have thousands of kinds of measurements that repeat, including pressures, temperatures, voltages, currents, device positions, computer states, and so on. Each measurement is called a channel, because its value is eventually transported, or channelled, through the telemetry system to a part of a user's display designated specifically to register that measurement. On an electrical-system engineer's computer screen, a list or a graph can display all the values of a certain channel — for example the spacecraft's electrical supply voltage — as they come down in real time. And as the data is always stored for later retrieval, the engineer can query it and construct reports and plots spanning any period in the past. *Cassini* sends down over ten thousand channels of engineering data. Each channel's data, routed from within packets via decom maps, corresponds to a measurement on the spacecraft, and a display (or a possible display) on the ground.

Channels are given unique names to identify the repeating measurements they represent. A typical name consists of a letter followed by an identifying number and a terse, abbreviated description of the measurement. As an example from *Cassini*, channel E-1263 (see Figure 1.10) refers to the electrical current, represented by the letter "I," that is being output at the moment by one of its three radioisotope thermoelectric generator (RTG) power supplies, RTG-3.[32] The value of the measurement and the time it was made come directly from the packet data. The channel identification is deduced in ground telemetry software via a decom map, based on the packet's source identified in its header, and the electrical-current value's predictable location within the packet's data field. The English-language notation appended to this basic channel information comes from a program in the ground telemetry system. Naming conventions vary, but in this case "E" refers to general engineering measurements. An "A" usually means a measurement from the spacecraft's attitude control system, "C" refers to the on-board command and data processor, and "S" includes engineering measurements of values and states in various science instruments. Science team members call S-channels their "housekeeping" data. The science data itself, such as data that makes up an image, is usually not commutated into channels (at least for a spacecraft using packet-mode communication), because science data packets typically do not share their data fields among many different measurements. "M"-channels represent monitor data that indicate performance of systems within the DSN, such as the received signal power level, or the antenna pointing direction.

Ground-based display systems offer the opportunity to create new channels, called *derived* channels, whose values are computed on the ground from the values reported in telemetry from the spacecraft. For example, F-0283 in Figure 1.10 is a derived channel reporting power in watts, created by multiplying the spacecraft's current and voltage values reported in E-1255 and E-1254.

Channelized engineering telemetry comes from sensors that have limited precision. Many, if not most, sensors on interplanetary robots generate eight bits of data, so the values they output can have only 2^8 discrete values, i.e. 0 to 255_{10}. A sensor is not usually calibrated in a linear fashion such that a measurement of zero

E-1255	RTG1_OUT_V	29.972306479000004 (Volts)	218	2008-060T05:21:51.177
E-1254	RTG1_OUT_I	7.681226852599999 (Amps)	192	2008-060T05:21:51.177
F-0283	RTG_1B_PWR	230.22408536085177 (Watts)	230.22409E0	2008-060T05:21:51.177
E-1260	RTG2_OUT_V	29.924157873000002 (Volts)	218	2008-060T05:21:51.177
E-1259	RTG2_OUT_I	7.8672812388999995 (Amps)	196	2008-060T05:21:51.177
F-0284	RTG_2B_PWR	235.42176582413464 (Watts)	235.42177E0	2008-060T05:21:51.177
E-1264	RTG3_OUT_V	29.919143408 (Volts)	215	2008-060T05:21:51.177
E-1263	RTG3_OUT_I	7.8541246615 (Amps)	200	2008-060T05:21:51.177
F-0285	RTG_3B_PWR	234.98868209172795 (Watts)	234.98868E0	2008-060T05:21:51.177

Fig. 1.10. A sample of engineering measurements in telemetry from the *Cassini* spacecraft. Six E-channel values have been de-commutated from data within downlinked packets, and converted for display by ground software. From left to right their columns contain: channel number, channel name, value converted to engineering units, the original data-number value, the year and day of year, and the time in hours, minutes and seconds. F-channel values are derived on the ground from E-channel data.

means zero volts, and a measurement of 255 means 255 volts. Instead, they are calibrated to narrowly reflect a range of values that are important for the specific measurement. *Cassini*'s electrical power supply is a 30-volt system in name, and the actual values of voltage will normally vary somewhere in a normally expected range, for example from -5 to $+36$. So a voltage sensor in the system will be selected and calibrated to reflect a range roughly in that neighborhood. A value of 0 from the sensor in this example may mean a system voltage of -5, and a value of 255 from the sensor may mean a voltage of $+36$. The raw binary data values in packets, $0000\ 0000_2$ to $1111\ 1111_2$ (0–255_{10}),[33] are called *data numbers*, DN. The meaningful values, for example the level of voltage represented by the data numbers, are called *engineering units* (EU), which are conversions from DN by ground-based telemetry software using pre-established calibration curves. Often, listings of engineering units appear on displays with an impossible level of precision because the conversion from DN to EU might be done without rounding or truncating the result. The DN value of E-1263 in Figure 1.10 is 200_{10} which appears in the figure's third column. That's as precise as it gets. The EU value, 7.854124... amps, is expressed with too many places following the decimal point to be meaningful.

1.2.23 CCSDS

Rules for such parameters as the number of bits comprising a packet header are not made up for every space-flight project; an international consortium provides a voluntary means for standardizing data structures and systems, as well as other aspects of spacecraft operations. The international Consultative Committee for Space Data Systems (CCSDS),[34] was formed in 1982 by the world's major space agencies to serve as a forum for discussion of common problems in the development and operation of space data systems. It is currently composed of ten member agencies, twenty-two observer agencies, and over one hundred industrial associates. Since its establishment, its members among the world's space-faring organizations have been realizing the benefits of using standard techniques for handling spacecraft data, eliminating unnecessary project-unique design, enhancing interoperability, sharing facilities, and reducing cost.

CCSDS has six specific areas of interest. The Spacecraft Onboard Interface Services Area works to improve the spacecraft's on-board data systems. The Space Link Services Area oversees the link interconnecting a spacecraft with its ground system, as well as one spacecraft with another, such as an orbiter with a lander or rover. This includes developing standards for radio frequency and modulation, coding, data compression, and navigation. The Space Inter-networking Services Area addresses networked interactions within the spacecraft and within the ground system. The Mission Operations and Information Management Services Area addresses applications required to operate a spacecraft and its ground system. The System Engineering Area works with the overall architecture for mission communications, operations, and cross-support and coordination. Finally, CCSDS's Cross Support Services Area addresses how resources are made available by one organization to another.

1.2.24 Remote Control

Commanding the spacecraft is, to a first approximation, telemetry in reverse. Formally called *telecommand,* this service is not unlike operating a television set with a remote control. Consider that each of the dozen or so buttons on a remote control causes the TV to take an action: select a channel; increase audio volume; turn power on or off; adjust brightness. Today's remotes transmit a 940-nanometer-wavelength infrared signal to the set. Normally invisible, a remote's infrared LED flashing in response to its pushed buttons can easily be viewed with a digital camera, such as the one in many cellular telephones, whose image detectors are sensitive in the near-infrared part of the spectrum just below the human eye's ability to see. The remote sends a discrete message of several timed-flash symbols, a different combination for each of the buttons. Each pattern of flashes usually repeats for as long as you push the button. The TV is programmed to decode the sets of infrared symbols that it receives; its software does the equivalent of looking up their meanings in a table, and takes appropriate actions such as changing the channel.

In a similar way, a spacecraft is programmed to recognize sets of symbols, this time on a microwave radio signal uplinked by the DSN. Where a TV may have a repertoire of a dozen or so commands, modern spacecraft can recognize thousands. Their symbols on the microwave uplink are very much like the symbols that make up telemetry data on the downlink: they are phase-shift modulations, usually grouping command data in packets that adhere to a CCSDS standard format. For most interplanetary spacecraft, command data occupies a subcarrier modulated onto the uplink. Error-detection and correction algorithms running onboard prevent the spacecraft from mistaking a command's meaning and carrying out the wrong action. Some of its more intelligent algorithms can even prevent valid commands from taking destructive actions, if they were to arrive at the spacecraft. Command data content can usually take the following forms:

1. "Do this right now." Turn on a heater; turn off an instrument; reset a timer; read out the contents of a specified memory location. The spacecraft executes these commands upon receipt.
2. "Do this list of tasks over the next six weeks." In this case, a sequence of individually time-tagged commands is uplinked, for example the sequence S33 mentioned earlier. The spacecraft's command computer stores the sequence, watches its built-in clock, and executes each command at the proper time. This category can also include short sequences of timed commands that only take a few minutes to execute, as well as commands that the spacecraft's computer passes along to an on-board science instrument's computer for it to execute on its own.
3. "Here's a software update." Commanding can carry large amounts of executable code that can be loaded into any of the spacecraft's computers. This includes the main command computers, the attitude control computers, and any of the instruments' individual computers.

   Voyager 2's computers, for example, were virtually new machines by the time the craft flew by Neptune. Their new capabilities included data compression, long camera exposure times, and the ability to use very short attitude-control thruster pulses (4 ms) which enabled new target-motion compensation capabilities [24].

   At launch, *Cassini*'s computers did not have the basic capabilities they would need to operate at Saturn. New versions of flight software were developed, tested, and uplinked during each craft's multi-year cruise, and its computers were restarted to activate the new loads. Many of *Cassini*'s science instruments have also received software upgrades and patches in flight.

   If you have a computer, you've probably downloaded software updates. The ability to do so benefits from some of the same communications protocols and data structures as a spacecraft uses in its commanding process.

Flight project teams are sensitive to the risks of commanding their spacecraft. There are few threats to a spacecraft in flight. Collisions with meteoroids large enough to do damage are rare, and have never yet destroyed an interplanetary craft. But improper commands can and do destroy missions. Computers will do exactly as they are told to do, to the letter, but sometimes the result isn't exactly what the human had intended. A commanding error consisting of a single mistaken character was responsible for causing the Soviet spacecraft *Phobos 1* to deactivate its attitude thrusters near Mars in September 1988. Without thruster control, the spacecraft could no longer orient its solar arrays toward the Sun, the batteries discharged completely, and the mission was lost. Another spacecraft in orbit at Mars lost its ability to point its solar panels when the U.S. *Mars Global Surveyor* succumbed in November 2006 to a commanding error that had placed a few bits of data into the wrong memory location months before.[35]

Voyager 2 was nearly lost shortly after launch when its operators, preoccupied with *Voyager 1* commanding activities, neglected to send *Voyager 2* a routine command in April 1978. In the absence of its regular command from Earth, the spacecraft "assumed" its radio receiver must have failed, and it executed preprogrammed contingency actions, turning off its primary radio receiver, and switching to its spare receiver, which proved to have a crippling flaw in its electronics. Attempts to switch back to the primary receiver failed, but engineers on the team figured out how to accommodate the backup receiver's problem (its phase-lock loop had lost its ability to track an uplink signal) using a workaround which is still in place today: Telecommunications engineers constantly watch the spacecraft's thermal state which directly affects the crippled receiver's "best-lock" frequency (BLF). Maintaining knowledge of the BLF's behavior, they work with the Deep Space Network to uplink a signal whose frequency varies throughout the day and day of year, backing out the Doppler shift that the Earth's movements induce, so that the spacecraft always receives a frequency near the BLF that it can use. This technique has also proven useful for spacecraft whose receivers are healthy, including *Cassini.*

Efforts to reduce the chances of human error are taken seriously in the entire process of commanding a spacecraft, and many software tools and procedures are called upon to help simulate, test, verify, and properly uplink commands that are free of error. Some quality-assurance engineers spend their entire careers refining the ability to minimize commanding errors on flight projects.

1.2.25 Beacons in Space

Subcarriers are useful. They can carry telemetry or navigation data on the downlink. They can carry command data on the uplink. Aside from these routine uses, there's a novel role for subcarriers that may become more common as spacecraft take on more autonomous functions, especially for those craft that must cruise for years to reach their destinations.

The traditional way to communicate with a spacecraft is to schedule large-aperture DSN facilities to track it several times per week, for several hours at a time. This has been the default mode of operation for many spacecraft during their long journeys to Mercury, Venus, Mars, Jupiter, Saturn, and beyond. Upon locking to the spacecraft's signal and telemetry, spacecraft analysts can check the engineering data to make sure the craft is operating nominally, and send it any necessary commands. But some spacecraft can be operated differently.

The *New Horizons* spacecraft was launched in January 2006. It will fly close by Pluto in July 2015. It would be expensive to obtain the DSN resources to track the craft every day or so to check up on it, so it was designed to check up on itself. Having been navigated past Jupiter for a gravity-assist kick in February 2007, it was put into sleep mode. Spinning slowly to maintain a desired orientation with its medium-gain antenna constantly transmitting its signal toward Earth, it will continue monitoring its own condition internally. If any situation were to arise on the spacecraft that would require interaction, it will turn off a subcarrier that is otherwise present on its downlink at a known frequency, to act as an alert. This subcarrier is called a *beacon.* Its presence indicates all's well, so it is called a "green" beacon. A DSN station can check on the spacecraft by simply observing the spacecraft's downlink on an open-loop receiver and FFT display in quick sessions, spanning only a few minutes per week — no need to program and lock the Block-V closed-loop receiver, no need to allocate, program, and operate a telemetry system.

If the DSN does not happen to see that "green beacon" of a subcarrier at the expected frequency, plans can be changed, and a regular telemetry-capturing DSN pass can be scheduled post haste to find out what the spacecraft's problem is. Since it's only necessary to view the *presence* of a carrier and observe whether there are any subcarriers, a small-aperture station can be used, without the need for the higher performance of a large-aperture station for extracting telemetry symbols from the downlink. Beacon-mode monitoring opens up new possibilities.

While gigantic antennas such as those in the DSN are necessary for collecting enough signal power to be able to decipher telemetry, even the antennas and receiving equipment used by some amateur radio astronomers are capable of detecting carrier signals and subcarriers from many distant spacecraft (see Figure 1.11). Even though the *Mars Reconnaissance Orbiter* spacecraft, whose downlink is shown, does not operate in beacon mode (its subcarriers carry telemetry and ranging data), this display illustrates how a small aperture antenna can make useful observations of spacecraft subcarriers. The same amateur also identified the *Voyager 1* spacecraft signal in 2006.

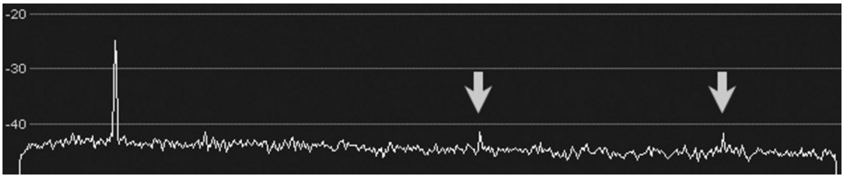

Fig. 1.11. In 2006 the Portuguese amateur radio astronomer Luis Cupido captured the X-band radio signal from the *Mars Reconnaissance Orbiter* spacecraft at Mars using his 5-meter aperture parabolic antenna. The tall peak on this FFT display represents the spacecraft's carrier. Note the two visible subcarriers below the arrows. While they may not be entirely unmistakable in a static image such as this, they can be seen to persist in the live view while the noise varies randomly around them. Image reproduced with the radio astronomer's permission.

In addition to its green beacon, *New Horizons* can activate any of seven other subcarriers, all at different frequencies that would show up clearly on an FFT display to indicate various on-board system conditions. Aside from the occasional glance from DSN to check its beacon, *New Horizons* will be commanded to awaken from hibernation once a year for about fifty days to acquire navigation data, and to conduct system checkouts using command and telemetry.

The engineering-demonstration spacecraft *Deep Space 1* tested beacon-mode monitor operations as one of its experiments in 1999 and demonstrated how the process can work. The spacecraft has to be capable of making intelligent summaries of its internal condition, controlling the beacons based on its self-assessment, and storing any pertinent information for downlink via telemetry if problems arise requiring attention. *Deep Space 1* showed in its engineering demonstrations that by using beacon-mode communications, a mission can reduce its cost and begin to decrease the demands on heavily-subscribed DSN resources. *New Horizons* may be only the first of many spacecraft to come that use beacon-mode monitoring as a part of nominal operations.

1.3 More than Telepresence

A spacecraft's link with Earth communicates information that connects the human senses to their distant, expanded[36] counterparts onboard the robot craft. This first chapter in *Deep Space Craft* covered telecommunications because it is one of the first building blocks on the way to understanding how a mission's science instruments and experiments are supported and operated, and, more importantly *why.* The instruments and experiments themselves will be the focus of Chapter 6.

Telecommunications enables telepresence. Consider how far telepresence might advance, given continued improvements in interplanetary exploration over the next several decades. Perhaps one morning you'll walk down a hallway and open a door marked, "Venus." As you step inside a room-temperature workroom you enter a virtual bubble on the surface of Venus — or Mars, or Titan, or Comet P/2058 DW18 LINEAR — and join your colleagues in making observations and conducting experiments and measurements from that virtual-reality outpost. Everything you see, feel, hear, and interact with across the spectrum is a high-fidelity presentation of the actual location in real time (as close to "now" as can be, given the speed of light).

Now to move from speculation to the next building blocks. A spacecraft's telecommunications system interfaces with its electrical supply to obtain power to operate; it relies on other spacecraft systems as well. Telecom's need to accurately point an antenna places requirements on the spacecraft's attitude control system. In the next chapter's focus, we'll see how the telecom system also provides the means to track and navigate the craft, revealing to navigators and spacecraft engineers what minor adjustments might have to be commanded to correct its flight path, and reporting on its precise trajectory to help scientists interpret the data it sends back.

Notes

[1]The gravity assist technique, explained in Chapter 2, offers a convenient means to make substantial trajectory changes without the use of much propellant.

[2]The word "bit" is a contraction for "binary digit," each having a value of 1 or 0.

[3]Chapter 2 will make it clear why sometimes it is desirable to arrange an early uplink, as in the previous case.

[4]The "Ace" moniker, which is typical for any interplanetary project's real-time Mission Controller, refers to the person's role as a single point of contact for operations.

[5]For example, the journals *Nature* and *Science.*

[6]The decibel, dB, is a base-10 logarithmic measure. The "m" means we're measuring milliwatts. -171 dBm equals $10^{-171/10}$ mW, or 7.94×10^{-18} mW.

[7]That we consider this painfully slow today illustrates progress made since 1965 when *Mariner 4* returned humanity's first images from Mars at 8.33 bits per second. In 2008, the DSN routinely supports 6 million bits per second from the *Mars Reconnaissance Orbiter.*

[8]Visitors to JPL can see the DSN operations control center from the viewing gallery in Building 230.

[9]The unit "hertz" (cycles per second) is named after the German physicist Heinrich Hertz, who made important scientific contributions to electromagnetism. The prefix "giga," for one thousand million (10^9), comes from the Greek *gigas*, meaning "giant." A "billion" is 10^9 in most English-speaking countries, and 10^{12} in many other countries.

[10]The IEEE name was originally an acronym for the Institute of Electrical and Electronics Engineers, Inc. Today, the organization's scope of interest has expanded into so many related fields that it is simply referred to as "the I-triple-E".

[11]Some antennas, called *phased arrays,* consist of arrays of active radiating and/or receiving elements instead of using reflection to concentrate a signal.

[12]The Deep Space Network's 34-meter diameter high efficiency antennas achieve nearly 75% efficiency at X-band wavelengths.

[13]In reality the signal loses no energy at all, no matter how far it propagates through empty space. It's just that the antennas we can construct will never be able to capture more than a very small portion of it.

[14]Quantity of energy transport through a unit of area.

[15]As often seen with light and sunglasses, microwaves can be polarized. Typical schemes are right- and left-hand circular, and linear.

[16]See http://msp.gsfc.nasa.gov/tdrss/oview.html

[17]See http://www.vla.nrao.edu

[18]See http://lambda.gsfc.nasa.gov/product/cobe

[19]See http://map.gsfc.nasa.gov

[20]See http://www.rssd.esa.int/Planck

[21]In keeping with the recognition that one person's "noise" can be another person's sought-after "data," note that mapping the variations in the intensity and spectrum of natural microwave radiation from a planet's surface can provide important scientific information regarding the surface's temperature, composition and other properties.

[22]Direct current, DC, indicates a flow of electrons in one direction only. Compare with alternating current, AC, in which the polarity and flow direction periodically reverse.

[23]This was the term for thermionic emission prior to discovery of the electron. A flow of either electrons or ions results when thermal vibrational energy overcomes the electrostatic force that would normally restrain them.

[24]From the Greek *di* meaning "two" and *odos* meaning "path."

[25]Metal-oxide semiconductor FETs are ubiquitous in the chips of today's digital and analog electronic systems.

[26]Most materials show a decrease in resistivity with decreased temperature, but this is not the same phenomenon as superconductivity, in which some materials exhibit zero resistance to electrical current.

[27]Refrigeration to achieve such low temperatures is done in the DSN using custom-built Joule-Thomson-cycle, or commercially available Gifford-McMahon-cycle cryocoolers.

[28]Klystrons are high-power devices requiring high-current, multi-kilovolt electrical supplies and active water cooling systems to operate. The DSN uses S-band and X-band klystrons with outputs rated at tens of kilowatts, and hundreds of kilowatts, and Ka-band klystrons rated at 1 kilowatt.

[29]For comparison, cable TV might have for its channel a microwave signal conducted by a shielded wire.

[30]Shannon's 1948 paper is available in various forms for download from: http://cm.bell-labs.com/cm/ms/what/shannonday/paper.html

[31]In this sense, encoding does not refer to cryptography. Shannon did, however, also contribute to the field of cryptography.

[32]More on these in Chapter 5 (see page 152).

[33]Subscripts indicate the number base. The binary 10_2 is equal to 2_{10}, and $100_2 = 4_{10}$.

[34]See http://public.ccsds.org

[35]See report at http://www.nasa.gov/pdf/174244main_mgs_white_paper_20070413.pdf

[36]Scientific instruments "expand" the human senses because they are not limited to the visual but span the entire spectrum from DC to gamma-ray.

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2 Navigating the Depths

2.1 Martian Miscalculation

It is 2:01 A.M. Pacific time September 23, 1999. Having fallen through interplanetary space for nine and a half months, the US$125 million *Mars Climate Orbiter* is beginning[1] to fire its on-board 640 N rocket engine. This is the long-awaited sixteen-minute Mars Orbit Insertion (MOI) burn, slowing the craft in order to place it into a fourteen-hour elliptical orbit over the planet's poles. Its planned mission will be to study Martian weather, and relay communications between surface vehicles and Earth. Shortly, the craft will pass behind Mars, and its radio signal will disappear from the DSN's receivers.

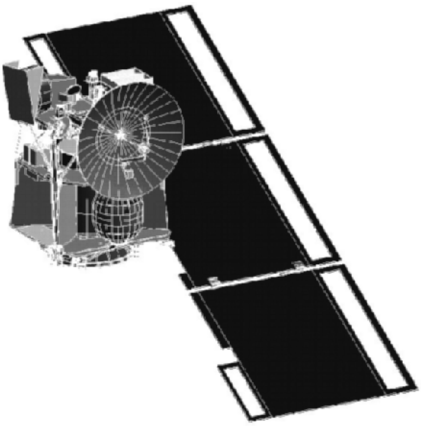

Fig. 2.1. The *Mars Climate Orbiter* spacecraft in cruise configuration. Image courtesy NASA/JPL-Caltech.

But something is amiss. The current navigation solution indicates the craft will arrive lower than the previously estimated target of 150 kilometers above the red planet's surface. A few hours ago, the navigation estimate was 110 kilometers, an altitude that could very well be dangerous, causing unacceptable atmospheric torque and heating on the spacecraft. Now the more accurate estimate says 95 kilometers, but, at that altitude, heating from aerodynamic friction from Mars's CO_2 atmosphere could be like a blowtorch.

Four days ago, there was an opportunity to do one final Trajectory Correction Maneuver (TCM), but it was deemed unnecessary and was cancelled, even though the navigation solution had shown more uncertainty than usual. The previous one, TCM number four on September 14, was a fifteen-second engine burn, giving the spacecraft a velocity change — ΔV — of 1.4 meters per second, intended to target 224 kilometers above Mars's surface for the MOI burn. Following this maneuver, the navigation solutions had exhibited much more uncertainty than would normally be expected under the circumstances. *Aviation Week and Space Technology* reported, “Several days after TCM-4, the navigation calculations had relatively poor convergence. The new numbers were trending to [predict a Mars closest approach of] 150-180 kilometers — but with uncertain confidence.” The magazine quoted the project’s flight operations manager: “The hard part is assessing navigation results and how much to believe them.” [1]

Up until a few hours ago, the flight team had therefore been expecting an altitude of at least 150 kilometers for the MOI burn, but there has been a gnawing feeling that the numbers have been a little too uncertain. Now Mars’s gravity is accelerating the spacecraft, and DSN is providing measurements of the trajectory with respect to the planet. This situation yields more accurate results from the currently running ground-based navigation software than interplanetary cruise measurements did. Doppler and ranging data drive solutions that are converging properly now.

DSN receivers have lost the signal. The spacecraft has slipped out of contact behind the planet as planned, with the engine still firing. The navigation program continues running, iterating the trajectory model and providing more confident results. The news is grim: a 75-kilometer flyby altitude.

The press has assembled, as they usually do to watch an exciting orbit insertion. This kind of event is more suspenseful than a launch. Knowing the spacecraft’s liftoff and cruise obviously were successful, this one remaining hurdle will determine whether the investment in funds, work-years, and the mission’s good fortune to date will pay off. Managers and dignitaries have filled up the mission support area, alongside the controllers and navigators. Those on the flight team who have access to the new numbers are quietly experiencing a horrible feeling. Numbers that had not converged well in recent days and weeks are now agreeing. And there’s nothing anyone can do but watch and hope that this new 75 kilometer figure is somehow mistaken. It must be! At 75 kilometers, friction in the atmosphere will cause tumbling and far too much heating.

Now it’s 2:26 A.M. Pacific time. This is the predicted time to re-acquire the spacecraft’s downlink signal as it emerges from behind Mars. The engine burn should be complete. The spacecraft should be in Mars orbit, and we should be receiving confirmation. There is no signal.

Continuous, exhaustive effort to re-acquire *Mars Climate Orbiter*’s signal occupied the next two days, after which it was abandoned. As the weeks and months passed, Lockheed-Martin, who built and operated the spacecraft for NASA, determined by analysis that the craft was almost certainly destroyed when its tanks of hydrazine and nitrogen tetroxide propellant overheated. The spacecraft most likely had tumbled out of control, blown apart, and burned up piecemeal in the Martian atmosphere.

In its report[2] the investigating board listed several findings that contributed to the failure. The root cause turned out to be confusion over units of measure. The spacecraft executed routine propulsive maneuvers all during cruise called Angular Momentum Desaturations (AMD), that hold the spacecraft’s attitude still by firing small thrusters for a few minutes while its on-board reaction wheels — electrically driven devices used for controlling the spacecraft’s attitude (we’ll visit all of this in the next chapter) — were slowed to pre-determined rotational speeds. Every time one of these AMD maneuvers was executed, thrusters applied small net accelerations to the spacecraft which in many cases were perpendicular to the line of sight from Earth, or nearly so. This meant that the accelerations were largely unobservable via the radio signal's line-of-sight Doppler shift, or the line-of-sight range measurements, and so they had to be detailed in telemetry from the spacecraft to the navigation team. This is a common condition for various spacecraft, and the maneuvers' telemetered results are simply recorded by the navigation software in a "small forces" file. In 1997 the *Mars Global Surveyor* had the very same situation, but it missed its MOI target altitude by only 4 kilometers, and is still orbiting the planet today. However, *Mars Climate Orbiter*'s thrusters' known impulse value (force × time) was input to the navigation software using the English units of pounds-force-seconds, while they should have been input in metric newton-seconds. The account of these small forces was therefore off by a factor of 4.45 (1.0 lbf = 4.45 Ns), not enough to immediately raise any red flags, but they built up sufficiently over time to cause the spacecraft's demise.

In the rest of this chapter, we'll explore all the interrelated factors involved with tracking and navigating a spacecraft in interplanetary flight, limiting our depth of coverage to be able to paint a coherent view of the whole picture. We'll examine all the main facets and how they fit together. The references offer opportunities for those readers who are interested in delving further.

2.2 Choice of Flight Path

An important concern in robotic interplanetary missions is the mass of the spacecraft, which largely dictates the capability required of its launch vehicle to achieve a desired trajectory. Trade-offs need to be made among factors such as the mass of the science instruments, electrical power supply, and other systems that a spacecraft will carry. Not least among them is the mass of propellant. Naturally, then, the preferred trajectory for traveling from Earth to a destination planet would be one that requires a minimum of propulsive energy. In 1920, the German engineer Walter Hohmann (1880–1945) demonstrated an efficient means to move a spacecraft between two different orbits. He published the concept in 1925 [3]. Why *two* orbits? Because the Sun is the dominant gravitational force here in our solar system, we see the Earth's solar orbit as the orbit of departure, and the second orbit is that of the destination planet about the Sun. Hohmann's transfer is an ellipse that is tangential to both solar orbits. The concept equally applies to two different Earth orbits; going from a low altitude initial orbit to a high geosynchronous orbit is a common example.

To reach another planet, then, a frequent trajectory choice is the Hohmann Transfer,[3] or an appropriate variation of it. See Figure 2.2 to consider this approach. A spacecraft on the launch pad is already in solar orbit by virtue of our planet's primordial momentum. If our destination is an outer planet, the task, after separating the spacecraft from Earth's gravitational grasp, is to modify its existing solar orbit so that it has an aphelion, the farthest point from the Sun, at a

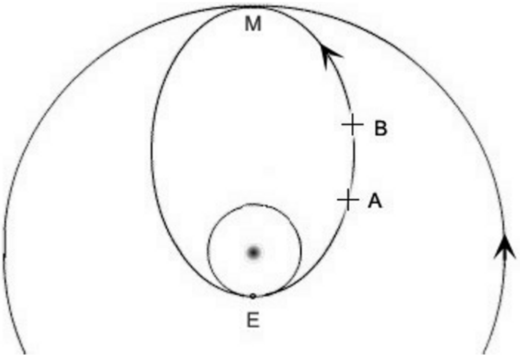

Fig. 2.2. Point E represents Earth orbiting the central Sun. The narrow ellipse represents the nominal orbit of a spacecraft in a Hohmann Transfer. The outer circle represents a destination planet's solar orbit. Points A and B are discussed in Subsection 2.3.2. Not drawn to scale.

distance equal to the destination planet's orbit. The perihelion of this orbit, the closest point to the Sun, is at the distance of Earth, point E in the figure. If we add enough energy to the orbit, tangentially in a short rocket-burst of acceleration while at perihelion, the effect will be to raise the subsequent altitude of aphelion. The spacecraft will then coast "up" against the Sun's gravitation to its new aphelion, almost like a baseball pitched straight up, slowing as it approaches point M in the figure.

It remains for mission planners to determine the correct time for launch based on the destination planet's motion. As an example, an opportunity to launch toward Mars occurs about every twenty-six months, and the transfer takes around eight or nine months. Once the spacecraft has completed the transfer, mission objectives prescribe what comes next. It can encounter Mars like a meteor, as did the three famous first rovers,[4] lowering themselves to the surface with heat shields, parachutes and air bags. A spacecraft can expend more propulsive energy and enter into Mars orbit, as *Mars Climate Orbiter* attempted to do in 1999. It can swing by Mars, gaining a slingshot boost using the gravity-assist technique as will the *Dawn* spacecraft early in 2009 en route to the main asteroid belt. Or, if the planet is not there when the spacecraft arrives, it will fall back and continue orbiting the Sun in its ellipse. This was the case when the *Magellan* spacecraft followed a Hohmann transfer to Venus. On its *second* loop around the Sun, it finally met up with Venus in 1990 as planned,[5] fired the solid-propellant rocket it had carried for fifteen months, and entered into orbit about the planet. In the case of Earth orbits, at the high point of a transfer to geosynchronous altitude a spacecraft can fire its apogee rocket motor (often a solid like *Magellan*'s) to raise its perigee altitude high enough to form a circular orbit.

2.3 Orbit Determination and Guidance

Navigating an interplanetary spacecraft entails two primary tasks. *Orbit Determination* (OD), is the computer modeling of its flight path, based on the physical laws of motion, observing the spacecraft's location in space, and evaluating how well the observations fit the model. The other task, *guidance,* is the correction of the spacecraft's flight path by applying brief periods of acceleration to the craft at predetermined opportunities, based on the results of the orbit determination process.

A spacecraft is always orbiting something, so its flight path is an orbit, or a portion of an orbit called a trajectory. Prior to launch, it's orbiting the Sun. The early portion of a launch trajectory is an Earth orbit, and interplanetary cruise is again a solar orbit. At its destination, the craft may orbit a planet, an asteroid, a planet's moon, or some other target of interest. Even spacecraft that have escaped the Sun's grip forever[6] are in orbit about the galactic center, although their navigation is (or was) reckoned along hyperbolic paths with reference to the Sun. In any case, orbit determination is treated as mainly a two-body problem involving the spacecraft and the primary body being orbited, although it does adjust for the small gravitational perturbations that another object may contribute; planetary orbits must account for the influence of a distant Sun, and solar orbits must accommodate the effect of any planet that comes nearby.

In the guidance task, navigators negotiate opportunities for applying acceleration to the spacecraft when needed, usually infrequently, to return the craft's motion to the desired path. For each event they specify commands that use the craft's on-board propulsive capability, first rotating the vehicle to align the rocket engine's thrust vector as needed, and then firing the engine for a duration calculated to impart the desired acceleration for trajectory correction or orbit trim.

Another means of accelerating the spacecraft, that can be included in some mission plans, is to use the gravity-assist technique. As we'll see later, when a spacecraft executes a close flyby of a massive planet or natural satellite, the craft can obtain a generous helping of acceleration at the expense of the natural body's orbital momentum instead of the craft's own propellant.

2.3.1 Kepler; Newton and his *Principia*

The discipline of orbital mechanics, including orbit determination and guidance, has been built upon the foundations laid by the German astronomer and mathematician Johannes Kepler (1571–1630)[7] and the English polymath Sir Isaac Newton (1643–1727).[8]

Kepler deduced three laws of planetary motion based on his studies using the observational data that his patron, the Danish nobleman Tycho Brahe (1546–1601),[9] had systematically compiled during his lifetime. In brief, Kepler's laws state:

1. A planet's orbit is an ellipse with the Sun at one focus.
2. A line drawn from the Sun to a planet sweeps out equal areas during equal intervals of time. Thus the planet travels faster when close to the Sun, and slower when farther.

3. The square of a planet's orbital period is directly proportional to the cube of its orbit's semi-major axis. Thus larger orbits have longer periods, and a planet's speed in a larger orbit is slower than one in a smaller orbit.

The first book of Newton's *Philosophiæ Naturalis Principia Mathematica*, or simply *Principia,* [4] established the foundations of classical mechanics in three laws of motion, which can be stated in distilled form as:

1. A physical body will remain at rest, or continue to move at a constant velocity, unless an external net force acts upon it.
2. The net force on a body is equal to its mass multiplied by its acceleration:

$$F_{NET} = ma \tag{2.1}$$

where m is the body's mass, and a is the acceleration applied.
3. For every action there is an equal and opposite reaction.

Newton's first law restates and attributes to Galileo Galilei (1564–1642), the principle we now recognize as inertia[10] that Galileo had described: "A body moving on a level surface will continue in the same direction at constant speed unless disturbed." Although Newton would not have known this, virtually the same observations had been made by the Chinese philosopher Mozi (ca. 470–390 BCE), and also by the influential Persian scientist Ibn al-Haytham (965–1039).[11]

With regard to the second law, note that the term "acceleration" in everyday usage means an *increase* in speed, while "deceleration" would correspond to slowing down. In classical mechanics, acceleration refers to any increase *or decrease* in instantaneous velocity. Motion along a curved path such as in orbit, even if speed happens to be constant, also involves acceleration since the velocity's directional component is changing.

In the *Principia*'s third book, Newton described the concept of gravitation as an attractive force that physical masses impart to one another across a distance, although he resisted hazarding any explanation of the nature of this force.[12] Even more importantly, Newton deduced that this attraction must apply everywhere, universally, as described by the following equation:

$$F_{GRAV} = G\frac{m_1 \cdot m_2}{d^2} \tag{2.2}$$

where

F_{GRAV} is the force exerted by universal gravitation
G is the constant of proportionality, the universal gravitational constant[13]
m_1 is the mass of the first object
m_2 is the mass of the second object
d is the distance between the masses

Newton did not specify a value for his constant of proportionality, but the results of experiments by Henry Cavendish (1731–1810) in determining the Earth's density eventually led others to estimate its value. The quantity $G = 6.674 \times 10^{-11} Nm^2kg^{-2}$ in use today has improved only moderately in accuracy since its first use in 1837.

As if to top it all off, Newton's independent co-discovery[14] and application of calculus (he called it "the science of fluxions") opened up the means to accurately determine the behavior of orbiting bodies according to Kepler's laws. With the *Principia*'s exposition of universal gravitation, together with the three laws of motion, Sir Isaac accomplished an enormous feat, explaining not only Kepler's laws of planetary motion, but also such effects as the planets' influence on motions of the Sun itself.

References [5] and [6] provide more complete reading about the application of the laws of Kepler and Newton to modern interplanetary navigation, which is the task of the OD process.

2.3.2 Models and Observables

The laws described above form the basis of a software system navigators apply to the problem of orbit determination, which we can call simply OD. Reference [7] discloses the algorithms in an early version of such a program. By design OD constructs a model of how the spacecraft is moving in three spatial dimensions and time, given data about the spacecraft's observed position and velocity from radiometric tracking by the DSN. Orbit determination in interplanetary flight is an iterative process, as is most any other navigation problem.[15] OD starts with an estimated model of the spacecraft's orbit. It incorporates specific observable parameters, and quantifies any error between the planned and the actual trajectory. Let's use a drawing to make some definitions.

Refer back to Figure 2.2, in which we are looking down from above the Sun's north pole. Orbiting bodies are revolving counter-clockwise. We'll assume the Earth is at point E orbiting the Sun, and our spacecraft is following the highly elliptical solar orbit shown — this will represent the situation known in advance. In a real case, this knowledge would have been acquired from the mission plans and OD iterations worked continuously since launch. The spacecraft's modeled nominal orbit would predict the position and velocity of the spacecraft at any point.

Using radiometric tracking techniques that employ the spacecraft's signal, it is possible to precisely measure the straight-line distance, or range, from point E in the drawing to the spacecraft at point A. This is done by timing the exchange of radio signals between Earth and spacecraft. And it is possible to know the radial velocity, or range-rate, of the relative Earth-spacecraft motion along line E–A. This kind of measurement is typically obtained by measuring the radio signal's Doppler shift, but it also becomes apparent as repeated range measurements vary over time. In making these measurements, the spacecraft's angular position in Earth's sky, primarily the angle called right ascension measured east to west (see Subsection 2.4.1), is also inferred to high precision. These quantities are known as the "observables." In the figure, consider that obtaining these line-of-sight range, angular position, and range-rate values can be obtained for the spacecraft at point B, and they obviously would be different values than for point A. Likewise, these observations can be made for many points along the modeled orbit, limited mainly by how often the spacecraft is being observed.

By looking at the nominal orbit depicted in Figure 2.2, and by considering the kinds of observables available, and by appreciating that the Earth's motions are precisely known, one can surmise that making these measurements repeatedly would indeed result in a good estimate of how well the spacecraft is following the computer-modeled nominal orbit, at least in the two dimensions represented on the page. The orbit-determination process does this, and its results show the errors between predicted and observed quantities as *residuals.* If the residuals seem to have a Gaussian distribution,[16] then the model is probably correct, and the distribution can be attributed to noise in the observations. If they show a trend, then (1) the spacecraft is off course, or (2) there is a systematic problem with the observations, or (3) the model is incorrect. If repeated iterations have been showing normally distributed results, but a trend then appears when no change has been made in the observing methods or systems, the navigator's judgment may indicate a need to adjust the spacecraft's state of motion.

The model of the interplanetary situation, against which the observables play, is built up using the laws of Kepler and Newton, and their employment of the mass, gravitation, and motion of the Sun. It also includes precise values, called ephemerides, for the mass, gravitation, rotation, and revolution of the Earth and other bodies in orbit about the Sun, and the spacecraft's state of motion determined from previous iterations. OD must also account for small forces such as radiation pressure from sunlight acting on the spacecraft, and the reaction from any outgassing, or even radiation, such as heat, that the spacecraft emits. Of course the list also includes the effect of thruster firings the spacecraft might use to manage its attitude.

So far we've considered measurements of the paths of spacecraft and planets in two dimensions. The third dimension, declination, which is perpendicular to the page in Figure 2.2, is also measurable to a limited degree with the same kind of line-of-sight range and range-rate values. Pretty good accuracy can be obtained if those measurements come from Deep Space Stations separated by a wide latitude on Earth. Using measurements, for example from Station 43 at Canberra, Australia, in the south (–35° latitude) and Station 63 at Madrid, Spain, in the north (+40°), offers a north-south separation of approximately 8,325 kilometers. This is only of limited value, though, because triangulation precision breaks down when two of the legs are hundreds or thousands of millions of kilometers long, and the baseline is only 8,325 kilometers, as was evident with the *Mars Climate Orbiter*. But there are some additional techniques that can contribute more precise position measurements and make up for this out-of-plane knowledge deficiency. *MCO* did not include them in its mission. One is very-long-baseline interferometry (VLBI), which we'll visit later on, and the other is optical navigation.

2.3.3 Optical Navigation

If the spacecraft has a camera on board, it might be used for navigation when it nears its primary target or other solar system bodies along the way. Members of the navigation team and the imaging science team coordinate to prepare commands for the spacecraft that point the camera and take images of a target body against the background stars. For this purpose, stars can be considered as infinitely far away and remaining in known fixed locations. These images, called "opnav" images, usually show the target body overexposed, revealing little scientifically useful detail on the body itself,[17] in order to make the fainter background stars visible. Using opnavs that come back from the spacecraft via telemetry, the optical navigation analyst calls upon software tools that determine the center of the observed body (if it subtends more than one pixel in size) based on a pre-existing model of the object's shape. The software helps identify the background stars, and provides navigation data of refined precision and accuracy to the OD process, including the third dimension, declination, which is less accurately measured using range and range rate alone.

2.3.4 Autonomous Navigation

Optical navigation forms the basis of a newly emerging capability useful for some types of interplanetary missions, autonomous navigation, or "Autonav" for short. A prototype of an Autonav system flew on the *Deep Space 1* project, which began as an engineering mission designed to demonstrate several new technologies including electric propulsion. The spacecraft navigated itself successfully, and then conducted important science observations of its targets.

Part of NASA's "New Millennium" program, *Deep Space 1* departed Earth in 1998 and flew by an asteroid and then a comet. After launch and insertion onto its solar orbit using traditional navigation techniques, an initial orbit model based on the mission plan and post-launch OD solutions was provided to the spacecraft's software while in flight. The spacecraft engaged its autonomous navigation system and used opnavs to further determine its own orbit, and then it used this information on repeated occasions to predict its trajectory and carry out course corrections necessary to achieve its targets. Reference [8] further describes *Deep Space 1*'s mission.

The basic idea behind the Autonav technique is fairly simple, but it can only be implemented for missions that operate in a part of the solar system where there are plenty of relatively nearby objects, having well-known orbits, to serve as opnav targets. *Deep Space 1* operated in the main asteroid belt, where ephemerides are known for several thousand asteroids. The on-board Autonav software operated the spacecraft's camera to obtain opnav images of selected asteroids against the background "stationary" stars. In theory, one such image can be analyzed automatically to determine a line-of-sight vector from the spacecraft to the object. If another opnav is taken of a second body, widely spaced, its analysis then provides a second line-of-sight vector, and where they cross marks the spacecraft's position. Repeating the process then builds up knowledge of the spacecraft's states of position and velocity necessary to determine its orbit and ultimately to apply corrections to it. Figure 2.3 illustrates this situation for a simple case. In reality, the spacecraft moves during the interval between acquiring opnav images, adding complexity to the process.

Software components of an Autonav system must include a self-contained opnav acquisition and processing engine, as well as its own orbit-determination engine, and another system able to determine and apply needed corrections to the spacecraft's trajectory using the on-board propulsion capability.

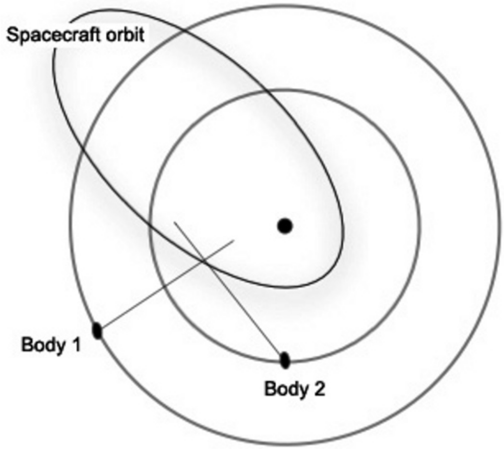

Fig. 2.3. Autonomous navigation software obtains input by acquiring images of known objects against a background of known "fixed" stars to establish line-of-sight vectors along which the spacecraft is located.

Another application of Autonav made headlines in July of 2005 when NASA's *Deep Impact* spacecraft had been flown, using both traditional radiometric and autonomous navigation, into the path of Comet Tempel 1, where it released a 300 kg copper impactor and moved out of the way. The impactor carried its own camera, Autonav system, and thrusters. The impactor's Autonav engine identified the comet's nucleus amid a confusion of bright cloudy outbursts while in communication with the flyby spacecraft, and the system autonomously executed three maneuvers, guiding itself to a successful impact that was observed from Earth. The impact event revealed many of the comet's properties, as revealed in images and spectra that the flyby spacecraft acquired and telemetered to Earth. Reference [9] details this extraordinary accomplishment in the words of its navigator. Reference [10] is the more technical treatment, with more references.

2.4 Making Measurements

Based upon a precise system of coordinates, repeated measurements of a spacecraft's velocity and position in the sky supply all the data needed for OD. The same coordinates and measurements are also the basis for making course corrections and guiding the craft, and reckoning its proximity to natural bodies in interplanetary space.

2.4.1 Coordinate Systems

To make sense of any modeling, prediction, measurement, or controlling of a spacecraft's flight path, we need to use common reference frameworks, including both spatial coordinates and time. For spatial coordinates, the observables from DSN stations are first referenced to the familiar terrestrial topocentric framework of latitude and longitude, which are based on the instantaneous locations of Earth's rotational axis and the Earth's equator. That's easy enough, because the Earth has, so to speak, those two built-in potential references, although the location of Earth's rotational axis does wander significantly — you just have to track it. But for navigating the depths of space far from Earth, what reference to use?

Just as the location of a point on the Earth's surface can be specified by its latitude and longitude, the position of an object in Earth's sky can be specified by its declination and right ascension.[18] Spacecraft angular positions, as well as planets and other bodies, are measured in a celestial framework whose reference plane is that of the Earth's equator at a particular epoch, or moment in time. In current use is the first day of Julian year 2000 at 12:00 hours TT (terrestrial time.[19]) Just as degrees of latitude denote excursions north or south of the equator in the terrestrial frame, degrees of declination, positive and negative, denote points north and south in the celestial frame. Terrestrial longitude begins at the prime meridian intersecting Greenwich, England. Similarly, celestial "longitude," expressed as right ascension, also has an origin. This is designated to be the position of the vernal equinox, the direction to the Sun when it crosses the celestial equator at the moment of equinox for the epoch year in the northern hemisphere's summer. These conditions are referenced by the term that names the epoch, today's currently used epoch being "Equator and equinox J2000.0." But there's been a subtle shift.

In the late 1950s and early 1960s, radio astronomers were finding natural sources of radio noise in the sky that were not always associated with any visible star or other object. Using widely separated radio telescopes in attempts to resolve these "quasi-stellar radio objects" with the technique of interferometry, it soon became clear they were compact sources. Reference [11] recounts this discovery. Decades later, we know that each of these objects, whose descriptor as been shortened to "quasar," is the enormously energetic disc of matter engaging the super-massive black hole(s) in the center of a young galaxy thousands of millions of light years away [12]. The brightest quasars' central masses consume matter at a rate estimated to be on the order of hundreds of Earths per hour. While the nature of quasars is therefore itself a compelling subject of investigation, these most distant of known objects make convenient "fixed" points upon which to base a celestial reference frame.

Hundreds of quasars now form the basis of the International Celestial Reference Frame (ICRF), whose axes are consistent with the J2000.0 system. The ICRF is maintained as one of the responsibilities of the International Earth Rotation and Reference Systems Service (IERS), in a collaboration between l'Observatoire de Paris and the United States Naval Observatory.[20] On January 1, 1998, the International Astronomical Union adopted the ICRF as its fundamental reference system. The celestial equator and the equinox are now precisely measured quantities. Given that some planetary ephemerides can be determined using radar, and others by radio navigation of spacecraft that encounter the planets, spacecraft and planetary ephemeris values are "tied" into the ICRF when high-precision measurements are made of both spacecraft and quasar locations together using VLBI, as discussed later in subsection 2.4.5. The observation is called a "frame tie."

No matter the complexities of spatial coordinate systems, the OD process has to include transformations between terrestrial and celestial reference frames to resolve Earth-based observables with celestially referenced objects in the solar system. Time is the other dimension.

Measurements having to do with time in interplanetary navigation are based on the standard called *Temps Universel Coordonné* (UTC), or Coordinated Universal Time. This standard is similar to the familiar Greenwich Mean Time (GMT), but it is more precise because GMT is based on the Earth's minutely variable rotation rate and the passage of a fictitious "mean" Sun — one whose rate of passage through the daily sky is an average of its values over Earth's annual motions through perihelion and aphelion. UTC, on the other hand, uses seconds defined in the International System of Units (SI), as "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom."[21] UTC is maintained as a weighted average of the time kept by about three hundred atomic clocks in over fifty national laboratories worldwide, in a system known as *Temps Atomique International*. It allows the opportunity, informally confined to the beginning of each year, for adding or subtracting a leap second to keep UTC close to GMT.

UTC, then, is the only time-scale we need to keep in mind throughout *Deep Space Craft,* although the Glossary defines the many other variations you may encounter elsewhere, including ET, TT, TDT, TDB, UT, UT0, UT1, and UT2.

To make useful measurements of range, you have to know the DSN stations' locations to a precision of centimeters at the time of your range observation. The largest influences on their locations in interplanetary space are the Earth's revolution about the Sun, and its daily rotation. The values of these motions have been refined over centuries of astronomical observations and are very well known. Attaining centimeter precision, though, means having to realize that the Earth does not rotate on a fixed axis in space. The Earth's rotational axis, which itself defines the ordinary framework of terrestrial latitude and longitude, is subject to motions on various time scales of which the IERS keeps track. There is the well-known precession of the equinoxes of over a period of about 26,000 years. On top of that there is a wobble with a period of about 433 days, called the Chandler wobble after its discoverer, the American astronomer Seth Carlo Chandler (1846–1913). This is a nutation typical of a non-spherical spinning mass. Additional, smaller nutations are also caused by the gravitational torque exerted by the Moon, and by displacements of matter in different parts of the planet including the mantle, the melting Greenland ice, and other motions of fluids. Oceanic tides impart diurnal and semi-diurnal variations in the poles' locations having amplitudes of a fraction of milliarcsesond mapped on Earth's surface. All told, the relatively short-period nutations cause the poles to migrate on the order of tens of meters across the surface over periods measured in years.

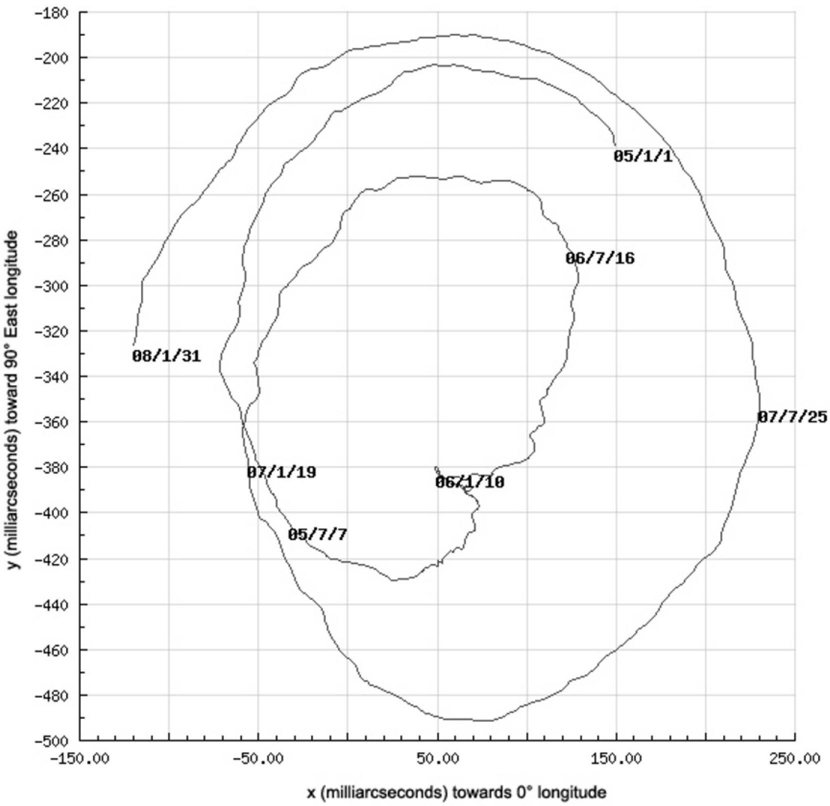

Fig. 2.4. Motion of the Earth's rotational axis in milliarcseconds from January 1, 2005 to January 31, 2008. Dates are year/month/day. Image courtesy International Earth Rotation Service.

As polar motions are tracked and reported, corrections are regularly applied to the latitude and longitude values of the DSN stations. But there's more. The continents the DSN stations sit on are moving, as Earth's convecting fluid mantle gradually drags the crustal tectonic plates at rates up to 8.5 cm per year. The DSN carries out measurements of this motion by observing quasars using the VLBI technique.

Having identified the necessary frames of reference, and all the terrestrial movements to be accounted for, we have a basis upon which to measure observable quantities, such as Doppler shift and ranging, that feed into orbit determination. Measurements made by the DSN stations, from their precisely known topocentric coordinates of latitude and longitude, can be transformed to a geocentric coordinate system, one that is more convenient when relating to other solar system objects. The geocentric-equatorial system has its origin at the center of the Earth, and the circle of the Earth's equator defines its fundamental plane.

2.4.2 Measuring the Doppler Shift

When a source of sound waves is moving toward an observer, each wave that arrives has had less distance to travel than the wave that arrived before it. Thus the waves arrive more frequently than they otherwise would have. Conversely, if the distance between the source and observer is increasing, each arriving wave has farther to travel. If all the waves are traveling at the same speed, then the time it takes to transverse the longer distance is greater, and the waves arrive at the observer's location less frequently — at a lower frequency. The effect is observable only on the component of a source's velocity that is directly toward or away from the observer. In everyday experience, there are many examples of this effect, named for the Austrian physicist and mathematician Johann Christian Andreas Doppler (1803–1853) who described it in 1842. The change in pitch of its siren that one hears when an ambulance approaches and recedes is a familiar one.

The example of frequency-shifting sound waves illustrates the principle of the Doppler effect that also occurs with radio waves, light, and other electromagnetic radiation when there is relative radial motion between the source and recipient. For sound waves propagating through the air, motion of the air itself will affect the observed frequency, but electromagnetic radiation requires only the medium of space-time itself for propagation, so the relative motion between source and observer alone induces the Doppler shift. In this case, the relationship between the transmitted frequency f and the received frequency f_{rec} is:

$$f_{rec} = f + \frac{fv}{c} \tag{2.1}$$

where v is the line-of-sight, i.e. radial, component of relative velocity (positive for approaching, negative for receding) and c is the speed of light. Note that Doppler has no effect on the speed of propagation. It only affects the frequency. Blue light propagates at the same velocity as red light or radio. Also, consider that the source may have motion that is not radial to the observer, in which case the observable effect along the line of sight would be:

$$v_{s,r} = v_s \cdot \cos\theta \tag{2.2}$$

where $v_{s,r}$ is the radial component of the source's velocity, v_s represents the source's actual forward velocity in the observer's frame of reference, and θ is the angle between the source's forward velocity and a line of sight to the observer. While it might be convenient to be able to observe the entire absolute motion of the source, measurements of the radial component of velocity, along with distance measurement, are quite sufficient for input to the orbit determination process to fit to the nominal orbit. As we saw in *Mars Climate Orbiter*'s case, $v_{s,r}$ will be zero if the motion is at right angles to the observer's line of sight.

Knowledge of the Spacecraft's Frequency

Accurate knowledge of f, the transmitted frequency in equation 2.1, is essential for measuring the spacecraft's velocity. Ideally, a spacecraft's transmitter would output a nice, stable-frequency radio signal with a value of f known precisely enough to permit meaningful Doppler shift measurement when solving for v in equation 2.1 or 2.2. But a spacecraft's transmitter has too many limitations to be able to satisfy that desire. It must be lightweight, and it must consume a minimum of power from the spacecraft's limited electrical supply. Also, extreme temperature variations can be expected on a spacecraft, some of which may affect the transmitting electronics' frequency stability. In short, a spacecraft's transmitter simply cannot be expected to provide an adequately stable, known frequency on its own, for the purpose of navigation. Many spacecraft are equipped with a frequency reference called an Ultra-Stable Oscillator (USO), which can provide moderately good frequency stability. USO electronics are maintained in an "oven" on the spacecraft that keeps a temperature stable to within a fraction of a degree Celsius. A USO is useful for some radio science observations, but is not stable enough for routine navigation.

Coherence

Coherence is the solution. A massive, power-hungry frequency standard, supplied with uninterruptible electrical power, housed in a climate-controlled basement in each of the three Deep Space Communications Complexes worldwide, provides an extremely stable frequency reference that the DSN stations' transmitters use to generate their uplink frequency. Once a spacecraft receives the stable uplink, it typically switches to a mode in which it generates its own downlink transmitter's frequency based on the uplink it is receiving. In fact the downlink waves are phase-coherent with the uplink. That is, the timing of the peaks and troughs of the downlink signal maintain a fixed relationship with those of the uplink.

When received on the ground, the downlink frequency can readily be compared to the uplink because the same reference frequency that supplies the uplink transmitter is also available to the DSN's downlink receiver. And, yes: the Doppler effect is doubled, shifted once as the spacecraft receives the uplink, and shifted again as the DSN receives the downlink, so dividing the observed shift in half yields the useable result. Doppler shifts due to all the known motions — Earth's rotation, revolution, and the spacecraft's nominal orbit — are subtracted out by DSN based on predictions supplied from the navigation software. What remains, the *Doppler residuals,* represent valuable navigation data that, along with additional input, will lead to iterating a navigation solution: estimating where the spacecraft is in relation to its predicted orbit.

The highly stable frequency standard the DSN usually uses is a hydrogen maser at the heart of the DSN's frequency and timing system. The device keeps a microwave signal resonating within in its tuned cavity via a feedback arrangement. The signal's frequency, based on oscillation between two "hyperfine" levels in the energy of hydrogen atoms, is 1,420,405,751.768 Hz. Additional electronics in the frequency and timing system multiply the frequency to desired values, all the while benefiting from its extraordinary stability — a few parts in 10^{15} over a span of ten hours is typical. In addition to providing the basis of the DSN transmitter's frequency, the frequency and timing system distributes frequency reference signals, as well as time values based on the frequency standard, to all the other systems in the DSN, including the receivers, as mentioned, the telemetry decoders, the uplink command system, and the systems that point the antennas.

Benefitting from the highly stable reference frequency, the Doppler-shift measurements processed in the navigation software can lead to extraordinary results. Navigators of the *Cassini* spacecraft, using an X-band radio link to and from the distance of Saturn, a round trip on the order of 3×10^{12} meters, routinely report radial velocity measurements to better than 0.1 mm per second precision. To visualize this degree of precision, imagine holding your hands one meter apart, and then bringing them together at the rate of 0.1 mm/sec. It will take you ten thousand seconds — over 2.7 hours. This would be a very tiny increment of speed on anybody's speedometer, yet this is the precision available for navigating a vehicle through its eye-of-the-needle encounters at enormous distances from Earth.

Doppler shift measurements during the course of an eight- to twelve-hour DSN pass, observing the spacecraft's coherent downlink while it passes across the sky, provide more information than simply the radial component of the spacecraft's velocity. They also provide precise measurements of right ascension and declination — the angles locating the spacecraft in the plane of the sky. While there are encoders in each antenna's mechanical system that read out the direction the antenna is pointing to within thousandths of a degree, these are not important other than to control antenna pointing. More precise angle data stems from accurate timing of Earth's rotation combined with that component of change in the Doppler shift that is due to our planet's motion.

Here's how. When a DSN station watches a spacecraft rise in the east, that station is speeding toward the spacecraft as the Earth rotates. When it sets in the west, the DSN station is speeding away from the spacecraft. And as the spacecraft passes across the station's meridian of longitude, the diurnal Doppler shift passes through its minimum before reversing sign. Given the DSN's highly stable and precise timing system, this relative motion can be translated into right ascension values with good precision and accuracy. Declination values are less precise because the spacecraft's relative motion in the north-south direction, while usually present, is less pronounced than its east-west motion across the sky. In short, the signal's Doppler shift observed at a DSN station is the sum of the long-term geocentric velocity of the spacecraft (caused by the spacecraft's own motion and the Earth's revolution in solar orbit) and the topocentric short term, daily, sinusoidal variations due to the rotation of the Earth. The amplitude of the sinusoid is proportional to the cosine of the spacecraft's declination, and its phase, varying with the time of day, includes information about the spacecraft's right ascension. See Figure 2.5.

2.4.3 One, Two, Three Way

The signal coming down from a spacecraft that has not received an uplink signal is called a *one-way* signal. The frequency of the one-way signal is based upon the

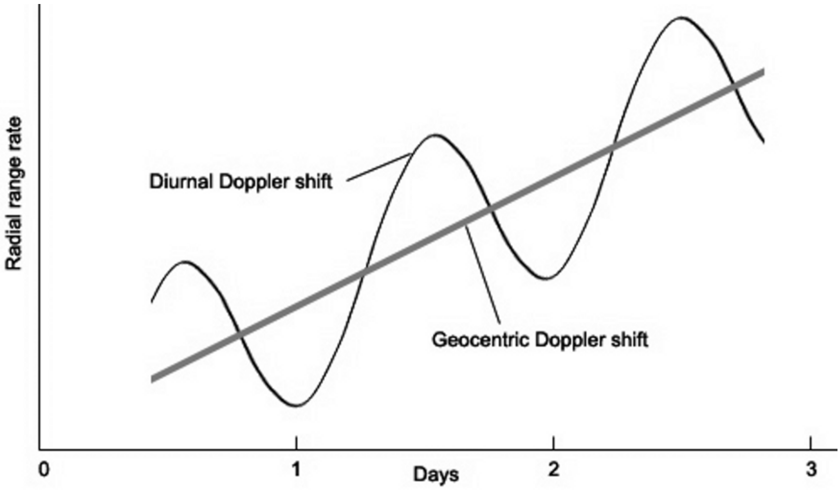

Fig. 2.5. Diurnal Doppler shift is caused by the Earth's daily rotation, while the more gradual geocentric shift reveals motion of the spacecraft combined with Earth's yearly revolution about the Sun.

spacecraft's own frequency standard. Whether it uses a USO or not, the electronic oscillator is usually based on the vibrations of a crystal — much the same principle as that of the operation of a digital wristwatch. Even though the one-way signal does not exhibit the highly stable frequency required for navigation, it has no trouble conveying telemetry that carries science and engineering data from the spacecraft.

Once a spacecraft has received the uplink signal, and is generating a downlink frequency coherent to the uplink reference signal, and the DSN receiver has locked onto it, the system is said to be in *two-way coherent* mode. On rare occasions, the typical spacecraft can be commanded to ignore the uplink as a frequency reference, and continue generating its own downlink frequency. This condition, which is useful for calibrating the on-board oscillator, and for some science experiments, is called two-way non-coherent (TWNC, pronounced "twink"). TWNC has to be in its "off" state to enable accurate navigation.

Two-way mode assumes that the DSN station that is transmitting the uplink is the same one that is receiving the downlink during one session. If a different station is receiving the downlink, the mode is called *three-way.* Three-way can be either coherent or non-coherent, depending on whether or not the received signal is being referenced to an uplink signal. Uplink from a DSN station to a spacecraft at a great distance, such as *Voyager 1* for example, might never be received by the same DSN station during the session while it is supplying the uplink, because the long round-trip light time exceeds the period of time that the spacecraft is in view before it sets below the western horizon. As of late 2008, *Voyager 1*'s round-trip light time is about thirty hours. One DSN station may provide an uplink toward *Voyager 1* from the time the spacecraft rises in the east until it sets ten or twelve hours later, without ever seeing a two-way coherent downlink. Later the next day, that DSN station or another one will capture *Voyager 1*'s three-way coherent downlink (meanwhile supplying an uplink for the next day's station to receive).

To avoid radio interference, a spacecraft does not transmit the exact same frequency signal that it receives on the uplink. Instead, the spacecraft's electronics will multiply the frequency of the uplink signal it receives by a predetermined fraction to create its downlink frequency. *Cassini*, for example, multiplies the X-band uplink signal it receives by 880/749 to generate its X-band downlink frequency.

During typical operations, the DSN will lock its receiver to a spacecraft's one-way downlink signal at the start of its tracking activity, and begin extracting and decoding telemetry. Shortly thereafter, the station will initiate an uplink. Round-trip-light-time later, if TWNC is off, the spacecraft's two-way coherent downlink will complete its trip to Earth. This coherent downlink, stable enough for navigation, will usually be a slightly different frequency than the one-way signal was. So, the DSN receiver will lose lock on the one-way signal, and an operator or an automated system will have to direct the receiver to change frequency and acquire lock on the new coherent downlink frequency. This typically requires a couple of minutes, and so any telemetry or other data will be lost for the out-of-lock period. Careful planning, though, can result in having the command sequence that is running on board the spacecraft effect a pause in the data it is sending down, carefully timed in anticipation of the out-of-lock event. *Cassini* routinely does this, although any last minute changes in DSN uplink timing can thwart the valiant plan and result in a couple of minutes' loss of telemetry.

In addition to its importance for navigation, measuring a spacecraft's Doppler shift while it is passing close by a body, such as an asteroid, a planet, or a moon, can also be valuable as a science experiment, as mentioned in Chapter 1, and as we'll examine in Chapter 6. Tracking the spacecraft in coherent two-way or three-way mode can measure the spacecraft's minute accelerations caused by the target body's gravitation, and these accelerations constitute an important measurement of the body's mass.

2.4.4 Measuring Range

When ranging is employed, the uplink radio link from the DSN carries a series of recognizable signals called ranging tones that it imposes on the carrier (or a subcarrier) using phase modulation as discussed in Chapter 1. When the spacecraft receives the ranging tones, it sends them right back on its downlink radio signal. The DSN ranging system records both the timing of each ranging tone's uplink, and the timing of the downlinked tone's receipt. In theory, the elapsed time reveals the line-of-sight distance that the radio signals travel, at the speed of light, c, to the spacecraft and back: range data. Ranging measurements can currently achieve a precision of about one meter for a spacecraft at the distance of Saturn, but only because several factors are taken into account:

1. Based on tests conducted with the spacecraft before launch, the delay caused by the electronics within the spacecraft is a known value, typically measured in nanoseconds.

2. The distance from the DSN antenna to the receivers and ranging system computers located in the Signal Processing Center at each complex is also known. It is usually measured anew just before a tracking pass begins, to account for any changes of equipment or connectors, or in the lengths of the long wires or fiber optic cables due to temperature.
3. Corrections are made for the amount of Earth's atmosphere and ionosphere the uplink and the downlink signals have to pass through, which varies with the DSN antenna's elevation angle as the spacecraft rises and sets. This is because c has slightly different values for propagation through vacuum, air, water vapor, and plasma. Delays from propagation through the atmosphere and the ionospheric plasma can introduce range errors from about two meters at zenith to ten meters at low antenna elevation.
4. Sparse interplanetary plasma also changes c slightly, but its effect can be calibrated by comparing Doppler to range, or by comparing the effects at two different frequency bands. Otherwise, it is accepted as noise in the ranging data. High levels of noise from dense plasma in the Sun's corona can prohibit obtaining valid ranging data when the line of sight to the spacecraft passes within a degree or so of the Sun's limb.
5. Relativistic effect. Rapidly moving objects experience time dilation according to the provisions of special relativity. While tiny,[22] the effect is a known quantity, and can be included when computing range values.[23]

The result represents the line-of-sight distance to the spacecraft. These measurements are of course based on the location of the DSN station. Since the precise location of the DSN station is known, the range measurements can then be reduced to a common reference location, the Earth's center, for input to the orbit determination process.

As with Doppler shift measurements, range measurements reveal diurnal and longer-term results like those seen in Figure 2.5. Range over time provides range rate. And, taken over periods of days range rate also provides indications of the spacecraft's angular position in the sky: right ascension and declination. As mentioned in subsection 2.3.2, ranging from stations in both the northern and southern hemispheres of Earth give useful declination values.

Ranging is not always employed every time a spacecraft is tracked, but flight projects usually do so whenever they can. Since the process requires modulating the uplink radio signal to the spacecraft, and modulating the downlink from the spacecraft, ranging competes for power in the normally power-limited downlink signal. In some cases the spacecraft has to be commanded to turn telemetry modulation off to make range modulation "loud" enough to use. But if the communications link has enough power, as is the case for *Cassini* and many other missions, range measurements can easily share the available link margin.

2.4.5 VLBI — Very Long Baseline Interferometry

Measurement of right ascension and declination is a side effect that comes from measuring a spacecraft's radio Doppler shift and range. And we saw that measuring declination, the north-south dimension in the sky, can only be done with limited accuracy using either Doppler or ranging, or both. When certain assumptions are inaccurate within a spacecraft's modeled nominal orbit or with the forces acting on the spacecraft, Doppler and range measurements of declination can be inadequate to make orbit model iterations converge on the spacecraft's true position along the north-south axis, as was unfortunately seen in the loss of *Mars Climate Orbiter*.

Every spacecraft sent to Mars since the loss of *Mars Climate Orbiter* has included VLBI as a third radiometric technique to measure its angular position on the plane of the sky. Though it produces highly accurate results, VLBI is relatively expensive in terms of resources, time, and effort. It requires the use of DSN stations on two different continents at the same time, during the limited windows of opportunity when both might have the spacecraft in view simultaneously. Both stations must have antennas with apertures of at least 34 meters, because they will be observing some very faint radio sources. While any given spacecraft is setting low in the western sky as seen in Australia, it is just rising, still low above the eastern horizon as seen in Spain. Or it is setting from California's point of view while rising on the eastern Australian horizon, or setting in Spain while rising in California. Some spacecraft have fewer than these three overlap opportunities. Apart from the task of scheduling some of the busiest antennas on two continents, VLBI also depends on substantial ground-based data communications capability, and computer data storage and processing power as well, although the latter requirement is easier to satisfy today than it was less than a decade ago.

Here's how it works. The VLB part of VLBI, the very long baseline, consists of the distance between the two DSN stations in use. It's what gives the technique its high resolving power. Interferometry is the science and art of treating the two widely separated antennas as if they were one aperture — one enormous radio telescope — the size of the baseline itself. Not the collecting power, meaning the total area available to collect a signal (that's what an array does; see Chapter 1), but the power of spatial resolution is what counts in this case. VLBI therefore is a technique of great interest not only to navigators of spacecraft, but to radio astronomers[24] and optical astronomers,[25] as well.

Waves of electromagnetic radiation can interfere with one another. If two waves of microwave energy at the same frequency arrive upon a single antenna — or are combined from two or more antennas — they can cancel each other out if they are out of phase, or they can augment one another if they are in phase (waves on the ocean can also do this). This principle gives the technique of interferometry its name. What gives it its high resolution is the ability to precisely time the arrival of wavefronts as they enter each widely separated antenna, and then correlate them. If the DSN antenna in Spain, for example, happens to lie closer to the spacecraft than the Australian DSN station, a single wavefront from the spacecraft will hit the Spanish antenna, then a number of microseconds later it will hit the Australian station. The VLBI technique undertakes the task of identifying each incoming wave — there are billions every second — and measuring the difference in time between their arrivals at each station. It identifies them by recognizing similar groups of waves as if they were fingerprints. The precise length and orientation of the baseline is known in advance. As one can imagine, measuring this time difference can then yield the angular position of the spacecraft. It's a daunting task, certainly, and there's more to it.

Recall from subsection 2.4.1 that quasars form the pillars that hold up the International Celestial Reference Frame. For the first step in using VLBI to observe a spacecraft's position, both DSN stations slew to a single quasar that happens to be near the spacecraft in the sky (in the plane of the sky, that is. The quasar itself may be billions of light years away). They record the microwave noise coming from the quasar for ten minutes. Then both stations slew to the spacecraft, and record ten minutes of the "noise" coming from the spacecraft (actually the radio signal, but here it is treated as noise). Then, if time remains before the object sets, both antennas may slew back to the same quasar, or a different one, and record its noise, just for good measure.

The recordings of these observations of noise comprise huge data sets of high-resolution samples digitized and stored on disc. All the recordings are transmitted later, after the observations, to a central processing workstation. Here, they are fed into the *correlator.* This is a powerful computer program running on readily available hardware. The correlator analyzes and then "recognizes" the shapes of the random waves of noise from the quasar observations, and of the pseudo-noise from the spacecraft, received by both stations. It then matches up the wavefronts, that is it correlates them, and based on the times of the recordings, it establishes a precise value for the right ascension and declination of each of the observed objects — the quasars and the spacecraft. Now, since the positions on the sky of quasars are very well known because they form the basis of the reference frame itself, the coordinates of the spacecraft are pinned down as absolutely as can be possible. The use of quasars helps reduce or even cancel out errors that may be introduced from clock errors or instrument delays because their positions are well known from many previous observations, and because their locations are fixed.[26] A successful VLBI observation can yield values for a spacecraft's right ascension and declination to a precision of 5 nano-radians (about 2.87×10^{-7} degree), and because this result is achieved *independently* from the regular Doppler and range measurements, it can be taken as unambiguous, overriding any errors in modeling the dynamic forces on the spacecraft. Reference [13] provides more technical detail.

Not all VLBI observations are successful. There are many opportunities for flaws in the process of coordinating and executing an observation using two antennas on two continents, capturing and communicating massive data sets, and running a successful correlation. For one, observations at low elevation in the sky are typically difficult. There may be rain somewhere between the station and the horizon it is observing, contributing too much microwave noise or attenuation. There is certainly a large corridor of radio-refracting atmosphere, and plasma-laden ionosphere. Computer discs have been known to fill up before observations have completed. Communicating the large files is more common a task today, but in years past it could often fail or take too much time. When a mission calls for VLBI observations to augment the normal Doppler and ranging navigation, a larger number of the observations are commonly scheduled than are actually needed, to hedge against possible failures.

VLBI observations in support of spacecraft navigation go by various names, and may have slightly modified techniques. They have been called ΔVLBI, a name that just further describes the above technique, where the delta refers to the difference between quasar and spacecraft. In ΔDOR or DDOR, DOR (pronounced "door") stands for Differenced One-way Range, which seems a little misleading because although the signals are differenced, and the observations are done in one-way communications mode, at least with the quasars, they are not primarily range measurements. If a quasar is not used, sacrificing some accuracy, the observation may be just called a DOR.

Sometimes the DSN carries out VLBI observations of quasars and spacecraft operating in the proximity of solar system bodies, without a flight project's request or concurrence, in order to update models of planetary ephemeris based on J2000.0 with relation to the ICRF. These are the frame-tie observations mentioned in Subsection 2.4.1.

Voyager 2 used VLBI en route to Uranus and Neptune, because the limits of Doppler and ranging in determining its right ascension and declination had been exhausted at about the distance of Saturn [14]. *Mars Global Surveyor,* launched in 1996, achieved its target without the use of VLBI. Its Mars orbit insertion came well before the loss of *MCO* and the subsequent scrutiny of navigation techniques by higher NASA management. *Cassini* never used any VLBI to get to Saturn, even though its interplanetary cruise, from 1997 to 2004, spanned the *MCO* accident. *Cassini* project navigators were able to demonstrate high confidence in the excellent convergence of solutions using Doppler, ranging, and opnav data, along with four perfectly successful "gravity assist" planetary flybys.

2.4.6 Putting it all together

The observables — radiometric navigational data in the form of coherent Doppler shift, ranging, and VLBI when available, as well as any opnav data — enter the OD program as values of range, right ascension, declination, and each one's rate of change. OD compares them to predicted observables that it has calculated based on its model of the spacecraft's dynamics, its nominal orbit incorporating the laws of motion and all the known forces acting on the spacecraft. Data representing solar system body ephemerides, DSN station locations, and calibrations, also enters the OD engine. The system works out its solution using a procedure called weighted linear least-squares estimation, resulting in a new estimated orbit that can be published as a reference for all users, such as the science teams who are planning how to point their instruments to capture images and spectra of an upcoming target. Reference [13] has the technical detail. The latest OD solution also lets users interpret the results of observations they've already made. Finally, navigation team members analyze the OD results to determine what, if any, guidance corrections will need to be applied to the spacecraft.

2.5 Correction and Trim Maneuvers

When the popular press compares a precise Mars landing to a golfer's hole-in-one, they're missing something. Professional golfers like Tiger Woods would score hundreds of holes-in-one, had they the ability to precisely track the ball, and some three or four opportunities to adjust its trajectory during the course of each flight after it has left the tee. Interplanetary spacecraft are equipped with propulsion systems (discussed in Chapter 4) that are capable of making small corrections to their trajectories or orbits during their months or years in flight.

The few minutes of powered ascent a spacecraft enjoys from its launch vehicle determines its final trajectory to the greatest degree, so every launch strives to be an extraordinarily good "tee-off," and most are indeed as good as can be. Some go into the drink. But launches are hardly ever good enough to precisely achieve the mission's target, be it a planet, a comet, or an asteroid, without a little help along the way. Following a spacecraft's ascent from Earth, typically after a few days or weeks spent acquiring Doppler and range data and working the first iterations of a nominal orbit model, navigators call upon the spacecraft's propulsion system. Its task, or rather the navigation team's task and the spacecraft flight team's task, is to execute a Trajectory Correction Maneuver (TCM) and remove the flight path errors left after launch before they have a chance to become too large. Additional opportunities for executing TCMs may occur later in flight.

Usually a small propulsive maneuver undertaken while in solar orbit is called a TCM, but when a spacecraft is in a closed orbit about a planet, the same kind of propulsive maneuver is called an Orbit Trim Maneuver (OTM). In either case, a spacecraft's rocket engine or thrusters[27] operate to impart a force accelerating the spacecraft in a desired direction for a predetermined period of time, resulting in a change of velocity or ΔV. TCMs and OTMs typically generate forces that impart only small quantities of ΔV, for example from ten millimeters per second to several meters per second. Maneuvers are called "deterministic" if they must be performed as part of the original trajectory design. Others are called "statistical" when they compensate for the variations that are a normal part of the navigation process, such as clean-up following a flyby. Many maneuvers are a combination of both.

Some mission designs include the need to execute a deterministic maneuver that imparts a relatively large ΔV in order to set up for a particular gravity-assist flyby that would not be possible to reach otherwise. These are called Deep Space Maneuvers (DSM). By design, each uses a good percentage of the propellant a spacecraft carries (as we'll see later, the gravity assist itself will prove well worth the DSM's expenditure of propellant). The *Messenger* spacecraft executed a DSM on December 12, 2005 that consumed eighteen percent of the spacecraft's fuel and oxidizer. This 524-second main engine burn imparted a ΔV of 316 meters per second, putting the craft on track for a 3,140-kilometer-altitude gravity-assist Venus flyby October 24, 2006, en route to its target Mercury. Messenger's gravity-assist trajectory includes a total of five DSMs, and dozens of TCMs, followed by an 830 m/s ΔV orbit insertion maneuver on March 18, 2011, using its 600 N main engine. Once in orbit, the spacecraft will execute a pair of OTMs once every

Mercurian year — eighty-eight Earth days. *Cassini* executed one DSM, using its 440 N main engine, to slow down in solar orbit by 450.2 m/s setting up for its first gravity-assist Venus flyby. There were twenty-three TCM opportunities en route to Saturn, of which seven were not required and were cancelled. Upon arrival, the main engine provided a 626 m/s ΔV for orbit insertion — slowing to allow Saturn's gravity to permanently capture the spacecraft.[28] During its four-year prime mission of seventy-nine orbits, there were opportunities for 160 OTMs, many of which did not have to be executed because there was little deviation from the desired orbit.

To adjust a spacecraft's flight path, an aim-point is selected near a target body, no matter whether the body lies directly ahead or will be encountered much later along the arc of the spacecraft's orbit. Maneuver designers then specify an orientation for the thrust vector which the spacecraft will use to point its engine, and they specify a ΔV value to be imparted that will adjust the flight path to arrive near the aim-point. Consider as an example a spacecraft located near the arrowhead above point B, back in Figure 2.2 on page 52. A propulsive maneuver might be performed when the spacecraft is near that location in order to adjust course to achieve a future flyby of planet E at a desired miss distance. (For this illustration, we'd have to assume a timing that would allow the planet to be at that point again to meet the spacecraft as it descends along its ellipse.) In fact it is common practice to execute a propulsive maneuver near apoapsis, the high point in orbit, when the spacecraft is moving at relatively low velocity, and the OTM's effect is to raise or lower the upcoming periapsis altitude.

The process of selecting an aim-point in itself can be complex, especially if the target body is to be the subject of scientific investigation. In that case, there can be difficult tradeoffs to make among many competing factors such as geometry and illumination, timing requirements, attitude control's need for unobstructed celestial references or avoidance of torque induced by an atmosphere, a science team's desire for atmosphere sampling, communication constraints, and conservation of propellant. When the target body is to be used primarily to obtain a gravity assist boost, though, science objectives can take a back seat to the navigation requirements.

2.5.1 The Target Plane

As a tool to use in preparing for TCMs or OTMs, and to use in reconstructing the actual flight path after the fact, a construct known as the B-plane is envisioned, together with the definition of some associated vectors. Refer to Figure 2.6.

The spacecraft's trajectory approaching a target body is usually a curve that is hyperbolic with respect to the body's location. That is, the craft will fly past the body unless it is intended to impact. The path is considered hyperbolic during approach even if plans call for the spacecraft to use its propulsion system near the body to enter into orbit around it, such as in a Mars orbit insertion maneuver. The target plane, or B-plane, is defined as being perpendicular to the asymptote S of the incoming hyperbolic path that passes through the target body's center. You can generally regard the asymptote as a straight line representing an average of the curved trajectory. Since a spacecraft's trajectory exhibits various amounts of curvature, the asymptote by definition is based on the spacecraft's velocity vector

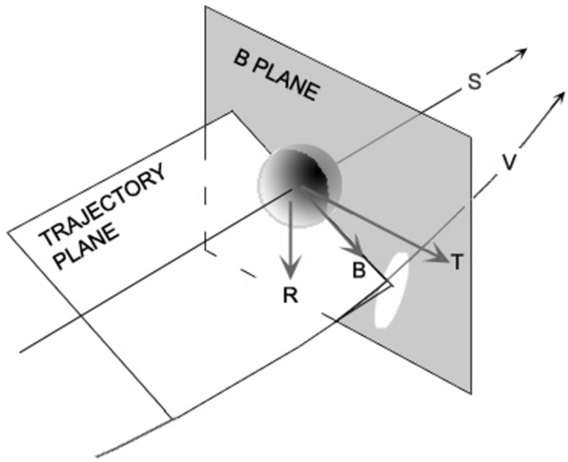

Fig. 2.6. The B-plane is defined to be normal to asymptote of the spacecraft's incoming trajectory V at the time of closest approach. Vector S is parallel to the asymptote and passes through the target body's center of mass. Vector T lies arbitrarily within the ecliptic or the body's equatorial plane in most cases. Vector R is perpendicular to T and S. B is perpendicular to S and lies in the trajectory plane.

at the time when the target body's gravitational influence becomes the dominant one affecting the spacecraft. That velocity is called the velocity at infinity, V_∞. The vector B, sometimes called the "miss" vector, extends from the body's center to the point at which the spacecraft's asymptote penetrates the B-plane at the targeted aim-point (parallel to S) that the TCM seeks to achieve. The B vector specifies the point of closest approach *as if* the target body had no mass and did not deflect the flight path. Vector T is arbitrarily defined to lie within a plane such as the ecliptic, or a body's equatorial plane, and vector R is perpendicular to both T and S.

The B-plane construct provides a means for visualizing the predicted or actual effects of a TCM or OTM in a two-dimensional coordinate system that can be graphed in coordinates of T and R, whose origin are at the center of the body. In Figure 2.6, notice the small white ellipse in the B-plane, centered on the asymptote. This represents the predicted targeting accuracy. The probability of achieving the target point is specified as a value of standard deviation usually in the range of one to three sigma (σ). This is how OD solutions are represented on the B-plane, telling you that the spacecraft will probably pass through the B-plane somewhere within the ellipse. In normal operations, consecutive iterations of OD solutions over time can usually be expected to converge with less and less error, in smaller and smaller ellipses, each centered somewhere within the previous one. Time-of-flight error shows up along the asymptote perpendicular to the B plane.

Figure 2.7 shows a B-plane graph for the *2001 Mars Odyssey* spacecraft, which launched on April 7, 2001. Its TCM-1 in May of that year imparted a ΔV of 3.6 m/s

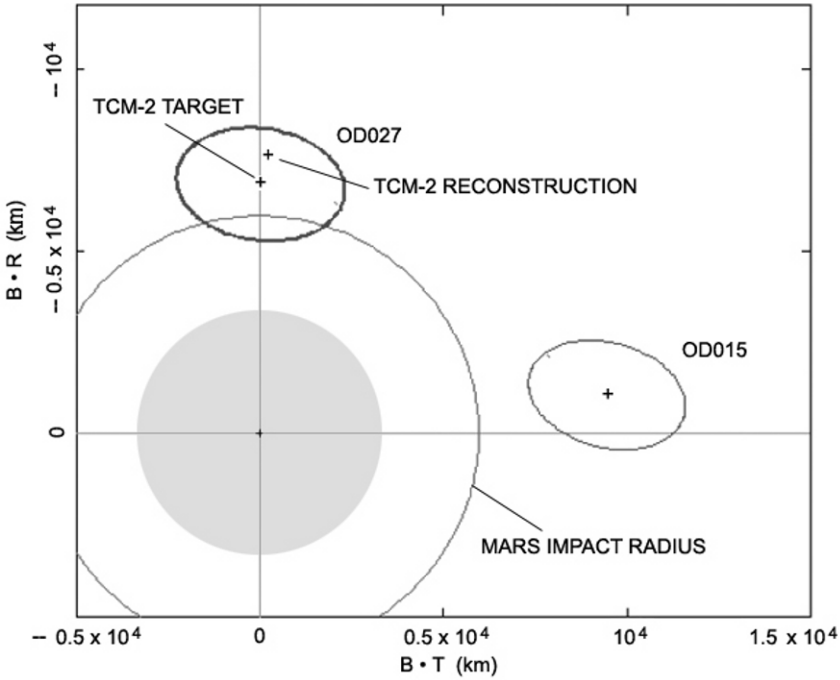

Fig. 2.7. *2001 Mars Odyssey* spacecraft B-plane with orbit determination solutions and TCM-2. Graphic adapted from NASA/JPL. Reference [15] details the process.

to correct its trajectory by cleaning up errors that were contributed during launch due to some approximations employed to simplify launch strategies. By October of the same year the craft was closing in on the red planet, heralding NASA's first attempt at orbit insertion there since *Mars Climate Orbiter*'s failure at MOI in 1999. *Odyssey*'s date with Mars was to be October 24, 2001. In the figure, a grey circle represents the planet Mars, centered at the origin of T and R. The circular line concentric with Mars indicates the boundary on the B-plane within which the spacecraft will probably impact Mars. This line is larger than the planet's grey circle because, as you will recall, the B-plane convention treats the planet as not having any mass or gravity. It remains for computations outside of this targeting display to determine where gravitation will have its effect, and the results are imported. This graph shows that the spacecraft should be safe from atmospheric drag-down or direct impact as long as the OD solutions place the spacecraft's aim point outside the impact circle.

The ellipse on the right in the figure shows the result of orbit determination solution OD015, in which the spacecraft's B-plane target would have been 10,000 kilometers from Mars, if it were allowed to continue on that path. But a TCM was executed on July 2, giving a ΔV of 0.9 m/s to move *Odyssey*'s aim point closer to

Mars, and position it over the north pole so it could enter into a polar orbit. The predicted result of TCM-2 appears in solution OD027 to the north of Mars on the figure. You'll notice there is some probability the spacecraft might impact Mars as a result of this TCM, since the prediction ellipse intersects the impact circle. The "reconstruction" of TCM-2, an accounting done with OD runs after the TCM had been accomplished, shows a confident location well outside the danger zone.

To execute a TCM, the spacecraft rotates to orient its rocket engine in a direction that the navigation team has calculated using maneuver design software, and which the Ace has uplinked to the vehicle a few hours in advance. Then the spacecraft ignites its liquid-propellant rocket (or a set of smaller thrusters), allowing the burn to proceed for a period of time specified in the maneuver commands. Finally, commands in the maneuver sequence tell the craft's attitude control system to rotate it back to its normal cruise orientation, which accommodates such factors as control of solar heating or communications. The craft then continues along its free-fall path until the next propulsive maneuver.

Odyssey had its share of navigation challenges en route, including Doppler and range observations that had to be taken close to the horizon in Earth's sky and plagued with noise, frequent autonomous propulsive maneuvers on the spacecraft contributing ΔV while taking care of reaction wheel momentum desaturations, and some unexplained variations in Doppler shift measurements. But it also had the benefit of several VLBI ΔDOR observations along the way that provided precise right ascension and declination data, contributing to confident OD solutions. TCM-3 provided 0.45 m/s ΔV on September 17; TCM-4 needed to nudge the spacecraft only 8 cm/s ΔV on October 12; and opportunities to execute a TCM-5 just before MOI were deemed unnecessary [15]. Figure 2.8 reveals the ever-shrinking B-plane error ellipses following the TCMs, and the eventual placement of the spacecraft only one kilometer away from its target altitude of 300 kilometers above Mars on the B-plane for orbit insertion. The figure has a wide grid of dashed lines on the B-plane representing areas of coordinates mostly along $B \cdot R$ that would place the spacecraft at various specified altitudes above the planet, and along $B \cdot T$ that would result in various near-polar orbit inclinations.

2.5.2 Maneuver Execution

It is November 9, 1997. *Cassini* has been free of Earth's gravity, orbiting the Sun on its own for twenty-five days. During the October 15 launch, its Centaur upper stage had fired to slow down the spacecraft in its solar orbit, placing it on a trajectory that would take it falling inward toward Venus's orbit for a gravity-assist flyby of the planet. Today, *Cassini*'s TCM-1 will clean up the errors resulting from last month's launch and injection into its interplanetary transfer orbit. The 34-meter aperture DSN station in Spain known as Station 54 is providing an X-band radio uplink to *Cassini*'s low-gain antenna — the high-gain antenna dish is pointing toward the Sun to provide shade and prevent the spacecraft from overheating. The downlink signal from *Cassini*'s LGA is a relatively strong –145 dBm, and this signal is phase-locked to the DSN's stable uplink in two-way coherent mode. Still relatively close to Earth, *Cassini*'s radio waves only take 1 minute and 17 seconds to propagate home.

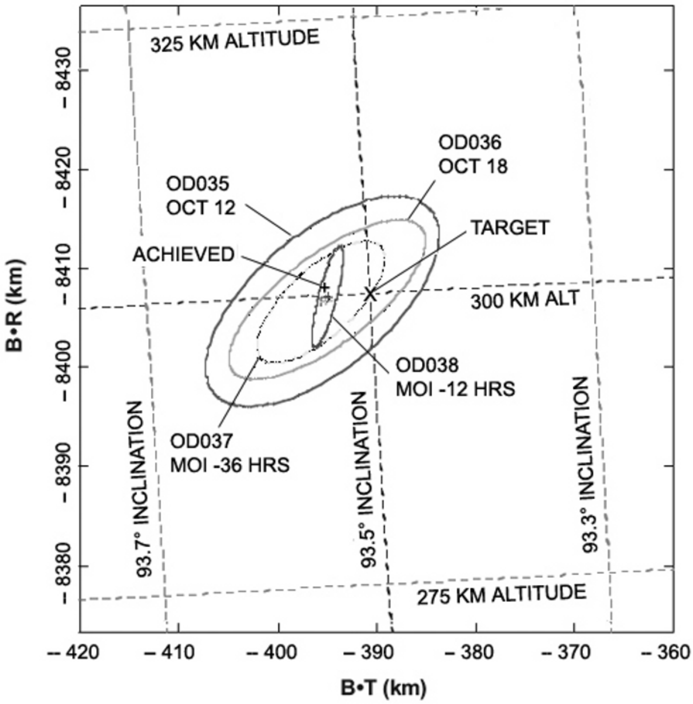

Fig. 2.8. *2001 Mars Odyssey* spacecraft B-plane shows orbit determination solutions converging as the spacecraft approached Mars for orbit insertion on October 24, 2001. The planet is situated outside this graph toward the bottom. Graphic adapted from NASA/JPL.

Now that telemetry shows the spacecraft's main-engine cover has opened and stowed under control of the ongoing command sequence (this hemisphere of motor-driven ribs and meteoroid-protecting fabric folds away from the pair of aft engine nozzles like the canopy on a baby stroller), the Ace sends a "mini-sequence" of commands to execute TCM-1, which the spacecraft team and navigation team had previously prepared. Now as the time-tagged commands start executing, the attitude control system begins rotating the spacecraft by causing the propulsion system to fire short bursts from some of its 0.9 N rocket thrusters mounted on struts. After a few minutes, the craft has finished rolling and yawing into the right attitude for the main engine burn, and the thrusters again fire quick bursts to stop the last turn. All of these actions are showing up clearly in the real-time Doppler shift displays because the turns cause the body-mounted LGA to move a few meters with respect to Earth. The next OD run will account for the velocity changes, each a few millimeters per second, that occurred as a side effect of the turns. Communications with Earth are unbroken since the low-gain antenna covers a large portion of sky from *Cassini*'s point of view, including the bright blue Earth. Turns for TCMs and OTMs later in the mission, after the HGA is in use, will interrupt communications when the narrow radio beam sweeps away from Earth.

The commands' time-lags allow a few minutes' settling time for the liquid fuel and oxidizer to finish sloshing around in their tanks. Now two solenoid-driven valves in the propulsion system slam open, admitting pressurized mono-methyl hydrazine and nitrogen tetroxide into the main engine's combustion chamber for the first time in flight. They ignite on contact. For 34.6 seconds, the chamber and exhaust nozzle heat to incandescence while producing 440 newtons of thrust, giving the spacecraft a ΔV of magnitude 2.7 m/s in the direction called for by the navigation team's maneuver design software. Valves close. The Ace's computer screens show red alarms — numbers representing temperatures in blocks of colorful reverse video. These will persist for hours while the engine gradually cools back down.

Figure 2.9 displays the Doppler residuals in hertz of the signal that the Spanish Station 54 was receiving from *Cassini* during its TCM-1 main engine burn.

On the lower left side of the figure, *Cassini*'s downlink frequency appears at the zero mark on the display (its actual value is 7.175121157971 GHz). It appears as a flat line because the Doppler shift induced by Earth's rotation and revolution, and *Cassini*'s known existing relative velocity, has been subtracted out. Suddenly the frequency increases, steadily for 34.6 seconds, and then settles down to a new flat line roughly 80 Hz higher than it was. This measure of the line-of-sight frequency

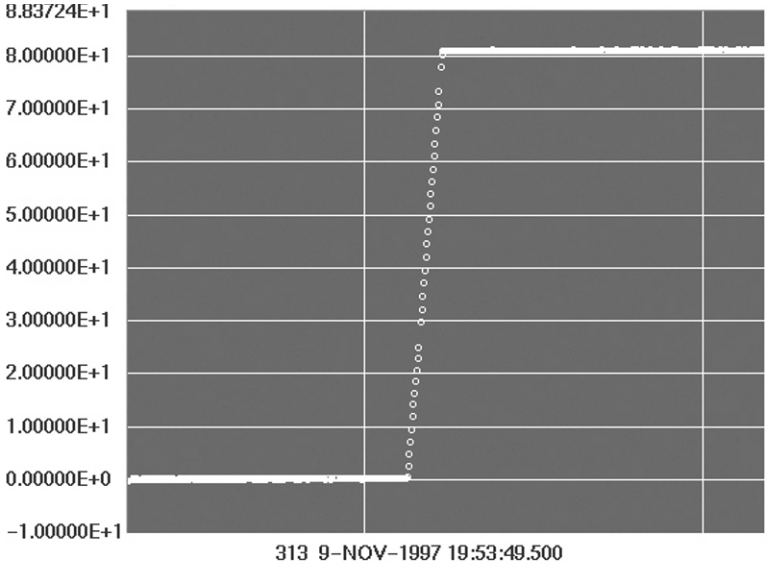

Fig. 2.9. Doppler shift residuals observed during *Cassini*'s TCM-1 main engine burn. The TCM's line-of-sight component induced a frequency change of slightly more than 80 Hz. Courtesy NASA/JPL.

shift resulted from the Earth-line component of *Cassini*'s ΔV. The roughly 80 Hz translated into a measured velocity change of 1.49 m/s, which is the value expected to be seen on Earth for a total 2.7 m/s along its velocity vector (see Equation 2.2 on page 62).

The following day, *Cassini*'s press release concluded, "Spacecraft health remains excellent as *Cassini* continues its voyage, with its first gravity assist, or swing-by, of the planet Venus planned for April 26, 1998. This maneuver will help *Cassini* gain velocity to make possible its long journey and arrival at Saturn in 2004."[29]

The solar heating didn't harm the spacecraft while its HGA of a sunshade was pointing away from the Sun during the TCM. In fact, the spacecraft team chose to leave the vehicle in its TCM-1 burn attitude for another hour, watching the on-board temperatures to help characterize *Cassini*'s thermal response.

2.6 Gravity Assist

A student employed for the summer at JPL in 1961 succeeded in obtaining practical numeric approximations to solutions of one of the oldest problems in dynamic systems, the Restricted Three-Body Problem involving the Sun, a planet in motion, and a passing spacecraft. Without the benefit of high-speed digital computers, no mathematician in history had been able to arrive at a solution. Leonhard Euler (1707–1783) had approximated a solution by inserting the assumption of a stationary planet. Henri Poincaré (1854–1912) had shown the constraints on solving the problem [16].

The summer employee at JPL was the American UCLA student Michael Minovitch (1935–). Working independently, his approach was to ignore the Sun's gravitation while the spacecraft was within the planet's sphere of greater gravitational influence, called the Hill sphere.[30] His technique did, however, account for the planet's all-important orbital motion about the Sun, which Euler had set aside. In a Sun-centered reference frame, he found that a spacecraft could obtain enormous quantities of ΔV in interplanetary flight using only nominal propellant expenditures for TCMs to target the planets, a gain almost too good to be true! Until this time, it seemed exploring Saturn and points beyond would be impractical. The Titan-III-Centaur launch system, which we'll examine in Chapter 4, was capable of inserting a low-mass craft onto outer solar system trajectories, but such flights to Saturn and beyond would be too slow to be useful. There were plans for gigantic nuclear-fission-propelled launch systems to achieve slightly faster flights, but these would prove not to be technically feasible, and in retrospect would have been too environmentally threatening.[31]

On his own initiative, Minovitch set up a major computational project at UCLA to work out his invention, which he called *gravity propulsion.* Both UCLA and JPL had IBM 7090 "super computers" which were in great demand among users for scientific and engineering work in the early 1960s. These room-filling, cutting edge, fully-transistorized machines with thirty-two thousand words of memory took an average of "only" 34 μs to carry out one floating-point arithmetic operation.[32] Minovitch's success in gaining access to relatively large allocations of time on this hardware made it possible for him to pursue the development of a gravity propulsion system of enormous value to interplanetary missions[33] and he freely contributed the results to JPL. Astronomers had long known how a comet's orbit can be modified when it passes a planet. The German-born rocket engineer Krafft Ehricke (1917–1984) described in 1962 the mechanics of its potential applications to interplanetary flight [17]. At a time when many researchers still regarded the effect as a nuisance, Minovitch came up with numerical solutions for putting *gravity assist* to work in practical terms. Although he didn't discover any new fundamentals of physics, he did the math (see references [18], [19], and [20]), and he did it in time for a unique opportunity.

2.6.1 A Grand Tour

In 1965 the American aerospace engineer Gary Flandro (1934–) discovered there was a rare opportunity to make use of Minovitch's "propulsion system." For three consecutive years once every 176 years, the planets align in such a way that a single probe can launch from Earth and fly by all the gas giants, gathering enough velocity at each passage to propel it to the next. Working with principles he was able to derive in collaboration with Minovitch, Flandro discovered a family of trajectories capable of visiting all the gas giant planets. Flandro, who was also employed part time at JPL while pursuing his advanced degrees at Caltech, saw that there were thirty-day launch periods during 1976, 1977, and 1978 [21], and later mission planners would show that 1977 uniquely offered an opportunity to pass the planets at a distance that permitted close encounters with their moons.

The nascent United States space program was unable to obtain a commitment of funding for such a "grand tour" of our solar system, as detailed in reference [22], but JPL built the twin *Voyagers*, which NASA approved for a mission to only fly by Jupiter and Saturn,[34] with enough margin in electrical power, propellant, and computer programmability that one of them just might still be able to take advantage of the fortuitous alignment after completing its officially sanctioned objectives. In Flandro's words, "...there is no question in my mind, that had [NASA] fully realized what was going on in the spacecraft assembly building at JPL, they would have been most displeased" [23]. The *Voyagers* left in 1977, the optimal year for a scientifically bountiful flight,[35] and *Voyager 2* did indeed fly a "grand tour" of the gas-giant systems.

Voyager 2's reconnaissance of the Jovian planets and their moons succeeded in making copious scientific discoveries at each planetary system, many of them completely unexpected, all thanks to the gravity-assist technique. *Voyager 1* did have an opportunity to take a gravity-assist boost from Saturn that would have propelled it to Pluto, but this opportunity was traded away for the chance to inspect Saturn's large atmosphere-covered moon Titan at close range. This choice included a flight through Titan's Earth-occultation zone where the spacecraft's radio signal passed through Titan's atmosphere on its way to Earth (we'll visit this experiment again in Chapter 6).

Early in 2007, however, another craft sped by Jupiter, stealing a kick from that planet for a free ride all the way to Pluto. The *New Horizons* spacecraft gained a ΔV of 3.83 km/s from its encounter with Jupiter, and it has a date with the dwarf planet Pluto and its moon Charon in July 2015. Many other missions have depended on gravity-assist. The first was *Mariner 10*, which flew past Mercury. *Pioneer 11* blazed a trail past Jupiter, using the kick to achieve the first Saturn flyby. *Galileo* used gravity-assist to reach Jupiter orbit, *Cassini* to reach Saturn orbit, and the recent *Messenger* to reach Mercury. There are many more examples.

2.6.2 How it works

How can gravity propel a spacecraft in any useful way? As a spacecraft approaches a planet, gravity causes the craft to accelerate. But after it passes the planet, won't gravity just slow it back down again? From the planet's point of view, this is indeed the case. The spacecraft's velocity reaches its maximum at closest approach to the planet, and then slows down again. See panel A in Figure 2.10, illustrating a Jupiter flyby as seen from above the planet's north pole. The planet-relative magnitude (shown by the labeled arrows' lengths) of a spacecraft's velocity outbound, V_{OUT}, will decay to that of the inbound velocity V_{IN}, even though the planet's gravity will effect a change in the velocity's direction (shown in the figure as bending).

But a spacecraft in heliocentric orbit will experience a net ΔV from the encounter, with respect to the Sun, as reference [24] succinctly explains. See panel B in Figure 2.10, which shows a new vector labeled V_{JH}, Jupiter heliocentric velocity.

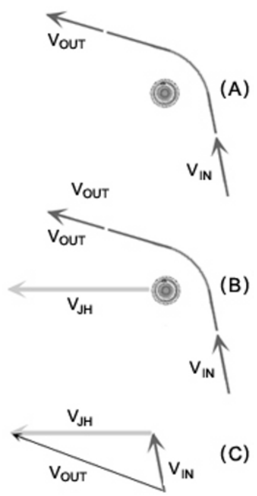

Fig. 2.10. Gravity-assist using Jupiter as seen from above the planet's north pole. Jupiter's motion about the Sun is from right to left.

Gravitation allows an *elastic collision*[36] to take place that temporarily connects the spacecraft to the planet as it moves in orbit about the Sun. To gain a boost, a spacecraft approaches a planet from behind in its progress about the Sun, traveling faster than the planet's escape velocity to avoid capture. The spacecraft's gravity assist comes at the expense of the planet's orbital momentum in the following way: since the spacecraft is a physical object, its mass exerts its own gravitational pull on the planet. The planet, being tugged from behind, loses an infinitesimal amount of its orbital momentum[37] while the spacecraft obtains a substantial kick. The planet's loss is too small to be measured, but it can be calculated.[38] Gravity doesn't so much propel the spacecraft as connect it to a reservoir of propulsion, the planet's angular momentum in solar orbit. A tradeoff occurs wherein angular momentum is conserved overall. To a first approximation, the spacecraft appears to bounce off the planet, although no contact actually occurs during the elastic collision.

Panel C in Figure 2.10 adds a large portion of V_{JH} to the spacecraft's inbound velocity V_{IN}. The resultant vector V_{OUT} has a magnitude substantially greater than that of V_{IN} from the Sun's point of view. The portion of V_{JH} available to the spacecraft will vary with the spacecraft's proximity to the planet during flyby, as well as its direction of flight and the geometry of the encounter.

So, the trick is to fly a Hohmann transfer (or variant) to any convenient nearby planet, and then use a gravity-assist flyby to gain enough ΔV to reach your target, or to proceed to the next gravity-assist flyby. Timing must be planned to take advantage of planetary alignments that happen to be available. *Galileo* used one Venus flyby and two Earth flybys during three solar orbits to gain the energy to reach Jupiter. *Cassini* used two flybys of Venus, one of Earth, and one pass by Jupiter during two orbits of the Sun to reach Saturn. *Cassini*'s gravity assists gave the spacecraft a total of about 14 km/s ΔV capability. Had the spacecraft been required to carry propellant in its propulsion system to provide this boost, it would have been too massive to launch at all, let alone reach Saturn: the ΔV *Cassini* obtained via gravity assist would have required about 75,000 kg of propellant — over twenty-four times the amount the craft actually carried.

Flying *ahead* of the planet in its solar orbital motion can accomplish a *reduction* in the spacecraft's speed with respect to the Sun. This is true while outbound from the Sun, and just the opposite on an inbound leg. Messenger used this technique flying by Earth in 2005, and Venus in 2006, reducing its orbital altitude above the Sun en route to Mercury. The Galileo spacecraft flew in front of Jupiter's moon Io just before executing its Jupiter Orbit Insertion maneuver. This flyby removed a substantial 175 m/s of Galileo's speed relative to Jupiter, which allowed the spacecraft to carry less propellant mass than it would have otherwise needed to enter Jovian orbit.

During a gravity assist, the craft "feels" no acceleration, even though it may make a sharp turn and more than double its speed toward its destination: an accelerometer, or an observer, on board the spacecraft would report only continuous free-fall. During the gravity-assist maneuver, every atom in the spacecraft experiences the same gravitational force, with negligible gradient, or difference in force across the body. It is the presence of a force gradient that permits one to feel a sense of acceleration when riding in a jet plane or in a Space Shuttle during liftoff.

2.7 A Familiar Connection Severed

In most of our earthly experience, the direction we point the nose of our moving vehicles matters greatly to their navigation, whether the vehicles are automobiles or airplanes or sailing vessels: it determines the path the vehicle will follow. From the start, the discipline of *guidance and control* has meant managing a craft's attitude: the guidance, i.e. navigation, of rocket-propelled missiles through the air depends on controlling where its nose is pointing, and where the thrust-providing exhaust is pointing. The airborne missile's attitude dictates the path it will take while the rocket's aft-directed rocket is providing thrust, and after it has shut off as it glides to its destination. Guidance results from control of attitude.

Once a vehicle leaves the atmosphere, the connection is broken between attitude and flight path as long as it is coasting, which turns out to be most of the time for an interplanetary craft. After a few minutes of intense rocket thrusting during launch, a spacecraft may coast for years in free-fall, during which its attitude has no relation at all to its guidance, except during its typically short-duration, infrequent propulsive maneuvers. We may still see the traditional term "Guidance and Control" applied to systems that control a spacecraft's attitude or its propulsion, but in interplanetary space we have to understand it in a different way. When a spacecraft needs to make a change in trajectory, it must manage its attitude to point thrusters or a rocket engines in precisely the appropriate direction before applying force.

For the most part, then, an old familiar link is broken. A spacecraft is almost always free to rotate in every which way it needs, to point its instruments, to point its communications antennas, and to manage its thermal state, all without affecting the path it follows through space. In the next chapter, we'll examine how a spacecraft controls its orientation in space.

Notes

[1]Radio signals disclosing the spacecraft's state take 10 minutes and 55 seconds to reach Earth from Mars at the speed of light, but it's conventional to relate events in Earth-receive time as we see them occur.

[2]See the *Mars Climate Orbiter* Mishap Investigation Board Report: http://www.space.com/media/mco_report.pdf

[3]The Hohmann transfer orbit offers a practical and efficient use of energy. Another means, called the "fuzzy orbit" can be computed using drift between Lagrange points, which uses even less propellant but requires increased travel time.

[4]*Pathfinder*, carrying *Sojourner*, landed in 1997, and the Mars Exploration Rovers *Spirit* and *Opportunity* landed in 2003.

[5]*Magellan* left Earth early to clear the Shuttle launch facilities for *Galileo.*

[6]*Voyager 1* and *2, Pioneer 10* and *11,* and *New Horizons* comprise the complete list of spacecraft on interstellar trajectories as of 2008. The *Pioneer*s are no longer being tracked.

[7]Biography of Johannes Kepler: http://en.wikipedia.org/wiki/Johannes_Kepler

[8]Biography of Isaac Newton: http://en.wikipedia.org/wiki/Sir_Isaac_Newton

[9]Biography of Tycho Brahe: http://en.wikipedia.org/wiki/Tycho_Brahe

[10]We can measure and compute quantities of mass and inertia, but their fundamental nature remains a subject of investigation.

[11]Biography of Ibn al-Haytham Haytham: http://en.wikipedia.org/wiki/Ibn_al-Haytham

[12]With his theory of general relativity, Albert Einstein set gravitation in a new framework where mass distorts space-time, but its fundamental nature is still under investigation.

[13]"Big G" is a different constant from "little g," which represents a local gravitational acceleration that can have different values on different planets.

[14]The most recognized co-discoverer is Gottfried Wilhelm Leibniz (1646–1716), whose notation is still in general use.

[15]Indeed, the process parallels a disciplined approach to acquiring knowledge in any field, i.e., beginning with conjecture, progressing to belief supported by evidence, and then confirming the belief by testing it rigorously against all available evidence.

[16]The Gaussian distribution: http://en.wikipedia.org/wiki/Normal_distribution

[17]One notable exception is the 1979 discovery of active volcanism on Jupiter's moon Io in an opnav frame by *Voyager* navigation team member Linda Morabito [25].

[18]In Figure 2.2, positive declination would be the angle measured upward in the out-of-page dimension. Angles in the plane of the page would be right ascension.

[19]Terrestrial time is a theoretical ideal time on the surface of Earth. Its value is the International Atomic Time (TAI, from the French *Temps Atomique International*), plus 38.184 seconds.

[20]See IERS website: http://www.iers.org

[21]See SI definition of second: http://physics.nist.gov/cuu/Units/second.html

[22]Special relativistic effects on a spacecraft moving at 3 kilometers per second, for example, would exhibit errors in timing on the order of 5 parts in 10^{10}.

[23]Science experiments that intentionally measure range to a spacecraft while it is nearly behind the Sun can serve to test the general relativistic effect of time dilation deep in the Sun's gravitational field [26].

[24]See VLBA website: http://www.vlba.nrao.edu

[25]See Keck Interferometer website: http://planetquest.jpl.nasa.gov/Keck

[26]Quasars and all other objects in the universe do move, but it would take thousands of years to measure any quasar movement from Earth because of their extreme distance.

[27]Thrusters are typically dual-use components on a spacecraft. On the one hand several can be operated in concert to cause a small net thrusting force on the entire craft for a TCM or OTM. On the other hand they can be operated singly or in pairs by the attitude control system to change the spacecraft's rotation rates, as we'll examine in the next chapter.

[28]See www.jpl.nasa.gov/basics/soi

[29]See *Cassini* news release: http://saturn.jpl.nasa.gov/news

[30]Named for the American astronomer and mathematician George William Hill (1838–1914) who based his work on that of French astronomer Édouard Roche (1820–1883). The Hill sphere is also called the Roche sphere.

[31]Since a spacecraft inherently experiences only the free-fall condition while obtaining a gravity-assist ΔV, the spacecraft can benefit from gravity propulsion while in its fully-deployed state, which might include booms or antennas that cannot safely be in an extended position during periods of high-thrust rocket propulsion.

[32]Compare the performance of 1961's IBM 7090 with that of a 2008 personal laptop performing 10^9 floating-point operations per second, with 4 gigabytes of solid-state memory and vast amounts of disc storage.

[33]For a one-paragraph summary of the gravity-assist propulsion system mathematics (in short, it involves patching asymptotes) and its context in astronautics, see page 34 of reference [19]. This is the argument the inventor presented to the UCLA professor who would award him access to the computer.

[34]The *Voyagers* were not the first to use gravity assist. *Mariner 10* launched in 1973 and used a Venus flyby to reach the orbit of Mercury, demonstrating operational use of the technique.

[35]The 1976 opportunity would have required a dangerously-close flyby through Jupiter's intense radiation zone. The 1978 launch period would have passed Jupiter at too great a distance to encounter its diverse moons. An earlier opportunity had occurred in 1801,

but U.S. President Thomas Jefferson's administration would not have considered funding an interplanetary flight. The next such opportunity will occur in 2153.

[36]In an elastic collision, the colliding bodies' total kinetic energy remains constant and is not converted into a different form of energy such as heat.

[37]In losing energy, the planet orbits closer to the Sun, so it actually speeds up imperceptibly.

[38] *Voyager 1* changed Jupiter's orbital speed by about 30 cm per 10^{12} years.

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3 Spacecraft Attitude Control

3.1 A Distant Rocking

Today *Voyager 1* is sending telemetry via Station 14 in California's Mojave Desert, one of the Deep Space Network's 70-meter diameter tracking antennas, to the handful of engineers responsible for the craft.

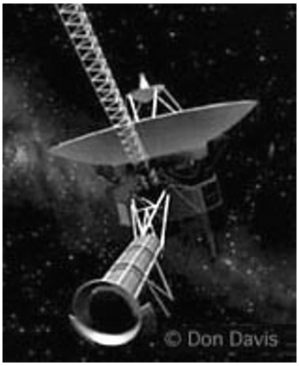

Fig. 3.1. One of the twin *Voyagers*, viewed from the end of its power supply boom. The science boom, not visible here, extends out the opposite side. Adapted from animation cell © Don Davis, reproduced by permission.

Among the computer screens full of numbers and plots here in *Voyager*'s realtime operations support area, we take notice of a single data display that shows the spacecraft tracing its constant, slight changes in attitude, its orientation in space, rocking back and forth hour after hour. The craft is never still. As many spacecraft do, it is slowly oscillating about its three axes under computer control. The graph before us clearly shows three lines of measurements gradually building themselves into a plot, as radio symbols finish crossing the 16.2-trillion-meter distance,[1] a journey of fifteen hours at the speed of light. In seconds, the symbols are decoded in the desert, error-free, into bits of telemetry data. Milliseconds later, a program running on the computer in front of us is parsing those bits, and displaying some of them on this screen as points on the graph.

There is a vertical scale to the left of each line whose values range from zero at center, up to +0.10° and down to –0.10° (see Figure 3.2). Measurements in three *telemetry channels,* which we discussed in Chapter 1, appear on this plot. Labeled "PITCH, YAW, and ROLL," they keep reporting on *Voyager*'s relentless attitude changes, extending their individual lines pixel by pixel. A few pixels appear every minute, building from left to right on the screen. After a few hours, the three traces of data points, including the sawtooth-shaped yaw trace, reach the right-hand side of the screen, and the display scrolls the graph over to make more room to continue plotting. Every bit of this, and other engineering data from *Voyager*,

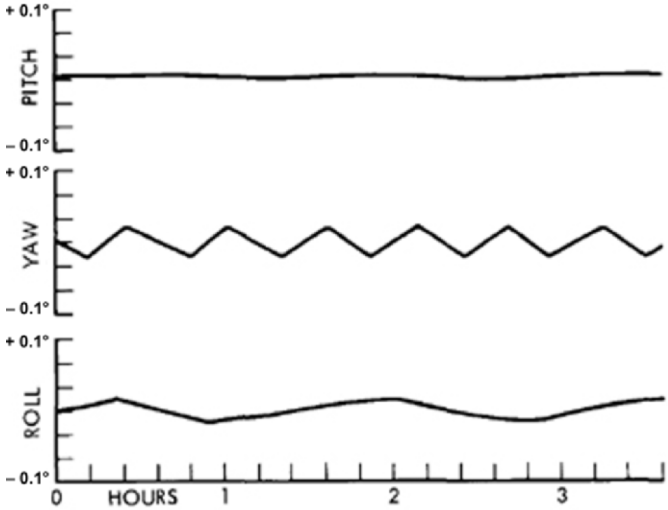

Fig. 3.2. *Voyager 1*, over sixteen thousand million kilometers distant, has been reporting its constant changes in pitch, yaw, and roll for more than thirty-one years. As usual, there happens to be hardly any pitch motion. All the elbows in the yaw line, and the first two in the roll line, show when the attitude control system caused a thruster to fire. Deadbands other than the 0.1° values shown here may be selected via command. Courtesy NASA/JPL-Caltech.

is being stored for analysis and maintained in an off-line archive. And of course the science data from *Voyager 1*'s six functioning instruments, as they sense the environmental conditions out past the solar wind's termination shock, within the *heliosheath*, is being stored and distributed to *Voyager* Project Scientist Ed Stone (1936–) and his teams of investigators.

The total mass of the spacecraft including propellant is about 730 kilograms as of late 2008. Each thruster firing exerts a little less than 0.9 N of force at an arm of about half a meter from the spacecraft's center of mass. To get an idea of how much work it takes to nudge the spacecraft's mass in each direction, see Table 3.1, which shows the moment-of-inertia magnitudes I for rotation about each of *Voyager*'s three orthogonal axes. In this application, moment of inertia can also be called mass moment of inertia or angular mass, expressed as the integral of the radius squared times the infinitesimal increments of mass:

$$I = \int_{axis}^{edge} r^2 \delta m \tag{3.1}$$

where δm is the mass variation out along radius r from the axis of rotation to its extremity.

Table 3.1. Moments of Inertia on *Voyager*'s Body Axes (as of Saturn-Uranus cruise). Adapted from [3].

Motion	About Axis	Moment I, kg/m^2
Pitch	X	4183
Yaw	Y	588
Roll	Z	3945

In the table, note that it is rotation about the Y-axis, motion in yaw, which exhibits the smallest value of I, and therefore naturally experiences the most rapid change, clearly visible in the yaw trace in Figure 3.2.

If you stand in front of the full-scale model of the *Voyager* Spacecraft in the Von Kármán Auditorium where public lectures are held on the JPL campus, facing the model square on, the gold record of messages from Earth mounted prominently on the exterior seems to point out the center of the spacecraft's mass. The craft's optical-instrument scan platform extends off to the right. The RTG boom (Radioisotope Thermoelectric Generators supply *Voyager*'s electrical power) projects out the left side. A thin fiberglass truss-work magnetometer instrument boom is collapsed inside a shiny cylindrical canister on the *Voyager* model's left side, illustrating its state at launch in 1977. Once the spacecraft is in flight, this lightweight boom extends 13 meters up to the left. The craft's width, from the scan platform to the outboard end of the RTG boom, is 8.5 meters (see images on pp 294 and 295 in Appendix A).

If you were to walk over toward your left and approach the shielded end of the outboard RTG, you'd have a view of the spacecraft similar to the view in Figure 3.1. Lifting the RTG up would apply motion about the spacecraft's X-axis, which motion is called *pitch*. If you could twist the spacecraft's attitude by turning the outboard end of the RTG boom as though it were a helm, that motion would be rotation about the Y-axis, or *yaw*. This involves the least amount of torque, since the moment of inertia in yaw is the smallest of the craft's three degrees of freedom as evident in Table 3.1. *Roll* denotes motion about the vertical Z-axis, which goes up through the center of the high-gain antenna dish and down into the auditorium floor.

3.2 The Attitude Control System

A spacecraft's attitude has to be measured and reported, stabilized, and controlled for a number of reasons. For one, a high-gain radio antenna may need to point steadily toward Earth for communications, which is usually the case with *Voyager*. Onboard instruments have to be pointed precisely toward their targets. For some observations, an optical device such as a camera may need to track a target long enough to collect sufficient light, without letting the target's apparent drift cause the image to smear while the spacecraft speeds by. So not only the correct attitude, but also precisely controlled rates of attitude change, may be required to track a target that exhibits fast relative motion, compensating to prevent image smear. And as we have seen, attitude stability is needed for guidance: firing the rocket engine to make minor corrections to the spacecraft's flight path requires keeping the nozzle pointed in exactly the right direction during the burn.

Attitude control is one of the highly refined technologies essential to interplanetary flight. Advanced software can in certain tasks seem nearly human. While it will never pass a Turing test,[2] it will be convenient and appropriate in this chapter to treat the attitude control software and hardware somewhat anthropomorphically: the attitude control system "realizes" its situation, "knows" where to find Earth, and "takes appropriate actions." Here are the basic processes that an attitude control system undertakes:

Process inputs. The attitude control system parses real-time sensory input from specialized devices on the spacecraft including instruments that observe celestial bodies, and gyroscopes that sense vehicle rotation, as well as histories of these inputs.

Account for sloshing propellant, etc. Attitude control algorithms have to account for the effects of propellants within tanks if they slosh, affecting the spacecraft's center of mass and moments of inertia. Any flexible booms the spacecraft may have will exhibit mechanical resonances that tend to wiggle the vehicle, and these forces have to be accommodated. Also, the gyroscopic effects of any spinning masses, such as reaction wheels, must be taken into account.

Estimate dynamic situation. Given all the sensory input, and algorithms to deal with modes of sloshing and vibration and spinning mass, the system estimates the spacecraft's current state of rotation — attitude control is all about rotation around one or more axes. The state of the spacecraft can only be known within bounds of its sensory and computational capabilities while the spacecraft is rotating, so we speak of estimates rather than exact determinations.

Compare with desired situation. There is always a desired state of rotation in one or more axes that has been commanded: holding steady to fire an engine, rotating so as to track a passing target of interest, or turning to communicate with Earth. The attitude control system compares its currently estimated dynamic state to the desired state and decides what to do about any difference between them.

Apply torque as needed. Based on the difference between the commanded and the currently-estimated dynamic states, attitude control issues signals that change the spacecraft's condition: for example, *Voyager*'s attitude control system directs the propulsion system to fire quick bursts from mass-expulsion devices — rocket thrusters — to modify the craft's rotation rates and orientation. The thruster-firings evident in Figure 3.2 were keeping the antenna dish facing Earth. On a different spacecraft, the attitude control system may have the option to directly operate other devices such as reaction wheels to accomplish similar tasks. We'll examine these devices shortly.

Do routine housekeeping. As do all of a spacecraft's systems, an attitude control system formulates engineering telemetry messages and passes them to the telecommunications system for relay to Earth. We saw evidence of this at the beginning of the chapter. And like other systems it accepts, parses, and executes commands that the telecommunications system receives and relays to it.

Work reliably. All attitude control system processes must function as reliably as fine clockwork. The system must run without software bugs. It must be able to monitor a host of parameters regarding its own operations, and recognize any of a number of commonly expected problems. It must be able to take corrective actions when appropriate, including switching to redundant hardware or calling for assistance from other on-board systems. When problems do occur, the system must be able to collect all pertinent information about the problem and be prepared to issue a report to controllers on Earth. The system must be able to request the spacecraft's central computer to configure the vehicle to a known safe condition, and await further instructions from Earth. It must also be able to operate in a *critical mode* which would allow the spacecraft to continue executing a mission-critical task, such as an orbit insertion, at all cost.

Recognize anomalous torque. This is one of the many conditions an attitude control system must watch out for. If an attitude-control thruster valve were to stick open, perhaps due to some foreign matter preventing full closure, the system will sense the resulting constant torque, perhaps after counts of thruster firings to counteract it exceed a nominal value. It will have to recognize the problem, and take appropriate actions. This could mean directing the propulsion system to swap to its backup branch of plumbing to correct the problem.

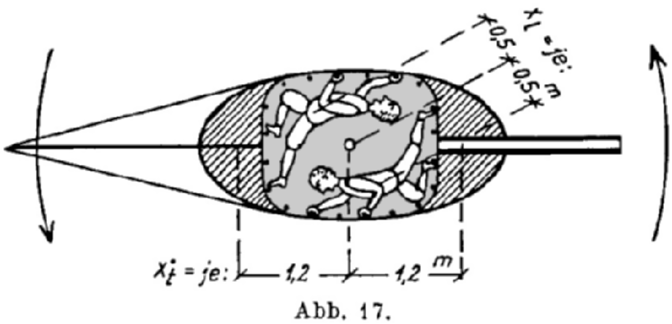

Fig. 3.3. In 1925, the German engineer Walter Hohmann (1880–1945) realized some means of attitude control would be required for spacecraft. He envisioned a system of handholds inside the vehicle that the crew could use to rotate it. Image adapted from [4].

Meet other demands. The attitude control system is called upon to serve many demands. It is often expected to satisfy a large fraction of the requirements that a spacecraft's overall design has to meet, and with some spacecraft, this can require exceptional technical achievements. For example, of all the extraordinary technical challenges that faced the *Hubble Space Telescope*'s design and implementation, including its optics, meeting the requirements on its *pointing control system* was widely viewed as the most difficult. The following are among the demands an attitude control system may have to respond to:

1. Control the motion of various articulated appendages on the vehicle, such as scan platforms, which point optical instruments toward their targets, or gimbal actuators that adjust the craft's main rocket engine nozzle pointing, or solar arrays that track the Sun and keep the spacecraft's batteries charged. It is for this reason that the system is often known as an Attitude *and Articulation* Control System (AACS).
2. Know where the Sun is. For a spacecraft whose panels must track the Sun and keep an electrical current flowing to sustain the vehicle's operation, this is a crucial task.
3. Maintain thermal control. Knowing where the Sun is in relation the spacecraft's state of rotation enables it to manage where sunlight and shadow fall on the vehicle, and keep the thermal state of the spacecraft and its instruments within predetermined limits. As an example, during their inner solar-system cruise phases, both *Galileo* and *Cassini* had to be constantly protected by keeping built-in sunshades (*Cassini*'s HGA served as one) facing the Sun. The Mercury-orbiter *Messenger*'s ability to function depends directly on such shading. And some science instruments on the spacecraft may have radiators that cool their optical detectors. They do so by facing deep cold intergalactic space, and they may not be able to withstand much direct sunlight.
4. Avoid burning the optical detectors. AACS has to comply with rules programmed onboard, such as never to point an instrument aperture within a certain number of degrees of the Sun, lest its optics concentrate sunlight onto sensitive detector electronics and fry them.
5. Know where the Earth is. Normal communication requires a high-gain radio antenna be squarely aimed toward home, and if this ability is lost only low-rate rudimentary communication is possible.[3]
6. Know where all the targets of interest are. An advanced AACS can keep tabs on the locations of any number of celestial bodies including a planet of interest, its natural satellites, as well as the Sun and Earth. This lets human controllers use a relatively high-level of commanding, such as the equivalent of "point the cameras to the center of Iapetus," instead of having to spell out precise targeting coordinates by hand, as less-capable systems may require. To implement this, AACS maintains knowledge of the bodies' motions and computes their positions out through time, using a built-in software engine called an *inertial vector propagator.*

Realtime and later: AACS's tasks are important in real time, when the craft must keep itself in the correct attitude, pointing its instruments accurately as targets come and go. In addition, a history of all the spacecraft's attitude changes supplied by the AACS serves an important function in later ground-based reconstruction of instrument pointing and spacecraft trajectory, as scientist teams proceed to analyze the results of their observations. A history of thruster firings made under AACS control is important telemetry for use in navigation, as we saw in the previous chapter.

It may be of interest to note that *Voyager*'s AACS reprogrammable flight computer accomplishes all its tasks using 4K words of memory — 8K counting the prime and usually inactive backup computer.

In the following sections we'll have a look at many of the ways various spacecraft employ AACS, we'll examine the system's many linked devices and disciplines, and we'll touch upon the propulsive capabilities, which are discussed at greater length in the next chapter.

3.3 Intersecting Disciplines

Expertise in the field of spacecraft dynamic attitude control spans several disciplines including control theory, rocket propulsion, orbital mechanics, and astronomy, as well as the enabling mathematics and physics that are ubiquitous throughout space flight.

Control theory: Spacecraft attitude control is of course primarily a control system. A simple example of control theory can be found in an automobile's cruise-control system, whose task is to keep an eye on the speedometer and issue adjustments to an *actuator* that moves the engine's throttle. Given a desired *reference* speed target by the human, the cruise control sends *output* signals to the automobile's throttle, while obtaining *feedback* information from the speedometer about the system's condition. It varies its control output until the difference between reference and speedometer, called the *error signal*, is minimized. Figure 3.4 illustrates at a high level the basic closed-loop system that applies to automobiles and spacecraft. Cruise control and AACS each utilize the *closed-loop* architecture illustrated there. Inputs from body states affect system outputs. The results of those outputs are monitored, generating an error signal that feeds back into the control algorithm.

As a basis for comparison, an *open-loop* control system is much less sophisticated. For example, a cruise-control system of decades past consisted merely of a direct mechanical friction-locked throttle position-holding knob. Start driving up or down a hill, and the open-loop system fails to maintain control of the vehicle's dynamic state. The human observes the error and then has to provide the control-system feedback by readjusting the lever.

The Scottish physicist James Clerk Maxwell (1831–1879), who is widely known for his contributions to our understanding of electromagnetism, conducted what is perhaps the first formal analysis of a control system in 1868 [5]. His study of the dynamics of a mechanical engine-speed governor helped him see how to remedy the phenomenon of "hunting," wherein he traced surges and unstable behavior to the lags inherent in the mechanical feedback. The Wright Brothers succeeded in their achievements in controlled gliding flight in 1900, and powered flight in 1903, largely because they had correctly reasoned that any free-flying object would need a control system to manage the craft's roll, pitch, and yaw. For their machine, they

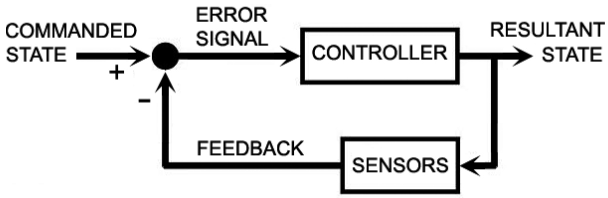

Fig. 3.4. The basic functions of a closed-loop control system. Arrows indicate data flow. Negative feedback from sensors combines with input representing the desired or commanded state to control the dynamic behavior of the system. An example might be taken from an automobile's cruise control: given a commanded state of 100 kilometers per hour, and data from the sensor showing the vehicle's speed to be 60 kilometers per hour, the error signal would tell the controller that an additional 40 kilometers per hour is required.

developed a system of moving the surface of the airfoils ("wing warping"), which the pilot could use to control the craft's attitude. Later, development of control theory [6] became important in World War II for weapons-fire control, leading to further evolution of guided missile controls and eventually space flight.

Rocket propulsion: For a spacecraft in free-fall, control theory can interface with rocket science when an AACS needs to apply a torque[4] to change the spacecraft's rotation rate. The way in which AACS interfaces with thrusters in its output path is analogous to the way a cruise-control system interfaces with the automobile engine's throttle. Components of the propulsion system accelerate and expel mass from an onboard supply in controlled directions and amounts, applying Newton's third law to answer AACS's call for torque.

Orbital mechanics: In turn, rocket propulsion under AACS's control interfaces in a couple of ways with orbit or trajectory control and determination, aspects of the art of navigation that we surveyed in the previous chapter.

First, the use of thrusters for attitude control is usually designed to produce a balanced force when applying torque to a spacecraft. For example, applying a roll torque to a spacecraft may mean firing two thrusters, each one on an opposite side of the craft, expelling mass in opposite directions. If only one thruster were to fire, the spacecraft would still feel a rotational torque about its roll axis, but the unbalanced thruster's force would also translate into nudging the whole vehicle somewhat, affecting its trajectory. Slight imbalances always exist in propulsion systems due to differences in thruster efficiency, impingement of a plume on part of the spacecraft, or nozzle misalignment, so attitude control using thrusters must always be accounted for in the navigation process.

Second, when intentional course corrections are carried out, AACS is centrally involved in directing the thrust vector in the proper direction, and managing the vehicle's attitude throughout the burn period. The AACS on some spacecraft also uses an accelerometer to determine when to cut off thrusting. As we saw at the end of the previous chapter, the only time in which a spacecraft's attitude relates to its path through space is when propulsion is used.

Astronomy: A spacecraft's intrinsic body axes of pitch, yaw, and roll, must be reckoned with an external reference frame in order to be able to estimate and control the spacecraft's interactions with the outside universe.

The first way the field of astronomy intersects with attitude control is in providing the external reference frame. Attitude control systems commonly use the reference frame defined by the standard epoch J2000.0 mentioned in the previous chapter. The spacecraft's attitude, then, is described by expressing the relationship between its own internal reference frame and the equator and equinox of J2000.0.

The relation of the spacecraft's orientation to the external, astronomical reference frame can be represented using a variety of methods that handle three-dimensional rotations. Figure 3.5 illustrates as one example the three Euler (pronounced "oiler") angles, named for the prolific Swiss mathematician Leonhard Euler (1707–1783). This and additional methods, including quaternions, are discussed in reference [7].

The second way astronomy intersects with attitude control is in the workings of appliances such as Sun sensors, which measure the apparent position of the Sun, and various devices that reckon star positions, called star trackers, star scanners, and stellar reference units (the branch of astronomy that deals with precise positions and motions of stars is *astrometry.*) All these *celestial reference* devices, each of which we'll examine later in the chapter, provide inputs to AACS for it to use in estimating the spacecraft attitude in relation to the external reference frame. Some of the latter devices achieve recognition of the "fixed" distant stars by color and brightness, or by reckoning their patterns in the sky.[5] Modern stellar reference units may contain built-in catalogs of thousands of stars including their positions, brightness, colors, and variabilities.

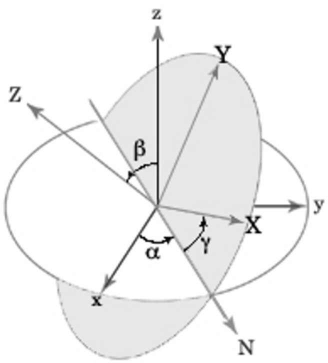

Fig. 3.5. Euler angles α, β, and γ express the relative orientation of two coordinate systems, one fixed, labeled xyz, and one rotated, XYZ. The line of intersecting nodes is labeled N.

Finally, astronomy has accumulated knowledge of the movements of target bodies of interest to a spacecraft's science investigations. Ephemerides of these natural bodies are known as a result of decades, and even centuries, of observation. And there is feedback when investigations of a target body from a precisely navigated spacecraft help refine knowledge of the body's orbit, rotation rate, and polar motions. This can be useful academically in the long term, as well as practically in the short term when optical-navigation imaging is employed to reduce uncertainty in a target's ephemeris to help negotiate an upcoming close encounter.

3.4 Stability

There are two common ways to keep your spacecraft's attitude stable. Setting the whole vehicle spinning about its central axis is one way, wherein the gyroscopic action — the inherent rigidity in space of the spin axis — of the rotating spacecraft mass about its center is itself the stabilizing force. This is a passive, open-loop means of stabilization. The other way is by using active three-axis control in a closed-loop system, as we'll see in the next subsection. Then there is the uncommon third means of maintaining stability in two out of a spacecraft's three axes while orbiting a planet, that of gravity gradient. This takes advantage of the fact that a body's axis of minimum inertial moment will naturally rotate to point toward the planet. Since the force of gravitation decreases with the square of distance, the spacecraft feels a slightly greater tug on its parts that are closer to the planet. If the orbiting body's mass is not distributed spherically, it will eventually rotate to align its axis of greatest to least mass toward the planet. The Earth's Moon, and many other natural moons in our solar system have in the same way become "tidally" locked over time, to present the same face toward the planet. This passive technique was tested in low and geosynchronous Earth orbits in the 1960s. Large enough attitude oscillations persist, so that this technique cannot meet the requirements of most modern spacecraft. Some student-developed Earth orbiters do use the technique, though, by extending a boom six meters or so in length with a small mass at its end which ends up pointing toward Earth.

3.4.1 Going for a Spin

Examples of spacecraft using the simple spin-stabilization method are numerous, and they include the *Voyager*'s predecessors *Pioneer 10* and *Pioneer 11* whose missions in the 1970s were to venture beyond Mars for the first time, through the main asteroid belt, and past Jupiter and, for *Pioneer 11*, Saturn. For such an ambitious foray into the deep outer solar system, it made sense to keep things as simple as possible, and spinning the spacecraft for stability was the best choice. A spinning platform, though, is not ideal for operating a camera that must be pointed steadily at one spot, so the Pioneers' optical instruments were designed to look radially outward and build up images line by line, scanning a narrow slice of the whole local sky in a circle as the craft flew, spinning, by its targets.

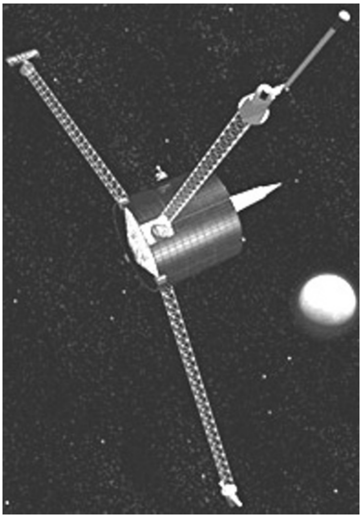

Fig. 3.6. The spin-stabilized *Lunar Prospector* spacecraft. Image courtesy NASA/Ames.

Scientists who measure the particles and the magnetic and electric fields surrounding planets, and the fields and particles in interplanetary space (and probably interstellar space too, thanks to *Voyager*), and those who wish to sample other aspects of a spacecraft's immediate environment, usually prefer to have their instruments constantly sweeping the local medium. So for them, a spin-stabilized craft is a fine platform.[6] It was a natural choice for *Lunar Prospector*, a mission flown by the NASA Ames Research Center in Mountain View, California. Reference [8] tells its whole story. This spacecraft collected data from the Moon using no cameras or other optical science instruments. Figure 3.6 depicts this spacecraft, whose radial symmetry is obviously designed for spinning. *Lunar Prospector* carried out much of its sensing of the lunar environment and surface employing a total of five instruments, mounted at the ends of three radial booms, that by design were most effective when being swept around constantly. The spacecraft rotated at 12 rpm about its Z-axis.

Measurement from Earth of the spacecraft's fine-scale changes in velocity, revealed by the Doppler shifts in its two-way phase-coherent radio signal, helped *Lunar Prospector* map the lunar gravity field and thereby characterize the distribution of surface and subsurface lunar mass. Gravity field mapping is an objective well suited to a spin-stabilized craft. By comparison, a three-axis stabilized craft's velocity is often affected by thruster firings, masking the accelerations induced solely by the gravity field under study. Spinners need propulsion systems and rocket thrusters too, to set spin rate, and perhaps to change the direction of the spin axis. But their thrusters are typically commanded to operate deliberately, instead of automatically, and only once in a long while.

Pointing cameras and other devices from a spinning platform presents challenges. The first spacecraft to orbit Venus, *Pioneer 12* (also known as *Pioneer-Venus 1*),[7] was launched in 1978 and returned data from Venus orbit until 1992. This cylindrical spacecraft carrying seventeen scientific experiments was spin-stabilized, but the great distance from Venus to Earth required it to use a one-meter diameter high-gain antenna to maintain communications. The spacecraft's design met this demand by mounting the HGA above the body center along its Z-axis, and constantly rotating it opposite the spacecraft's spin (approximately 15 rpm) using an electric motor, keeping it "de-spun" and trained on Earth throughout its flight.

The European Space Agency's *Ulysses* spacecraft, launched in 1986, operated well into 2009 in a unique high-inclination orbit about the Sun, 80° to the ecliptic plane (it attained this inclination using a Jupiter gravity-assist flyby), on a mission to characterize the heliosphere as a function of solar latitude. This highly successful spin-stabilized spacecraft had no cameras or other optical instruments, but it made many fundamental discoveries. One science experiment it carried, though, turned out to be a bit troublesome, because the spin affected a 7.5 meter-long boom. This component of the radio and plasma wave science instrument extends directly out along the spin axis, on the side of the spacecraft opposite the HGA. Uneven solar heating at certain portions of its solar orbit, combined with the boom's non-rigid mounting system, caused the axial boom to flex and impart an unacceptable amount of nutation to the spacecraft — a dynamic instability, which if left unchecked, would cause the axially-mounted HGA to wobble off Earth-point and lose contact as the spacecraft continued to spin and nutate. Specially developed procedures, involving periods of continuous uplink for over a dozen weeks at a time from the busy DSN and other facilities, succeeded in keeping nutation under control. This special procedure required programming the spacecraft to "watch" the Earth's relative position as a function of received uplink signal strength and spin rotation angle. *Ulysses*'s Attitude and Orbit Control Electronics system then fired a thruster once every three rotations to actively counteract and damp out the nutation. If the uplink were to be interrupted at the wrong time, though, the nutation could have resulted in loss of the mission. This active control of a spin-stabilized spacecraft represents an unusual case, but it attests to the ingenious capabilities that can be programmed into an attitude control system in flight.

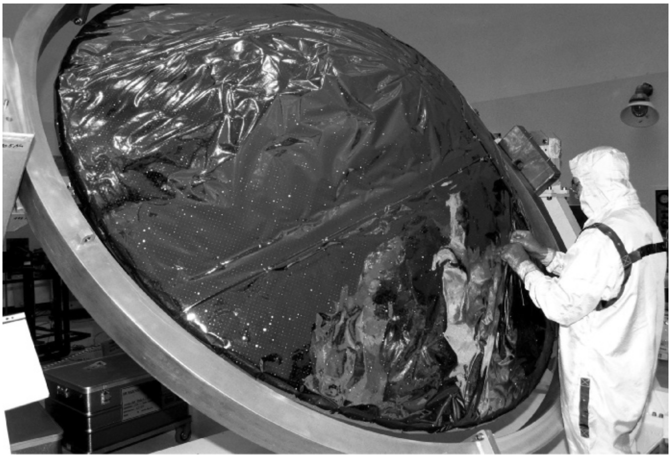

Fig. 3.7. The European Space Agency's *Huygens* Probe is a spin-stabilized craft. Here it is receiving an application of multi-layer insulation in the Kennedy Space Center's Payload Hazardous Servicing Facility six months before launch. The probe's 7-rpm spin was imparted during release from *Cassini* in December 2004. Image courtesy NASA/KSC.

Five months after arrival in Saturn orbit in 2004, the *Cassini* spacecraft was placed on a trajectory that would have it impact Saturn's moon Titan. A sequence of commands executing aboard the three-axis-stabilized spacecraft requested AACS to rotate it to a specific, pre-planned attitude. Once the attitude was achieved, *Cassini* then ejected the European Space Agency-built *Huygens* Probe it had carried from Earth, even though it was very distant from Titan at the time, and still climbing out to apoapsis in Saturn orbit. Upon release, three compressed 300 N springs expanded to push it away at 0.3 meters per second. As it departed, a curved track and roller system started *Huygens* slowly spinning, ensuring that its pre-planned attitude would remain unchanged. *Cassini* recovered from the reaction torque, turned to photograph its 319 kilograms projectile, then later it executed an OTM to avoid colliding with Titan along with *Huygens*. Before release, the

Huygens Probe had been aligned to the precise attitude that it would need to properly engage Titan's atmosphere with its heat shield without burning up. *Huygens* maintained this precise attitude, due only to its 7-rpm spin, for three weeks as it continued to orbit Saturn. When it finally slammed into Titan's atmosphere it executed a flawless descent on parachutes through the mysterious haze.

Similarly, the NASA *Galileo* spacecraft imparted a spin of 10.5 rpm to the atmospheric probe it carried to Jupiter, before releasing it on July 13, 1995. Its spin-stabilization preserved the probe's optimum angle of attack for nearly five months of free-fall until its successful atmospheric entry and descent on December 7 of that year.

Many interplanetary craft undergo a period of spin-stabilization during their launch phase. Typically, a three-axis-controlled launch vehicle places its payload in low-Earth orbit. Then, just before a powerful upper-stage rocket ignites to inject the spacecraft on its interplanetary flight, dedicated rocket thrusters fire to spin up the combined spacecraft and upper stage like a fireworks pinwheel. This provides stability while the injection burn proceeds. The 1,420-kilogram *Dawn* spacecraft, launched in 2007 to destinations in the main asteroid belt, was spun up to 46 rpm along with its attached 2,220-kilogram third-stage solid-rocket motor, to ensure attitude stability for the duration of the 87-second burn. Following this, the spacecraft needed to reduce its spin rate to near zero so that the craft's three-axis stabilization (similar to *Cassini*'s) could take over for the duration of its flight. For this it was equipped with a pair of so-called yo-yos, a commonly used system.[8] Once released, centrifugal force from the rapidly spinning spacecraft flung the two 1.4-kilogram metal masses radially outwards on 12 meter long cables that had been wrapped around the vehicle. They were let go at the end of their travel. In the four seconds this procedure lasted, the vehicle's angular momentum was literally dumped overboard, de-spinning the spacecraft and its spent, soon-to-be-detached, solid rocket. This same principle is at work when an ice skater extends his arms to stop twirling.

3.4.2 Three-axis control

As the alternative to spin stabilization, a spacecraft may be designed for active three-axis stabilization, which is the category of system *Voyager* uses. This approach is more complex and more expensive than spin-stabilization, but it offers a more maneuverable platform for pointing sophisticated optical instruments, aiming communications antennas, carrying out TCMs and OTMs, and for undertaking special operations such as described for *Cassini*'s release of the Titan probe.

At a high level, the capabilities needed for a spacecraft's basic three-axis stabilization system are:

1. A way of continuously sensing and estimating the angle between each of the spacecraft's three body axes and the external reference frame, and its rate of change;
2. The ability to determine the difference between the commanded state of rotation about each of the three axes and the observed state;

3. Some means of applying torque to the spacecraft that can rotate it in positive and negative directions about each of its three axes.

While all of these components are applicable to three-axis stabilized craft, some of them may also apply to spin-stabilized vehicles discussed above. The most important difference is that continuous automated attitude control activities are largely relinquished in the typical spinner, in favor of enjoying the built-in gyroscopic stability of the spinning spacecraft mass. Having noted this, we'll proceed to discuss the system of three-axis stabilization in particular.

Referring to the simplified closed-loop control system model depicted in Figure 3.4, we can interpret capability No. 1 in the list above as being indicated by the "sensors" box in the figure. Capability No. 2 above points to the figure's black circle combining feedback with the commanded state. Capability No. 3, applying torque to the spacecraft, would be seen as the output of the controller in the figure accomplishing the "resultant state." Within the "controller" box, and in the combiner circle, sophisticated algorithms run to compute estimates of the spacecraft's three-axis states of rotation, compare them with the external three-dimensional reference frame, generate the output signals dictating control torques that need to be applied, and watch out for potentially problematic or catastrophic situations — all the while producing telemetry and responding to command.

3.4.3 Hybrids

In summary, there are advantages and disadvantages to both spin stabilization and three-axis stabilization. Spin-stabilized craft do well with fields and particles instruments, but they may need complicated electro-mechanical systems to de-spin antennas or optics that need to point steadily at one spot. Problems with nutation can also arise. Three-axis stabilized craft can point optical instruments and antennas with ease, but they may have to carry out special rotating maneuvers to best utilize their fields and particle instruments. If thrusters provide the stabilization, observations must be designed knowing that the spacecraft is always rocking back and forth, perhaps unpredictably (to wit *Voyager*'s constant motion in Figure 3.2).

The *Galileo* Jupiter-orbiter spacecraft, launched after many delays on October 18, 1989, was designed to spin continuously for attitude stabilization. Mechanical devices on each of its three radial equipment booms could be adjusted to minimize nutation by varying the boom's angle forward or aft slightly along the Z-axis. *Galileo*'s cameras, other optical instruments, and a radio antenna for receiving signals from its Jupiter atmospheric probe, had to be precisely pointed. These requirements drove implementation of a dual-spin capability that turned out to be very complex. The lower half of *Galileo* hosting the optical devices was rotated by electric motors in the anti-spin direction, at precisely the 3 rpm nominal spin rate, to permit stable pointing. This arrangement meant devising a means for transferring electrical power and data communications across the constantly moving spin bearing. While generally successful, the feat was sometimes troublesome during operations. For some periods, an all-spin mode was needed, for example prior to probe release, in which the de-spin motor was commanded to stop. When this was done, *Galileo*'s computers experienced repeated resets, a problem that was traced to momentary interruptions in the power and data commutators when there was no relative motion across the bearing. The remedy was to create a "quasi-all-spin" mode that kept the de-spun section moving very slowly to help the commutator maintain electrical contact without interruption.

The *New Horizons* spacecraft (see page 296 in Appendix A) is using spin stabilization for much of its cruise out to Pluto and other Kuiper Belt objects. During launch from Earth early in 2006, its spin rate was increased to 68 rpm for maximum stability while its solid-fuel rocket motor burned, with characteristic unevenness, to inject the vehicle onto its fast interplanetary trajectory. Then after injection, its spin was reduced by releasing yo-yo weights to 5 rpm for the long haul past Jupiter and on to its intended targets. During its planned encounters, *New Horizons* will stop spinning and go into three-axis stabilization mode, as it also does during periodic checkouts en route.

3.5 Attitude Control Peripherals

There are a number of items under the category of input devices, the *sensors* that gather information about the state of the system being controlled. And there are the various *actuators,* the output devices that an AACS uses to exercise its control over the system. Broadly, AACS sensory inputs come from either celestial or internal reference devices. Its use of output devices applies torque to the spacecraft in various ways, bringing its attitude and rotation rates into conformity with commanded states.

3.5.1 AACS Input Devices

Celestial Reference

A *Sun sensor* is a common AACS celestial-reference — sky-watching — input device. It is an optical sensor with a wide field of view that reports on movements of an image of the Sun in two axes across its light-sensitive detector. The traces of *Voyager*'s excursions in yaw and pitch in Figure 3.2 on page 88 are readouts from a Sun sensor. Typically, spacecraft have at least two of these important devices for redundancy in case one were to fail. For a *Voyager* or *Cassini*, whose Sun sensors have a view along the Z-axis, the devices are sensitive to spacecraft attitude changes in two degrees of freedom, pitch and yaw, and they report these to ACCS. They do not sense activity in roll.

The large parabolic reflector of *Voyager*'s High-Gain Antenna, HGA, is usually facing back toward the Earth, which is nearby the Sun as seen in *Voyager*'s sky in the far reaches of the solar system. The HGA was therefore designed with a hole in it, through which the Sun sensors have a view toward the inner solar system.[9] In April 2002, engineers switched off *Voyager 1*'s primary Sun sensor, and activated the backup. After twenty-five years in flight, it had begun showing some signs of degradation.[10] On *Cassini*, Sun sensors occupy two holes through the spacecraft's HGA, widely spaced so that attitude control could be maintained in case a stray ring particle were to damage either the prime or the backup Sun sensor while the spacecraft orbits Saturn. The European Space Agency's *Mars Express* spacecraft, orbiting Mars since late 2003, has two Sun sensors, one of which was used for initial attitude determination following launch.

Another kind of device on the typical interplanetary spacecraft looks off approximately at right angles to the Sun sensor's view, to provide additional reference information by observing one or more background stars. *Star-watching devices,* as with many components on a spacecraft, are usually present in a redundant pair providing for backup in case one were to fail. On *Voyager*, the Canopus Star Tracker, named for the single bright star it was designed to watch, provides measurements in the one remaining degree of attitude freedom: excursions in roll. Measurements from this device are seen in the bottom panel of Figure 3.2 (page 88) as they are reported to AACS. *Voyager*'s Canopus tracker can be trained on other bright stars besides Canopus, by rolling the spacecraft, although only one star can be tracked at a time.

Fig. 3.8. The backs of *Voyager*'s sun sensors are visible on the white HGA above the heads of the people affixing the famous golden record. Two of the four yaw thrusters can be seen below the record. Image courtesy NASA/JPL.

Somewhat more advanced than *Voyager*'s single-star tracking device, a "V-slit" star scanner provides complete attitude reference while affording more freedom of motion. Three-axis-stabilized craft that use these devices must execute a rotating maneuver to obtain a star-scan attitude reference, while spin-stabilized craft can use them for continuous reference. See Figure 3.10 and we'll explore how it works. The scanner views the background of stars through two slits that are not parallel to one another. As the spacecraft rotates, the appearance of a star in the first, vertical slit, produces a voltage proportional to the star's intensity, called a "clock" signal. The time at which the same star passes through the next slit, the slanted one, marks the "cone" signal. After accumulating a number of these events in memory, the tracker's built-in computer algorithms, referring to an internal database of star position and brightness information, can proceed to deduce the spacecraft's attitude. The spinning *Galileo* Jupiter-orbiter spacecraft used this kind of device, as did the three-axis-stabilized *Magellan.*

More mature in design than the single star-tracker or the V-slit scanner is an autonomous Stellar Reference Unit (SRU). Two of these devices are fixed to the *Cassini* spacecraft's side, looking orthogonally to the Sun sensor's view (see page 330 in Appendix B). The SRU is not constrained to view only one star, nor is it constrained to view a moving star field. It observes the entire field of stars in whatever direction it is pointing, and it accomplishes recognition of a number of them based on the stars' observed geometry and intensity, by comparing them against its built-in catalog. It can do this whether the spacecraft's attitude is changing or not. This sophisticated device provides attitude reference for all three axes at once. A high-performance modern SRU may have a square field of view 8° or so on a side, be able to recognize and track a dozen stars at once, with onboard knowledge of thousands. It can be expected to report the observed spacecraft attitude to AACS in reference to the J2000.0 inertial reference frame with high accuracy.

Star-watching devices are sensitive instruments. They can be confused if a bright nearby object such as a planet or a ring system enters their field of view, or if its view is blocked by the night side of a planet. Mission commanding sequences must therefore tell the AACS in advance to ignore input from such devices for periods when such an obstruction may be present, or else attitude knowledge may become corrupted. For *Voyager*, simply executing a turn may result in an attitude from which all celestial reference — the Sun and one background star — is lost.

Usually, before a star-watching device can begin to recognize stars and provide reference information to AACS, the Sun must be visible within the Sun sensor, narrowing down possibilities for the spacecraft's attitude and providing an important initial scenario. V-slit scanners and SRUs can then continue to provide reference data after the Sun has left the Sun sensor's view. In anomalous situations when a spacecraft's AACS has lost all attitude

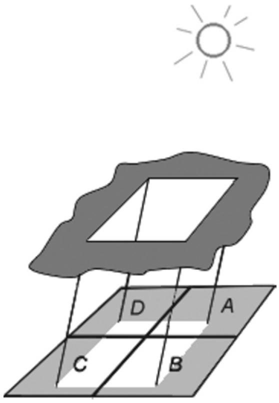

Fig. 3.9. In one type of sun sensor, four rectangular photovoltaic cells, A, B, C, and D, receive varying amounts of illumination based on incident sunlight falling through a rectangular aperture centered above them. If the sun-line were normal to the sensor, all four cells would have the same amount of illumination and would output the same electrical signal.

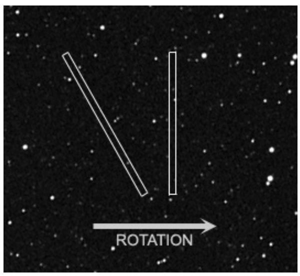

Fig. 3.10. Artist's conception of a V-slit star scanner's view against a field of stars. Spacecraft rotation first passes a star through the vertical "clock" slit as the slits move to the right. The star's subsequent passage through the slanted "cone" slit, based on a-priori knowledge of star-field geometry, provides enough information to determine spacecraft attitude in three axes.

knowledge, a typical autonomous protective response is to execute a maneuver that rotates the spacecraft, sweeping the Sun sensor's field of view around the 4π-steradian sky until the Sun is re-acquired.

Some orbiter spacecraft also carry a *Horizon sensor*. This optical instrument detects visible or infrared light from the planet's limb, or from its atmosphere, and provides information on the spacecraft's orientation with respect to the planet about two orthogonal axes.

Inertial Reference

Self-contained attitude reference devices that do not depend on external input are needed since celestial reference devices such as Sun sensors, star trackers, star scanners, stellar reference units, and horizon sensors, cannot be used under all conditions during a mission, as noted above. For such times, for example when a spacecraft passes into the shadow of a planet, a spacecraft's attitude control computer may need to have an independent reference. *Inertial reference* inputs are generated by *angular-velocity sensing* devices, known as gyroscopes (from the Greek words meaning "rotation" and "to see"),[11] or "gyros" for short, which do not depend upon making any observations outside of themselves.

There are a number of mechanical principles that can serve as the basis for gyroscopes. A small, rapidly spinning mass can be readily used because of its gyroscopic property of rigidity in space stemming from the mass's angular momentum. Employing a set of low-friction gimbals, a spinning-mass-gyro-based Inertial Reference Unit (IRU), is able to measure the apparent rotation of the gyro, which is largely fixed in space, as the spacecraft basically rotates about it. *Voyager*'s IRUs employ spinning-mass gyros, whose output provides rates of spacecraft rotation. Typically, a complete inertial reference unit uses three gyros, one each to sense excursions in pitch, roll, and yaw. These devices have been widely used in aviation for decades.[12]

Don't throw away your celestial reference devices yet, though. Spinning-mass gyroscopes are imperfect attitude references, because there is always some frictional coupling between their motor-driven internal spinning masses and their gimbaled mounts within an IRU. So they precess. The result is that the reference signals they produce typically drift, and exhibit errors that build up over time in reckoning the spacecraft's true attitude. Gyros that use different physical properties, which we will see below, also suffer from inaccuracies, even though they may not be subject to friction. Inertial references, then, are typically called upon for relatively short periods when celestial references cannot be used. To be useful, an IRU's errors have to be calibrated in flight using celestial references. Once an IRU's drift rates are known, they can be routinely compensated for by commanding the IRU to update stored drift-bias values regularly from Earth following calibration maneuvers. The *Hubble Space Telescope*, for example, requires this procedure to be done once every several days. Some spacecraft only use their gyros for infrequent maneuvers, so their drift calibrations may be carried out just prior to each use.

The *NEAR-Shoemaker* spacecraft, launched on its near-Earth asteroid observing mission on February 17, 1996, and the *Cassini* spacecraft orbiting Saturn, are the first interplanetary craft to use gyros that have no spinning parts. *Messenger*, launched in 2004 for Mercury, and many Earth-orbiting craft also use them. Their inertial reference elements, known as Hemispherical-Resonator Gyros (HRGs), operate on a different physical principle from the gyroscopic rigidity in space. These intriguing devices sense movement of a standing mechanical wave induced in the rim of a fused-quartz (crystalline silica, silicon dioxide SiO_2) hemispherical shell about 3 centimeters in diameter. The wave is akin to that in a crystal wine glass ringing like a bell when struck (see Figure 3.11). Null points in the wave travel about the rim at a different rate than the glass itself, when it is rotated about its axis of symmetry. The British professor George Hartley Bryan (1864–1928) first described this principle in 1890 [9]. The feat HRG devices accomplish is to induce a continuous ringing-vibration in the hemisphere, and detect and track the null points' motions with great sensitivity, by taking advantage of its piezoelectric[13] properties. Other than their vibrating sensor shells, hemispherical resonator gyros have no moving parts, and have nothing to wear out.

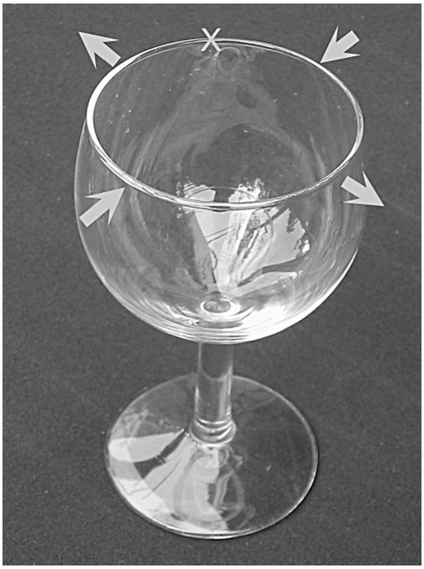

Fig. 3.11. A wine glass serves as an analog for a hemispherical resonator gyro. If the glass is made to ring audibly, a snapshot of rim dynamics would show flexing as indicated by arrows, which periodically reverses. Nodes between arrows such as X exhibit minimum flexing. These nodes precess about the rim at a different rate than the glass itself when rotated about its vertical axis.

Laser gyros are commonly used in aviation applications and are employed on some spacecraft. They use the Doppler shift of light to sense attitude rate changes about each axis in which they are mounted. The *Clementine* spacecraft, which orbited the Moon in 1994, employed these devices, as does the *Mars Express* spacecraft. Two light beams are sent in opposite directions along a medium in one plane — either a fiber optic line, or vacuum and mirrors. When the system is rotated in-plane, light going along one path travels farther than the light going in the opposite path during transmission, as seen in the familiar Doppler effect. This causes the light waves to interfere with one another, producing measurable patterns known as Sagnac Interference, named for the French physicist Georges Sagnac (1869–1926) who studied the phenomenon and identified its cause. Spaceborne systems usually use several kilometers of optical fiber wound in a coil for each of the three axes of rotation to be measured.

Micro-Electro-Mechanical Systems (MEMS) gyros[14] use another principle. MEMS gyros, produced using the same silicon etching processes that are used to make electronic chips, employ tiny, rapidly vibrating flexible arms. The principle at work is the same that we observe in a Foucault pendulum: Vibrating or oscillating objects tend to continue moving in the same plane. Rotating the system results in a Coriolis-effect[15] torque that can be measured. MEMS gyros typically use the piezoelectric effect to keep their test masses vibrating, as well as to generate an error-signal voltage proportional to rotation. Also known as "ceramic gyros," the inexpensive devices are found in today's consumer electronics including digital cameras to provide image stabilization, hand-held 3-D computer input devices that control cursor position or game components, and the Segway® Personal Transporter. NASA's New Millennium Space Technology-6 program included the launch of *TacSat 2* into low Earth orbit in December 2006. This small spacecraft demonstrated the use of an integrated SRU and three-axis MEMS gyro set for attitude control reference, called the Inertial Stellar Compass. This compact, low-power package that combines celestial and inertial references has a mass of 3 kilograms and draws only 3.5 watts from the spacecraft electrical supply.

There's one more kind of inertial reference device spacecraft carry to send input to AACS. On *Cassini* and other spacecraft, an *accelerometer* provides measurements of the force applied to the spacecraft during rocket engine burns for TCMs and OTMs. In most cases, AACS parses accelerometer input to compute when to shut off the engine after it has provided a specified value of ΔV. Science instruments use accelerometers as well. The *Huygens* Atmospheric Structure Instrument, carried aboard the *Huygens* Probe (see page 327 in Appendix B), contained, among its other components for measuring temperature and pressure, three accelerometers that registered forces acting on the probe in all three axes as it descended through Titan's atmosphere. *Huygens*'s Surface Science Package also included accelerometers that measured the force of landing (15 g), as well as Titan's natural gravitational force on the surface (a little less than 1/7 g). When the *Mars Global Surveyor* and the *2001 Mars Odyssey* spacecraft were executing aerobraking maneuvers, dipping into Mars's upper atmosphere, on-board accelerometers generated data that were used to derive atmospheric density values. Atmospheric entry vehicles that carried the *Mars Pathfinder* (1997) and Mars Exploration Rovers *Spirit* and *Opportunity* (2004) to the planet's surface also reported forces experienced by on-board accelerometers. Accelerometers on the rovers themselves indicate which way is down during surface operations. Many Earth-based navigation systems use accelerometers to add up all the movements of a vehicle — for example, an airplane — and form a complete picture of the vehicle's path from point to point.

3.5.2 AACS Output Devices

Mass Expulsion We've alluded to rocket thrusters earlier in this chapter, as well as in the previous one. In the next chapter we'll look more closely at how they work. For the present, we'll consider their role as common AACS output devices. Systems employing thrusters for attitude control are also referred to as mass-expulsion control (MEC), or reaction-control systems (RCS), named for the reaction obtained from the action of expelling mass according to Sir Isaac Newton's third law. By selecting which of several MEC thrusters to use, AACS can apply torque to a spacecraft about any of its axes. Varying the amount of time thrusters apply torque will vary the spacecraft's attitude change rates.

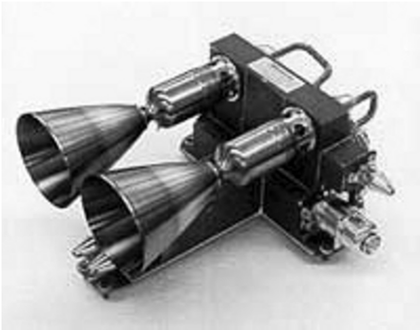

Fig. 3.12. *Magellan* rocket thrusters. The largest ones seen here developed 445 N during TCMs and Venus orbit insertion. The mid-size 22 N thrusters (right side) controlled roll while the 445 N thrusters were in use. The smallest, 0.9 N, were used for routine reaction-wheel desaturations. Courtesy NASA/JPL.

The ten *Mariner*-class spacecraft that JPL built in the 1960s were intended to explore the inner solar system. Six of them survived launch and accomplished their missions to Venus, Mars, and Mercury. These were the first interplanetary spacecraft to depart from the spin-stabilization design and use three-axis control. Their mass-expulsion devices were as simple as can be. Each *Mariner* spacecraft was equipped with a total of twelve small nozzles mounted at the ends of its four radially oriented solar panels. When the spacecraft's AACS called for a torque to be applied, it opened an electrically controlled valve for 20 ms, supplying compressed cold dry nitrogen to each of two opposing nozzles. This permitted gas to escape from a common tank, providing a thrust of about about 0.1 N from each nozzle and forcing the spacecraft to rotate. Reference [10] describes the system. In the interest of relating to familiar experience, consider the consequence of letting go of a garden hose while its nozzle is expelling water. The action of water accelerating out through the nozzle produces a reaction causing the nozzle to travel backwards.

The two *Voyagers* are *Mariner*-class spacecraft, but the mass-expulsion control system accessible to their AACS is more sophisticated than that of the previous *Mariner*s. Each *Voyager* has sixteen small liquid-propellant rocket thrusters that deliver a push of about 0.9 N each. Note that two of *Voyager*'s yaw thrusters, a prime and a backup, are visible in Figure 3.8.

Voyager's AACS operates the thrusters in pulses lasting a number of milliseconds during which an electrically controlled valve opens to spray hydrazine (N_2H_4) onto an electrically heated catalyst in the combustion chamber, which causes the propellant to decompose explosively, rapidly expelling hot gas. After encountering Uranus in 1986, the software capability to reduce each thruster pulse from 10 ms to 4 ms was developed, tested, and installed on the spacecraft in flight. This permitted finer attitude control during long camera exposures in the dimly lighted Neptunian environment (less than 1/1600 the sunlight that we enjoy on Earth), while also extending the life of *Voyager*'s propellant supply.[16]

Attitude control thrusters may be called upon to apply large torques to a spacecraft, typically while a more powerful rocket is operating to impart significant ΔV to the spacecraft. During launch, *Voyager* ignited a solid-propellant rocket motor that provided a final increment of speed to begin its free-fall cruise to Jupiter. Because solid rocket motors typically burn somewhat unevenly, they can impart strong off-center components of thrust and perturb the spacecraft's attitude. To maintain control, each *Voyager* used four 445 N monopropellant thrusters on struts straddling the solid rocket motor. Figure 3.13 shows where all the RCS engines and thrusters are mounted on the *Magellan* spacecraft in a similar arrangement to that of *Voyager*, at the ends of four struts. Because the struts reached out from below the spacecraft's center of mass, thrusters mounted there were able to overcome torques resulting from the 67-kN solid rocket's 84-second burn that resulted in an acceleration force up to 7 g placing *Magellan* into Venus orbit. The figure does not show the solid motor, which was jettisoned after use. Mounting attitude control thrusters out on struts increases their leverage, or control authority, since the distance out from the center of mass determines how much torque a thruster can wield on the spacecraft when it applies its given amount of force.

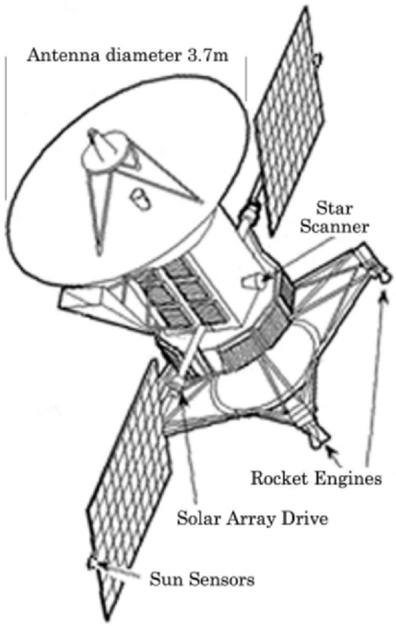

Fig. 3.13. The NASA Venus-mapping *Magellan* spacecraft. Adapted from NASA/JPL-Caltech image.

Reaction Wheels There's another kind of output device for applying torque for three-axis stabilization. Electrically powered reaction wheel assemblies (RWAs), can impart a torque under control of AACS to the whole spacecraft. Note that reaction wheels are sometimes called "momentum wheels," but the latter name is also applied to a different system, called control-moment gyros, which we will discuss separately. In the RWA system, small but fairly massive wheels are mounted aboard the spacecraft with their rotational axes fixed. *Magellan*, whose three electrically driven reaction wheels were mounted near the center of mass with their axes oriented orthogonally to one another, is a good example. To rotate the vehicle in one direction, the attitude computer causes one of the wheels to accelerate in the opposite direction and remain spinning. When the wheel has finished accelerating, the spacecraft itself has acquired a steady rotation rate. To stop the vehicle's rotation, the AACS would simply slow down the same wheel. This system provides a means to trade *angular momentum* back and forth between the whole spacecraft and its reaction wheels. In practice, RWAs that use a fluid lubricant are usually operated with some residual spin, or *bias,* to prevent lubricant stagnation near zero rpm.

Consider that a large mass, such as a whole spacecraft, changing its attitude at a relatively low rate, can have the same angular momentum as a small mass spinning rapidly. In reference to equation 3.1 on page 88, the spacecraft has a high

I while a small mass would have a low I. Angular momentum, expressed as the vector quantity $\overrightarrow{H}$, is the product of an object's moment of inertia, I, and its angular velocity, which is typically expressed as the vector omega, $\overrightarrow{\omega}$:

$$\overrightarrow{H} = I \cdot \overrightarrow{\omega} \tag{3.1}$$

Physics requires that in the absence of any externally imposed torque, the angular momentum of a whole system, such as a spacecraft containing reaction wheels, must remain constant. Adding torque to a reaction wheel, spinning it up and increasing its angular momentum, has the effect of decreasing the angular momentum of the rest of the spacecraft — the decrease can mean it begins rotating "backwards." Likewise, decreasing a reaction wheel's $\overrightarrow{H}$ will increase that of the rest of the spacecraft. The total angular momentum vector of the spacecraft at any time while under RWA control, then, will have two components (in the absence of externally applied torque). Expressed in spacecraft-body frame:

$$\overrightarrow{H}_{Total} = \overrightarrow{H}_{SC} + \overrightarrow{H}_{RWA} \tag{3.2}$$

where $\overrightarrow{H}_{SC}$ represents the component due to spacecraft angular rates, and $\overrightarrow{H}_{RWA}$ is that due to the reaction wheels. On the *Cassini* spacecraft, each electrically driven reaction wheel has a mass of 14.5 kilograms, a diameter of 30 centimeters, and a maximum speed around 3,000 rpm. These are effective in rotating the approximately 5,700 kilogram spacecraft at rates up to about 1.5 mrad/s in pitch and yaw, and twice that in roll, the axis with the smallest moment of inertia. Reference [11] gives the context, details, and performance of *Cassini*'s system. Wheels provide excellent stability and precise control for pointing optical instruments, meeting the *Cassini* science requirements ranging from 8 μrad precision for a one-second observation to 160 μrad for 100 seconds. Minutely varying the speed of a rapidly spinning small-I device affords a precise level of control on the larger-I spacecraft not unlike the way a reducing gear train offers fine-scale vernier-control of an output shaft's angle.

A good "seat-of-the-pants" way to visualize the basic mechanics of reaction wheels at work on a spacecraft is to carry out a thought experiment. Imagine holding a battery-powered electric drill while sitting, feet up, in a swivel chair. There is a circular 10-kilogram concrete paving stone with a spindle installed through its center and inserted into the drill's chuck. Keeping the concrete disk's spindle aligned vertically, you apply torque and begin to spin the heavy wheel via the drill. The result is that you and your seat begin rotating, as the reaction to adding angular momentum to the heavy wheel.[17] Now, reverse the drill-powered wheel, and you and your swivel chair will rotate in the opposite direction. One can easily imagine how vivid the results would be were one to be free-falling in orbit instead of sitting in a chair on *terra firma.*

Incidentally, the spinning masses of reaction wheels on a spacecraft do exhibit gyroscopic effects, but these are side effects that the attitude computer is tasked with calculating and working around during normal operations. Reaction wheels should not be confused with a spacecraft's mechanical spinning-mass gyroscopes, which as we have seen are *input* devices that provide inertial attitude references.

Reference gyros employ much smaller spinning masses, and their spin axes are not rigidly affixed to the spacecraft. Reaction wheels are strictly output devices that AACS uses for directly controlling attitude. Neither should reaction wheels be confused with control moment gyros, which are discussed below.

In practice, there is almost always some measure of external torque being applied to a spacecraft from solar photon pressure, gravity gradient, or atmospheric drag. These cause excess momentum to eventually build up in a reaction-wheel system as it strives to keep the spacecraft in a desired dynamic state. In its attempt to counteract a torque it senses on the spacecraft, AACS will continue to increase the reaction wheel's spin rate. Friction within a reaction-wheel system tends to cancel out excess momentum buildup, rather than contribute to it.

How can solar photon pressure affect a spacecraft's attitude? Light (and electromagnetic radiation at other wavelengths) that strikes a surface exerts a force upon it. Even though photons have no mass, because they travel at the speed of light, their energy exhibits momentum. The amount of force a spacecraft feels is related to the received energy from the Sun, which diminishes as the square of distance, and of course the amount of area illuminated. If the surface reflects light at all, it will add another component of force due to the reaction from turning it around and sending it back. The angle at which the surface faces the Sun is another factor. To estimate the total amount of solar light-pressure force:

$$F = \left(\frac{F_S}{c}\right) A_s (1 + r) \cos \Theta \tag{3.3}$$

where

F is the force in newtons,
F_S is the Sun's radiated energy in W/m^2. For example at Earth's location, $F_S=$ 1371 W/m^2, and it is approximately 1 percent this amount at the distance of Saturn,
$c =$ the speed of light, about 3 $\times 10^8$ m/s in vacuum,
$A_s =$ the area of the spacecraft's illuminated surface in m^2,
$r =$ the surface's reflectance: 0 for a perfect absorber, 1 for a perfect reflector,
$\Theta =$ the illuminated surface's angle of incidence to the Sun.

This force, although small, acts on the whole spacecraft, pushing it away from the Sun. But if there is an offset between the center of photon pressure on spacecraft's Sun-facing side and its center of mass, this will result in an external *torque* being applied to the spacecraft in a fixed direction, gently trying to rotate the spacecraft. The attitude control system senses the tiny rotation, and commands the reaction wheels to accelerate to cancel out this torque. An example is the *Mars Climate Orbiter*, that had one large solar panel to generate its electrical power, attached to only one side of the spacecraft (see Figure 2.1 in Chapter 2 on page49).

A word about the solar wind may help avoid confusion. The Sun's *light* exerts the noticeable pressure. Charged particles streaming out from the Sun, known as the *solar wind,* do not have an appreciable force on a spacecraft. Though they do have mass, they are too sparsely distributed in interplanetary space, and they travel slowly in comparison with light.

Gravity gradient can also cause a constant torque if the spacecraft is orbiting a planet. Flight through the upper reaches of the atmosphere of a planet being passed or orbited can also impose a torque, if the center of exposed area differs from the spacecraft's center of mass.

No matter the source of a constant externally generated torque, as the RWAs compensate, wheel speeds might eventually become excessive. Approaching maximum rpm is called "saturation," in which the spinning wheels are carrying as much angular momentum as their mechanical design can safely tolerate, beyond which the assembly might suffer damage.

So, to maintain wheel speeds within prescribed limits, excess momentum (excess wheel speed) must be occasionally removed from the system. This can be done by somehow applying torques to the spacecraft to hold it steady, while the attitude computer causes the wheels to slow down, typically, and acquire a desired preset speed, which may be zero, or it may be a bias of some rpm value in one direction or the other. This task is done during maneuvers variously called angular momentum desaturation (desat), reaction-wheel desaturation, momentum unload, or momentum dumping maneuvers. Many spacecraft use a system of thrusters to apply the torque needed to steady the spacecraft for desaturations. *Magellan*'s RCS thrusters were called on routinely to do this while in Venus orbit.

Magnetic Torquers The *Hubble Space Telescope*'s pointing control system uses reaction wheels to control the spacecraft's attitude. The system makes it possible to point to a target without deviating more than 0.007 arc-second — the width of a human hair viewed at a distance of more than a kilometer. Operating in Earth orbit, it is subject to relatively strong photon pressure from the Sun, plus gravity gradient from Earth, so its reaction wheels must occasionally be desaturated. But *HST*'s optics, including its 2.4-meter diameter primary mirror, are exquisitely sensitive and could easily be contaminated and rendered useless if there were rocket thrusters routinely expelling clouds of exhaust. So *Hubble* employs an alternative way to hold a steady attitude during its reaction wheel de-saturation maneuvers. The solution is to employ magnetic torquers — electromagnets in the form of four 8.5 meter-long wire-wrapped bars arrayed around the spacecraft's exterior. When energized with electric current, under control by AACS, their interaction with the Earth's natural magnetic field is powerful enough to hold the spacecraft's attitude steady while the reaction wheel speeds are modified during desaturations. Many spacecraft that operate in Earth orbit, where the magnetic field is useable (its strength at orbital altitudes is less than half a Gauss), rely on this kind of system. Tens of thousands of kilometers out, though, the field effectively ends, and torquers cannot be used.

The *Spitzer Space Telescope*[18] orbits the Sun at about the same distance as Earth does, trailing along behind the Earth in its yearly progress. As of late 2008 its distance is nearly 1×10^8 km from Earth. Reaction wheels provide steady attitude control as the telescope points toward its targets, and rotates it to point its HGA to Earth. While the spacecraft's location is convenient for making observations in deep space without the Earth getting in the way (which can often interfere with *HST*'s observations), there is no magnetic field strong enough for magnetic torquers to use during reaction wheel desaturations. *Spitzer*'s optics, designed for infrared astronomy, are even more sensitive than *Hubble*'s when it comes to contamination, because they are kept cold for infrared viewing — only 5.5 kelvins — so that its instruments can observe in the far-infrared part of the spectrum (see page 298 in Appendix A). If the spacecraft were equipped with hydrazine thrusters like *Magellan*'s, the ammonia and other products in their exhaust clouds would quickly finds ways to condense on the frigid optical surfaces and contaminate them. So to stabilize during desaturations, Spitzer issues pressurized cold dry nitrogen from nozzles, despite the relative inefficiency of such a system, a throwback to the original *Mariner* spacecraft's means of three-axis attitude control.

Spacecraft (Launch)	**Planets**	**AACS Input Devices** (dof = degree-of-freedom)	**AACS Output Devices** (Excluding any jettisoned)
Voyager-1 Voyager-2 (1977)	Jupiter Saturn Uranus Neptune (Flybys)	1-dof Canopus Star Tracker 2-dof Sun Sensors (2) 2-dof Gyroscopes (3)	0.9-N Trajectory-Correction Thrusters (4) 0.9-N Attitude Thrusters (12) Scan Platform Gimbal Actuators (4)
Magellan (1989)	Venus (Orbiter)	1-dof Star Scanner (1 with redundant channels) 2-dof Sun Sensors (2) 2-dof Gyroscopes (4)	Reaction Wheels (3) 445-N Orbit Injection Attitude Thrusters (4) 22-N Attitude Thrusters (8) 0.9-N Attitude Thrusters (12) 1-dof Solar Array Drive Mechanisms (2)
Galileo (1989)	Jupiter (Orbiter)	Sun Acquisition Sensors (4) Star Scanners (2) 2-dof Gyroscopes (2) Accelerometer (1)	10-N Attitude Thrusters 400-N Main Engine (1) Spin Bearing Actuator (1) Scan Platform Actuator (1) Linear Boom Actuators (2)
Mars Global Surveyor (1996)	Mars (Orbiter)	Mars Horizon Sensor (1) Celestial Sensor (1) Sun Sensors (2) 1-dof Gyroscopes (4) Accelerometers (4)	Reaction Wheels (4) 2-dof HGA Gimbal Actuators (2) 4-N Thrusters (12) 2-dof Solar Array Drive Mechanisms (2) 659-N Main Engine
Cassini (1997)	Saturn (Orbiter)	3-dof Star Trackers (2) 2-dof Sun Sensors (2) 1-dof Resonator Gyros (4) Accelerometer (1)	Reaction Wheels (4) 445-N Main Engines (2) 2-dof Engine Gimbal Actuators (2) 0.9-N Attitude Thrusters (16)

Fig. 3.14. Peripheral devices on the inputs and outputs of AACS for six spacecraft. Adapted from [11].

Control Moment Gyros While not applicable to most interplanetary spacecraft, we'll discuss these devices to distinguish them from RWAs. The International Space Station (ISS,) is equipped with control-moment gyros (CMGs). These are spinning-mass devices, also called gyrodynes, whose rotors are on the order of 100 kilogram mass, kept going at a constant speed by electric motors (note this difference from reaction wheels, which vary their speed). The gyroscopic properties of rigidity in space and precession are used to apply torque to the whole spacecraft. To turn the spacecraft, you rotate the *spin axis* of a CMG (recall RWA spin axes are fixed to the spacecraft body). CMGs are attached to the spacecraft structure via a set of gimbals to permit movement of their axes. Brute force precession then results in a torque applied to the whole spacecraft. The space station uses a set of four CMGs to provide controllability in three axes, keeping one as a spare in case of failure in one of the others. While CMGs have the same purpose as that of reaction wheels, note that the operating principle is different. RWAs apply torque by changing rotor spin speed; CMGs force-tilt the rotor's spin axis without necessarily changing its speed. CMGs are best suited to applications on very massive spacecraft such as today's ISS, or the *Mir* space station of the past. A set of CMGs may consume a few hundred watts of electrical power, and produce thousands of newton-meters of torque.

Another thought experiment may be appropriate to illustrate CMGs in operation. Imagine[19] sitting feet-up in your swivel chair, holding the cordless-drill-powered 10-kilogram concrete disk as in the reaction wheel thought experiment. This time, let it spin with its drill-mounted axle *parallel* to the floor. Increase its spin to maximum and keep it at that speed. Now tilt the drill, bringing its axis of rotation to an angle with the floor. Precession will cause you to rotate, just as it causes the space station to rotate.

Ancillary Actuators Attitude control is one function of AACS, articulation is the other. Following is a list describing some of the more common spacecraft components under the control of an AACS:

1. Solar array drives: Spacecraft that depend on sunlight for their electrical power supply require the photovoltaic cells on their solar panels to face the Sun. Solar array drive mechanisms have one or two axes of freedom, each operated by an electric motor. AACS maintains knowledge of the Sun's position, and can orient the photovoltaic to face it, or to employ an offset requested by the electrical power subsystem to reduce the amount of power they generate by pointing them slightly away from the Sun.
2. Engine gimbal actuators: Some spacecraft control the direction their main rocket engine's nozzle is pointing, to keep the rocket thrust directed through the spacecraft's center of mass. Based on the 1970s *Viking* Mars orbiter's design, *Cassini*'s two gimbal actuators control each main engine, constantly making small adjustments in the engine's position to compensate for shifting propellant mass, under control from AACS.
3. Scan platforms: Spacecraft that carry optical instruments on moveable platforms depend on AACS to maintain control of their pointing. *Voyager*, for example, can articulate its scan platform in two degrees of freedom. *Galileo* was able to articulate its optical instrument platform in one degree of freedom. A second degree of freedom was provided by adjusting the de-spin rate in roll of the spacecraft's lower despun section, under AACS control.
4. High-Gain Antennas: HGAs often occupy booms protruding from the spacecraft, and can be articulated in one or more degrees of freedom.

5. Linear Boom Actuators: The *Galileo* spacecraft had three booms extending radially from its spinning central body: two RTG booms and a science instrument boom. These needed to be adjusted slightly up or down along the roll axis to minimize wobble or nutation. In flight, AACS controlled linear actuators supporting the booms that were able to extend or contract up to 5 centimeters to make the necessary adjustments. These are described in reference [12].

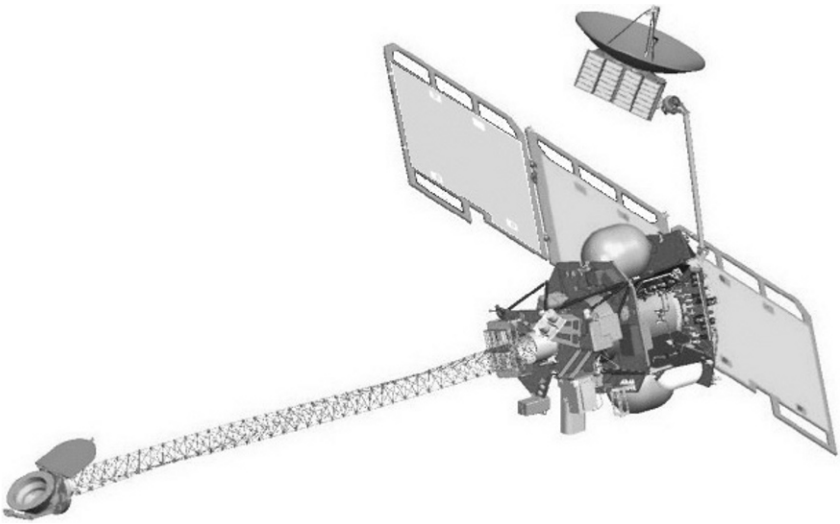

Fig. 3.15. *2001 Mars Odyssey* spacecraft has an articulated high-gain antenna, HGA (upper right) and articulated solar arrays. Image courtesy NASA/JPL-Caltech.

3.6 Scientific Experiments with AACS

Many of the engineering systems or subsystems on a spacecraft can also participate in experiments that directly provide valuable scientific data. Telecommunications radio can actively probe an atmosphere; Doppler shift, usually a tool for navigation, can be used to measure a natural object's mass. Attitude control can participate, too. *Galileo*'s AACS serendipitously made a scientific discovery unrelated to the normal business of tracking stars for attitude estimation. While *Galileo* was orbiting Jupiter, it was realized that because high-energy particles leave a trace in the scanner's data, the star scanner could actually be used as an instrument to measure the flux and energy of those particles, by calibrating and analyzing its noise signal. The data showed that the particles trapped in Jupiter's magnetic belts were predominantly less than 2 MeV electrons. Another discovery came in 2000 when the second magnitude star Delta Velorum-A was in the *Galileo* star scanner's field of view. The star drew notice by dimming below the star scanner's detection threshold for about eight hours. Subsequent analysis of the star scanner data, plus the work of amateur and professional astronomers, revealed that the star is an eclipsing binary, and the brightest one known [13]. The star's dim companion has an orbital period of 45.2 days. The eclipse, which lasts for eight hours once each orbit while the star's companion passes in front, causes a dimming that can even be seen with the unaided eye.

AACS can also help scientists investigate the density of an atmosphere on a planet under study. Accelerometers can be used in this application, if the spacecraft is intended to enter an atmosphere, as in the case of *Huygens* or *Mars Pathfinder*. The amount of atmospheric drag a spacecraft will experience depends on these factors:

$$F_{drag} = 1/2 \rho V^2 C_D A \tag{3.1}$$

where

F_{drag} = force in newtons,
ρ = atmospheric density in g/m^3
V = velocity in m/s
C_D = the spacecraft's coefficient of drag, and
A = the area of the spacecraft impacted in m^2

The spacecraft's drag coefficient should be known precisely from design and test for a spacecraft intended to enter an atmosphere, as is the area exposed to atmospheric friction. With velocity known from navigation data, telemetered measurements of force sensed via accelerometers on board can then permit solving for the unknown atmospheric density.

Even if a spacecraft is not designed for atmospheric entry, it can report on the amount of torque it experiences when flying close by a planet or other object that has gas associated with it. *Cassini* flew through the watery and gaseous geysers that erupt from Saturn's moon Enceladus. While its science instruments directly sampled the plume's constituents, the torque that AACS reported helped estimate the plume's density. *Cassini* routinely flies close enough to Saturn's largest moon, Titan, to sense the upper reaches of that moon's atmosphere. As the spacecraft flies past the 5,150 km-diameter proto-Earth-like object, AACS reports the torques felt on the spacecraft body, varying over time with altitude above Titan. Some of these targeted encounters come closer than 1,000 km to Titan's intriguing surface.

The quantity of torque on the spacecraft as it flies by Titan applies directly toward revealing Titan's atmospheric density. This torque can be estimated as:

$$\boldsymbol{R}(t) = \int_0^t \{\boldsymbol{T}_{ATMOS} + \boldsymbol{\epsilon}\}\delta t \tag{3.2}$$

where

$\boldsymbol{R}$ is the accumulated angular momentum vector. Its time-derivative denotes the per-axis body torque that AACS constantly estimates. *Cassini* reports its value in telemetry, which it computes after filtering to reduce the effect of noise.

$\boldsymbol{T}_{ATMOS}$ represents the torque contributed by the atmosphere,

ϵ is a vector quantity containing small torques that integrate to near zero, such as from gravity gradients and photon pressures.
t is time, which is indicative of altitude above Titan's surface as the spacecraft flies by.

Reference [11] describes this experiment, including how the torque values are reduced to provide atmospheric density information.

In 1993 after the *Magellan* project had completed all its prime scientific objectives at Venus and a number of extended-mission objectives, the spacecraft was also used to study Venus's atmospheric density as a function of altitude by measuring torques the atmosphere exerted on the spacecraft. The craft had two rectangular solar-photovoltaic panel appendages whose drive mechanisms could rotate them about one axis. AACS canted the two panels in opposite directions, making a "windmill" out of the spacecraft. Orbit trim maneuvers then lowered *Magellan*'s orbit periapsis, its closest point to the planet, until it was dipping into the high atmosphere. The craft's AACS reported on the RWA rotational speeds resulting from the torque to help characterize the free-molecular flow in the upper reaches of our sister planet's CO_2 atmosphere. The experiment is described in reference [14].

3.7 AACS Faults and Protection

We'll visit the subject of fault protection more specifically in a Chapter 5, but before leaving the subject of AACS we should characterize a few more of its responsibilities in regard to the basic need for reliability mentioned on page 91. AACS can take care of itself in the remote reaches of the solar system by recognizing "routine" problems as well as extraordinary ones. It does this by running software routines called *fault-protection monitors,* each of which is tasked to watch for a specific kind of problem. *Voyager*'s AACS has dozens of fault-protection monitors watching for limits to be violated or failures to occur. An advanced AACS such as *Cassini*'s has hundreds of fault-protection monitors. We considered the case of anomalous thrust, which is one of the extraordinary anomalies AACS fault-protection monitor routines look for. Additional monitors are triggered in cases such as when AACS cannot find or identify a needed celestial reference, or if it were commanded to point an instrument too close to the Sun, or when the reaction wheels are reaching their momentum saturation.

Normally, routine command sequences include reaction-wheel desaturation maneuvers at intervals that keep the wheel speeds well within limits. Should momentum build up unexpectedly in an RWA, or if regular commanding were to neglect RWA speeds inadvertently, AACS's fault-protection response algorithms would automatically interrupt the regular sequence of commands executing to perform an RWA momentum desaturation. On some spacecraft this automated step might take place routinely, and on other spacecraft it would constitute an extraordinary anomaly.

Additional fault-protection monitors can invoke built-in fault-protection response algorithms to take appropriate action in just about every kind of imaginable anomaly. Many can autonomously swap over from a failed part to a spare. And

AACS is ultimately called upon when other systems detect problems that require interrupting the normal sequence of operational commands. The request to AACS may be to rotate the spacecraft to an attitude known to be thermally safe, and which will permit communications with Earth for troubleshooting and repair.

Notes

[1]This is *Voyager 1*'s distance from Earth as of December 2008, at which time the spacecraft is on roughly the opposite side of the Sun from the planet, and heading away and north at 3.6 astronomical units per year on its hyperbolic solar-escape trajectory.

[2]In 1950 the English mathematician Alan Turing (1912–1954) proposed a test: A human engages in a natural-language typewritten conversation with a machine, which passes the test if a human judge cannot reliably tell it is not another human.

[3]The *Voyagers* are too far from Earth to use their low-gain antennas for communications. Their only choice is to point their high-gain antennas accurately.

[4]The use of reaction wheels is an alternate to direct thruster control, although these devices also require occasional use of thrusters to manage their own rotation rates.

[5]Patterns of the distant stars do not change appreciably despite a spacecraft's travels throughout the solar system. Their great distances prevent parallax from interfering with AACS's ability to recognize them in the same patterns familiar to us from Earth.

[6]The three-axis-stabilized *Voyagers* are routinely commanded to execute rotations about their Z-axes for the benefit of fields and particles investigations.

[7]The *Pioneer* missions were all managed by NASA's Ames Research Center.

[8]This remarkable animation by Dan Maas (1981–) of Maas Digital LLC, of the Mars Exploration Rover launch and mission, includes spin-up and yo-yo controlled de-spin following the upper stage burn: http://www.maasdigital.com/mervideo-large.html

[9]During design, the *Voyager* Sun sensors were modified, including the addition of amplifiers, to permit their use beyond Saturn [15].

[10]See the *Voyager* Project press release:
http://www.jpl.nasa.gov/news/features.cfm?feature=548

[11]The French physicist Leon Foucault (1819–1868) coined the word "gyroscope" in 1852 when he was attempting to use a gimbaled spinning-mass device to observe the Earth's rotation. The attempt failed due to friction and unwanted torque in his system, and Foucault is better known for his use of a pendulum to display our planet's daily motion. Any device that enables one to see rotation is worthy of the name gyroscope, whether or not the device itself involves a rotating mass.

[12]Note that inertial attitude references for a spacecraft represent a different discipline from that of inertial *navigation* in aviation and other Earth-based applications. Inertial navigation systems serve to model the vehicle's entire progression from one point to another by precisely measuring and tracking all its accelerations. While there may be accelerometers aboard an interplanetary spacecraft, they are used for tasks other than point-to-point navigation.

[13]Piezoelectric materials, typically crystals or ceramics, expand and contract in response to the application of an electric current. They also generate an electrical current when mechanically compressed or stretched. A crystal earphone demonstrates the former effect, and the latter effect is employed in the household push-button spark generator used to light a cooking flame.

[14]Also called micro-machines and micro systems technology.

[15]Coriolis effect, described in 1835 by French scientist Gaspard-Gustave Coriolis (1792–1843), is an apparent deflection from a straight path of a moving object, when viewed from a rotating frame of reference. Air masses moving south in Earth's northern hemisphere are deflected west as seen from the rotating surface, due to Coriolis effect.

[16]As of late 2008, *Voyager 1* and *Voyager 2*, launched in 1977, have used up little more than two thirds their 100-kilogram complement of propellant.

[17]Don't actually try this at home! The rapidly spinning massive wheel would pose a danger of personal injury.

[18]See http://www.spitzer.caltech.edu

[19]Again, don't actually try this, because the spinning concrete mass would present a danger of personal injury.

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4 Propulsion

4.1 Liftoff

It's the morning of September 5, 1977, sunny and warm on Florida's Atlantic coast. Forty-eight meters above the pad, the *Voyager 1* Mission Module and its Injection Propulsion Unit sit fastened atop a Centaur third stage rocket whose tanks are full of cold liquid hydrogen and liquid oxygen, more than 16,000 kilograms in all. Small amounts of these cryogens are boiling off, venting visibly into the humid air from just below an oversized fairing. The powerful Centaur is about a meter wider than the Titan III-E core,[1] so its larger fairing protrudes just above the Titan's second stage. There's little obvious demarcation, but the first stage makes up about two-thirds of the central core. Stages one and two are mostly tanks of Aerozine-50 fuel[2] and nitrogen tetroxide oxidizer — over 137,000 kilograms of these propellants in total. Strapped to the sides of the core are two solid-fuel booster rockets, together called stage zero, carrying nearly 385,000 kilograms of a mixture including powdered aluminum and ammonium perchlorate. Today's launch will be the final use of a Titan III-E.[3]

Fig. 4.1. *Voyager 1* rides a Titan III-E launch vehicle with Centaur upper stage, leaving Earth half a month after its twin, *Voyager 2*. Image courtesy NASA-KSC.

It's getting close to 9 A.M. Eastern Daylight Time, and in a moment, the solids will ignite. *Voyager* spacecraft engineers have already postponed this launch twice while they modified their interplanetary robot to address problems seen during *Voyager 2*'s boom deployment sixteen days earlier. All is ready at the Cape Canaveral Air Force Station for this attempt.

Even before lift-off, as it sits on the launch pad the stack enjoys 1,415 km/h of eastward velocity relative to the Earth's core because of the planet's rotation. This free velocity that the launch vehicle won't have to provide is the main reason for using a site only 28.5° in latitude above the equator. At the countdown's end comes a brilliant flash, billows of white smoke, and seabirds fleeing the roar. Cables drop away, and the 633,000-kilogram stack rises accelerating in reaction to the solid boosters' combined thrust of 11.7-million newtons — over 2.4 million pounds of force.

Rocketing high in the clear blue sky almost two minutes into its eastward-arcing flight at 60 km altitude, stage one in the Titan's core ignites. Its two liquid propellants mix and burn spontaneously in twin Aerojet General engines, together producing 2.3 million newtons of thrust. The exhaust nozzles articulate, changing their aim under control of the Titan's flight computer to maintain stability in pitch and yaw. Now the spent solid boosters unlatch and tumble away, still smoking as they begin falling towards the sea.

The payload fairing separates in half and is jettisoned. At an altitude of 100 kilometers, the air is thin enough that there are no longer aerodynamic forces to jeopardize *Voyager*, therefore no need to keep accelerating this extra mass. Having burned for two and a half minutes, stage one separates and drops away as the single engine of stage two ignites, passing 167 km.

While the vehicle has been accelerating, its range-safety radio receiver has been listening for commands from launch control on the ground. This system is capable of shutting down the engines and destroying the vehicle with an explosive charge, but fortunately has not received any such radio signal. There is also a second, independent, system on board that can sense catastrophic accelerations and autonomously issue the destruct command.

Something has gone wrong. Stage two burns out after only three minutes. Its fuel-oxidizer mixture ratio has been running a little too rich in fuel, so it has not provided enough of a boost. It disconnects from the Centaur, which fires its twin Pratt and Whitney engines and provides a 133-kN thrust for just long enough. It burns 544 kilograms more propellant than planned, but succeeds in reaching its target velocity with only 3.4 seconds margin — too close for comfort, but sufficient. Had this under-burn occurred two weeks earlier during *Voyager 2*'s departure on a higher-energy trajectory, its whole Grand Tour mission would have been lost. At an altitude of 200 km, *Voyager 1* separates from the Centaur. Its 18.3 km/s Earth-relative velocity is more than enough now to escape our planet's grasp, but before it can coast all the way to Jupiter it will need another 1.7 km/s.

Coasting close to Earth's orbit, and moving in the same direction, *Voyager 1* is in its own solar orbit. The command sequence running aboard *Voyager*'s Mission Module ignites a 76.5 kN solid-propellant rocket motor built into the attached Injection Propulsion Unit. The unit has four 445 N hydrazine-powered engines arrayed around the solid motor. They will pulse on and off under control of the Mission Module's attitude control system to stabilize its attitude in pitch and yaw, keeping the thrust vector aligned tangent to Earth's solar orbit while the spacecraft obtains the final kick that it needs to reach Jupiter. Four 22 N thrusters pulse to maintain the spacecraft's attitude about its roll axis while the solid rocket burns, depleting its propellant in 43 seconds.

The burn is complete. The spacecraft is again coasting, but this time it can free-fall all the way to Jupiter. It has been injected into an approximate Hohmann transfer solar orbit, the high point of which will be 754 million kilometers from the Sun. *Voyager*'s Injection-Propulsion Unit is no longer needed and must be jettisoned, otherwise its mass will interfere with normal attitude control functioning, for which 0.9 N thrusters on the Mission Module will suffice for decades to come. First, two pyro valves[4] operate, reducing pressure in the hydrazine line feeding the 445 N and 22 N thrusters, to minimize torque on the spacecraft during separation. Then a self-sealing disconnect mechanism breaks the connection. Explosive bolts fire, and the modules separate from one another. Both will approach Jupiter, but only the Mission Module will communicate with Earth and continue on past Saturn. Six days later, the Mission Module, henceforth known simply as *Voyager 1*, is commanded to execute a small trajectory correction maneuver, firing its 0.9 N thrusters with hydrazine from the same small tank that fed the Injection Propulsion Module. This maneuver fine-tunes *Voyager 1*'s course to Jupiter.

4.2 Newton's Third Law

Throw a mass in one direction as fast as you can. The reaction is a force called *thrust,* and its magnitude varies with how much mass you throw, and how fast. One device that can do this outside of an atmosphere is the *chemical rocket,* which forms the basis of many spacecraft propulsion systems. Chemical rockets fueled by black powder (gunpowder) were in use in and around China during the thirteenth century, well over four hundred years before Isaac Newton expressed the law of motion that we know as, "For every action there is an equal and opposite reaction." Airplane and boat propellers use this principle. They accelerate the ambient fluid aft, resulting in forward thrust. Jet engines resemble rockets perhaps more closely because they burn chemicals in a chamber, producing heat which expands gases that accelerate out the nozzle,[5] giving the reaction that thrusts the airplane forward. They breathe air. A rocket differs in that it does not take in air to obtain oxygen for combustion. All the chemicals needed to accelerate mass out a rocket's nozzle are carried on board, so it does not have to interact with any outside medium to produce thrust.

A rocket is a simple internal combustion engine. It converts heat — thermal energy — into mechanical motion — kinetic energy. Among such "heat engines" in practical use, rockets are the most efficient. The theoretically attainable efficiency increases with operating temperature[6] so a rocket's efficiency is high because it typically runs hotter than other kinds of engines. Automotive engines typically achieve around 25 percent efficiency in converting the available thermal energy produced from chemical reactions to mechanical work. An airliner's turbofan jet engine has about 32 percent efficiency. Various kinds of fossil-fueled electrical power plants operate from 36 percent to 60 percent. Early experiments with liquid-fueled chemical rocket engines achieved 64 percent efficiency.

4.2.1 Water as Reaction Mass

To illustrate some basic propulsion system concepts, load one liter of water into a two-liter plastic soda bottle, and devise a cap that can be released after you've pressurized the air above the water using a bicycle pump. Invert the bottle on its launch pad, and pull the release cord. When the bottleneck opens, energy stored in the compressed air forces the water rapidly out, propelling the soda bottle skyward. You've just demonstrated the following:

1. The action of expelling mass in one direction produces a reaction thrusting your rocket in the opposite direction, as total momentum is conserved.
2. Most of the mass in your water-bottle rocket consists of propellant. A liter of water has a mass of 1 kilogram, and the compressed air perhaps 10 grams. The empty plastic bottle has a mass of 50 grams, so the ratio of expelled mass to that of the "vehicle" is high: 20.2.
3. The more energy you store in the rocket by pumping air, the faster the propellant mass will exit, and the better your rocket will perform.
4. The rocket's total mass including propellant decreases while it operates, so over time less and less mass needs to be accelerated.

Serious enthusiasts have developed water-bottle rockets that achieve 200 km/h and trajectory heights of hundreds of meters. Aside from demonstrating the four principles shared by all chemical rockets, these simple devices in fact share an important constituent with a Centaur upper stage. The Centaur carries hydrogen (H_2) and oxygen (O_2) propellants, packed densely in liquid form, that combine chemically to produce water (H_2O). So, water is the mass that the Centaur's rocket engines expel, using energy not from compressed air, but energy released from the combustion of the propellants. The heat of combustion means that the reaction mass is gaseous water, in place of the bottle rocket's liquid. Moreover, the heat of combustion supplies energy to expel mass at velocities much higher than our bottle-rocket can accomplish.

Chemically combining hydrogen and oxygen yields nearly the maximum amount of energy that chemical reactions can theoretically yield. This is the reason that many high-performance launch vehicles, including the European Ariane and the U.S. Space Shuttle, use hydrogen and oxygen for propellants. Only reactants including hydrogen and fluorine will release more energy. Being so highly reactive, fluorine is difficult to handle, and the product of it combining with hydrogen becomes one of the most corrosive substances known — hydrofluoric acid — when mixed with water. For this reason fluorine does not find use as a practical propellant.

4.2.2 Rocket Science

The image of "throwing mass" to gain a reaction, expressed in the first two sentences in this Section (page 121), sums up the heart of rocket propulsion. The most important factors governing rocket performance are mass and the speed with which the rocket can eject it. While additional factors may come into play, such as gravity and atmospheric drag, we can understand the relationship between mass and velocity using the equation expressed by the Russian-Soviet rocket scientist Konstantin Tsiolkovsky (1857–1935), who pioneered many of the concepts required for flight outside an atmosphere [2], today known as the discipline of *astronautics.* In 1903

[3] he published what was subsequently named in his honor *the Tsiolkovsky Rocket Equation:*

$$\Delta V = v_e \ln \frac{m_0}{m_1} \tag{4.1}$$

This equation, and all its connotations and implications enjoy clear exposition in Arthur C. Clarke's non-fiction 1950 book, *Interplanetary Flight* [4]. Here, we'll emphasize just a few of its more prominent applications in spacecraft propulsion systems. In Equation 4.1,

ΔV (Delta V) is the change in velocity that a rocket-powered vehicle will experience by expelling some of its mass in the opposite direction.

v_e is the effective velocity at which a rocket expels mass. The highest achievable v_e today is around 4.5 km/s for liquid-propellant engines, and 2.5 km/s for solid-propellant rocket engines. Non-chemical propulsion systems can take the figure an order of magnitude higher. Actual velocity may differ from the effective velocity if a propulsion system bleeds off propellants to run turbo-pumps or the like.

m_0 is the initial vehicle mass, including propellant, prior to operating the propulsion system.

m_1 is the vehicle's remaining mass after the propulsion system has stopped operating.

ln means natural logarithm, using the constant e (about 2.718) for a base. It is sometimes written "$\log_e$."

To achieve a useful ΔV, we need some combination of a large m_0 (note that its value grows exponentially as the desired ΔV increases), a small m_1 and a high v_e. If our water-bottle rocket's v_e had a sustained value of 50 km/h our vehicle would achieve a ΔV of about 153 km/h were it not for air resistance and Earth's gravitation.

4.2.3 A Solid Rocket Example

A solid-propellant rocket engine (these are discussed more at length in Subsection 4.4.1) such as the one *Voyager* used for interplanetary trajectory injection might have an initial mass of 1,120 kilograms. Its final mass after burning out all its propellant in forty-three seconds might be about 80 kilograms, so most of this solid rocket motor's mass is obviously propellant. The value of m_0 over m_1 for such an engine would be 14. Solids such as this motor can be expected to expel mass at a v_e of 2.5 km/s almost continuously during a burn. It is possible to fire the motor without adding any other components to it. It only needs to be ignited to produce its total of 6.6 km/s ΔV. This would be more than enough ΔV to leave the surface of Mars and escape the planet's gravitational hold entirely. By itself, however, the rocket motor cannot maintain a stable attitude, nor would it serve any useful purpose.

To make it useful, build an Injection Propulsion Unit (IPU), around the solid. The IPU has four 445 N yaw and pitch control thrusters, plus four 22 N roll thrusters, and 100 kilograms of hydrazine (liquid) propellant in a tank. For the case of *Voyager*'s IPU, our system's m_0 is up to 1,235 kilograms so far. But this equipment is not smart enough to operate its own attitude control thrusters, and by itself it still serves no useful purpose. The intelligence is in the Mission Module, the payload that will detach and carry out its mission. During its forty-three-second final injection onto a near-Hohmann transfer to Jupiter, the Mission Module's AACS operates the IPU's thrust-vector control devices, maintaining stability in pitch, roll, and yaw, while the solid rocket motor fires.

Adding the Mission Module payload and its adapter brings m_0 to 2,055 kilograms and $m_1 = 1{,}016$ kilograms. We'll assume an effective exit velocity of the rocket's exhaust, v_e of 2.5 km/s, and assume it remains constant until all the propellant has exited the nozzle. Further note that the system is in free-fall and not fighting against gravity or air friction. Equation 4.1 provides that the vehicle will achieve a ΔV of about 1.8 km/s, supplying the remaining energy needed for coasting to Jupiter.

4.2.4 Making Comparisons

A useful figure of merit for propulsion systems is *specific impulse.* This measure describes a rocket's efficiency and permits easy comparison among rocket systems of various technologies, whether solid- or liquid-chemical, electric propulsion, or some other. *Impulse* is the change in momentum (mass × velocity) brought about by a rocket's thrust, and specific impulse is the impulse per unit of propellant. Written I_{sp}, specific impulse can be based on propellant mass,[7] or on the propellant *weight,* which is its mass affected by Earth's standard gravity, g_0. The latter version is more commonly seen. In this usage, the units of I_{sp} are seconds. In a simplified form:

$$I_{sp} = \frac{v_e}{g_0} \tag{4.2}$$

where

v_e is the exit velocity of the rocket's reaction mass, its exhaust, along the axis of thrust, in meters per second, and

g_0 is "standard gravity," the gravitational acceleration at the surface of the Earth, which has a value of 9.80665 meters per second per second, or m/s^2.

The units of "seconds" for I_{sp} values may at first glance appear confusing. But weight and thrust are both measures of force, so they cancel out, leaving a value in units of seconds. This happens to be convenient since different systems of measurement such as English or SI each recognize the unit of seconds without any need to convert between them.

For the typical solid-propellant rocket motor with $v_e = 2.5$ km/s, the I_{sp} would be about 255 s. The highest-performance liquid propellant rockets, with $v_e \approx 4.4$ km/s, have I_{sp} values a little over 450 s (see Table 4.1). Electric propulsion systems currently in use can achieve over 3,000 s. As we'll later see, the drawback to the extreme efficiency of electric systems, typically ion engines, is that they generate only small amounts of thrust. But I_{sp} is a measure of *efficiency,* not merely thrust. We can understand I_{sp} as the number of seconds an engine can produce its thrust from a given amount of propellant. That given amount of propellant is defined to be the weight of propellant equivalent to the force of thrust the rocket achieves.

To illustrate a specific example of I_{sp}, the Thiokol Star-37 solid rocket motor listed in Table 4.1 is rated at 76,500 N of thrust. This is equivalent to 7,800 kilograms of force,[8] which has the same magnitude as 7,800 kilograms of weight on Earth. The motor would produce its rated thrust for 306 seconds (its I_{sp} rating) in order to use up 7,800 kilograms of propellant. Keep in mind this is a hypothetical figure for reference purposes. The motor doesn't even contain that much propellant, and it only burns for forty-three seconds. The amount of propellant in the Star-37 solid rocket motor is 1,039 kilograms; note that $\frac{1039}{7800} \times 306$ s $\approx$ the motor's actual burn time.

Another useful measure is a rocket's *total impulse*. This is the total amount of integrated thrust that the system, including engine and its entire supply of propellant, can provide during its useful life. It is expressed in newton-seconds (see Figure 4.4).

Table 4.1. Comparison of selected rocket engine efficiencies by their I_{sp} values.

Engine	Vehicle	Propellant(s)	Thrust	I_{sp}, sec
Rocket Research TVA	*Voyager*	Hydrazine	0.9 N	200
Thiokol Star-37-E	*Voyager* IPU	Solid Al & NH_4ClO_4	76.5 kN	284
Kaiser-Marquardt R4-D	*Cassini*	MMH & N_2O_4	445 N	300
Aerojet LR 87	Titan III	Aerozine-50 & N_2O_4	1218 kN	302
Snecma Vulcain 2	Ariane 5	Liquid H_2 & O_2	1340 kN	434
P&W RL-10A-3	1977 Centaur	Liquid H_2 & O_2	109 kN	444
SSME	Space Shuttle	Liquid H_2 & O_2	0.09 N	453
Boeing NSTAR	*Dawn*	Xenon ions	0.09 N	3100

4.3 Interplanetary Travel Becomes Possible

Propulsion systems represent the truly enabling technology for departing Earth and reaching the other bodies in the solar system. Once astronomers began to unveil the real scales of distance in the solar system in the seventeenth century, it became obvious one could not depend upon an atmosphere to fly like a bird to the Moon and planets, or go there in a balloon. The daunting problem was clearly one of attaining the tremendous velocities necessary to enable travel among the planets. Such facets as telecommunications capabilities, electrical power, control mechanisms, and observational instruments were ancillary to the central problem of achieving high velocity. For example, the American rocket pioneer Robert H. Goddard (1882–1945), when he realized that technologies were becoming available to actually launch a rocket to the Moon, envisioned using just a few kilograms of flash powder[9] igniting on impact with the lunar surface so that visual observers on Earth could verify the success of the flight.

4.3.1 Nozzles

While earlier rockets were not efficient enough to accomplish a flight to lunar distance or beyond, what made it possible for the successors of Goddard and his contemporaries to actually reach the Moon and planets was the nozzle design adopted by Goddard and other experimenters. The nozzle is a component common to all chemical propulsion systems, whether a rocket is liquid- or solid-fueled.

As we have seen, propelling a vehicle to velocities high enough for interplanetary flight comes down to a propulsion system's ability to expel gas at high speed. The chemicals that react at high temperature and pressure within a rocket engine's combustion chamber are only a start; the nozzle's job is to best convert the combustion chamber's thermal energy into mechanical kinetic energy.

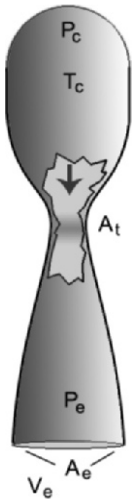

Fig. 4.2. de Laval nozzle. Gas goes supersonic at throat then expands. Notations discussed later in the text.

When the Swedish engineer and inventor Gustaf de Laval (1845–1913) was working on steam turbines, he wanted a means for directing high-speed steam into the buckets of an impulse turbine wheel. In 1897 he designed a nozzle whose diameter converged to a small throat and diverged into a wider bell. This convergent-divergent configuration constricted the out-flowing high-pressure steam until it reached the speed of sound, then let it expand again, producing an extremely high exit velocity.

The *de Laval nozzle* design applies directly to rocket engines. As shown in Figure 4.2, hot gas at temperature T_c exits the combustion chamber due to the high chamber pressure P_c created by combustion. As it is forced through a narrowing channel the gas velocity increases due to the venturi effect. The convergence is designed so that the gas goes supersonic at the throat, whose area is A_t. This is called a *choked* flow. As it travels farther into the expansion part of the nozzle its pressure and temperature decrease. This converts more thermal energy into kinetic energy, further increasing the speed of the exiting mass while its pressure decreases. Downstream of the throat, a long bell shape helps direct most of the exhaust gas into a straight line, minimizing non-axial motion and increasing axial thrust. Examining the *Magellan* 445 N thrusters shown in the previous chapter on page 107 reveals a typical rocket engine designed for operation in a vacuum with a narrow-throated nozzle leading from the combustion chamber into its long, widening exhaust bell.

As gasses heat and expand within the combustion chamber, they exert pressure on all its sides. Since they accelerate out through the nozzle, the result is a thrust in the opposite direction. The amount of thrust a rocket engine will produce in an airless environment is given by:

$$F = \dot{m}v_e + p_e A_e \tag{4.1}$$

where

F is the force of thrust. The newton is the SI unit,
$\dot{m}$ is the mass flow rate through the nozzle, kg/s
v_e is the exhaust gas exit velocity relative to the rocket, m/s,
p_e is the exhaust pressure at the nozzle exit, pascals, and
A_e is the area of the nozzle exit in m^2.

This equation, using notation seen in Figure 4.2, assumes that the exhaust is choked and reaches Mach 1.0 at the minimum cross-sectional area in the nozzle. Throat area directly affects the mass flow rate, and the exit velocity V_e for any given mass flow depends on the ratio of the throat's area A_t to the exit area A_e.

The $\dot{m}v_e$ term is the "momentum" portion of thrust resulting directly from accelerating mass. Since thrust is produced as the reaction to accelerating mass, why is there the added term $+p_e A_e$? This is because in the nozzle, the accelerated exhaust undergoes expansion that creates additional pressure across the nozzle's area. This "pressure thrust" provides some additional push.

If the rocket is operating within an atmosphere, the ambient atmospheric pressure P_0 must be subtracted from P_e. This means that nozzles designed for operation within an atmosphere, such as that of a first stage launch vehicle, will differ in shape from those designed solely for use in interplanetary space. For best efficiency, its length and exit area will be adapted to bring P_e close to the value of the ambient atmospheric pressure (even though this may seem counterintuitive from Equation 4.1).

4.4 Propulsion System Designs

Whether part of a launch vehicle or a spacecraft in interplanetary flight, the propulsion system responds to the vehicle's control computers and provides thrust on demand for accelerating the whole vehicle or applying torque to rotate it. This section looks at the range of propulsion systems in use today on interplanetary spacecraft including the solid- and liquid-propellant systems that are applications of *chemistry* and *chemical thermodynamics*. We'll also examine electrically powered systems which achieve notably better performance than chemical rockets but at lower thrust levels.[10]

4.4.1 Solid Rocket Motors

Solid-propellant rocket motors (SRMs) are perhaps the simplest propulsion systems. A mixture of fuel, oxidizer, and combustible binding agent, which do not react until they are ignited, are molded into a low-mass shell that is equipped with a nozzle. The propellant is fitted with ignition devices that respond to an electrical pulse to initiate burning. Like a firework, once ignited, the solid propellant continues burning until it is exhausted. There is no stopping it.[11]

Since SRMs provide all their impulse in one shot, they are used for one-time events such as the example described with *Voyager*'s IPU, giving a final kick to achieve an intended trajectory. The *Dawn* spacecraft, bound for the main asteroid belt, and the Mercury-orbiter *Messenger* spacecraft used a Star-48 for this purpose. The *Magellan* spacecraft carried the same Thiokol[12] motor on its fifteen-month trip to Venus, and ignited it at the right moment to obtain the ΔV to terminate its trajectory to Venus and enter into orbit about the planet. Earth-orbiting spacecraft, such as communications satellites, often use an SRM to transfer from low orbit to high geosynchronous orbit, or to circularize the orbit upon arrival at geosynchronous altitude.

The typical fuel in an SRM is aluminum powder and the typical oxidizer is ammonium perchlorate, NH_4ClO_4. Some formulations include powdered iron to serve as a catalyst. The well-mixed solid chemicals are typically held together by a rubbery polymer, called a hydroxy-terminated polybutadiene binder (HTPB). Together the mixture is known as an ammonium perchlorate composite propellant. Reference [5] discusses its physical and chemical combustion processes. Mixtures of this sort are commonly used in rocket motors ranging from hobbyist devices to the strap-on boosters for a variety of space launch vehicles, including the Titan, Ariane, Delta, and Space Shuttle. Ready-made SRMs for spacecraft can be obtained in many sizes. *Voyager* used a small SRM of 37 inches (94 cm) diameter which provided a nominal 76.5 kN average thrust during its forty-three-second burn, at an efficiency of $I_{sp} = 284$ s. The Ariane-5 launch vehicle's 3-meter diameter strap-on SRMs each provide 6,470 kN nominally for 130 seconds, at an efficiency close to that of the Star-37 with $I_{sp} = 275$ s. Solid rocket motors that hobbyists can buy achieve I_{sp} values comparable to these, even though they may have diameters only in the neighborhood of 2.5 cm and thrust ratings on the order of 10 N.

The solidified propellant in an SRM is molded with a cavity down the center that functions as the combustion chamber. Burning starts when an electrically fired igniter sprays flames into the chamber, then combustion proceeds to consume propellant radially outward to the motor case. The cavity's shape and surface area determines the rate at which the propellant mass burns and dictates how much of its thrust is generated as the burn proceeds. The frequently used Thiokol "Star" series, whose number designation indicates the motor's approximate diameter in inches, is named for the shape of its central cavity. A star shape, or more accurately an an asterisk shape with five radial spurs (see Figure 4.3), provides maximum thrust shortly after ignition that remains fairly constant throughout the burn, increasing slightly then decreasing just before

Fig. 4.3. Solid rocket motor cross section. Grey represents the solid propellant molded within the motor casing. The black star represents the cavity in the propellant that serves as combustion chamber.

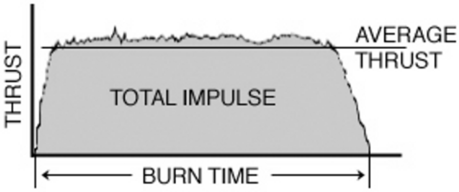

Fig. 4.4. This graph illustrates how one kind of solid rocket motor might achieve its rated (average) thrust, measured in newtons, quickly after ignition, then decrease to minimum thrust at propellant depletion. Its total impulse, expressed in newton-seconds, is the integral of thrust over time, shown as the area in grey.

burnout. This is roughly shown by the graph of thrust versus time in Figure 4.4, which is an artist's conception. In contrast, a cylindrical core gradually increases its thrust and achieves maximum force near the end of its burn.

SRM nozzles in small motors such as the Star-37 are often made of molded graphite. The larger Thiokol Star series motors have a nozzle whose throat is made of graphite fiber embedded in a carbon matrix, called 3-dimensional carbon-carbon. This material is stronger, stiffer, and lower in mass than any metals, and can withstand the 3,400 K temperatures and 4.5 MPa pressures (T_c and P_c in Figure 4.2) produced by combustion, values typical for a wide variety of SRMs. The Star motor case is titanium, and the de Laval nozzle is fitted with a carbon-phenolic exit cone. Other SRMs, such as the Space Shuttle boosters, may have cases made of steel. Advanced versions, made of lightweight composite of graphite fiber and epoxy, are called graphite-epoxy motors (GEMs).

Fig. 4.5. The Thiokol Star-48B Solid Rocket Motor is 48 inches (122 cm) in diameter. Image © ATK Launch Systems Group, reproduced by permission.

4.4.2 Liquid Monopropellant Systems

Compared to SRMs, liquid-propellant systems have the enormous advantage that the rocket engine can be shut down and restarted many times, as long as a propellant supply is available. Liquid-fed rockets are also more efficient. When a liquid turns to gas in an engine, its volume increases roughly a thousand-fold, and because it is heated, it expands even more, leading to high pressure in the combustion chamber. Of liquid-propellant rockets, there are monopropellant (single-chemical) and bipropellant (dual-chemical) systems. Monopropellant is the choice for a midrange-I_{sp} motor when simplicity is important, because this kind of system is only a little more complex than a solid rocket motor. Simplicity in a system can be a factor in achieving high reliability, and there are many spacecraft flying multi-year missions using monopropellant systems without failure.

When we speak of monopropellant systems for an interplanetary spacecraft, we'll assume the propellant is hydrazine, and exclude systems like the cold-nitrogen thrusters that the *Spitzer Space Telescope* uses for attitude control management. True, cold nitrogen is a single chemical, and it offers propulsion to torque a spacecraft, albeit at an I_{sp} under 70 s. But hydrazine undergoes explosive decomposition in its engine, giving an I_{sp} above 200 s, a value we'd expect from a rocket, though not quite as high as from an SRM, or from a bipropellant system as we'll see shortly.

The single liquid propellant chosen for a spacecraft application has to contain enough potential chemical energy to be effective without being too unstable to handle and store safely. Research in the 1950s and 1960s led to the conclusion that hydrazine is well suited for interplanetary craft. Hydrazine, N_2H_4, is derived[13] from ammonia, NH_3. It has an ammonia-like odor, and its density and freezing and boiling points are very close to those of water. Its utility in rocket engines stems primarily from its *enthalpy*, a measure related to the amount of energy a chemical reaction releases or absorbs[14] (in the case of rockets, we are interested in *exothermic* reactions which release energy).

Hydrazine's utility also includes its stability in long-term storage, the ease with which it can be brought to decompose, and the generally benign chemistry of its exhaust products. Finally, hydrazine-supplied propulsion systems are minimally susceptible to leakage because the fluid does not have to be stored under very high pressure to be effective, and the hydrazine molecule is large enough that the system's valves can reliably block its passage until needed.

When hydrazine decomposes in the presence of a catalyst, it breaks down into nitrogen and hydrogen while releasing energy. Additional chemical reactions may take place among the decomposition products including the production of and further reactions with ammonia, but the main exothermic chemical reaction is:

$$N_2H_4 \rightarrow N_2 + 2H_2 \tag{4.1}$$

wherein

one molecule of hydrazine splits into one molecule of nitrogen and two molecules of hydrogen, releasing thermal energy.

The energy released when hydrazine decomposes will raise the temperature in a small combustion chamber[15] upwards of 800 °C in a few milliseconds [6]. Adding to hydrazine's utility, the substance doesn't readily decompose upon contact with everyday materials and temperatures during handling. But it is toxic and it causes burns on the skin, so handling it requires protective clothing and care.

Compare this to the liquid monopropellant hydrogen peroxide, H_2O_2, which finds applications where humans may be exposed to the exhaust, such as with "rocket belts."[16] Hydrogen peroxide decomposes exothermically in the presence of a catalyst as follows:

$$2H_2O_2 \rightarrow 2H_2O + O_2 \tag{4.2}$$

wherein

two molecules of hydrogen peroxide split into two molecules of water and one molecule of oxygen, releasing thermal energy.

The exhaust products, steam and oxygen, exiting the rocket nozzle at around 1 km/s are relatively benign, and while hot, the nozzle does not produce a flame. The decomposition of hydrogen peroxide is not as highly exothermic as that of hydrazine, and will typically raise the temperature in a small combustion chamber to 650 °C or so. Concentrated H_2O_2 is tricky to transport and store, however, and it can violently decompose under a variety of circumstances that might be encountered if precautions are not taken.[17]

Contributing to the simplicity of monopropellant systems is the absence of any need to mix different chemicals in precise proportions for proper combustion, or the need for separate plumbing on the spacecraft for managing and isolating more than one chemical. But monopropellant systems do have more parts than SRMs, which have all their components integrated into a unit: propellant supply, combustion chamber, nozzle, and igniter. A liquid-fed system's components will be distributed about the spacecraft to a greater degree.

A tank holds the liquid propellant. Typically, the tank is pressurized by a head of gas to force propellant into the engine(s) without requiring any pumps. Many spacecraft simply operate their monopropellant system in *blowdown mode* in which the tank's internal pressure decreases with propellant usage. The *Voyager 1* and *Voyager 2* spacecraft are doing this right now. An effect of this mode is that the propellant flow rate to the engine(s) decreases over time, affecting the amount of thrust delivered (and to a lesser degree the engine's I_{sp} value). Alternatively, a spacecraft might be equipped with an additional tank holding a pressurant (gas such as nitrogen or the inert helium). In the *pressure-regulated mode* of operation, pressurant is admitted into the propellant tank to keep its pressure static and the propellant flow rate constant as the rocket burn continues. If available, this mode is typically used for specific, usually prolonged, rocket burns required to deliver a precisely determined ΔV, such as in an orbit insertion maneuver.

In either case, tubing ducts the propellant under pressure from the tank to thrusters or engines where a valve prevents entry into the combustion chamber until thrust is needed. The combined valve, combustion chamber, and nozzle is sometimes called a *thruster-valve assembly.* There are typically filters, pressure transducers, and other sensors incorporated along the way. Most spacecraft are equipped with a redundant set of plumbing and thrusters, each set supplied from the common propellant tank. If there is a failure in one set, the propulsion system can switch it off and use its twin. In redundant systems, pyro valves and additional plumbing components add to the parts count.

When thrust is called for, a command from the spacecraft's controller results in passing an electric current through a solenoid valve, whose electromagnetic coil pulls the valve open and holds it open for a duration that can be anywhere from fractions of a millisecond to a number of minutes. Hydrazine squirts into the combustion chamber in an amount that depends on such factors as the supply pressure and the valve-open time. Entering the chamber, the hydrazine encounters a permanently mounted catalyst — typically iridium — which has been deposited onto a high-surface area bed of supporting alumina (Al_2O_3) granules. The catalyst is usually pre-heated by a built-in electrical-resistance heater to around 180 °C to ensure the reaction starts and proceeds in a consistent manner, avoiding "cold starts," which can damage the catalyst bed.

4.4.3 Liquid Bipropellant Systems

Liquid bipropellant engines are more efficient than monopropellant systems, but they come with the cost of increased complexity [7]. Their higher I_{sp} (refer to Table 4.1 on page 125) is due to higher-energy chemical reactions producing more heat in the combustion chamber and higher exit velocities at their nozzles. We've looked at launch vehicles' bipropellant systems that burn hydrogen and oxygen and produce water vapor. They sustain this simple exothermic reaction:

$$2H_2 + O_2 \rightarrow 2H_2O \tag{4.3}$$

Their drawback is that it takes the most complex of rocket engines to employ the reaction efficiently enough for use in flight.[18] Turbine-driven pumps have to propel fuel and oxidizer into the combustion chamber at enormous rates. An ignition system must start the burning. Temperatures in the chamber reach above the boiling point of iron, so the combustion chamber and nozzle are designed with walls having internal ducts through which fuel is forced to flow, actively cooling these components before it is admitted, preheated, into the chamber. In contrast, propulsion systems that operate on interplanetary spacecraft having mission durations measured in months or years do not have the option to carry cryogenic propellants, even though they provide the highest available energies. For these spacecraft, other chemical reactants offer convenience for long-term onboard storage, and they release fair amounts of chemical energy in simpler engines that do not need to use ignition systems or pumps.

Robert Goddard knew that liquid bipropellants were capable of yielding the highest energies for rocket engines, and he used gasoline and liquid oxygen to achieve the world's first flight of a liquid-propellant rocket in 1926. Unfortunately Goddard did not receive recognition for his work and vision until after his death. In 1929, working independently, the German physicist Hermann Oberth (1894–1989), who self-published a book on rocket science [8] (it was originally his PhD thesis, rejected[19] as utopian), launched a liquid-propellant rocket with the help of his students, one of whom was Wernher von Braun (1912–1977). Later, Oberth worked with physicist von Braun to produce the German V-2 liquid-propelled rocket at Peenemunde. Subsequently Oberth found himself working for his ex-student on liquid-propelled space rockets in the United States, where von Braun's leadership

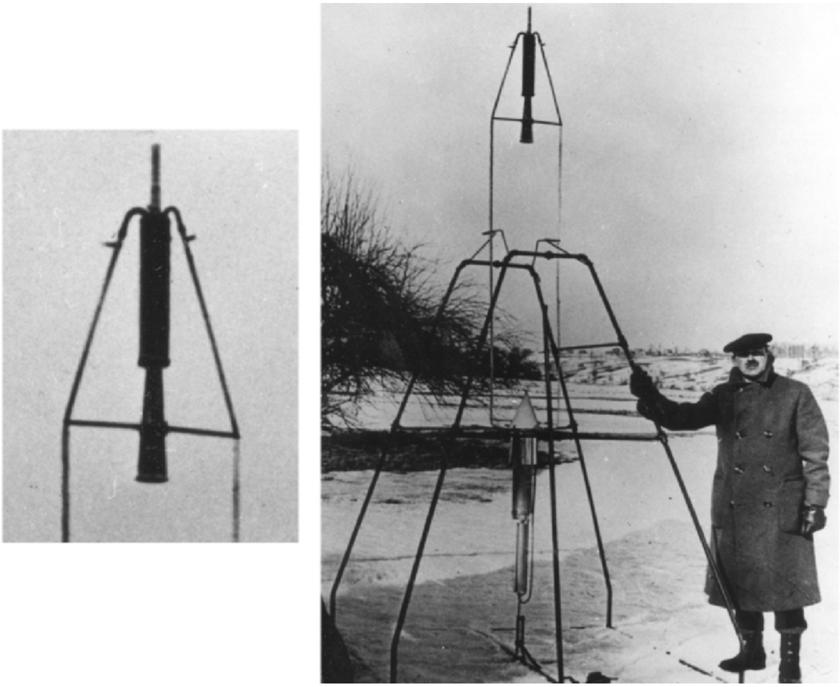

Fig. 4.6. Robert H. Goddard with his liquid-bipropellant rocket in its launch support frame. Detail (left) shows the combustion chamber and exhaust nozzle. For stability, the propellant tanks were mounted below the nozzle and capped with a cone for protection from the overhead exhaust plume. Adapted from image courtesy NASA.

gave America a multi-stage liquid-propelled Saturn V launch vehicle to take humans to the Moon.

The typical small-engine bipropellant system on an interplanetary spacecraft uses mono-methyl hydrazine, MMH ($CH_3N_2H_3$), for fuel and nitrogen tetroxide (NTO) (N_2O_4), for oxidizer.[20] These chemicals are called *hypergolic* because they ignite spontaneously on contact with one another. In general practice, slightly more MMH is introduced to the combustion chamber than the amount that would support ideal combustion, in order to make the mixture[21] slightly fuel-rich. This provides a more optimal exhaust molecular weight and improves nozzle performance and I_{sp}. The products of MMH-NTO combustion are many, and they vary according to conditions in the engine and the precise fuel-oxidizer ratio, but they include nitrogen, water, hydrogen, and carbon dioxide in a blue-white flame.

Figure 4.7 shows the skeleton of a bipropellant system one can typically find on a modern spacecraft such as *Cassini*, *Galileo*, *Messenger*, and many others. They're largely similar to the system with which the two *Viking* orbiters entered Mars orbit

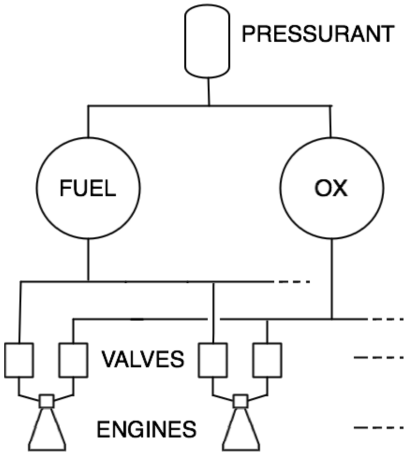

Fig. 4.7. A simplified schematic for a pressure-fed bipropellant spacecraft propulsion system. Many components along the pressurization and propellant lines have been left out for clarity.

in 1976 using MMH and NTO while cold nitrogen gas thrusters maintained control of the spacecraft attitude.[22] MMH fuel and NTO oxidizer are pressure-fed to the entrance of two electrically controlled valves on each engine or thruster (only one is shown in the figure, for clarity). When thrust is called for, an electrical current holds both valves open. MMH and NTO pass through orifices designed to maintain the desired flow rates for each chemical. Inside the combustion chamber the mixture ignites spontaneously without the aid of a catalyst. Chamber and nozzle begin to glow red- and then white-hot. They're typically made of a super-alloy of steel and niobium (also called columbium) metal that can withstand the high temperatures.

Figure 4.7 includes a pressurization system that has components common to both the fuel and oxidizer tanks. Additional components in the system (not illustrated in the figure) include valves to protect against any inadvertent mixing of fuel and oxidizer — even fumes allowed to mingle can burn and burst the lines open. *Mars Observer* provided a lesson on this subject.

Contact with the *Mars Observer* spacecraft was lost on August 21, 1993, three days before its scheduled arrival at Mars. Launched on September 25 the previous year, the spacecraft carried a dozen scientific instruments designed to report on the Martian topography, surface composition, and atmosphere, and seasonal changes on the red planet. The 980 million dollar mission was intended to send the first U.S. spacecraft to study Mars since the 1976 *Viking* missions.[23] In preparation for the Mars Orbit Insertion burn, plans called for propellant tank pressurization to ensure proper flow rates for MMH and NTO entering the 445 N bipropellant engine. Commands were sent to open valves to admit helium pressurant from the common source into both propellant tanks, but then communications were lost and never restored. The NASA review board found it most likely that upon operation of the valves, a small amount of hypergolic chemicals that had previously diffused upstream past check valves must have mixed and reacted violently within the propulsion system lines. A burst would have torqued and spun the spacecraft beyond the capability of its attitude control system to manage. Under such a condition the solar arrays would no longer provide power to operate the spacecraft or charge its batteries.

The remainder of components which for clarity are not shown in Figure 4.7 are in-line filters that prevent foreign matter from entering and jamming a valve or a thruster, check valves that prevent reverse flow of propellant or pressurant, shutoff valves, and filler ports. Also note that this illustration shows only one of two redundant systems of thrusters that are present on most spacecraft to hedge against failures. Temperature and pressure sensors are also installed at many locations among tanks and lines, and position sensors report on the state of every valve. All the valves are operable by command, one time each for pyro valves and multiple times for others. And as in every on-board system, telemetry from all the sensors goes to the spacecraft's information system for relay to the engineers' displays on Earth (see Figure 4.8).

FUEL TANK						
E-1708	FU	TANK	TF1	146	23.98	08-126T02:22:57
E-1706	FU	TANK	TF2	144	22.29	08-126T02:22:57
E-1701	FU	TANK	TF3	144	22.92	08-126T02:22:57
E-1908	FU	TANK	TF4	144	23.40	08-126T02:22:57
E-1906	FU	TANK	TF5	142	23.10	08-126T02:22:57
E-1901	FU	TANK	TF6	143	22.73	08-126T02:22:57
OXIDIZER TANK						
E-1735	OX	TANK	TO1	144	23.03	08-126T02:22:57
E-1733	OX	TANK	TO2	146	23.59	08-126T02:22:57
E-1928	OX	TANK	TO3	143	23.05	08-126T02:22:57
E-1935	OX	TANK	TO4	145	22.85	08-126T02:22:57
E-1933	OX	TANK	TO5	144	22.30	08-126T02:22:57
E-1728	OX	TANK	TO6	142	21.18	08-126T02:22:57

Fig. 4.8. Routine telemetry from the *Cassini* Spacecraft in Saturn orbit showing the temperatures of six sensors on the MMH fuel tank and six on the NTO oxidizer tank. The first columns identify engineering telemetry channel numbers and names (see page 38 in Chapter 1). The numbers in the 140s are *data numbers,* and the twenty-something numbers are *engineering units* in degrees C, followed by the time each measurement was received on Earth in year, day of year, hours, minutes, and seconds UTC. Courtesy Caltech/JPL/NASA

4.4.4 Tanks in Free-fall

Automobile fuel tanks depend on Earth's gravity to feed the engine, and so do the tanks in an aircraft unless it is certified for inverted flight. Without the benefit of gravity or a constant vehicle acceleration to keep a spacecraft's propellant at the bottom of its tank and the pressurized gas above, some other means must be employed to ensure propellant will drain into lines feeding the engines or thrusters.

One way to accomplish this is to include an internal flexible diaphragm across the middle of the tank. During pre-launch filling, propellant is introduced below the barrier and pressurizing gas such as helium or nitrogen is introduced above it. As propellant is demanded when a thruster fires, gas pressure squeezes it out somewhat like toothpaste from a tube. For tanks too large to accommodate this kind of bladder, pressurant gas mixes in with the propellant. To ensure that only propellant and not pressurant gas feeds from the tank when operating, a structure of vanes extends up from the bottom inside the tank to collect the liquid propellant via surface tension and "wick" it down toward the output port. This *propellant management device* is designed to provide enough propellant to allow the engine to start. Once the engine is firing and the craft is accelerating, propellant readily migrates downward to continue feeding the system, and the pressurant gas separates out above the propellant.

4.4.5 Dual Modes and Hybrids

Bipropellant propulsion systems can be designed to operate in two modes if hydrazine is selected as the fuel component. For example, the *Juno* spacecraft, planned to orbit Jupiter beginning in 2016, has a dual-mode propulsion system. It will operate in bipropellant mode burning hydrazine and N_2O_4 hypergolics in an engine designed for maneuvers requiring relatively large ΔV such as orbit insertion. It will operate in monopropellant mode by supplying hydrazine alone to small heated-catalyst thrusters for trajectory correction maneuvers and spin control.

Hybrid solid-fluid-propellant rocket engines use a solid propellant and a liquid or gaseous propellant. Control of the fluid component allows in-flight shutdown and restart. Some designs include an ignition system, and some are hypergolic. Hybrids are mentioned here for completeness, but they have not yet taken an appreciable role in interplanetary craft.

4.4.6 Electrical Propulsion

Some propulsion systems employ electrical rather than chemical energy to expel mass, and these typically produce the highest exit velocities and I_{sp} values yet achieved. Robert Goddard experimented with electrical propulsion components in 1906, and Hermann Oberth wrote on the subject in 1929 [8]. Three kinds of electric propulsion systems are in general use: electrostatic, electrothermal, and electromagnetic. To operate, all of them require electrical power supplies on the order of hundreds to thousands of watts.

Electric propulsion systems that have to date been used in interplanetary flight are the electrostatic variety. They obtain thrust by accelerating ions using high-voltage static electric charges. In these systems, called *ion engines,* neutral atoms of propellant from a tank of gas, typically xenon, are first stripped of one or more of their electrons (neutral xenon atoms have fifty-four electrons), making them subject to manipulation by magnetic and electric fields. This plasma is then focused by magnets into a beam and accelerated out the exit by exposure to a system of grids carrying high electrical potential. The result is a stream of heavy xenon

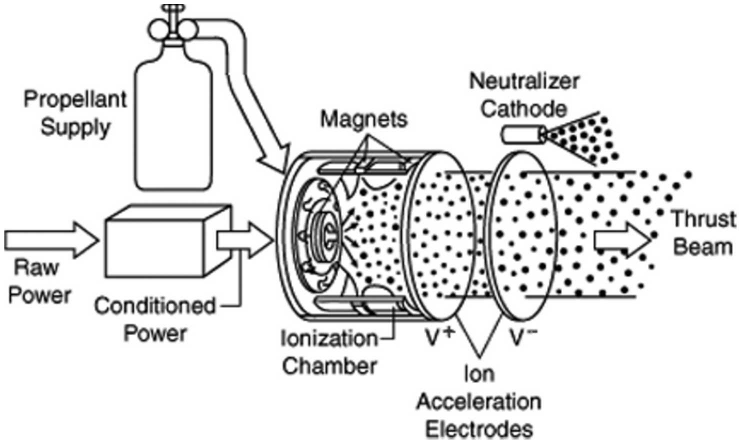

Fig. 4.9. A simplified schematic for an electrostatic ion engine in use on the *Dawn* spacecraft. Raw electrical power from solar photovoltaic panels is conditioned to the appropriate voltage and supplied to the engine. Xenon atoms from the 450-kilogram on-board gas supply are ionized, focused into a beam by magnets, and accelerated by electrodes or "grids" having high positive and negative electrical potential. An external cathode emits free electrons into the beam to neutralize the engine's electrical potential. Image courtesy NASA/JPL-Caltech.

ions out the exhaust at a v_e in the neighborhood of 35 km/s. Expulsion of all these positively charged particles would result in the engine, and the spacecraft, acquiring a negative charge which could interfere with the positive-ion exhaust stream, possibly attracting a cloud of them back to the vehicle. To counteract this effect an electron gun emits electrons back into the exhaust beam, keeping the spacecraft at a neutral charge. The noble gas xenon is a good choice for a propellant in an ion engine because it is mostly chemically inert, it is not radioactive, and its ions are more massive than those of any other inert, non-radioactive gas.

Ion engines have very high values for I_{sp} and total impulse but they only produce a small amount of thrust (see Table 4.1). This means they can only be effective in free-fall, operating continuously for long periods of time. The *Deep Space 1* spacecraft,[24] whose mission in 1998 through 2001 was to demonstrate a dozen engineering technologies in flight, operated its 0.09 N ion engine for 678 days — longer than any propulsion system had ever been continuously operated. In doing so, it used 74 kilograms of its 81.5-kilogram supply of on-board xenon propellant to give it a total ΔV of 4.3 km/s — greater than any spacecraft had yet achieved (excluding via gravity assist). With *Deep Space 1* having proven the technology in interplanetary flight, NASA launched the *Dawn* spacecraft in September 2007 on a ten-year science mission. The spacecraft is using ion engines that thrust continuously for years at a time. Reference [9] reports the specifics. *Dawn*'s task is to enter into orbit around the main-belt asteroid Vesta in 2011, then leave orbit, cruise to the asteroid Ceres, and orbit it in 2015 — all using ion thrust. The cruise from

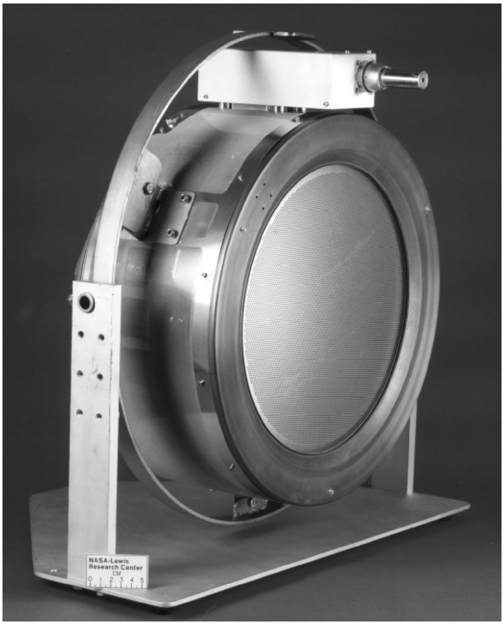

Fig. 4.10. An ion engine capable of 0.09 N thrust, three of which the *Dawn* spacecraft carries in the main asteroid belt. The high-speed ion exhaust issues from the circular grid, while electrons are expelled from the gun atop the engine. Image courtesy NASA/LRC.

Vesta to Ceres includes nearly continuous ion engine operation for just less than three years.

The Soviet space program developed ion engines that do not rely on electrically charged grids. Called Hall-effect[25] thrusters, their negative charge for accelerating ions comes from a plasma of electrons, conveniently making the exhaust electrically neutral. These have operated in Earth orbit, but not as yet on interplanetary spacecraft. These devices' I_{sp} values are comparable to grid-based ion engines but have the advantage that the technology does not involve grid erosion, and they may be developed to achieve even better performance.

For completeness we should recognize three other means of electric propulsion used on Earth-orbiters even though they have not been used in interplanetary flight. The resistojet and the arcjet are electrothermal devices; the magnetoplasmadynamic thruster is an electromagnetic device.

Resistojets use a heavy electric current to heat a resistive element[26] such as a wire to temperatures in excess of 2,000 °C. Propellant gas such as argon or nitrogen, or liquid such as water or hydrazine, is introduced to the high-temperature element in a "combustion" chamber where it greatly expands and exits through a convergent-divergent nozzle. Many commercial communications satellites use resistojets for station-keeping,[27] such as the Aerojet MR-501B which produces 360 mN of thrust with an I_{sp} near 300 s. Total impulse for resistojets can range on the order of 10^5 Ns.

Arcjets, another electrothermal system, work basically the same way as resistojets, but the heat source is an electrical arc (a spark), typically near 3,000 °C, which heats and ionizes the propellant, causing it to expand out the nozzle. Arcjet I_{sp} values can range from 500 s to 2,000 s depending on the propellant, and total impulse can exceed 10^6 Ns.

Electromagnetic thrusters depend on fully ionizing the propellant using an electric arc, after which it is capable of responding to a magnetic field. A magnetic field is created by the electric arc itself, and usually augmented by additional magnets in the engine. The use of magnetic fields to move plasma is reflected in the name magnetoplasmadynamic thrusters (MPD). The principle they employ was discovered to be useful in this application during the development of arcjet thrusters. When electrons move along a spark in a magnetic field, they are accelerated at 90° to the arc according to the Lorentz force,[28] providing the mass flow to obtain thrust. One variant of the MPD thruster, called the pulsed plasma thruster, uses a solid propellant that ablates and ionizes in the spark, typically in short bursts of low thrust measured in μN, useful perhaps for fine velocity adjustments of spacecraft flying in formation.

4.5 Basic Systems

Propulsion systems are fundamental to interplanetary flight. But additional systems, like telecommunications and attitude control, are to be found involved with every kind of interplanetary spacecraft. In the next chapter, we'll explore the other basic technologies making up the infrastructure with which an interplanetary craft provides support to its payload of scientific instruments. These include structure, electrical power, thermal control, computers, and mechanical devices. Our focus and nomenclature will change from viewing these as systems in their own right, to parts of the flight system that is the spacecraft.

Notes

[1] *Voyager*'s design took advantage of this extra width by incorporating a high-gain communications antenna 3.7 meters in diameter, as wide as the fairing would allow.

[2] Aerozine is a mixture of hydrazine, N_2H_4 and unsymmetrical dimethyl hydrazine, $C_2H_8N_2$.

[3] The Titan III-E expendable launch vehicle, the most powerful of its time, was produced by Lockheed-Martin. The two solid-rocket boosters were made by United Technologies, and the Centaur third stage was supplied by General Dynamics. The United States Air Force provided the launch facilities and services.

[4] A pyrotechnic device, ignited by an electrical jolt on command, burns solid chemical charges, creating pressure that forces a valve to operate. Once fired, the valve cannot be operated again.

[5] Jet engines found on airliners and business jets also drive fans that accelerate ambient air which bypasses the core jet exhaust, augmenting thrust and reducing noise.

[6]What is important is the temperature difference between its source and drain — the source being chemical activity within the combustion chamber, and the drain being the engine's environment into which the exhaust flows.

[7]In such cases, I_{sp} is expressed in newton-seconds per kilogram.

[8]Kilogram-force is not included in the International System of Units.

[9]In reference [10], Goddard describes experiments he conducted using Victor flash powder, which was a commercially available mixture of magnesium and other chemicals for use in photography.

[10]For completeness we should recognize that gravity-assist, which we visited in Chapter 3 (page 78), constitutes a propulsion system in a class separate from mass expulsion systems employing Newton's third law of motion. Powered by the primordial planetary motion in our solar system, gravity-assist propulsion can provide crucial quantities of $\varDelta$V without using any hardware on the spacecraft. It permits a spacecraft to carry less mass in its on-board propellant supply. Gravity assist is largely a *numeric* device employed during mission planning that depends on computational systems here on Earth as much as a rocket thruster relies on nozzle design.

[11]Hybrid solid-liquid rocket engines are an exception.

[12]Thiokol has been known as Morton-Thiolol Inc., ATK (Alliant Techsystems) Thiokol, and lately ATK Launch Systems Group. The name "Thiokol" was derived from the Greek *theio* ("sulphur") and *kola* ("glue"), alluding to the constituents and manufacture of solid propellant.

[13]Hydrazine can be made by combining two ammonia molecules by first removing one hydrogen atom from each.

[14]All substances possess stored potential energy in their inherent chemical (and nuclear) bonds. The substance's particles exhibit kinetic energy in the continuous motion of its particles. Enthalpy, symbol H, refers to the total, which for chemical reactions is often expressed in kilo-joules per mole, kJmol^{-1}.

[15]We'll call this part of the rocket engine the "combustion" chamber even though it is designed to contain decomposition rather than true combustion.

[16]See http://www.tecaeromex.com for information about rocket belts.

[17]The drug-store variety of hydrogen peroxide is typically a 3% solution in water, but bubbles of oxygen mark its decomposition when it comes in contact with the enzyme catalase in blood.

[18]For more information on examples of these sophisticated rocket engines, search the Internet for "vulcain engine" and "space shuttle main engine."

[19]Oberth was eventually awarded his PhD, based on the same paper, in Romania.

[20]In most cases a few percent of additional chemical such as nitric oxide (NO) is added to NTO to inhibit tank corrosion, and the mixture is called mixed oxides of nitrogen (MON).

[21]Mixture is generally expressed in propellant weight rather than volume.

[22]The *Viking* landers used hydrazine monopropellant systems to brake and control their descent.

[23]Two Soviet spacecraft, *Phobos 1* and *Phobos 2* launched in 1988. *Phobos 2* succeeded in orbiting Mars and collecting data until its failure in 1989.

[24]See http://nmp.nasa.gov/ds1

[25]The Hall effect refers to a difference in electrical potential on opposite sides of a conductor through which a current, created by a perpendicular magnetic field, is flowing. Named for Edwin Hall (1855–1938), who discovered it in 1879.

[26]A residential electric room heater typically uses resistive electrical heating.

[27]Station-keeping refers to the use of propulsion to make small changes in a geosynchronous orbit to remain on the planned location.

[28]The Lorentz force, named for the Dutch physicist Hendrik Lorentz (1853–1928), applies to charged particles moving in a magnetic field; they experience a force that is perpendicular to their velocity and the magnetic field. See http://en.wikipedia.org/wiki/Lorentz_force

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5 More Subsystems Onboard

Until now, we've looked into telecommunications, attitude control, and propulsion systems from a general point of view encompassing their components in flight as well as their components on Earth. The systems of telecommunications and navigation encompass parts of both the spacecraft and the Deep Space Network facilities worldwide. The propulsion system spans launch vehicle, upper stage or injection propulsion unit, and mission module. In this chapter our focus shifts to view flight components as *subsystems* on a spacecraft, which is seen as a flight *system.* For this purpose we define the spacecraft as the "mission module" part that operates in the vicinity of a target of interest after having jettisoned any ancillary modules.

5.0.1 Hierarchy

The spacecraft's operation and engineering team members speak, for example, of an attitude-control subsystem or a propulsion subsystem aboard the spacecraft (flight system). This hierarchy generally spans the following levels, although there may be considerable overlap in nomenclature between the two lowest levels:

1. System, e.g. flight system.
2. Subsystem, e.g. propulsion subsystem, telecommunications subsystem.
3. Assembly, e.g. propellant tank assembly, high-gain antenna assembly.
4. Subassembly, e.g. tank temperature sensor, X-band waveguide.

5.0.2 Spacecraft Bus

The core of an interplanetary spacecraft is usually called a *bus.* It is a mechanical housing including all vehicle subsystems mounted within or attached to it. Its purpose is to support a payload of scientific instruments reliably with everything they need:

- Mechanical load bearing and alignment.
- Delivery to target. This encompasses tracking, course corrections, and flybys or atmospheric entry, descent, and landing as applicable.
- Electrical power generation, storage if applicable, conditioning, and distribution.
- Aperture pointing. This is the attitude and articulation control subsystem's job.

– Uplinked command data, and
– Telemetry downlink. Both of these are provided by the telecommunications subsystem.
– Data storage, processing, and redundant backup as applicable.
– Protection from such threats as thermal extremes, dust, radio-frequency noise, stray electrical potentials, sunlight in camera, excessive accelerations, and galactic cosmic rays.

Engineers responsible for the spacecraft bus work on loosely aggregated teams in specific disciplines and interests. These may be the same people who designed, and tested pre-launch, the very subsystems they watch flying in interplanetary space. Generally one manager and one secretary provide leadership and support to the whole team, perhaps up to forty women and men. Often these engineers are also working on the design, assembly, and/or testing of different vehicles which are yet to launch, although they will always put aside their other projects when it comes time for a launch or a landing. Other teams on the project, or shared by many projects, handle navigation, planning, command preparation, real-time operations, and data management.

The people responsible for the instruments, for which the bus exists, are usually teams of scientists, typically led by a world-leading expert Principal Investigator (PI) working with graduate students and support staff. Many a PI may be found flying similar instruments on several spacecraft and perhaps carrying university-level teaching responsibilities at the same time.

The relationship between the engineers and their spacecraft bus on the one hand, and scientists and their instruments on the other, is not unlike the crew and passengers participating together on the voyage of an oceangoing research vessel. The vessel provides a platform, electrical power, data communications, and protection for the scientists' instrumentation, and carries them to targets they selected where they can carry out experiments and observations. And if one of the passengers were to suffer problems with an instrument, everyone aboard the ship would do their best to help work around the difficulty.

5.1 Electrical Power Subsystem

There are only three practical sources of electrical power in use today to run the computers, radios, motors, and other such devices on an interplanetary spacecraft: solar panels, batteries, and radioisotope thermoelectric generators. We'll visit each of these. Note that batteries can serve either as a pre-charged primary source of power for a spacecraft, or as a temporary storage device for a subsystem that generates power by using solar panels.

5.1.1 Voltage and Current

The *voltage* in an electric circuit is a measure of the difference in electrical potential between two points in a circuit.[1] It can be visualized by analogy as the water *pressure* in a residential plumbing system. Its SI unit, the "volt," is named after

The Italian physicist Alessandro Volta (1745–1827). Electric current is the measure of flow of electric charge in a conductor,[2] the SI unit for which is the *ampere* (commonly shortened to "amp"), named for the French physicist and mathematician André-Marie Ampère, André-Marie (1775–1836). In common usage, electric current is often called "amperage." As current flows through a material it usually encounters resistance. This is measured in the SI unit *ohm,* named after the German physicist Georg Simon Ohm (1789–1854), who discovered the relationship among voltage, current, and resistance and described it in 1827 in the expression we know as Ohm's Law:

$$V = IR \tag{5.1}$$

where V is the electrical potential measured in volts, I is the current measured in amperes, A, and R is resistance in the circuit measures in ohms, Ω.

The analogy with water flowing in pipes offers an intuitive grasp of Ohm's law. If water pressure increases, then the flow will increase given a constant resistance in the pipes. Increase the resistance, for example by narrowing a section of pipe, and the result will be lower current flow and a higher pressure difference that can be measured across the restriction.

There are two basic types of electrical current. *Direct current* (DC), is the constant flow in one direction through a circuit supplied, for example, by a battery or solar panel. Alternating current (AC), reverses direction periodically. In doing so, its associated magnetic field also alternates. This permits AC electric power to be easily transformed into higher or lower voltages as needed. It is produced by alternators to feed cities and towns, or by inverters that change DC into AC on a spacecraft. The frequency of alternation is expressed in hertz (Hz), as in, for example, the familiar 50 or 60 Hz residential service, or the 400 Hz power supply on an aircraft (recognizable by the high-pitched background hum in the cabin intercom).

The relationship between voltage, current, and power[3] is expressed as follows:

$$W = VI \tag{5.2}$$

where W is power measured in watts, V is circuit voltage, and I is the current measured in amperes, A.

Finally, connecting solar cells or the cells of a battery in *series* increases circuit voltage, and connecting them in *parallel* increases the available current. Series connection means the positive terminal of one cell is connected to the negative terminal of the next cell. Parallel connection means connecting all the positive terminals together and connecting all the negative terminals together.

5.1.2 Solar Panels

In 1905, Albert Einstein published a paper [4] which not only proposed the idea of *energy quanta,* but also explained the *photoelectric effect.*[4] Currently this effect is providing the means for his native country to convert sunlight into more than two terrawatt-hours of electric power per year for public consumption.[5] Nearly 40% more power is available from the Sun above the atmosphere than at the surface —

a total at all wavelengths of 1,371 W/m^2 in Earth orbit — so the photoelectric effect is also a prime source of electrical power for interplanetary spacecraft on missions conducted within the realm of the innermost four or five planets in our solar system. Devices that harness the effect, collecting the electrons that flow from an illuminated material to produce electric power are called *photovoltaic,* (PV). The *solar cell,* patented in 1946, is a PV device intended to use sunlight rather than some other source. A solar *panel* supports the cells as they face the Sun, contains the wiring which connects the cells electrically in collections of series and parallel circuits, and helps control the cells' temperature as we'll see later. See references [5] and [6] for complete information about space-qualified solar cells and panels respectively. Solar panel *arrays* [7], sometimes called "wings" because of their appearance, consist of multiple panels and deployment mechanisms.

Cell Technology

Messenger (Mercury), *Dawn* (asteroids), and *Juno* (Jupiter) are examples of the many interplanetary spacecraft designed to use arrays of photovoltaic cells to supply their electric power. Each cell is a flat section of a crystalline or polycrystalline semiconductor material such as silicon[6] fitted with electrical conductors. Crystalline gallium arsenide (GaAs) PV cells are more efficient than silicon (Si), and they perform better at higher temperatures, but are more expensive. The most efficient in converting energy from light to electrical power are multi-junction cells that respond to a wide spectrum of solar irradiation using thin layers of different materials, achieving upwards of 35% efficiency. These are also called "multi-bandgap" cells.[7] Adding optical elements to collect and concentrate sunlight onto the cells has been demonstrated to achieve 47% conversion efficiency. For comparison, the earliest Earth orbiters' silicon cells were about 6% efficient. In-flight experience with the *Magellan* spacecraft showed that its solar panels converted 7.3% of the incident solar energy into usable electrical power at the time it was beginning to orbit Venus. Table 5.1 compares the photovoltaics used by various spacecraft.

Table 5.1. Comparison of selected solar panels used in flight.

Spacecraft	Destination	Cell Material	Output	Articulation
Messenger	Mercury	GaAs/Ge	450 W	1 dof*
Mars Global Surveyor	Mars	Si & GaAs	1000 W	2 dof
Dawn†	Asteroids	InGaP/InGaAs/Ge	1300 W	1 dof
Venus Express	Venus	GaAs	1400 W	1 dof
Mars Odyssey	Mars	GaAs	1500 W	1 dof
Magellan	Venus	Si	1600 W	1 dof

GaAs = gallium arsenide; InGaP= indium-gallium phosphide; Si = silicon; Ge = germanium. Output listed is total from panels or arrays, measured at the distance from the Sun to the spacecraft's destination.
*dof = degree(s) of freedom in relation to spacecraft bus.
†*Dawn*'s solar arrays produced over 10 kW at a distance of 1 AU from the Sun.

Maximum Power Point

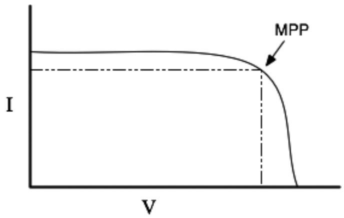

Fig. 5.1. A solar panel's maximum power point is calculated as the highest value of the product of I × V while they vary under changing conditions in flight.

Electronic circuitry on the spacecraft that regulates electrical power supplied from solar panels may include a *maximum power point,* (MPP) tracker. A solar panel's output voltage and current vary with the incident sunlight and with its temperature — note that the temperature may change substantially as a spacecraft enters and exits eclipse when orbiting a planet. The MPP is calculated as the product of current and voltage, and its maximum is seen as the largest-area rectangle within the current-voltage plot in Figure 5.1 at any moment while the values for current and voltage are changing. The MPP tracker samples a panel's voltage and current and uses this information to dynamically adjust the load so the maximum possible power is always obtained for a given amount of illumination. This capability can increase the useful output to be expected from a panel or array by a few percent and may result in reducing the mass of cells needed to be carried.

Degradation in Flight

There are a number of factors that act to degrade a solar panel's performance. Energy it receives from the Sun that is not converted into electricity is either reflected away or converted into heat, raising the cells' temperature. In general, as temperature rises, a solar cell can produce slightly more current but substantially less voltage, amounting to degradation of power output (this is where an MPP tracker can help). For silicon solar cells this temporary degradation is approximately half a percent for each degree Celsius of temperature rise. Gallium arsenide cells exhibit about half that amount.

Within a few hundred hours after initial deployment, a solar panel's performance may be expected to decrease by a percent or so, depending upon the type of cell, as a result of an initial "light-induced degradation" or "light soaking" which certain cell materials experience due to small-scale changes in chemistry. In addition, energetic particles from the Sun, including the solar wind and coronal mass ejections, can damage the crystalline structure of solar cells, further degrading their performance over the months and years. When the damaging particles of a solar coronal mass ejection strike a solar panel, degradation in the vicinity of a few percent may be seen almost immediately, although cells can recover perhaps 1% of their performance after a few weeks. At temperatures around 100 to 200 °C the crystalline structure is able to adjust itself to reduce some effects of radiation damage — a phenomenon called damage annealing. Electrical interconnections among the individual cells on a panel can fail in flight as a result of thermal cycling and mechanical stress, leading to more performance degradation. Diodes are included among a panel's

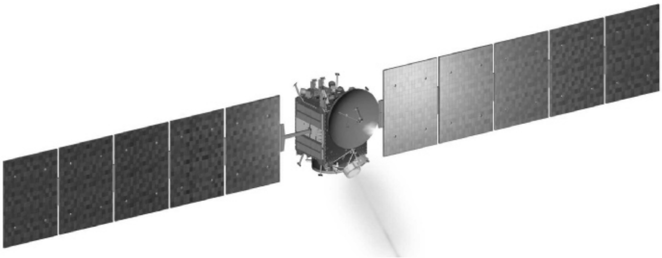

Fig. 5.2. The *Dawn* spacecraft uses ten solar panels configured in two arrays to supply power for operating in the main asteroid belt with ion engines. Image courtesy NASA.

interconnections for this reason, to prevent cutting off current from functional cells. Operating in Venus orbit from 1990 through 1994, *Magellan*'s solar panels suffered degradation of about two-thirds of their capability due to the factors mentioned here. The effects of such degradation must be taken into account when planning the photovoltaic capacity a spacecraft design will require.

Incidence vs. Output

Solar panels must face the Sun to produce power, and many spacecraft are able to articulate the panels in one or more degrees of freedom to obtain maximum power when needed by facing them normal to the sunline, or to point away somewhat when unneeded power production might result in absorbing or generating too much heat. Power output from a flat solar panel decreases in proportion to the cosine of its angle of incidence to the Sun. Note that some spin-stabilized spacecraft, such as *Lunar Prospector* [9] are designed with a cylindrical solar panel surrounding the bus. This kind of panel can produce only a fraction the output power of a flat panel facing the Sun, because only the patch of cells nearest the sub-solar line on the cylinder produce full power. Each of the other cells' output would fall off as the cosine of their individual sun-normal lines, for the most part, and half the panel's cells have no illumination at all.

In a flight system using solar panels, rechargeable batteries are employed in a secondary role to supply electrical power to the spacecraft prior to panel deployment, and temporarily while the spacecraft flies in eclipse through the shadow of a planet or other body, where the loss of light interrupts the PV supply of electricity.

5.1.3 Batteries

Batteries not only provide temporary electrical power storage on PV-powered spacecraft, but they can also serve as the *primary* source, supplying all the electrical power a spacecraft needs if it is on a short mission. In 1957 the first spacecraft, *Sputnik I*, operated a vacuum-tube-technology radio transmitter in Earth orbit. The primary batteries that kept it transmitting continuously for three weeks accounted for over a third of the spacecraft's 83.6-kilogram mass [10]. Other examples include the *Pioneer* Venus atmospheric probes which operated in 1978 [11], the *Galileo* atmospheric probe delivered to Jupiter in 1995 [12], and the *Huygens* atmospheric probe which today rests silently in moist sand on Saturn's moon Titan [13].

In General

Primary (single-use) batteries are designed to store their energy "on the shelf" before being used — sometimes for long periods — and then provide electrical current until depletion. *Secondary* batteries are designed with the ability to be charged, partly or fully discharged, and recharged again hundreds or thousands of times. Most batteries in common use have the ability to maintain a steady nominal voltage until near end of charge, at which time the voltage drops off rapidly under load.

Battery technology varies widely in chemistry and structure, but all battery designs draw from the branch of chemical science called *electrochemistry* to store energy in chemical form and release it as electrical current. Count Alessandro Volta published a description of his "voltaic pile" in 1800. This stack of alternating copper and zinc discs each separated by brine-soaked paper produced an electric current, and six years later the English chemist Humphry Davy (1778–1829) described the device's electrochemistry [14].

The word "battery" actually refers to grouped items of any kind. An electrical battery is a group of electrochemical cells connected together (in common usage a single cell is often called a battery, too). Each cell contains two electrodes — anode and cathode — made of a conductor of electrons such as a metal. Both electrodes are in contact with an electrolyte, a substance that conducts free ions. A solution of potassium hydroxide (KOH) in water is a widely used electrolyte. If two different electrolytic chemicals are used in a cell, they may be separated by a barrier of a salt that prevents mixing but conducts electrons.

The cathode is the positive terminal. Inside the cell, it receives electrons from the electrolyte in what is called a reduction reaction while the negative terminal, the anode, contributes electrons to the electrolyte in an oxidation reaction. In balance with this internal flow of ions, a useful electrical current flows through an external load connected across the electrodes until the battery's energy is depleted. It is the particular chemistry in a cell that determines its nominal output voltage, not its structure or its size. The area of its electrodes, though, determines the amount of current a cell can produce. Multiple cells are connected in series inside a battery to increase its voltage at a given current rating. The capacity of a battery to supply power is given in units of current and time — ampere-hours (Ah) — or power and time — watt-hours (Wh). A 1600 Wh battery can supply 400 W of power for four hours before it is depleted. If a rating is given in units of Ah, multiply it by the battery's nominal voltage to determine Wh.

Battery Comparisons

A useful figure of merit for comparing battery performance is *specific energy*, also called gravimetric energy density. It represents the ratio of the battery's power output capability to its mass. Expressed in J/kg, or more commonly Wh/kg, when reduced to basic SI units it becomes m^2/s^2. Like the value I_{sp} in the last chapter, specific energy is an *intensive quantity* whose value does not depend on the actual amounts of the properties which it describes; the amounts are only hypothetical. Since specific energy represents the energy per unit mass, comparing batteries' specific energy values shows how much mass a spacecraft has to be designed to carry in order to meet its battery power requirements. Table 5.2 compares the chemistries, applications, and specific energies of selected batteries.

Rechargeable Batteries

Any *rechargeable* battery serves its purpose because it has a high *cycle durability.* That is, it can be charged, discharged, and recharged many times. Consider the nickel-metal-hydride rechargeable batteries popular in the consumer market. They have high energy densities[8] but they also have high *self-discharge rates,* losing around 1% per day of their stored energy after charging, under no load (though improved versions are on the way). Self-discharge rates are not a concern with nickel-cadmium (NiCd) batteries, used historically on spacecraft and widely in consumer products, but they are more expensive, and their cadmium is toxic. NiCd batteries also exhibit a "memory" effect: when they are habitually only partially discharged before being recharged, they lose their ability to cycle deeply. This can be remedied in flight by an operational procedure called *reconditioning* in which the battery is intentionally brought to a deeply discharged state and then fully recharged. This procedure takes great care, and can interrupt normal operations for days at a time. Even better performing batteries are nickel-hydrogen (NiH_2), such as those carried by the *Hubble Space Telescope* and many interplanetary spacecraft. They have no such memory effect, and their performance and reliability are well proven. NiH_2 cells' internal pressure increases during use, so they are enclosed in a pressure canister to contain their H_2 gas. They are expensive, because they are manufactured only in low quantities almost exclusively for use on spacecraft.

5.1.4 RTGs

Radioisotope Thermoelectric Generators (RTGs), find application on journeys to distances from the Sun at which photovoltaic systems become impractical. For example *Voyager 1*'s range as of late 2008 is over 107 times the Sun-Earth distance where incident sunlight has only $(107^2)^{-1}$ the power it sheds here on Earth for a given collecting area. That's one part in 11,449 of the 1,371 W/m^2 useable here via photovoltaics[9] — hardly enough to power a clock. RTGs make it possible to conduct far-ranging interplanetary operations.

Heat Source

Different from reactors, which sustain fission chain reactions, RTGs operate in a passive mode and have no moving parts. They generate power by using heat produced by the natural decay of a radioisotope, an element with an unstable nucleus. RTGs begin producing power once they're assembled, and they cannot be shut off. Plutonium-238 (^{238}Pu) is typically the radioisotope heat-source used in

Table 5.2. Comparison of selected batteries listed in order of specific energy, Q.

Spacecraft	Nominal Chemistry	Application	Capacity	Q, Wh/kg
Huygens	$Li\text{-}SO_2$	Primary	1600 Wh	280
Various Earth-orbiters	Li-Polymer	Secondary	Various	180
Energizer Alkaline AA	$Zn\text{-}MnO_2$	Primary	4 Wh*	150
Venus Express	Li-Ion	Secondary	2000 Wh	120
Sputnik I	$Ag_2O\text{-}Zn$	Primary	2500 Wh*	90
Mars Recon Orbiter	Ni-MH	Secondary	150 Wh*	80
Mars Global Surveyor	$Ni\text{-}H_2$	Secondary	640 Wh	65
Magellan	Ni-Cd	Secondary	840 Wh	40
Consumer automotive	$Pb\text{-}H_2SO_4$	Secondary	2400 Wh*	35

$Li\text{-}SO_2$ = lithium-sulphur dioxide; Li-polymer cells employ a solid composite such as polyacrylonitrile; $Zn\text{-}MnO_2$ = zinc-manganese oxide; $Ag_2O\text{-}Zn$ = silver oxide-zinc; $Ni\text{-}H_2$ = nickel hydrogen; Li-Ion = lithium-ion; Ni-MH = nickel and the hydride of a complex alloy of various metals; NiH_2 = nickel hydrogen; Ni-Cd = nickel cadmium; $Pb\text{-}H_2SO_4$ = lead and sulphuric acid. Capacity listed is total for the spacecraft's complete set of batteries. Automotive and alkaline cells included for comparison; they are not used on spacecraft.
*Approximate value.

interplanetary flight, in the form of ceramic capsules containing plutonium dioxide (PuO_2). ^{238}Pu is created by synthesizing neptunium (^{237}Np) and irradiating it with neutrons. It has a half-life of 87.7 years[10] as it decays into uranium, then eventually to lead, so its effectiveness declines to $0.5^{1/87.7}$ of its utility per year, or about a 1% annual degradation.

Plutonium is a source of sociopolitical "heat" as well due to its extraordinary toxicity and the consequences were it to be dispersed in the biosphere. It is also argued that mining and processing raw materials to create the substance is hazardous. Reference [19] presents results of research on how people, groups, and communities respond to information about low-dose radiation exposure.

Flight Safety

^{238}Pu produces mostly alpha radiation (helium nuclei), which is effectively shielded by the RTG's case, and low levels of the more penetrating gamma and neutron radiation. RTGs are designed to contain their nuclear fuel in a range of launch and reentry accidents. The conditions of accidentally reentering the Earth's atmosphere at interplanetary speeds, such as during a gravity-assist flyby, are much different from those during launch. NASA missions proposing to use RTGs require environmental impact reports, safety analyses, safety review by an interagency panel (NASA, the U.S. Department of Energy and Department of Defense), and Presidential approval to launch.

Mission planners recognize that in the process of a gravity-assist flyby there may be failures on approach to Earth, for example in telecommunications and thus

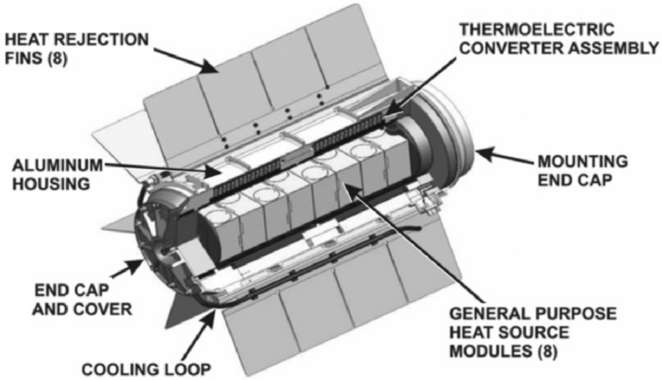

Fig. 5.3. Multi-mission radioisotope thermoelectric generator. Image courtesy NASA.

control of the spacecraft. The encounter is designed, therefore, so that such failures would result in a condition that poses minimal risk to humans regardless of its effects on the mission. The correct term for this category of design has unfortunately been so misused that a mistaken meaning has virtually become the default. *Fail-safe* does not mean "safe from failure." It means that the situation resulting from a failure is a safe one. The RTG-powered *Cassini* mission included an Earth-gravity-assist flyby that represents a good example of fail-safe design. *Cassini*'s aim-point on the Earth-approaching B plane (for example see Figure 2.8 on page 76) was never moved directly toward Earth. Instead, navigators only moved the aim point parallel to a line tangent to Earth's impact radius on the B plane. This way, a telecommunications failure would have had a safe outcome, avoiding Earth impact. In order to make this approach possible, the spacecraft carried extra propulsion-subsystem ΔV capability.

Seebeck Effect

RTGs use *thermocouples* to generate electrical power from their internal heat sources. A thermocouple consists of a junction of two dissimilar metals or other conductors. When there is a thermal gradient across the junction, i.e. one side hot and one side cooler, it produces a useful electric current. The major principle at work here is the Seebeck effect, named for the German-Estonian physicist Thomas Seebeck (1770–1831) who discovered in 1821 that a conductor with a temperature gradient across it generates a voltage. Thermocouples, or thermopiles which contain multiple thermocouples connected in series, are used in everyday applications. For example, gas-fueled residential furnaces are often designed with a small thermopile heated by the pilot flame. This arrangement provides electric power in the neighborhood of 650 mV with a current around 100 mA to operate the furnace's gas valve under control of a wall-mounted thermostat switch (note the fail-safe design: the gas valve shuts if the pilot fails to remain lit). Thermocouples used in RTGs are typically made of silicon-germanium junctions that can produce over 700 mV per degree Celsius of thermal gradient. The thermal gradient in an RTG spans the 700 °C internal heat source at one end of the junction and the exterior metal fins radiating heat into deep space on the other end. One RTG with its multiple thermocouples can typically produce up to 300 W of electrical power continuously for years. An RTG's output decreases predictably over time as its heat source decays.

5.1.5 Power Conditioning and Distribution

For electrical power to be delivered continuously and reliably to the other subsystems and the instruments it must be conditioned to meet their requirements. This involves the following:

1. DC supply regulation. The voltage generated by an electrical power source may vary, but a spacecraft's subsystems require well-regulated voltage and an ample supply of current. For example, a spacecraft's subsystems might require a supply of 30 VDC $\pm$ 0.5 V to operate correctly. So prior to distribution to the subsystems, a regulator circuit takes in the varying-voltage power from the source, typically a higher voltage than desired. The regulator outputs a steady voltage of the desired value and converts the excess electrical energy into heat. A radiator plate thermally coupled to the regulator disposes of the heat by emitting it into deep cold space.
2. Batteries (on some spacecraft). Once the power from a solar array has been regulated to the proper voltage, it connects to an electrical distribution bus (here a different meaning of "bus" than with "spacecraft bus") and to the secondary batteries. While solar power is available it charges the batteries and supplies the subsystems at the same time. In shadow when power production stops, the batteries seamlessly discharge into the distribution bus providing uninterrupted power (see Figure 5.4). Each battery connects not directly and permanently to the bus, but through protective fuses and controllable switches that can remove a battery from the bus if necessary.
3. Switching on command. Not all components on the spacecraft need to be powered on at all times. It is desirable to be able to switch things on and off. This can be done using either relays or solid-state devices. In either case the spacecraft's command computer sends a low-power signal to the device. In the case of a relay, the low-power signal energizes an electromagnet that operates larger contactors, connecting power from the distribution bus to the component being supplied. Typically, the relays are designed to latch and remain in the new state — on or off — after receiving a control signal. Solid-state switches perform the same function without using any moving mechanical parts, however they may be subject to spurious operation. The solid-state power switch on *Cassini* suffers hits from random galactic cosmic rays a few times per year, causing some of its switched outputs to trip (see page 9).
4. Circuit protection. Should a device on the spacecraft malfunction and begin drawing too much electrical power, a circuit-breaking device will interrupt the supply of electrical power to it. This can be accomplished with mechanical circuit breakers that trip based on the increased temperature resulting from an anomalously high current draw. Solid-state switches are designed to accomplish

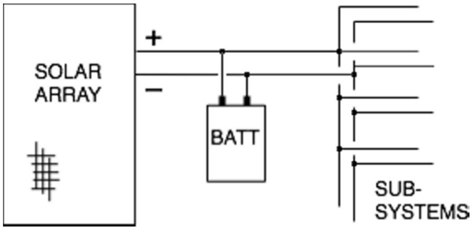

Fig. 5.4. Simplified electrical subsystem concept for a spacecraft with solar array. Regulators, fuses, switches, and redundant batteries are omitted to clarify how subsystems are seamlessly fed by solar or battery power. When solar power is available it charges the battery while at the same time feeding the subsystems. In the absence of sunlight the battery feeds the subsystems. In addition to multiple subsystem feeds shown, additional lines would extend to inverters, converters, and pyrotechnic capacitor banks.

this task without any mechanical components. Both mechanical and solid-state breakers provide a means to reset the interruption on command.

5. Inverters. The DC that solar arrays, batteries, and RTGs provide does not satisfy the needs of every subsystem or science instrument on the typical spacecraft. Some may need AC, so at least one of the switchable items supplied from the distribution bus may be an inverter to produce AC of a specified frequency and voltage for distribution to subsystems that require it. Modern solid-state inverters are efficient at changing a DC supply into an AC output, typically exceeding 90% conversion efficiency, the remainder showing up as waste heat.
6. Converters. While most subsystems may only require the nominal voltage present on the distribution bus (e.g. 30 VDC), some may require higher or lower DC voltage. A DC-DC converter meets this requirement.
7. Pyrotechnic initiation. Spacecraft use electro-explosive, or pyrotechnic, devices to operate single-use components such as propulsion-subsystem valves, parachute mortars, and exploding bolts. Initiating (firing) a pyrotechnic device takes a powerful jolt of current. Supplying such a jolt can cause an unacceptable drop in the distribution bus voltage beyond the regulator's ability to compensate, which might cause problems for other subsystems. Before firing a pyro, the electrical subsystem is commanded to gradually charge a bank of capacitors, which will then discharge rapidly to supply the needed spike of electric current to the pyro without affecting bus voltage.

As with other subsystems, almost every component in a spacecraft's electrical power subsystem has a duplicate that can take over in case its twin should fail. This usually includes solar panels, batteries, RTGs, regulators, switches and circuit protectors, inverters, and converters. Also as in other subsystems, measurements are made at many points in the electrical power subsystem to show voltage, current, and switch configurations in telemetry sent to Earth. Batteries on a spacecraft may be equipped with heaters, pressure-measuring transducers if appropriate, and temperature sensors. Figure 8 in reference [22] illustrates the complete *Cassini* electrical power subsystem.

5.1.6 Power Margin

For spacecraft such as *Voyager*, *Cassini*, and *New Horizons,* which do not carry secondary batteries that can accommodate excessive loads for limited periods, power consumption is constrained to remain below the available RTG output at all times. The difference between the amount of electrical power available on the spacecraft and the power required to operate its subsystems is called the *power margin.* On many spacecraft there is not enough power to operate everything at once, so instruments or subsystems have to be turned off at times, and certain operations that use high levels of power, such as the imaging radar on *Cassini*, have to be carefully planned. Attempting to draw more power than is available can trigger automated protective responses that can have undesirable consequences, so a power margin of at least several watts is usually maintained to guard against power transients and miscalculations. In late 2008 for example, the *Voyager 1* spacecraft is operating with a 37-watt power margin as it expends 245.7 watts to operate its subsystems and instruments. Any power generated but not used on a spacecraft is converted to heat in its regulator.

5.2 Structure Subsystem

A structure subsystem provides the skeleton — mechanical support and alignment for the spacecraft's other subsystems — while contributing a minimum amount of mass. This subsystem has mechanical attachment points for lifting the spacecraft during ground handling prior to launch, and for securing the spacecraft to the launch vehicle. The spacecraft bus is largely part of structure subsystem, although the term "bus" is also taken in a broader sense to include the other engineering subsystems.

5.2.1 Functions

During launch, the longitudinal acceleration forces on the spacecraft make its components much heavier than their normal weight on Earth's surface. At 7 *g*s, a 100-kilogram tank of propellant can exert a force of more than 6,800 N that the structure subsystem must support without failing. While transferring the spacecraft's entire load to the launch vehicle, it must prevent introducing an unacceptable amount of misalignment to components it supports such as propulsion subsystem thrusters, optical sensors and instruments, and communications antennas. In addition to the longitudinal acceleration during launch, there can be lateral forces reaching more than one *g*, plus acoustic vibrations that the structure must withstand without falling apart. Any components that exhibit vibrational resonances at the expected frequencies during launch must be modified or strengthened; the launch is one of the most mechanically stressful situations any spacecraft will experience.

Depending on the material used on various spacecraft, the structure may provide thermal conductivity to assist with temperature control, without deforming under thermal gradients or changes. Depending on the structure's material, it provides electrical conductivity to prevent stray potential charge buildup among the other subsystems, serving as an electrical "ground," or *equipotential ground plane.* Finally, a structure subsystem can shield equipment, to some measure, from micrometeoroids and radiation including high-energy particles encountered in interplanetary space, as well as radio frequency interference generated on board.

Fortunately, spacecraft structures do not have to comply with aerodynamic constraints (unless intended for atmospheric entry), and may be designed instead for optimal mechanical performance. The structure does, however, need to meet precise center-of-mass constraints for balance during launch, in addition to meeting requirements imposed by attitude control or propulsion subsystems.

5.2.2 Materials

The materials selected to make up a spacecraft structure are selected based on their properties of strength, stiffness, and resistance to stress, fracture, fatigue, and corrosion. Thermal expansion and thermal and electrical conductivity also need to be considered, as well as ease of manufacture and cost. Minimizing mass is an overarching concern, so lightweight materials find extensive use. Among the many choices available are the following examples:

- Aluminum and its alloys are widely used because they are lightweight, easy to machine, and easy to fasten.
- Magnesium and its alloys are used less frequently because of susceptibility to corrosion.
- Titanium and its alloys can be up to three times as strong as aluminum or magnesium, with only a modest increase in mass.
- Composites such as carbon-fiber-epoxy have around twice the strength and stiffness of titanium for a given mass, so these are becoming prolific in spacecraft structures (and also in many other applications ranging from aircraft to bicycles). Their thermal properties are excellent as well; they conduct heat better than many metals and have nearly ideal thermal expansion characteristics.

5.2.3 Components

Structure subsystems are arrangements of trusses, frames, monocoque or semi-monocoque surfaces or panels, and fasteners. Both trusses and frames distribute loads using a minimum number of discreet members. *Trusses* are often made of *struts* which have fittings at their ends for attaching them where needed. Struts are usually employed in pairs joined at an apex, forming a triangle to support a load. *Frames* are often made from a single piece of machined metal or molded material. *Monocoque,*, from the French for "single-shell," is a construction technique in which an object's skin supports structural loads. *Semi-monocoque* combines skin with bulkheads or ribs for added support, a technique widely used in aircraft. See Figure 5.6 for an example of trusses, monocoque panels on a frame, and semi-monocoque structures.

5.2.4 Examples

In the 1960s and 1970s a series of *Mariner* spacecraft incorporated hexagonal or octagonal bus designs of magnesium or aluminum alloy metal framework. Each side of the polygon bus consisted of an enclosed rack or *bay* holding a number of rectangular electronic circuit cards mounted parallel to one another, and other assemblies. Figure 5.5 illustrates this basic layout for the *Ranger 7* spacecraft sent to impact the Moon in 1964, a precursor to the *Mariner* structure design.

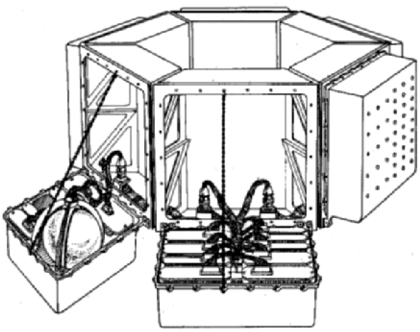

Fig. 5.5. Hexagonal bus design of the *Ranger 7* spacecraft. Courtesy NASA.

Voyager 1 and *Voyager 2* are *Mariner*-class spacecraft whose bus continues the polygon ring structure design with ten sides.[11] Each of the ten bays forming the two meter-diameter decagon is enclosed by two monocoque panels called *shear plates.* The inboard shear plates support electronic cabling coming from circuit boards within the bay and connecting among the other bays, and the outboard shear plates are either solid, or have openings covered by louvers for thermal control. Triangular arrangements of struts support *Voyager*'s large parabolic communications dish above the decagonal bus, and struts below attached the bus to the spacecraft's propulsion module which was jettisoned after launch. Additional trusses support *Voyager*'s three RTGs and a fiberglass instrument boom to the left of the bus as described on page 89, and science instruments are supported by a carbon-fiber trusswork boom on its right. This central polygon-ring structural design is common not only to the busses of *Voyager* and the many other *Mariner* spacecraft, but also houses the electronics on *Pioneer 10*, *Pioneer 11*, *Magellan*, *Galileo*, *Cassini* (see Figure 5.6), the *Hubble Space Telescope*, and the *Spitzer Space Telescope.* Figure 4 in reference [22] illustrates the complete *Cassini* structure subsystem.

In a departure from the polygon-ring structure, some spacecraft employ flat honeycomb-core panels that form a single rigid box to contain and support the spacecraft's components, sometimes including diagonal panels to maintain the structure's shape. The core structure of the *Dawn* spacecraft is a graphite composite cylinder with tanks of hydrazine and xenon propellant mounted inside. Flat panels for mounting *Dawn*'s other hardware are honeycomb aluminum core sandwiched between face sheets made of aluminum or composite materials (see Figure 5.1.2). Other spacecraft whose structures are made of flat panels include *Mars Global Surveyor*, *Stardust*, *Mars Express*, *Venus Express*, and many Earth-orbiting communications spacecraft. Solar panels are usually based upon a honeycomb design. When structural panels are made of electrically non-conductive materials, a conductive foil tape may be employed to ensure that electric charges are evenly distributed throughout the structure.

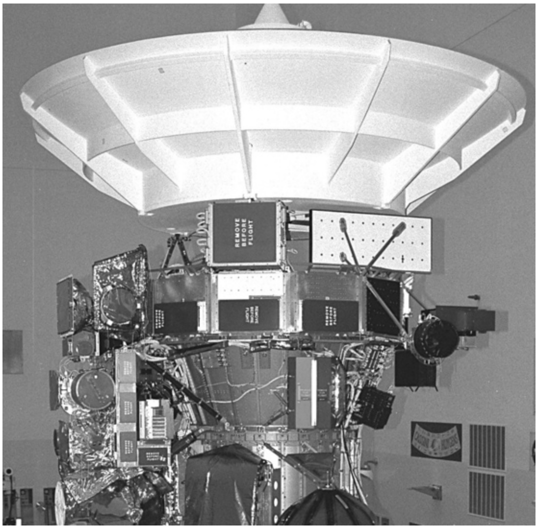

Fig. 5.6. Some of the outboard monocoque shear plates on *Cassini*'s octagonal-ring bus frame are visible across the middle of this image. Semi-monocoque structures include the HGA above, and the conical upper and cylindrical lower equipment modules below the bus. Graphite-epoxy struts with machined titanium end-fittings, arranged in triangles, support science instruments seen to the left and right, and a propellant tank at the bottom of the image. Image courtesy NASA/JPL.

5.2.5 Pre-Launch Structural Testing

In one stage of pre-launch testing, the assembled spacecraft is placed upon a shake table to subject it to modes of vibration that are expected during its ascent on the launch vehicle. Depending on the launch system, these might include random vibrations from 20 Hz through 2,000 Hz. On the shake table, a computer controls the amplitude of the random vibrations to simulate the launch, and accelerometers and other test sensors measure the spacecraft's response. Normally, individual components such as science instruments, attitude control sensors, and other assemblies will have already been subjected to vibration and mechanical shock testing to qualify them for flight. During the later whole-spacecraft vibration test, components such as these may be replaced on the spacecraft structure subsystem by non-functional objects duplicating the components' mass and shape. This is always the case with RTGs, which are mounted to the spacecraft just before launch. Another vibration test employs the use of huge loudspeaker arrays in a chamber to simulate the acoustic environment during launch. Acoustic noise might be expected to reach levels beyond 140 dB (100 W/m^2). Spin-stabilized spacecraft are also subjected to pre-launch dynamic spin balance testing.

During pre-launch testing in March 2000, NASA's *High Energy Solar Spectroscopic Imager* spacecraft suffered structural damage when the shake table at JPL was inadvertently allowed to produce ten times the intended 2-g level of vibrational acceleration. The cause was found to be the failure of a component in the shaker mechanism that had not been discovered before testing began. Following disassembly and repair, the spacecraft was launched successfully in February 2002.

5.3 Command and Telemetry Subsystem

The typical interplanetary spacecraft has two main sets of "brains" made of computer hardware and software. One is the redundant pair at the heart of attitude control, which we examined in Chapter 3. The other pair is usually considered the spacecraft's central computer. It is given various names on different spacecraft, such as Command and Data Subsystem (CDS), or Command and Data Handling subsystem (C&DH). To be generic, we'll call it the Command and Telemetry Subsystem (CTS). *Voyager* employs two separate computer pairs for the command and telemetry functions, called the Computer Command Subsystem and the Flight Data Subsystem, but more recently designed spacecraft combine the command and data functions, an example of which is *Cassini*'s CDS. It is interesting to note that the name of *Voyager*'s Computer Command Subsystem reveals the novelty, in the 1970s, of using a computer for storing and executing sequences of commands. Computers are ubiquitous on modern spacecraft, but this has not always been so. Over sixteen thousand individual commands were radioed in real time to *Pioneer 10*, and a similar number to *Pioneer 11* during their Jupiter flybys in 1973 and 1974. Each command was timed to the tenth of a second, accommodating the 46.n-minute light-speed propagation time so the spacecraft would receive and execute it exactly when needed to operate the instruments on board.

5.3.1 CTS Roles

This subsystem has the role of directing all the other subsystems' activities based on the individual commands or sequences of commands it receives from Earth. It stores commands that are to be executed at a future time, runs the spacecraft's clock, and executes stored commands at their designated times. It also collects, manages, processes, formats, and stores telemetry data to be sent back to Earth from all the subsystems and science instruments. Finally, CTS runs programs that constantly monitor the spacecraft's health status and invoke corrective actions when necessary. During flight operations, it is common to employ spare CTS hardware on the ground, running the same software that runs on the flight system, in order to test command sequences before uplinking them to the spacecraft.

5.3.2 Data Storage

When telemetry cannot be sent home in real time, for example if the high-gain antenna is not on Earth-point while the spacecraft's instruments are making observations, the data must be stored for later transmission. *Voyager*, *Magellan*, *Galileo*, and many other spacecraft were equipped with tape recorders to store telemetry data before transmitting to Earth. *Voyager*'s eight-track digital tape recorder, which has a capacity of about 100 Mbytes, records data at rates of up to 115.2 kilobits per second, and plays it back at any of a number of specific lower rates for transmission to Earth.

Tape recorders are electro-mechanical assemblies designed to operate in harsh conditions of temperature and radiation, as well as to survive the vibrations of launch. They are subject to failure. In 1990, one of *Magellan*'s two tape recorders was turned off after four months in Venus orbit due to a high error rate, and the backup recorder permitted the spacecraft to carry out the rest of its mission, as detailed in reference [23]. While *Galileo* approached Jupiter in 1995, its 109-Mbyte tape recorder exhibited problems that required a workaround (stopping and reversing tape movement before its end-of-reel was reached) for the rest of its mission in Jupiter orbit [24].

Cassini and the *Near-Earth Asteroid Rendezvous* spacecraft each carry two 2-Gbit solid-state data recorders which operate without any moving parts. They are however, susceptible to the passage of energetic particles such as the protons in the solar wind and coronal mass ejections, and cosmic ray particles, any of which can cause stored data bits to flip from 1 to 0 or vice-versa. Software routines running on board typically repair such corruptions in short order by virtue of the error-detection and correction (EDAC) bits within the stored data's packets.

In addition to storing bulk telemetry data for transmission, a data storage device may also be called upon to store backup copies of the executable software code that runs in all the spacecraft's computers.

5.3.3 Data Bus

Here is yet another use of the word "bus." The spacecraft's main computers transfer data between one other and among the other subsystems using a *serial data bus.* This may be understood as analogous to the network that connects computers and printers and servers in an office environment. *Cassini*'s computers, for example, use the MIL-STD-1553B data bus which was originally designed for aircraft control systems [25]. This standard defines the mechanical, electrical, and functional characteristics of a pair of wires carrying data at 1 Mbit per second. At each subsystem or instrument, a remote terminal called a *bus interface unit* manages the transfer of data in and out of the bus. All the components of this bus appear in duplicate on the spacecraft, to permit redundant availability in case of failure. Figure 12 in reference [22] illustrates the complete *Cassini* information subsystem.

5.3.4 Heater Control

Another function of a CTS is to help with spacecraft thermal control by automatically parsing input from selected temperature sensors and issuing commands to cycle electrically powered heaters on or off as appropriate.

5.3.5 Heartbeat

CTS makes sure that the main and peripheral computers aboard the spacecraft are alive by constantly checking up on them. One of the dual-redundant CTS computers is designated the prime, and the other the backup. The prime computer periodically sends out a signal across the data bus called a "heartbeat," typically about once per second. The backup might be designed to do this online as well. Each of the spacecraft's main computers, for example both of the dual redundant AACS and the backup CTS (and instruments, in many spacecraft designs), acknowledge the heartbeat indicating that they are all functioning properly. In the event a heartbeat is not acknowledged, the CTS software will take action based on its programmed rules. It may wait for another heartbeat to be acknowledged from the same subsystem and simply take note of the missed beat, meanwhile reporting the event to Earth. At some point it can take further action such as to direct the unresponsive computer to reset, or to swap to its backup. The heartbeat is akin to the application of a *watchdog timer,* a method widely used in other subsystems and instruments to detect the occurrence of a fault, as indicated by the absence of a normally expected action.

5.4 Fault Protection

Fault protection might be considered a subsystem in its own right even though it is "only" software code. It is a discipline expressed in routines that run on AACS, CTS, science instruments, and other subsystems, and it can affect the flight system as a whole. We'll examine some of its applications in this section.

Minor problems, those that develop slowly as revealed in telemetry, are typically managed by flight controllers observing the trend and sending commands from Earth to manage the situation. An example of this was seen in June 2008 on *Cassini* when the bus-interface unit serving the magnetometer instrument became balky and would not pass data to or from the instrument. Controllers sent commands to characterize and address the problem, eventually shutting off the instrument and powering it back on, restoring the bus interface unit's function. A similar problem occurred with Cassini's infrared spectrometer in November, 2008.

A malfunction of a time-critical nature, such as a hydrazine thruster valve jamming in the open state, perhaps due to a foreign particle lodging in the valve, cannot wait for humans on Earth to recognize the problem and respond. Such malfunctions must be detected, analyzed, and dealt with autonomously on board because light-speed alone can expand communication with controllers to hours, during which a fault might develop into a more serious failure compromising the mission. Autonomous fault protection comprises thousands of lines of sophisticated, thoroughly tested software code running onboard the spacecraft. Fault protection consists of *monitor* routines which watch for specific malfunctions, and *response* routines which address the detected malfunction based on programmed rules.

Many of the subsystems' computers, including the science instruments, run fault-protection monitor routines designed to recognize internal faults and invoke appropriate corrective actions. Often the corrective actions, or responses, are internal to the subsystem, for example a science instrument shutting itself off and turning on a replacement heater while the rest of the spacecraft continues operating nominally. But the appropriate response to some faults is to take steps to ensure the spacecraft's safety by requesting CTS to invoke "safing." Based on programmed rules and the immediate circumstances, the CTS can decide whether on not to comply.

5.4.1 Safing

Safing is a spacecraft state that the CTS imposes as a fault protection response which interrupts any sequence of normally ongoing commands. CTS issues commands that shut off non-essential electrical loads in order to maintain a positive power supply, and commands that turn on heaters if necessary to maintain a safe thermal state. Safing includes autonomously commanding AACS to rotate the spacecraft to a predetermined attitude that avoids letting sunlight fall on any sensitive instrument apertures or radiators, while keeping any solar panels illuminated. The safing configuration is often designed to have AACS switch from reaction wheel control (if applicable) to thruster control in order to reduce complexity and power consumption, and to ensure positive control of the spacecraft's attitude. On a spacecraft that uses beacon mode, CTS would configure the radio frequency subsystem to display the appropriate subcarrier based on the type of fault the spacecraft has experienced. Safing configures a state in which the spacecraft is commandable from Earth, keeping the appropriate antenna, such as the HGA, trained on Earth, and in some cases selecting a lower-than-normal command bit rate to improve the uplink telecommunications performance. Once the spacecraft is in safing, controllers on Earth take over to analyze the original fault(s) via telemetry, often sending commands to read out various parts of spacecraft memory related to the problem.

5.4.2 Fault-Tolerant Architecture

Fault protection begins with a spacecraft design that incorporates redundant subsystem or component hardware so that it can continue to function normally in case one of them fails in flight, making it *single-fault tolerant.* For example if AACS computer A should fail, AACS computer B would be available to take over. If propulsion thruster branch A were to fail, propulsion thruster branch B would be available.

In addition to such redundant availability of components, the ability to *cross-strap* offers an additional level of flexibility and improved single-fault tolerance. For example, CTS-A may have the ability to interface with either AACS-A or AACS-B, and each of these AACS subsystems would have the ability to interface with sun sensor A or sun sensor B, star scanner A or star scanner B, and with either thruster branch A or B, and so on.

Fault tolerance can mean some degradation in performance in case of some faults; for example, if multiple failures were to preclude the use of reaction wheels, then AACS could employ thruster control to manage the spacecraft's attitude. The degradation in this case would be in instrument or antenna pointing precision, since thruster control has by nature a coarser and more cyclic pointing capability than control under wheels.

The architecture of the mission itself might be fault-tolerant. The *Huygens* Doppler problem is a recent example of this. The *Huygens* probe's receivers are permanently installed aboard the *Cassini* orbiter spacecraft, and its transmitters are on the Titan atmospheric probe itself. During a test the European Space Agency carried out early in 2000, engineers found that the Doppler shift resulting from *Cassini*'s planned 5.6 kilometers per second closure rate during *Huygens*'s approximately three-hour mission would mean the receiver's bandwidth was too narrow to allow parsing telemetry symbols in the probe's equipment aboard *Cassini*. Receiver parameters had been frozen in hardware and firmware, so they could not be manipulated by command to solve the problem (this component was constrained not to have that level of fault tolerance). The solution was to redesign the early part of *Cassini*'s orbital tour of Saturn to reduce the closure rate. Instead of passing by Titan at 1,200 kilometers altitude during *Huygens*'s mission, the new altitude would be 60,000 kilometers, giving the *Huygens* communications path a much larger angle to *Cassini*'s incoming trajectory instead of being nearly in line with it. The signal's Doppler shift would be much smaller, and the receiver regained the ability to capture all of *Huygens*'s telemetry.

5.4.3 Fault-Protection Monitors

Fault-protection monitor routines sense input from engineering sensors on the spacecraft and register any deviation from the normally expected values from them. They are often simple algorithms consisting of relatively few lines of code, and unless intentionally disabled are called into action regularly, for example once every second. The Radio-Frequency-Loss monitor that sensed *Cassini*'s transmitter shutdown during the Iapetus encounter period (page 9) registered anomalous input from the primary X-band traveling-wave tube amplifier when its power was shut off anomalously. In all, *Cassini* has over 1,300 programs that handle fault detection, containment, and recovery [27].

Reference [28] lists fifty-four of the 130 separate rules (analogous to fault-protection monitor routines) that are running right now on the *New Horizons* spacecraft which is on its way to Pluto and the Kuiper Belt. Among the routines are the following, whose titles are fairly self-explanatory, listed here to offer a sense of the kinds of fault conditions being monitored on a typical spacecraft:

1. Unhealthy star tracker
2. Star tracker replacement heater failure
3. Loss of guidance and control processor heartbeat
4. Loss of science instrument heatbeat[12]
5. Unexpected C&DH processor reboot
6. Unhealthy MIL-STD-1553 data bus
7. Expiration of command-loss timer

8. Critical temperature too hot
9. Critical temperature too cold

The algorithm known as *command-loss* serves as a good example of the many fault-protection routines constantly running on most interplanetary spacecraft. Every time a command is received via the telecommunications subsystem and passed to the CTS, this algorithm resets a timer in its software or hardware to a default value — typically a number of days. The timer then counts down until another command is received. Should the timer decrement all the way to zero, it cues CTS to take pre-programmed action under the assumption that the spacecraft's telecommunications subsystem has failed, since no command data transmissions have been received from Earth. These actions can include turning off the spacecraft's radio receiver and swapping to a backup in an attempt to re-establish communications.

While the command-loss timer (CLT) can save a mission from failure in case of problems with the spacecraft's radio or command-detection capabilities, any hardware swapping due to *inadvertent* CLT expiration is something to be avoided (recall the nearly disastrous example with *Voyager 2*, page 42). In flight operations, the Ace normally sends at least one command to the spacecraft every time it is being tracked, just to reset the CLT. Many projects use a specific "command-loss timer reset" command that takes no other action on the spacecraft but to exercise its command-parsing routines, thus resetting the timer.

5.4.4 Fault-Protection Responses

When a fault-protection monitor routine registers the failure for which it has been watching, CTS responds, if it is in a mode in which response is appropriate, by issuing a series of pre-stored commands to appropriate subsystems. These commands are designed to address the fault, perhaps by switching one component off and switching on a backup component. It may also invoke spacecraft safing, which it will carry out only if it would be an appropriate response for the situation.

5.4.5 Critical Commands

In contrast with the routine, ongoing sequences of commands that a spacecraft's CTS executes day after day in normal operations, some command sequences are designated "critical." Commands in a critical sequence must execute so that the mission can proceed, and failure to execute a command in a critical sequence may spell mission failure. The command sequence that executes to place a spacecraft in orbit about its destination planet is an example. If some fault were to occur on the spacecraft while it is turning and firing its engine to achieve orbit, it would not serve the mission well if it were to quit executing commands and turn to a safe attitude. "Safing" at the wrong moment would not be safe at all. Typically when a critical sequence is running, both the prime and backup CTS computers operate together, executing the commands in parallel. If one of the computers should fail, the other would take over seamlessly. Any faults that occur somewhere on the spacecraft are noted, but no corrective action is taken until after the critical sequence has completed execution.

If any faults have occurred during critical sequence execution, information about the fault that has been stored is sometimes called an "egg." CTS will deal with any such eggs by executing stored commands prescribed to take care of the situation(s) after the critical sequence has completed, and the spacecraft is in a more normal state. As an example, the *Phoenix Lander* executed a critical sequence over the course of several minutes in May 2008 upon arrival above the north polar region of Mars to separate from its cruise stage, deploy its parachute, release its heat shield, deploy the landing legs, start radar altitude measurements, release the chute, and operate its hydrazine thrusters to right itself, touch down, and then deploy its solar panels. After the end of this critical sequence, the spacecraft's nominal sequence continued. It operated the onboard camera to confirm panel deployment, view a foot pad on soil, scan the horizon, and then transmit the images to Earth via the *Mars Reconnaissance Orbiter* passing overhead. Had there been any "eggs," such as from a component overheating on the way down, *Phoenix Lander*'s CTS would have executed appropriate fault-protection response actions before continuing to execute the nominal sequence. Operating the camera and transmitting images from its site on Mars would have had to wait.

5.4.6 Recovery from Safing

In its state of safing, no harm is expected to come to the spacecraft, but on the other hand it is not being productive. If reaction-wheel attitude control had been shut off as part of entry into safing, the recovery from safing will reduce propellant usage and the occurrence of random small ΔV that thruster control produces, possibly affecting navigation. The goal of recovery from safing is to resolve the original fault well enough to continue. Recovery is done by commanding the spacecraft to (1) reconfigure itself to its regular operational state, and (2) resume executing the nominal sequence of commands beginning at an appropriately selected point.

5.5 Thermal Control Subsystem

Here on the surface of Earth we know that a metal object can become hot enough in the summer sunshine to be painful to the touch. A solar panel trained on the Sun while orbiting Mercury can exceed 400 °C, while portions of the same spacecraft that are shaded from direct sunlight radiate their heat away and can easily reach –200 °C, colder than an Antarctic winter by a hundred degrees. Many of a spacecraft's components, such as computers, batteries, and other electronics, can only operate when in the neighborhood of room temperature, around 24 °C. Propellants such as hydrazine must be kept from freezing (0 °C), decomposition, or boiling (114 °C), and are normally kept between 10 °C and 50 °C on the spacecraft. In addition to absolute temperature limits, some of a spacecraft's components may also have constraints on thermal gradients — the amount of temperature change across a component which may cause misalignment in an optical device. Some components have thermal stability constraints — how much their temperatures are allowed to change.

A spacecraft's thermal control subsystem is responsible for maintaining temperatures on the spacecraft within ranges that allow normal operation and prevent damage to any of its components. In conjunction with the selection of structural materials, thermal control also takes into account the effects of thermal expansion and contraction that may affect alignment or balance of components. On the typical interplanetary spacecraft, cooling is entirely passive, using no pumps or electrically operated equipment such as refrigeration; heating is largely passive, but is often augmented with electrical or radioisotope heat sources.

Temperature control is also closely associated with the spacecraft's attitude control, especially for missions that take the spacecraft to the inner solar system. The *Cassini* spacecraft, for example, was required to face its high-gain antenna directly toward the Sun until it was beyond the orbit of Mars so that the dish could cast shadow over the rest of the spacecraft. The *Galileo* spacecraft operated under a similar constraint during its inner-solar system gravity-assist trajectory, as explained in reference [30], which is a complete account of the mission. *Messenger*, operating at Mercury, must keep its sunshade in the right orientation or suffer rapid mission failure.

5.5.1 Radiative Heat Transfer

Radiation is the significant mechanism by which heat is transferred to and from interplanetary spacecraft. The mechanism of conduction has significance among the spacecraft's internal components. The two remaining mechanisms familiar on Earth, convection and vaporization, generally find only sparse application among robots in deep space.

Radiation is the transmission of energy by electromagnetic waves (or photons. The term also applies to particle emission from radioactive substances). An object can both absorb electromagnetic energy — in this case heat — and radiate it. Surface properties such as color determine the amount the object will absorb and radiate. Consider:

α represents an object's absorptivity. In theory it varies from a value of 0 if it were to reflect all the energy that falls upon it, to 1 if it were to absorb all incident energy.

ε represents emissivity. A value of 0 means it would not emit any energy, and 1 means it emits perfectly.

Let's consider a hypothetical example: a flat aluminum plate facing perpendicular to the Sun's radiation in space at the distance of Earth from the Sun. Aluminum is known to have absorption value of 0.379 in sunlight ($\alpha_S = 0.379$). We can assume the plate, like a spacecraft, will radiate in the infrared (IR) — around 0.1 to 100 mm in wavelength — rather than at higher wavelengths such as light unless it is hot enough to be incandescent. Warm aluminum is known to have an IR emissivity of about 0.035 ($\varepsilon_{IR} = 0.035$). Just to keep it simple we'll assume the back of the plate is insulated and it does not absorb or emit any energy.

How hot will this metal plate become in sunlight? In time, its incoming and outgoing energy will balance as:

$$G_S \cdot \alpha_S = \varepsilon_{IR} \sigma T^4 \tag{5.1}$$

where

G_S is the incident solar energy. At the distance of Earth from the Sun, it has a value of $= 1371$ W/m^2.
σ is the Stefan-Boltzman constant 5.67x10^{-8} W/m^2/K^4 (K is temperature in kelvins), and
T is temperature in kelvins.

To solve for the plate's equilibrium temperature:

$$T_{eq} = \left(\frac{G_S \alpha_S}{\varepsilon_{IR} \sigma}\right)^{1/4} \tag{5.2}$$

$$T_{eq} = \left(\frac{1371 \; x \; 0.379}{0.035 \; x \; 5.67x10^{-8}}\right)^{1/4} \; = \; 715K \; = \; 442^\circ \; C \tag{5.3}$$

This hypothetical scenario serves to illustrate that a piece of bare metal can get pretty hot in sunlight.[13] A component on a spacecraft at such a high temperature could cause damage.

Let's change the hypothetical aluminum plate's energy balance by painting it white. Space-qualified white paint can have an $\alpha_S = 0.252$ and an $\varepsilon_{IR} = 0.853$. This would bring the plate's T_{EQ} to a more amenable 290 K or 17 °C. Table 5.3 lists various surfaces and their thermal performance.

Heating by radiation directly from the Sun may be a major contributor to a spacecraft's thermal state, but it is not the only source. Solar energy can come to a spacecraft indirectly by reflecting off a planet or other body, and a thermal engineer must take this into account. *Albedo* ("whiteness" in Latin) is the ratio of diffusely reflected sunlight to incident sunlight. Earth's albedo[14] of 0.29 means the object reflects 29% of the incident sunlight at all wavelengths. Venus's albedo is 0.75. For a spacecraft flying near a planet, the thermal input to the spacecraft's

Table 5.3. Selected surfaces and their thermal properties. In part from [31].

Material	α_S	ε_{IR}	T_{EQ}* K	°C
Aluminum (6061-T4)	0.379	0.035	715	442
Polished Aluminum	0.200	0.031	628	355
Steel (AM 350)	0.567	0.267	476	203
White enamel	0.252	0.853	290	17
Black paint	0.975	0.874	406	133
Aluminized teflon	0.163	0.800	264	–9
OSR†	0.077	0.790	220	–53

*T_{EQ} is assumed in space, 1371 W/m^2 incident, Earth's distance from Sun, back of surface insulated. †Optical Solar Reflector: mirror of quartz over silver.

energy balance will include the solar radiation coming from a planet's albedo, as well as the thermal radiation generated by the planet itself.

5.5.2 Heat Generation

Aside from solar heating, the thermal control subsystem must accommodate heat that is generated on board by components such as electronics, heaters, electric motors, batteries, and rocket engines. Many of these objects within the bus are painted black to more effectively radiate their heat and absorb it from one another, helping to even out the temperature within their areas of the bus. Most rocket engines on interplanetary craft cool themselves radiatively. During operation, combustion chambers and nozzles can, depending on the length of a burn, glow white-hot. Shielding on the spacecraft structure protects other components from their IR radiation, and it is their direct exposure to deep space alone that lets them achieve thermal equilibrium, then begin to cool down when the burn is complete.

5.5.3 Conductive Heat Transfer

Conduction transfers heat by molecular agitation within a material, without causing any transport of the material as a whole. Objects that are in mechanical contact with one another aboard the spacecraft transfer heat among themselves by conduction. Exterior surfaces heated by radiation that connect mechanically with internal components will transport heat inside. And components that generate their own heat, such as electronics, will also distribute their heat by conduction to mounting surfaces in addition to the radiative process described above.

5.5.4 Components

A thermal control subsystem must impart an overall α_S and ε_{IR} to a spacecraft to bring its temperature balance to a desired state given the solar radiation. In short, a spacecraft operating in the inner solar system needs to reject incoming solar radiation, and one operating in the outer solar system will be designed to absorb it. *Magellan*, the Venus orbiter, was white overall, as is *Messenger*, the Mercury orbiter. *Galileo*, the Jupiter orbiter, was mostly black, as are the *Voyagers*. In order to reach the outer solar system, however, a spacecraft may need to cruise past the inner planets for gravity assist, in which case it needs to be able to accommodate both situations. Aside from the overall spacecraft, many individual components need to address thermal balance locally while contributing to the flight system as a whole. The following thermal control subsystem components help the thermal engineer accomplish this goal.

Multi-Layer Insulation

When visitors first encounter a large scale model of the *Cassini* spacecraft, a frequent question is, "Why is it gold?" The spacecraft's jacket of multi-layer insulation (MLI) has an outer layer made of aluminized Kapton. The transparent film has an

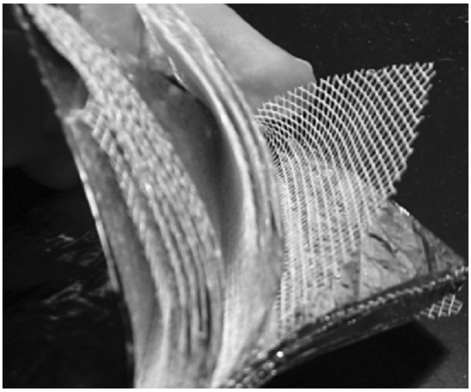

Fig. 5.7. Close-up of a patch of multi-layer insulation blanket material, viewed edge-on. MLI patch courtesy JPL/NASA.

amber tint, so the silvery-color vacuum-deposited aluminum on its backside gives the impression of metallic gold from the front. The high-performance polymide film Kapton is similar in appearance to nylon film, which is familiar in the form of aluminized helium-filled balloons.[15] *Cassini*'s MLI is typical of many applications on interplanetary spacecraft.

The first layer of back-side-aluminized 25 μ thick Kapton, reflects about 85% of the incident solar radiation; i.e. its α_S has a value of about 0.15. With an emissivity ε_{IR} of about 0.8, it radiates some of the remaining heat from both sides. That heat radiates across the next layer, a net made of Dacron about 50 μ thick, and encounters a layer of 7 μ thick Mylar polyester film aluminized on both sides. Again, most of the incoming heat is reflected, and the remainder absorbed and fractionally radiated across the next Dacron net spacer. The spacer net limits any transfer of heat via conduction through the blanket. This repeats for many layers, ending in an inside layer of aluminized Kapton. Kapton is sometimes used for all the layers instead of Mylar. All the layers are perforated with small circular holes every centimeter or so to prevent trapping gas and inflating like a balloon during ascent from Earth. *Cassini*'s MLI blankets have seventeen layers of thin film and sixteen Dacron net separators. At the distance of Saturn, *Cassini*'s MLI serves to keep *Cassini* from radiating too much IR.

MLI also serves for micrometeoroid protection. An incoming high-speed sub-millimeter-size particle will shatter, melt, vaporize, and/or ionize as it strikes, perhaps penetrating the outer layer. Subsequent layers absorb the cloud of debris before any damage can be done to spacecraft components. On some spacecraft, struts hold the MLI blankets several centimeters out away from the spacecraft structures to give enough room for the debris to disperse.

Where extreme heat resistance is required, ceramic cloth such as Nextel makes up at least the outer layer of MLI. This is the case with *Messenger*, as it was with *Magellan*. Section 8 in reference [22] describes the *Cassini* thermal control subsystem.

The Remarkable Optical Solar Reflector

When a spacecraft is designed to operate at or less than the distance of Venus to the Sun, its thermal control components will include optical solar reflectors (OSRs). The *Messenger* spacecraft's solar panels have two rows of OSRs alternating with each single row of solar cells (see Figure 5.8) in order to keep the panels' temperatures under control. Each OSR is a small square, on the order of a few centimeters on a side, fastened to a solar panel or other spacecraft surface with a thermally conductive adhesive. OSRs manipulate solar absorptivity α_S and infrared emissivity ε_{IR} in a unique and clever way. Polished metal typically exhibits a fairly desirable low α_S, but its ε_{IR} is also quite low. See Table 5.3. (The rule of thumb is: A poor reflector is a good emitter; a good reflector is a poor emitter.) An OSR consists of a thin transparent quartz plate with a layer of bright metal, usually silver, applied to its back surface. In this way it is very much like a household mirror whose glass is silvered on the back. These are called second-surface mirrors because the silver is the second surface that light strikes, after passing mostly through the first surface.[16] The trick is this: Light striking the quartz of an OSR reflects off a little, then it mostly encounters the bright metal where nearly all of it reflects back out. The metal absorbs little heat due to its low α_S. The quartz has a very high ε_{IR}, however, and being in conductive contact with the bright metal, radiates away copious infrared energy. The solar panel substrate is thermally conductive, so OSRs can cool the adjacent solar cells. The backs of *Messenger*'s solar panels are entirely covered in OSRs, as were *Magellan*'s.

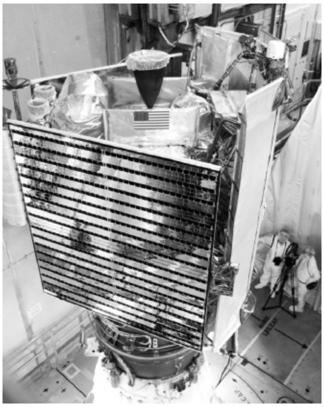

Fig. 5.8. Solar cells are in thin dark strips between bright Optical Solar Reflectors on the *Messenger* spacecraft's solar panel. Image courtesy NASA.

Shades

Many spacecraft hide from the sun behind shades. *Cassini* and *Galileo*, as mentioned, faced their high-gain antennas toward the Sun while in the inner solar system. *Cassini*'s rigid, white-painted HGA shaded the rest of the spacecraft (with the exception of the magnetometer boom extending eleven meters out into the sunlight, which has its own MLI for thermal protection). *Galileo*'s HGA deployment had not been attempted while in the inner solar system, and its mesh construction would not have provided useful shade anyway. It was equipped with large dedicated shades instead.

Where *Messenger* operates, the incident sunlight wields a whopping 15,000 W/m^2. *Messenger* carries a highly reflective, heat-resistant sunshade on a titanium frame. Roughly in the shape of a quarter cylinder and measuring about 2 × 2.5 meters, the thin MLI shade has front and back layers of white Nextel ceramic cloth surrounding multiple layers of Kapton. Temperatures on the shade's sunward side reach 370 °C, while the shaded spacecraft bus remains near 20 °C.

Heat Pipes

There's only one currently operating interplanetary spacecraft that carries heat pipes, which are devices containing a fluid that migrates and changes state to remove heat from within the bus and carry it to radiators. *Messenger*'s unique thermal requirements warranted carrying the additional complexity and mass of diode (one-way) heat pipes. One variation of a heat pipe is a sealed tube lined inside with a porous wick material and charged with a working fluid such as Freon. Heat inside the bus causes the pipe's internal fluid to evaporate and move to the cooler end where it condenses, thus transporting heat that is then radiated away. Heat pipes are classified as "passive" cooling systems, since they require no power to operate, other than the unwanted heat.

Louvers

Rectangular panels of louvers can be seen on the external surfaces of many spacecraft. These lightweight thermal control devices operate automatically, most of them requiring no electrical power or command signals. Resembling Venetian blinds, they open when bus-internal temperatures are on the high side, allowing IR to radiate away into space. They close when internal temperatures are cooler, reflecting IR back inside. Louvers are usually designed to operate using bimetallic strips, which curl and uncurl depending on temperature, in much the same way a mechanical residential thermostat operates.

Radioisotope Heater Units

In addition to electric heaters that operate under control of commands from CTS, many spacecraft are also equipped with radioisotope heater units (RHUs). These begin producing heat from the natural decay of a radioisotope when they are manufactured. They continue producing heat for decades and cannot be shut off. They use the same modular heat sources that power RTGs. Each RHU produces about one watt of heat and weighs about forty grams. Strategically placed within the bus or on structural extremities where needed, their heat is distributed by thermal conduction and IR radiation. Mars landers and rovers use a few RHUs inside their warm-electronics boxes; *Cassini* caries eighty-two of the units.

5.5.5 Atmospheric Entry

Entering a planet's atmosphere at interplanetary speeds presents a significant thermal problem, and this helps make the entry, descent and landing phase (EDL) an exciting part of a mission. A heat shield has to convert most of the spacecraft's speed (kinetic energy) into thermal energy (heat) while protecting the spacecraft lest it almost completely vaporize from atmospheric friction. Atmospheric-entry heat shields have a blunt shape to create a pressurized cushion of atmosphere that pushes the heated shock layer forward, away from the spacecraft, from where it flows back around and dissipates.

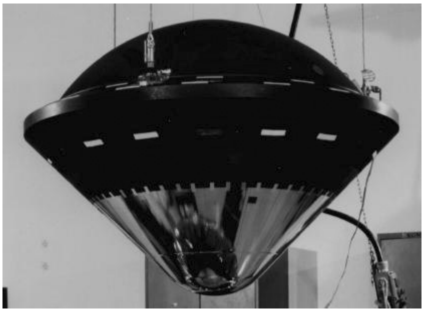

Fig. 5.9. The *Galileo* Atmospheric Probe measured Jupiter's upper atmosphere in 1995. Its heat shield's shape is optimized for Jupiter's dense, mostly H_2 atmosphere. Image courtesy NASA.

In 1951, the American engineers Harry Julian Allen (1910–1977) and Alfred J. Eggers, Jr. (1922–2006), while working for the U.S. National Advisory Committee for Aeronautics before it became NASA, made the discovery that a blunt, high-drag shape made the most effective atmospheric-(re)entry heat shield, because the heat it generated was inversely proportional to its coefficient of drag.

The leading surface of an atmospheric-entry heat shield typically has the shape of a spherical section, and the remainder is conical, with a backshell covering the enclosed payload. This *sphere-cone* shape provides a small amount of lift during entry, which can act to lengthen the vehicle's period of drag, reducing its peak force of deceleration. A system of parachutes and pyrotechnic devices separates the heat shield after use and removes the backshell to leave the payload exposed.

Even though most of the superheated gas remains out of direct contact with the shield as it enters an atmosphere at high speed, the shield must still be able to withstand an enormous amount of heat radiating onto it at close range. Atmospheric molecules in the shock preceding the heat shield are both dissociated (e.g. N_2 molecules split into two nitrogen atoms) and ionized (electrons stripped off) during entry. The ionization interferes with any radio transmissions from the spacecraft enough to disrupt communications.

A common heat shield design uses a substance that ablates — sublimates or pyrolizes (burns off) — creating a protective IR-opaque boundary that helps push the hot shock front forward and reduces radiative heating. The IR opacity is an important factor because the forward shock wave can reach enormous temperatures. The shock in front of *Galileo* reached 15,000 °C, but the shield itself saw a maximum of about 3,700 °C [33]. Similarly *Huygens*'s shock was in the neighborhood of 12,000 °C while the shield reached 1,200 °C. Ablative materials are usually dense, which means heat transfer by conduction causes a condition known as thermal soak. A heat shield needs to be ejected shortly after the temperature drops enough that pyrolysis ends, before too much heat is allowed to soak towards the

Table 5.4. Comparison of selected atmospheric entry heat shields, listed in order of maximum heat flux. Values are approximate.

Spacecraft	Destination	Shield Material	Max Heat Flux	Interface Speed
Galileo	Jupiter	Carbon phenolic	13.4 kW/cm^2	47.4 km/s
Stardust	Earth	PICA	1,200 W/cm^2	12.8 km/s
Genesis	Earth	Carbon-carbon	850 W/cm^2	11 km/s
Apollo 11	Earth	Fiberglass, elastomer	800 W/cm^2	11 km/s
*MSL**	Mars	SLA-561V	230 W/cm^2	6 km/s
Huygens	Titan	AQ60 Si Fiber-foam	200 W/cm^2	6.1 km/s
Phoenix	Mars	SLA-561V	56 W/cm^2	5.6 km/s
MER	Mars	SLA-561V	54 W/cm^2	5.7 km/s
Viking	Mars	SLA-561V	24 W/cm^2	4 km/s

SLA = Super Light weight Ablator, a proprietary substance made by Lockheed Martin.
PICA= Phenolic Impregnated Carbon Ablator.
*Mars Science Laboratory is currently planned for Mars landing in 2012.

back of the thermally-conductive shield and into the spacecraft. NASA designed the phenolic-impregnated carbon ablator (PICA), for the *Stardust* mission's return capsule containing cometary and interstellar dust. PICA is much less dense than the super lightweight ablator (SLA), that has been used on many Mars atmospheric entry and landing missions (see Table 5.4).

The *Galileo* atmospheric probe achieved a remarkable feat while falling into the massive planet Jupiter's upper atmosphere in 1995. Moving at 170,600 kilometers per hour relative to the hydrogen atmosphere, the 339-kilogram probe lost over one quarter of its mass as the heat shield ablated, reaching a peak temperature of 16,000 K, and experiencing forces up to 230 g during deceleration. For reference, note that the Sun's photosphere has a temperature of 5,800 K. The *Galileo* probe heat shield withstood about 25 kW/cm^2, as compared with 106 W/cm^2 for a Mars lander (heating is roughly proportional to the cube of atmospheric entry speed, depending on atmospheric properties). After completing its successful mission and returning telemetry to Earth via the *Galileo* Jupiter orbiter, the probe eventually broke apart and vaporized deep within the giant planet's interior where temperatures ultimately rise to perhaps 30,000 °C [30].

5.5.6 Thermal-Vacuum Testing

Prior to being shipped to the launch pad, a spacecraft is loaded into a chamber that can be evacuated and heated with Sun-simulating lamps to test its thermal design implementation. The spacecraft is typically powered up and operating, sending telemetry and responding to commands just as it will in flight. Thermal readouts are analyzed, while equipment and heaters are power-cycled in various appropriate conditions of heating. Heat radiating away from the spacecraft in the vacuum chamber is absorbed by liquid-nitrogen cooled chamber walls. While the *Cassini* spacecraft was undergoing its weeks of thermal-vacuum testing at JPL, a special liquid-helium-cooled panel was positioned to help test its set of optical instruments, which included sensitive infrared spectrometers and imagers. During this kind of extensive test, many of the spacecraft's materials undergo an initial out-gassing, after which high-voltage components can be turned on without experiencing electrical arcing. After removal from the test chamber, any necessary modifications to thermal blanketing, shades, or other components can be made prior to shipment to the launch site.

5.6 Mechanical Devices Subsystem

Due to the constraint imposed on a spacecraft's size by the launch vehicle's aerodynamic fairing, many parts of a spacecraft are stowed in a collapsed configuration and then deployed following separation from the launcher. Some ingenious devices have been developed to configure a spacecraft and its instruments post launch. Configuration changes may all be accomplished shortly after launch as was the case with *Voyager*, or they may take place in stages. The *Mars Global Surveyor* deployed its solar arrays after separating from the launch vehicle, then assumed slightly different configurations for interplanetary cruise, propulsive maneuvers, aerobraking, and subsequent orbital operations. In addition to the single-use deployment devices that we'll list and describe here, there are also devices that serve continuously, such as the commandable motors that operate with feedback control to manage solar array pointing, high-gain antenna articulation, and optical instrument aiming. This section describes a representative few of the single-use devices in the Mechanical Devices Subsystem that enable a spacecraft to change its configuration.

5.6.1 Release Devices

Most of a spacecraft's deployable components, such as solar panels and booms, are stowed under spring tension during launch. All that need be done is to release the few points holding the components back, and they will swing into deployed configuration on their own, often under the control of automatic rate-limiting devices.

A spacecraft that depends on solar power to operate will deploy its arrays shortly after launch while the secondary battery is supplying the vehicle's electrical power. Once the solar panels have been deployed and are supplying power, more time can then be taken to deploy the spacecraft's other components.

Explosive Bolts

One of the many pyrotechnic release devices found on spacecraft is commonly known as the explosive bolt. More properly, the devices are called *pyrotechnic fasteners.* In some applications it is the bolt that is frangible, but more often the frangible part of the fastener is the nut, also called an explosive nut. Spacecraft components that are to be separable on command, such as in a solar-panel release mechanism, may employ a regular bolt and a frangible nut such as the one depicted in Figure 5.10. These devices are available in a wide range of sizes and tensile strengths. The nut's large central threaded hole accepts the bolt, which is tightened to normal tension, holding the separable components together. Each of the two smaller holes in the nut is fitted with a pyrotechnic device that will explode on command. Upon firing both pyros, the nut breaks into two separate pieces, flying apart generally in the direction of the arrows in the figure and releasing the bolt, at which time the components previously held together are free to separate. A metal cup surrounding the nut prevents the pieces from causing damage.

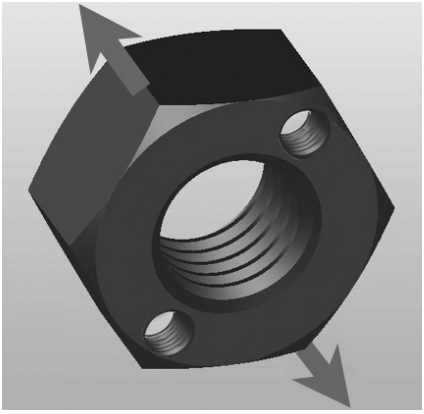

Fig. 5.10. Frangible nut.

Once the explosive nuts holding *Magellan*'s solar panels in their launch position were fired, a spring-loaded hinge was free to swing the panels up into their deployed positions extending out from the bus. *Voyager*'s RTG boom and science instrument boom were deployed in similar fashion, followed by the locking of a support strut below each boom to hold it in place.

The Guillotine

The *Dawn* spacecraft's solar array deployment represents another typical technique. Each of the *Dawn* spacecraft's solar arrays consist of five solar panels, as can be seen in Figure 5.1.2 on page 148. Each panel in an array connects to the next one with spring-loaded hinges. During launch, the panels of each array were folded into stacks on either side of the spacecraft. A single cable, passing through a hole in each panel, held all five panels of each array securely against the bus. When it came time to deploy the arrays, a pyrotechnically powered (dual-redundant) guillotine was fired. The explosive charge drove the blades through the cable, cutting it. The panels were all then free to swing open under the force of the spring-loaded hinges connecting them together, until they arrived at the dual-wing configuration for flight.

Spring-Loaded Hinges

Flight-qualified spring-loaded hinges for connecting and deploying solar panels are available with built-in micro-switches that provide a dual-redundant indication when the hinge has completed its movement and the panel is deployed. As the switches actuate, telemetry relays the fact to engineers on Earth. These hinges often include a damping mechanism to limit the force with which the panels are driven to their deployed position, and a latch to lock the panels in place once deployed.

5.6.2 Extensible Booms

As we'll see in the next chapter, some science instruments need to be held at a distance from the spacecraft bus in order to avoid picking up interference. Magnetometers, for example, must be free of strong magnetic fields on the bus so that they are free to characterize a planetary magnetic field. This is the case with *Voyager*, *Galileo*, *Cassini*, *Mars Odyssey*, *Lunar Prospector*, and many other spacecraft.

Twisting Fiberglass

The Astromast® is a fiberglass boom made of three longitudinal rods that run the length of the boom — thirteen meters, in *Voyager*'s case. The rods are held in a triangular cross-section by fiberglass trusses and diagonal filament struts, all fastened with flexible joints. The entire boom is collapsed by twisting it and laying it in coils into a small canister — *Voyager*'s was only about 70 centimeters in length. Deployment takes place in a controlled fashion by slowly letting out a central lanyard as the boom extends under the spring-force of its twisted fiberglass rods. The boom, and the instruments mounted to it, rotates as the boom deploys.

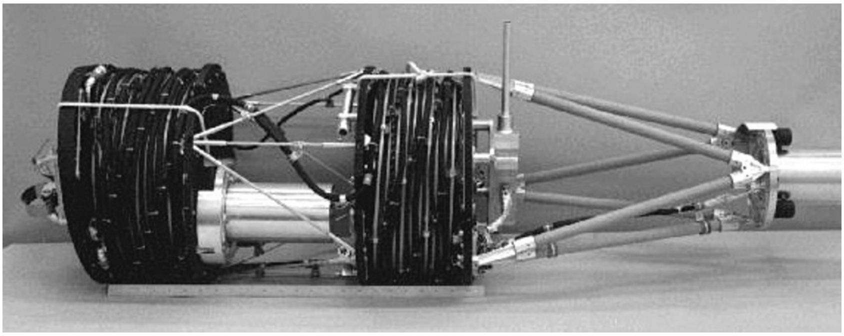

Fig. 5.11. *Galileo* magnetometer boom in collapsed configuration prior to being loaded into its canister and integrated with its deployment mechanism. The outboard magnetometer instrument is located at the far right of the image, and the inboard (mid-boom) magnetometer is at left of middle. This boom extended in flight to nine meters in length. Image courtesy NASA/JPL.

A potential source of error in the magnetometer instruments' measurements is the amount of twist in the long fiberglass magnetometer boom established after deployment. To compensate, a magnetic coil, which can be energized on command to create a magnetic field of known strength and orientation to calibrate the instruments, is mounted on the spacecraft

Shape-Memory Booms

Many spacecraft need to extend long narrow booms, typically to act as antennas for instruments that sense low-frequency radio waves or plasma waves that originate naturally in interplanetary space. The *Voyager* spacecraft each deployed two ten-meter-long antennas, and the *Cassini* spacecraft deployed three. They are made of a flat metal tape that resumes its "memorized" curl as it feeds out from a spool, very much like a carpenter's steel tape measure, but having a more pronounced curl. Sometimes two such tapes reel out simultaneously, engaging to form a hollow rod. A beryllium copper alloy is used for antennas, and stainless steel is used for structural elements.

The Foldable Flattenable Tube® can be envisioned by taking a plastic soda straw and folding it up, compressing it into a small rectangular volume, and watching it tend toward regaining its original shape when released. High-strain tubular composites can provide antenna or structural elements which deploy to twenty meters in length from a stowed volume of 0.02 m^3 weighing about a kilogram.

5.7 Science Instruments

From the point of view of an engineer responsible for the spacecraft bus or its subsystems, science instruments are seen as subsystems which can be commanded on or off, supplied with electrical power when on and supplemental heating when off, and which communicate over the data bus like any other subsystem. But these comprise the spacecraft's payload, designed by distinguished scientists and engineers to carry out sophisticated and sensitive observations to learn about nature. The designers have tailored their instruments to the spacecraft's stringent requirements of mass, electrical draw, data compatibility, temperature constraints, and structural integrity. They are the reason for flying the spacecraft.

Notes

[1]An electrical circuit is the path of electric current from a source, such as a battery, through conductors and components, and returning to the source in an unbroken loop. The current flow can be switched off by breaking the conductor at any point in the loop.

[2]The flow of electric charge includes electrons in a wire, ions in an electrolyte (fluid), and both ions and electrons in a plasma (ionized gas).

[3]Power is defined as the rate at which energy is transferred or at which work is performed, or the amount of energy expended for a period of time.

[4]The French physicist Alexandre-Edmond Becquerel (1820–1891) first noted the photoelectric effect in 1839.

[5]Two things should be noted when comparing space and terrestrial applications: (1) the air-mass coefficients zero and one, AM0 and AM1, are often mentioned when speaking of a system's efficiency. AM0 represents the solar spectrum outside Earth's atmosphere, and AM1 at Earth's surface; and (2) the oft-stated average 342 W/m^2 of solar power available at Earth's surface takes into account that half the planet is not illuminated, and that sunlight strikes the daylit surface at varying angles.

[6]In addition to a variety of crystalline cells, thin-film sheets of multi-junction amorphous silicon are found in many Earth-based PV systems, but these are not efficient enough for applications in space.

[7]Band gap refers to gaps between bands of electrons in the structure of atoms.

[8]High specific energy is of great interest in the field of renewable-source technology for Earth-bound automotive design.

[9]The most efficient photovoltaic cells in use on spacecraft to date convert to electric current at most 35% of the 1,371 W/m^2 insolation available at Earth orbit.

[10]This is a different isotope from the weapons-grade ^{239}Pu which has a half-life of 24,110 years.

[11]See scale models at http://SpacecraftKits.com

[12]The list includes one heartbeat-loss detector for each of six named science instruments.

[13]In actuality the metal's emissivity value increases at higher temperatures, bringing the equilibrium temperature lower than this value.

[14]There are two schemes of expressing albedo. Bond albedo values range from 0 to 1 as does reflectivity. Earth's is 0.29. The geometric albedo, of which Earth's is 0.367, is in reference to an idealized (Lambertian) disk, and its values can range higher than 1 due to the opposition effect (see page 195).

[15]Aluminized nylon-film balloons are sometimes referred to as aluminized Mylar.

[16]Optical instruments such as reflecting telescopes generally use first-surface mirrors in which the bright metal is applied to the top of the glass substrate. This arrangement prevents the "ghost" reflection which can be seen in second-surface mirrors, and does not subject any wavelengths of interest to absorption by the glass. It also allows the glass substrate to be thick and sturdy.

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6 Science Instruments and Experiments

By the beginning of the Space Age in 1957, astronomers had for centuries been developing increasingly powerful instruments with which to obtain views, images, and spectral information about the objects in interplanetary space and beyond. Foremost among these was the 200-inch diameter Hale Telescope atop Mt. Palomar in California, situated in the clear stable air above the most dense and turbulent parts of our atmosphere [1]. Its cameras and spectrometers have been evolving, since the telescope became operational (after thirteen years of mirror polishing) in 1949, to make best use of Hale's large aperture and precise focus. Today, it even has an *adaptive optics* system that uses a small deformable mirror to "un-twinkle" the objects it observes through the turbulent air, the better to learn about their nature.

Only six decades before Hale's first light, the Lick Observatory's 36-inch diameter refractor had become not only the world's largest telescope, but also the first mountaintop[1] observatory [2]. As it happened, the new science of spectroscopy was just beginning to offer astronomers the means to determine the temperatures and compositions of stars, and much more. The invention of photography followed on its heels, and a steady development of instrumentation and techniques for learning about our place in the universe has been gaining momentum ever since. Humans are by nature curious, and scientific inventions such as the telescope help satisfy our curiosity about the universe by attempting to explain the nature of our greater circumstance and predict its behavior.

Three and a half centuries after Galileo Galilei turned his homemade 30-power refracting telescope toward Jupiter and its moons, the space age suddenly provided the opportunity to place instruments entirely above our murky atmosphere, and up close to the very planets, natural satellites, asteroids, and comets that have been objects of interest and mystery since humans first looked upward. Carried by the *Mariners* and the *Voyagers*, vacuum-tube based television cameras began in the 1970s to outperform the 500-ton Hale telescope in obtaining close-up views of Mercury, Mars, and the miniature solar systems of the giant outer planets. Radar has mapped the cloud-hidden surface of our sister planet Venus. Space-borne instruments are examining solar-system objects and the larger universe in more parts of the spectrum than the early astronomers even dreamed existed. Said Charles F. Hall, project manager when *Pioneer 10* encountered the giant planet in 1973, "We are only twelve generations away from Galileo and his first crude look at the planet, yet now we are actually there, measuring the characteristics of the planet itself." [3]

Today, highly sensitive instruments of every description are reporting their findings to the scientists worldwide who design them, place them aboard the many craft flying deep in space, operate them, and analyze and publish their results, all to obtain pieces of the puzzles that address the big questions. These instruments, and the data they return, are the whole reason behind all the intricate steps involved in carrying out interplanetary missions.

In this chapter we'll first visit the big questions that interplanetary missions and their instruments seek to address. We'll see how science instruments aboard an interplanetary spacecraft go about acquiring data to answer these questions. We'll examine the major disciplines of imaging and spectrometry in detail, and then consider representative specimens of several kinds of instruments in these and other disciplines. After touching upon some special experiments that make use of unique opportunities in flight, we'll trace the path that science data follows from the instrument or experiment in interplanetary space all the way to the pages of the scientific and popular literature, to the public at large. The numerous citations in this chapter offer a sample of the enormous variety of scientific data being returned from interplanetary space.

6.1 Questions

Scientific questions to which NASA seeks to apply its resources and capabilities toward addressing are listed below (reproduced courtesy NASA Science Mission Directorate). They are general enough to represent similar lines of inquiry by other space agencies and institutions worldwide that prepare missions and instruments to address them.

> **Planets:** How did the sun's family of planets and minor bodies originate? How did the solar system evolve to its current diverse state? How did life begin and evolve on Earth, and has it evolved elsewhere in the Solar System? What are the characteristics of the Solar System that lead to the origins of life?
>
> **Astrophysics:** What are the origin, evolution and fate of the Universe? How do planets, stars, galaxies and cosmic structure come into being? When and how did the elements of life in the Universe arise? Is there life elsewhere?
>
> **Earth:** How is the Earth system changing? What are the primary forces acting on the Earth system? How does the Earth system respond to natural and human-induced changes? What are the consequences of change in the Earth system for human civilization? How will the Earth system change in the future?
>
> **Heliophysics:** How does solar variability affect human society, technology, and the habitability of planets? What are the hazards and resources in the Solar System environment that will affect the extension of human presence in space? How and why does the Sun vary and what are the consequences? What are the fundamental physical processes of the space environment?

6.2 Payload

Atop a launch vehicle, the *payload* is understood to be the spacecraft whose mission comprises the reason for buying the launch vehicle. A closer look at the spacecraft reveals it is composed of a bus along with its own payload: the equipment or instrumentation for which the spacecraft is flown. A communications satellite's payload is its transponders, which relay communications from one part of the Earth to another. The payload of an interplanetary spacecraft on a scientific mission is its scientific instruments, which help provide answers to some of the questions asked above.

6.3 Scientific Instruments

Most scientific investigations undertaken by an interplanetary spacecraft are done by means of instruments, such as cameras, spectrometers, magnetometers, and dust detectors, which we'll examine in this section. But some investigations, such as measurements of the mass of a planet or a moon, are carried out via experiments, some of which bypass the use of dedicated instruments, and those we'll visit in Section 6.4.

6.3.1 The Four Categories

Interplanetary spacecraft carry so many different kinds of scientific instruments that it may seem a difficult task to make sense of them all. But each can be understood by considering its basic principle of operation and where it fits among four broad categories of observation methods.[2] A useful first step in understanding a spacecraft's scientific instrument, then, is to determine which of the four categories properly characterize it. There are remote-sensing and direct-sensing instruments. Most are designed to operate in a passive mode, and some are designed to use active sensing.

Categories: (1) Remote / (2) Direct

Remote-sensing instruments obtain data about an object at a distance. Cameras form images of their targets, and spectrometers sort out and measure wavelengths of light coming from an object at a distance (which may often be less than an "astronomical" distance from the spacecraft).

Direct-sensing instruments measure properties of phenomena that make actual contact with the instrument. Magnetometers measure the magnetic field in the spacecraft's vicinity generated by a planet or the Sun, and dust detectors characterize particles that enter the detector, such as the dust in Saturn's ring plane.

Categories: (A) Active / (B) Passive

Both remote-sensing and direct-sensing instruments can be either active or passive by design:

Active-sensing instruments supply the energy needed to probe an object and then capture the response. An imaging radar instrument, for example, sends out pulses of radio energy that reflect back into the instrument from the target. An alpha-particle X-ray spectrometer (APXS), exposes its target, such as a rock that it touches, to energetic particles coming from a radioactive source within the instrument, then measures the X-rays that the target emits in response to being bombarded.

Passive-sensing instruments observe what's already there, without supplying any probing energy. This category includes remote-sensing cameras and spectrometers, and direct-sensing dust detectors and magnetometers.

Table 6.1. The Four Broad Categories of Instruments with examples.

	(1) Remote	(2) Direct
(A) Active	Example: Radar	Example: TEGA*
(B) Passive	Example: Camera	Example: Magnetometer

*TEGA is the Thermal and Evolved Gas Analyzer on the *Phoenix Mars Lander*. It is a high-temperature furnace and mass spectrometer being used to analyze Martian ice and soil samples delivered to it by the lander's robotic shovel.

Where does active end and passive begin? If a camera or other optical sensor provides its own illumination — as did an instrument aboard the *Huygens* Probe as it neared Titan's dimly-lit surface — should it be categorized as an active instrument? Perhaps such an instrument could also function without providing illumination, though not as efficiently. Could a camera be called "active" because its electronics would not function without a supply of electrical power? Distinctions such as these four categories may lose their usefulness at some point, though they are generally helpful in most cases. Where does direct end and remote begin? Consider the nephlometer that descended below a parachute in December 1978, measuring the particles suspended in Venus's dense, hot CO_2 atmosphere. Because the probe was descending *through* the clouds it was measuring, one might call it a direct, *in-situ* measurement. But the nephlometer was separated from the cloud particles by a two-centimeter-diameter window made of three-millimeter-thick sapphire in the probe's pressure-sealed titanium hull, so it was sensing the particles remotely. An instrument that pulls in samples of atmosphere to analyze, as did the gas-chromatograph-mass-spectrometer aboard the same *Pioneer* Venus probe, would be categorized as making direct measurements *in-situ*. Incidentally, because the nephlometer could not have functioned without its pulsed gallium arsenide laser diode to illuminate the cloud particles, it qualifies as an active-sensing instrument.

6.3.2 The Questions and the Instruments

The payload an interplanetary spacecraft carries is selected to address the objectives deemed important for the mission. These objectives respond directly to questions, or aspects of questions, such as ones we visited in Section 6.1. Every instrument or experimental capability on board has specific purposes according to the mission's objectives. To illustrate this point, let us look at *Cassini*'s objectives with regard to Titan. This category is one of five for the mission, which also include the planet, the rings, the magnetosphere, and the other moons. The seven specific Titan objectives are listed below, and Table 6.2 indicates which instruments in *Cassini*'s payload apply to these objectives. Radio science addresses all seven objectives, but it is not listed in the table of instruments because it is really more an experimental capability than an instrument, as we'll see later on. The *Huygens Probe*, which *Cassini* carried to Titan, is a spacecraft in its own right with its own payload of instruments to address a whole set of complementary questions. Of the objectives listed, *Huygens* addresses all but number 6. *Cassini*'s Titan objectives were as follows:

1. Determine the most abundant elements, and most likely scenarios for the formation and evolution of Titan and its atmosphere.
2. Determine the relative amounts of different components of the atmosphere.
3. Observe vertical and horizontal distribution of trace gasses; investigate energy sources for atmospheric chemistry; determine the effects of sunlight on chemicals in the stratosphere; study formation and composition of aerosols.
4. Measure winds and global temperatures; investigate cloud physics, general circulation and seasonal effects in Titan's atmosphere; search for lightning.
5. Determine the physical state, topography and composition of Titan's surface; characterize its internal structure.
6. Investigate Titan's upper atmosphere, its ionization and its role as a source of neutral and ionized material for the magnetosphere of Saturn.
7. Determine whether Titan's surface is liquid or solid, analyze the evidence of a bright continent as indicated in *Hubble Space Telescope* images taken in 1994.

Table 6.2. Instruments on the *Cassini* Spacecraft which address the mission's seven scientific objectives for Titan. Objectives of an instrument not in the table, CDA, do not include Titan.

#	CAPS	CIRS	INMS	ISS	MAG	MIMI	RDR	RPWS	UVIS	VIMS
1	•	•	•			•			•	•
2	•	•	•	•		•			•	•
3		•		•				•	•	•
4		•		•				•	•	•
5							•			
6	•		•		•	•		•	•	
7							•			

CAPS: *Cassini* plasma spectrometer; CDA: cosmic dust analyzer; CIRS: composite IR spectrometer; INMS: ion and neutral mass spectrometer; ISS: imaging science system; MAG: magnetometer; MIMI: magnetospheric imaging instrument; RDR: radar; RPWS: radio and plasma wave science; RSS: radio science system; UVIS: UV imaging spectrograph; VIMS: visible and IR mapping spectrometer.

We could repeat the process of mapping mission objectives to the payload of six instruments on *Huygens*, and we could do the same for any of hundreds of spacecraft. Instead, the reader may extrapolate the way questions and objectives are addressed by instruments from the single example presented above, adapted from information courtesy NASA/JPL-Caltech.

6.3.3 Imaging Science Instruments

Almost every interplanetary spacecraft carries an imaging device — a camera or other imager — for making scientific observations. Images are also very popular in the media, so most interplanetary missions, recognizing their ultimate ownership by the citizens and worldwide community who support them financially, waste no time making "raw" images available to the public as quickly as possible.[3] Later, the mission's imaging science teams process the images to extract scientific data for analysis and subsequent inclusion in formal publications. *Juno*, due to launch in 2011 and arrive in Jupiter orbit five years later, is unique in many ways. It will be the first interplanetary spacecraft to carry a camera primarily for the purpose of public interest (*Juno*'s main scientific tasks in Jupiter polar orbit are to be non-visual).

Imaging science spans quantum theory, photon sensors, and the design of optics and subsystem hardware, and it includes the design of sophisticated software tools with advanced graphics capabilities. These software tools, which run on commonly available hardware and operating systems, are put to use extracting scientific data from images, and for planning instrument pointing and exposure settings to take advantage of the often unique observational opportunities offered by a mission's navigation and science planning teams.[4] In interpreting image content, imaging science branches out into planetary geology, atmospheric fluid dynamics, astronautics and orbital dynamics, and astrophysics. Among the many discoveries of note that have been made by imaging science in our "backyard" of the Solar System are:

- Active volcanism continuously resurfacing Jupiter's moon Io;
- Ancient flooding on Mars;
- Water geysers confirmed originating in deep crevasses on Saturn's moon Enceladus;
- The cratering history of planets, moons, and other objects indicating the relative ages of their surfaces;
- Nitrogen geysers on Neptune's moon Triton;
- Newly found outer-planet satellites.
- Exquisite structure and dynamics in Saturn's ring system.

Optical Cameras

Optical cameras are passive remote-sensing instruments. Appendix B has two examples.

The optics in a camera-type imaging instrument focus light onto a plane where an image detector is located. They achieve specific light-gathering capability, magnification, and field of view for the instrument. Baffles and shades built into the optics keep out unwanted stray light. Additional optical components in most imaging instruments include selectable filters and operable shutters.

Filters reject unwanted wavelengths or polarizations of light while admitting those desired for a particular observation. *Galileo*'s and *Voyager*'s imaging instruments were equipped with eight-position filter wheels which could be commanded to rotate and place any single filter in the light path. *Cassini*'s narrow-angle imaging instrument has two overlapping filter wheels with a total of twenty-four filters providing as many as one hundred useful filtering combinations. Different filters are useful for various imaging functions including measuring atmospheres, penetrating haze, viewing surfaces, and searching for lightning.

Shutters in the optics interrupt light from reaching the image detector until an image is to be taken. Shutters on some spacecraft, including *Voyager*, *Galileo*, and *Cassini*, use mechanical devices which move shades across an opening in an opaque plate. Electronic shutters, used on the *Mars Reconnaissance Orbiter* spacecraft's Mars Color Imager instrument (MARCI), as well as some new cameras on the consumer market, incorporate a liquid crystal that changes from opaque to transparent when voltage is applied to the material.

Refracting Optics A lens bends light by refraction as it passes among the media of air or vacuum and glass because light propagates through glass and other transparent solids at a lower speed than it propagates in vacuum or air. The varying incidence angle across a convex lens's surface, and its varying thickness, serve to bend all the light rays toward points on the focal plane. The difference in propagation speed is expressed as a material's *index of refraction.* The refracting telescope, or *refractor*, which employs lenses to focus light from a larger aperture to a smaller image, is one choice for the optics on a spacecraft.

The oldest known lenses to be manufactured were probably used to produce burning by concentrating sunlight, as mentioned in *Clouds*, a Greek play dated to 423 BCE [8]. It's easy to demonstrate how a lens provides a simple imaging system by holding a magnifying glass in front of a plain white sheet of paper and observing the image of any source of light, such as a window, which forms on the paper. When the lens is just the right distance from the paper all the source's details become visible in the image: the Venetian blinds; the shrubs outside the window.

The multiple-element primary lens in the telescope on *Voyager*'s wide-angle camera, at six centimeters diameter, is probably smaller than the typical magnifying glass. Its focal plane is 200 millimeters behind the first lens element in the front of the telescope. The telescope's lenses are carefully designed to correct for various errors in image replication[5] that are obvious with a magnifying glass such as distorted or out-of-focus edges, and color aberration.

Reflecting Optics The reflecting telescope is the choice for larger-aperture optics in a spacecraft's imaging instrument, mostly because large lenses are massive, and supporting them reliably by their edges becomes a problem. Also, lenses absorb or reject some useful wavelengths of light. Reflecting telescopes on spacecraft usually employ a variation on the Cassegrain optical design (see page 13) using lightweight curved mirrors mechanically supported across their backs, to fold a long optical path (focal length) into a short physical space.[6] Table 6.3 lists the properties of optical assemblies on several interplanetary spacecraft's imaging instruments. The *Voyager* camera optical designs, inherited from *Mariner 10*, were copied with slight modifications (although completely different image detectors were installed) for use on *Galileo* and *Cassini*.

Table 6.3. Optics used by various spacecraft imaging instruments.

Instrument	Type	Aperture	Focal Length	FOV*
Voyager wide-angle	Refractor	6.0 cm	200 mm	3.2°
Cassini wide-angle	Refractor	6.0 cm	200 mm	3.5°
Mariner 10 narrow-angle	Reflector	18 cm	1500 mm	0.42°
Voyager narrow-angle	Reflector	18 cm	1500 mm	0.42°
Galileo narrow-angle	Reflector	18 cm	1500 mm	0.42°
Cassini narrow-angle	Reflector	19 cm	2000 mm	0.35°
MRO HiRISE†	Reflector	50 cm	12000 mm	1.1°

*Field of view.
†*Mars Reconnaissance Orbiter*'s High-Resolution Imaging Science Experiment.

Scan Platforms The *Voyager* spacecraft and the *Galileo* spacecraft were equipped with moveable platforms holding all their optical instruments so they could be pointed independently of the spacecraft's attitude. *Voyager*'s scan platform carried out many observations, moving in azimuth and elevation, while the spacecraft kept its high-gain antenna trained on Earth. With *Galileo*'s HGA failure (page 17), it was not possible to train it on Earth for communications, nonetheless its optical instruments were able to point largely independently of spacecraft attitude. The *Messenger* spacecraft's wide-angle and narrow-angle imaging instruments occupy a platform that can pivot in one degree of freedom to reduce their demands on spacecraft attitude while in Mercury orbit.

Mars-orbiting spacecraft are generally designed with a nadir-facing panel supporting their optical instruments. Rigidly attached to the bus, the instruments depend on spacecraft attitude for pointing their apertures. Typically the HGA and solar panels are articulated to maintain communications and electrical power, while the nadir panel faces down to the planet. This arrangement is used on many spacecraft. The Pluto-flyby spacecraft *New Horizons* has its optical instruments fixed to the bus.

The *Cassini* spacecraft was originally designed with two scan platforms, each supported at the end of a boom on either side of the bus. One platform was to articulate and aim the optical instruments, the other was to allow direct-sensing instruments to manage their own orientation, while the bus-mounted HGA faced Earth to maintain communications. Both appendages were deleted from the design to reduce pre-launch costs, and the instruments were fixed to the bus, requiring the whole spacecraft to be rotated to point the instruments, recording their data for later communications sessions. This increased operational complexity post-launch, and prohibited many instances of simultaneous observations and communications that would have been possible with the moveable platforms. But more importantly, the deletion enabled funding and launch of a highly capable mission.

Optical Image Detectors

Now that both *Voyager* spacecraft have shut off their vacuum-tube television sensors for good,[7] the *charge-coupled device* (CCD) is the only kind of visible-light image detector operating in interplanetary space.

The CCD CCD image detectors consist of rectangular or linear arrays of photoelectric cells made of isolated silicon capacitors called *photogates.* They're also called *wells.* Each photogate represents one pixel of an image. As a photon strikes one of these photosensitive cells, the photoelectric effect causes an electron-hole pair to occur at the quantum-mechanical scale. Additional photons striking the well increase its charge of electrons. Electronics in the instrument containing the CCD can read out the value of charge on every photogate by operating each line of photogates in the device as a shift register, stepping the charge along each row of pixels under control of a clock signal, and measuring the individual charge emerging after each shift with a built-in amplifier. The instrument's electronics assembly converts the values to digital data and outputs data sets comprising images to the spacecraft's telemetry subsystem or CTS.

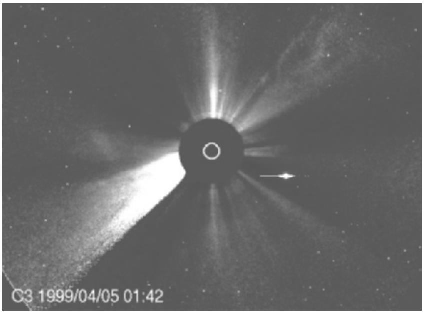

Fig. 6.1. CCD image from the *Solar and Heliospheric Observatory* spacecraft's Large Angle and Spectrometric Coronagraph instrument. Circular occulting disk in the instrument blocks out the Sun to allow corona and mass ejections to be seen. The white circle represents the Sun's size. The bright planet Jupiter, on the far side of the Sun, can be seen to the Sun's lower right, with horizontal lines "blooming" due to overexposure and resultant charge spill-over to adjacent pixels. Image courtesy SOHO/LASCO [9].

If a single photogate's capacity is reached, which may be on the order of a few hundred thousand electrons, any additional electron-producing photons will cause electric charge to bleed from the over-exposed pixel into adjacent pixels in its row. This condition can be seen with the bright Jupiter image near the middle-right in Figure 6.1.

To envision the process of capturing an image using a CCD in an instrument, consider the magnifying glass image projected on paper as mentioned above. If you were to draw a grid of one thousand tiny squares on the paper covering the image, you could see that the squares in the grid would have various intensities of light incident upon them. To transmit the image, at least in black and white, to a friend in another room who has a pencil and an empty grid on paper, you could estimate a number from 1 to 10 representing the brightness of each square in the grid, then read off the values, line by line, until the recipient had shaded in each square on his paper's grid with corresponding levels of grey. This is analogous to how a spacecraft instrument's image is captured and sent to Earth.

Continuing to envision the CCD's operation, this time at the quantum-mechanical level, imagine capturing rain in a rectilinear array of a thousand wineglasses, where each raindrop represents an electron freed by an incident photon. After the duration of the exposure (when the rain stops), you pick up a wineglass from one corner of the array, and pour its contents into a graduated beaker to measure the volume of water in units of 1 to 10 (don't forget to record the value). Now you discard the graduated beaker's contents and pick up each of the other wineglasses in the row. Working in one direction toward the beaker, pour each glass's contents to the adjacent empty glass or beaker, eventually measuring — and recording — the volume of rain collected in every wineglass in that row. Repeat the transfers and measurements row by row (each row has its own graduated beaker) until all one thousand glasses in the array have been tallied and emptied. Store your data until it's time to transmit it.

Within the space-borne instrument, the pixels, or grid-squares, are CCD wells several microns on a side, and they number in the millions. Also, there are usually more then ten levels of grey to measure. An instrument operating in a typical twelve-bit-per-pixel mode would generate an integer from 0 to 4,095 to represent the light level to which each pixel has been exposed.

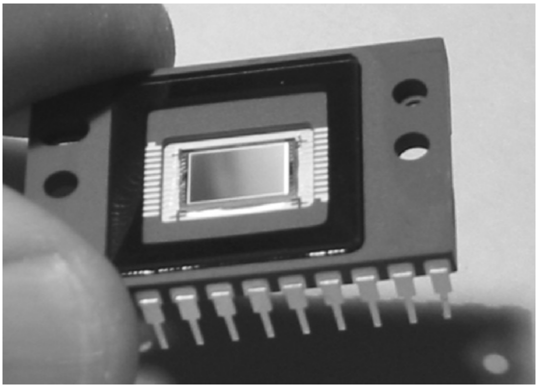

Fig. 6.2. The Kodak KAF-0402ME CCD image detector has 393,216 accessible pixels each 9 μm in size, arranged 768 horizontally by 512 vertically, visible here in the innermost rectangle. This rectangle would be situated at the focus of the imaging instrument, with the top of the silicon surface precisely in the instrument's focal plane. The twenty-four connector pins are for powering its internal electronics, providing clock and reset signals, and reading out the value of electric charge on each pixel. This particular model has been popular in amateur astronomy imaging work.

The human eye can discriminate at most one-tenth that number of grey levels,[8] but computer image-processing software can use every one of them to tease out detail that would be hidden to the unaided human eye. For example, the software could be directed to assign different colors to otherwise invisible grey-level gradations, producing false-color images revealing all the detail present in the 4,096 steps (0–4,095).

A CCD imaging detector has extraordinary efficiency. *Quantum efficiency* is a measure of how many electrons are freed within a material for each incident photon. It reflects a device's ability to convert light to a measurable electron charge. Photographic film has a quantum efficiency around 10%. Quantum efficiency for a CCD can reach 90% under laboratory conditions with the optimum light wavelength, and those in use on interplanetary craft range up to about 50% or higher. Vidicon vacuum-tube detectors such as *Voyager*'s exhibit a peak quantum efficiency of roughly 50% at blue-light wavelengths in the laboratory. They have much poorer dynamic range (about 1/100 the sensitivity) and lower resolution capability than CCDs, all while consuming more power. In the process of sensing photons by converting them to electronic charges and then transferring them to the instrument's electronics during readout (akin to pouring rainwater from glass to glass to beaker in the thought-experiment above) CCDs typically exceed 0.99999 efficiency (in the analogy, this amounts to few lost raindrops). This is called the device's *charge transfer efficiency.* A large fraction of the individual photons striking each of the detector's wells can be counted. The value of the fraction is equal to each well's quantum efficiency times the device's charge transfer efficiency. Most CCDs used in optical instruments are illuminated on their front sides. Light strikes the wells, but only after passing through a surface used for transferring charge during readout. Some CCDs are designed to be illuminated through their substrate layers, in which case the substrate is made extra-thin. Backside illuminated CCDs are most sensitive in blue light, with quantum efficiencies over 90%. The high-resolution Long-Range Reconnaissance Imager (LORRI) on the *New Horizons* mission to Pluto uses a back-side illuminated CCD.

CCD Array Types High-quality, space-qualified CCDs can be expensive. The Solid-State Imager (SSI) on the *Galileo* spacecraft had one of the first ever produced, a CCD with 800 × 800 pixel wells. A research team at Texas Instruments and JPL manufactured thousands of them before two were found to be of high-enough quality for flight. One was sent to Jupiter, the other became a spare. *Cassini*'s CCDs are two-dimensional arrays of 1024 × 1024 pixels. Space-qualification of an image detector includes special packaging within the integrated circuit to ensure it will survive the vacuum, radiation, and temperature conditions expected.

In the imaging instruments on some spacecraft, a two-dimensional CCD (that is, a device in which there are multiple rows of photogates, such as *Cassini*'s) is not needed at all. If the spacecraft has regular motion in orbit above a planet's surface, as does the *Mars Reconnaissance Orbiter*, this motion can be used to supply the second dimension. In such a case a single-dimension device called a CCD linear array (with a single row of wells), serves to build up an image as the scene moves by the detector. Most fax machines use a CCD linear array, building up an image of the page as it moves across the sensor and through the machine. A photocopy machine steps a light source and a CCD linear array across the glass platen to build its image, as does a graphics scanner. This technique is sometimes called "push broom" imaging.

The *Mars Reconnaissance Orbiter*'s High-Resolution Imaging Science Experiment (HiRISE) employs CCD linear arrays as the image detector at the business end of its enormous optical assembly — the most powerful optics ever flown on an interplanetary mission (see Table 6.3; also see Appendix B, p 321). The detector's spectral filters and overlapping elements produce color images. The longest part of the detector spans 20,264 photogates (pixels), and receives light from the optical assembly through red spectral filters. Additional elements form rows of 4,096 pixels illuminated through blue-green filters, and 4,096 pixels through a near-infrared filter. As the Martian surface passes across the CCD elements due to spacecraft motion, a two-dimensional image builds up which theoretically could be infinite in length and 20,264 pixels wide. Memory in the instrument puts a practical limit on image length to about 40,528 lines. HiRISE is capable of 1 μradian resolution, which translates to 0.3 meters from its nominal orbital height of 300 kilometers. It has imaged all of the landers on Mars: *Viking 1 Viking 2*, *Mars Pathfinder* (which deployed the *Sojourner* rover), the *Spirit* and *Opportunity* Mars Exploration Rovers, and *Phoenix.* HiRISE has also spotted many of these landers' ancillary hardware such as heat shields, back shells, and parachutes. In an extraordinary feat of imaging, HiRISE caught the *Phoenix* lander descending to Mars's surface beneath its parachute (see Figure 6.3).

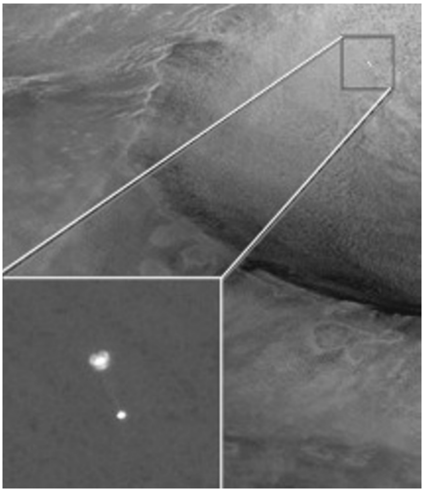

Fig. 6.3. CCD image acquired by the *Mars Reconnaissance Orbiter*'s High-Resolution Imaging Science Experiment on May 25, 2008 showing the *Phoenix* lander parachuting its way to the Martian surface. From image ID PSP_008579_9020 courtesy NASA/JPL-Caltech/University of Arizona.

Infrared-wavelength Image Detectors Instruments that form images from infrared light wavelengths use detectors different from CCDs. For wavelengths a little longer than visible red light, called near-infrared (3.5 μm), detectors can be made of indium antimonide. For the slightly longer mid-IR (6.0 μm) infrared wavelengths, the detector pixels are made of silicon doped with arsenic. Examples include the *Spitzer Space Telescope*'s Infrared Array Camera (IRAC), and the infrared channel of *Cassini*'s Visual and Infrared Mapping Spectrometer, VIMS.

Detector Cooling and Shielding Photons of light aren't the only source of electrons in a CCD's wells. Heat within the CCD also generates electrons, which act as noise in an image. To reduce this noise, which is called *dark current,* the detector must be cooled. In interplanetary space, this can be done effectively by entirely passive means. The CCD chip is bonded in a thermally conductive way to a structure that mechanically connects with a large plate facing deep space. All these mechanical components are thermally conductive and thermally isolated from the rest of the spacecraft, so heat generated within the CCD conducts its way to the plate where it radiates away. The CCDs on *Cassini* normally operate at –90 °C. *New Horizons* keeps its imaging CCDs below –98 °C, and *Messenger* keeps its imaging CCDs between –38 °C and –14 °C for nominal performance while orbiting Mercury.

Besides sensing photons, CCDs are good at registering high-energy particles. Protons in the solar wind can be seen in many raw images from interplanetary spacecraft using CCDs. They produce short, randomly oriented thin bright streaks in a otherwise high-fidelity image. The rapidly moving clouds from solar coronal mass ejections can cause a blizzard of such streaks in imagers operating near the Sun. Many examples of these can be seen in video clips on the SOHO website[9] that record particularly violent solar activity. The environment close to Jupiter, in which *Galileo* operated, also presented energetic particles that interfered with many of *Galileo*'s electronics. The *Galileo* Solid-State Imager CCD detector was largely enclosed in 1 centimeter-thick shields made of the dense metal tantalum.

Color Images To produce an image in the same natural colors seen by the human eye requires three images, each taken through a different spectral filter: red, green, and blue. Cameras on the consumer market (still or video) accomplish this in one of two ways: either (1) by using an optical splitter, three filters, and three image detectors behind the shutter, or (2) by using a detector constructed with three filters and three wells making up each pixel. Imaging science instruments on interplanetary spacecraft almost always work differently. They are designed to maintain flexibility, high resolution and accuracy, and reduce complexity. Not every exposure the instrument makes is part of a natural color view. Many other filter modes are commonly used, so the instrument is designed around one CCD, every pixel of which has had its performance calibrated under laboratory test conditions. When a natural color image is desired, the red, green, and blue filters are rotated into the optical path while three images are shuttered sequentially. Upon reconstruction on Earth, each of the three images feeds into its corresponding red, green, and blue channel in the image-processing software. Probably the only drawback to this approach is that the spacecraft has moved somewhat during the amount of time required for capture of three exposures, but this can be accounted for during planning, so that color images are not attempted when spacecraft motion relative to the target is too great.

Color images from a linear CCD array can be made by using separate linear detectors, each supplied with color-filtered light. The HiRISE instrument has this capability, although its spectral filters are not red-green-blue, so the resulting color images do not exactly correspond to the colors the human eye would detect viewing Mars directly.

Motion Sequences Repeated images taken of a single target over time may be compiled on Earth into short video sequences revealing motion. One such series of images explains a decades-old mystery in Saturn's rings.

Voyager stills of Saturn's F Ring taken in 1980 and 1981 showed surprisingly complex structure.[10] The images also revealed two small new satellites: Prometheus, orbiting closer to Saturn than the F Ring, and Pandora, outside the ring. They were understood to "herd" the ring particles into their narrow band. But in the *Voyager* images it appeared the F Ring had some sort of braiding. Could this have been related to the "shepherding" satellites?

For the answer, imagine a sequence of images like the one in Figure 6.4, an image *Cassini* acquired in 2008 viewing the unlighted (north) side of the F Ring, which lies some 3,400 kilometers beyond the outer edge of the main ring system. The main rings and Saturn are all toward the bottom of the image. Prometheus has just passed apoapsis in its orbit, where it entered the midst of the F Ring. Its motion is now toward the lower left; all orbital motion is from right to left. The slanted gore in Saturn's F ring reveals Prometheus's gravitational influence that largely resolves the *Voyager* question.

An extraordinary video available for viewing online comprises seventy-two *Cassini* imaging science frames that follow Prometheus as it enters the F Ring and interacts with its particles.[11] The video may be found by searching the web based on its identification, PIA08397. Viewing it, and the longer, wider-angle companion video linked from its site, easily demonstrates why *Voyager* saw "braids."

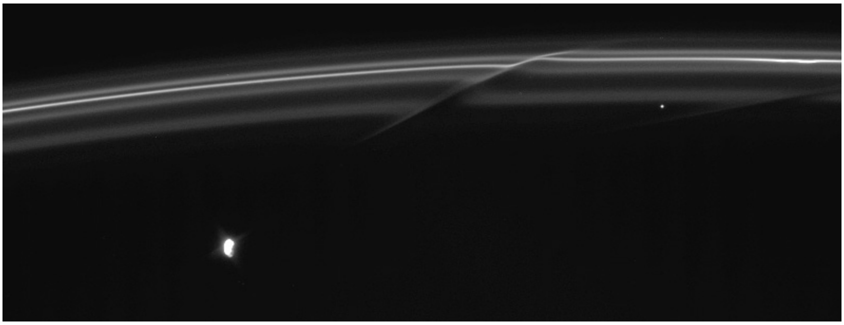

Fig. 6.4. *Cassini* narrow-angle camera visible-light image of Saturn's F Ring and 102 kilometer long-satellite Prometheus after having entered the ring at the moon's apoapsis. Taken in January 2008 at a 62° phase angle when the spacecraft was approximately 1.5 million kilometers from Saturn. Scale is 9 kilometers per pixel. A background star appears below the ring in the upper right. F Ring particles orbit Saturn at 16.45 kilometers per second at its outer edge (top of image) and 16.46 kilometers per second at its inner edge, completing an orbit of Saturn in roughly 14.9 hours. The different orbital velocities have caused the gore from Prometheus's previous apoapsis, near the star, to further slant and begin dissipating. Courtesy *Cassini* Imaging Team and NASA/JPL/Space Science Institute. Detail from image ID: PIA09834.

Beyond Imaging Modern imaging instruments can take on some of the functions that have in the past been accomplished by dedicated (passive remote-sensing) polarimeter instruments and photometer instruments. This does not mean that dedicated instruments are no longer needed for these functions; indeed some spacecraft may have requirements for instrument sensitivities beyond an imaging instrument's capabilities. But one can include a set of polarization filters on a sensitive imaging instrument's filter wheel, and obtain effective polarimetry measurements via the imager. Polarimetry provides information about such phenomena as the distribution of cloud particles or ring particles, and information on their size, shape, and composition. Reference [10] describes some of the investigations of *Voyager*'s photopolarimeter instrument — a combination of polarimeter and photometer. Photometers measure the intensity of light. This function is combined with imaging in the *Spitzer Space Telescope*'s Multiband Imaging Photometer. See reference [11] for a description of its application investigating a supernova remnant in Cassiopeia.

Target Illumination

For passive remote-sensing optical cameras, target illumination intensity and angle can be widely variable.

Sunlight is the usual source of illumination for taking images in interplanetary space,[12] and its intensity decreases as the square of the distance. Saturn, at roughly ten times the Sun-Earth distance, has about 1/100 the useable solar illumination here on Earth.

The angle at which a target is observed can be varied to provide fundamentally different measurements of its properties. *Phase angle* is the angle between incident and reflected light — the angle between a ray of light from the Sun to the target and the line of sight from the target to the observer. It varies in value between 0° and 180°. If you look at the Moon when it is full, the phase angle is low. There is not much of an angle between the line from the Sun behind you to the Moon, and the reflected light returning to your eye.

When viewing objects at low phase angle such as the full Moon from Earth, one sees little or no evidence of shadows of craters and mountains on the lunar surface, making it more difficult to notice these geologic features. Such features become more dramatically shadowed and pronounced when seen at higher phase angles, as easily demonstrated by viewing the Moon from Earth in a small telescope when it is at its half-Moon phase. The approximately 90° phase-angle helps bring out the detail on the lunar surface, especially near the terminator where shadows are the longest. This also applies, of course, to observing objects with a spacecraft's imaging instruments. In addition, special observations can be made at very low and at very high phase angles.

Opposition Effect At zero phase with the Sun directly behind the observer, a target body may exhibit *opposition effect,* also called "opposition spike," which is an observed brightening beyond the value expected from reflection alone. It is most pronounced when viewing surfaces covered with a covering of dust, soil, or decomposed rock known as *regolith* in an airless or nearly airless environment. Examples include the Moon and Mars. Looking for evidence of the opposition effect therefore reveals information about the surface being observed. Three major contributors to the opposition effect are:

1. Disappearance of shadows: At low phase illumination, shadows lie behind surface particles where they cannot be seen.
2. Crystal retro-reflection: Like retro-reflective paint used on highway signs, some natural crystals in surface minerals can return light more directly toward its source than expected from the more common reflective scattering.
3. Coherent backscatter: Reflected light waves interfere with one another in constructive fashion, reinforcing intensity [12].

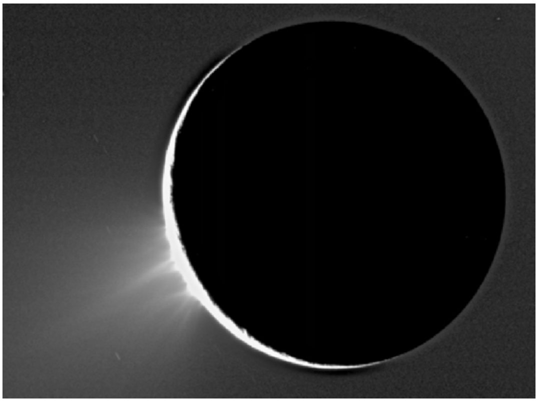

Fig. 6.5. High-phase-angle view of Enceladus shows small particles of ice issuing from its south-pole geysers. North is toward upper right. The small particles appear bright due to forward scattering of sunlight. Phase angle (Sun to target to observer) = 161°. Image ID: PIA07758. Courtesy *Cassini* Imaging Team and NASA/JPL/Space Science Institute.

Forward-scatter vs. Backscatter Backscatter of light is dominant under low phase-angle illumination. This is the normally experienced reflection and scatter of light back towards the source and observer seen, for example, when reading a book or looking at the Moon and planets from Earth. On the other hand, at high phase angle, observations of *forward scatter* become important. When the size of particles in a target such as a planetary ring or an atmosphere are small, especially when they begin to approach the size of the wavelength of light, they scatter light more effectively in the forward direction than in the backward direction. In everyday experience, this is evident as small dust particles and defects on an automobile windshield become all too visible when driving toward the rising or setting Sun.

High-phase observations are often planned to search for small-particle phenomena. Jupiter's ring was discovered in 1979 after *Voyager* science planners had dedicated one high-phase observation looking from within the shadow back toward the Sun near the planet's limb where a ring could exist, although the observation was actually expected to rule out a ring. Saturn's E Ring, created by ongoing geyser activity on the moon Enceladus, which orbits Saturn in the E Ring's densest region, is clearly visible in a set of images returned from *Cassini* while the spacecraft was positioned deep within the planet's shadow. The large image can be found in Appendix C (page 339), and also at reference [13]. It was a high-phase observation of Enceladus in November 2005 at a phase angle of 161° (see Figure 6.5) that revealed icy geysers issuing from crevasses in the 500-kilometer diameter moon's surface. The existence of these geysers offered an explanation for Enceladus' having been long known for its high geometric albedo (1.375), the highest of any solar system object. Ice crystals, falling back to the surface from the geysers, blanket Enceladus' surface with highly reflective ice particles.

Optics for High-Energy Photons

Instead of being reflected in the optics designed for focusing infrared, visible, or ultraviolet light, X-rays and gamma rays fly right past the atoms that make up a conventional mirror, like pebbles tossed into a body of water. To focus high-energy photons into an image, grazing-incidence mirrors have to be designed to bend the paths of incoming photons by causing them to "skip," not unlike the way a stone can be skipped across the surface of a pond. To collect enough photons to make an image requires mirrors to be nested in concentric modified cylinders. Designs of this kind are known as Wolter telescopes, named for the German physicist Hans Wolter (1911–1978) who proposed them in 1952. Figure 6.6 illustrates the *Chandra X-Ray Observatory*'s mirrors in cross section.

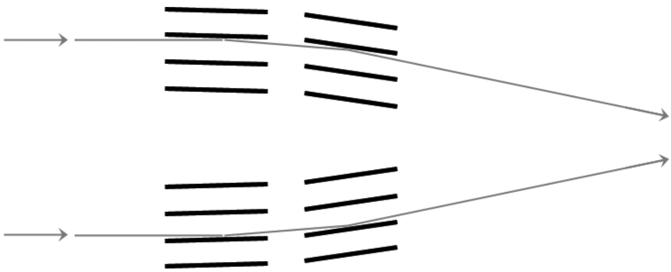

Fig. 6.6. Cross-section schematic of the x-ray mirrors in a Wolter telescope. The *Chandra X-Ray Observatory* uses four nested modified-cylindrical mirrors with an outer diameter of 1.2 meters and a focal length of 10 meters. The first set of mirrors have paraboloid shapes, the second are hyperboloid.

Imaging Radar

Imaging radar is an active remote-sensing technique. Appendix B has one example.

Light neither easily penetrates the dense clouds that hide Venus's surface from view, nor does it reveal much surface detail below the haze of Saturn's moon Titan; passive, light-based remote-sensing techniques are therefore inadequate for viewing their surfaces. Applications of imaging radar, known as *synthetic aperture radar,* (SAR), are responsible for providing high-resolution two-dimensional views of these hidden surfaces. SAR's probing radio pulses have longer wavelengths than light, so they are easily able to penetrate the clouds and haze. SAR radio frequencies are usually in the neighborhood of 13 GHz, with wavelengths around 2 centimeters.

To create a radar image, a spacecraft passing within about 1,000 kilometers of the target surface — the lower the altitude, the better the available resolution — sends pulses of radio energy down and toward either the right or the left side of its ground track (off-nadir pointing). Each pulse is modulated with a different code, related to time of transmission, so it can be recognized among all the other radar pulses reflecting back from the surface. As one radio pulse is scattered and reflected back from the surface, the spacecraft travels along its track a certain distance collecting the reflection. It is this motion during reception that enables computer processing to *synthesize* a receiving aperture that is much larger than the physical aperture (antenna) on the spacecraft, increasing the available resolution of the resulting image. If a spacecraft were to traverse 1 kilometer while it is receiving echoes from a pulse, its synthetic aperture would be 1 kilometer, compared to the physical aperture of only about 4 meters in the case of *Magellan* or *Cassini*. The spacecraft's radar receiver measures the following attributes in the reflected signal in order to create a two-dimensional image:

1. The code modulated onto the pulse. This lets the receiving processor match the echo with the precise time it was transmitted.
2. Intensity, or strength, of the echo. This gives a characterization of vertical structure on the surface. A flat canyon wall facing square on to the spacecraft will reflect a strong echo, while a flat lake or sea will let most of the incident radar energy skip away without reflecting back.
3. The time delay between transmission and reception. Because each pulse has a recognizable code modulated onto it, the receiving electronics can discriminate which pulse is returning when. This forms one of the two dimensions of an image of the surface: every reflection's round-trip time, at the speed of light, provides one coordinate on the map, a line of signals of equal range.
4. The Doppler shift of the pulse's echo. This provides the second of two dimensions for the image to be constructed. The Doppler shift is an indication of how far ahead or behind the spacecraft the echo is coming from. And again, each pulse's imbedded code lets the receiving processor identify which pulse is being reflected back. This measurement provides cross-range lines on the resulting image as lines of equal Doppler shift.

Capturing and discriminating the attributes listed above represents a large amount of signal processing and data processing once the radar receiver has collected the echoes of its pulses. Some of this processing takes place within the radar instrument in order to pass packets of useful data to the CTS for storage and downlinking. Once received on Earth, further intensive processing produces an image strip.

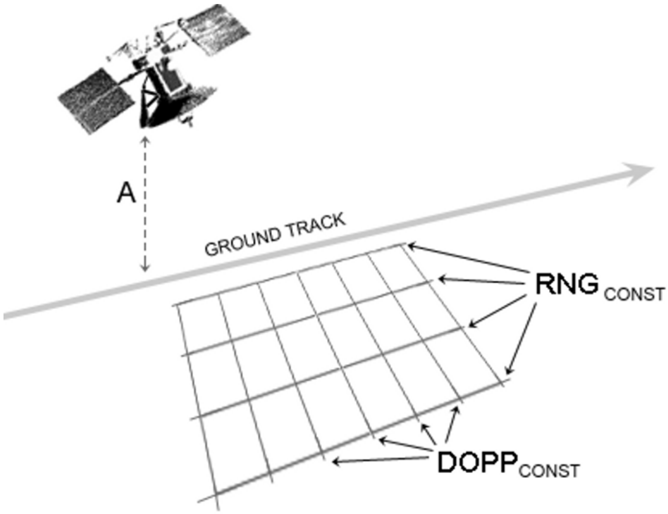

Fig. 6.7. Synthetic aperture radar creates images from reflections of the microwave radio pulses that it transmits toward one side of the spacecraft's ground track. Bright and dark pixels on an image indicate strong and weak echoes received, placed in the two roughly orthogonal dimensions of the image: (1) lines of constant Doppler shift (increase or decrease in frequency) and (2) lines of constant Range (distance, based on round-trip time interval). "A" indicates altitude of spacecraft above the surface which can be measured via altimetry.

The Magnetospheric Imager

Magnetospheric imagers are passive remote-sensing instruments.

Planets which have strong magnetic fields also have a magnetic "bubble" called a *magnetosphere,* which is generally teardrop-shaped with a tail extending away from the Sun. A magnetosphere deflects charged particles in the solar wind largely around the planet and down the tail. It is possible to obtain an image of a planet's magnetosphere. This is because free electrons normally gyrate around the lines of magnetic force in a magnetosphere. Once in a while these electrons collide with ions, and this charge-exchange collision results in the formation of a neutral atom. A neutral particle is not subject to magnetic fields, so it is flung from the magnetosphere in a random direction. The task of a magnetospheric imager is to sense the flight direction of these energetic neutral atoms (ENAs) and form an image based on their deduced origins.

Cassini's Magnetospheric Imaging Instrument (MIMI) is the first such instrument to operate in deep space. MIMI actually includes several instruments, some of which detect ions. The one that forms images of magnetospheres is the Energetic Neutral Atom Camera, part of its Ion and Neutral Camera (INCA). It filters out charged particles that enter the instrument using a set of metal plates, given high-voltage electrical charges, set edge-on to the incoming particles. ENAs continue

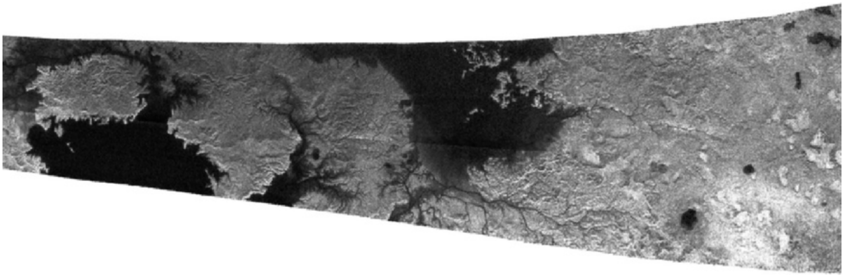

Fig. 6.8. Section of a SAR swath showing Titan's northern polar region which *Cassini*'s radar instrument obtained in April 2007, late winter on Titan's northern hemisphere. The section of swath shown here is about 220 kilometers wide at its left edge and increases to about 400 kilometers wide at right. North is toward the top. This section is about 1,100 kilometers from left to right, excerpted from the 6,700 kilometer long SAR swath obtained on *Cassini*'s twenty-ninth flyby of Titan. *Cassini* uses five separately aimed beams to obtain SAR image data during selected Titan flybys. Closest approach was 950 kilometers above the surface. These lakes are thought to contain a mixture of methane and ethane, the latter of which was confirmed in another Titan lake (see page 208). Complex shorelines show some well-developed tributary systems that drain thousands of square kilometers of surrounding terrain. Brighter areas within the lakes may represent the lake bottom — at the radar's 2-centimeter wavelength, the liquid may be transparent for tens of meters, propagating radar echoes from the lake bottom. Image ID: PIA09217. Courtesy NASA/JPL-Caltech.

through these slots to the detector, while charged particles are diverted and collide with the plates. The detector uses penetrable metal foils, imaging micro-channel plates, and internal digital processing, to determine each ENA's arrival direction, its energy, and its composition, whether hydrogen or oxygen.

6.3.4 Altimeters

Altimeters are active remote-sensing instruments. Appendix B has one example.

Altimeter instruments measure the distance between a spacecraft and a body's surface. They operate by transmitting pulses of light or radio that reflect back from the surface and recording the elapsed time each pulse takes at the speed of light. The altimetry science team knows the spacecraft's distance from the center of the target body from navigational data, so the altimetry results can be processed to show height of terrain on the target body, and presented as topographical data on maps.

Cassini uses its radar instrument to take altimetry data of Titan's surface during some flybys of this large satellite of Saturn, obtaining a vertical accuracy of about 100 meters. Because the HGA must be turned to the nadir to perform altimetry measurements, they cannot be taken simultaneously with SAR observations.

Magellan, while observing Venus's surface with SAR, switched at high speed between its side-looking HGA and a separate nadir-pointing altimeter antenna several times per second. In this way it was able to take both SAR imaging data and altimetry data during every orbit. This is illustrated in Figure 6.7. *Magellan*'s altimetry was accurate to about 30 meters.

The successful *Mars Global Surveyor* carried a laser altimeter called the Mars Orbiter Laser Altimeter (MOLA). A similar device was originally developed and flown on the *Mars Observer* spacecraft, which was lost prior to Mars orbit insertion. While it operated in Mars orbit, MOLA sent infrared laser pulses (1,064-nm wavelength) toward the nadir, ten per second, lasting 0.8 μs each, and it measured the elapsed time for each echo. It received the echos using a 50-centimeter diameter Cassegrain telescope, and was able to achieve a precision of 37.5 centimeters in the distance to Mars's surface. Knowledge of the orbit parameters yielded accuracy in topographical measurements of better than 10 meters. *Messenger* is carrying the Mercury Laser Altimeter, which will be used in a similar way to measure that planet's topography for the first time.

6.3.5 Microwave Radiometers and Scatterometers

Radiometry measurements are taken in passive remote-sensing mode, scatterometry in active remote-sensing mode.

Radar instruments by design must be able to receive microwave energy from their targets in order to register their own echoes from SAR or altimetry observations. It follows that they would also have the ability to operate during some observations in a passive mode, simply receiving the natural microwave emissions from a target body. The strengths and precise frequencies of such emissions provide science teams information about surface properties, including thermodynamic temperature to an accuracy of 1 or 2 °C. The *Jason 2* spacecraft, launched in 2008, carries a dedicated microwave radiometer in Earth orbit to measure water vapor content in the atmosphere. Incidentally, MOLA (which used infrared light, not microwaves) operated in a passive radiometer mode to measure the natural infrared emission from Mars's surface when it was not operating in its active altimeter mode.

Scatterometry is another capability of radar systems as well as dedicated scatterometers. The *Quickscat* spacecraft, launched in 1999, uses its scatterometer to measure near-surface wind speed and direction on Earth's oceans under all weather conditions. Scatterometers operating in Earth orbit can measure wind speed and direction over the oceans, because wind-induced waves on the surface have backscatter signatures that vary depending on wave height. Operating typically from a higher altitude than for SAR observations, *Cassini*'s radar instrument transmits pulses to its target Titan in a non-imaging mode. The reflected and backscattered signal captured on return to the instrument provides science teams information about wide areas of the surface including its dielectric constant — a parameter related to a material's ability to reflect radio waves. Water ice is known to have a high dielectric constant and hydrocarbons have a low value, so this information is useful for studying Titan's surface where terrain is largely water ice and lakes are liquid hydrocarbon.

6.3.6 Optical Spectroscopic Instruments

Optical spectroscopic instruments are passive remote-sensing devices. Appendix B has one example. Spectroscopic instruments designed for viewing a light source directly with the eye or camera are called *spectroscopes.* Instruments that provide their results numerically or graphically are called *spectrometers* and *spectrographs.* All of them divide an optical-wavelength electromagnetic signal such as infrared, visible, or ultraviolet light, typically incoming through a telescope, into its component frequencies at high resolution, and they measure the signal's intensity or radiance at each resolved frequency. In doing so a spectrometer reveals many things.

Consider how many wavelengths or colors comprise white light. Given its strength here on Earth, sunlight can be broken down into its constituent wavelengths with enormously fine resolution; thousands of individual wavelengths and meaningful features can be measured in the solar spectrum.[13]

Data from optical spectroscopic instruments can lead to knowledge of a light source's many properties. Depending on the nature and condition of the source this may include temperature, pressure, density, luminosity, chemical composition, state(s) of ionization, rotation rate, relative velocity, mass (under some specific circumstances), and the composition and density of material intervening between the source and the instrument. Optical spectroscopic instruments have led to many important findings. A few examples include:

- The discovery and naming of a mysterious, light-absorbing substance in the Sun ("helium") before it was identified on Earth [15];
- Compositions of solar system objects' atmospheres and surfaces;
- Clouds containing complex organic compounds in interstellar space;
- The expansion of the universe [16];
- Confirmation of liquid on the surface of Saturn's moon Titan [17], [18].

Background

In 1666 Sir Isaac Newton recognized that sunlight is composed of all the colors familiar to the human eye. He introduced the word *spectrum.* The English astronomer William Herschel (1738–1822) discovered the *infrared* (from the Latin, "below" red) portion of the spectrum in 1800, and in 1801 the German chemist and physicist Johann Ritter (1776–1810) discovered the *ultraviolet* (Latin "beyond" violet) portion.

In 1814, the German optician Joseph von Fraunhofer (1787–1826) noticed that when he dispersed the sun's spectrum widely he could see a number of dark lines amid the otherwise continuous colors; today, these are called the Fraunhofer lines. Fraunhofer also invented the use of fine *gratings* to disperse light into its spectrum, which had some advantages over the use of prisms to do the same.

In 1848, Léon Foucault placed a bright arc-light behind a flame containing sodium vapor. Sodium generates a yellow-orange coloration in an otherwise blue flame, as one can readily see by sprinkling salt over the gas burner on a stove. Foucault noticed that the continuous spectrum of his bright light showed a dark line where there would otherwise be yellow-orange. The hot sodium gas was absorbing the yellow-orange wavelengths right out of the light.

Eleven years later the German physicist Gustav Kirchhoff (1824–1887) formulated three laws of spectroscopy [19]. Two of these linked the phenomena that Foucault had observed: a hot tenuous gas (such as the sodium in a flame) will emit specific, discrete colors; and the same tenuous gas will absorb the same specific wavelengths. In Foucault's experiment, the sodium in the flame, while hot, was cooler than the bright arc light behind it, making it possible for the sodium to absorb more energy from the arc light. Kirchhoff's other law,[14] the first of his three, stated that a hot solid object or high-pressure gas produces light having a continuous spectrum — no dark lines, no bright lines.

Kirchhoff and the German chemist Robert Bunsen (1811–1899), who began working together in 1859, explained that the Fraunhofer lines observed in the otherwise continuous solar spectrum were due to absorption by elements in the cooler outer regions of the Sun. They recognized that every atom and molecule must have its own spectral "fingerprint." Suddenly it became possible to analyze the atmosphere of the Sun — and the distant stars!

Separating the Colors Prisms, as Newton found, bend different wavelengths of light to different angles as they pass into, through, and out of the prism's transparent material, resulting in a rainbow of separated wavelengths. Refined in 1882 by the American physicist Henry Rowland (1848–1901), Fraunhofer's optical gratings are preferred over prisms for dispersing light into spectra in virtually all spectrographic instruments today. They are made of fine parallel reflective grooves, or open slits, spaced on the order of the size of light wavelengths of interest, and they disperse colors by redirecting incident light waves so that they interfere with one another variously at different angles leaving the grating surface. Reference [20] details the physics underlying this interaction. Gratings achieve much better dispersion than prisms, and they do not absorb any of the wavelengths of interest as prisms can.

Continuous Spectra, Emission Spectra, Absorption Spectra We know from Kirchhoff's first law that a hot solid body emits a continuous spectrum. An example can be seen by observing the spectrum of a hot piece of metal, such as the tungsten filament inside an operating incandescent light bulb. One can view this spectrum by looking at the bulb's color-dispersed reflection in the finely grooved surface of a digital versatile disk (DVD) or a compact disc (CD).

But it's the emission, and more often the absorption features that are the quarry of the optical spectroscopic instruments on an interplanetary spacecraft. Emissions and absorptions reveal the composition of their sources and more. Again, a DVD can be used to view discrete emission lines from a hot gas such as the orange-glowing ionized neon in a household night-light, just by holding it at the correct angle in a darkened room. At least four groups of neon's discrete emission lines can easily be observed in this way. Many more examples of colorful gas emission spectra can be found online.[15] As for observing absorption features, some of the more prominent Fraunhofer absorption lines caused by gasses in the Sun's outer atmosphere can be seen in a homemade DVD-based spectroscope [21][16] when viewing a reflection of the blue sky or a white cloud (to prevent serious eye injury, never view a direct reflection of the Sun).

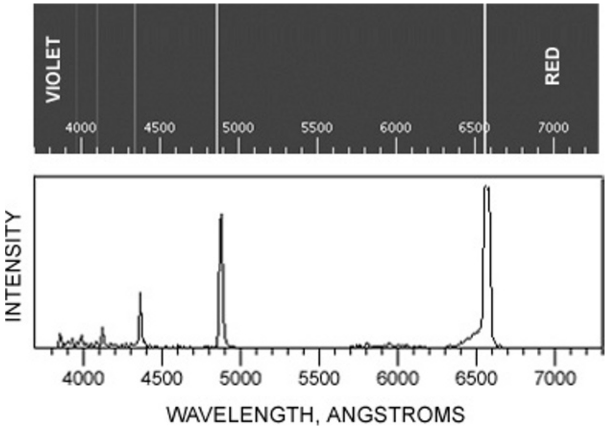

Fig. 6.9. Hydrogen emission spectra. Bright lines in the top panel's spectrographic view represent light emitted from hot hydrogen gas. The contrast level of each line indicates intensity of emission at a discrete wavelength. The same information is represented in plot form in the bottom panel, where the height of each peak represents its intensity. Horizontal axis is wavelength in angstroms, Å. The *plot* versions are preferred in general scientific use today. Adapted from [22].

Figure 6.9 illustrates how the bright lines of an emission spectrum seen in a spectroscope (or DVD reflection) can be represented in different forms, as can an absorption spectrum. One form is a photograph of it, called a spectrograph. The plotted form, in which it is easier to notice finer, lower intensity features, is in more common use today than the photographic (spectrographic) form.

The bright, clearly separate features in an emission spectrum, and the dark, equally discrete features showing absorption in an otherwise continuous spectrum can be seen in the spectra of virtually all the chemical elements and their compounds. The lines reveal not only the presence and abundance of elements in observed sources, but also their states of ionization; hot neutral calcium, for example, has one "fingerprint" in emission lines. Hotter calcium that has had one of its electrons stripped off — to become singly ionized — has a different fingerprint. Doubly ionized and triply ionized calcium have different and clearly recognizable signatures.

Spectral features are to be found not only in the visible wavelengths that Kirchhoff and Bunsen experimented with but are also dispersed throughout the electromagnetic spectrum from radio through infrared, visible light, ultraviolet, all the way to X-rays and gamma rays.

Sources of Spectral Features Many of the higher energy phenomena that appear in X-ray and gamma ray spectra are of interest mostly to astrophysicists who study high-energy objects and events such as stars, novae, supernovae, and galaxies. For studying the objects in interplanetary space, such as the surfaces and atmospheres of planets, moons, comets, and asteroids, the wavelengths of interest are in the

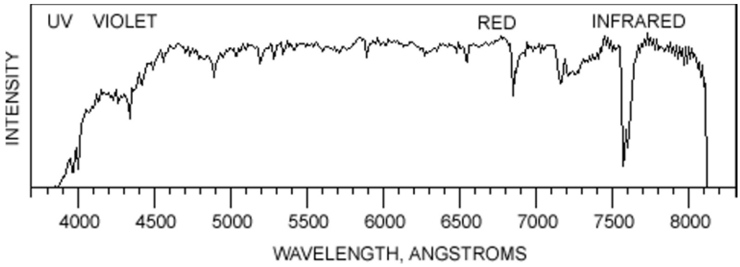

Fig. 6.10. Solar spectrum as viewed from Earth's surface, shown in plot form. The many dips in what would otherwise be a continuous arc show the result of certain wavelengths being absorbed either from the Sun's outer regions or the Earth's atmosphere. The deep absorption feature on the right, in infrared wavelengths near 7,600 Å, is due to molecular oxygen, O_2, in Earth's atmosphere. Nitrogen, the largest constituent, absorbs most strongly in the ultraviolet. Adapted from [22].

lower-energy microwave, infrared, visible, and ultraviolet parts of the whole spectrum. And they may come from two different physical phenomena. The first is quantum mechanics. The second, addressed on page 206, is mechanical motion.

Emission and absorption associated with atoms is explained by quantum mechanics. We can use a simple semi-classical description by imagining an atom of hydrogen consisting of its single proton for a nucleus with a single electron orbiting it. If a photon of the right energy or wavelength (light's behavior can be described both as particles and waves) were to collide with this atom in the right way, the atom would absorb the light energy by boosting the electron up into a higher orbit. This is absorption. Photons of other energies pass through the atom with no effect. When photon interactions occur in tremendous numbers of atoms, absorptions of the particular wavelengths of light is evident in one or more absorption feature in a spectrum: dark bands in a photographic product, or *dips* in a plot.

Emission occurs when our hydrogen atom's electron drops back down to its "regular" orbital distance from the nucleus. As the electron loses energy by dropping, it emits a photon of the same wavelength as the photon it absorbed to get to its higher orbit. Because hydrogen and other atoms can have many different states of energy, in which electrons may be boosted to higher and higher orbits, or knocked off entirely in the case of ionization, there are many more possibilities for energy absorption and emission exchanges. These emissions, when multiplied by all the atoms undergoing transitions, result in emission features on a spectrum — bright lines in a spectrographic product or *peaks* on a plot (see Figure 6.9).

In this model of the atom, which the Danish physicist Niels Bohr (1885–1962) proposed in 1913, electrons can only jump between certain orbits, changing energy states in specific amounts called *quanta* (in the later Schrödinger model,[17] electrons are understood as standing waves instead of orbiting particles). Atom energy-level diagrams called "Grotrian diagrams"[18] illustrate all the various transitions between electron energy states available for various species of atoms. Reference [23] has examples, and online searches easily produce Grotrian diagrams for any atom of interest.

The above thumbnail explanation of the quantum-mechanical basis for emission and absorption leaves out some components, not least among them special-relativistic effects. In reference [24] the American physicist Richard P. Feynman (1918–1988) succinctly explains quantum electrodynamics, which is the best theory in current use relating to the interactions between light and matter.

Spectral lines appear to have various widths. In the infrared, visible, and ultraviolet, any apparent broadening is largely the result of Doppler shifting as the atoms move about within the emitting or absorbing gas. At microwave frequencies, Doppler broadening may be accompanied by the effects of molecular collisions, depending on the pressure of the gas. This effect is called pressure broadening.

Quantum Energy The energy of a photon can be expressed in electron-volts (eV) as an alternative to identifying a wavelength. Electron-volts are more frequently used when describing X-rays and gamma-rays, and wavelength is more the common descriptor for UV and lower energies. For comparison, though, the energy of photons in the visible range varies from about 2 eV toward the red end to about 4 eV for violet. UV goes to about 100 eV. X-ray photons have energies from there up to 100 keV, and gamma-rays can exceed 1 MeV (see page 342 in Appendix D). The relation between wavelength and quantum energy is:

$$E = h\frac{c}{\lambda} \tag{6.1}$$

where

E is the energy in electron volts eV,
h is the Planck constant of proportionality between a wave or photon's energy and its frequency, $6.62606876 \times 10^{-34}$ J·s (joule-seconds),
c is the velocity of light, in vacuum = 299,792,458 meters/s, and
λ is the wavelength.

The second kind of interaction with photons, in addition to the quantum jumps electrons make between available energy levels within atoms, is mechanical motion of molecules in the gas phase. Molecules rotate and vibrate, and photons are generated and absorbed in conjunction with these motions. The photons involved in quantized rotational motion have lower energy levels than those of visible light, with wavelengths typically in the infrared and microwave regions of the spectrum. Quantized vibration and electronic motion produce wavelengths a little shorter than those associated with rotation. Observations in these parts of the spectrum are useful for scientists who investigate the molecular constituents of atmospheres, comet tails, and the interstellar medium.

In addition to these molecular-level interactions with photons, motion of a light-emitting or absorbing gas, such as the violent convective movements of incandescent gas on the Sun, contribute Doppler shifts that are largely random. The resulting wavelength shifts serve to broaden spectral lines.

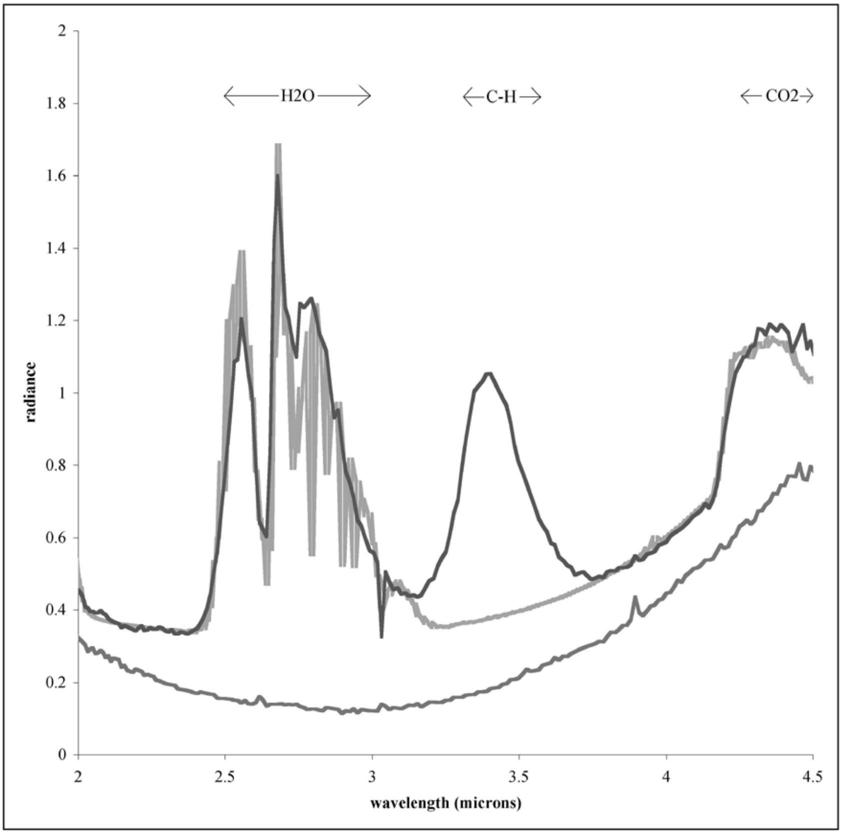

Fig. 6.11. Two infrared spectra acquired by the *Deep Impact* spacecraft's infrared spectrometer showing Comet 9p/Tempel-1. The bottom spectrum was taken of the comet nucleus 0.7 seconds before impact by *Deep Impact*'s 364-kilogram smart projectile. It includes reflected IR and thermal emission. Above this, the grey line represents a predicted model, and the black line represents the emission spectrum from the 700 °C plume observed 0.6 second after impact. Note the peaks indicating the presence of water (H_2O), hydrocarbons (C-H) (not modeled), and carbon dioxide (CO_2). The instrument's resolution is not high enough to separate individual types of hydrocarbons. From [25]. Reprinted with permission from AAAS.

Reflectance Spectra Materials exposed to light, such as solar system objects in sunlight, exhibit spectral signatures in the way they reflect and absorb at different wavelengths. Observing the spectra of sunlight or radio waves reflected from an asteroid, a planet, or other body can therefore provide important clues to the chemical makeup of its surface or cloud-tops.

Reflection spectra have been used to categorize minor planets, or asteroids, into three categories based on their observed sunlight-reflectance along with albedo measurements. Unfortunately, the effects of *space weathering,* which results from bombardment by solar wind and radiation on asteroids' surfaces, may complicate spectral identification or their compositions. Reference [27] explores this effect observed by the asteroid-visiting *Hayabusa* spacecraft. Spectral observations of asteroids indicate minerals on their surfaces and link them to meteorites found on Earth:

1. Carbonaceous or C-type asteroids comprise around three-quarters of the minor planets. Their reflectance spectra reveal compositions that include silicates, oxides and sulfides, similar to carbonaceous chondrite meteorites. Most C-type asteroids occupy the outer regions of the main asteroid belt.
2. Silicaceous or S-type asteroids comprise about 17 percent of known asteroids. Their reflectance spectra indicate silicates as in stony material, similar to ordinary chondrite meteorites. They typically occupy the main asteroid belt's inner regions.
3. Metallic or M-type asteroids form the remainder of main-belt types, found mostly in the middle of the main belt. Their spectra generally indicate the presence of metallic iron, matching the iron meteorites.

Spectra for Reference Scientists need to refer to known spectra that have been demonstrated in the laboratory to be able to identify chemical species in their spectral observations. The U.S. National Institute of Standards and Technology maintains a freely accessible reference database of many thousands of evaluated spectra in all parts of the measurable electromagnetic spectrum — a chemical "fingerprint" database — along with explanatory information.[19] Computer algorithms serve as tools that can mathematically identify a laboratory spectrum most closely resembling a target's spectrum.

Infrared reflectance spectra returned in July 2008 from the *Cassini* visual and infrared mapping spectrometer (VIMS) included an unambiguous dip in the graph around 2 microns wavelength, showing that Ontario Lacus on Titan's surface contains liquid ethane. The American planetary scientist and physicist Jonathan Lunine (1959–), a leading Titan expert, had remarked in 2006, "We won't be 100% sure until we can dip our toes in one" [28] about whether the lakes seen in radar images on Titan's surface actually contain liquid. The dip in the *Cassini* VIMS data is every bit as good as dipping toes.

Some Representative Instruments

It remains for the designs of individual instruments to be sensitive to a selected part of the electromagnetic spectrum, to gather light through optical assemblies from targets or portions of targets, to disperse and measure the wavelengths of captured energy, and to return results of these measurements in useful ways. We'll visit some representative instruments that employ various ways of making observations.

Infrared Spectrographs As a result of the expansion of the universe, much of the visible and ultraviolet radiation emitted from the most distant stars, galaxies, and quasars appears to us Doppler-shifted into the infrared part of the spectrum. The *Spitzer Space Telescope*, launched in 2003 into solar orbit trailing the Earth, makes observations of these distant objects as well as objects in closer galaxies and in our own. Many of *Spitzer*'s targets are invisible to our eyes because interstellar gas and dust block their light. *Spitzer*'s infrared science instruments are kept at a temperature near 1.4 K by a system using liquid helium to refrigerate them in order to minimize their contribution of infrared noise, and they are able to see through such obscurations. One of *Spitzer*'s three science instruments is a spectrograph.[20]

Spitzer's Infrared Spectrograph (IRS) supports over thirty classes of investigations into phenomena in the universe. It uses two pairs of high- and low-resolution instrument modules to cover the mid-infrared wavelengths from 5.3 to 40 μm. Each module has its own entrance slit that admits infrared light to diffraction gratings and then to detectors. The detectors are arrays of 128 $\times$ 128 silicon photogates doped with arsenic for two shorter wavelength arrays and with antimony for two longer-wavelength arrays. Ball Aerospace built IRS under contract to JPL and Cornell University based on designs and prototypes constructed at Cornell.

In an example of *Spitzer*'s many spectrographic observations in the mid-infrared, Figure 6.12 shows the rich molecular emission spectrum IRS acquired by observing the sun-like star AA Tauri about 450 light years away in our galaxy. This star has a disk of protoplanetary gas and dust that is probably in the early stages of forming a planetary system. In reference [29] the astronomers report finding a high abundance of simple organic molecules and water vapor. Among them are hydrogen cyanide (HCN), acetylene (C_2H_2), and carbon dioxide (CO_2). Diamond shapes in the figure mark rotational transitions of OH.

Back in the solar system, near-IR results from the *Hayabusa* spacecraft investigating asteroid Itokawa may be found in reference [30].

Thermal Infrared Instruments As passive remote-sensing instruments, far-infrared (thermal) spectrometers cover regions of the spectrum useful not only for identifying the composition of molecules and atoms in a distant source, but also for remotely measuring temperature across cool or warm surfaces such as those of moons or planets. Infrared spectrometers accurately measure the flux of energy present in thermal wavelengths, so they can also function as radiometers by measuring the intensity of infrared energy coming from a target. In the past, this function might have required a separate instrument, a radiometer, to measure the intensity. Reference [31] describes how *Cassini*'s Composite Infrared Radiometer-Spectrometer was used to discover unexpected heating on in the south-polar region of Saturn's 500-kilometer diameter icy moon Enceladus, where active geysers were later confirmed.

Mapping and Imaging Spectrometers Passive remote-sensing instruments, mapping spectrometers create images somewhat as imaging instruments do. Their number of pixels is typically smaller than in an imaging instrument, but every pixel tells a story: it contains a range of spectral measurements. Thus a single "image" from a mapping spectrometer samples spectra over an area, such as part of a body's

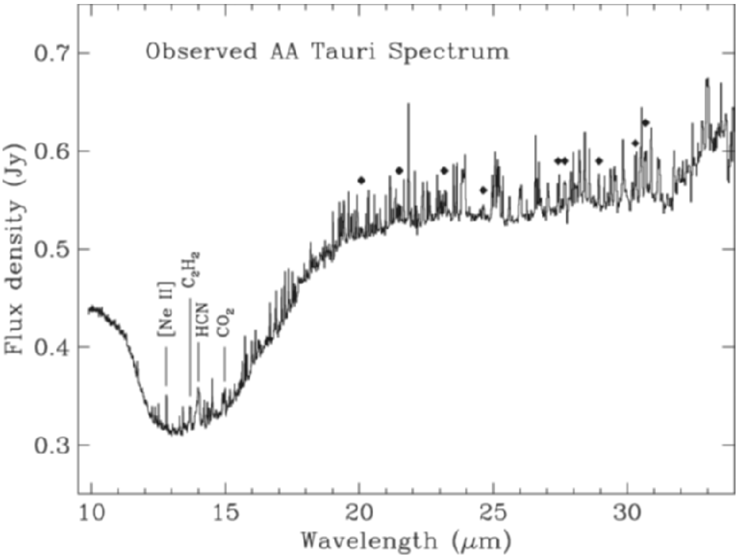

Fig. 6.12. Sun-like star AA Tauri in our galaxy displays mid-infrared signatures of organic compounds in its protoplanetary disk as revealed by *Spitzer Space Telescope*'s infrared spectrograph. From [29]. Reprinted with permission from AAAS.

surface. The "image" product is called a cube because it has not only length and width, but also the "depth" of spectral data. Reference [32] describes the *Cassini* Visual and Infrared Mapping Spectrometer observations of the *Huygens* landing site on Titan, and reference [33] describes discoveries by the *Galileo* Jupiter orbiter's NIMS instrument. Reference [34] describes *Cassini*'s UV Imaging Spectrograph observations and results.

Thermal Emission Spectrometers These passive remote-sensing instruments measure temperature and infrared emissivity of their targets. In doing so they provide key data needed to determine chemical compositions. While in orbit, the *Mars Global Surveyor*'s TES, developed by Arizona State University, measured thermal infrared energy emitted from Mars to study Mars's atmosphere and its geology. It gave scientists a first detailed survey of Mars's composition, as reported in reference [35].

The miniature thermal-infrared emission spectrometer (Mini-TES), was developed also by Arizona State University, for the Mars Exploration Rovers *Spirit* and *Opportunity.* It scans the local Martian surface and reports IR emission and temperature in three-dimensional views, giving information for determining the chemical (mineral) composition of its targets in its neighborhood on the surface, and of the lower atmospheric boundary layer. The instrument collects light through a Cassegrain telescope whose periscopic feed can swivel 360° in azimuth. Its detector is crystalline deuterated triglycine sulfate, sensitive to wavelengths from 5 to 29 μm.

Mars Exploration Rovers Mini-TES surface results are presented in reference [36], and a Mini-TES Mars atmospheric observation appears in reference [37].

Neutron Spectrometers are passive remote-sensing instruments that sense not light, but the energy distribution of free neutral subatomic particles, and are useful for detecting hydrogen atoms on or near the surfaces of solar-system bodies. These atoms serve as a good marker or proxy for the presence of water molecules, each with two hydrogen atoms. Neutron spectrometers can also detect traces of hydrogen implanted on an airless body's surface by the solar wind. To remotely detect hydrogen, the instrument identifies "cool" (low-energy) neutrons in the environment, which are those that have bounced off nuclei of hydrogen atoms somewhere on a solar-system body's surface.

Cosmic rays[21] colliding with atoms in the target body violently dislodge neutrons and other subatomic particles, and can cause the emission of gamma rays when atoms excited by a collision return to their normal state. Some of the neutrons escape directly to space, as high-energy "hot" neutrons. Other hot neutrons go into the crust, where they collide with other atomic nuclei, bouncing around like ping-pong balls. If these neutrons only run into heavy atoms, they do not lose very much energy in the collisions, and are still traveling at close to their original speed when they finally bounce off into outer space. Imagine ping-pong balls bouncing off rocks. They still have "warm" velocities when they reach a spacecraft's neutron spectrometer.

If neutrons collide with something near their own mass, though, they lose energy — imagine ping-pong balls colliding with other ping-pong balls. They leave the area with lower energy, to be detected as "cool" neutrons in the instrument. These, together with evidence such as a drop-off in the number of "warm" neutrons detected, help provide evidence for hydrogen.

Neutrons are typically detected using "scintillators," materials such as lithium-rich glass which give off a pulse of light when struck by a neutron, its brightness directly related to the neutron's energy.

Reference [38] describes *Lunar Prospector*'s evidence of water ice on the Earth's Moon based on results from its neutron spectrometer. The *Mars Odyssey* spacecraft also carries a neutron spectrometer [39].

Gamma-Ray Spectrometers are passive remote-sensing instruments. By measuring the spectra — the distribution of energies — of gamma rays naturally being emitted from a solar system body, scientists can identify signatures of a variety of elements in the instrument's data return. As mentioned above, these gamma rays include emissions from hydrogen, and therefore can also imply the presence of water.

The source of gamma rays that the spectrometer measures can be either radioactive elements on the target body, or collisions with cosmic ray particles. Measurements of gamma-rays' energies (or wavelengths, see Equation 6.1) serve to sketch a signature of the atom that emits it. Gamma rays may be detected using a high-purity germanium semiconductor crystal, which produces pulses of electric charge when interacting with gamma rays.

The *Messenger* spacecraft carries a gamma-ray and neutron spectrometer instrument (GRNS) for use in Mercury orbit beginning in 2011. Results from this instrument should answer the question of whether there is frozen water within perpetually shaded craters at Mercury's poles, suspected based on radar observations from Earth described in reference [40]. Reference [41] describes evidence for subsurface water ice on Mars based on results from the *Mars Odyssey*'s gamma-ray spectrometer. The *Phoenix* lander was sent there in 2008 to confirm this finding.

6.3.7 Mass Spectrometers

Mass spectrometers are direct-sensing instruments that actively process their samples. On a spacecraft, they admit substances, often in the gaseous state, and determine the chemical species present in the sample, called the *analyte.* They do this by first ionizing the analyte, and then measuring its mass-to-charge ratio. The quantity of charge, Q, resulting from ionization can be inferred theoretically, resulting in determination of mass, m. The measurement of its mass-to-charge ratio, Q/m, involves subjecting the ion analytes to electric and magnetic fields in a mass analyzer, and sorting them into a detector on the basis of the way they respond to these forces. The amount a particle is deflected when subjected to measured force within the instrument depends on its Q/m; the less-massive ions are deflected more than the higher-mass ions according to Newton's second law of motion (see page 54). The instrument's detector registers the number of particles of per atomic mass unit sensed. Mass spectrometers on interplanetary spacecraft are used typically to identify unknown atomic species and compounds in the samples it takes in from atmospheres, comet ejecta or similar plumes, and from planetary surfaces.

A unit often used for expressing atomic mass is the dalton.[22] (this is not an SI unit per se, but SI accepts its use.[23]) One dalton is approximately[24] equal to the mass of one proton or one neutron — the electrons have very little mass — thus a value of 1 Da would indicate the presence of hydrogen, a single proton in a mass spectrometer, and a value of 44 Da would indicate the presence of carbon dioxide, CO_2, where:

One carbon atom, typically with six protons and six neutrons $\approx$ 12 Da, and
Two oxygen atoms, each with eight protons and eight neutrons $\approx$ 32 Da.

To imagine the physical operation of a mass spectrometer, picture a person standing in place throwing objects the size of baseballs. The thrower imparts a similar amount of force to each object, and each is also subject to the constant force of Earth's gravity. Knowing the forces involved, one can estimate or measure the mass of each object thrown. A baseball will go farther than a baseball-size lead ball, given equally applied forces, due to its greater mass. A ball of styrofoam might go farther than a baseball (if we were to ignore air resistance). Registering the numbers of objects piling up at different distances from the thrower provides a report on the number of objects in each category of mass — a mass spectrum.

The *Huygens* mass spectrometer applied various oscillating electric forces to the stream of analyte ions to separate them for measurement. For example, when it came time to apply a 120 V field oscillating at 2 MHz, ions of 16 Da would resonate and pass to a detector while other, non-resonant ions could not make it all the way to the detector. Other voltage-frequency combinations selected ions of other masses for detection. An online animation, reference [42], clarifies the concept nicely.

Each ion that reaches the detector typically collides with a metal target, releasing a shower of electrons, which constitute an electronic signal that is then amplified, analyzed, and reported in telemetry.

Reference [43] describes the detection of polymers with the mass spectrometer on the *Giotto* spacecraft that encountered Comet Halley in 1985. A technical description of the Ion and Neutral Mass Spectrometer on *Cassini*, and the results of its encounter with the icy plume issuing from Enceladus are presented in reference [44]. Reference [45] reviews *Viking*'s use of a mass spectrometer on the surface of Mars in 1976. On *Viking* (and the 2008 *Phoenix* lander as well), as in many applications such as atmospheric analysis, additional instruments or laboratory-like processors on the spacecraft conditioned and fed various samples into a mass spectrometer.

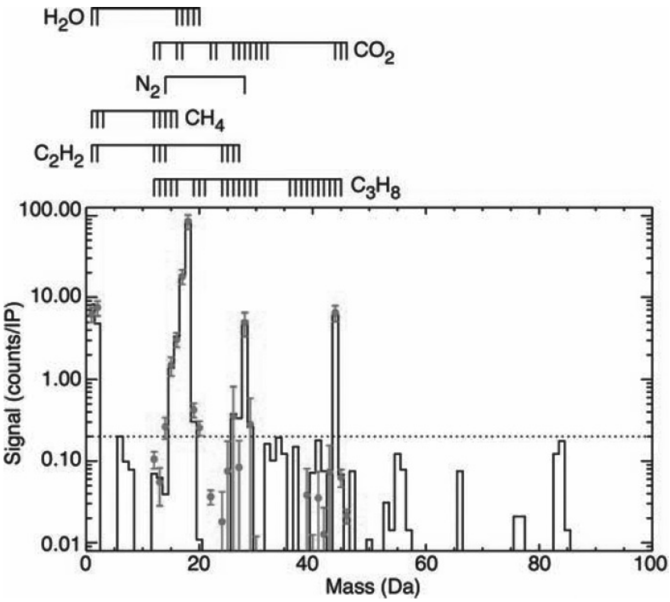

Fig. 6.13. The *Cassini* Ion and Neutral Mass Spectrometer sampled Enceladus's icy plume during a close flyby on July 14, 2005. It registered molecules whose atomic mass correspond to H_2O, CO_2, N_2, CH_4 (methane), C_2H_2 (acetylene), and C_3H_8 (propane). Vertical axis values are counts per integration period. Dotted horizontal line shows the 1-σ noise level. From [44]. Reprinted with permission from AAAS.

6.3.8 Atmospheric Analysis Instruments

Atmospheric analysis instruments are direct-sensing instruments (Appendix B has one example). As with mass spectrometers, their role as "laboratory in a box" qualifies them qualify for the "active sensor" classification, although some may include strictly passive components such as thermometers. The active instruments may carry out specific laboratory routines involving many valve operations to route, prepare, separate, detect, analyze, and report on samples of atmospheric gas. Reference [46] provides a general description of *Huygens*'s atmospheric instruments.

Gas Chromatographs, (GC), such as the one aboard the European Space Agency's *Huygens* Titan probe, separate a sample of mixed gases, the analyte, into its constituent gasses. It's fairly simple in principle — it could almost be described as a filter — but a GC is complex to build. Once its job separating is done, a GC passes the analytes in time order according to species, to a detector.

The "column" is where a GC accomplishes the task of separation. The column is a long thin tube. On earthbound GCs the tube is usually made of glass, but for use on a spacecraft glass is too fragile. The tube is made of stainless steel called "silico" steel whose interior wall has a glassy quality. *Huygens*'s columns are capillaries up to 20 meters in length. Applied to the interior walls is a chemical coating, the molecules of which are known to hinder the passage of specific gasses, although the coating doesn't prevent passage of a specific gas the way a filter holds back particulate matter from flowing oil or water. The coating just adsorbs them (retards their flow) while a different gas in the sample flows by more quickly. All the analytes eventually exit the column, propelled by the carrier gas, just at different times. There may be multiple columns. *Huygens*'s GC fed three columns, each having a different interior coating chemistry known to operate on a different set of gasses.

Once a spacecraft's GC is turned on, it is probably expected to continue operating for the life of the spacecraft, which may be on the order of hours while it parachutes to the surface as did *Huygens*, or toward its deeper levels, as did *Galileo*'s probe. When it is first turned on, the GC opens a valve to permit a pure "carrier" gas to begin flowing through all the columns. The gas chosen does not chemically react with the columns' coatings. It continues flowing through the columns as long as the instrument operates. *Huygens*'s GC had a 3-liter supply of hydrogen for carrier.

After the carrier gas has been flowing for a specific period, a freshly acquired sample of the atmospheric gas is introduced by opening a valve for a short period and admitting the analyte. The carrier gas, already flowing, mixes with it and propels it through the column(s) under specific pressure and temperature conditions. The separate gasses of the analyte then emerge from the GC at different times. The GC feeds these products to the next science instrument, usually a mass spectrometer, which detects and quantifies each species of element or compound present in the sample. The combination of GC and mass spectrometer is known as a GCMS.

Huygens 's GCMS took samples every thirteen minutes. Ten of these minutes were spent conducting analysis of a sample, and three minutes each cycle the carrier gas was permitted to clean and purge the columns in preparation for the next sample to be taken. Reference [47] describes findings from the *Huygens* GCMS and other *Huygens* instruments.

Aerosol Collector and Pyrolizer, (ACP) instruments (direct, active) collect and prepare samples to feed to a GCMS instrument. Aerosols (any particles suspended in the atmosphere such as cloud droplets) are drawn in by the ACP and separated from the gaseous atmosphere. They are then processed by evaporating then pyrolizing — heating until they turn to gas — and then transporting them on cue to the next instrument, the GCMS. Reference [48] considers exobiological implications of the *Huygens* ACP results.

Atmospheric Structure instruments make direct-sensing measurements and report on physical properties such as atmospheric pressure and temperature during the spacecraft's mission, using passive-mode sensors such as barometers and thermometers. The *Huygens* atmospheric structure instrument (HASI) also used active means to measure electrical properties of the atmosphere including conductivity, the electric component of electromagnetic waves, DC electric field strength, and ion conductivity. HASI measured accelerations imparted to the spacecraft and used a radar altimeter to measure height above the surface when it was below 60 kilometers altitude. See page 327 in Appendix B. Reference [47] describes findings from HASI and other *Huygens* instruments.

6.3.9 Active Spectrometers

These may be classified as active direct-sensing instruments if instrument hardware comes in contact with the target (such as an APXS) and active-remote if they affect their target and capture results at a distance (such as a ChemCam). Appendix B has three examples.

On the macroscopic scale, one can determine some characteristics of an object by tapping it and sensing how it responds. Without picking an object up, you can tell whether it's made of glass or tin just by the way it responds to a tap. Active spectrometers operate on the quantum level in an analogous way. The device "taps" a sample's atoms and molecules by shooting nuclear particles or high-energy photons into them, then observing the response in an appropriate part of the electromagnetic spectrum.

Alpha-particle X-ray Spectrometer (APXS) instruments are designed to be placed in contact with their targets. An APXS bombards its target, typically a rock or surface soil, with alpha particles — helium nuclei made of two protons and two neutrons — from a radioactive source inside the instrument. The Mars Exploration Rovers' APXS's alpha source is radioactive curium, ^{244}Cm. When the particle strikes the target mineral, it penetrates only a short distance and interacts with atoms in the target. The interactions result in alpha-particle backscatter, proton emission, and X-ray emission. The instrument detects and reports on the energies sensed in each of these modes, and analysis of spectral signatures in the data indicates the target's mineral composition. Reference [49] elaborates on the APXS's technique and presents some results from Mars. APXSs by nature don't help much in identifying the atoms heavier than silicon in a sample, for example the important constituent iron.

Mössbauer Spectrometer instruments function in a manner similar to the APXS, but the Mössbauer uses a radioisotope that emits gamma rays of just the right energy range to "ping" a rock's atoms. The resulting spectrum of emissions from the target mineral is especially helpful in determining the presence of iron, aiding geological analysis. Reference [50] describes Mössbauer findings from the rover *Opportunity* related to the iron-bearing minerals jarosite and hematite on Mars.

X-Ray Fluorescence Spectrometers bombard their targets with high-energy photons such as X-rays or gamma-rays then register the spectra of secondary, lower energy X-ray emissions from the target. This process is "fluorescence," the same process one can observe in the "black light" fluorescence of many everyday objects; bombarded by higher-energy UV photons, they emit lower-energy visible light. Reference [52] describes the *Hayabusa* spacecraft's use of X-ray fluorescence spectrometry in the analysis of an asteroid's minerals.

Laser-Induced Remote-sensing Spectrographs operate from a distance of several meters away. They bombard their targets with focused high-energy photons in the infrared, causing a small part of the target to vaporize at high temperature. Then they observe the spectra of emissions from the hot gas created on the target. Reference [53] describes the *Mars Science Laboratory* spacecraft's anticipated use of a Laser-Induced Remote-sensing Spectrograph called "ChemCam" intended for analysis of Martian minerals.

6.3.10 Magnetometers

Magnetometers are passive direct-sensing instruments (Appendix B has one example.). These instruments are often found on interplanetary spacecraft mounted on long fiberglass booms (see page 176). They're kept away from the electric currents and magnetic materials to be found within the spacecraft bus so they can respond to magnetic fields created by the Sun or the planets, as well as disturbances in the magnetic field lines near a planet caused by its satellites.

Magnetometers in common use are of two different designs. Scalar magnetometers sense only the magnitude of a magnetic field; vector magnetometers can sense a field's directional component. Dual-technique magnetometers can provide coverage in either mode. Each *Voyager* carries four flux-gate magnetometers which are returning data as they explore the outer reaches of the Sun's magnetosphere. References [54] and [55] describe *Voyager 1*'s 2004 penetration of the solar-wind termination shock at 94 AU — ninety-four times the Sun-Earth distance. *Voyager 2*'s magnetometers and other instruments sensed its having penetrated the shock farther south and at about 86 AU in July 2008 [56].

Flux-gate magnetometers use alternating electric currents in coils of wire to continuously magnetize, de-magnetize, and re-magnetize a susceptible core. Measuring the amount of current required to change the core's saturation will vary if there is an ambient magnetic field aligned in such a way that it makes it easier for the coil to saturate the core in one polarity than in another.

Helium magnetometers, instead of using coils and cores, use high-frequency alternating electric current discharges and infrared optical pumping to excite ionized helium in a cell. And not too unlike the flux-gate magnetometer, measuring the changes in energy absorbed by the helium indicates the effects of an external magnetic field.

Reference [57] recounts the discovery of initial evidence for Enceladus's plumes by the magnetometer on *Cassini*, after which high-phase imaging, and flights through the plume were performed.

6.3.11 Radio and Plasma Wave Detectors

Radio and plasma wave detectors are passive remote and direct-sensing instruments. They are open-loop receivers whose commandable settings can span frequencies from below audio to tens of MHz in radio waves and plasma waves generated by various phenomena in the target planetary environment.

Radio waves propagate in vacuum. Plasma, a sparse fluid of electrons and ions in a spacecraft's environment, can propagate waves of many varieties. Reference [58] explores the physics of plasma waves.

Radio and plasma wave instruments are related in that the frequencies of interest are in the same ranges, and that they can often share the use of a single antenna system. *Voyager*'s Planetary Radio astronomy instrument and its Plasma Wave instrument share a dipole antenna consisting of two 10-meter-long metal rods that deployed from a reel after launch. *Cassini*'s Radio and Plasma Wave instrument uses three such antennas.

The instruments are designed to detect radio emissions, plasma waves, plasma temperatures, densities, and density fluctuations. They measure properties of waves including frequency, amplitude, polarization, and direction of arrival. They help investigate these phenomena within planetary magnetospheres and ionospheres, the solar wind, and interactions between magnetospheres and solar wind. They can detect lightning on a planet, and they can detect dust particles that collide with the spacecraft and ionize.

Reference [59] describes the results of searching for lightning on Saturn using the *Cassini* radio and plasma wave science instrument.

6.3.12 Impact and Dust Detectors

Impact and dust detectors are passive direct-sensing instruments.

The *Pioneer 10* and *Pioneer 11* spacecraft, which were the first to fly through the main asteroid belt and navigate the vicinities of Jupiter and Saturn, each carried 234 impact detectors consisting of individual thin steel cells on the back of the HGA. At the time, it was not known whether the asteroid belt would pummel and sandblast a passing spacecraft, or whether it was a benign environment. Fortunately for outer-planet exploration, the latter is true, and a total of eight spacecraft have transited the belt.[25] Each of *Pioneer*'s impact-detector cells contained pressurized gas. When these cells were impacted, measurement of the rate of gas leakage would characterize the impactor by the size of the hole it created in the thin steel. There were also two optical meteor detectors. Results from the impact cells on these spacecraft indicated some initial penetrations in the vicinity of Earth, decreasing until the spacecraft flew by Jupiter. *Pioneer 11* also recorded penetrations while flying by Saturn. Reference [60] describes *Pioneer 10*'s characterization of particles in the asteroid belt.

Direct observations of dust grains in interplanetary space are of interest for learning about processes that led to the origin of our solar system, and by extension, those of exosystems. The *Vega*, *Giotto*, *Galileo*, *Ulysses*, *Stardust*, *Rosetta*, and *Cassini* spacecraft were equipped with dust analyzers for this reason, and to help investigate their targets' localities.

The *Cassini* spacecraft's Cosmic Dust Analyzer (CDA) is an advanced version of the one *Galileo* operated in Jupiter orbit. Operating in Saturn orbit, it is capable of measuring and reporting many properties of dust grains that impact the detector up to once per second, including their mass, speed, charge, arrival direction, and elemental composition. The instrument's high-rate detector component can count up to 10,000 impacts per second. As a dust particle enters the bucket-shaped dust analyzer, a series of four variously inclined grids sense its passage based on the grain's electric charge. The electrical signals from all the grids, generated by the grain's passage, can be analyzed to determine the grain's charge and its direction of flight, and a time-of-flight mass spectrometer provides the mass and species data. Animations on the CDA investigators' website[26] illustrate these operations.

Reference [61] describes the *Cassini* CDA investigation of Saturn's E Ring of fine particles, and reference [62] is a basic text on dust in interplanetary space.

6.3.13 Charged Particle Detectors

Charged particle detectors are all passive direct-sensing instruments. They are sensitive to particles much smaller than dust grains. These instruments characterize the presence of individual species of neutral and ionized atoms, and subatomic particles: electrons, protons, and nuclei.

High-energy Particle Detectors on a spacecraft characterize energetic electrons trapped within planetary magnetic fields, and the energy and composition of incident atomic nuclei — cosmic rays — originating from the Sun and other locations in the universe. *Voyager*'s Cosmic Ray Subsystem instruments measure the presence and angular distribution of particles from planets' magnetospheres, and from sources outside our solar system in interstellar and intergalactic space. The *Voyager* instruments are sensitive to electrons of 3-110 MeV and nuclei with energies from 1-500 MeV and species from hydrogen to iron. The Energetic Particle Detector on *Galileo* was sensitive to the same nuclei with energies from 20 keV to 10 MeV. Reference [63] describes *Voyager*'s cosmic ray subsystem and the effects of a local interstellar magnetic field.

Low-Energy Charged-Particle Detectors are designed for sensing particles with mid-range energies, higher than plasma and lower than cosmic rays. *Voyager*'s low-energy charged particle detector is sensitive from around 10 keV to about 3 MeV.

The *Ulysses* and *Cassini* spacecraft were equipped with instruments of similar capability. The low-energy charged particle environments of Jupiter and Saturn measured by *Voyager* are presented in references [64] and [65].

Plasma Instruments measure properties of ions and electrons in the spacecraft's immediate vicinity including density, pressure, velocity, and chemical structure. The detectors in general resemble mass spectrometers designed to characterize ions and electrons. Reference [66] describes the plasma composition and dynamics found within Saturn's magnetosphere using the *Cassini* plasma spectrometer.

6.3.14 Summary

This section has not covered all the instruments that are in use in interplanetary flight. Rather, the sample presented may provide a sense of the kinds of instruments aboard spacecraft and the ranges of sensitivities that support investigations going on all across our solar system today.

6.4 In-Flight Science Experiments

Remote and direct-sensing instruments acquire data as constantly as possible during the normal course of a spacecraft's mission while encountering its targets. Science teams take advantage of every opportunity to operate their instruments to take images, spectra, particle and field data as the spacecraft follows its trajectory. Beyond these routine operations there are often unique opportunities to carry out experiments that use the instruments and spacecraft capabilities in special ways. Such important opportunities for in-flight science experiments are often planned into a mission long before it launches.

6.4.1 Solar and Stellar Occultations

Solar and stellar occultation experiments are passive remote sensing experiments.

To *occult* is to hide in the transitive sense of the word. From the spacecraft's point of view, a target such as a planet occults the Sun or a more distant star while the spacecraft's motion carries it into position behind the object. Solar and stellar occultations present once-in-a-lifetime opportunities for flyby spacecraft such as *Voyager* (Jupiter, Saturn, Uranus, Neptune) or *New Horizons* (Pluto and Kuiper belt). These occultation events are planned in advance — typically pre-launch — so that the appropriate passive remote-sensing instruments have been included on the spacecraft and so that they have been commanded to be viewing the Sun or the distant star while it disappears behind an atmosphere of a planet, a satellite, or a ring system. Obtaining spectral data during such an event offers the ability to investigate the chemical composition, structure, pressure, and other aspects of the target occulting the Sun or star. Figure 2 in reference [67] lists the abundances of seven molecular species measured, by absorption features in the spectrum, during a stellar occultation of Titan by *Cassini*'s Ultraviolet Imaging Spectrograph.

Stellar occultations are valuable for measuring structure in a planetary ring system, as the starlight's intensity changes and blinks as rings pass in front of the star. Reference [10] describes a stellar occultation *Voyager* observed with Saturn's rings. Reference [69] describes two stellar occultations the *Cassini* spacecraft observed while investigating the geyser plumes on Saturn's small icy moon Enceladus. Reference [70] breaks the news that Saturn's rings might be older than widely thought due largely to new results from stellar occultation experiments.

Appendix C showcases the unique imaging data which the *Cassini* spacecraft obtained, deep in shadow, during an occultation of the Sun by Saturn in October 2006.

Fig. 6.14. *Voyager 2* backlit image of Titan obtained during solar occultation on August 25, 1981. In addition, spectral instruments obtained data on Titan's atmospheric composition and structure. See reference [68] for information on this and other *Voyager* imaging from Saturn. Image courtesy NASA/JPL.

6.4.2 Radio Science Occultations

Radio science (RS) occultation experiments are active remote-sensing experiments. *Voyager 1*'s successful execution of the crucial Titan Earth occultation in 1981, during which the Radio Science team measured the diameter of the moon's solid body, invisible until then due to its hazy atmosphere, is covered in reference [71]. The radio occultation experiment also provided new data on the nature of the thick atmosphere on this largest of Saturn's satellites. Passing the S-band and X-band radio carrier signal through Titan's atmosphere — telemetry had been turned off to add power and purity to the carriers — *Voyager* revealed that the temperature and pressure on Titan permitted methane to possibly exist in the vapor, liquid, and solid state, just as water has its triple-point near Earth's surface.

Radio Science measurements such as these are obtained by observing on Earth, using the DSN as a part of the science instrument, how the spacecraft's radio signals are refracted and attenuated in the distant target atmosphere. Additional effects on the radio signal, such as scintillation, polarization, and changes in phase or frequency, can reveal many other atmospheric properties.

Obtaining basic information about Titan's atmosphere in occultation was a high-priority scientific objective for the *Voyager* project. Had *Voyager 1* failed for some reason to execute the important radio occultation experiment, the still-approaching *Voyager 2* spacecraft would have been redirected to make a repeat attempt. In doing so, the new trajectory for *Voyager 2* would have sacrificed the ability to tour the distant systems of Uranus in 1986 and Neptune in 1989. Titan and its atmosphere were such important scientific targets that *Voyager 1*'s trajectory to Pluto was traded for the ability to conduct the occultation experiment.

When executing a radio science occultation experiment, the spacecraft is typically commanded to generate its downlink frequency by reference to an internal frequency source, which on many spacecraft is an *ultra-stable oscillator* (USO). While the USO has inferior frequency stability to that of an uplink signal for generating a *coherent* downlink stable enough for precise navigation (see page 63), the USO is a stable enough reference for conducting short-duration occultation experiments. Any uplink signal to the spacecraft will be cut off by the body being probed during occultation, so the spacecraft must operate in *non-coherent* mode during the experiment.

Radio science occultation experiments have been carried out at all the major planets having atmospheres, and of course at Titan. Reference [72] is a succinct technical description of results from the *Voyager 2* Neptune and Triton radio science occultations in 1989. Reference [73] describes the first direct measurements of Mars's atmosphere. These were made via radio science occultation.

As an indication of the accuracy — thus the high value — of radio science occultation experiment data, the temperatures that the *Huygens* Probe reported while descending through Titan's atmosphere on a parachute in 2005 proved to be in excellent agreement with the values obtained during *Voyager 1*'s 1981 radio occultation. Figure 1 in reference [74] shows their remarkable concurrence.

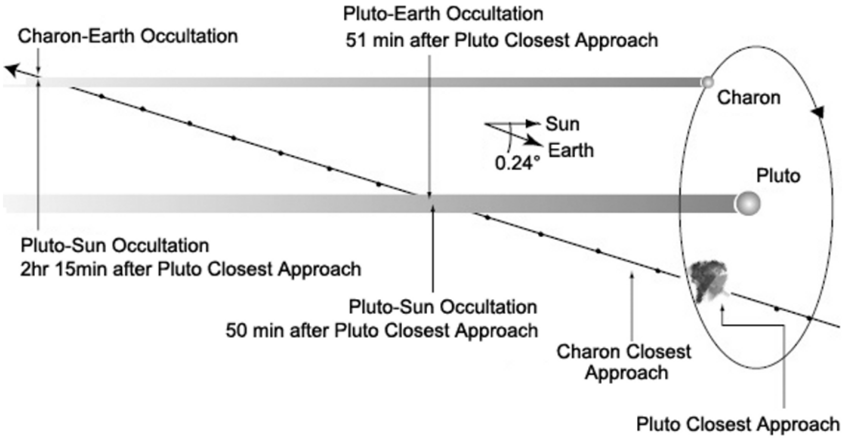

Fig. 6.15. The *New Horizons* spacecraft's planned flyby encounter of dwarf planet Pluto and its satellite Charon on July 14, 2015, with occultation experiments. Closest approach distance to Pluto is 10,000 kilometers; flyby speed is 14 kilometers per second with respect to Pluto. Closest approach to Charon is 27,000 kilometers. Pluto's two smaller moons will also be observed, through there are no occultations of them. Ticks on the trajectory asymptote are at 10-minute intervals. Image courtesy JHU/APL/NASA.

6.4.3 Radio Science Celestial Mechanics Experiments

Celestial mechanics (CM) experiments are active direct-sensing experiments. What classifies them as "active" is the uplink from DSN and coherent downlink being affected in measurable ways by the target.

Locking the spacecraft's receiver to a stable uplink signal, producing a coherent downlink, and locking the DSN's closed-loop receiver to it is one of the basic requirements of a CM experiment. In addition, the spacecraft is constrained to be in a thrust-free mode, for example spinning for stability or using reaction wheels, to avoid contaminating the experiment with non-gravitational accelerations. The Radio Science team is able to accurately deduce the spacecraft's velocity to a precision on the order of a small fraction of a millimeter per second by measuring the received signal's Doppler shift. Based on precise knowledge of all pre-existing velocities, such as Earth's rotation and revolution, and the target body's and the spacecraft's proper motions, the residual velocity changes seen in the Doppler are attributable to the acceleration to the spacecraft caused by the target body's mass. The mass value for the target as a whole, and under some conditions data on the distribution of mass across the target, are the results obtained from CM experiments.

Given a value for mass, if a model of the body's morphology based on images is also available to scientists, then investigators can accurately determine the body's density — its mass per unit volume — a parameter that provides important clues to its internal composition.

To make best use of the short period of time a spacecraft spends near its target during a CM flyby, it is important to establish a coherent communications link early. A typical practice is to schedule the DSN antenna to begin its uplink one round-trip light time before the spacecraft's downlink is expected to be received on Earth, called an uplink in the blind. This way, the stable uplink reference frequency arrives at the spacecraft just as it is beginning its communications session with Earth, so it can spend a maximum amount of time in coherent mode providing useable Doppler measurements. The *Cassini* encounter with Iapetus described in Chapter 1 used this early-uplink technique.

Not mentioned in Chapter 1, however, was the fact that *Cassini*'s Ka-band transmitter was on, providing an additional pure tone free of telemetry-symbol phase-wiggles, coherent (via a multiplier) to the uplink signal from DSN Station 63 in Spain. Having coherent radio links in different frequency bands permits calibration of the effects of interplanetary plasma, improving the CM experiment's accuracy.

The current estimate for Iapetus's mass is 1.083 g/cm^3, only slightly more than that of water and suggesting only a small amount of rocky material present. Reference [75] presents this (with refined precision) and additional CM findings in the Saturnian system. *Cassini* measured the density of Saturn's moon Hyperion in this way, finding that the spongy-looking object is about half as dense as that of water, which has a density close to 1 g/cm^3. This means Hyperion must be very porous. Reference [76] describes the *NEAR-Shoemaker* spacecraft's CM experiment, which operated in similar fashion, to investigate the mass of the main-belt asteroid 433 Eros in December 1998. References [77] and [78] describe the *Hayabusa* spacecraft's characterization of near-Earth asteroid 25143 Itokawa using CM mass determination and other techniques.

6.4.4 Superior Conjunction Experiments

Spacecraft that operate in or near the ecliptic plane will pass behind the Sun, or nearly so, once a year as viewed from Earth. The moment the Sun, Earth, and spacecraft are aligned with the spacecraft on the far side of the Sun is known as superior conjunction. The angle measured between Sun, Earth and the Probe (spacecraft), or SEP angle, decreases as the Earth's orbital motion makes the spacecraft appear to approach the Sun in the sky prior to conjunction and move away after. Generally, while the SEP angle is less than 3°, communications involving telemetry may not be possible between Earth and spacecraft due to radio noise from the Sun. During a period of several days centered around superior conjunction, the spacecraft is usually commanded to carry out few if any tasks, to help ensure its safety in the absence of the ability to communicate. During this period, at least three kinds of special experiments may be possible:

1. Solar Corona Characterization Radio Science Experiments
   The superior conjunction period may open up opportunities to study the Sun via active remote sensing. Scientists interested in characterizing the solar corona [79] may take advantage of the radio link from the spacecraft by arranging to have the spacecraft turn telemetry off to produce an unperturbed signal. While the Sun's outer atmosphere modifies the carrier radio signal received from the spacecraft, the radio scientist records and later analyzes effects imposed on it by the Sun such as scintillation, attenuation, and rotation of polarization.
2. General Relativistic Radio Science Experiments
   The period close to solar conjunction, in some cases, can present an opportunity to conduct another kind of active direct-sensing experiment. General Relativity (GR) holds that the path of light or other electromagnetic radiation bends by a detectable amount in the presence of a strong gravitational field, due to the space-time curvature caused by the mass. When the opportunity arises to measure the distance between Earth and a spacecraft while its radio link passes close by the massive Sun, the GR effects of time dilation in a strong gravitational field can be measured. Reference [80] describes an experiment carried out with *Cassini* in 2002, confirming the general-relativistic prediction to an accuracy of twenty parts per million, an experimental accuracy fifty times greater than similar measurements had obtained.
3. Engineering Tests
   It is common for an engineering test to be conducted when the SEP is between about 5° and 2°, during which period the Ace sends hundreds of benign "no-op" commands to the spacecraft many times per day. Telemetry, usually set to a low bit rate for the conjunction period, allows telecommunications engineers to tabulate how many commands are being rejected due to solar interference.

6.4.5 Radio Science Gravitational Radiation Searches

Gravitational radiation searches are active direct-sensing experiments.

One of the predictions of General Relativity is gravitational radiation: the emission of gravitational waves that propagate through space-time at the speed of light. They have not been directly detected to date. A binary pulsar was found in 1974 by the American scientists Russell A. Hulse (1950–) and Joseph H. Taylor, Jr. (1941–). Work by Hulse, Taylor, and others confirmed that the pair's orbital period was decreasing by the precise amount predicted by GR if the pulsar were radiating gravitational waves, thus constituting an *indirect* detection of gravitational radiation. Hulse and Taylor were awarded the 1993 Nobel Prize in Physics for this discovery. Taylor confirms the existence of gravitational radiation in reference [81].

Originating from distant events involving the acceleration of immense masses such as orbiting and coalescing neutron stars or binary black holes orbiting their barycenters, gravitational waves are predicted to radiate in specific ways. Upon passage of gravitational waves through our solar system, the effect would be a miniscule change in the distance between spacecraft and Earth that fits a predicted pattern, alternately stretching and compressing space in a way that would rhythmically affect the distance.

Certain spacecraft can participate in searching for the expected deformations in space-time when such waves pass through the solar system. Those using thrusters for attitude control, such as *Voyager*, cannot participate because the relatively large, unpredictable non-gravitational accelerations their thrusters produce would overwhelm any detection of the sought-after signal. The spin-stabilized *Galileo* and *Ulysses* spacecraft, and the *Cassini* spacecraft under reaction-wheel attitude control, have helped conduct gravitational wave searches. Each experiment is conducted when the spacecraft is generally on the same side of the Sun as is the Earth — near opposition — in order to take advantage of the minimal interference from solar plasma on the radio link. The science data consists of long-term continuous measurements of Doppler shift in the coherent radio link between spacecraft and Earth, which would register slight changes in relative speed during a wave's passage. The joint NASA/ASI experiment with *Cassini* was sensitive to frequencies on the order of 10^{-4} to 10^{-1} Hz. Reference [82] describes the gravitational wave search and other radio science experiments for the *Cassini* spacecraft.

Detecting gravitational waves is a high-priority objective for science, and there are Earth-based observatories in several locations being designed and operated to attempt detection. One is the *Laser Interferometer Gravitational Wave Observatory (LIGO),* [83] coordinated by the California Institute of Technology and Massachusetts Institute of Technology. Earth-based gravitational radiation observatories have an inherent lower limit in sensitivity to gravitational waves of about 10 Hz. Space-based detection attempts complement the ground-based experiments because the latter are sensitive to far lower frequencies (longer gravitational wavelengths).

Gravitational Waves vs. Gravity Waves

Note that the term *gravitational wave* refers to the GR effect from cosmological events producing gravitational radiation. The term *gravity wave* refers to a completely different physical phenomenon. The latter is used to describe a type of atmospheric or oceanic fluid oscillation in which equilibrium is restored by the force of a planet's gravity after a disturbance in the fluid.

6.4.6 Bistatic Radio Science Observations

Bistatic radio science observations are active remote sensing experiments. During a close pass of a target of interest, the spacecraft's radio transmissions are commanded to shut off any telemetry or other modulations so they produce pure, strongly focused tones in the microwave bands such as S-band, X-band, or Ka-band. The spacecraft's attitude is commanded to continually follow precise attitude and rotational rates designed by the experimenter. While flying by the target, the spacecraft rotates so that its radio beam traces out a precise path across its surface in such a way that its reflected and scattered energy will be directed toward Earth.

To convey a sense of how this works, imagine holding a laser pointer, aiming its beam so it strikes a mirror on a table as you walk by. But you have to keep aiming it accurately enough that the bright spot on the ceiling from your laser pointer's reflected beam remains on a specific target, say a fire sprinkler, located across the room. This illustration doesn't account for motions of the target body (the mirror) or the Earth (the fire sprinkler) as is the case in an actual bistatic experiment.

Experiments of this nature have been performed using a spacecraft situated near Venus, Titan, the Earth's Moon, and other objects. Results of bistatic radio science experiments are produced by analyzing the properties of the returned, mostly-backscattered signal. But these observations also have the possibility of returning a *specular* reflection, as from a mirror on a table, if the spacecraft's radio beam were to strike a calm liquid surface. Such a result would add additional data for interpreting SAR images of Titan's surface such as in Figure 6.8.

Note that in some literature this kind of experiment is also called "bistatic *radar*" due to its roots in earthbound radar technology, but it normally wouldn't involve the spacecraft's *radar instrument*, such as a SAR instrument. Reference [84] describes a bistatic experiment that the lunar-orbiting *Clementine* spacecraft carried out to measure polarization effects on the signal returned from the lunar surface.

6.4.7 Gravity Field Surveys

Gravity field surveys are active remote-sensing experiments. These involve a spacecraft orbiting a solar system body. The minute Doppler shifts in the radio signal in coherent mode are the science data. They reveal the small accelerations as a spacecraft approaches a concentration of mass on or beneath the body's surface. Receding from the mass concentration, the spacecraft slows by a small amount. These changes in speed during the spacecraft's orbit provide enough data for the investigator to map the object's mass distribution.

Mapping the gravity field of a planet or other object serves at least two purposes. First, accurate navigation in orbit at a planet or other body requires a model of the body's gravity field variations to be able to predict small perturbations to a spacecraft's orbit. Second, gravity field measurements have the unique advantage of revealing mass distribution both above and below the body's surface. Such measurements are valuable in analyzing the nature of features identifiable in imaging data. Gravity field mapping of Earth helps geologists identify mineral and petroleum resources. It also helps characterize the basic geological processes going on within the planet and affecting the shape and properties of its surface.

One of the *Juno* mission's primary scientific objectives is to characterize the gravity field of Jupiter to learn about how the planet's mass is distributed. Reference [85] describes *Mars Global Surveyor*'s gravity-field mapping of Mars.

6.4.8 Calibrations and Ground Truth

Scientific measurements are made by using instruments that have quantifiable error. Calibrations are carried out by instruments on a spacecraft to acquire baseline data for comparison with an actual observation, thus allowing instrument errors to be quantified.

Prior to carrying out an infrared spectral measurement of a target, the IR spectrometer will be aimed toward a spot of deep space free of any bright objects in its field of view. An absolute reference value is obtained, and any defects in the instrument's sensors can be recorded and later included in data analysis. For the same reason, radio science experiments always begin and end with a measurement of the spacecraft's unobstructed, unmodulated radio tones lasting tens of minutes before and after encountering the target. Many imaging instruments may be aimed toward a special calibration target mounted on the spacecraft bus. *Voyager*'s calibration target was a rectangular plate mounted below the bus (see Appendix A, page 294) coated with a material of known grayscale and albedo values. The spacecraft's scan platform could aim the cameras so that the target plate would fill the field of view for calibration. The same target plate on *Voyager* serves as the thermal radiator for the spacecraft's electrical system regulator, so *Voyager*'s infrared instrument, the infrared radiometer-spectrometer (IRIS) could be calibrated. The operation of every science instrument and experiment includes some sort of procedure or other means for calibrating its measurements.

Mars landers have calibration targets with grayscale and color samples that have been photographed and measured accurately before launch so that images from Mars can be adjusted to most closely match the brightness and spectral characteristics of scenes on Mars. Images returned from the 465 °C surface of Venus by the Soviet landers *Venera 9* and *Venera 10* in 1975, and *Venera 13* and *Venera 14* spacecraft in 1982 included imaging targets for calibration against the Venusian basalt (see Figure 6.16). Reference [86] describes use of the *Venera 13* calibration target in image color reconstruction.

If an area of a target, such as the surface of Mars, has had direct *in-situ* measurements made of its mineral content, or high-resolution imaging or spectroscopy of its local environs by a landed spacecraft, such measurements serve as *ground*

Fig. 6.16. The Soviet *Venera 13* spacecraft returned this image of the Venusian surface east of Phoebe Regio in the planet's equatorial region. Image calibration target is visible on the right. A drilling arm gathered samples for the onboard X-ray fluorescence spectrometer to analyze. Image courtesy NSSDC/GSFC.

truth data to calibrate or otherwise aid interpretation of similar data taken of other areas from orbital height. As an illustration, the Mars Exploration Rover *Opportunity* identified the iron-bearing mineral hematite on the surface, confirming observations of the mineral from orbit by *Mars Global Surveyor*'s thermal emission spectrometer. *Opportunity* also identified millimeter-sized hematite-rich spherules, which scientists nicknamed "blueberries," embedded within layered rock.

6.5 Science Data Pipeline

Upon reception and decoding by the DSN, telemetry data is delivered to the flight project operations team. Any portions of data that were expected to be present in a recent downlink, but are missing, are the concern of data management personnel who use automated tools to account for the data. By reviewing operations logs and problem reports, they determine whether it may be possible to recover the missing data. Often, missing data can be recovered easily from within the DSN or its communications facilities — indeed it happens automatically in most cases after a few hours. If data goes missing due to reception problems, for example heavy rain at the DSN station, it may be lost for good, unless the spacecraft still has it onboard and can be commanded to replay the missing portion, but in most cases this is an unlikely scenario.

After filling any gaps, a data management engineer ensures that the project's data repository is up-to-date, properly copied to back-up media, and catalogued, with data available online so the science teams can begin to retrieve it, all within minutes or hours of reception on Earth. Science team members are typically PhD-level scientific professionals tenured in academia, and their graduate students, as well as professional scientists and their staff from industry and scientific institutions worldwide.

From a science team's institution anywhere in the world, an authorized user can connect to the data repository and formulate a request — called a query — which when submitted will return the requested data, selected by parameters in the query the investigator is interested in, such as creation time or received time. If two or more DSN stations happened to collect the same data, the query server will automatically select the best-quality data from the repository to fulfill the query.

In addition to science data, the investigator teams need other products to support scientific analysis. To place their observations in precise context are files (called kernels) known as SPICE — an acronym for Spacecraft, Planet, Instruments, C-matrix (camera angles), and Events. These and related files provide the needed context. They include spacecraft and planetary ephemerides, instrument mounting alignments, spacecraft orientation, sub-spacecraft longitude and latitude, distance to target, illumination geometry, spacecraft sequences of events, data needed for certain time conversions, and so on. These products are generated by the Navigation and Ancillary Information Facility (NAIF) under the direction of NASA's Planetary Science Division.[27]

Once the science data and the required kernels have been obtained, the science teams proceed with analysis. Preliminary analysis may take a few hours prior to a news conference, but thorough analysis can require months before results are ready to be submitted for formal publication, and in some cases it can take years or decades before thorough understanding in greater context emerges.

6.5.1 Television, Radio, and Newspapers

When a spacecraft lands on Mars, when a launch occurs, or when a propulsive insertion maneuver places a spacecraft in orbit at a distant planet, the news media are usually on location at the responsible space operations center, reporting on success or failure of the event. Aside from occasional follow-ups that may appear in newspapers, on television or radio, one must usually look elsewhere for information about the progress of an interplanetary mission of interest.

6.5.2 WWW Media

Websites operated by interplanetary exploration projects are usually the first place to find results that are published in their "raw" unprocessed state, long before the scientists responsible for results analyze their data or present their findings in peer-reviewed journals. Flight projects are eager to use the high-leverage vehicle of the Internet, which can reach a large audience without requiring large expenditures, to convey information to the taxpayers in various nations who actually own the missions. These websites may be easily found by searching the Internet using the name of a mission and its target planet or object (including the latter helps disambiguate the search results. For example, searching with words such as, "Voyager Neptune" or "Pathfinder Mars" will produce fewer results having to do with automobiles).

National space agencies' web pages are informative sites to visit. There are currently over three dozen space agencies. Following are some selected organizations (listed alphabetically):

– China National Space Administration: http://www.cnsa.gov.cn
– European Space Agency (ESA): http://www.esa.int
– (French) National Center of Space Research (CNES): http://www.cnes.fr
– Italian Space Agency (ASI): http://www.asi.it
– Japan Aerospace Exploration Agency (JAXA): http://www.jaxa.jp
– Russian Federal Space Agency: http://www.roscosmos.ru

- Ukraine National Space Agency (NSAU): http://www.nkau.gov.ua
- U.S. National Aeronautics and Space Administration (NASA): http://www.nasa.gov

NASA and "Internet Archive," a non-profit digital library based in San Francisco, have made available a comprehensive compilation of NASA's collection of photographs, historic film and video, at http://www.nasaimages.org. The site combines twenty-one major NASA image collections into a single, searchable resource. This is a five-year project at no taxpayer cost. The products are free of charge to the public.

In addition to websites maintained by space agencies and individual space flight projects, the scientific peer-reviewed journals discussed in the next subsection also maintain a presence on the web. Convenient searching and access to many such journals is provided by *SpringerLink,* at http://www.springerlink.com, a leading interactive database for high-quality journals, books, reference works and archives in science, technology, and medicine.

6.5.3 Peer-Reviewed Journals

Peer-reviewed journals such as *Nature, Science,* and many others, publish scientists' findings after careful screening by the editors. They select reputable and important work from among many submissions, then enlist referees from among the authors' scientific peers who are not connected with the work under review. Publication follows only after successful critique.

The scientific journal *Nature* has been published weekly since 1869, born of the increasing scientific progress of nineteenth-century Britain. It is published today by Nature Publishing Group in London and has an estimated weekly readership of 600,000. The website is http://www.nature.com.

Science is a scientific journal with a weekly readership estimated at one million, published by AAAS, the American Association for the Advancement of Science, headquartered in Washington, D.C. It was first published in 1890. The website is http://sciencemag.org.

Fig. 6.17. Publications of a few of many scientific organizations that serve as formal peer-reviewed vehicles for presenting discoveries made using interplanetary spacecraft.

Space Science Reviews, published by Springer Netherlands, is an international journal on scientific space research. Its emphasis is on scientific results from astrophysics and the physics of planetary systems, of the Sun, of magnetospheres and of the interplanetary medium. *Space Science Reviews* publishes invited papers and topical volumes, engaging guest editors with appropriate expertise. The journal may be found online at http://www.springerlink.com/content/102996.

Icarus is the International Journal of Solar System Studies, the official publication of the Division for Planetary Science of the American Astronomical Society (AAS). *Icarus* reports results of new research in astronomy, geology, meteorology, physics, chemistry, biology, and other scientific aspects of our solar system or extrasolar systems. It may be found online at icarus.cornell.edu.

The *Proceedings of the U.S. National Academy of Sciences* (*PNAS*), report on results in the physical, biological, and social sciences. The *Proceedings* may be found at http://www.pnas.org.

Most of the publications referenced throughout this chapter are suitable for readers interested in the technical scientific results of interplanetary missions. For those who may be more interested in the engineering and applied science aspects of interplanetary flight, similar technical publications may be found through the American Institute of Aeronautics and Astronautics (AIAA), or through the IEEE, as well as similar institutions around the world.

The editors of *Science News,* a publication of the Society for Science and the Public, have since 1928 been keeping vigilant watch on the major peer-reviewed journals, publishing concise reports of new developments in all fields of scientific interest. In June 2008, *Science News* reduced its print frequency, and turned instead to the Internet to provide its most up-to-date reports, listing them in print biweekly to subscribers. Online at http://sciencenews.org.

6.5.4 Meetings of Scientific Institutions

There are hundreds of scholarly organizations in the world dedicated to the sciences. Scientists who conduct experiments and operate instruments on interplanetary spacecraft are usually members of one or more of these major scientific organizations and often attend and present to regular and special meetings and conferences held by these organizations in many parts of the world. They include:

- The Royal Society
- American Astronomical Society (AAS)
- Division for Planetary Sciences of the AAS
- Division on Dynamical Astronomy of the AAS
- U.S. National Academy of Sciences
- Royal Astronomical Society
- American Geophysical Union
- European Geophysical Union
- Geophysical Society of America
- Geological Society of America
- Asia Oceania Geosciences Society

Their publications and website carry announcements of upcoming meetings. Not all of them require attendees to be members of the organizations, and public events sometimes are held in conjunction with these scientific peer gatherings.

6.5.5 Hands on the Data

In many cases entire raw data sets from interplanetary missions are easily available to just about anyone. By signing up at the PDS website, for example, one receives announcements when new data becomes available (see Figure 6.18).

PDS_Notification_Manager@jpl.nasa.gov, MESSENGER Release

Date: Tue, 15 Jul 2008 16:20:34 -0700 (PDT)
From: PDS_Notification_Manager@jpl.nasa.gov
To:
Subject: MESSENGER Release 3

[NASA] PDS RELEASES MESSENGER DATA

The Planetary Data System announces the third release of data from the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission. This release includes EDR (raw) data from the first Mercury flyby (M1) from all of the instruments. In addition, in accordance with the project archive plan, CDR (calibrated) data from the MDIS, MAG, and MASCS instruments from the Mercury 1, Venus 2, and Earth flybys are included in this release. The remaining instruments will provide calibrated data for all of the flybys to date in release 5, scheduled for 15 March 2010.

Data sets from the following experiments are now available:

EPPS (Energetic Particle and Plasma Spectrometer)
GRNS (Gamma Ray and Neutron Spectrometer)
MAG (Magnetometer)
MASCS (Mercury Atmosphere and Surface Composition Spectrometer)
MDIS(Mercury Dual Imaging System)
MLA (Mercury Laser Altimeter)
XRS (X-Ray Spectrometer)
RS (Radio Science)

SPICE data for the mission to date are also included.

The data can be accessed from:

http://pds.nasa.gov/subscription_service/SS-20080715.html

To access all data archived in the PDS, go to:

http://pds.nasa.gov.

Fig. 6.18. Data set availability announcement from NASA Planetary Data System (PDS). EDR stands for "Experiment Data Record." Courtesy NASA/PDS.

6.5.6 An Expanding Presence

Since the beginning of the space age, each mission within the solar system has posed new questions with the data it has returned.

After the *Mariner* flybys of Mercury, Venus, and Mars, more capable spacecraft brought more advanced instruments to orbit these planets and carry out in-depth investigations. *Galileo* and *Cassini* carried the most advanced instrumentation of their time into orbit to tour the realms of Jupiter and Saturn, addressing pressing questions that arose from the *Pioneer*s' and the *Voyager*s' brief flyby encounters. *Messenger*'s task is to orbit Mercury, and *New Horizons*'s is to fly past Pluto and explore the Kuiper belt of unknown icy worlds past Neptune.

It is the members of the world's science community who discover new questions as well as new facts, and who develop advanced instrumentation capable of extending the range and reach of our human senses to investigate compelling scientific puzzles: What is the nature of the ice-covered global oceans on Jupiter's moon Europa and Saturn's Titan? Where do the continuous geysers of Saturn's tiny Enceladus get their power? Why does there seem to be no trace of surface iron on Mercury, given its massive iron core? What is the extent of Mars's subterranean water?

Scientists seek opportunities to fly advanced instruments on new missions to be planned and designed by engineers and scientists and organized and funded by the world's space-faring institutions and governments,[28] to explore unfamiliar places throughout our planetary back yard and beyond.

Notes

[1]The Lick Observatory occupies the summit of Mt. Hamilton in California.

[2]Scientific flight experiments, as well as instruments, may also be categorized in the same way.

[3]Individual flight projects' web sites usually have the latest raw data. Virtually all processed images from solar system exploration by many nations are available in several formats, including highest resolution downloads, from the NASA Planetary Data System, http://pds.jpl.nasa.gov.

[4]The U.S. Geological Survey provides free image-processing software called ISIS which is intended for manipulating images from planetary missions. See http://isis.astrogeology.usgs.gov.

[5]Errors, or aberrations, in the location of focused rays at or near the focal plane which are negated or reduced by a high-quality refracting optical instrument include spherical aberration, coma, chromatic aberration, astigmatism, and others.

[6]Variations on the Cassegrain design may include Schmidt-Cassegrain, Maksutof-Cassegrain, and Schmidt Cameras, which use thin lenses, called corrector plates, at the front end of the telescope, and Ritchey-Chrétien Cassegrain designs.

[7]The last optical instruments on *Voyager*'s scan platforms were shut down in 2003. The image detectors in both narrow-angle and wide-angle cameras were devices called vidicons. These vacuum tubes functioned in a way partly similar to the familiar cathode ray tube, CRT. An electron beam was swept in a raster, stepping line by line, across an antimony trisulfide coating inside the flat end of the tube at the focal plane. The electron

beam's current varied slightly according to the intensity of light in different parts of the image focused onto the coating by the camera's optics, and these variations were converted into image data for transmission via telemetry.

[8]By some accounts the human eye can only sense on the order of forty different grey levels.

[9]http://sohowww.nascom.nasa.gov

[10]The following NASA/JPL images may be found online. *Voyager 1*: PIA02292, PIA02293, and PIA02263, and *Voyager 2*: PIA01951, PIA01387, and PIA0138.

[11]Following is a description of the video of Prometheus, the F Ring, and Pandora available online (saturn.jpl.nasa.gov) which intuitively conveys some nuances of orbital mechanics in Saturn's ring system. (Because the video views the objects from their southern side, the rotation direction is opposite that seen in Figure 6.4, otherwise the description generally applies to the Figure. Emphasis added.):

"The moon Prometheus slowly collides with the diffuse inner edge of Saturn's F ring in this movie sequence of *Cassini* images. The oblong moon pulls a streamer of material from the ring and leaves behind a dark channel.

"Once during its 14.7-hour orbit of Saturn, Prometheus (102 kilometers across) reaches the point in its elliptical path, called apoapsis, where it is farthest away from Saturn and closest to the F ring. At this point, Prometheus's gravity is just strong enough to draw a "streamer" of material out of the core region of the F ring.

"Initially the dust-sized material drawn away from the ring appears to form a streamer pointing *ahead* of Prometheus in its orbit. (All orbital motion is towards the right in the movie.) Over time, the streamer falls increasingly farther behind Prometheus because material in the F ring is orbiting slower than the moon. The streamer gets longer and a darker "channel" starts to be seen (to the left of the streamer in the movie).

"The creation of such streamers and channels occurs in a cycle that repeats each Prometheus orbit: when Prometheus again reaches apoapsis, it draws another streamer of material from the F ring. But Because Prometheus orbits faster than the material in the ring, this new streamer is pulled from a different location in the ring about 3.2 degrees (in longitude) ahead of the previous one.

"In this way, a whole series of streamer-channels is created along the F ring. In some observations, 10 to 15 streamer-channels can easily be seen in the F ring at one time (see video PIA07712). Eventually, a streamer-channel disappears as shearing forces (i.e., Keplerian shear) act to disperse the constituent dust particles.

"The movie shows just under half of a complete streamer-channel cycle. The dark frames in the movie represent the period during which Prometheus and the F ring pass through Saturn's shadow.

"The images in the movie were acquired by the *Cassini* spacecraft narrow-angle camera on Nov. 23 and 24, 2006. The movie sequence consists of 72 clear spectral filter images taken every 10.5 minutes over a period of about 12.5 hours.

"The original images were cropped to show only the region around Prometheus and the nearby portion of the F ring. The movie covers the region between 138,000 and 142,000 kilometers radially from Saturn and 1 degree in longitude from Prometheus on each side. Each frame was re-projected such that the vertical axis represents distance from Saturn and the horizontal axis represents longitude around Saturn. Image scale is 10 kilometers per pixel in the vertical direction; the images cover 0.005 degrees of longitude in the horizontal direction. Because of the re-projection, the F ring appears straight, rather than slightly curved, as it otherwise would.

"Since the F ring has an elliptical shape, its radial distance from Saturn varies by about 1,000 kilometers around the ring. This accounts for the apparent vertical movement of the ring over the course of the movie. Only a very small part of the ring appears in each of the re-projected frames, so the difference in the ring's radial distance from left to right across any single frame is small enough as to be effectively unnoticeable.

"The *Cassini-Huygens* mission is a cooperative project of NASA, the European Space Agency and the Italian Space Agency. The Jet Propulsion Laboratory, a division of the California Institute of Technology in Pasadena, manages the mission for NASA's Science Mission Directorate, Washington, D.C. The *Cassini* orbiter and its two onboard cameras were designed, developed and assembled at JPL. The imaging operations center is based at the Space Science Institute in Boulder, Colorado, U.S.A." Caption courtesy *Cassini* Imaging Team and NASA/JPL/Space Science Institute.

[12] The exceptions are starlight imaged in optical navigation frames, and the lamp with which the *Huygens* Descent Imager and Spectral Radiometer illuminated Titan's surface.

[13] A large-format, highly detailed solar spectrum showing thousands of absorption features may be found on the web at

http://www.noao.edu/image_gallery/html/im0600.html.

[14] Kirchhoff's laws are here brazenly simplified and paraphrased to more succinctly illustrate Foucault's finding. For a precise version see reference [19].

[15] See http://astro.u-strasbg.fr/~koppen/discharge

[16] This article is widely available for download from educational institutions. Search for "DVD spectroscope."

[17] The Austrian-Irish physicist Erwin Schrödinger (1887–1961) introduced this model of the atom in 1925.

[18] Named for their inventor, German astrophysicist Walter Grotrian (1890–1954)

[19] See http://www.nist.gov

[20] *Spitzer*'s other two instruments are the Infrared Array Camera and the Multiband Imaging Photometer which measure the location and brightness of an object.

[21] Cosmic "rays" are fast-moving particles, usually protons from the Sun or other sources in the galaxy or beyond. Less commonly, they may be nuclei of atoms as heavy as iron.

[22] Named for the English scientist John Dalton (1766–1844) who investigated atomic theory

[23] The SI unit is the kilogram. The dalton, Da, also known as the unified atomic mass unit, amu, or u, is defined to have one-twelfth the mass of a carbon-12 atom, equal to $1.66 \times 10^{-}27$ kg.

[24] The difference between a dalton and the actual mass of an atom or ion is small enough that the dalton serves as a proxy for atomic mass in identifying the chemical species.

[25] Spacecraft that have transited the main asteroid belt are *Pioneer 10, Pioneer 11, Voyager 1, Voyager 2, Galileo, Ulysses, Cassini-Huygens,* and *New Horizons.*

[26] http://www.mpi-hd.mpg.de

[27] See naif.jpl.nasa.gov for more information about SPICE kernels.

[28] Some instruments, even entire missions, are funded by the members of private organizations such as The Planetary Society, http://www.planetary.org.

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7 Mission Formulation and Implementation

7.1 Announcement of Opportunity

Wanted: Proposals for a US$325-million project to go to Mars. The Announcement of Opportunity (AO) that NASA sent out reads as follows:[1]

> AO 02-OSS-02
> RELEASE DATE: May 1, 2002
> NOTICE OF INTENT: June 3, 2002
> PROPOSALS DUE: August 1, 2002
> The National Aeronautics and Space Administration (NASA) Office of Space Science is releasing a Mars Scout Announcement of Opportunity (AO 02-OSS-02) for the next mission(s) in the Office of Space Science Mars Exploration Program (MEP). Selections of proposals through this AO, once released, are intended to provide one or more mission(s) to be launched by December 2007. One or more Mission of Opportunities may also be selected. The science objectives covered by this AO include those in the currently defined MEP.
> Participation is open to all categories of organizations, foreign and domestic, including industry, educational institutions, nonprofit organizations, NASA centers, and other Government agencies. This solicitation will be open through August 1, 2002. Upon the release date, specific guidance for proposal preparation will be available via the World Wide Web site: http://spacescience.nasa.gov.
> Inquiries of a scientific or technical nature should be directed to Dr. James Garvin, Solar System Exploration Division, Code SE, Office of Space Science, NASA Headquarters, Washington, DC 20546-0001.

In previous chapters we've come to know what an interplanetary flight involves, and how the science instruments and experiments address specific scientific questions. This chapter introduces a sense of what it takes to formulate and implement such an interplanetary mission. We'll list the major milestones involved, and illustrate a few of them with examples. In part, we'll follow some of the ultimate results of the AO quoted above.

The mission that resulted from the above AO was eventually named *Phoenix*. The whole mission spanned a relatively short period of time[2] from AO through the end of its primary mission, so it makes a good, compact example. It has also been well documented in the popular media, so it may already be somewhat familiar to the reader. Even though compact, *Phoenix* illustrates all the major phases in the life of almost any interplanetary venture (reference [1] gives an overview of the *Phoenix* mission design). We'll look in on *Phoenix* again after we define the eight classifications of missions, and touch upon how their different designs or implementations compare. But first, some perspective.

7.1.1 Financial Perspective

To put the AO-price tag for the *Phoenix* mission to Mars in perspective, it's about twice the cost of the 2008 Warner Bros. Batman film *The Dark Night*. This movie generated revenues worldwide of US$355 million in the first week after its release.

The United States allocated about $17,000 million in the 2007 budget for NASA. According to U.S. Space interest groups,[3] when divided by the number of American taxpayers that year, the amount works out to approximately $1.09 per week.

Out of the above-mentioned total allocated to NASA, about $1,600 million, or 10.6%, went in 2007 to robotic solar system exploration, followed by about the same dollar amount in 2008. Human space flight, identified in the 2008 NASA budget as "Exploration Systems and Exploration Capabilities, " received $10,200 million. Aeronautical Research received $732 million.

7.1.2 About Scout

NASA's Mars Scout Program is intended to augment the longer-term Mars exploration endeavor by responding quickly to important new discoveries. It is managed by JPL for the NASA Office of Space Science. The AO on page 241 represents the first project in the Scout program; it was driven by the discovery made by *Mars Odyssey*, using its gamma-ray spectrometer, of water ice just below the surface in two arctic regions on Mars, which is discussed in reference [2]. This Scout program mission will be designed to confirm the finding, and investigate its importance to the possibility of past or present habitats for microbial life.

7.1.3 AO Responses

In response to the 2002 AO cited above, NASA received twenty-five proposals and awarded up to $500,000 for each of them to conduct feasibility studies describing project cost, management and technical plans, implementation, educational outreach, and small business involvement. Six months later, NASA selected four to proceed with detailed studies. Three were focused on Mars's atmosphere, one of which would fly a "free return" trajectory and bring samples back to Earth. The fourth would land a spacecraft within the Arctic circle to dig for water ice, measure the atmosphere, and survey the landscape. This one, proposed by a partnership including the University of Arizona, JPL, Lockheed Martin Space Systems, and the Canadian Space Agency, was selected, and it was given a budget cost-capped at $386M including launch.

According to the proposal, the lander would use designs and hardware left over from two previous unsuccessful missions (their cost is not included in the total mentioned above). *Mars Polar Lander* was lost while attempting to land "in the blind" (without transmitting telemetry during descent) near the Martian south pole in 1998. The *Mars Surveyor 2001* project was cancelled, largely due to inherent risk, but valuable lander components had been properly stored. Rising from the ashes of these missions, the spacecraft named *Phoenix* was intended to do the following from the surface in the high northern latitudes:

1. Explore the Martian arctic soils for possible indicators of life, past or present.
2. Examine potential habitats for water ice.
3. Enhance our understanding of Martian atmospheric processes.
4. Measure volatiles, such as water and organic molecules in the northern polar region of Mars.

We'll return to the story of *Phoenix*'s progress toward the Martian ice fields as an example of mission formulation and implementation, but first, here's a broader view.

7.2 Spacecraft Classifications

Missions are formulated according to their objectives. Broadly, we can categorize any craft operating in interplanetary space as falling into one of eight classifications, although some missions may share qualities of more than one class. Appendix B gives an example of each.

7.2.1 Engineering Demonstration Spacecraft

Before deciding to use a particular piece of equipment or software-based system, a spacecraft designer needs assurance that a unit of its design, or one very like it, has proven itself in flight. This means new technologies, no matter how promising, are not often incorporated for use on spacecraft that have to depend upon them to carry out scientific missions. On the other hand, new designs of bus equipment and science instruments can offer large improvements in mass and power requirements that are difficult to turn down. So once in a while an interplanetary spacecraft is designed for a mission primarily to test new concepts in hardware and software. The items of new technology undergo rigorous testing and evaluation in flight, after which similar designs may be confidently selected for upcoming scientific missions. One example is the electric ion propulsion system demonstrated on the engineering mission *Deep Space 1*, then later employed as the primary propulsion system on the *Dawn* spacecraft for its scientific mission.

Components, whether hardware, software, or a system of both, are assigned a *technology readiness level* (TRL) to indicate their maturity. This rating system helps in deciding whether a spacecraft under development should depend on a particular technology for its mission. NASA defines the TRLs as:

TRL 1: Basic principles observed and reported.
TRL 2: Technology concept and/or application formulated.
TRL 3: Analytical and experimental critical-function proof of concept.

TRL 4: Component and/or breadboard validation, laboratory environment.
TRL 5: Component and/or breadboard validation, relevant environment.
TRL 6: System/subsystem prototype demonstration, relevant environment.
TRL 7: System prototype demonstration, space environment.
TRL 8: Actual system flight-qualified via test/demonstration, ground or space.
TRL 9: Actual system flight-proven through successful mission operations.

One engineering demonstration spacecraft can succeed in bringing several components to TRL-9. The spacecraft can also be expected to carry at least some instrumentation for collecting science data to make use of important scientific opportunities encountered in the course of its flight. Once the mission's primary engineering objectives have been met, such a mission may be assigned new objectives that are entirely scientific in nature. Sometimes scientific observations can be carried out even while engineering demonstrations are in progress.

7.2.2 Observatory Spacecraft

Observatory spacecraft are flown in interplanetary space in order to raise their instruments above the Earth's atmosphere and take them far away from the heat and glare of the planet. The *Spitzer Space Telescope* is an example. *Spitzer* occupies a nearly circular solar orbit trailing the Earth as both go around the Sun. Neither the *Hubble Space Telescope* nor the *Chandra X-Ray Observatory* operate in deep space, if we define that as the distance to the Moon or more — *Hubble*'s orbit reaches 610 kilometers, and *Chandra* reaches 133,000 kilometers from Earth. Nonetheless, they are good examples of observatory spacecraft. Each can point their apertures into dark sky during part of all of their orbits, and they can make observations deep into space-time capturing electromagnetic wavelengths and energies that are not observable from Earth's surface because of atmospheric absorption (see Appendix D, page 343).

There were four spacecraft in NASA's Great Observatories Program designed to observe the universe in wavelengths from infra-red to gamma-rays: *Spitzer* observes in the infrared; *Hubble* observes in the near-infrared, visible, and near ultraviolet; *Chandra* observes X-rays; and the *Compton Gamma Ray Observatory* observed in the most energetic part of the spectrum from 1991 through 2000. Many other observatory spacecraft have been flown in Earth orbit, including the *Infrared Astronomical Satellite*, launched in 1983, and the *Cosmic Background Explorer*, launched in 1989. The *Planck* spacecraft, due to launch in 2009, will observe the cosmic background radiation with high sensitivity.

7.2.3 Flyby Spacecraft

Flyby spacecraft are designed to make observations from a solar orbit or escape trajectory as they pass by an object. They do not carry enough ΔV capability to enter into orbit at their targets. The *New Horizons* spacecraft is planned to execute flyby observations of Pluto and Charon the way *Voyager 1* and *Voyager 2* observed the gas giant planets and their satellites.

7.2.4 Orbiter Spacecraft

Orbiters are designed to cruise to a destination body and then enter into orbit about the body upon arrival. A substantial velocity change will be needed near the target body, so the orbiter spacecraft has to carry an adequate ΔV capability. *Messenger*, *Galileo*, *Cassini*, and all the Mars orbiters are bulging with propellant tanks to supply the ΔV, as can usually be seen in images of them.[4] Since orbiters remain in the target system for repeated orbits, they can accomplish in-depth studies. Conducting an orbiter mission involves frequent tracking for navigation and communications. Orbiters designed to observe the planet constantly, like the Mars orbiters, function best in a circular or near-circular orbit. They typically have highly repetitive agendas, and these may benefit from automated operations both onboard and on Earth, such as the use of template-driven command sequence preparation. Orbiters such as *Galileo* and *Cassini* were designed to remain in highly elliptical orbits about their planets, and to make frequent fine orbital adjustments to set up close flybys of the planets' natural satellites. All this requires ongoing efforts at science planning, command preparation, and engineering activities, to prepare unique command sequences.

7.2.5 Atmospheric Spacecraft

To enter and study the atmosphere of a planet or Titan (the only body besides the planets in our solar system with an appreciable atmosphere) requires making a large change in speed. As its interplanetary journey ends, the spacecraft will have a high velocity with respect to the target, only increased by the body's gravitation. An atmospheric spacecraft is therefore protected by a blunt heat shield that will rapidly decelerate the spacecraft by converting its kinetic energy into heat which radiates and conducts away. An onboard system will then need to release and separate the spacecraft from the heat shield after its aerobraking function has ended. Additional deployments such as of instruments and parachutes will also have to occur.

7.2.6 Lander and Penetrator Spacecraft

A spacecraft intended to touch down gently on the surface, or to bury itself in the surface's uppermost layer(s) will by nature also have to deal with a high approach velocity. If there is an atmosphere, a heat shield may serve to aerobrake. Parachutes, thrusters, and/or airbags may be employed to bring the velocity down to a workable range. Landers and penetrators will likely be designed with limited radio transmitting power to conserve mass; once on the surface carrying out their observations, they might need to rely on additional spacecraft nearby, such as an orbiter, to communicate with Earth.

7.2.7 Rover Spacecraft

Rovers have to land, so they share the need to reduce approach velocity. Once on the surface, they have the enormously useful ability to carry direct-sensing science instruments to individual targets of interest to measure their composition and mechanical properties. Some rovers can communicate directly with Earth, some rely on communications relay capabilities, and some can do both.

7.2.8 Communications and Navigation Spacecraft

There isn't a good deep-space example of a dedicated communications spacecraft. A decade or so ago there was a proposed Mars Communications Network consisting of a network of Mars-orbiting communications spacecraft intended to serve both surface and orbiting craft in the future, but it never survived its concept-development phase. Today, the requirements for communications relays between surface vehicles and Earth are being met (though sometimes marginally) using spacecraft already in Mars orbit carrying out their own scientific observations. These spacecraft are *Mars Express*, *Mars Odyssey*, and *Mars Reconnaissance Orbiter*. The *Mars Global Surveyor* spacecraft also relayed data before the spacecraft was lost. These orbiters transmit and receive command and telemetry data to and from the surface vehicles via UHF radio. The surface vehicles operating today are MER-1 and -2, named *Spirit* and *Opportunity* respectively, and, until recently, the *Phoenix* lander. *Mars Global Surveyor* supported the relay with the *Pathfinder* Lander, which in turn communicated via UHF with its rover *Sojourner*.

7.2.9 Size and Complexity

Another dimension to these classifications of spacecraft is the size, complexity, and cost of its endeavor. At one end of the spectrum is the flagship mission such as a US$1,000 million (1970s dollars) *Viking*, a $1,400 million mission two-nation *Galileo*, or a $3,000 million multi-national *Cassini-Huygens*. Such programs tend to have long development and/or operational lifetimes, they represent a large investment of space agency resources, and they may have contributions from multiple organizations and space agencies.

At the other end of the spectrum is the 1997 *Mars Pathfinder* whose team airbagged a small lander and rover onto the surface for $150 million — less than the cost of 2008's Batman film. In reference [3], *Pathfinder* project manager Tony Spear colorfully describes lessons learned from this cost-capped, short-schedule mission, which responded to the mid-1990's NASA philosophy of "faster, better, cheaper." Several small missions are sometimes commissioned as segments of one program. *Pathfinder* was a mission in the NASA Discovery program mentioned below.

7.3 Making a Mission

The interplanetary flight projects we've visited up until this chapter — *Cassini* in orbit at Saturn, *Mars Climate Orbiter*'s unfortunate arrival, *Voyager*'s launch and ongoing flight, and many others — have all been described in Phase E of their missions. Here we'll put this in the larger context of the rest of the usual phases of deep space missions.

As we'll see, designing a mission involves more than orbital mechanics and trajectory design. Reference [4] provides a complete guide to those aspects of mission design, and together with the AIAA-developed software it includes and explains, it can support a self-guided study resulting in a design for a technically valid mission to anywhere in the solar system. On the other end of the spectrum, reference [5] approaches similar subjects without any mathematics whatsoever. The present chapter views selected facets of mission formulation and implementation from a perspective complementary to the existing literature.

The AO cited previously did not mark not the beginning of the *Phoenix* mission's lifetime. It was, rather, the result of an involved process at NASA Headquarters of formulating the concept of a series of missions that would accomplish some desired scientific goals. NASA was responding to the priorities of the scientific community, bringing the concept to a tangible level that could be brought into reality given the current state of technology. As we'll see, though, not all missions are the subject of an AO like the one that resulted in the *Phoenix* mission.

7.3.1 Decadal Surveys

The roots of many missions are in *decadal surveys* that the U.S. National Research Council (NRC) conducts among members of the scientific community and the general public via space-interest groups. These assess priorities for U.S. participation in planetary research programs for an upcoming decade. They evaluate opportunities for planetary science, and recommend priorities for federal investment. Other decadal surveys are conducted for Earth science, astronomy, astrophysics, and additional disciplines. In addition to input from members of the affected planetary science community, the 2002 planetary science survey generated over 54,000 replies from members of the general public. Missions to Mars were ranked among the top five by 91% of these respondents. This and other information provides guidance to the Planetary Science Division of the NASA Science Mission Directorate. One result was NASA's Mars Exploration Program's creation of the Mars Scout Program, designed to respond in short order to new discoveries by conducting "missions of opportunity."

7.3.2 Competed Missions

Missions in the NASA Mars Scout Program, such as *Phoenix*, are *competed.* That is, NASA prepares and issues an AO, supports competition among selected respondents, then awards the mission to a winner. Competed missions are to be kept within strict cost and schedule limitations.[5] The 2006 NASA budget allocation included $94 million to support the full competition for *Phoenix.* Other competed U.S. programs besides Mars Scout include:

– The Discovery Program[6] has competed fifteen missions to date, including *Mars Pathfinder* and its *Sojourner* Rover, *Messenger* to Mercury, and the *Dawn* mission to two main-belt asteroids.

- The New Millennium Program[7] was designed to test new technology in flight. To date it has included *Deep Space 1*, *Deep Space 2*, and half a dozen Earth-orbiting missions.
- The New Frontiers Program[8] to date has included the *New Horizons* mission, which is en route to Pluto, and the *Juno* mission, planned to launch toward Jupiter.

7.3.3 Assigned Missions

On the other hand are *assigned* missions, also called *directed* missions. These are typically larger and more expensive than competed missions, and some are also known as *flagship* missions. A classic example of an assigned set of missions was the Apollo Program, which President John F. Kennedy directed NASA to undertake in 1961, and which placed the first humans on the lunar surface in 1969. Additional assigned NASA missions have included *Pioneer*, *Mariner*, *Voyager*, *Magellan*, *Galileo*, and *Cassini*. While these missions themselves are "assigned", many of their components, sometimes including the spacecraft itself, might be offered to bidders worldwide for competition. Lockheed-Martin won the competition to produce and fly the *Magellan* spacecraft for JPL, *Galileo*'s retro-propulsion module was provided by the Federal Republic of Germany, and many of *Cassini*'s instruments were competed worldwide. Future NASA flagship missions currently under study include an orbiter for Jupiter's moon Europa, and a mission to Saturn's moon Titan.

The assigned flagship missions *Galileo* and *Cassini* both had early mission-definition phases that turned out to be complex. *Galileo*'s mission went through five redesigns as the launch vehicle choices starting shifted in 1979, and eventually stabilized following *Challenger*'s loss in 1986. First envisioned as one mission in a NASA program called *Mariner Mark II*, *Cassini* evolved through budget cuts and re-definition to become a flagship emerging from the *Mariner Mark II* program's cancellation. By 1989 the program included the NASA-developed Saturn orbiter *Cassini* and the ESA-developed Titan atmospheric and surface spacecraft *Huygens*. Eventually, ASI would develop the mission's communications gear, and engineers and scientists in eighteen nations would coordinate the technical contributions. Program definition and design progressed through a number of configurations, finally producing a set of complete and stable specifications that became the basis to start building electronics in 1993 for spacecraft assembly, testing, and eventual launching in 1997.

7.3.4 Administration

The reason an interplanetary mission can come together at all is its administration. In the U.S., this starts with NASA, who, as we have seen, creates the *program* under which a mission is to be flown. Note that the program level is above the flight *project* level. NASA then develops a program concept far enough advanced to allow a competitive process for selecting a contractor to undertake the project, or to direct one of its centers to lead the project's formulation and implementation.[9] Project-level management may be compared to the management of large oceangoing vessel. The shipping company that owns that vessel and many other vessels would, in this analogy, be NASA and program management. Analogies aside, the highly technical aspects of scientific expeditions in interplanetary flight require that their leaders and staff have world-class expertise in the technical areas the mission encompasses.

Flight project management is responsible for:

1. Formulation: assessing feasibility, technology, concepts, and risk; building the team, developing ops concepts, and establishing requirements and success criteria; preparing plans, budgets, schedules and administrative control systems.
2. Approval: acknowledgment by the decision authority that the project has met stakeholder expectations and formulation requirements, and is ready to commit the budget resources to implementation.
3. Implementation: executing approved plans for project development and operation, and the use of management control systems to ensure proper performance.
4. Evaluation of the project's performance, and incorporation of evaluation findings to ensure adequacy of planning and execution.

In many cases the project manager concentrates on the technical and science issues facing the mission, and a deputy project manager, if assigned, generally takes care of the business side of management.

Organization

No single human can wrap his or her mind around an interplanetary flight project, even for a compact mission like *Phoenix*, so the project manager needs to skillfully divide the task among trusted associates. A project manager depends on a staff of experts and teams in all the various fields involved, for example:

- Financial and workforce resource administration
- Mission Planning
- Navigation
- Risk Management, Mission Assurance
- Flight System Development and Operations
- Deep Space Network Technology
- Project Science
- Ground System Development
- Command Sequence Development
- Realtime Operations
- Data Management
- Public Engagement

No small part of pulling an interplanetary mission together, from components gathered from all around the Earth, is assembling an organization. Most flight project managers have had years of experience in various areas of interplanetary flight, experience that helped them gain insight into many of a project's intricacies. Their managerial wisdom guides the task of organizing, and they have lots of help.

An institution with a "matrix" organization like JPL strives to be able to pull expert employees together from its various "home" divisions, sections, and groups — one axis of the matrix — into various tasks on various flight projects in all their various phases — the other axis. Over its lifetime, any given flight project will tap the work of people from dozens of sections having names such as "Telecommunications," "Mission Architecture," "Business Operations," and "Space Science."

Risk Management

Risk is a measure of uncertainties in achieving objectives within defined cost, schedule, and other constraints. Recognizing that risk can be associated with all aspects of a project, management polls every member of the flight team to identify potential risks of all kinds, and one or more staff members are assigned to document them. The process is known as *Probabilistic Risk Assessment.* It brings together experts in the mission and in the disciplines of mission assurance and quality control to work on identifying and categorizing specific project risks.

An example of risk might be the collision of a spacecraft with an unknown object while passing through the main asteroid belt. Risks are recognized to have three components: a potential root cause, likelihood, and a consequence. In the example, the root cause would be the presence of an unknown object on a collision course. The likelihood, we know today, is low. But the consequence, were the event to occur, would be highly undesirable: loss of the mission.

Hundreds of risks might be identified on an interplanetary flight project. To manage them, the person(s) assigned to the task will research each one and establish its location on a matrix such as the one shown in Figure 7.1. Analysis will place each identified risk in a box on the matrix. A risk such as our example would appear in row 1 in "likelihood," and in column 5 in "consequence." This risk falls in the grey area.[10] In our example, management might decide to spend some limited resources

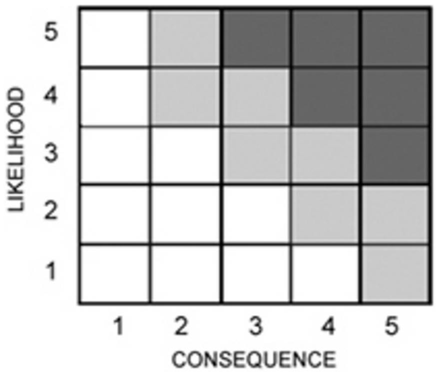

Fig. 7.1. Risk matrix. Likelihood ranges from minimum of 1 to maximum of 5. Severity of consequence ranges from minimum of 1 to maximum of 5. Different missions may have various versions of such a matrix with more precise meanings for the gradations.

to further research what is known about the content of the asteroid belt. Otherwise, the mission might accept the "grey" risk and move forward. If analysis were to show that some "grey" risks could be moved to the white area with acceptable measures of impact to schedule, mass, cost, or other resources, management would likely authorize the mitigating activities. Any risks that fall in the black area are initially treated as unacceptable, and will be the subject of more vigorous analysis, and possibly formal reviews. Changes to the spacecraft or mission that serve to mitigate such risks will be given a high priority.

A more realistic example of a risk is that of an erroneous command being sent to the spacecraft. Because the flight team will generate and uplink many thousands or millions of commands to the spacecraft in the course of its lifetime, the likelihood of an erroneous command is higher than the bottom rung. Consequences of erroneous commands range from benign to catastrophic, so this risk might be expected to appear in the "unacceptable" area on the matrix. Mitigations for this risk typically are built into flight operations, including testing command sequences prior to uplink, controlling the "pedigree" of products in the uplink stream, extensive use of checklists, and having two people check each other when sending command data up to the spacecraft, to ensure only the intended products are actually sent.

Discussing the mitigation of risks identified during development of the 1996-launched cost-capped *Mars Pathfinder* mission, project manager Tony Spear comments:

> "To no one's surprise, the entry, descent, and landing phase emerged as the biggest mission risk, with the airbags as [its] most risky element. So we allocated additional $ and schedule reserves to airbag design and test, including a series of drop tests at the Lewis Plum Brook facility in Sandusky, Ohio, not initially planned." [3]

Pathfinder landed successfully on the fourth of July 1997 in Ares Vallis and deployed an instrument-bearing solar-powered "micro-rover," which returned important ground-truth science data.

7.3.5 Mission Phases

Whether assigned or competed, NASA missions progress through a standard set of phases in their formulation and implementation. They are:

Formulation

- Pre-Phase A: Concept Studies
- Phase A: Concept and Technology Development
- Phase B: Preliminary Design and Technology Completion

Implementation

- Phase C: Final Design and Fabrication
- Phase D: Subsystem Assembly, Integration and Test, Launch

– Phase E: Flight Operations, Sustainment, and Data Analysis
– Phase F: Closeout

There can be varying amounts of overlap and iteration across adjacent phases. In fact, Phases C and D are often simply taken together as “Phase C/D.” Prior to Phase A, any number of preliminary activities may take place, from concept studies to feasibility checks, if not full-blown feasibility studies. It takes a lot of work to even publish the AO. Missions like a *Galileo* or a *Cassini*, or a Europa orbiter have lengthy paths of evolution before Phase A is formally begun. But once that phase is underway, a spacecraft has a much greater chance at actually leaving Earth.

Before formally proceeding from one phase to the next, management has a Key Decision Point (KDP). Several KDPs are visible and labeled in Figure 7.4. Studying the figure reveals how reviews and other activities lead up to a KDP half a dozen times during a project’s life. At each KDP, the decision authority determines the project’s readiness to progress to the next phase in its life cycle. They serve as gates through which projects must pass. Decisions made at these points lead to:

– Authority to proceed to the next KDP, or
– Approval to continue to the next KDP pending resolution of specific actions, or
– Disapproval, in which case follow-up actions might include any of the following:
  – Requests for more information
  – A “delta” independent review, to address changes (delta) implemented
  – Request for a Termination Review
  – Direction to continue in the current phase
  – Project re-direction

Information on the definitions of phases in mission formulation and implementation is courtesy NASA.[11]

7.3.6 Reviews

Project team members see reviews as goals to be ready for, and project management uses them to ensure that the mission will meet its schedule and remain within budgeted amounts of mass, electrical power, time, money, and other constraints. Reviews provide information to management for informing Key Decision Points.

In addition to the major review points indicated in Figure 7.4, during a project’s life cycle there are many more categories of reviews along the way. Once mission implementation is in progress, all the dozens of subsystems and instruments will have their own individual design and implementation schedules of activities at lower levels within the project, such as pre-test reviews and pre-ship reviews for individual assemblies and subsystems, and acceptance testing reviews for components received from suppliers.

Table 7.1 gives an idea of the kinds of reviews a deep space flight project is likely to include, but more reviews populate the schedule in a project’s lifetime than the table shows. Not all the reviews listed in Table 7.1 are conducted for every flight project. Moreover, special reviews might be called for based on the specific needs of a particular project. Questions were raised about *Phoenix*’s descent radar, particularly whether echoes from its heat shield after release might confuse the radar into

Table 7.1. A list of some reviews likely to be conducted during a mission.

Mission Concept Review	Center Management Council Review
System Requirements Review	Mission Definition Review
System Definition Review	Preliminary Non-Advocate Review
Project Mission System Review	Preliminary Design Review
Non-Advocate Review	Critical Design Review
System Integration Review	Governing Program Mgmt Review
Mission Directorate Review	System Integration Review
Pre-ship review	Operations Readiness Review
Flight Readiness Review	Launch Readiness Review
Launch Vehicle Flight Readiness Review	Launch Vehicle Launch Readiness Review
Critical Event Readiness Review	Sequence Approval Meetings
End of Prime Mission Review	Decommissioning Review

"thinking" the lander had arrived near the ground, causing the descent engines to shut off prematurely. In response, NASA formed a Radar Independent Review team composed of key radar experts to evaluate the activities of the *Phoenix* radar team. The review team was chartered to determine whether the situation had been properly characterized, whether the important risks associated with its performance had been identified and mitigated, and that any remaining unmitigated risks represented benign enough consequences to the mission. The *Phoenix* project followed all the Independent Review Team's recommendations, and the reviewers endorsed *Phoenix*'s approach.

Looking back over all the reviews of his *Phoenix* Lander, Project Manager Barry Goldstein said, shortly before landing in May 2008, "There are a lot of issues we had to face on *Phoenix*. We've been working for the last five years in testing this vehicle. There were a number of recommendations, over two dozen recommendations made by the various review boards. . . . We've addressed each of these. In addition to that, and I would suggest more importantly, we've addressed and found other areas of concern that could have caused the loss of [*Mars*] *Polar Lander*. There are over twelve."[12]

7.3.7 Pre-phase A: Concept studies

The outcome of Phase-A preliminary analysis activities will be the description of a reasonable spacecraft configuration, and the identification of any significant risks involved in realizing the mission's cost, schedule, or technical achievability. It will also include a cost and schedule estimate and a determination of any trade studies that might be required. In short, it is a professionally done conceptual design. It may not be the best design; that will be the outcome of Phase B, Mission Definition. For now, we can examine a couple of the highlights of preliminary analysis.

If you were thinking about adding a room atop the garage, you would probably be forming ideas about the project long in advance, such as what its purpose would be, how much it might cost, and what kind of amenities it would need to meet its objectives. This is analogous to the level of pre-Phase-A thought. This phase might generate some preliminary numbers, but until there's a general consensus among everyone impacted, for example residents, neighbors, and homeowner organizations, not a great deal of money and effort will be expended. Once it appears it is possible within all the constraints, and it is truly desirable, there comes a yes/no decision point: Yes, hire an architect and begin spending money; No, postpone the idea for a few years and perhaps revisit it. There may be other options, such as "Yes, but…".

One of the initial tools for pre-planning an interplanetary project is the graphical output of computer programs showing relevant factors involved in making the journey. If you compare flying a spacecraft to another planet to throwing a dart at a moving target, consider also that the thrower is on a moving platform, and the Sun's gravity curves the trajectory of the dart. For a flight to Mars, there is an opportunity to launch from Earth every 25.6 months as the planets move into favorable positions. Where does one find information that helps decide when to launch, how long the trip will take, what the arrival conditions will be, and how much of a rocket it will need? Porkchops!

Porkchops

The peculiar name derives from the porkchop-shaped computer-generated contours (see Figure 7.2) that display important characteristics of an interplanetary flight path for a given launch opportunity. They're technically known as *Launch-Arrival Plots.* Typically, they show launch and arrival dates and the corresponding departure energy (C_3, as discussed below). Sometimes the charts will include other useful information for the specific mission under consideration, such as the solar longitude on the planet upon arrival, travel time, or the angular position in the sky of the planet and spacecraft upon arrival. The latter is important if the destination happens to be within several degrees of the Sun, possibly hampering radio communications.

Making porkchop plots of the mission's trajectory options is understood to be the first task for considering the viability of a mission, because they show the basic requirements of the launch vehicle, which greatly influences mission cost. For spacecraft that will use rocket thrust to brake into orbit, or that will enter an atmosphere upon arrival, a porkchop plot computed for arrival conditions can also give a preliminary estimate of the propellant load or aerobraking capability the spacecraft will need when it reaches its target. Once we consider the key quantity C_3, we'll return to a representative porkchop chart and examine all the information it displays.

Characteristic Energy (C_3)

The porkchop shapes themselves show C_3 values, no matter what other data might also appear along with them on a chart (again, Figure 7.2). C_3 is an intensive quantity telling twice the energy per unit mass required to set off on an interplanetary

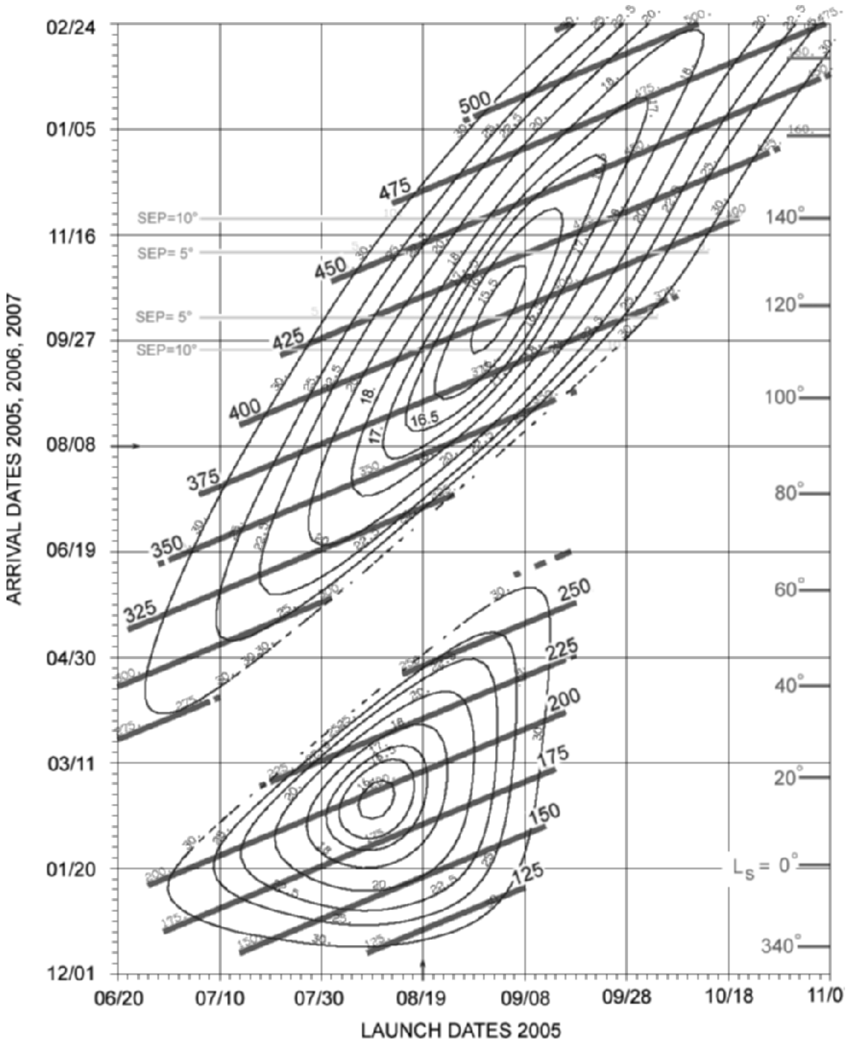

Fig. 7.2. Porkchop plot for 2005 Mars launch opportunities. Launch date axis has ticks every two days. Arrival date axis has ticks every five days. Curves show C_3, slanted lines indicate travel time in days. L_s indicates the planet's sub-solar longitude on arrival. SEP is Sun-Earth-Probe angle. Some numbers have been enlarged for readability. Readers who wish to examine this image close-up and in color on the web should search for "JPL MARS PORKCHOP." Image courtesy NASA/JPL-Caltech.

trajectory. To plan a launch for an interplanetary flight, one must have an idea of how much energy the spacecraft will require its launch vehicle to provide. This amount of energy is called "escape energy" or *Characteristic energy.* This is the amount of kinetic energy (velocity squared) per unit mass that will be required *after* breaking free of Earth's gravity (or the gravity of a different body being departed), to change a spacecraft's solar orbit to a desired trajectory. The term is written C_3, its units are km^2/s^2, and it is equal to the square of the hyperbolic excess velocity relative to the departure body.

$$C_3 = (V_\infty)^2 \tag{7.1}$$

where

V_∞ is the spacecraft's velocity at "infinity," which really means a distance great enough that one can begin to ignore the gravitation of the body being departed. It's the velocity you have when departing from, or arriving at, an object's sphere of gravitational influence.[13]

To illustrate why the units of characteristic energy C_3 are distance squared over time squared, consider that the value for energy, expressed in the SI units $kg \cdot m^2/s^2$, when divided by kg to normalize per unit mass, lets the kg cancel out.

If you consider a ballistic trajectory moving upward from Earth, such as a baseball thrown, the mass will be on a trajectory that will return to Earth. It's C_3 has a negative value. For a launch into Earth orbit, there is no excess velocity over and above its separation from Earth. A launch having a C_3 equal to zero just barely escapes, reaching "infinity" with zero speed left over. To begin a trajectory to another planet, such as a Hohmann transfer orbit, C_3 will be more than zero, and the trajectory will become hyperbolic with respect to Earth — beyond the tendency to fall back to the surface, and in an elliptical orbit with respect to the Sun. To illustrate, consider an example using the square root of ten: A spacecraft leaving Earth's grasp with 3.162 kilometers/s additional velocity would have C_3 of about 10 km^2/s^2. This is enough to depart on a long flight to Venus. A short flight to Saturn would require a C_3 of 109 km^2/s^2.

So, C_3 can be used to consider flights to anywhere anytime, as long as you can look up a launch vehicle's capability specified in C_3 available to a payload of a given mass. Reference [6] provides a thorough technical explanation of how C_3 is computed, but for our purposes we can consider it as simply a figure of merit to use in comparing various launch options. The rocket chosen must have a C_3 capability a nominal amount more than the C_3 required by the spacecraft's worst-case selected trajectory, obtained from a porkchop plot (having a little extra margin is always a good idea). So, as soon as the mission has made a final selection for its launch and arrival dates, or spans of dates — called the *launch periods*[14] — and the required C_3 values are known from the porkchops, and margins are agreed upon, one can go shopping for a launch vehicle.

Hosts of other parameters are considered during preliminary analysis. How much mass the spacecraft will have is fundamental to determining which launch vehicle can provide it the required C_3. Mass is also fundamental to the range of capabilities the craft will have. How much mass must be allocated for generating electrical power depends on how much power the subsystems and instruments will need. And the mass must include all the spacecraft's subsystems and science instruments. The spacecraft's mass will also depend greatly on the amount of propellant it will need to carry to accommodate its arrival C_3 (if it is an orbiter or lander-class spacecraft). More than half of the *Cassini-Huygens* 5,712-kilogram launch mass consisted of propellant. If the spacecraft is intended to land, then its arrival C_3 may have to be met by additional means such as aerodynamic heat shield, parachute, airbags, or retro-rockets, all contributing additional mass. Further analysis and design will determine the details of all these subsystems, and in Phase B, a stable budget for quantities such as mass and electrical power will have been established. But let's return to the porkchop.

Back to the 'Chops

Examining the porkchops in Figure 7.2, the curved lines represent constant values of departure C_3. Along the horizontal axis are potential launch dates in 2005, and the vertical axis presents dates for arrival at Mars in 2005, 2006, and 2007. To pick a C_3 value that happens to fall at the intersection on the rectangular grid for convenience, look at the launch date of 8/19/2005, and go up to the intersection with the arrival date 08/08/2006. The value printed on the C_3 contour at this intersection is "17," meaning after separating from Earth's gravitation on 08/19/2005, the launch vehicle must provide an additional 17 km^2/s^2 to set off on a flight to Mars. This is the energy required for a ΔV of 4.123 (the square root of 17) kilometers per second. Recall the discussion of ΔV on page 123. Applying values that appear in the same figure, the *Mars Reconnaissance Orbiter* spacecraft launched August 12, 2005, and arrived at Mars on March 10, 2006.

The figure shows two sets of contours. The lower porkchop represents "Type-1" trajectories, which complete their flights while traveling less than 180° true anomaly around the Sun. "Type-2" are represented in the upper chop. These extend along trajectories that exceed 180°. All the plotted C_3 values are based upon solutions to some orbital mechanics equations from Lambert's theorem,[15] which gives the relationship between two planets in orbit and the time taken to traverse the distance between them.

Mission Architecture, Mission Design...

The names of various roles in formulating a mission include Mission Architecture, Mission Design, Mission Integration, and Mission Planning, and can include others. Reference [7] details many of their corresponding technical responsibilities. Different projects might have specific definitions for these roles and more, but it is safe to say that *Mission Architecture* is undertaken first, typically as part of a project's pre-Phase A activities. The mission architect comprehends and responds to the highest-level requirements envisioned for a project, and his or her work will paint an overall picture of the project, answering questions such as: Will the mission land a spacecraft on the surface of a planet after aerobraking and thrusting? Will it orbit and study a planet with nadir-pointing instruments? Will it tour a gas

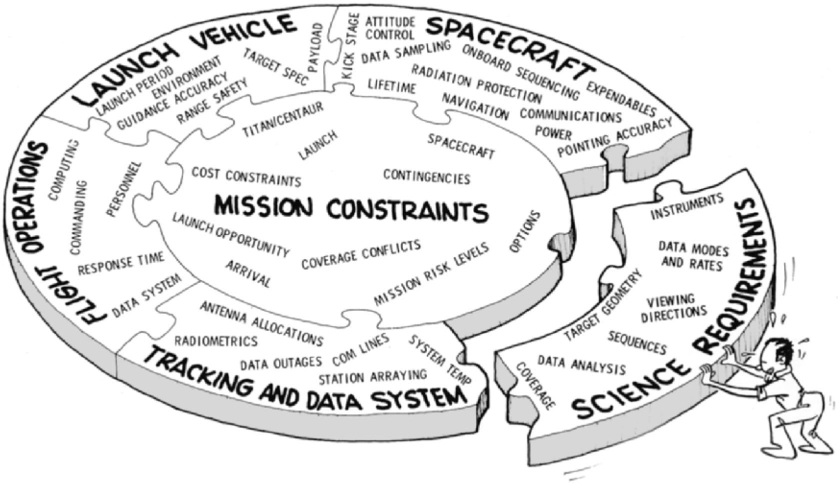

Fig. 7.3. Mission Architecture. Someone must make certain that all parts of the mission design puzzle fit together properly to meet the scientific objectives. That individual is often known as the mission architect and, like a building architect or perhaps even an expedition leader, must carefully match the requirements and capabilities of the many diverse technical elements comprising the overall project, with nothing overlooked in the process. Diagram concept and details courtesy of Charles Kohlhase, with sketch by Richard Rackus.

giant planet in long, highly elliptical orbits while encountering its satellites? How will the spacecraft get to its destination? How long will it operate?

A civil architect defines a building to respond to the client's needs, and produces all the plans and details that the contractors will require for fabrication of the building. In a similar way, a mission architect broadly defines the interplanetary project. All of the detailed requirements for the mission fall out of its architecture: spacecraft design, pointing accuracy, memory capacity, propellant load, launch vehicle, trajectory, DSN tracking needs, contingency plans, and many more. These are the detailed, specific requirements that the engineers, designers, integrators, and planners, and people in many other roles will use to create and fly the mission. The mission architect's task involves elements of analysis, planning, and design in its course.

Mission Design is the name often associated with creating the spacecraft's trajectory. A mission designer will work out the navigational aspects of launch, Earth orbit, interplanetary trajectory injection, propulsive maneuvers en route, and activities upon arrival such as orbit insertion and orbit trim, as well as special operations such as aerobraking.[16]

Mission Integration may or may not appear in a project's organization. If it does, its role will be downstream from mission architecture, with the task of making all the pieces of the mission "play" together. A mission integrator brings the flight system, ground system, and mission science into a coherent plan in which the project's scope, schedule, risks, objectives, and cost all fall within given constraints. If the "integration" role is not explicitly identified within a project, the corresponding responsibilities will be found within Mission Planning.

The role of *Mission Planning* may start out during or following the process of architecture or integration, issuing guidelines and constraints to carry out the mission using the architecture that has been built. It also has ongoing functions, which include allocating and tracking consumable resources such as the use of ΔV capability based on propellant mass, or the number of times a spacecraft's limited-life actuators have been cycled. The Mission Plan, a document this team produces, becomes a central reference for carrying out every aspect of mission operations. A flight team member can find in the Mission Plan not only a description of a typical day in the mission's life, but also the precise dates and times for all trajectory events accurately projected throughout the mission's lifetime. In addition, Mission Planning adapts to developments in the mission such as the need for orbital changes based on scientific discoveries that would benefit from repeated or closer encounters with a target, and it responds with changes to the mission that might be driven as the result of anomalies.

When looking for a more precise description of the responsibilities in one of the roles described above, it may be best to look into a specific flight project. The role definitions may change over the years, and they can be dependent almost entirely on the capabilities and interests of the individual persons involved, and reflected accordingly in the project's organizational chart. Reference [8] puts this in context via a 2002 interview with the Voyager mission architect, the American scientist, engineer, and artist Charles Kohlhase (1935–).

7.3.8 Phase A: Concept and Technology Development

Some of the concepts that apply to pre-Phase A activities cross over into Phase A, and vice-versa, in varying amounts for different missions. Once there is a decision that a particular interplanetary mission is to be created, it can be said that Phase A has begun. This key decision point appears in Figure 7.4 as "KDP A" for assigned missions, and "Down Select" for AO-driven (competed) missions. The processes are iterative; there may be responsibilities and activities that overlap across the pre-Phase A and Phase A boundary.

Phase A in a mission's life cycle is when the flight project works to develop the mission concept, and defines the necessary technical and managerial approaches. Detailed requirements for all parts of the mission are written and formally reviewed, and a preliminary Project Plan is produced. For competed missions, this is the period when proposals resulting from the AO are formally reviewed and one is selected.

7.3.9 Phase B: Preliminary Design and Technology Completion

The task of Phase B is to define everything the mission will do and how it will meet all its requirements. Everything must fit, with acceptable risk, within constraints in cost and schedule. This includes specifying the scientific objectives, the launch,

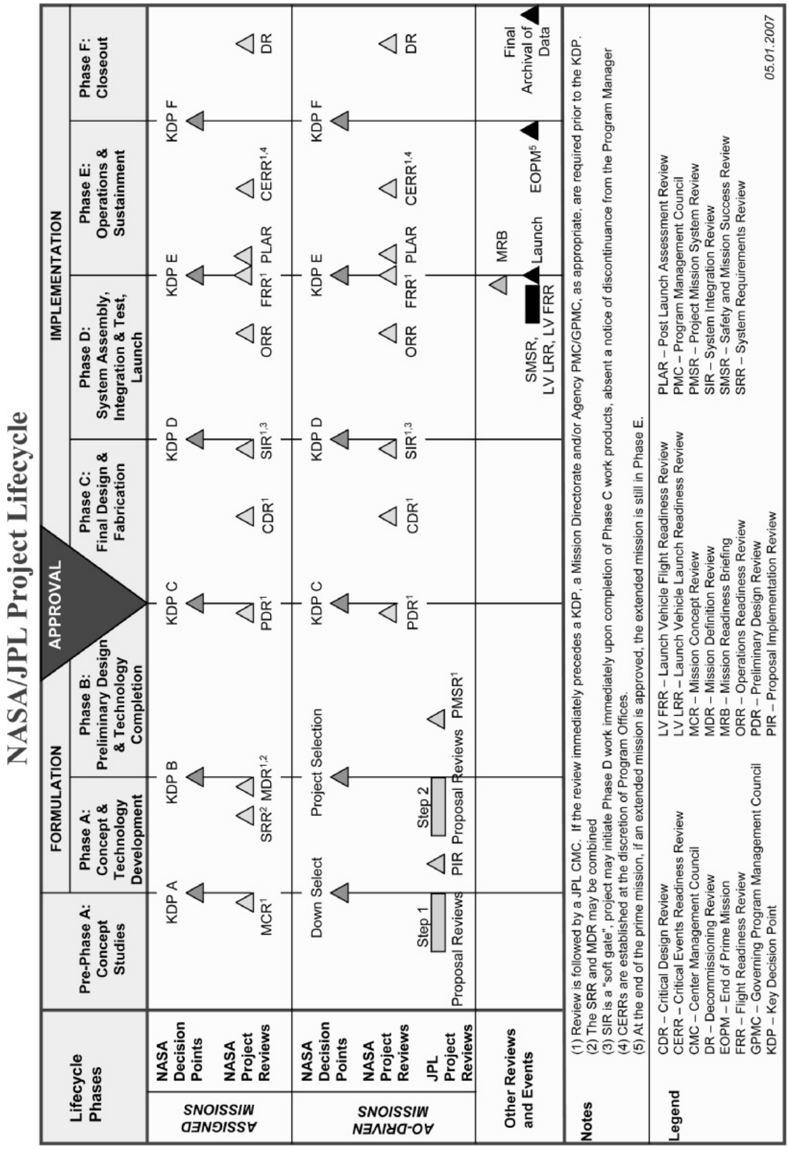

Fig. 7.4. NASA Project Lifecycle. Courtesy NASA.

interplanetary flight, arrival, operations, and data return, as well as plans and facilities for data analysis, all in the baseline Project Plan. The Project Plan, written by the project, is an agreement among the NASA program management, the director of the participating NASA center, the project manager, and for AO-driven missions, the Principal Investigator (PI). The plan, which will be reviewed by peers, experts, and non-advocates, will cover all the financial and administrative plans, the scientific objectives, and the process of meeting them.

At the end of Phase B comes the Preliminary Design Review (PDR), which will largely inform "KDP C" to determine whether the mission will be given authority to proceed.

Termination Review Barely more than a month before *Phoenix*'s PDR, the mission became subject to possible termination. Congress had imposed a new set of cost-control guidelines on NASA, modeled on the 1983 Nunn-McCurdy act, which aimed to prevent weapons systems cost overruns. The NASA provision imposes an automatic cancellation of funding on programs that experience 30% or greater cost overruns. At 15%, the law requires the project to undergo a termination review. On January 28, 2005, one was conducted on *Phoenix*. The project survived, however, with the additional funds it needed to carry out its 150-day prime mission on Mars.

Approval

All the Phase A and B activities and reviews in a mission's life cycle have been leading up to formal approval to proceed with the mission. There have been many decisions made involving subsystems, instruments, hardware, and software, along the way. For assigned and competed missions alike, an affirmative outcome of key decision point "KDP C" (Figure 7.4) means the project may commit to expenditures with the assumption that the mission is going to fly. This is the big decision point in a mission, and it is normally preceded by a PDR. In *Phoenix*'s case, the PDR was held earlier than the actual transition to Phase C, and it was a Confirmation Review on June 2, 2005, that would determine whether to proceed into Phase C.

> It is 9 A.M. on Monday March 7, 2005. A table has been set with continental breakfast selections in the hallway, where a lone board member brews tea and picks up a pastry outside the small conference room. Inside the room, the Preliminary Design Review is in progress, and a voice on the PolyCom speakerphone is posing a comment. A handful of women and men are seated around the central table amid stacks of papers and laptop computers. These review board members are listening and writing. Some of their suit jackets are draped over the backs of their chairs. Bags and brief cases sit on the floor close at hand. Up at the front of the table, a young *Phoenix* engineer stands silently beside a PowerPoint presentation cast onto the screen by a ceiling-mounted LCD projector. His face is familiar to the dozens of attendees who sit and stand in the back of the room, but instead of his usual attire in jeans and flip-flops, his sharp business suit seems anomalous. It conveys not only the gravity of the review, but a professional hopefulness about the mission

> to Mars being scrutinized for approval. After several minutes, discussion addressing the person's comments via speakerphone comes to a close, and the engineer goes on with his presentation.
> During the executive session in the final hours of the review, the board members have the room to themselves to discuss their findings. Request For Action (RFA) forms have been assigned various presenters and their teams during the days-long review. NASA Headquarters will interpret the results of this review, and also from the June 2005 Confirmation Review, to determine whether the *Phoenix* Mission to Mars will proceed.[17]

On June 2, 2005, NASA released the news that *Phoenix* was "Go" for continuation into Phase C and on to launch. *Phoenix* Project Manager Barry Goldstein's comments were widely publicized: "The confirmation review is an important step for all major NASA missions. This approval essentially confirms NASA's confidence that the spacecraft and science instruments will be successfully built and launched, and that once the lander is on Mars, the science objectives can be successfully achieved."

7.3.10 Phase C: Final Design and Fabrication

During Phase C, the project completes the design that meets the detailed requirements, and fabrication of test and flight article components, assemblies, and subsystems begins. Documented designs, requirements, and other mission specifications and texts are placed under formal change control, and activities begin to focus on preparing for the Critical Design Review (CDR), and the System Integration Review (SIR), at which the project demonstrates that the design has matured sufficiently in Phase C to support proceeding with full scale fabrication, assembly, integration, and test. The project also demonstrates that the technical effort is on track to complete flight-system and ground-system development, as well as mission operations, to meet performance requirements while remaining within cost and schedule constraints. Reports of progress against management plans, budget, and schedule, as well as risk assessments are presented in the CDR. Phase C culminates at key decision point "KDP D" shown in Figure 7.4.

7.3.11 Phase D: Assembly, Integration and Test, Launch

During Phase D (perhaps better called "Phase C/D" due to all the iteration between the phases), the project performs system assembly, integration, and testing. These activities focus on preparing for the Flight Readiness Review (FRR). Phase D culminates in key decision point "KDP E" shown on Figure 7.4. Assemblies delivered to be integrated are subject to *acceptance testing* to verify that they work to specifications. Parts are also subjected to *qualification testing* to determine their characteristics in operations all the way out to the extremes of the envelopes, for example of temperature or pressure.

Parts Qualification

Appendix E, Chronology, lists the successful missions. In the history of interplanetary flight there have been many, many failures, and they seem to have been concentrated in the early years of space flight. A scroll through the missions listed on the Goddard Space Flight Center's website[18] will show an apparent trend: Lessons learned quickly and urgently have paid off in fewer failures as time went on. This permitted confidence to grow. The *Rangers*, the *Pioneers*, the *Mariners* (including the *Voyager*s), and many others were all built and launched in pairs at least. Then there was one *Galileo*, and one *Magellan.* One *Cassini*, one *Venus Express*, one *Messenger*, and one *New Horizons* are all doing well today. Plotted on Figure 7.1, flying only one of a kind would register as low in probability of failure, though the severity of the consequence of loss is high.

Contributing to the increasing confidence has been the process of *parts qualification.* Components — for example, small electronic parts such as integrated circuit chips and, to a lesser extent today, discrete components like transistors and resistors — are tested before selection. Extreme conditions effectively "weed out" the weaker samples. Ones that pass go to further testing in environmental chambers simulating the vibration, vacuum, sunlight, temperature, and other conditions they will encounter in flight if selected.

ATLO stands for Assembly, Test, and Launch Operations. When ATLO is in progress for some random spacecraft, any visitor to JPL might chance upon a quiet procession when pieces of flight hardware are in motion from one of the several laboratory buildings to a large high-bay cleanroom, where a spacecraft is being built up and tested.

> Today is August 6, 2008. Eastbound along the middle of Explorer Road at JPL, first comes a white sedan with a roof-mounted red rotating beacon, being driven slowly by a Wackenhut security guard. Next is an old yellow CNG-powered forklift, flanked by two engineers walking in the road, clad in bright orange vests with stripes of reflective tape. Sitting well padded in the forklift's grip is an article of flight hardware wrapped in electrically-conductive semi-translucent plastic. There's no telling what this wrapped component is by looking at it from the sidewalk, but no matter its description and function, it is not long for this Earth.
>
> This one is actually a component of the *Mars Science Laboratory* spacecraft, which is coming together in Building 179, the Spacecraft Assembly Facility (SAF), in full view of visitors who occasionally appear in the mezzanine gallery with their cameras. This component on the move is a product of years of planning and months of fabrication and testing, and represents a substantial investment in money, research, planning and reviewing, creativity, skilled labor, and quality control. Its movement from its previous laboratory to SAF is under the watchful eyes of the engineers who had some hand in creating it. The third and fourth of them are walking behind the forklift to its left and right, while a fifth comprises the convoy's end, walking in the middle of the road — almost as if guarding the flight hardware with his life.

During ATLO all the spacecraft's subsystems and instruments are integrated inside a *cleanroom,* which is supplied with filtered air. People working on the spacecraft don disposable overalls, hair covers, and shoe covers. Despite the absence of large pink ears, these "bunny suits" resemble a child's costume. But they protect sensitive equipment and instruments from the hair and particles of skin that humans naturally shed. Prior to entering the filtered-air cleanroom, each bunny-suited person takes an air shower to remove dust then passes through an air lock. The cleanroom interior environment has a controlled level of contamination by airborne dust particles, aerosols, and chemical vapors, having been cleaned by continuous recirculation through high-efficiency particulate air filters and ultra-low penetration air filters. Classifications of cleanrooms are specified according the number of airborne particles of size $\geq 0.5\mu$ present per cubic foot (0.03 m^3). A class-100 (ISO-5 certified)[19] cleanroom would have only one hundred such particles per cubic foot, compared to the millions per cubic foot in an office environment.

Even though the spacecraft might still be spread out in several separate parts while electrical power is applied during ATLO, its electronic components are running and communicating with each other. The spacecraft's central CTS computer, if not the telecommunications subsystem, is sending telemetry through cables to engineers typically situated in office space adjacent to the cleanroom. Engineers send commands to the spacecraft, verifying that each in its repertoire of many thousands of discrete commands operates properly, with measured and recorded results. Special tests are arranged in the cleanroom to fire pyrotechnic devices and actuate mechanical subsystems via command. The pyro devices will later be replaced with fresh ones, but these tests prove that the firing signals work, and that expected results are observed.

Before ATLO is complete, the spacecraft is wrapped in protective covering and transported to facilities where vibration testing and thermal-vacuum testing is carried out. Finally, it is broken down and transported to its launch site, where it is again assembled and tested prior to mounting atop its rocket.

January 9, 2007: MEPAG Meeting # 16 The Mars Exploration Program Analysis Group Meeting is not a review. Rather, it is an open, informative meeting for all members of the Mars science community, including international colleagues. Among the many topics the meeting covers is a glimpse into *Phoenix*'s progress through Phase D. According to live commentary provided to the public by *NASA Watch,* Dr. John McNamee spoke for the NASA Mars Exploration Program about the status of *Phoenix*:[20]

> The spacecraft is built, and is fully integrated. Fully functional software has been delivered. Waiting for some radar hardware. Large portion of environmental test program has been completed, including cruise vacuum testing. Surface thermal/vacuum testing is all that remains. Planning to ship [the spacecraft from Littleton, Colorado, to the Florida launch site] in the middle of May. Launch [period] opens on 3 August [2007]. First images of the landing site by *Mars Reconnaissance Orbiter* were frightening. We think we now have viable landing sites with suitable rock distribution. The radar has received a huge amount of attention. What we [initially] thought was a sys-

Fig. 7.5. The shipping container for *Galileo*'s deployable HGA is being loaded aboard its truck at JPL in 1986 for transportation to Florida. The container is empty for this trip, following the tragic launch failure of Space Shuttle *Challenger*. *Galileo* will be trucked back piecemeal to JPL from its launch site in Florida, eventually for modification and return to the launch pad in 1989.

> tem we could not make work, now we think [is] something that will perform adequately, if not perfectly, for entry, descent and landing.

Later in the day, Dr. Peter Smith, primary investigator for *Phoenix* Science, said, "We had a panic attack two years ago that we would not be able to scrape samples [from the frozen-solid Martian arctic soil]. So we put a power tool — a rasp — on the end of the arm. This is the sort of tool people use to make ice sculptures." He showed the attendees some recent images of ground-based tests where rock-hard ice samples were taken successfully at –90°C.

Testing, Testing

Test is ATLO's middle name, but the testing process begins well before the start of ATLO. Thorough testing is fundamental to a mission's success. As described in reference [3], the *Mars Pathfinder* project conducted proof-of-concept tests for its riskiest subsystems less than a year after the project started in 1993, six years before launch. These included the airbags, rover mobility, and the lander's solid-state X-band transmitting amplifier.

Project engineers try to have parts and assemblies delivered as early as possible to ATLO so that exhaustive testing can be undertaken. "Breadboard" electronics, which are early versions of circuitry under development, are typically replaced in the test lab by the more advanced engineering models of the assemblies, then by the actual flight articles, all subjected to thorough testing.

End-to-end tests are conducted to ensure that two-way communications through the developing ground system and flight system are robust. The path will have to support the flight system and subsystems testing that occur during ATLO. In *Pathfinder*'s case, external tests ran concurrently with ATLO, including dropping lander models on parachutes in Idaho, firing the descent-assist rockets in the Mojave desert, and a series of rigorous airbag tests in the Plum Brook Space Power Facility at NASA's Glenn Research Center in Ohio. This is the world's largest vacuum chamber, and it was pressurized with a simulated Martian atmosphere. Also in parallel with ATLO, *Pathfinder* engineers conducted tests of cruise stage separation, and lander and rover separation, at JPL, in the Mojave Desert, and at Lockheed Martin in Colorado. The aerobrake heat shield was tested during ATLO at the NASA Ames Research Center in northern California. According to *Pathfinder*'s manager Tony Spear,

> "Nothing beats testing the spacecraft [under conditions] as close to the actual flight conditions as possible. This we knew at the outset and planned for it, but we came away from this project really understanding how important this is."

7.4 Flying a Mission

7.4.1 Phase E: Flight Operations and Data Analysis

Launch marks a boundary between Phase D and Phase E, although perhaps it is not as sharp a boundary as might be imagined. Flight software might need to be developed, tested, and installed on the spacecraft during its cruise, and ground system development may need to continue. During Phase E, the project implements the Mission Operations Plan that was developed in previous phases. This phase culminates in key decision point "KDP F" shown on Figure 7.4.

Phase E has been our point of view in all the previous chapters: operating and navigating the craft, and collecting data for scientific analysis and publication. These activities are concurrent, and they are inseparable until the end of mission operations occurs. Mission planners speak of them together, using the initials for Mission Operations and Data Analysis: MO&DA.

Primary Mission Operations

Before and during ATLO the mission operations system takes shape. This is the collection of managers, engineers, scientists, and administrators who have put together the procedures, the hardware, and the software that will fly the mission in accordance with plans developed during previous phases.

The primary mission operations period encompasses cruise to the destination(s), arrival — or flyby(s) for that class of spacecraft — and operations after arrival until end of mission. Consider that arrival has different meanings for different classifications of spacecraft. Planetary orbiters have their orbit-insertion rocket burns.

Fig. 7.6. *Phoenix* lifts off. A Delta II rocket lit up the early morning sky over Cape Canaveral Air Force Station in Florida as it carried the *Phoenix* spacecraft on the first leg of its journey to Mars. The powerful three-stage rocket with nine solid rocket motors lifted off on August 4, 2007 at 5:26 A.M. EDT. Image ID 181867main_Liftoff. Courtesy NASA.

Atmospheric and lander spacecraft have their aerobraking via heat shield, followed by additional means of deceleration. Observatory spacecraft might mark arrival simply by achieving Earth or solar orbit at sufficient distance.

Cruise The purpose of the cruise segment of operations is to reach the destination. Having been placed on its planned trajectory by the launch vehicle during several minutes of thrusting at most, the spacecraft has acquired the kinetic energy needed to reach its target. Small adjustments are made via the Deep Space Maneuvers and Trajectory Correction Maneuvers that we visited in Chapter 2. Cruise is also the appropriate time to power up science instruments and check them out, perhaps taking advantage of opportunities to calibrate them. Short cruises to the nearby planets are typically packed with such activities. During longer cruises to the outer planets, there may be periods of relative quiet or, as in the case of *New Horizons*, even hibernation. All the while, operations teams prepare for arrival or encounter by finalizing and testing procedures, developing operational interface agreements among teams, hiring and training new team members, conducting operations readiness exercises and tests, and implementing any needed improvements in DSN capabilities.

Arrival As with a launch, for many classes of spacecraft an arrival is a make-or-break event.

> May 25, 2008: *Phoenix* EDL. The atmospheric Entry, Descent, and Landing event has filled all forty seats in the upstairs visitor's viewing gallery with dignitaries including local members of Congress, college presidents and trustees, state officials, and all their personal guests. The JPL Mars Program Chief Engineer Gentry Lee (1942–) is conducting a lively and informative interaction with the crowd as they look down past him into the recently remodeled Deep Space Operations room and its adjacent, glass-walled, Mission Support Area at JPL.
> At Mars, three orbiting spacecraft have coasted into segments of their orbits visible to both *Phoenix* and Earth. Their orbits were adjusted in recent months to be ready for this moment. They will support these minutes of EDL by capturing signals from *Phoenix* and relaying them via DSN to JPL and other facilities. Beyond the glass wall down in front are a few dozen men and women who are DSN operations engineers, *Phoenix* spacecraft engineers and managers, and some scientists. Many are sitting or standing near positions labeled, "PHOENIX TELECOM," "DSN OPERATIONS CHIEF," and a dozen other titles, wearing headsets connected to a wireless local voice network. Each of these participants is paying attention to a desktop computer monitor, while live television interviews proceed on the floor amid the buzz. Roving videographers mill around, and large rear-projection screens cover the far wall with animations and data being received from Mars.
> No more EDL commanding can be done from Earth. All *Phoenix*'s events are being driven by the command sequences already on board. The *Phoenix* EDL engineer's voice is on the audio feed, calling off events every few minutes as signals arrive from Mars indicating their occurrence: "Cruise stage separation." "Parachute deployment!" Each announcement is met by elated cheers and applause here in the gallery and down on the ops floor. Conference rooms around JPL and Caltech, as well as in Tucson, Arizona, where the University of Arizona has its *Phoenix* Science Operations Center, are also filled with people eagerly watching these events via live video. Live news media and webcasting are reaching an even wider audience.
> "Radar acquisition... parachute release!" Now a period of silence seems much longer than the two minutes or so it really took. The visitors have been briefed, and all know this means the lander's radar altimeter has acquired echos from the surface. The 12-meter diameter parachute has let go, and the spacecraft's eight hydrazine monopropellant thrusters have taken over to ease the vehicle down to the surface of a distant world, maintaining its attitude while continuing to brake. The 300 N rocket engines fire continuously but for the quick interruptions directed by *Phoenix*'s onboard attitude control system that keep the vehicle upright.
> "Sixty meters. Standing by for touchdown.
> "Touchdown sequence detected."

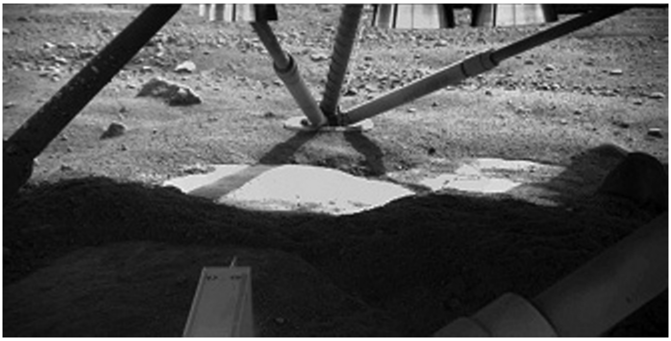

Fig. 7.7. The Robotic Arm Camera captured this image underneath the lander on the fifth Martian day of the *Phoenix* mission. Descent thrusters on the bottom of the lander are visible at the top of the image. This view from the north side of the lander toward the southern leg shows smooth surfaces cleared of overlying soil by the rocket exhaust during landing. The abundance of excavated smooth and level surfaces adds evidence to a hypothesis that the underlying material is an ice table covered by a thin blanket of soil. The bright-looking surface material in the center, where the image is partly overexposed, may not be inherently brighter than the foreground material in shadow. The *Phoenix* Mission is led by the University of Arizona, Tucson, on behalf of NASA. Project management of the mission is by NASA's Jet Propulsion Laboratory, Pasadena, California. Spacecraft development is by Lockheed Martin Space Systems, Denver. Image ID 20080531.html, courtesy NASA/JPL-Caltech/University of Arizona/Max Planck Institute.

Implementing Command Sequences The daily bread-and-butter activity in Phase E is the compilation and development of command sequences; scrutinizing, iterating, and testing them; uplinking them to the spacecraft; confirming the spacecraft receives them; and then watching the craft execute them to return valuable science data. The process is different among the various classes of spacecraft:

- Observatory spacecraft such as *Spitzer* and *Hubble* base their command sequence development on proposals solicited and received from the scientific community over the months and years prior to real time. Proposals that pass the evaluation process are worked into appropriate parts of upcoming command sequences, often combined into similar groups to optimize the amounts of attitude change or instrument configurations required to carry out the observations.
- Sequences for planet-mapping missions, for example at Mercury, Venus, Earth, and Mars, are worked on schedules that involve largely repetitive operations, taking basically the same kinds of observations while the planet rotates below the spacecraft's near-polar orbit, constantly presenting different longitudes for examination.
- Encounter sequences for the flyby spacecraft such as *New Horizons* and *Voyager* are worked far in advance, and realize their payoffs during relatively brief encounters.
- Sequences for planetary-system touring craft such as *Galileo* and *Cassini* can be viewed as a hybrid between planet-mapping and flyby classes. While orbiting

their primary gas-giant hosts they do have many repetitive opportunities while close to the host planet, but they also have frequent, individually planned flyby encounters among the giant planets' families of moons.

– Sequences for the landers and rovers on Mars are worked on a daily schedule. They also have longer-range plans that are frequently updated.

Surface Operations Phoenix has at least two communications passes a day as orbiters glide into position overhead in the Martian sky to relay data to and from Earth. The operations team in Tucson, Arizona, analyzes telemetry received the day before to determine what science activities to perform and when to perform them. As long there is good communication and the spacecraft is healthy on a daily basis, the team prepares an uplink package of commands and sends it to the lander via DSN and Mars orbiter relay in the Earth-time evening. Telemetry the next day reveals the results. This is called a *tactical timeline.* In case the spacecraft does not receive a new command sequence, it will fall back to a so-called "run-out" sequence, which is always stored on board, to take and store images and weather data for downlink during subsequent communications opportunities. *Phoenix* also has a *strategic timeline* to plan activities over a span of seven to fifteen days in advance, which is modified based on discoveries on the tactical day-to-day timeline.

The Mars Exploration Rover operations teams have a very similar approach to developing and uplinking command sequences. Scott Maxwell (1971–) is the Rover Driver team leader on the Mars Exploration Rover project at JPL.

It's Saturday August 23, 2008, and Scott is on stage with wall-size images projected behind him. He's advancing through views of "his twins," the rovers *Spirit* and *Opportunity*, and landscapes on Mars they've sent back from the surface. He's speaking to a crowd at the Gnomodex convention[21] in Seattle, Washington. In part of his presentation, which he calls a "crash course in how we drive Mars rovers," he describes a typical day in the life of his project. Driving a Mars rover doesn't work the way one might initially think it does, for example pushing forward on a joystick and the rover goes forward. "Pushing forward on the joystick would mean nothing happens for ten minutes while the signal propagates to the rover at the speed of light," says Maxwell. "Then the rover would start moving, but you wouldn't know. Even though it's started sending data back right away, telling you what it's doing, it takes another ten minutes coming back." He goes on:

> "Just imagine trying to back your car out of the driveway under that arrangement. So instead, we have a *daily tactical cycle* of operations, which works like this:
> "You take advantage of the fact that the rovers are solar powered. When the Sun goes down at night in the Martian sky, the rovers have to shut down. But before they do that, they send back pictures and other data to tell about the world around them. They tell what the world looks like, the lay of the land, and everything they were doing that day. Then the rovers go to sleep, and we go to work. We work the Martian night shift."

Communication with the rovers, comprising telemetry data on the downlink and command data on the uplink, normally goes via relay, also called crosslink, with the *Mars Reconnaissance Orbiter* or the orbiting *Mars Odyssey* spacecraft. The link between orbiters and rovers is UHF radio, and the link between orbiters and DSN is X-band. Images come back from the rovers via this "com path" in stereo pairs, and they contribute to a three-dimensional model that engineers and scientists maintain of the world around the rovers. "We have 'Mars the video game' sitting on our desktops," says Maxwell. A simulated rover in the virtual Martian world can be "driven" around inside the simulation to demonstrate how actual rover commands will operate, to assist planning and testing. "We can paint lines to show where the rover's tracks are going to go. Not limited in perspective, you can spin that simulated world around, back away from it, and look at it from all different angles. We can overlay the terrain with a grid, for scale." He continues:

> "The tactical timeline has a lot to it.
>
> "We get together in the morning, we get the data down from the rover, we do a quick assessment of that data to look for any anomalies; to look at the rover's health and safety. We get a basic plan formulated for what we want the rovers to do for the day, and then we have a big meeting where we sketch out a more detailed plan, and make sure everything we have in mind fits within our time and energy budgets. For example we might want to take some pictures and then drive. Do we have enough time to do those things during the day before we have to shut down for our comm path?
>
> "We then split apart out of that meeting and all go furiously work on implementing parts of that plan in parallel — multiple different people working on different parts — to translate those plans into the commands that the rover's going to actually execute. Then we get back together for another meeting where we show each other a first draft of what we're doing and make sure we're all on the same page, and everybody's ok with it. Then we split up again, do a whole bunch more refinement and implementation of that plan, breaking down everything into commands for the rover. We're thinking about anomalous cases: if we drive off course, is the rover going to catch that correctly? Should we really go this way, instead of that way, around this rock? We're making sure that everything we're putting into the command sequence correctly deals with all kinds of off-nominal contingencies. For those of you who are software developers, it's like writing typically five hundred to a couple thousand lines of code a day, where a single error costs three hundred thousand dollars, and maybe in fact sacrifices a priceless international space asset.
>
> "So then we get back together, look at everything we're going to do, every single command we're going to send to the rover that day. We review the sequence carefully, line by line, and the whole team takes a look at it, and tries to make sure we've poked at it properly, and that we've thought of every possible contingency. We go off and run all that through a bunch of software tools, and get back together again and do a second review. Every command we're going to send to the rover, we've looked at twice. And if we still can't find anything wrong, we take all the commands that made the simulation do the right thing, we send them up to the rover, then we go home and go to sleep. That's one day. One tactical cycle of operations.

Fig. 7.8. On May 19, 2005, *Spirit* captured this view of the Sun sinking below the rim of Gusev crater on Mars. From Pancam mosaic taken 6:07 P.M. Mars local time, for which the time and energy budgets allowed its daily command sequence to keep it awake briefly after sending that sol's (Martian day's) data to Earth via the *Mars Odyssey* orbiter. The Sun appears only about two-thirds the size that it appears from Earth. Image ID PIA07997. Courtesy NASA/JPL/Texas A&M/Cornell.

> "When the sun comes up in the Martian sky, the rover receives its commands, and executes them through the course of the day. Then the sun goes down in the Martian sky, and the rover sends us back pictures and other data telling us what it actually did — on a good day it looks just like the simulation — then the rover goes back to sleep, and we go back to work. We have that cycle going on every single day."[22]

Serendipitous wind storms on Mars have chanced to clean dust accumulations on the solar panels on *Spirit* and *Opportunity*. But the slopes, and the rocky landscapes all pose dangers (the atmosphere is low in density, so the wind poses no danger). If a rover were ever to tip over, it would have no way to right itself. The crowd responded with a good laugh when Scott commented, "Any time the pictures are right-side up is a good day."

The daily cycle doesn't leave the tactical crew any time to spend planning the longer-range activities — the overall strategy. A team made up of a different mix of scientists and engineers periodically updates a *strategic cycle* plan, which for MER, as in the case of *Phoenix*, is informed by events during the tactical cycle.

Orbital Touring Projects like *Galileo* or *Cassini* conduct extensive tours in the miniature solar systems of the giant outer planets. But the spacecraft don't just go there and look around. Mission designers begin producing sets of candidate mission tours long before the spacecraft leaves Earth. One such tour is illustrated in Figure 7.9. Each candidate set of orbits offers different specific opportunities for acquiring science data, such as flybys of natural satellites under specific lighting conditions, choices of orbital inclinations, and coverage of the planet's huge magnetic envelope. The science teams vet hundreds of such tour-set options, and tradeoffs are nego-

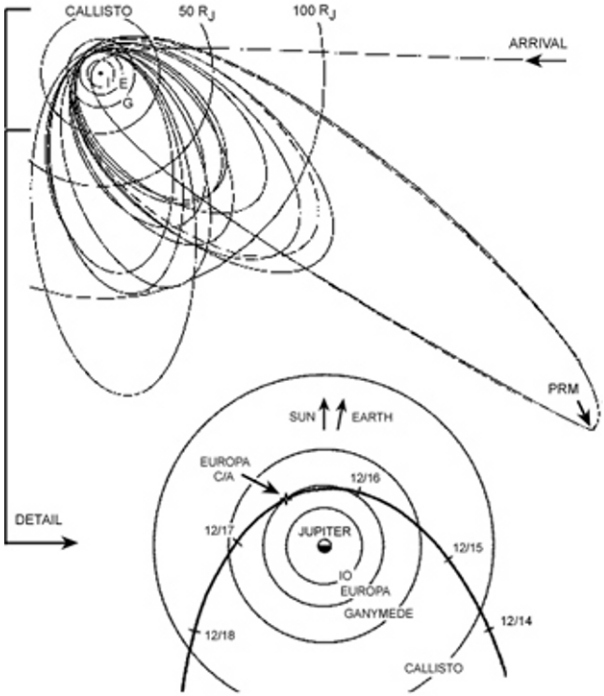

Fig. 7.9. *Galileo*'s prime-mission orbital tour, view looking down from above Jupiter's north pole.

Top: G = Ganymede, E = Europa, I = Io, R_J = Jupiter radii (1 R_J = 71,492 km), PRM = Perijove Raise Propulsive Maneuver. Initial orbit after insertion came inside the orbit of the Galilean moon Io, and extended more than 250 R_J where a propulsive maneuver at apoapsis added orbital energy to increase the altitude of subsequent periapses. Each subsequent orbit had a period of approximately two months. Jupiter's orbital motion is toward the right. Orientation is Sun-fixed with Sun towards top of page.

Bottom: Closer view of *Galileo*'s 205-kilometer encounter with Europa on December 16, 1997. Science observations taken during this encounter are detailed in Table 7.2. C/A = Closest approach. Images courtesy NASA/JPL-Caltech.

tiated in a process that occupies the science team members for many of the years spent in cruise. Finally, a number of months before arriving, the project's science group selects a winning design.

At this point, the science observations and experiments, as well as the major navigation and engineering operations such as software uploads and orbit trim maneuvers, can be scheduled into the framework of the chosen orbital tour geom-

Table 7.2. Observations executed during *Galileo*'s encounter with Europa 205 kilometers above its surface in December, 1997. Information courtesy NASA/JPL-Caltech.

Observation	Instrument	Epoch UTC SCET
Europa atmosphere	UVS	15 Dec 1997 04:51
Io eclipse	SSI	07:42
Jupiter spectral scan	NIMS	09:57
Start Europa gravity field	RS	18:04
Jupiter C/A (Range = 629,000 km to center)		22:36
Europa search for hot spots	PPR	16 Dec 1997 01:58
Europa Mineos linea	NIMS	03:18
Europa Pwyll color stereo	SSI	03:27
Europa-Magnetosphere interaction	F&P	03:44
Europa Closest Approach (Range = 1,770 km to center)		04:05

SCET = Spacecraft Event Time; UVS = Ultraviolet Spectrometer; SSI = Solid-State Imager; NIMS = Near-IR Mapping Spectrometer; RS = Radio Science (experiment, not an instrument); PPR = Photopolarimeter-Radiometer; F&P = Fields and Particles instruments; Europa radius = 1565 km.

etry. Mission planners then document the selected tour, showing, to the minute, the times at which hundreds of events will take place: every ring-plane crossing, every flyby of a moon, every apoapsis and periapsis, every change in the orbit's inclination, every OTM opportunity. Next, each team generates the sequences of commands needed to perform the activity from their point of view. The imaging science team generates commands that will point the cameras and obtain imaging data during each flyby of a moon or the host planet. The spacecraft engineering team generates commands to perform attitude control of the spacecraft and articulation of its appendages. The radio science team prepares for occultation experiments and object mass determinations. A mission planner submits a high-level request to the DSN for the tour's communications and navigational needs, so that later a sequence team member can meet with other flight project representatives to negotiate specific DSN station coverage for each portion of the tour. The whole tour is divided into a large number of individual command-sequence periods to work into preliminary products.

At some point, typically months or weeks before real time, the preliminary sequences are taken off the shelf and updated, then they go to a team who integrates them into a final sequence covering operations for several weeks. In addition to producing these command sequences, this team also publishes a list called the Integrated Sequence of Events (ISOE) for every sequence. Based on commands in the sequence and agreed DSN schedules, the ISOE shows all the minutely-detailed activities of the spacecraft and of the DSN down to the millisecond.[23] When each command sequence has been reviewed, approved, and released to operations, an Ace retrieves the file containing thousands of absolute-timed commands, and installs it onto the spacecraft in flight.

Late in the game, each sequence may have one or two opportunities to be updated *after* it has been installed on the spacecraft, after radio navigation and opnavs have refined the ephemerides for an upcoming target object such as a moon. In such cases the vectors that tell the spacecraft how to point to the object might be updated by overwriting their locations in spacecraft memory. In other cases the timing of whole blocks of pre-designated observation commands can be moved back or forward by up to a few minutes, to adjust for small changes in the navigation team's latest orbit determination run.

Table 7.3. Comparison of Mars Exploration Rover and *Cassini* Science Operations Characteristics. Information courtesy [9].

	CASSINI	MER
Science Opportunities	Unique	Repeatable
Science Leadership	Multiple PIs	Single PI
Science Debate Forum	Typ. Within Discipline Groups	More Between Groups
Time Dependency	Predictive Ops	Reactive Ops
Downlink Assessment	Infrequent Contributions	Highly Dependent
Science Plan Generation	Largely Parallel Process	Serial and Parallel
Timeline Optimization	Do Mostly Unique Designs	More Reusable Templates
Planning Cycle Duration	Weeks, Months	Hours

Mission Redesigns during Phase E

The idea of making changes to a mission's design after launch may at first sound impossible. The prospect is expensive and might be difficult, but it can certainly be done to both the spacecraft itself via software changes or special command sequences, and to the mission via trajectory or ground system changes.

The entire *Voyager 2* mission to the Uranus and Neptune systems was possible only after substantial redesign of the spacecraft's capabilities. Recall the description of the new command-data software installation from page 42, and the reference there to a full description of the redesign (Lanny Miller et al., cited on that page).

Recall also that the redesign of DSN uplink procedures prevented *Voyager 2*'s mission from being lost (page 42). Those special procedures have been in use with *Voyager 2* since 1977.

Again, a Phase E redesign of spacecraft and DSN capabilities prevented loss of most of the *Galileo* mission's science data return. Recall the discussion of the failure of *Galileo*'s 4.8-meter aperture HGA to deploy (page 17), and the full description of the recovery campaign (Bill O'Neil et al., cited on that page).

Impending loss of all the *Huygens* mission telemetry was prevented by a post-launch redesign of the initial orbits that *Cassini* would make after arrival at Saturn. Recall that the telemetry symbols from the *Huygens* Probe would have been

Doppler-shifted outside the relay capability with *Cassini.* Page 163 recounts the mission design change, wherein a 1,200-kilometer flyby of Titan was replaced by a 60,000-kilometer flyby to reduce closure rate during *Huygens*'s descent into Titan's atmosphere.

Extended Mission Operations

Any interplanetary mission that has been successfully launched and navigated to its destination(s), and operated successfully during its prime mission, can fully expect funding to be approved for some length of extended mission operations. The cost of developing an interplanetary mission from pre-Phase A through the nominal end of Phase E simply dwarfs the cost of merely continuing to operate it for a few years.

As extended missions complete and additional extensions are negotiated, eventually staff reductions will offer a reduction in the cost of continuing into a second or third extension. During its primary operations at Jupiter and Saturn, the *Voyager* project had a staff of full-time employees numbering in the hundreds. Today, only a dozen highly skilled engineers and scientists are on the project roll, and many of them devote only part time to Voyager.

In the late months of Phase E, after all mission extensions have played out, the project produces a Systems Decommissioning/Disposal Plan in preparation for Phase F.

A program may continue, though, after one of its projects comes to an end. The next mission in the NASA Mars Scout program has just been approved, as *Deep Space Craft* goes to press, continuing past the *Phoenix lander*'s completion. Called *MAVEN,* for *Mars Atmosphere and Volatile Evolution,* the mission will address the question, "What happened to Mars's atmosphere?" by focusing on "the other half of the story" (besides the planet's surface), which concerns the planet's previously dense atmospheric envelope, long ago protected by a global magnetic field.

7.4.2 Phase F: Closeout

During Phase F, the project implements the Systems Decommissioning/Disposal Plan developed in Phase E, and performs analyses of the returned data and any returned samples. The phase ensures archiving of mission engineering and science data, as well as curation of samples.

As a mission draws to a close, not all is bad news. Personnel departing one mission have usually started to become involved in some phase of another mission, which they might join and see through some or all of its phases. Coveted square footage in the office buildings is released to ease the local "space" problem. DSN resources, always heavily oversubscribed, are free to support different objectives.

After mission operations have ceased, the project's archived data will be available years and decades later, for various independently funded research activities. Many a PhD has been earned based on research into the interplanetary data archives.

Spacecraft Disposal

Many spacecraft are abandoned in place or in orbit. *Ulysses*, having completed its prime mission in solar polar orbit, is today running out of the hydrazine it needs for attitude control. Launched in 1990, its X-band TWTA failed on January 15, 2008. Since then, science data has been coming to DSN at lower bit rates via the spacecraft's S-band transmitter, but the loss of the X-TWTA meant loss of heat in a critical location, and the hydrazine in its propellant lines is approaching freezing. In an effort to maintain operations for as long as possible, thrusters are being fired solely to keep the fluid moving, but this will exhaust the tank probably before the end of the year. Following propellant exhaustion, *Ulysses* will no longer be able to point its HGA toward Earth, and it will be abandoned in orbit (periapsis is about 1 AU, apoapsis about 5 AU), perhaps to collide with Earth or an asteroid some thousands of years from now, or to be flung into a different orbit by a close call with Jupiter.

Galileo was intentionally commanded to plunge to its destruction within Jupiter to prevent any possibility it might collide with Europa and possibly introduce Earth-based microbial life on a body that has a warm saltwater ocean. *Cassini* will probably be directed into Saturn for similar reasons. There is a high probability that at least Titan and Enceladus have liquid water somewhere in their interiors.

The arctic Sun will soon set permanently on the *Phoenix* Lander. Its prime mission ended at the beginning of September 2008, and it continued operating on an extension from NASA. Before the onset of Martian autumn on December 26, 2008, though, the angle between Mars and the Sun in Earth's evening sky decreased to less than 3° on November 26, 2008 as the red planet passed around behind the Sun, making communications difficult and then impossible as the angle further narrows. By the time communications would be possible again in the Earth's morning sky, the Sun will be too low in the arctic Martian sky for *Phoenix* to generate power. The spacecraft and its instruments were never designed to survive the polar Martian autumn or winter. According to project manager Barry Goldstein on September 9, 2008:

> "Now that the sun is not constantly above the horizon at our landing site we are generating less power every sol [Martian day]. When we landed in late May, and through much of our mission, we generated about 3,500 watt-hours every sol. We are currently at about 2,500 watt-hours, and sinking daily. With the remaining sols we need to scurry to squeeze the last bit of science out of the mission."[24]

Later that month, the LIDAR instrument in *Phoenix*'s meteorological station reported snow falling from the clouds, sublimating before reaching the ground. *Phoenix*'s last transmission was received on November 2, 2008, and on November 11 NASA announced *Phoenix*'s mission was over. It had exceeded its planned 90-day lifetime by more than two months, and met all its original objectives. The Sun's departure from the Martian arctic, plus the accumulation of dust on its solar panels, marked the craft's demise. As winter sets in, *Phoenix* will become encased in carbon dioxide ice. The question remains as to whether there will be any attempts to re-establish contact when the Sun rises once again the in the Martian arctic, in late October of 2009.

Notes

[1]Announcement of Opportunity reproduced courtesy NASA HQ. Actually, this is just an announcement of the announcement, since the AO's many particulars were specified online.

[2]Six years is relatively short by today's standards, but in the space age's early days this might have seemed an eternity.

[3]National Space Society and U.S. Space Foundation, based on census bureau information.

[4]*Cassini*'s huge fuel and oxidizer tanks are not visible from outside the spacecraft.

[5]The Nunn-McCurdy act imposes a termination review if costs exceed 15% of the allocated amount, and automatic termination at 30%.

[6]See http://discovery.nasa.gov.

[7]See http://nmp.nasa.gov.

[8]See http://newfrontiers.nasa.gov.

[9]The entire structure and all the details of NASA's space flight program and project management organization may be found online by searching for "NASA Procedural Requirements NPR 7120.5D."

[10]Color risk-matrix charts are given green, yellow, and red squares corresponding to our white, grey and black, indicating safe, caution, and unacceptable.

[11]See NASA Procedural Requirements at http://nodis.gsfc.nasa.gov

[12]From SpaceFlightNow, http://spaceflightnow.com/mars/phoenix/080522landingpre.html.

[13]Gravitation does not really have a finite sphere of influence. Every mass gravitationally affects every other mass in the universe. What is meant here is the point where a spacecraft is more affected by the planet than by the Sun.

[14]*Daily firing windows* are short opportunities, seconds to hours, on each day during a launch period.

[15]Named after the Swiss mathematician, physicist and astronomer Johann Heinrich Lambert (1728–1777), who first computed in 1761 the time required to travel along an elliptic arc between two specific endpoints.

[16]Free downloadable software, called the Swing-By Calculator, SBC, is available from http://jaqar.com. It lets the user find trajectories from a departure planet to an arrival planet or heliocentric orbit via multiple planet swing-bys.

[17]This vignette was fabricated based on conditions typical of flight project reviews.

[18]See http://nssdc.gsfc.nasa.gov/planetary/chronology.html.

[19]ISO stands for International Organization for Standardization. See http://www.iso.org.

[20]NASA Watch is a private website that acts as a watchdog on NASA: http://nasawatch.com.

[21]Gnomodex is a yearly conference (in their words a *confluence*) of leading bloggers and new media.

[22]Quoted by permission.

[23]A sample ISOE page may be seen at http://www.jpl.nasa.gov/basics/soe.gif

[24]From *Phoenix* website, http://phoenix.lpl.arizona.edu/09_09_pr.php.

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[2] W.V. Boynton, W.C. Feldman, S. W. Squyres, T. Prettyman, et al. Distribution of hydrogen in the near surface of Mars: evidence for subsurface ice deposits. *Science*, 297(5578):81–85, July 5 2002.

[3] Anthony (Tony) J. Spear. Mars Pathfinder's lessons learned. *Acta Astronautica*, 45(4-9):235–247, March 1998.

[4] Charles D. Brown. *Spacecraft Mission Design, Second Edition*. AIAA Education Series. AIAA American Institute of Aeronautics and Astronautics, 2 edition, August 1998.

[5] Graham Swinerd. *How Spacecraft Fly*. Springer, November 14 2008.

[6] Howard D. Curtis. *Orbital Mechanics for Engineering Students*. Butterworth-Heinemann, December 27 2004.

[7] James R. Wertz and Wiley J. Larson, editors. *Space Mission Analysis and Design*. Microcosm Press, 3 edition, October 1999.

[8] http://www.planetary.org/explore/topics/space_missions/voyager/stories_kohlhase.html, 2002.

[9] L. Cheng, N. Spanovich, A. Vaughan, and R. Lange. Opposite ends of the spectrum: Cassini and Mars Exploration Rover science operations. JPL Section 317 Noontime Seminar, June 26 2008.

8 Onward

Deep Space Craft serves mainly as a snapshot of interplanetary flight as it exists today, but we'll close with a glance toward the horizon. Existing literature already covers many of the areas where development can be expected in the technologies benefiting interplanetary flight and helping to address scientific questions. Reference [1] covers them well, and it also constitutes a complement to the present book. This chapter lists and very briefly identifies a selected few of many promising technologies which may soon be expected to offer improvements in the craft of interplanetary flight.

There are larger fronts, though, to touch upon, and we will also do this briefly since they are speculative. Should there be a breakthrough discovery in the Search for Extraterrestrial Intelligence (SETI) or a long-sought confirmed detection in some other nascent scientific field, such as gravitational radiation, then whole new areas of investigation — brand new sciences — will open up to inquiry, answering hosts of long-held questions and raising many more about the rich cosmos we live in. Likewise, the detection of Earth-like planets in extrasolar systems, along with the ability to determine the content of their atmospheres, is waiting in the wings immediately beyond today's resolving ability.

Perhaps the more important choices on the horizon, though, will be how best to benefit from the perspective of our Earth as a planet in a solar system, and to further cooperate internationally and apply the tools of planetary exploration to monitoring the content of our shared atmosphere and the health of the biosphere. Dedicated international efforts may have a chance to reverse the effects of the industrial age on our ability to sustain a living habitat for future generations. Here the stakes are broad and high, and without effective effort, irreversible environmental degradation is highly probable.

We also have the ability and the opportunity to develop plans for the long-term safety of human societies and the biosphere as we know it, by detecting and tracking the potentially hazardous natural bodies that cross the Earth's orbit. The probability of a devastating impact is low for any given year, but the potential consequences are too serious to ignore.

8.1 Spacecraft Bus Technologies

One can speculate about many potential increments in technology that are further beyond the immediate horizon. Instead we'll mention some promising spacecraft bus[1] developments that are currently in progress:

- Ka-band Radio Telecommunications: Traditionally, capabilities for communicating telemetry and command data have been based upon radio links of increasing frequency and shorter wavelength. S-band and X-band, around 2 to 12 GHz, are in wide use across the solar system. Some Earth-orbiting spacecraft communicate over Ku-band, around 15 GHz. Ka-band data communications, at microwave frequencies around 30 GHz, are beginning to come into operation now. *Cassini* uses pure unmodulated Ka-band radio tones for radio science experiments, but the *Mars Reconnaissance Orbiter* has an experimental telemetry-modulated Ka-band capability, which has demonstrated data rates of 6 Mbit/s — ten times higher than previous communications from Mars. The *Juno* mission to Jupiter, planned for launch in 2011, will rely on modulated Ka-band for communications, as will the *James Webb Space Telescope* planned for a 2013 launch. The advantages of increasing the frequency of the carrier signal include the ability to transport data at higher rates, a reduction in the size of antennas on the spacecraft and on Earth, and an improvement in navigational tracking performance.
- Free-Space Optical Telecommunications: The next logical step for increasing the bandwidth for data communications is to move beyond microwave. Optical communications are commonplace in earthbound applications today at wavelengths in the ballpark of 850–1,625 nm. Modulated light traveling through thin glass (silicon-dioxide) fiber-optic cables brings high-speed Internet, cable-TV, and telephone communications to millions of people worldwide. When conducted outside the confines of optical fibers, the developing technology is known as free-space optical telecommunications. *Galileo* participated in such an optical communications experiment when it flew by Earth the second time for gravity assist en route to Jupiter. Two sets of laser pulses transmitted from Earth to the spacecraft over a distance of 1.4 million kilometers can be seen in Figure 8.1, which is a long-exposure image made by the *Galileo* spacecraft's imaging system. In the image, taken on December 10,1992, the second day in the eight-day experiment, the sunlit part of the planet (west central United States) is on the right, and the night side is on the left. *Galileo*'s camera was scanned from the bottom to top of the frame (approximately south to north), smearing terrain features, but showing individual pulses. The five larger spots in a vertical column near the pre-dawn centerline represent pulses from the U.S. Air Force Phillips Laboratory's Starfire Optical Range near Albuquerque, New Mexico, at a rate of 10 Hz. Those visible to the left are from JPL's Table Mountain Observatory near Wrightwood, California, at a rate of 15 Hz. The *Galileo* Optical Experiment demonstrated pointing a laser "uplink" from Earth to a spacecraft using ground-based telescopes "in reverse." No data transfer was attempted, but the experiment portends the day when laser downlinks may be generated by ultra-lightweight equipment on a spacecraft, and uplink data is received on board by small, lightweight telescopes instead of large, massive HGAs. JPL's Tracking and Data Acquisition Technology Development Office operated the experiment for NASA's Office of Space Communications Advanced Systems Program.

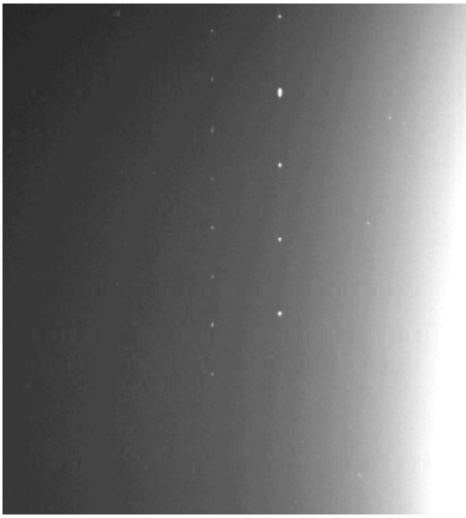

Fig. 8.1. *Galileo*'s detection of lasers from Earth's twilight edge. Image ID: PIA00230 Courtesy NASA/JPL.

– Advanced Photovoltaics: Both space-borne and earthbound applications are the beneficiaries of increasingly efficient solar cells and panels. One promising avenue for improvement is multi-junction thin film (low mass) photovoltaics. Each film of a layered cell is made of a material sensitive to a different wavelength component of sunlight, and can pass other wavelengths to adjacent layers for improved efficiency.
– Nuclear Power: RTGs are becoming more highly advanced, requiring smaller quantities of radioisotope material to supply the heat to generate electricity. New methods of converting radioisotope-generated heat into electricity promise to bring higher efficiency, thus further helping to reduce the mass of radioisotope carried aboard. In conjunction with the trend toward lower power requirements onboard spacecraft due to advances in electronics and micro-mechanical systems, the need to pursue the highly controversial issue of flying nuclear-fission reactors might be obviated. Sometimes mistakenly called a "Stirling RTG,"[2] the Stirling Radioisotope Power System (SRPS) may generate electrical power for deep-space missions in the future. In the laboratory, these devices are already demonstrating a reduction in the amount of radioisotope material required, in comparison with conventional no-moving-part RTGs, by a factor of four. They demonstrate a good increase in specific energy as well. These devices are being developed by the NASA Glenn Research Center and the U.S. Department of Energy. In an SRPS, a general-purpose radioisotope heat source provides the thermal energy, and exterior fins provide radiative cooling. The thermal gradient goes from about 650°C at the heat source (beginning of mission) to about 120°C at the fins. A small Stirling engine uses this gradient to produce mechanical energy, which is then converted to electrical energy. The SRPS's

pressure-sealed engine uses a piston to drive an alternator. The alternator's AC output is converted on-board to DC before it leaves the SRPS. Currently, the device's overall system efficiency is over 20%, compared with an RTG's typical efficiency of less than 10%.

- Miniaturization of mechanical systems: Miniature sensors and actuators can be made using fabrication processes similar to those used to manufacture integrated electronic circuits. For example the Micro-Electronic Mechanical System (MEMS) gyroscope (see Chapter 3) was first demonstrated in December 2006 on the *TacSat 2* spacecraft. Such miniature devices are generally less expensive, draw less power, and are more reliable than the macro-scale mechanical devices they replace — qualities well suited to interplanetary craft. In addition to miniaturizing gyros, micro-mechanical systems can benefit the designs of science instruments as well. Entire laboratory chemical processes can be carried out using microscopic tubes, pumps, and reaction chambers integrated with electronics on a single chip.
- Computing and data storage: One need look no further than the desktop to appreciate the development of computing and data storage. The trend toward smaller, faster computers was canonized in 1965 by the American businessman Gordon E. Moore (1929–) as an informal law stating that the number of transistors an inexpensive integrated circuit can employ increases exponentially, approximately doubling every two years. Moore's Law has fortuitous implications for the availability of increasingly lightweight, low-power, computing hardware enabling interplanetary missions to achieve faster and more complex data handling and communications processing. Recall from Chapter 1 the ability to approach the Shannon limit in error-free information transport that the low-density parity-check technique can achieve (page 36) given a large enough number of parallel processors. Apart from advanced hardware, software system development also is steadily evolving, so spacecraft design and testing tools, fault protection systems, intelligent agents, and communications coding algorithms represent a few of many possible areas for continuous improvement.
- Electric Propulsion: Ion engines have come into their own. First demonstrated in interplanetary flight by the *Deep Space 1* spacecraft's technology demonstrations, ion engines, powered by photovoltaics, have enabled the *Dawn* spacecraft to become the first spacecraft to achieve orbit about a solar system body other than Earth, leave that orbit, then enter into orbit about a second body. The extraordinary efficiency of ion propulsion (page 125) makes this technology a promising one for future interplanetary missions.
- Photon Propulsion: Much has been said about the promise of solar sailing — reference [2] is a good account — and while this technology has not yet been demonstrated in flight by a dedicated spacecraft,[3] demonstrations in the near future are likely to produce useful results. Photon propulsion uses thin-film, large-area reflectors to obtain miniscule acceleration from sunlight, not from the solar wind, whose sparse and relatively massive particles pass right through solar sails without imparting much at all of their kinetic energy. Sustained over long-duration flights, photon propulsion has the potential to enable scientific missions deep into interstellar space.

8.2 Science

It's really all about the science. Spacecraft busses exist to carry and support scientific instrumentation, and the instrumentation is there to address the big questions such as ones we touched upon at the beginning of Chapter 6. Important results are pending in many disciplines. Some of them will surely be enabled by the capabilities of new and advanced spacecraft and ground systems.

8.2.1 Gravitational Wave Astronomy

Kirchhoff opened an enormous field of discovery in 1859 when he created the science of spectroscopy (page 203), enabling scientists to learn the chemical makeup of distant objects. If it does turn out to be technically possible to observe Einsteinian gravitational radiation as it propagates through the fabric of space-time (see page 224), the first such discoveries will open up unprecedented fields of inquiry in new directions, comparable in magnitude to the far-reaching branches of Kirchhoff's new science.

Such a discovery might be just around the corner. In addition to the searches conducted by members of the planet-exploring spacecraft fleet, and the Earth-based gravitational observatories such as *LIGO* that we examined in Chapter 6, in the near future systems of dedicated spacecraft will join the search. One might be the *DECi-hertz Interferometer Gravitational Wave Observatory* (*DECIGO*), a Japanese mission whose planned sensitivity to gravitational waves will be mainly between 0.1 Hz and 10 Hz. The experiment will consist of three spacecraft, free-flying 1,000 kilometers apart, whose relative displacements will be measured by a Fabry-Perot Michelson interferometer. The first step planned is a *DECIGO Pathfinder* mission to demonstrate the required technologies prior to finalizing the *DECIGO* designs and putting it in flight. *LISA*, the Laser-Interferometer Space Antenna, is a joint venture being planned by NASA and ESA to exhibit sensitivity to gravitational waves between 10^{-4} Hz and 10^{-1} Hz. This mission also plans to fly a technology demonstration, *LISA Pathfinder*, before finalizing the *LISA* design.

While highly unlikely, even if it were discovered that direct detection of gravitational radiation is impossible for some physical reason yet unrecognized, while disappointing, this in itself would also be an important discovery about the physical nature of our universe.

8.2.2 Earth-mass Exoplanet Discoveries

On March 8, 2009, the number of planets known to orbit stars besides our own Sun was 342. Until this day, we had never actually seen a planet of another star. All had been found indirectly, by the star's induced wobble or by brightness variations during eclipses in the distant stellar systems. On this historic day a team led by astronomer Paul Kalas of the University of California, Berkeley released the first-ever visible-light image of such an exoplanet [3]. Detected and confirmed in HST visible-light images, it occupies an 80-year orbit about Fomalhaut, a star 25 light-years away. Another team, led by Christian Marois of the Herzberg Institute of

Astrophysics in Victoria, British Columbia, announced on the same day infrared images of three exoplanets orbiting a star 130 light-years away known as HR 8799 [4]. Marois and his colleagues obtained these images using various ground-based telescopes.

Launched in March, 2009, the *Kepler* Spacecraft may soon detect Earth-mass exoplanets, perhaps in habitable zones around other stars in our galaxy. More exoplanet discoveries will most likely be made as instruments and techniques continue to improve, such as applications of space-based interferometry, which uses widely separated telescopes to synthesize a large aperture. Habitable exoplanets might also be found using applications of orbiting interplanetary occulting disks, which block out the bright central star of a system while a second spacecraft's telescope looks for planets, free of the star's glare.

8.2.3 SETI

Another field for enormously important potential discovery is the Search for Extraterrestrial Intelligence (SETI). Two-way communication is not to be expected, because the round-trip light time to any exosystem found to be the source of intelligible signals would surely be prohibitive. But a single, confirmed, one-way signal reception is all it would take to thoroughly vitalize the fields of study related to exobiology, as well as additional SETI search campaigns. While perhaps disappointing, it would also be a worthwhile scientific discovery to learn that detection efforts at various wavelengths produce no results — which is the case as of today.

8.2.4 Habitat Identification

Within our solar system there are several potential habitats that may be suitable for some forms of life as we know it here on Earth. The *Phoenix* spacecraft returned promising data on the chemistry of the water-ice rich soil in Mars's arctic region. A warm saltwater ocean is likely to exist beneath the thin water-ice shell of Jupiter's moon Europa. And there seem to be sub-surface oceans on other satellites of Jupiter, and on Saturn's big satellite Titan. Saturn's tiny moon Enceladus, whose fine water-ice geysers contain organic chemicals, is an interesting target of study as well. The possible detection of actual forms of life within our own solar system, whether microscopic or otherwise, is probably in the distant future, but the confirmed detection of possible life-form-friendly *habitats* is right at hand.

8.2.5 Improving Sensor Capability

Apart from exciting breakthroughs that may occur in the near future, there is gradual but continuous advancement in the development of many technologies related to remote sensing and on-site direct-sensing capabilities. To pick a few examples, improvements are being made in the physics of electromagnetic detectors. CCD detectors work well in the visible range of the spectrum and higher energies; the

Chandra X-ray Observatory uses a CCD. New detectors for use in the UV and X-ray parts of the spectrum will benefit by the further development of micro-channel detector image intensifiers. Development in scintillation detectors (see page 211) applies to gamma-ray observing instrument design. On the infrared end of the spectrum, developments in higher pixel-count advanced semiconductor detectors made of such materials as mercury cadmium telluride, indium antimonide, germanium, or silicon are likely to advance.

Some future generations of in-situ measuring stations might obviate any need to mount expensive sample-return missions to Mars or to other bodies, but such technologies don't appear to be in the near term. Substantial advances will have to be made in miniature robotic technologies that can be used to determine the age of minerals to within 10% or so, before they could outperform Earth-based analysis of extraterrestrial samples. So Mars sample return is still a current goal for the planetary science community.

On Earth, more laboratory reference spectra are constantly being added to the scientific databases in all parts of the electromagnetic spectrum. These databases are an essential counterpart to the spectroscopic instruments operating in flight. Additional data entries will help scientists identify atomic and molecular combinations, observed in the features of spectral data returned from space-borne instruments, that may be currently unrecognized. Recently, as detailed in reference [5], the technique of rotational spectrometry has demonstrated that it can permit identification of more kinds of molecules in interplanetary and interstellar space.

8.3 Print and Electronic Media

Publications for peer-review — the major science journals — as well as the popular media are becoming electronic. An indicator of this trend is the recent decision by the publishers of the popular weekly magazine *Science News* to shift to more dependence on its website for timely dissemination of scientific headlines, and a reduction in the frequency of hardcopy distribution to biweekly.[4]

One only has to use websites like *http://sciencemag.org* for a short time to appreciate the enormous convenience which the Internet can bring to readers, students, and professionals exploring topics related to interplanetary flight, and, for that matter, all of science. It is the author's hope that the reader is accessing the content of *this book* electronically, as well as many other books and journals. Paper doesn't need to be manufactured from living, CO_2-loving trees in order to convey the *information* contained in books and other printed media. It may soon be unnecessary, in a well-developed information age, to expend oil and other limited resources to deliver content using automobiles and trucks. The printed media, especially in technical fields, are doing a superb job branching out into the electronic web. It is likely that the trend toward electronic communications media will to continue to grow, and indeed it would be helpful for sustaining our planet's health.

8.4 Human Journeys

Aside from the Moon, the only remaining objects in our solar system where it is physically possible for a human to set foot, given the existing or currently developing space-suit technology, are Mars and the asteroids. By the time this actually happens, if it does, these destinations will have been thoroughly examined by robotic explorers, ensuring the safest and most scientifically productive locations and means for humans to visit. As already mentioned, future-generation advancements in robots capable of offering high-fidelity telepresence may eventually obviate any need for humans to go to an asteroid, for example, in the flesh. Given such highly-evolved in-situ robotic stations, it is even possible that the desire to set foot on Mars might yield to a greater desire not to infect a pristine alien world with the microbes humans would by nature carry from Earth.

But Mars is a compelling place to explore and compare with our home, and it will be explored one way or another. Current scientific knowledge has it that 4×10^9 years ago, the next planet out from Earth had its own magnetic field, as does Earth today. The field protected Mars's atmosphere, and there were warm saltwater oceans on the surface. But as the planet's global magnetic field eventually dwindled, the Sun's waves of charged particles were free to blow away the atmosphere, which then caused the oceans to disappear.

As for the interstellar distances, unless we could somehow prepare for a journey lasting several hundred thousand years or more, we will never ride star-ships to planets beyond our solar system, even if SETI were to reveal a viable destination.

8.5 Earth-Protective Measures

While more are planned for the near future, many spacecraft bearing instrument packages are currently in Earth orbit investigating and reporting on the conditions of the seas, the winds, the clouds and the state of our atmosphere. Launch of the 407-kilogram *Orbiting Carbon Observatory* spacecraft unfortunately failed on February 24, 2009 when its payload fairing failed to separate. Meanwhile on Earth, advances in technologies such as the photovoltaics originally developed for space flight may offer us some of the valuable tools we need to drastically reduce the amount of carbon and other greenhouse gases we introduce into our atmosphere.[5]

We know of previous destructive meteor impacts to our planet's surface, the latest being a relatively benign airburst event — likely a small comet or asteroid — in Tunguska in 1908. We know about some of the major collisions in Earth's deeper past, and we know the probability of impacts among the planets in today's solar system. About 35,000 tons of material from asteroids and comets enter our atmosphere each year. On average about one 10-gram object makes it to the surface without burning up for every 2,500 square kilometers across our planet's surface in the course of a year. A 1-meter diameter object strikes our planet about once a year, but larger impacts have smaller probabilities of occurring. Reference [6] characterizes the danger to us today. A 100-meter diameter impactor has a probability of colliding with Earth once every thousand years, but it would cause a 100 megaton (4.3×10^{17}J) event. It is estimated there are 300,000 near-Earth asteroids of this size in our orbital neighborhood. A 1-kilometer diameter impactor collides only about once every 65,000 thousand years, with its result in the 100,000 megaton range. But even a smaller impactor of around 200 meters in diameter, were it to fall in the ocean, could cause a tsunami destructive to coastal lands. According to reference [7], an impact anywhere in the Atlantic by an asteroid of 400 meters diameter would cause a 100-meter high tsunami to inundate the coasts on both sides of the ocean.

Already, small programs are in operation to discover hazardous objects. An example is the U.S. program called Lincoln Near-Earth Asteroid Research (LINEAR) uses a network of several robotic telescopes that scan the ecliptic autonomously on clear nights. LINEAR is responsible for most of the near-Earth asteroid discoveries — thousands per year — over the past decade. Several comets bear the name LINEAR for their discoverer.

We have demonstrated the ability to fly to the asteroids and comets, and it might be possible to undertake missions to change the course of a menacing object were one discovered to be on an impact trajectory. Will tomorrow's visionary and talented scientists and engineers find it prudent to prepare contingency plans and hardware to actually carry out such a maneuver? As of today we have the telescopic and computational tools to necessary find many of the potentially dangerous objects in the solar system, so it would seem a relatively simple task to detect, catalog, and track as many of them as we can — and to be vigilant to spot and track fresh comets arriving from the outer solar system. The effort requires no new technology and only moderate resources. What is needed is the will and motivation to look for them, and to set in place an infrastructure that will help protect our home planet for generations to come.

8.6 Earthbound Dividends

The importance of space exploration to humankind has been pointed out by the American-Iranian space enthusiast Anousheh Ansari (1966–) on her website[6] by reminding us of the eloquent 1970 response of Dr. Ernst Stuhlinger, then Associate Director for Science at NASAs Marshall Space Flight Center, to a letter from one Sister Mary Jucunda, who worked among starving children of Kabwe, Zambia, Africa. She had questioned the United States' allocations of thousands of millions of dollars to space exploration. Below is an excerpt from his well-publicized letter. After expressing his admiration for her dedication to people who are in need, he goes on:

> "Efficient relief from hunger, I am afraid, will not come before the boundaries between nations have become less divisive than they are today. I do not believe that space flight will accomplish this miracle overnight. However, the space program is certainly among the most promising and powerful agents working in this direction.. . .
> "Significant progress. . . is frequently made not by a direct approach, but by first setting a goal of high challenge which offers a strong motivation

> for innovative work, which fires the imagination and spurs men to expend their best efforts, and which acts as a catalyst by including chains of other reactions.... Space flight without any doubt is playing exactly this role.
> "Besides the need for new technologies, there is a continuing great need for new basic knowledge in the sciences if we wish to improve the conditions of human life on Earth.... We need more young men and women who choose science as a career and we need better support for those scientists who have the talent and the determination to engage in fruitful research work.... Again, the space program with its wonderful opportunities to engage in truly magnificent research studies of moons and planets, of physics and astronomy, of biology and medicine is an almost ideal catalyst, which induces the reaction between the motivation for scientific work, opportunities to observe exciting phenomena of nature, and material support needed to carry out the research effort....
> "How much human suffering can be avoided if nations, instead of competing with their bomb-dropping fleets of airplanes and rockets, compete with their moon-traveling space ships! This competition is full of promise for brilliant victories, but it leaves no room for the bitter fate of the vanquished, which breeds nothing but revenge and new wars. ... Although our space program seems to lead us away from our Earth and out toward the moon, the sun, the planets, and the stars, I believe that none of these celestial objects will find as much attention and study by space scientists as our Earth. It will become a better Earth, not only because of all the new technological and scientific knowledge which we will apply to the betterment of life, but also because we are developing a far deeper appreciation of our Earth, of life, and of man."

NASA commemorated its origins at a celebration hosted in September, 2008 by the Smithsonian National Air and Space Museum in Washington, DC. At the gathering, Neil Armstrong (1930–), the first human to set foot on the Moon, made these remarks:

> "Half century later, we look back on what has been accomplished. Our knowledge of the universe around us has increased a thousand fold and more. We learned that *Homo sapiens* was not forever imprisoned by the gravitational field of Earth.... We've sent probes throughout the solar system and beyond. We've seen deeply into our universe and looked backward nearly to the beginning of time....
> "Our goal — indeed our responsibility — is to develop new options for future generations: options in expanding human knowledge, exploration, human settlements and resource development, outside in the universe around us. Our highest and most important hope is that the human race will improve its intelligence, its character, and its wisdom, so that we'll be able to properly evaluate and choose among those options, and the many others we will encounter in the years ahead."

Notes

[1]See discussion of "spacecraft bus" in Chapter 5 (page 143).

[2]SRPS devices contain radioisotope heat sources, but the term "thermoelectric" doesn't technically apply to them (RTG stands for Radioisotope Thermoelectric Generator).

[3]The first attempt was carried out by the private space-enthusiast group The Planetary Society, whose *Cosmos 1* suffered from launch-vehicle failure in 2005.

[4]See http://sciencenews.org

[5]One benefit of realizing that our Earth's atmosphere is a very thin film upon a small fragile planet may be to encourage nations to work together to reduce CO_2 generation, and perhaps on more fronts as well.

[6]http://anoushehansari.com

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[1] Michel van Pelt. *Space Invaders - How Robotic Spacecraft Explore the Solar System.* Praxis, 2007.

[2] Jerome Wright. *Space Sailing.* Routledge, 1992.

[3] Paul Kalas, James R. Graham, Eugene Chiang, Michael P. Fitzgerald, Mark Clampin, Edwin S. Kite, Karl Stapelfeldt, Christian Marois, and John Krist. Optical images of an exosolar planet 25 light-years from Earth. *Science online*, November 13 2008.

[4] Christian Marois, Bruce Macintosh, Travis Barman, B. Zuckerman, Inseok Song, Jennifer Patience, David Lafrenière, and René Doyon. Direct imaging of multiple planets orbiting the star hr 8799. *Science online*, November 13 2008.

[5] Ron Cohen. With a closer look, chemists find molecules switch shapes slowly. *Science News*, 173(18):7, June 7 2008.

[6] Tony Reichhardt. Scaling the degree of danger from an asteroid. *Nature*, 400:392, July 29 1999.

[7] Jack G. Hills and Charles L. Mader. Comet/asteroid impacts and human society. *Annals of the New York Academy of Sciences*, 822:381–394, December 2006.

Appendix A: Typical Spacecraft

This appendix contains descriptions and images of a dozen spacecraft selected from the many that are currently operating in interplanetary space or have successfully completed their missions, plus one that is now preparing for launch. Included is at least one representative of each of the eight spacecraft classifications described in Chapter 7 (see page 243).

The scheme of limiting coverage of each spacecraft to a two-page spread in this appendix allows the reader to easily compare the various craft, their specifications, their missions, and their classifications, but it does not allow room to list all of a spacecraft's activities, discoveries and questions raised; indeed entire books can and have been written on each. Complete profiles of these and other spacecraft are, however, readily available at a single web site: http://nssdc.gsfc.nasa.gov/planetary.

Contents:

The *Voyager* Spacecraft

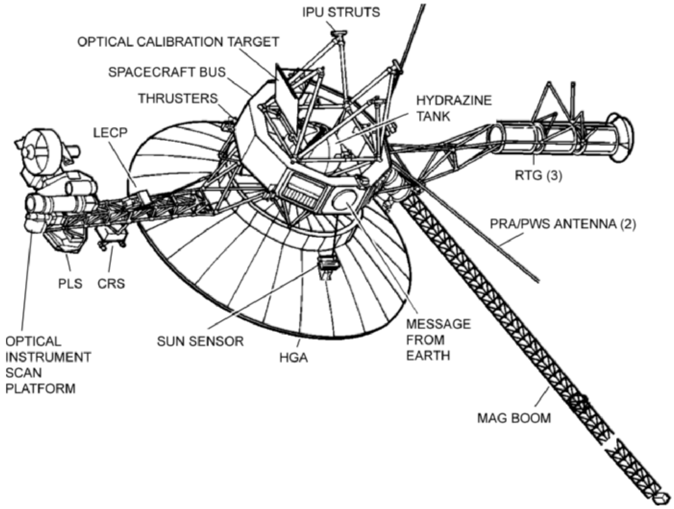

Fig. A.1. Each *Voyager* spacecraft measures about 8.5 meters from the end of the science boom across the spacecraft to the end of the RTG boom. The magnetometer boom is 13 meters long. Courtesy NASA/JPL.

Classification: Flyby spacecraft
Mission: Encounter giant outer planets and explore heliosphere
Named: For their journeys

Summary: The two similar spacecraft flew by Jupiter and Saturn. *Voyager 2* continued on to encounter Uranus and Neptune. Both are on solar-system escape trajectories, and have penetrated the solar-wind termination shock. In 1998, *Voyager 1* became the most distant human-made object.

Payload: Imaging science wide-angle and narrow-angle cameras, UV spectrometer, IR spectrometer-radiometer, photopolarimeter, on scan platform. Low-energy charged particle detector, plasma spectrometer, cosmic ray detector, magnetometers (4), plasma wave detector, planetary radio astronomy receiver, audio and video messages from Earth encoded on gold record.

Nation(s):	USA	**Mass at Launch:**	800 kg
Radio Link:	S- and X-band	**Stabilization:**	3-Axis, thrusters
Propulsion:	Hydrazine	**Electrical power:**	RTG
Launch date:	1977	**Launch vehicle:**	Titan-IIIE/Centaur

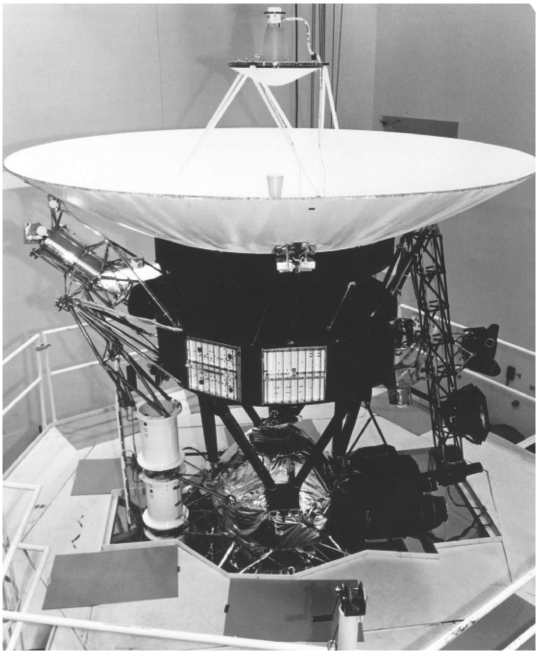

Fig. A.2. One of the *Voyager* spacecraft during vibration testing at JPL on March 25 1977. Mission module is attached atop the injection propulsion unit (IPU) which was later jettisoned. Science boom (right) and radioisotope thermoelectric generator (RTG) boom (left) are folded down in launch configuration. The 13-meter long magnetometer boom is stowed within canister above middle left. White cylinders are RTG mass simulators; actual RTGs were installed just prior to launch. Thermal control louvers were placed differently prior to flight; the golden record of messages from Earth was placed on the bay seen near the center of the image. Courtesy NASA/JPL-Caltech.

The *New Horizons* Spacecraft

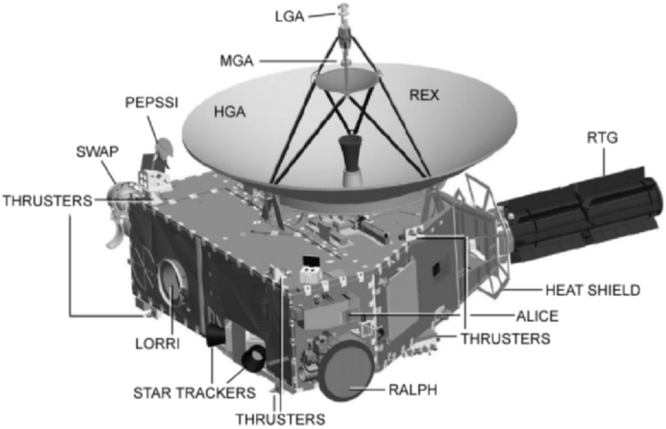

Fig. A.3. The *New Horizons* Spacecraft measures about 3 meters overall at its widest dimension. Courtesy NASA/JPL.

Classification: Flyby spacecraft
Mission: Encounter Pluto and Charon then explore Kuiper Belt
Named: For its journey

Summary: New Horizons took a gravity-assist from Jupiter in 2007 and will fly by dwarf planet Pluto and its moon Charon in 2015. It is expected to encounter one or more additional objects in the Kuiper Belt. Image courtesy Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute (JHUAPL/SwRI).

Payload: Seven instruments: Ralph, a 6-centimeter aperture telescope to feed its Multispectral Visible Imaging Camera and Linear Etalon Imaging Spectral Array. Alice, an ultraviolet imaging spectrometer. LORRI, the Long Range Reconnaissance Imager, which consists of a 20.8-centimeter aperture telescope with a CCD imager. SWAP, the Solar Wind Analyzer around Pluto, which measures charged particles from the solar wind. PEPSSI, the Pluto Energetic Particle Spectrometer Investigation, which characterizes neutral atoms. SDC, the Student Dust Counter. REX, the Radio Science Experiment, which functions as a microwave radiometer. It also records the received spectrum of the DSN's uplink during occultation experiments.

Nation(s):	USA	**Mass at Launch:**	478 kg
Radio Link:	X-band	**Stabilization:**	3-Axis thrusters or spin
Propulsion:	Hydrazine	**Electrical power:**	RTG
Launch date:	January 19, 2006	**Launch vehicle:**	Atlas-V/Centaur

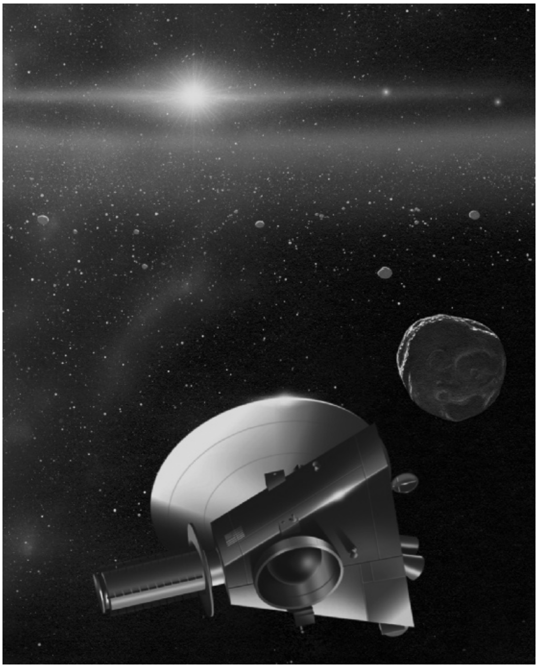

Fig. A.4. Artist's conception of the *New Horizons* spacecraft encountering a Kuiper Belt object. The Sun, about 45 AU away, appears in the glow of the zodiacal dust. The many objects in the Kuiper Belt, normally not visible because they are so far apart, are shown here to give an impression of the large number of icy worlds beyond Neptune. Image courtesy Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute (JHUAPL/SwRI).

The *Spitzer Space Telescope*

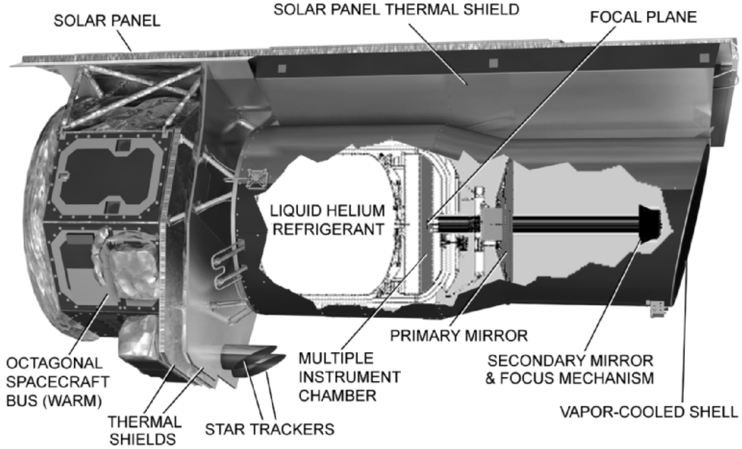

Fig. A.5. The *Spitzer Space Telescope* measures about 5 meters in length overall. Telescope shell cut away to reveal cooled telescope assembly within. Adapted from images courtesy NASA/JPL-Caltech.

Classification: Observatory spacecraft
Mission: Observe objects deep in the universe, galaxy, and solar system
Named: In honor of American astrophysicist Lyman Spitzer, Jr. (1914–1997). Originally *Space Infrared Telescope Facility (SIRTF),* renamed after launch.

Summary: One of the four NASA Great Observatories including *Hubble*, *Compton*, and *Chandra*. Orbits the Sun in an Earth-trailing orbit at about 1 AU, keeping its solar panel facing the Sun to shield the entire spacecraft from infrared radiation. The telescope has an 85-centimeter diameter primary mirror cooled to 5.5 K by boiling off liquid helium from an onboard 50.4-kilogram supply. This cools the telescope's optics via a vapor-cooled shell and also cools the instruments near the focal plane. Cooling permits *Spitzer* to observe deep into the infrared region of the spectrum without interference from warm optics. Upon exaustion of coolant in 2009, sunshade keeps telescope at 34 K (instruments 4 K cooler due to additional passive cooling).

Payload: *Spitzer*'s Infrared Array Camera operates simultaneously at 3.6 μm, 4.5 μmm, 5.8 μmm and 8 μmm wavelengths. The Infrared Spectrograph observes from 5.3 μm to 37 μm. The Multiband Imaging Photometer works from 24 μm to 160 μm.

Nation(s):	USA	**Mass at Launch:**	950 kg
Radio Link:	X-band	**Stabilization:**	3-Axis reaction wheels
Propulsion:	Cold nitrogen	**Electrical power:**	Solar
Launch date:	August 25, 2003	**Launch vehicle:**	Delta-II

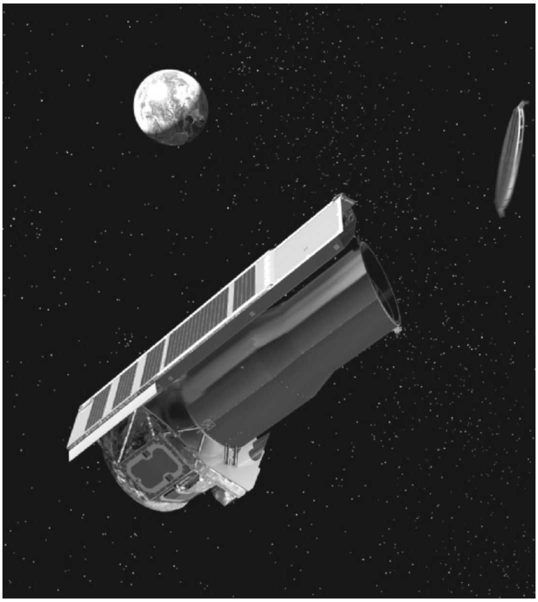

Fig. A.6. *Spitzer* releases its aperture dust cover in this artist's conception. Thermal blanketing on the warm spacecraft bus is not shown. The vapor-cooled shell which surrounds the whole telescope has an upper surface (facing the solar panel shield) of polished metal to reject heat. The lower half of the shell is painted black to best radiate heat (which can be better seen by searching online for image ID: sirtf0410_04). The parabolic high-gain antenna is affixed to the lower left end of the spacecraft bus and cannot be seen in this view. Image courtesy NASA/JPL-Caltech.

The *Chandra X-Ray Observatory*

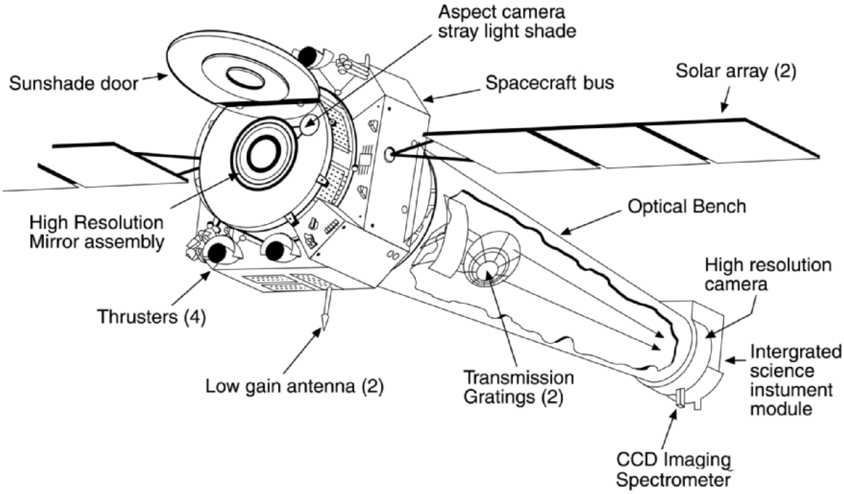

Fig. A.7. The *Chandra* spacecraft measures 13.8 meters in length. Its solar arrays span a width of 19.5 meters end-to-end across the spacecraft. Courtesy NASA/CXC/SAO.

Classification: Observatory spacecraft
Mission: Capture images and spectra of high-energy events in the universe
Named: In honor of Indian-American astrophysicist Subrahmanyan Chandrasekhar (1910–1995) (Not to be confused with lunar orbiter *Chandra-yaan*)

Summary: One of the four NASA Great Observatories (including *Hubble*, *Spitzer*, and *Compton*). Its mirrors' high angular resolution give *Chandra* one hundred times greater sensitivity than previous x-ray telescopes. Known as the *Advanced X-ray Astrophysics Facility* (AXAF) prior to launch. Operates in a 64.2-hour, 10,000-kilometer x 140,000-kilometer Earth orbit above the x-ray absorbing atmosphere. Data from *Chandra* has been greatly advancing the field of x-ray astronomy since August 1999.

Payload: The Advanced CCD Imaging Spectrometer (0.2–10 keV) and the High Resolution Camera (0.1–10 keV), both within the Science Instrument Module. Either of two spectroscopic gratings may be swung into the optical path downstream of the mirrors: the High Energy Transmission Grating (0.4–10 keV) or the Low Energy Transmission Grating (0.09–3 keV).

Nation(s):	USA	**Mass at Launch:**	4,620 kg
Radio Link:	S-band	**Stabilization:**	3-Axis, reaction wheels
Propulsion:	Hydrazine	**Electrical power:**	Photovoltaic
Launch date:	July 23, 1999	**Launch vehicle:**	STS *Columbia*/IUS

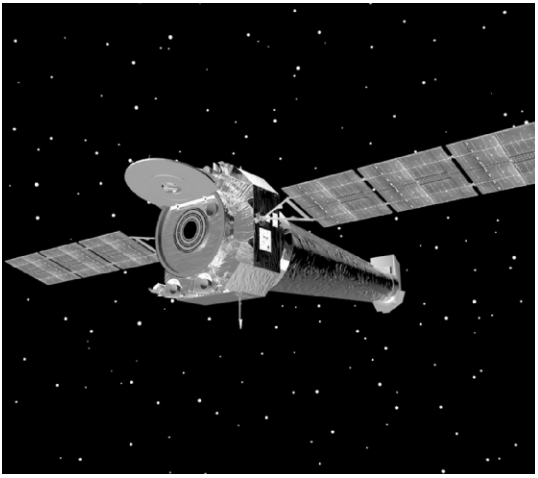

Fig. A.8. Artist's conception of the *Chandra* spacecraft. Concentric rings below the open aperture cover are the leading-edge rims of the 1.2-meter and smaller diameter nested high-resolution modified-cylindrical mirrors of *Chandra*'s Wolter grazing-incidence (see page 197) 10-meter focal length telescope, which extends toward the science instrument module at right. Courtesy NASA/CXC/SAO.

The *Galileo* Spacecraft

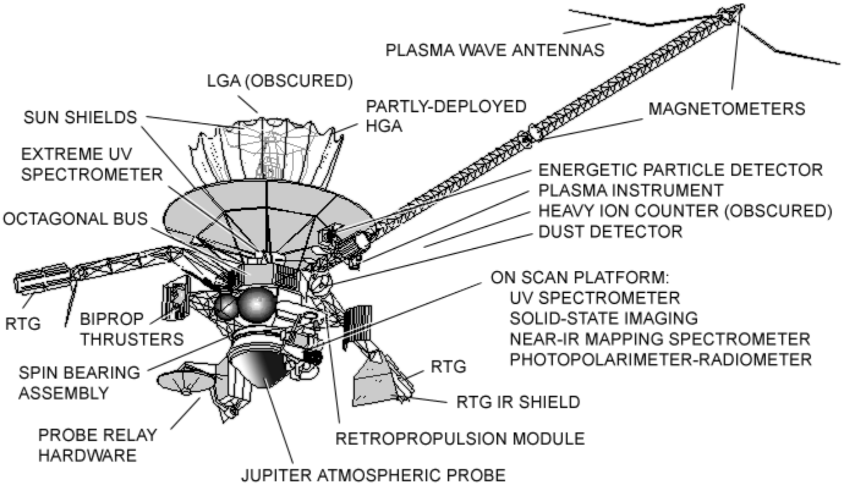

Fig. A.9. *Galileo* spacecraft in flight configuration. Spacecraft height is 5.3 meters. Components below the Spin Bearing Assembly are de-spun to permit pointing while upper part spins. From image courtesy NASA/JPL.

Classification: Orbiter spacecraft
Mission: Explore Jupiter, its moons, and its magnetosphere
Named: In honor of Galileo Galilei (1564–1642), who observed Jupiter and discovered its four largest moons in 1610

Summary: Observed Venus, Earth, and two asteroids en route; deployed Jupiter atmosphere probe; orbited Jupiter 1995–2003 and observed Jupiter and Galilean satellites at high resolution. Observed planet's magnetosphere and its interaction with Sun, Jupiter, and its moons. Observed comet Shoemaker-Levy 9 fragments impacting Jupiter in 1994. Deorbited to destruction in Jupiter September, 2003.

Payload: CCD imager, UV and extreme-UV spectrometers, near-IR mapping spectrometer, photopolarimeter-radiometer, energetic particle detector, dust detector, plasma spectrometer, heavy ion counter, magnetometers (2), plasma wave receiver.

Nation(s):	USA, Germany	**Mass at Launch:**	2,380 kg
Radio Link:	S-band*	**Stabilization:**	Spin
Propulsion:	Biprop	**Electrical power:**	RTG
Launch date:	October 18, 1989	**Launch vehicle:**	STS *Atlantis*/IUS

*X-band unusable due to failure of HGA to deploy, as illustrated in Figure A.9.

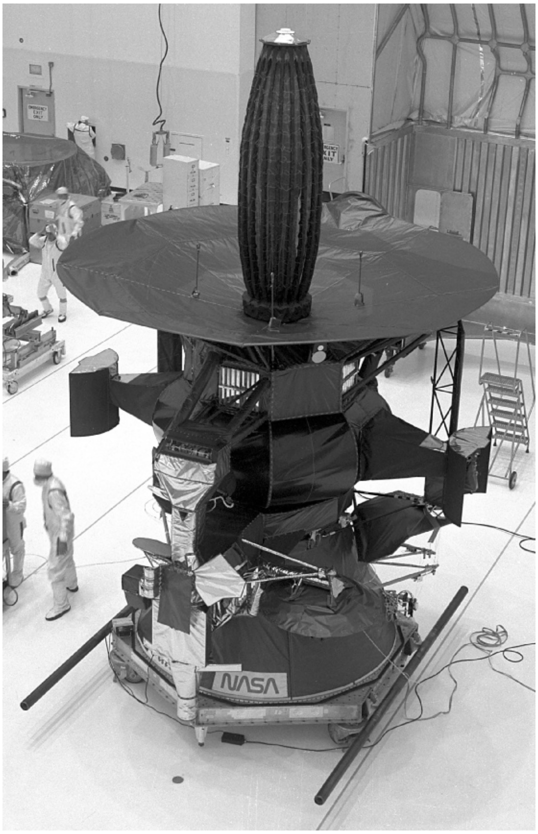

Fig. A.10. *Galileo* spacecraft. Science boom, folded downward, is left of center with end of stowed MAG boom just left of the NASA emblem. Low-gain antenna No. 1 is atop the stowed central mesh high-gain antenna. Large black circular component is bus sunshade. The heavy ion counter with its two circular apertures, obscured in the drawing on the previous page, is visible atop the bus to the right of center. Three of four hoist attachments, removed before flight, are visible protruding through sunshade. Image courtesy NASA/JSC.

The *Cassini* Spacecraft

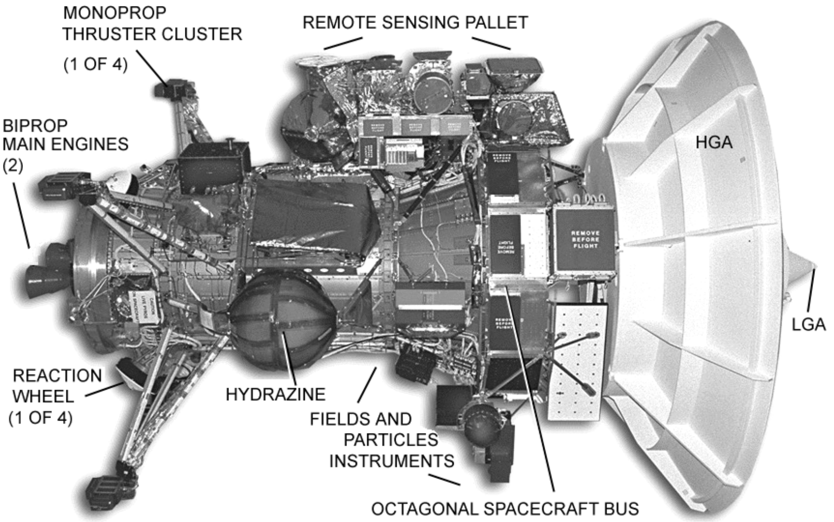

Fig. A.11. The *Cassini* spacecraft measures 6.3 meters in length. Not shown: RTGs, thermal blanketing, main engine cover, MAG boom, RPWS antennas, *Huygens* Probe. Covers on instruments and louvers placarded "REMOVE BEFORE FLIGHT." Optical remote sensing instrument apertures face out of page toward you; their radiators and star scanner apertures point toward top of page. The spacecraft's 6.8-meter length is largely due to the size of the bipropellant tanks inside. Image courtesy NASA/JPL.

Classification: Orbiter spacecraft
Mission: Explore Saturn, its moons and magnetosphere
Named: In honor of Italian-French astronomer G. D. Cassini (1625–1712)

Summary: Observed Venus, Earth, and Jupiter during gravity-assist flybys en route. Entered Saturn orbit July 2004, deployed *Huygens* probe (see page 308) December 2004 on a three-week free-fall to Titan. Currently orbiting Saturn, observing rings, moons, atmosphere, and magnetosphere.

Payload: CCD imagers (2), UV imaging spectrograph, visual and near-IR mapping spectrometer, composite IR spectrometer, cosmic dust analyzer, magnetometers (2), radio and plasma wave receiver, magnetospheric imager, plasma spectrometer, mass spectrometer, and radio-frequency instrumentation for radio science experiments.

Nation(s):	USA, ESA, ASI +	**Mass at Launch:**	5,712 kg with *Huygens*
Radio Link:	S- X- and Ka band	**Stabilization:**	3-axis, reaction wheels
Propulsion:	Biprop, monoprop	**Electrical power:**	RTG
Launch date:	October 15, 1997	**Launch vehicle:**	Titan-IVB/Centaur

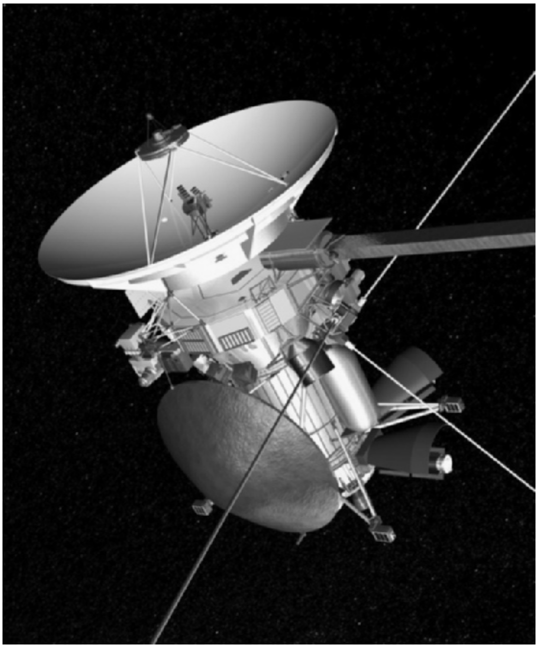

Fig. A.12. Artist's rendering of *Cassini* spacecraft in flight configuration, shown without blanketing. Three Radio and Plasma Wave (RPWS) antennas extend 10 meters, magnetometer (MAG) boom extends 11 meters. Note the complex of feed horns in the middle of the 4-meter diameter High-Gain Antenna (HGA), which permits the synthetic aperture radar to acquire five parallel image swaths. RTGs are equipped with shades to avoid IR glare in the optical instruments. The *Huygens* Probe is attached at left, and the optical instrument apertures point toward the upper right. Cosmic Dust Analyzer instrument is the drum near the image's center, and a helium tank for bipropellant pressurization is visible to its lower right. See also: www.jpl.nasa.gov/basics/cassini. Image © Gordon Morrison, reproduced by permission.

The *Messenger* Spacecraft

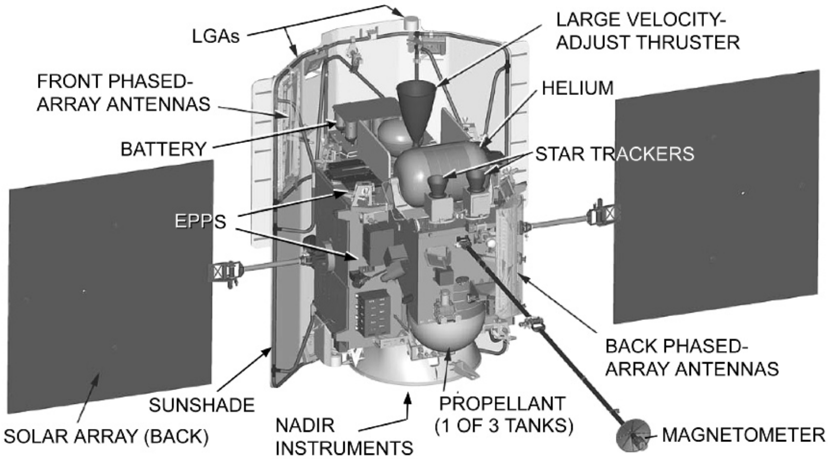

Fig. A.13. *Messenger* spacecraft in flight configuration measures 6 meters across the solar panels. Image courtesy NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

Classification: Orbiter spacecraft
Mission: Orbit and observe the planet Mercury and its environs
Named: For the Roman messenger of the gods, and as acronym for: MErcury Surface, Space ENvironment, GEochemistry, and Ranging

Summary: Messenger observed Earth, Venus, and Mercury during gravity-assist flybys, and will enter orbit around Mercury on March 18, 2011, after two more Mercury gravity-assist flybys while in solar orbit. Planned mission in Mercury orbit is one Earth year (about four Mercury years).

Payload: CCD imagers (2), gamma-ray and neutron spectrometer, x-ray spectrometer, UV visible and IR spectrometer, laser altimeter, magnetometer, and energetic particle and plasma spectrometer. All but the latter instrument (see EPPS in Figure A.13) are mounted on a nadir-facing panel inside the conical launch adapter.

Nation(s):	USA	**Mass at Launch:**	1,100 kg
Radio Link:	X-band	**Stabilization:**	3-Axis, reaction wheels
Propulsion:	Biprop, monoprop	**Electrical power:**	Photovoltaic
Launch date:	August 3, 2004	**Launch vehicle:**	Delta-II/Star-48

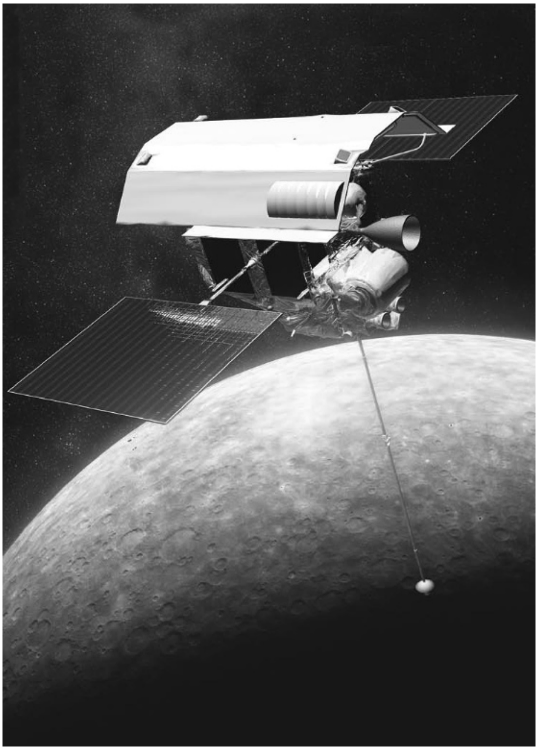

Fig. A.14. Artist's impression of the *Messenger* spacecraft orbiting Mercury. Attitude control keeps the entire spacecraft, except for the solar panels, constantly in the shadow of its ceramic-cloth sunshade. Image courtesy NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

The *Huygens* Spacecraft

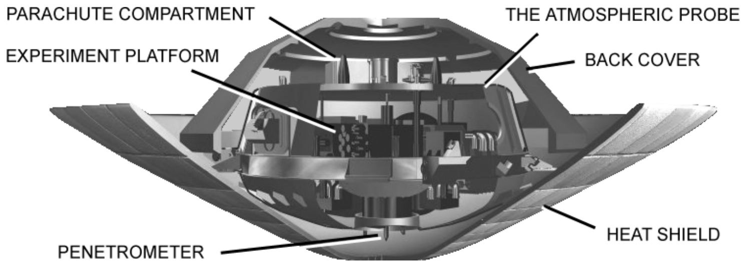

Fig. A.15. The *Huygens* spacecraft's atmospheric heat shield measures 2.7 meters in diameter. Image courtesy European Space Agency.

Classification: Orbiter spacecraft
Mission: Investigate the atmosphere and surface of Saturn's moon Titan
Named: For Dutch astronomer Christiaan Huygens (1629–1695) who discovered Titan

Summary: Huygens separated from *Cassini* in Saturn orbit December 25 2004, its batteries having remained inactive for over seven years. Then a timer turned on the Probe's electronics for a 2.5-hour investigation. The heat shield decelerated the probe from 22,000 to 1,400 kilometers/hour, reaching a peak of 14 g. At an altitude of 160 kilometers, a pilot parachute pulled off the back cover and deployed the 8.3-meter diameter main parachute, slowing the probe to 80 meters/second and releasing the heat shield. The instruments then deployed and began taking data. At 110 kilometers altitude and 40 meters/second the main parachute separated and a 3-meter diameter chute deployed to achieve descent to the surface within 2.5 hours. At a few hundred meters altitude a lamp switched on to illuminate the surface and help acquire images and spectra. The probe landed at 5 meter/second on soggy sand as a force-measuring penetrometer rod first bumped off a pebble and then entered the sand. Surface instruments characterized the soil, while the atmospheric instruments detected an abundance of methane vapor, presumably boiling away from the comparatively warm probe resting on the cold damp surface. At the 90 K surface temperature, rocks and sand are made of water, and the liquid is methane.

Payload: Aerosol collector and pyrolyser, gas chromatograph and mass spectrometer, descent imager/spectral radiometer, atmosphere structure instrument, Doppler wind experiment, and a surface science package containing multiple instruments to sample and characterize the surface.

Nation(s):	European	**Mass at Launch:**	319 kg
Radio Link:	S-band to *Cassini*	**Stabilization:**	Spin
Propulsion:	None	**Electrical power:**	Battery
Launch date:	October 15, 1997	**Launch vehicle:**	See *Cassini* (pg 304)

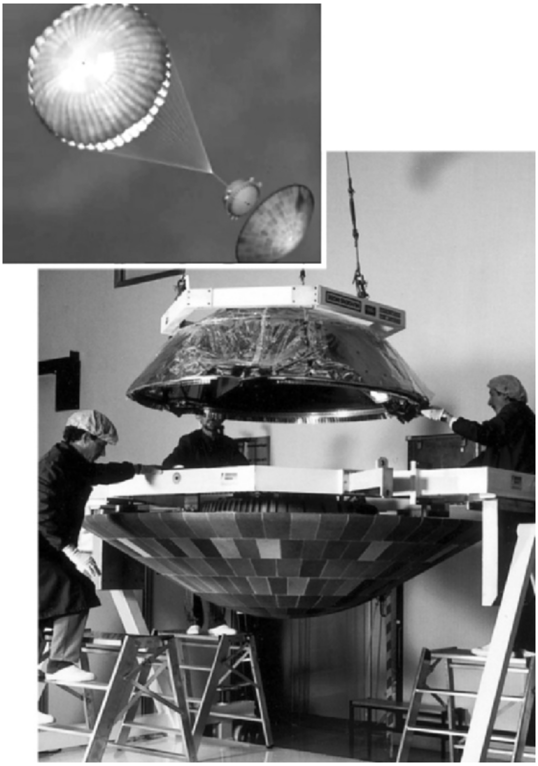

Fig. A.16. *Huygens* spacecraft during installation of the back cover. The top of the atmospheric probe itself is visible over the rim of the heat shield. In the inset above, the first pilot chute has already removed the back cover, and the 8.3-meter diameter main parachute slows the probe while the spent heat shield is released. Images courtesy ESA.

The *Phoenix* Spacecraft

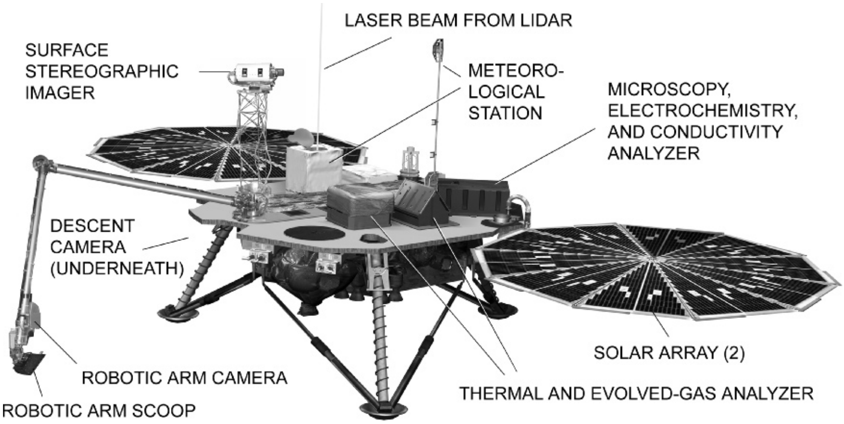

Fig. A.17. The *Phoenix* Mars Lander spacecraft measures 5.5 meters overall with solar arrays deployed. From image courtesy NASA/JPL.

Classification: Lander spacecraft
Mission: Study history of Mars's H_2O and habitability potential in arctic ice
Named: After the mythological bird that is reborn from its own ashes

Summary: Created from hardware and plans remaining from the failed 1998 *Mars Polar Lander* and the cancelled *Mars Surveyor 2001*, *Phoenix* landed within the Martian arctic circle on May 25, 2008. Imaging systems help identify targets, and a robotic arm digs through soil to water ice below and delivers samples to experiments, including miniature ovens, a mass spectrometer, and a chemistry lab-in-a-box, to characterize soil and ice chemistry.

Payload: Surface stereographic imager, thermal and evolved gas analyzer, microscopy, electrochemistry, and conductivity analyzer, meteorological station, robotic arm with camera, scoop, and thermal and electrical conductivity probe.

Nation(s):	USA	**Mass at Launch:**	350 kg
Radio Link:	UHF	**Stabilization:**	3-Axis to landing
Propulsion:	Monoprop	**Electrical power:**	Photovoltaic
Launch date:	August 4, 2007	**Launch vehicle:**	Delta II

Fig. A.18. Artist's conception of the *Phoenix* lander spacecraft. Having completed a ten-month journey, the spacecraft's cruise stage was jettisoned five minutes prior to atmospheric entry, then the aerobraking heat shield was released after parachute deployment. When on-board radar sensed it was down to 570 meters above the surface, the parachute was released and hydrazine thrusters carried it to a soft landing as seen here. Loss of sunlight in the winter, extreme cold, and carbon dioxide frost will prevent further operations by January 2009, and there is little chance *Phoenix* will survive the winter. See also page 269. Image courtesy NASA/JSC.

Mars Science Laboratory Spacecraft

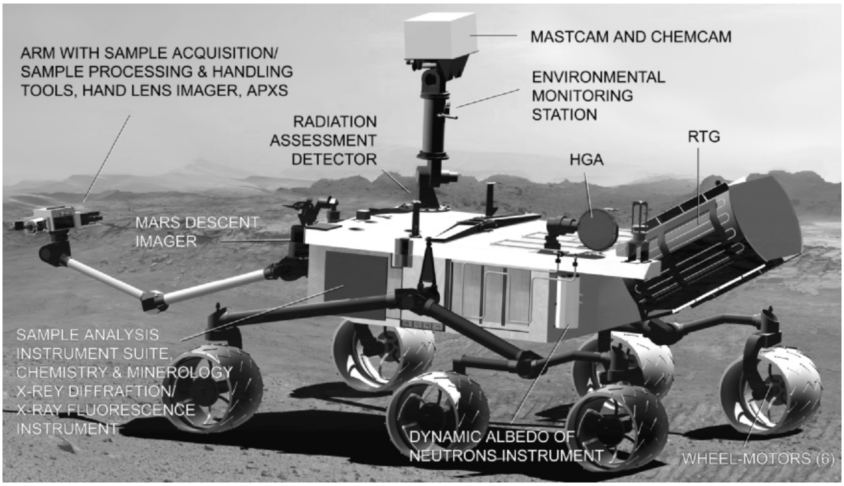

Fig. A.19. *Mars Science Laboratory* measures 2.8 meters overall. Adapted from artist's conception, image courtesy NASA/JPL-Caltech.

Classification: Rover spacecraft
Mission: Investigate past and present potential to support microbial life
Named: Descriptively (may be changed in or prior to flight)

Summary: Mars Science Laboratory plans to bring more than ten times the mass of previous rovers into the Martian atmosphere in late 2012, and will be the first at Mars to execute energy-dissipating S-turns before heat shield jettison. After parachute descent, a retrorocket-powered "sky crane" hovers and lowers the rover on cables to a soft touchdown. Rover itself is almost four times the mass of each 2003 Mars Exploration Rover *(Spirit* or *Opportunity).*

Payload: Descent imager, gas chromatograph, mass spectrometer, tunable laser spectrometer, x-ray diffraction, and fluorescence instrument, "geologist's hand lens" imager, APXS, mast camera, ChemCam (see pg 325; laser pulses vaporize target material up to 10 meters away; telescope with spectrometer identifies excited atoms), radiation assessment detector, environmental monitoring station, dynamic albedo of neutrons instrument, mast-mounted stereo navigation cameras, low-mounted stereo hazard-avoidance cameras, sample acquisition/sample preparation & handling system.

Nation(s):	USA	**Mass at Launch:**	3,400 kg*
Radio Link:	Ka-, X-band, UHF	**Stabilization:**	Mars gravity
Propulsion:	Electric motors	**Electrical power:**	RTG
Launch date:	Planned Oct-Dec 2011	**Launch vehicle:**	Atlas-V

* Launch mass includes cruise and descent hardware.

Fig. A.20. Artist's conception showing the *Mars Science Laboratory* spacecraft being let down to a soft landing by its sky-crane after aerodynamic entry with S-turns, parachute descent, and retro-stage activation. Image courtesy NASA/JPL-Caltech.

The *Deep Impact* Spacecraft

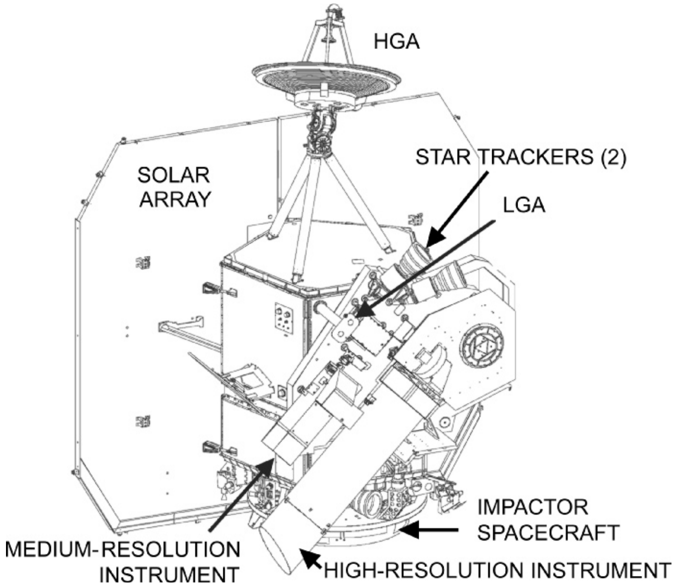

Fig. A.21. *Deep Impact* spacecraft is 3.3 meters in height. Courtesy NASA/JPL.

Classification: Impactor spacecraft.
Mission: Excavate material from comet 9P/Tempel for external observation
Named: For its mission (and in deference to the popular 1998 film)

Summary: On July 3, 2005, the flyby spacecraft released an impactor which navigated itself (see pg 58) to impact the next day. Typically, impactor spacecraft are designed for on-site measurements using direct-sensing instruments, though to date no such spacecraft has succeeded. *Deep Impact* penetrated the comet's surface purely to cause a crater and raise ejecta for the benefit of remote-sensing observations from the flyby spacecraft and from Earth. Now on an extended mission called Extrasolar Planet Observation and Extended Investigation to search for extrasolar planets via and transit methods en route to flyby of Comet Hartley 2 in October 2010.

Payload: Flyby spacecraft: 30-cm aperture telescope with high-resolution IR spectrometer and multi-spectral CCD camera, 12-cm aperture telescope for medium-res imaging. Self-navigating impactor: 12-cm aperture telescope for automatic targeting.

Nation(s):	USA	**Mass at Launch:**	650 kg + 370 kg impactor
Radio Link:	S-, X-band	**Stabilization:**	3-Axis
Propulsion:	Monoprop	**Electrical power:**	Photovoltaics/Battery
Launch date:	January 12, 2005	**Launch vehicle:**	Delta II

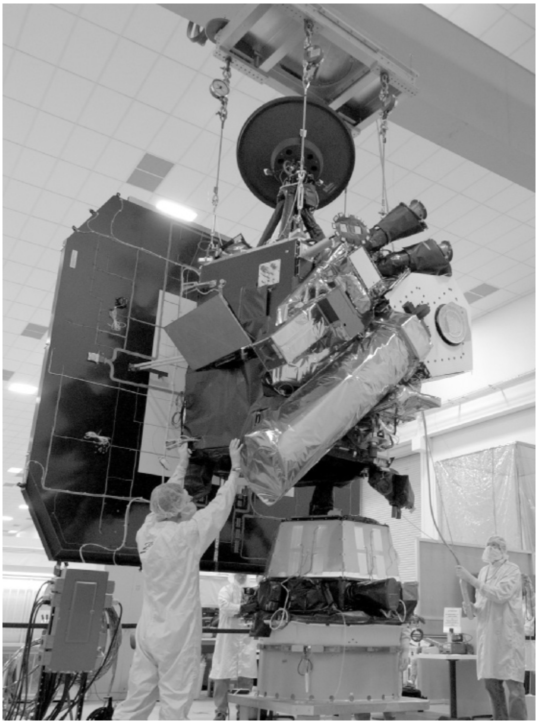

Fig. A.22. *Deep Impact* flyby spacecraft (above) being mated with the impactor spacecraft (shoulder-level). The impactor operated on battery power after separation, obtaining images and navigating autonomously via built-in hydrazine thrusters, to an impact with the comet at 10.2 kilometers/second. The impact released about 19 gigajoules (equivalent to 4.8 tons of TNT). It returned images on approach via its S-band radio link with the flyby spacecraft. Image courtesy NASA/JSC.

The *Deep Space 1* Spacecraft

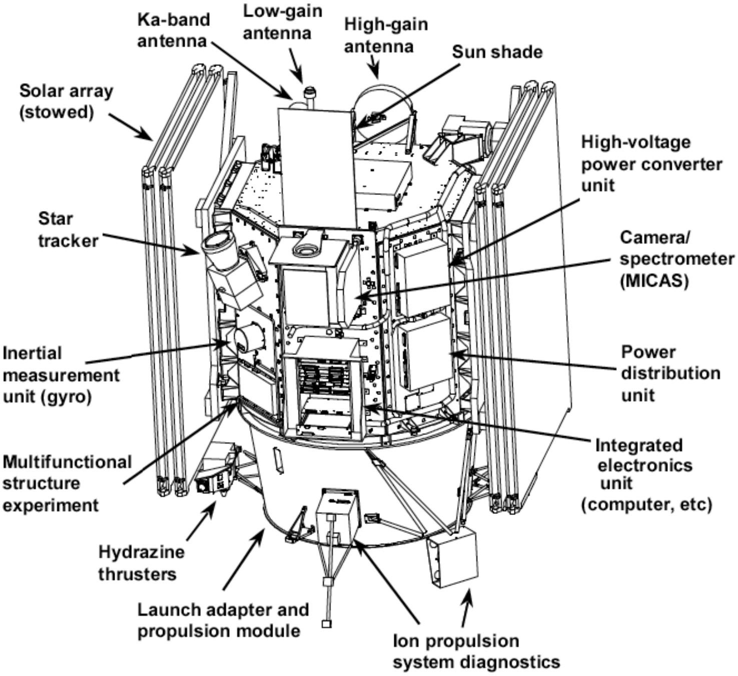

Fig. A.23. *Deep Space 1* spacecraft in launch configuration measures 2.5 meters in height. Courtesy NASA/JPL.

Classification: Engineering Demonstration spacecraft
Mission: Demonstrate twelve new technologies for use on scientific missions
Named: As first in a series of deep space technology testing missions

Summary: Demonstrated solar electric propulsion, solar concentrator arrays, autonomous navigation, autonomous remote agent, small deep space transponder, Ka-band solid state amplifier, beacon monitor operations, low power electronics, power actuation and switching module, and multifunctional structure. Miniature integrated camera/imaging spectrometer, and single-package ion and electron spectrometer instruments. Upon completion of technology testing objectives, acquired science data during flybys of asteroid 9969 Braille in 1999 and Comet Borrelly in 2001.

Payload: Twelve engineering experiments (including two science instruments).

Nation(s):	USA	**Mass at Launch:**	489 kg
Radio Link:	X, Ka-band	**Stabilization:**	3-Axis, thrusters
Propulsion:	Electric (ion)	**Electrical power:**	Photovoltaic
Launch date:	October 24, 1998	**Launch vehicle:**	Delta II/Star-48

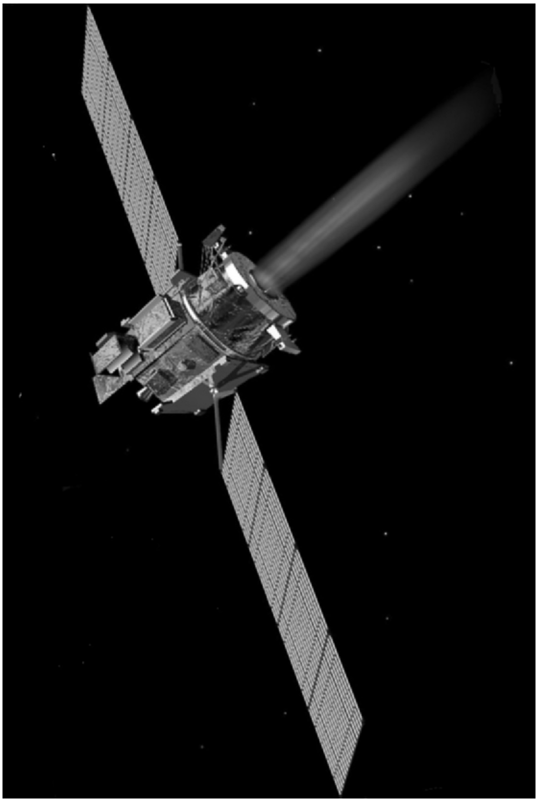

Fig. A.24. Artist's conception of the *Deep Space 1* spacecraft in flight configuration operating its solar-electric-powered ion engine. The solar arrays measure about 12 meters end-to-end across the spacecraft. Image courtesy NASA/JPL.

Appendix B: Typical Instruments

A scan through Chapter 6 will show that there are perhaps as many different science instruments as there are scientists who have questions. Since this appendix can't list them all, it shows one or more solid examples of each of the four instrument categories described in Chapter 6 (see page 183). Each entry lists the instrument's capabilities and ranges of sensitivities. Also included are one spacecraft engineering appliance (stellar reference unit) and one ground-based facility (DSN station).

*Designed as spacecraft attitude-control input device rather than part of the scientific-instrument payload. †Earth-based facility.

Solid-State Imager

Abbreviated: SSI **Spacecraft:** *Galileo*

Classification: Passive remote-sensing instrument

Captures: High-resolution images of targets including Earth, Moon, and Venus cloud-tops during gravity-assist flybys; asteroids Gaspra, Ida, and Dactyl; and the comet Shoemaker-Levy 9 impact with Jupiter en route; and from Jupiter orbit images of various levels in Jupiter's atmosphere and variations in color and albedo of Jovian satellite surfaces indicating differences in composition.

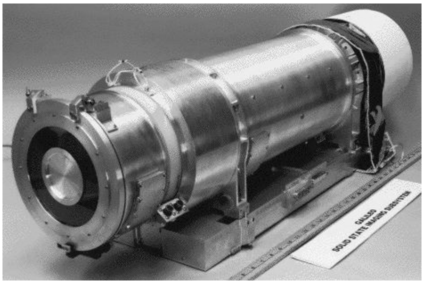

Fig. B.1. *Galileo* Solid-State Imaging instrument. Telescope aperture is the dark ring on left, with secondary mirror creating the central obstruction mounted on clear quartz aperture plate. Image courtesy NASA/JPL.

Basis of operation: Cassegrain reflecting telescope focuses light onto a radiation-shielded focal-plane detector through shutter and selected filter. Detector is passively cooled to about 163 K by thermally conductive attachment to external radiator plate. Aperture cover was jettisoned after launch.

Specifications: Focal length: 1,500 millimeters; Fixed focal ratio $f/8.5$; tweny-eight selectable exposure times between 0.004 sec and 51.2 sec; Field of view 8.13×8.13 mrad. Sensitive to visible through near-infrared light; eight-position wheel has seven spectral filters from 400 to 1100 nm wavelength plus clear; CCD built by Texas Instruments and JPL; RCA 1802 microprocessors control the instrument; CCD radiation shield is 1-centimeter thick tantalum.

Aperture:	176.5 mm	**Detector:**	800×800 pixel CCD
Power draw:	15W, 28 VDC	**Mass:**	29.7 kg
Assembled by:	NASA/JPL	**Location:**	Despun scan platform
Heritage:	*Voyager* narrow-angle camera telescope, shutter, filters		
Operated:	October 18, 1989 (launch), through September 21, 2003		

High-Resolution Imaging Science Experiment

Abbreviated: HiRISE **Spacecraft:** *Mars Reconnaissance Orbiter* (MRO)

Classification: Passive remote-sensing instrument

Captures: High-resolution images of surface of Mars resolving 1-meter features, and stereoscopic images permitting vertical resolution to 30 centimeters height. Three spectral filters allow color imaging.

Basis of operation: Cassegrain telescope with extraordinary focal length illuminates assembly of one-dimensional (line-of-pixels) CCDs. Spacecraft along-track motion supplies images' second dimension (push-broom mode). Light reaches focal-plane assembly via customary two-mirror Cassegrain optics plus a tertiary mirror in a path with two beam-folding flat mirrors. Focal-plane assembly at end of *twelve-meter* path holds fourteen overlapping 2,048-pixel staggered CCDs. Data stored in camera memory.

Specifications: 12-m focal length; $f/24$ focal ratio; All CCDs are 2,048-pixel linear; ten with red filter total a 20,000-pixel line, two have blue-green filters, two have IR filters, near red array center. Memory: 28 Gbit; Resolution: 1 μrad, 0.5 m at surface.

Fig. B.2. *MRO* HiRISE. Cassegrain telescope, with additional beam-folding optics in back, shown above enlargement of focal-plane assembly with fourteen linear CCDs (housed in back, see arrow). Courtesy NASA/JPL-Caltech.

Aperture:	50 cm	**Detector:**	Linear CCDs
Power draw:	68 W, 28 VDC	**Mass:**	65 kg
Assembled by:	Ball Aerospace	**Location:**	Nadir platform
Heritage:	*Deep Impact*, *Hubble Space Telescope*		
Operated:	In science orbit* (post-aerobraking) September 29, 2006, to present.		

*Also took calibration images en route, and early-orbit demos prior to aerobraking. Imaged Earth and Moon from Mars (ID: PIA10244).

Radar

Abbreviated: RADAR **Spacecraft:** *Cassini*

Classification: Active remote-sensing instrument

Captures: Microwave radio energy scattering and reflecting from a target which it has illuminated with its radar beam in active modes, and the microwave energy radiating naturally from a target in passive mode.

Basis of operation: RADAR is acronym for RAdio Detection And Ranging, but the technique has gone beyond these functions. *Cassini*'s radar operates in three active modes and one passive mode. Synthetic Aperture Radar (SAR) creates images from time delay and Doppler shift, measured in the return signal, to create two-dimensional images (see pg 199); altimetry sends radio energy straight down to surface and times its return, to measure distance; scatterometry measures strength of backscattered energy; radiometry measures natural microwave emission from target in passive remote-sensing mode.

Fig. B.3. Close-up of *Cassini* Radar multiple feeds near center of HGA used to acquire synthetic-aperture imaging data in five distinct beams. Radar electronics box is mounted atop the bus beneath HGA. Image courtesy NASA/JPL-Caltech.

Specifications: Emits coded pulses at 13.78 GHz (Ku-band). Resolution is a function of distance from the target. SAR resolution, 0.35 to 1.7 kilometers; altimeter, 24 to 27 kilometers horizontal, 90 to 150 meters vertical; radiometer, 7 to 310 kilometers.

Aperture:	4 m	**Detector:**	Microwave receiver
Power draw:	108 W, 28 VDC	**Mass:**	42 kg
Assembled by:	ASI, JPL	**Location:**	Atop bus and in HGA
Heritage:	Techniques developed for SIR-C and *Magellan*		
Operated:	October 26, 2004, to present.		

Mars Orbiter Laser Altimeter

Abbreviated: MOLA **Spacecraft:** *Mars Global Surveyor*

Classification: Active remote-sensing instrument

Captures: Measurements of distance between instrument and Martian surface. Data reduces to topographical mapping, providing information for estimating flow velocities and discharges in Martian surface channels. After laser failure on June 30, 2001, the instrument acquired IR radiometry data from the surface as a passive remote-sensing instrument.

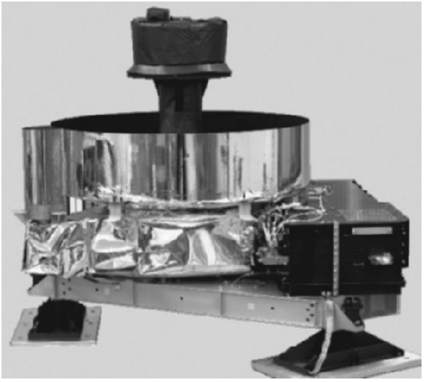

Fig. B.4. The *Mars Global Surveyor* Laser Altimeter. The laser is the small cylinder mounted on the left side of the large circular collector-mirror light shield. Telescope secondary mirror is supported in the black central column. Image courtesy NASA/GSFC.

Basis of operation: Pulses of laser light are aimed toward the surface. A portion of the output laser energy from each pulse is diverted to the detector to start a clock counter. Energy returning at the speed of light from the surface is collected by a reflecting Cassegrain telescope, which focuses the light onto the detector. Precise timing of collected pulse backscatter, compared against the counter, yields distance data. An 80C86 microprocessor controls the instrument's operation.

Specifications: Neodymium-doped yttrium aluminum garnet (Nd:YAG) near-infrared laser, wavelength 1,064 nm; Laser spot subtends 0.4 mrad, spreads to about 130 meters on Martian surface; 10 Hz pulse rate results in 330-meter spacing along ground track. Range resolution 37.5 centimeters; absolute accuracy depends on spacecraft orbital knowledge and is generally <10 meters.

Aperture:	50 cm	**Detector:**	Silicon-avalanche photodiode
Power draw:	34.2 W, 28 VDC	**Mass:**	25.85 kg
Assembled by:	NASA/GSFC	**Location:**	Nadir platform
Heritage:	*Mars Observer* MOLA		
Operated:	Orbit insertion (September 11, 1997) through spacecraft loss (November 2, 2006)		

Infrared Spectrograph

Abbreviated: IRS **Spacecraft:** *Spitzer Space Telescope*

Classification: Passive remote-sensing instrument

Captures: Infrared light via the *Spitzer* telescope optics from stars, galaxies, solar system objects, interstellar gas and dust, intergalactic gas and dust, and other targets, and breaks it down into its constituent wavelengths for measurement.

Basis of operation: Each of four spectrographs records spectra at a different level of detail and wavelength, λ, by introducing a grating into its light path and measuring the spatial distribution of the wavelengths dispersed by the grating. Instrument is cooled by liquid helium to about 1.4 K.

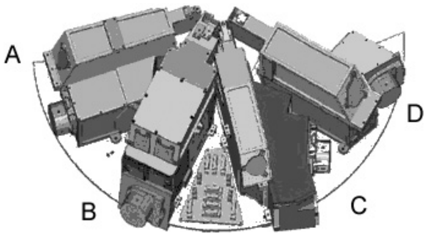

Fig. B.5. *Spitzer* IRS includes four spectrographs aligned radially within the chilled chamber behind the telescope's primary mirror. A: short-λ high-resolution, B: short-λ low-res, C: long-λ high res, D: long-λ low res. Courtesy NASA/JPL-Caltech, Spitzer Science Center.

Specifications: The short-λ high-resolution spectrograph (A) covers 10–19.5 μ; the short-λ low-resolution spectrograph (B) covers 5.3–14 μ; the long-λ high-resolution spectrograph (C) covers 19–37 μ; the long-λ low-resolution spectrograph (D) covers 14–40 μ. Detectors are 128 x 128 arrays. The shorter-wavelength silicon (Si) detectors are doped with arsenic (As); the longer-wavelength Si detectors are doped with antimony (Sb).

Aperture:	*Spitzer*'s 85 cm	**Detectors:**	Sb: Si and As: Si
Assembled by:	Ball Aerospace	**Location:**	Multi-instrument chamber
Operated:	September 12, 2003, to present.		

Chemistry and Camera

(Laser-Induced Remote Sensing for Chemistry and Micro-Imaging)

Abbreviated: ChemCam **Spacecraft:** *Mars Science Laboratory* (*MSL*)

Classification: Active remote-sensing instrument

Captures: Close-up micro-images of targets at 2–9 meters distance, and then emission spectra of plasma generated from a 1-millimeter diameter portion of a target when laser-heated to 10,000 °C (micro-imaging by itself can operate beyond 9 meters distance).

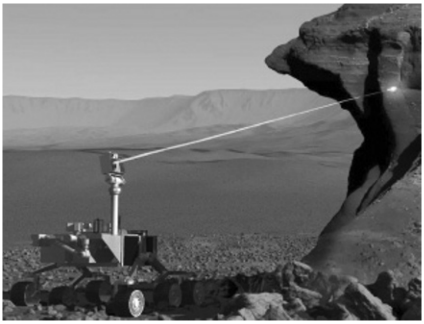

Fig. B.6. Artist depicts *MSL* ChemCam energizing a pre-selected and micro-imaged target 6 meters away. Note the infrared laser beam would not actually be visible. Image courtesy NASA/JPL-Caltech/LANL/J.-L. Lacour, CEA.

Basis of operation: CCD remote micro-imager provides telescopic close-up views of target from at least 2 meters distance through telescope on rover's mast. Up to seventy-five laser pulses are then focused through the same telescope onto a target, causing ablation of atoms in excited states. Three spectrographs disperse light from the ablated material into component wavelengths via gratings, and resolve and measure emission lines on linear CCD detectors. Spectrographs are fed via fiber-optic cable from the telescope. In energizing a target, this Laser-Induced Breakdown Spectrograph (LIBS) can remotely remove dust and weathering layers.

Specifications: Telescope: 10-centimeter aperture Schmidt-Cassegrain. Imager: field of view 30 centimeters at 10 meters; 80 μrad resolution. Laser: wavelength 1,067 nm (infrared); 30 mJ per 5-ns pulse, repeating at 15 Hz up to seventy-five pulses before recharging forty seconds; spectrographs sensitive to wavelengths from 240 to 800 nm with 0.09-0.3 nm resolution.

Aperture:	10 cm	**Detector:**	CCDs
Power draw:	7 W	**Mass:**	6 kg
Developed by:	LANL, CESR	**Location:**	Mast and body
Heritage:	Earth-based geology		
Operated:	Planned for Mars landing 2012.		

Magnetometers

Abbreviated: MAG **Spacecraft:** *Voyager 1* and *Voyager 2*

Classification: Passive remote-sensing instruments

Captures: Magnetic field measurements in the plasma media in planetary vicinities, interplanetary space, the solar heliosheath, and, it is hoped, interstellar space.

Basis of operation: Two low-field-strength sensors were extended by unfurling a three-rib fiberglass boom after launch (page 176 shows a similar boom in stowed configuration). Magnetometer "C" in Figure B.7 is at the end of the 13-meter long boom, and magnetometer "D" is approximately mid-boom. The boom removes the highly sensitive instruments from magnetic disturbances close to the spacecraft metals and electric currents. Two high-field-strength sensors ("A" and "B,") are permanently mounted near the spacecraft bus. Energizing a wire coil surrounding the HGA permits in-flight calibration of all four instruments. Fluxgate magnetometers are discussed in Chapter 6 (see page 216).

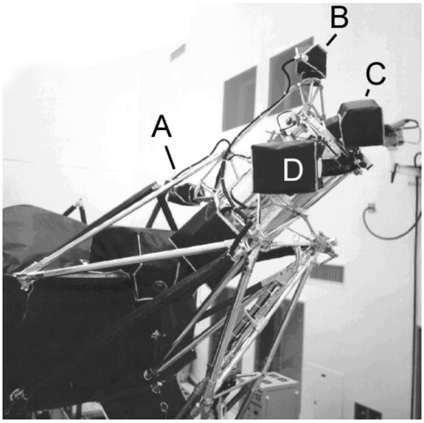

Fig. B.7. Four magnetometers on a *Voyager* spacecraft prior to HGA installation. Fiberglass boom stowed within cylinder behind magnetometer "D" will untwist and extend to hold magnetometer "C" out at a distance of 13 meters. High-field magnetometers "A" and "B" remain in positions shown. See also page 294 for deployed configuration. Image courtesy NASA/JPL-Caltech.

Specifications: On each spacecraft: two low-field-strength instruments with eight selectable dynamic ranges from ± 8.8 nT to ± 50000 nT; two high-field-strength instruments with two selectable ranges, $\pm 5 \times 10^4$ nT and $\pm 2 \times 10^6$ nT.

Aperture:	N/A	**Detector:**	Flux-gate
Power draw:	3.2 W	**Mass:**	5.5 kg (total of 4)
Developed by:	GSFC	**Location:**	On boom and near bus
Operated:	Continuously since autumn 1977.		

Atmospheric Structure Instrument

Abbreviated: HASI **Spacecraft:** *Huygens*

Classification: Passive direct-sensing instruments (except impedence sensors)

Captures: Measurements of acceleration in three axes, atmospheric pressure and temperature, acoustic events, electrical impedance, permittivity, and waves. Also processes radar altimetry data.

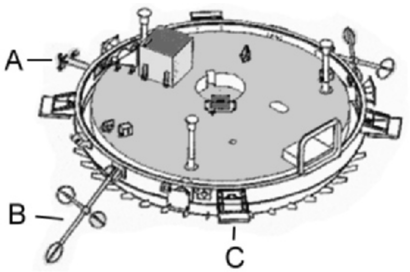

Fig. B.8. *Huygens* Probe with HASI sensors deployed. Inner cover (in place during flight operation) removed for clarity. "A" points out the pressure sensor inlet stub with two temperature sensors (microphone situated at its base), "B" shows one of 2 booms with electrical permittivity and wave sensors, "C" indicates one of four radar altimeter antennas, and the accelerometers are in the small housing near the spacecraft center. Data processing unit is upper left of center. Image courtesy ESA.

Basis of operation: Coordinated by the HASI data processing unit are twin temperature sensors, each dual-element platinum resistance thermometers. A Kiel-type inlet tube exposes atmosphere to temperature-calibrated silicon capacitive absolute pressure sensors in which the pressure bends a thin silicon diaphragm. Three orthogonally mounted piezoresistive accelerometers and one single-axis (spin) servo-accelerometer are situated near the spacecraft's center of mass. Two deployable booms measure the atmosphere's electrical properties. Each boom holds two ring-shaped elements, which are the transmit- and receive-mutual impedance sensors, and a disc-shaped relaxation sensor — these are active direct sensors.

Specifications: Temperature resolution 0.02 K; pressure resolution 1 Pa; acceleration 1–10 μg high-res, 0.9–9 mg low-res; acoustic threshold 10 mPa; AC electric wave strength threshold 2μV/m; mutual impedance 10^{-11} $(\Omega m)^{-1}$; relaxation intervals: 1 min, and 25 ms to 2 s, with 1 mV threshold.

Aperture: Kiel-type pressure inlet
Power draw: ≈ 5 W **Mass:** 5.7 kg total
Developed by: ASI **Location:** See Figure B.8
Operated: On January 14, 2005, from 09:15 to 13:30 UTC SCET.

Alpha Proton X-Ray Spectrometer

Abbreviated: APXS **Spacecraft:** *Sojourner* Mars Rover

Classification: Active direct-sensing instrument

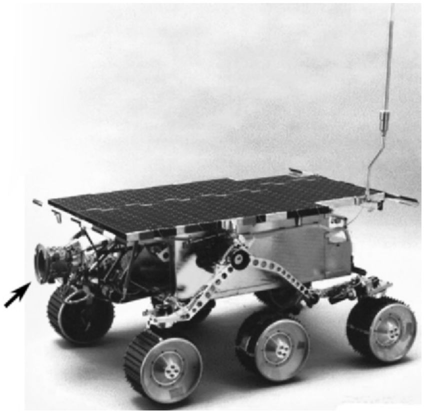

Fig. B.9. The APXS on the back end of *Sojourner*. Image ID JPL-25888BC courtesy NASA/JPL-Caltech.

Captures: Back-scattered alpha particles, protons, and X-Rays resulting from exposing a sample to a radioactive source in order to provide information on the chemical composition of Martian rocks and soil.

Basis of operation: Rover drives to a target of interest and deploys APXS into firm contact with the sample rock or soil. The radioisotope curium (^{244}Cm) within the instrument emits alpha particles (APs), which are helium nuclei consisting of two protons and two neutrons, with known energy. As these particles strike atoms in the target, the instrument records energy spectra in 256 channels resulting from each of three interactions: alpha particle elastic (Rutherford) scattering, alpha-proton nuclear reactions with certain light elements, and excitation of atoms in the target by alpha particles that causes them to emit X-Rays of characteristic energies. These spectra provide indications of atomic species of most of the target's elements, with the exception of hydrogen and helium. Some APXS instruments, such as those on MER, have an X-ray source as well as an AP source.

Specifications: Sensitivity to elemental composition approaching the parts-per-million range. Measured abundances of MgO, Al_2O_3, SiO_2, K_2O, CaO, TiO_2, MnO, and FeO, with best sensitivity to the lighter elements. *Sojourner* rover mobile mass 11.5 kg; delivered to Ares Vallis by the *Mars Pathfinder* lander.

Aperture:	N/A		
Power draw:	0.8 W	**Mass:**	0.74 kg
Developed by:	MPI, U of Chicago	**Location:**	See Figure B.9
Heritage:	Russian *Vega*, Phobos and Mars, 1996		
Operated:	July 4 through September 27, 1997.		

Mini-Mössbauer Spectrometer

Abbreviated: MIMOS-II **Spacecraft:** Mars Exploration Rovers (2)

Classification: Active direct-sensing instrument

Captures: γ-ray (gamma-ray) spectra from iron, by sensor head on robotic arm. Control and processing electronics within rover body. *Opportunity*'s MIMOS-II detected seven iron-bearing minerals at Meridiani Planum: olivine, pyroxene, magnetite, nanophase ferric oxides, kamacite, hematite, jarosite. In Gusev Crater, *Spirit* found the first six of these plus ilmenite and goethite.

Basis of operation: Instrument head remains in contact with target, cobalt (^{57}Co) illuminates it with γ-rays to probe for iron. Per Mössbauer effect, a fraction of source γ rays do not lose energy due to recoil, so they have almost the right energy to be absorbed by atoms in target. Sensor head accelerates source through a range of velocities, ± 12 mm/s, via linear motor, Doppler-shifting radiation to match target absorption energies. Detector senses resulting γ-ray emission from excited target atoms during hours of integration time.

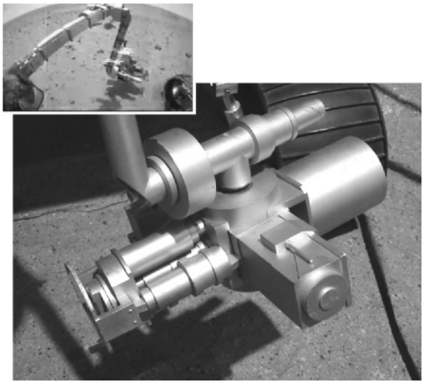

Fig. B.10. Mössbauer spectrometer sensor head is one of four units at the end of robotic arm. Inset: view from mast-mounted NavCam as arm extends toward target on Mars. MIMOS-II is at center in close-up, its aperture represented by concentric discs (APXS is on right, micro-imager behind MIMOS-II, RAT on left). NavCam image and instrument mockup on full-scale model courtesy NASA JPL-Caltech.

Specifications: Sensitive to 14.4 kev γ-ray emission indicative of iron, including its phase and oxidation state. Target integration time originally eight hours; >48 hours as of May 2007, about five half-lives of the ^{57}Co gamma-ray source since it was created.

Aperture:	1-cm diameter aluminum window		
Power draw:	2 W	**Mass:**	0.5 kg
Developed by:	University of Mainz, Germany	**Location:**	See Figure B.10
Heritage:	First developed for Russian Mars 1998 rover whose launch failed.		
Operated:	January 2003 through present.		

Stellar Reference Unit

Abbreviated: SRU **Spacecraft:** *Cassini*

Classification: Passive remote-sensing engineering appliance

Captures: Images of star fields. Automatically estimates spacecraft attitude based on the images.

Basis of operation: A small refracting telescope focuses wide-angle image of star field onto a CCD. SRU-internal JPL-developed computer code identifies up to five stars by referring to stored data and estimates spacecraft's attitude. Estimates are communicated to AACS. SRU constitutes primary source of *Cassini*'s attitude information, either rotating with respect to the star background or stationary. SRUs are permanently mounted with fields of view perpendicular to those of the other optical instruments. Note in Figure B.11 the SRU apertures point in the same direction in which the optical science instrument radiators face (white circle and other flat surfaces). This side of the spacecraft is constrained by flight rules never to face the Sun.

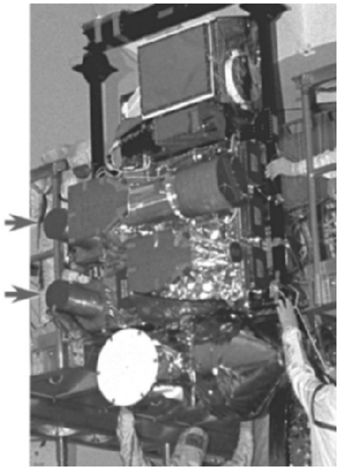

Fig. B.11. Two SRUs on *Cassini* remote sensing pallet. Upper SRU is situated directly left of imaging system narrow-angle camera, the boresight of which is orthogonal to those of the SRUs. From image ID: 97pc1028, courtesy NASA/JPL-Caltech.

Specifications: Limiting star visual magnitude, 5.6; number of stars in database, 5,000; field of view, 15°×15°; internal attitude knowledge resolution, 1 mrad.

Field of view:	7.5°× 7.5°	**Detector:**	1,024×1,024 px CCD
Power draw:	12 W	**Mass:**	10 kg
Assembled by:	Officine Galileo	**Location:**	Remote sensing pallet
Operated:	October 1997 through present.		

Deep Space Station 55

Abbreviated: DSS 55 **Facility:** Deep Space Network

Classification: Transmitting & Receiving Station

Captures: Microwave energy from spacecraft at X- & Ka-band frequencies for extraction of telemetry, ranging, Doppler, and radio science data. Also participates in scientific observations and engineering activities.

Basis of operation: Pointed by rotating in azimuth on wheels and circular steel track, in elevation on roller-bearings. Incoming radio intercepts parabolic main reflector, concentrates at quadrapod-supported subreflector, comes to focus at a mirror below central hole in main reflector. Radio beam, enclosed in a 2.5-meter diameter cylindrical waveguide, then encounters four more mirrors on the way to receiving equipment below ground level. Transmitter's output is ducted via the same mirrors and waveguides to the subreflector, from where it evenly illuminates the main reflector for propagation to spacecraft. Simultaneous uplink and downlink is standard practice. Every DSS connects with signal processing center via fiber optic cable.

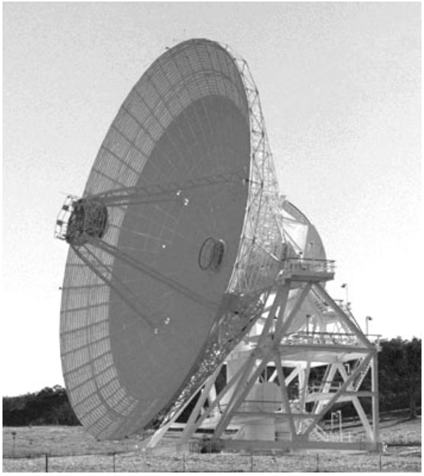

Fig. B.12. Deep Space Station 55, DSN's newest 34-meter aperture beam-waveguide deep space station. Located outside Madrid, Spain. Time-lapse video of construction: deepspace.jpl.nasa.gov/dsn/gallery/video.html. Image courtesy NASA/JPL-Caltech.

Specifications: One of nine 34-meter diameter DSN stations. Physical location specified in three dimensions to the millimeter. Downlink: 8.4–8.5 GHz X-band; 31.8–32.3 GHz Ka-band. Uplink: 7.145–7.235 GHz X-band, 17.5 kW.

Aperture:	34 m	**Detector:**	HEMT
Polarization:	Right- and/or left-circular	**Moving mass:**	300,000 kg
Developed by:	NASA/JPL	**Location:**	Madrid, Spain
Gain:	X-band 70 dB uplink, 68 dB downlink, Ka 79 dB downlink		
Operated:	Around-the-clock from October 2003 to present.		

Appendix C: Space

This appendix explains nomenclature for some regions and scales of space. It also provides some approximate values for distances, light-times, particle densities, and temperatures. A page is devoted to Jupiter's atmospheric features, and one to Saturn's elegant rings. Many of these features are easy to see when viewing Jupiter and Saturn from Earth.

Interplanetary Space is the space among the planets of our solar system and within the *heliosphere*, which is the Sun's realm of practical magnetic influence. Besides the planets, most of the material in interplanetary space is from the Sun. Fast-moving plasma known as the *solar wind* flies out from the Sun in all directions, faster in the solar polar regions than in the equatorial. Occasional bursts of ion clouds known as *coronal mass ejections* also fly outward from the Sun within the heliosphere.

Magnetic fields surround most of the planets and interact with the solar wind and mass ejections. Planets with strong magnetic fields such as Earth and the gas giants have *magnetospheres* that largely divert the solar ions around them.

Beginning beyond Neptune's orbit, a band of cometary bodies, called the *Kuiper Belt*, may extend outside the heliosphere. Its population includes bodies orbiting at a large range of inclinations compared to the planets, which are more or less confined to the ecliptic plane.

The solar wind slows to subsonic velocity at a front called the *termination shock*, located just beyond the outer edge of the heliosphere. *Voyager 1* and *Voyager 2* have already penetrated the termination shock and confirmed that its location is constantly changing. *Voyager 1* exited the shock at 94 AU toward the north and *Voyager 2* exited at 86 AU toward the south, and today they are flying through the region between it and the heliopause, the point where the interstellar medium and solar wind pressures balance. This region is called the *heliosheath.*

The distribution of mass in interplanetary space includes the Sun (99.85%) and the planets (0.135%). The remaining 0.015% makes up everything else: comets, planetary satellites, meteoroids, and plasma.

Interstellar Space is the space outside the heliosphere, where the Sun's magnetic influence cannot redirect incoming charged particles. Since the Sun is moving among the local stars and through intervening clouds of gas and dust, the heliopause is associated with a curved "bow shock," as illustrated in Figure C.1, along which interstellar material bunches up and flows around the heliosphere. The distance from the Sun to the heliopause and the bow shock is not known as of 2008, but they are estimated to begin at about 200 AU. Interstellar space lies beyond the bow shock.

Five spacecraft are bound for interstellar space: *Pioneer 10* and *Pioneer 11*, which are no longer communicating; *Voyager 1* and *Voyager 2*, and *New Horizons*, which may still be measuring their environment and communicating, when they penetrate the heliopause, to report on interstellar conditions within our galaxy.

A sphere of cometary bodies called the Oort Cloud is thought to lie well outside the heliosphere in interstellar space, at an estimated one light-year or so from the Sun. While no bodies have been observed within the Oort cloud itself, it is believed to be the source of all long-period comets that have been observed closer to the Sun.

Intergalactic Space The Sun and planets, all the local stars, and all spacecraft, while moving along their proper trajectories, are also orbiting the central region of our galaxy which contains a super-massive black hole about twenty-six thousand light years distant. Outside the galaxy's magnetic field are the vast reaches of space among the billions of galaxies in the universe.

Outer Space is a term used mostly in the popular literature to refer to any space that is outside most of the Earth's atmosphere, typically more than a hundred kilometers above the surface. All of space is permeated by gravitation, electromagnetic radiation, and plasma in various amounts. There is no empty space; there is no escaping Earth's gravity, or the Sun's, because the gravitation of any physical mass only diminishes with distance. In free-fall in orbit, however, a spacecraft experiences zero or near-zero *weight*.

Table C.1. Distances and Light-Times in Space.

Distance (approximate)	Light-time	Example
299,793 km	1 s	78% of the Earth–Moon average dist.
149,598,000 km (1 AU)	8.31 min	Sun–Earth average dist.
624,150,000 km	34 min	Earth–Jupiter at opposition.
16.2×10^9 km	15 hr	Earth–*Voyager 1**
63,000 AU	1 year	Light-year
4.2 LY	4.2 y	Nearest star
8.6 LY	8.6 y	Bright star Sirius
26,000 LY	26,000 y	Galactic center
2.53×10^6 LY	2.53×10^6 y	Nearest galaxy
14×10^9 LY	14×10^9 y	Farthest galaxies

AU = Astronomical Unit (average Sun-Earth dist.), LY = light year.
*As of December 2008.

Table C.2. Particle temperatures and densities in space, modeled.

Region	Temperature, K	Density, atoms / cm^3
Earth-vicinity	10,000	6
Neptune-vicinity	200,000	1.4
Termination shock	600,000	0.1
Heliopause	$2x10^6$	0.2
Bow shock	30,000	0.3
Interstellar cloud past heliopause	8,000	0.3
Local interstellar void	10^6	0.0001
Intergalactic medium	100	10^{-6}
Best lab vacuum	—	1000
Residence	2.7×10^{19}	295

Sensitive instruments can detect particles' temperatures, but physical masses, such as spacecraft and asteroids, are not affected by particles in such low densities, even though the particles may have temperatures in the hundreds of thousands of kelvins. They are mainly affected by exposure to incident sunlight and shadow.

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[4] John W. McAnally. *Jupiter: and How to Observe It.* Astronomers' Observing Guides. Springer, 2008.

[5] Ellis D. Miner, Randii R. Wessen, and Jeffrey N. Cuzzi. *Planetary Ring Systems.* Springer-Praxis, 2007.

Table C.3. Some Temperature Examples.

Kelvin	Degrees C	Degrees F	Example
0	–273.15	–459.67	Absolute zero
2.7	–270.5	–454.8	Cosmic microwave background
4.2	–268.95	–452.11	Liquid helium boils
20.28	–252.87	–423.16	Liquid hydrogen boils
35	–235	–390	Surface of Neptune's moon Triton
72	–201	–330	Neptune atmosphere, 1-bar level
76	–197	–323	Uranus atmosphere, 1-bar level
90	–180	–300	Surface of Saturn's moon Titan
100	–175	–280	Night-side surface of Mercury
134	–129	–219	Saturn atmosphere, 1-bar level
153	–120	–184	Mars surface nighttime low
165	–108	–163	Jupiter atmosphere, 1-bar level
195	–78.15	–108.67	Carbon dioxide freezes
273.15	0.0	32.0	Water freezes
288	15	59	Mars surface, daytime high
288	15	59	International standard atmosphere
373.15	100	212	Water boils
635	362	683	Venus surface
700	425	800	Day-side of Mercury
1500	1200	2000	Yellow candle flame
3700	3400	6700	Sunspots
5700	5400	9800	Solar photosphere
7000	7000	12000	Plasma in neon sign
$2x10^6$	$2x10^6$	$3.6x10^6$	Solar corona
$15x10^6$	$15x10^6$	$27x10^6$	Solar core

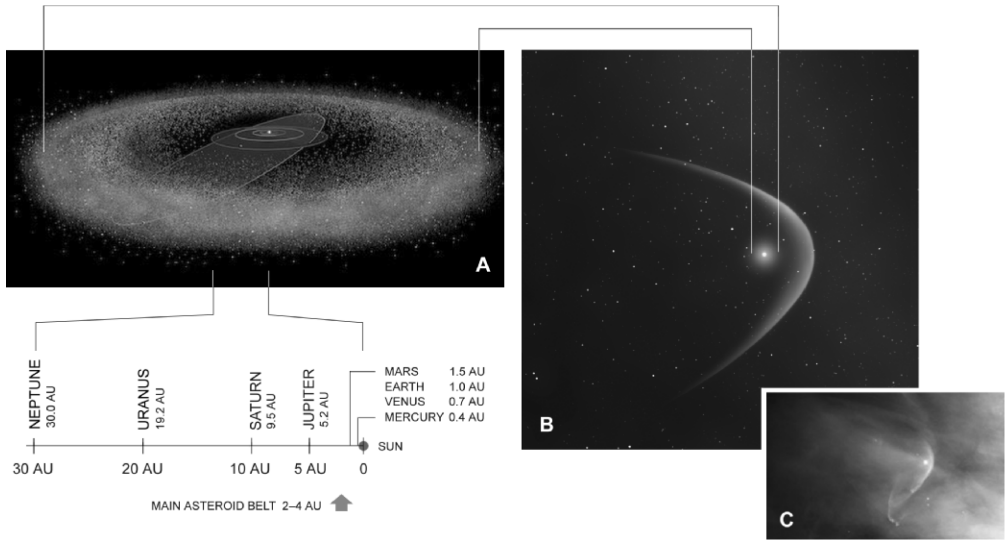

Fig. C.1. Rough approximations of scale of interplanetary space and the beginning of interstellar space. In order outward from the Sun are the terrestrial planets, the main asteroid belt, the gas giant planets, and the Kuiper belt. Next are the termination shock, where the solar wind goes subsonic, and the heliosheath (not illustrated). The heliopause marks the beginning of the solar bow shock, and interstellar space beyond. The spheroid Oort cloud of comet nuclei resides in interstellar space at over 50,000 AU from the Sun. Artist's conception panel (A) illustrates planets and Kuiper belt, showing Pluto's highly elliptical orbit, the aphelion of which is about 49 AU from the Sun. The Kuiper Belt may actually extend much farther than illustrated. Artist's conception panel (B) illustrates how panel (A) scales with the parabolic bow shock just outside the heliopause. Termination shock would be inside the light-grey area of bow shock, at roughly 90 AU (average of *Voyager* measurements), where the heliosheath begins. Panel (C) is an actual image of a stellar bow shock, about half a light-year across, where L.L. Orionis's stellar wind is colliding with gas and dust in the Orion Nebula about 1,500 light-years from the Sun. Panel (A) artwork © 2008 Don Dixon / cosmographica.com, reproduced by permission. Panel (B) by T. Pyle, Spitzer Space Science Center, serves to generally illustrate solar bow shock, but was created to illustrate Spitzer's actual view of R Hya's bow shock as the star moves through its local interstellar medium. Panel (C) image ID: STScI-PRC02-05 courtesy NASA Hubble Heritage Team STScI/AURA.

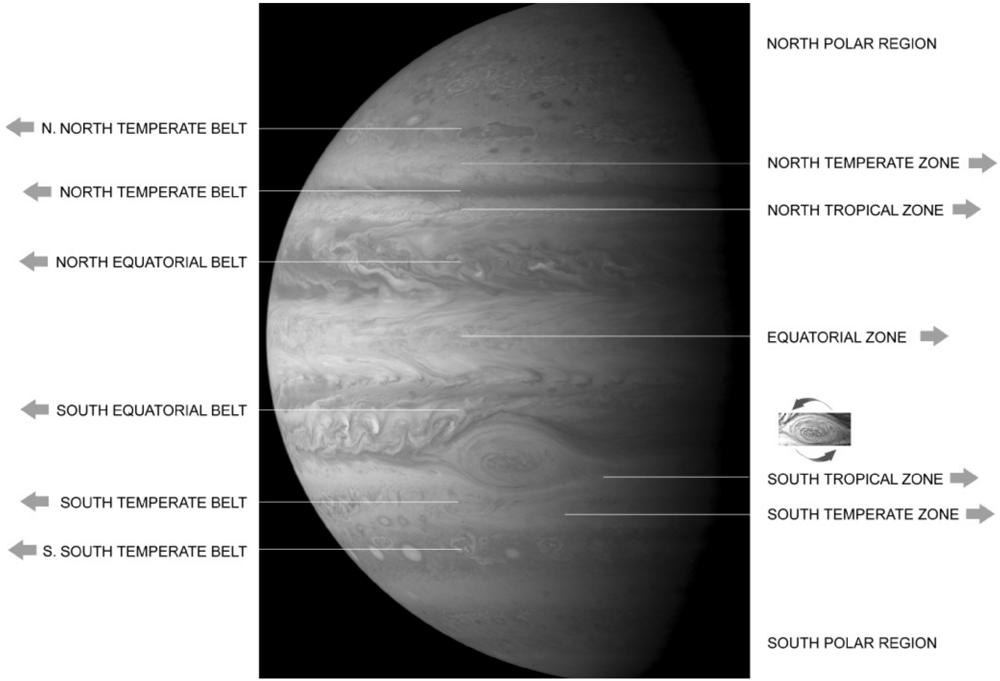

Fig. C.2. Identification of Jupiter's major atmospheric belts and zones. These are the ones that persist over the years. Features which are not always visible are not shown (e.g "bands" which may appear within zones, and some higher latitude belts and zones), but reference [4] provides complete information on all of these. Belts are the darker regions where clouds rise, and their winds blow from the east toward the west as indicated by the arrows. Zones are lighter in color. Their clouds descend, and their winds blow west to east. Wind speeds are generally on the order of 100 meters/second. The Great Red Spot rotates counterclockwise within the south tropical zone. Adapted from *Cassini* image ID: PIA04866 courtesy JPL/NASA/Space Science Institute.

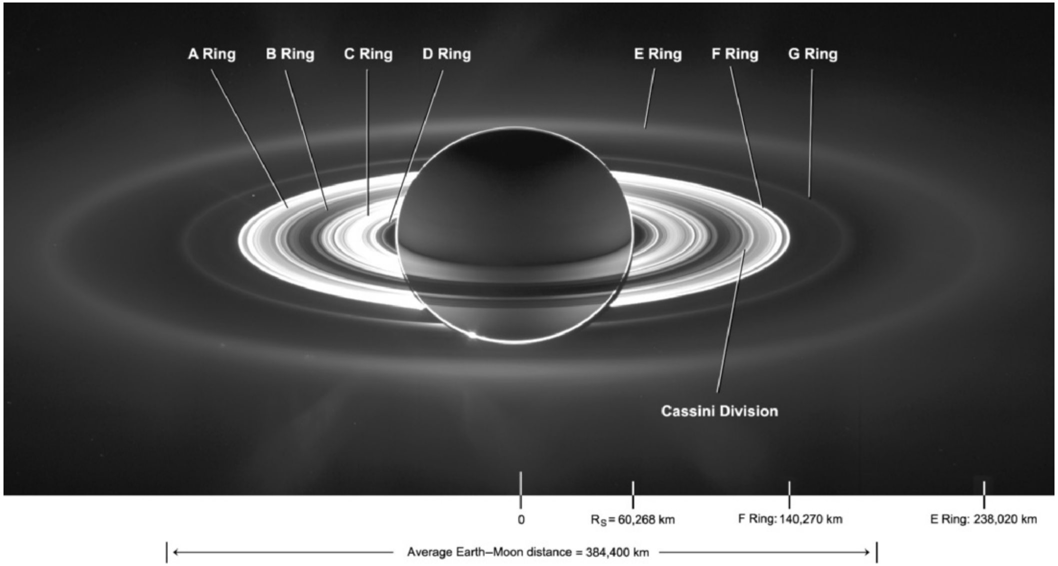

Fig. C.3. Saturn's rings identified. The broad A, B, and C Rings can be easily seen in a small telescope from Earth. Fine particles of the D, E, F, and G Rings (normally difficult to see from Earth) appear bright in forward-scattered light in this high-phase-angle mosaic of images taken while *Cassini* was in Saturn's shadow on September 15, 2006. Fine particles in the Cassini Division, transparent when viewed from Earth, also appear bright here, backlit in sunlight. The dense B Ring appears dark because it blocks light from passing through from below (south). Distances indicate Saturn radius (R_S), F Ring, and the densest part of the E Ring, whose diameter is greater than the average Earth-Moon distance. Explanations of the many features in this image may be found at www.jpl.nasa.gov/basics/saturn. For example, the distant Earth is visible just inside the G Ring on the upper left. Saturn's small moon Enceladus, imaged more than once in the mosaic, appears in the lower left of E Ring, which is created and maintained by the moon's geysers. Reference [5] provides full information on planetary ring systems. Radial clouds are artifacts of stray light. Only tens of meters in vertical thickness, Saturn's rings are made up of myriad particles of widely various sizes orbiting the planet. Adapted from image ID: PIA08329, courtesy JPL/NASA/Space Science Institute.

Appendix D: The Electromagnetic Spectrum

Figure D.1 illustrates the nomenclature associated with the electromagnetic spectrum that is generally applicable to interplanetary flight[1]. Electromagnetic radiation extends from the lowest energy and longest wavelength as radio waves up through infrared, visible and ultraviolet light, x-ray and finally gamma ray, which is the highest energy and shortest wavelength radiation (note the term “cosmic ray” does not denote any sort of electromagnetic radiation, but rather particles such as the nuclei of hydrogen through iron moving through our galaxy at high speed). The spectrum in the figure appears as a vertical list. A line drawn horizontally across the list would show the same electromagnetic radiation expressed in wavelength, frequency, and photon energy; there is no spectral distinction along the horizontal axis, only nomenclature.

Figure D.2 illustrates the effect on radiation in various parts of the spectrum of the Earth’s atmosphere and ionosphere. The atmosphere’s complete absorption of gamma-rays, x-rays, and much of the ultraviolet wavelengths allows life as we know it to exist here. The absorption of many of the wavelengths of infrared is a hindrance to ground-based IR astronomy, although high mountaintop observatories can gain some advantage. The fact that the ionosphere reflects some wavelengths of radio is a boon to long-distance earthbound radio communications, as the signals can reflect between Earth’s surface and the ionosphere, propagating around the planet long beyond the line-of-sight horizon.

It is worthwhile to consider that such a small part of the electromagnetic spectrum — visible light, a mere sliver across Figure D.1 — has served humans for all of history and prehistory in the quest to know more of the universe. Around the beginning of the space age it became possible to capture the wealth of additional information contained in additional bands of wavelengths (or photon energies). Among the many varied technologies now in hand, radio telescopes on Earth’s surface are capable of capturing views of otherwise invisible phenomena deep across intergalactic space such as those shown in Figure D.3; infrared robot observatories operating high above the atmosphere show us otherwise hidden phenomena such as the places and processes of stellar birth; and orbiting x-ray telescopes and gamma-ray observatories provide glimpses into the most energetic of cosmic events. Figure D.4 shows the remnant of the 1602 supernova (stellar explosion) named in honor of Johannes Kepler, who observed it in the constellation Ophiuchus. Published in observance of the explosion’s four-hundredth anniversary, the illustration comprises views in several parts of the electromagnetic spectrum separately and combined: two in X-ray, one in visible light, and one in the infrared.

Notes

[1]Some of the powers of ten in Figure D.1 are not labeled because their associated values are not used in general practice. For example x-rays and gamma-rays are more often identified by their photon energies, not by their frequency or wavelength. Similarly radio waves are commonly identified by wavelength and frequency; infrared, visible, and in many cases the ultraviolet, are usually described in values of wavelength alone.

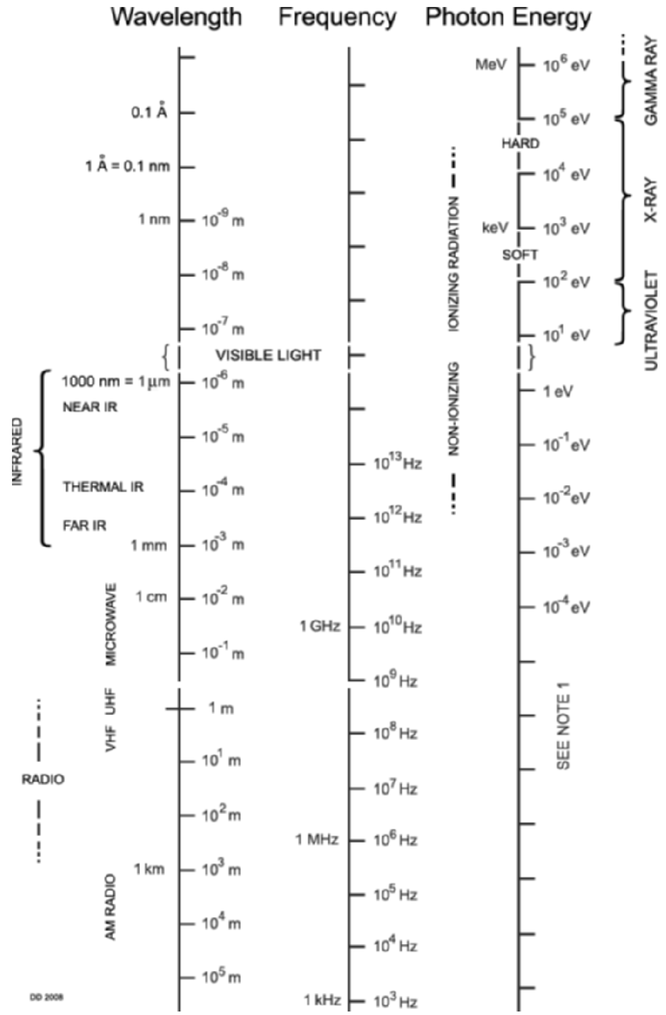

Fig. D.1. Wavelengths, frequencies and photon energy equivalencies. Commonly used electromagnetic spectrum nomenclature is shown. Å= Angstrom, which is one-tenth of a nanometer; μ = micro(-meter).

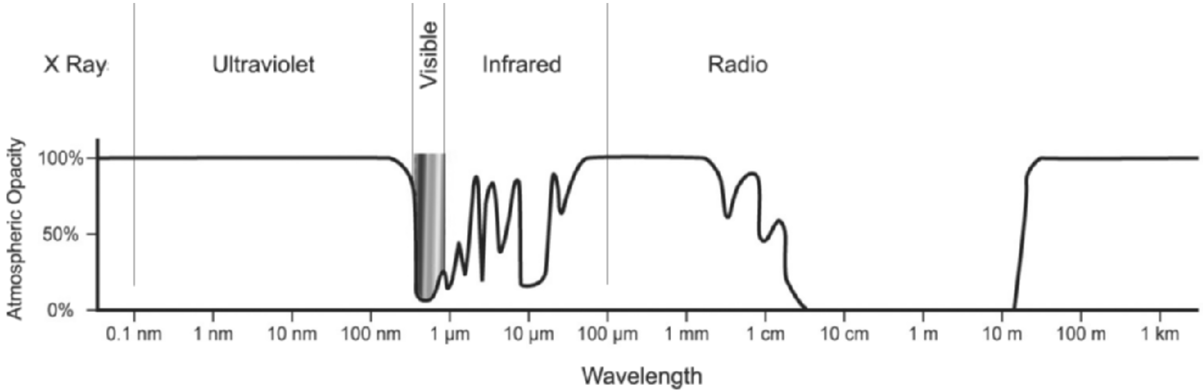

Fig. D.2. Opacity of Earth's atmosphere to various wavelengths. The Earth's atmosphere is 100% opaque to x-ray wavelengths (and to gamma rays, which are not illustrated in this diagram but would be further to the left). Opacity continues at 100% for most of the ultraviolet, but lessens, the atmosphere becoming more transparent, as wavelengths approach violet in the visible part of the spectrum. Visible light is only slightly absorbed, but infrared is absorbed variously at different wavelengths. Large portions of the far (right-side) infrared and millimeter-wavelength radio are blocked entirely, but longer wavelengths of radio, down to about 10 meters, enjoy perfect atmospheric transparency. Wavelengths longer than about 10 meters are blocked by the ionosphere. Figure D.1 shows frequency as well as wavelength. Adapted from image courtesy NASA.

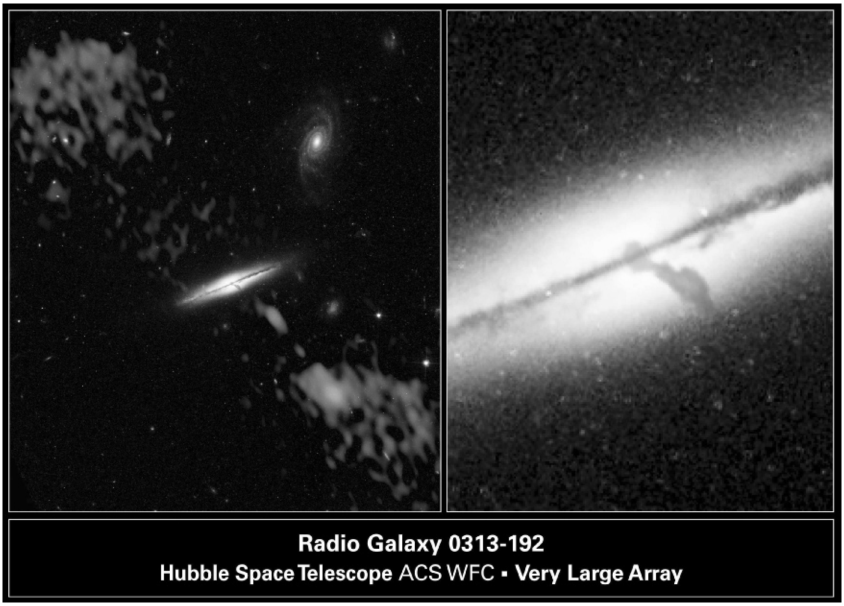

Fig. D.3. Radio and visible light view of galaxy 0313-192. About a billion light years distant, this spiral galaxy appears edge-on in this visible-light image by the *Hubble Space Telescope*. An energetic jet of high-speed particles can be seen in 20-centimeter wavelength radio "light" pouring out along the galaxy's poles thousands of light years into the surrounding intergalactic space, presumably powered by an accretion disk around the galaxy's central black hole. A closer view, made in 3-centimeter wavelength radio, is shown at right. The radio images, acquired by the Very Large Array of radio telescopes in Socorro, New Mexico, are shown in light grey superimposed on the visible-light image. The second spiral galaxy visible in the left-hand panel is about two hundred million light years closer to Earth than is 0313-192. View online in color by searching for image ID: STScI-PRC03-04. Courtesy NASA, NRAO/AUI/NSF and W. Keel (University of Alabama).

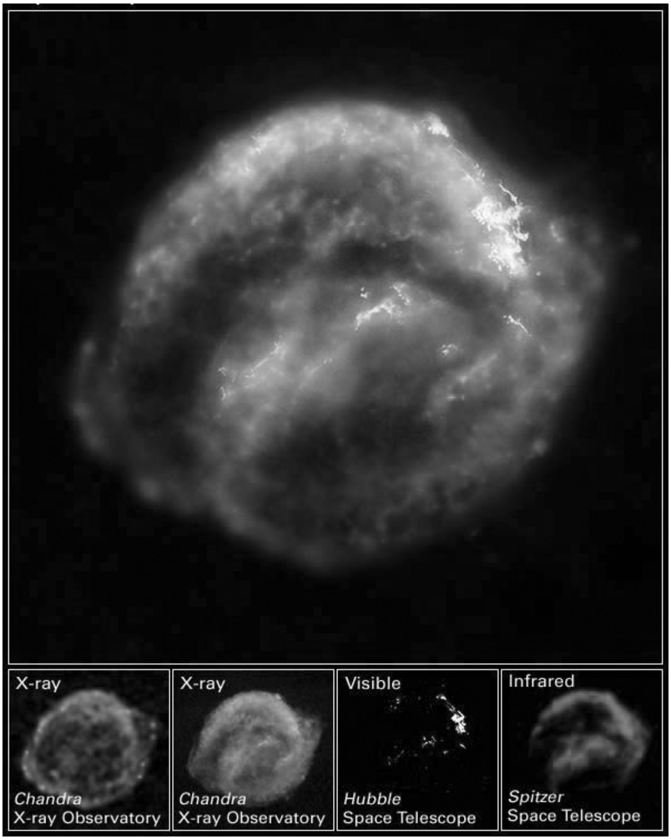

Fig. D.4. Multi-spectral view of SN 1604. The last known supernova in our galaxy appeared in 1604 and was observed by Johannes Kepler. Four hundred years later the *Chandra X-ray Observatory* in Earth orbit, the *Spitzer Infrared Space Telescope Facility* in solar orbit trailing the Earth, and the Earth-orbiting *Hubble Space Telescope* made observations of SN 1604, "Kepler's Supernova," in four different parts of the electromagnetic spectrum. These views are shown separately and combined in this figure. Spectra obtained in these various wavelength bands reveal processes ongoing as the debris shell continues to evolve and expand into the surrounding interstellar space. View online in color using image ID: STScI-PRC04-29a. Courtesy NASA, ESA, R. Sankrit and W. Blair (Johns Hopkins University).

Appendix E: Chronology

This time-ordered list of selected events of interest and importance to interplanetary flight includes not only a good number of spacecraft mission events,[1] which begin on page 351, but also the dates of some milestones in the Deep Space Network's history, as well as some historical breakthroughs in knowledge.

Circa 270 BCE

The Greek astronomer and mathematician Aristarchus of Samos (ca. 310–230 BCE) estimates Sun and Moon sizes and distances and proposes that the Earth revolves around the Sun, a theory that does not gain acceptance.

Circa 140

The Greek/Egyptian astronomer Claudius Ptolemaeus (Ptolemy, ca. 85–165) writes *Mathematike Syntaxis,* later known as the *Almagest,* an Earth-centered cosmological treatise.

1543

The Polish scholar Nicholaus Copernicus (1473–1543) cautiously publishes his theory of the Sun-centered solar system.

1572

November 2 A "new star," brighter in the sky than the planet Venus, is widely observed in the constellation Cassiopeia, and accurate observations of its location and brightness are recorded by the Danish astronomer Tycho Brahe (1546–1601), among others. It remained visible for two years. Located in our galaxy about ten thousand light years away, the remnant of this supernova, SN 1572, is a target of investigation today.

1600

The exact date of the invention of the telescope is not preserved in history, but it was in general use by this time, largely for Earth-bound applications.

1604

October 9 A star in our galaxy about twenty thousand light-years away explodes and produces a "new star" in the constellation Ophiuchus, appearing brighter in the sky than the planet Jupiter. Johannes Kepler is among the astromomers to observe it, and today the supernova remnant is named for him. See Figure D.4 on page 345.

1610

January 7 The Tuscan scholar Galileo Galilei (1546–1642) first observes Jupiter and its companion moons with a homemade astronomical telescope. Later in the same year he observed Saturn and noted, "...to my very great amazement Saturn was seen to me to be not a single star, but three together, which almost touch each other."

1612

December Galileo observes Saturn while the Earth was passing through its ring plane, viewing the thin rings edge-on. On the disappearance of Saturn's companions he notes, "I do not know what to say in a case so surprising, so unlooked-for and so novel."

1619

The German mathematician and astronomer Johannes Kepler (1571–1630), using the extensive stellar observations made by Tycho Brahe, completes formulation of his three laws of planetary motion.

1655

The Dutch mathematician and astronomer Christaan Huygens (1629–1695) proposes that Saturn was surrounded by "a thin, flat ring, nowhere touching, and inclined to the ecliptic." He discovers Saturn's largest moon Titan the same year.

1668

The English polymath Sir Isaac Newton (1642-1727) builds the first telescope to successfully use reflecting optics, a type now widely known as the Newtonian reflector.

1676

The Italian-French astronomer Giovanni Domenico (Jean-Dominique) Cassini (1625–1712) discovers a gap in Saturn's rings now named the Cassini Division in his honor.

1686

Newton publishes *Philosophie Naturalis Principia Mathematica.*

1704

Newton publishes *Opticks*, which includes his work with prisms and the spectrum of visible light.

1781

13 March The German-born astronomer William Herschel (1738–1822) discovers the planet Uranus using a large homemade Newtonian reflector telescope.

1800

13 March Herschel discovers the infrared part of the electromagnetic spectrum.

1801

The German chemist and physicist Johann Ritter (1776–1810) discovers the ultraviolet part of the electromagnetic spectrum.

January 1 The Italian astronomer Giuseppe Piazzi (1746–1826) discovers the first asteroid, Ceres. Initially regarded as a new planet, it is now recognized as one of millions of bodies orbiting the Sun in the main asteroid belt.

1842

The Austrian physicist Christian Doppler (1803–1853) describes the change of observed frequency when source or observer are approaching or receding.

1847

September 20 The American Association for the Advancement of Science (AAAS) is established and meets in Philadelphia, Pennsylvania, the following year. Publication of its journal *Science* begins in 1880.

1856

The Scottish physicist and mathematician James Clerk Maxwell (1831–1879) shows that Saturn's rings cannot be solid and must be made of "an indefinite number of unconnected particles".

1864

Maxwell formulates equations of electromagnetism and shows that light is an electromagnetic wave.

1869

August 18 A total eclipse of the Sun enables the English astronomer Norman Lockyer (1836–1920) and, independently, the French astronomer Pierre Janssen (1824–1907) to find a yellow spectral emission line at 587.49 nm in the solar corona spectrum and attribute it to an unknown element (later named helium).

November 4 Lockyer publishes the first issue of the journal *Nature*.

1880

July 3 AAAS begins publishing the weekly journal *Science*.

1886

The German physicist Heinrich Hertz (1857–1894) demonstrates the reception of electromagnetic waves with an antenna.

1877

September the Italian astronomer Giovanni Schiaparelli (1835–1910) claims to see straight channels (Italian *canali*) on the surface of Mars. Confirmed by some later observers but not others, they were popularized by the American astronomer Percival Lowell (1855–1916) but were ultimately proven to be optical illusions.

1895

Italian inventor Guglielmo Marconi (1874–1937) sends and receives radio signals, demonstrating the feasibility of radio communications.

1900

October 19 The German physicist Max Planck (1858–1947) proposes his black-body radiation law to describe the observed radiated spectra.

1903

December 17 First sustained, powered, and controlled flight of an airplane, piloted by the American inventor Orville Wright (1871–1948).

1905

March The German-born theoretical physicist Albert Einstein (1879–1955) shows that the photoelectric effect can be understood as light interacting with matter in discrete quanta of energy (photons).

1906

The American inventor Lee De Forest (1873–1961) creates the triode vacuum-tube amplifier.

1913

July The Danish physicist Niels Bohr (1885–1962) publishes a model of the atom involving electrons orbiting a nucleus, and photon emission based on electrons changing orbits.

1925

The German engineer Walter Hohmann (1880–1945) describes the minimum-energy interplanetary transfer trajectory.

1926

March 16 First liquid-propellant rocket launched, built by the American inventor Robert Goddard (1882–1945), using a DeLaval nozzle.

1930

The Hungarian-German-American engineer and physicist Theodore von Kármán (1881–1963) becomes director of the California Institute of Technology's Guggenheim Aeronautical Laboratory, later to help it become the Jet Propulsion Laboratory.

February 18 The American astronomer Clyde Tombaugh (1906–1997) discovers Pluto. Initially regarded as a new planet, it is now recognized as one of many similar bodies, called plutoids, orbiting the Sun in the region beyond Neptune.

1939

January and March The German-American physicist Hans Bethe (1906–2005) publishes two papers showing how nuclear fusion reactions produce energy in the stars.

1951

The American engineers Julian Allen (1910–1977) and A.J. Eggers (1922–2006) discover that the destructive frictional heating of atmospheric (re-)entry vehicles can be managed by using a high-drag, blunt-nose design.

1957 Begins the Space Age.

October 4 The Soviet Union launches *Sputnik I*, the world's first artificial satellite, into Earth orbit.

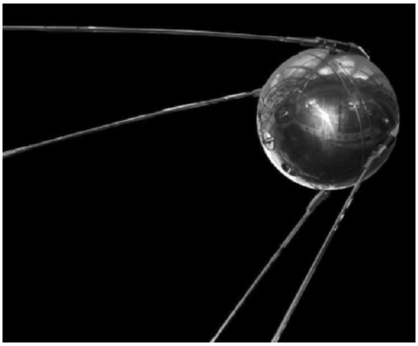

Fig. E.1. *Sputnik-I.*

1958

January 31 The United States launches its first satellite, *Explorer I*, into Earth orbit. Its subsequent identification of the Van Allen belts constitutes the first scientific discovery using a space-borne instrument.

29 July The US National Aeronautics and Space Administration (NASA) is established by act of Congress. It replaces the old National Advisory Committee on Aeronautics.

1959

January 4 The Soviet Union's *Luna 1*, launched January 2, passes by the Moon at a distance of 5,995 kilometers (launched 2 January) and enters heliocentric orbit, the first spacecraft to escape from Earth's gravitational hold.

March 4 The U.S *Pioneer 4*, launched the previous day, passes within 60,000 kilometers of the Moon.

September 14 The USSR's *Luna 2*, launched on September 12, impacts the Moon in the Palus Putredinus region.

October 7 The USSR's *Luna 3*, launched October 4, returns the first images from the lunar far side.

1961

August 23 The American mathematician Michael Minovitch describes "gravity propelled interplanetary space travel," later to be known as the "gravity assist" technique.

1962

April 26 The US *Ranger 4*, launched April 23, impacts the far side of the Moon.

August 27 The US launches *Mariner 2* to Venus.

December 14 *Mariner 2* Venus flyby at 34,773 kilometers.

1963

December 24 Deep Space Network (DSN) established by incorporating the worldwide facilities of JPL's Deep Space Instrumentation Facility.

1964

July 31 US spacecraft *Ranger 7*, launched July 28, crashes on the Moon between Mare Nubium and Oceanus Procellarum after returning 4,308 images.

November 28 The US launches *Mariner 4* to Mars.

1965

February 20 US spacecraft *Ranger 8*, launched February 17, impacts the Moon in Mare Tranquillitatis after returning 7,137 images.

March 24 The US *Ranger 9*, launched March 21, impacts in the lunar crater Alphonsus after returning 5,814 images.

July 15 *Mariner 4* flies by Mars at 9,846 kilometers, executing the first radio occultation at Mars, and returning the first images from another planet.

July 20 The USSR's *Zond 3*, launched July 18, passes the Moon at 9,200 kilometers, returning twenty-five images from the lunar far side. The spacecraft continues to aphelion at the orbit of Mars for a spacecraft test, re-transmitting the lunar images.

1966

February 3 The USSR's *Luna 9*, launched January 31, makes the first lunar soft landing using airbags and retrorockets. It returns panoramic images of the lunar surface and radiation measurements from Oceanus Procellarum through February 6.

April 3 The USSR's *Luna 10*, launched March 31, enters lunar orbit.

June 2 US *Surveyor 1*, launched May 30, lands on the Moon inside a 100 kilometer-diameter crater in Oceanus Procellarum by means of retrorockets. Surviving the lunar night, it returns 11,240 images through July 13.

August 14 US *Lunar Orbiter 1*, launched August 10, enters lunar orbit. Scouting potential landing sites for Surveyor and Apollo, it returns 229 images and other data through October 29 when it impacts the far side on command.

August 28 The USSR's *Luna 11*, launched August 24, enters lunar orbit. It acquires data on X-ray and gamma-ray emissions characterizing the lunar surface and measures the lunar gravity field and meteor and radiation flux through October 1.

October 25 The USSR's *Luna 12*, launched October 22, enters lunar orbit. It returns images and other data through January 11 1967.

November 10 *Lunar Orbiter 2*, launched November 6 (US), enters lunar orbit. It returns images and other data scouting potential landing sites for Surveyor and Apollo through October 11, 1967, when it impacted the surface on command.

December 24 *Luna 13*, launched December 21 (USSR), soft-lands on the Moon near Oceanus Procellarum. It returns panoramas and soil data through about December 31.

1967

February 8 Lunar Orbiter 3, launched February 5 (US), enters lunar orbit. It returns 626 images and other data scouting potential landing sites for Surveyor and Apollo through October 29, when it impacts the surface on command.

April 20 Surveyor 3, launched April 17 (US), soft-lands on the Moon inside a 200-meter crater in southeast Oceanus Procellarum. It returns data on the lunar soil and 6,326 images May 4.

May 7 Lunar Orbiter 4, launched May 4 (US), enters lunar orbit. Its mission is similar to *Lunar Orbiter 1* and *Lunar Orbiter 2*.

June 12 The USSR launches *Venera 4* toward Venus.

June 14 Mariner 5 (US) lifts off toward Venus.

July 22 Explorer 35, launched July 19 (US), enters lunar orbit to acquire data on interplanetary plasma, magnetic fields, energetic particles, and solar X rays.

August 5 Lunar Orbiter 5, launched August 1 (US), enters lunar orbit.

September 11 Surveyor 5, launched September 8 (US), soft-lands on the Moon in Mare Tranquillitatis.

October 18 Venera 4 enters Venus atmosphere and deploys multiple instruments which return data while the spacecraft descends by parachute, the first successful controlled entry and descent of a spacecraft into the atmosphere of another planet.

October 19 Mariner 5 flies by Venus at 4,000 kilometers returning data.

November 10 Surveyor 6, launched November 7 (US), soft-lands on the Moon in Sinus Medii.

1968

January 10 Surveyor 7, launched January 7 (US), soft-lands on the Moon near Tycho crater in the lunar highlands.

April 10 Luna 14, launched by the USSR on April 7, enters lunar orbit.

September 18 Zond 5, launched September 14 (USSR), flies around the Moon. It returns to Earth on September 21 in a controlled re-entry, carrying living biological specimens.

November 14 Zond 6, launched November 10 (USSR), flies around the Moon and returns to Earth November 17 in a controlled re-entry.

1969

January 5 Venera 5 (USSR) launches on a mission to Venus.

January 10 Venera 6 (USSR) launches toward Venus.

February 24 Mariner 6 (US) launches toward Mars.

March 27 Mariner 7 (US) launches towards Mars.

May 16 Venera 5 (USSR) flies by Venus and deploys an instrumented atmospheric probe which enters Venus' atmosphere and parachutes toward surface.

May 17 Venera 6 (USSR) executes a Venus mission similar to that of *Venera 5*.

July 20 Following a July 16 launch, Apollo 11's Lunar Module *Eagle* (US) touches down on the Moon, carrying the first humans to set foot on the lunar surface: Neil Armstrong (1930–) and Buzz Aldrin (1930–). Along with Command Module pilot Michael Collins, they return to Earth on July 24 in Command Module *Columbia*. After additional crewed landings by Apollo 12, 14, 15, 16, and 17, the last astronaut to set foot on the moon, Eugene Cernan, returned to Earth December 19, 1972.

July 31 Mariner 6 flies by Mars at a distance of 3,431 kilometers.

July 17 Luna 15, launched July 13 (USSR), enters lunar orbit.

*August 5 Mariner 7*flies by Mars at a distance of 3,430 kilometers.

August 11 Zond 7, launched by the USSR on August 7, flies around Moon. It returns to Earth August 14.

October Invention of CCD by the Canadian physicist Willard Boyle (1924–) and American scientist George Smith (1930–) at Bell Labs.

1970

August 17 Venera 7 (USSR) lifts off for Venus.

September 24 Luna 16, launched September 12 (USSR), returns lunar samples to Earth from Mare Foecunditatis.

October 24 Zond 8, launched October 20 (USSR), flies around the Moon, It returns to Earth October 27 in a controlled re-entry.

November 15 Luna 17, launched November 10 (USSR), soft-lands on the Moon in the Sea of Rains, and deploys an instrumented rover, *Lunokhod 1*, which travels over 10 kilometers taking soil analysis data.

December 15 Venera 7 soft-lands on Venus, returning data via orbiter.

1971

May 19 Mars 2 (USSR) launched toward Mars.

May 28 Mars 3 (USSR) launched toward Mars.

May 30 Mariner 9 (US) launched towards Mars.

October 3 Luna 19 (USSR) enters lunar orbit (launched September 28).

November 14 Mariner 9 (US) enters Mars orbit, becoming the first spacecraft to orbit another planet. It returned data until 27 October 1972 but continues to orbit Mars.

November 27 Mars 2 enters Mars orbit and makes scientific observations through August 22, 1972.

December 2 Mars 3 (USSR) enters Mars orbit, and delivers a lander that achieves a soft landing. Although the lander then quits functioning after twenty seconds, its touch-down is the first controlled landing on another planet (*Viking 1*, 1976, is the first which landed and succeeded in its mission).

1972

February 21 Luna 20, launched February 14 (USSR), soft-lands on the Moon near Mare Foecunditatis. It returns samples to Earth on February 22.

March 3 Pioneer 10 (US) launches toward Jupiter.

March 27 Venera 8 (USSR) launches toward Venus.

July 22 Venera 8 enters Venus atmosphere, soft-lands, and returns data from the surface for 50 minutes, 11 seconds, via orbiter.

1973

January 15 Luna 21 and *Lunokhod 2*, launched January 8 (USSR), reach the lunar surface.

April 5 Pioneer 11 (US) launches toward Jupiter and Saturn.

June 15 Explorer 49-RAE-B, launched June 10 (US), enters lunar orbit to make radio astronomy observations.

July 25 Mars 5 (USSR) launched towards Mars.

November 3 Mariner 10 (USA) launched on a gravity-assist trajectory toward Venus and Mercury.

December 3 Pioneer10 flies by Jupiter at 200,000 kilometers.

1974

February 5 Mariner 10 (USA) flies by Venus at 5,768 kilometers and obtains a gravity assist to Mercury.

February 12 Mars 5 (USSR) enters Mars orbit.

March 29 Mariner 10 makes its first flyby of Mercury at 704 kilometers.

June 2 Luna 22, launched May 29 (USSR), enters lunar orbit.

September 21 Mariner 10 makes a second flyby of Mercury, at 48,069 kilometers.

December 4 Pioneer 11 flies by Jupiter.

1975

March 16 Mariner 10 makes a third and final flyby of Mercury at 327 kilometers.

June 8 Venera 9 (USSR) launches toward Venus.

June 14 Venera 10 (USSR) launches toward Venus.

August 20 Viking 1 (USA) launches towards Mars.

September 9 Viking 2 (USA) launches towards Mars.

October 22 Venera 9 soft-lands on Venus and operates 53 minutes on the surface, returning data via orbiter.

October 25 Venera 10 soft-lands on Venus and operates 65 minutes on surface, returning data via orbiter.

1976

June 19 Viking 1 enters Mars orbit.

July 20 Viking 1 soft-lands on Mars, the first landing on another planet to succeed with an operable spacecraft.

August 7 Viking 2 enters Mars orbit.

August 18 Luna 24, launched August 9 (USSR), soft-lands on the Moon in Mare Crisium and returns soil samples to Earth on August 22.

September 3 Viking 2 soft-lands on Mars.

1977

August 20 Voyager 2 (USA) lifts off for Jupiter and beyond.

September 5 Voyager 1 (USA) launches toward Jupiter and beyond.

December 15 Voyager 1 overtakes *Voyager 2* in the main asteroid belt.

1978

May 20 Pioneer-Venus Orbiter (USA) launches toward Venus.

August 8 Pioneer-Venus Multiprobe (USA) launches toward Venus.

August 12 Explorer 59 (USA), also known as *International Cometary Explorer* (ICE) and *International Sun-Earth Explorer-C* (ISEE-C), lifts off to acquire data in heliocentric orbit then encounter comet Giacobini-Zinner.

September 9 Venera 11 (USSR) launches toward Venus

September 14 Venera 12 (USSR) launches toward Venus

December DSN Mark-III Data System implementation completed. This is an upgrade to the tracking system that establishes and maintains the links between spacecraft and flight project teams using 26-, 34-, 64-, and 70-meter aperture stations.

December 4 Pioneer-Venus Orbiter enters Venus orbit.

December 9 Pioneer-Venus Multiprobe's atmospheric entry probe (called *Sounder*) and three smaller probes enter the Venusian atmosphere.

December 21 Venera 12 (USSR) soft-lands on Venus and transmits data via orbiter for 110 minutes after landing.

December 25 Venera 11 (USSR) soft-lands on Venus and transmits data via orbiter for 95 minutes after landing.

1979

March 5 Voyager 1 flies by Jupiter and obtains gravity assist to Saturn.

July 9 Voyager 2 flies by Jupiter and obtains gravity assist to Saturn.

September 1 Pioneer 11 flies by Saturn.

1980

March DSN implements the ability to combine signals received from multiple antennas in real time to increase the effective aperture by arraying stations.

November 12 Voyager 1 flies by Saturn and enters a northerly interstellar trajectory.

1981

August 5 Voyager 2 flies by Saturn and obtains a gravity assist to Uranus.

October 30 Venera 13 (USSR) launches toward Venus.

November 4 Venera 14 (USSR) launches toward Venus.

1982

March 1 *Venera 13* soft-lands on Venus and transmits data via orbiter for 127 minutes after landing.

March 5 *Venera 14* soft-lands on Venus and transmits data via orbiter for 57 minutes after landing.

1983

June 2 *Venera 15* (USSR) launches toward Venus.

June 7 *Venera 16* (USSR) launches toward Venus.

October 10 *Venera 15* enters Venus orbit and conducts SAR imaging of the planet's surface.

October 14 *Venera 16* enters Venus orbit and conducts SAR imaging of the planet's surface.

1984

December 15 *Vega 1* (USSR) launches for Venus and Comet Halley.

December 21 *Vega 2* (USSR) launches for Venus and Comet Halley.

1985

January 8 *Sakigake* launches toward Comet Halley and Earth encounters on Japan's first interplanetary mission.

11 June *Vega 1* deploys atmospheric balloon and lander probe at Venus.

June 15 *Vega 2* deploys atmospheric balloon and lander probe at Venus.

July 2 *Giotto*, the first joint European interplanetary mission, launches toward Comet Halley.

August 18 *Suisei* (Japan) launches for Comet Halley.

September 11 *Explorer 59* encounters plasma tail of comet Giacobini-Zinner.

1986

DSN implements the Mark-IV Data System, a computer-network-based system that manages the links between spacecraft and flight project teams using 34- and 70-meter aperture stations.

January 24 *Voyager 2* flies by Uranus and obtains gravity assist to Neptune.

January 28 STS *Challenger* (USA) and crew tragically lost during ascent.

March 6 *Vega 1* flies by Comet Halley at 10,000 kilometers.

March 8 *Suisei* flies by Comet Halley at 151,000 kilometers.

March 9 *Vega 2* flies by Comet Halley at 3,000 kilometers.

March 11 *Sakigake* flies by Comet Halley at 7 million kilometers.

March 13 *Giotto* flies by Comet Halley at 596 kilometers.

1987

April DSN implements three X-Band high-efficiency 34-meter aperture stations. Additional upgrades to these antennas followed.

1988

May 29 DSN completes upgrade from 64-meter apertures to 70-meter.

July 12 *Phobos 2* (USSR) launches toward Mars.

1989

January 29 *Phobos 2* enters Mars orbit.

March 27 *Phobos 2* contact lost prior to deploying landers on the Martian moon Phobos.

May 4 *Magellan* (USA) launches toward Venus.

August 25 *Voyager 2* flies by Neptune and enters southerly interstellar trajectory.

October 18 *Galileo* (USA) launches toward Venus on a gravity-assist trajectory to Jupiter.

1990

January 24 *Hiten* (Japan) engineering test spacecraft launches into highly elliptical Earth orbit with apoapsis at lunar distance.

February 10 *Galileo* flies by Venus on a gravity-assist trajectory to Jupiter.

14 February *Voyager 1* turns on cameras after they had been dormant for nine years and captures images of the Sun and six planets. Cameras were then shut off permanently.

April 25 *Hubble Space Telescope* (USA) launches into Earth orbit.

July 2 *Giotto* flies by Earth for science data acquisition and gravity assist, the first encounter with Earth by a spacecraft approaching from deep space.

August 10 *Magellan* enters orbit at Venus.

October 6 *Ulysses* (Europe) solar-polar orbiter launches.

1991

April 11 *Galileo* HGA deployment attempts begin; antenna fails to open.

October 29 *Galileo* flies by asteroid 951 Gaspara at 1,600 kilometers en route to Jupiter.

December 8 *Galileo* flies by Earth on a gravity-assist trajectory to Jupiter.

1992

January 8 *Sakigake* flies by Earth.

February 8 *Ulysses* Jupiter flyby changes the spacecraft's inclination in solar orbit to about 80°, an attitude from which it can observe the Sun's polar regions.

July 10 *Giotto* flies by Comet Grigg-Skjellerup at 200 kilometers.

September 25 *Mars Observer* (USA) launches toward Mars.

December 8 *Galileo* flies by Earth a second time on a gravity-assist trajectory to Jupiter and carries out an optical communications experiment by observing laser illumination from Earth using the imaging science instrument.

1993

May 24 *Magellan* begins to circularize its highly-elliptical orbit via aerobraking in Venus' atmosphere, the first such operation at another planet. This results in the ability to acquire high-resolution gravity-field measurements.

June 14 *Sakigake* flies by Earth, within its geotail.

August 21 Contact with *Mars Observer* lost prior to Mars orbit insertion.[2]

August 28 *Galileo* flies by asteroid 243 Ida at 2,400 kilometers en route to Jupiter and discovers Ida's satellite, Dactyl.

December 12 *Hubble Space Telescope* refurbishment, correcting optical focus and making additional upgrades, completed in orbit,.

1994

February 21 *Clementine* (USA), launched January 25, enters lunar orbit.

July 16-22 *Galileo* observes the impact of fragments of comet Shoemaker-Levy 9 into Jupiter's atmosphere south of the equator.

October 13 Magellan impacts Venus in the termination experiment following experiments that used the solar panels as windmill blades to study the free molecular flow regime.

October 28 Sakigake flies by Earth at 7 million kilometers.

December DSN implements the first beam-waveguide 34-meter aperture stations. Additional upgrades to these antennas followed.

1995

July 13 Galileo releases its Jupiter atmospheric probe.

September 30 Pioneer 11's last signal detected, from about 45 AU.

December 7 Galileo enters orbit at Jupiter and collects telemetry and tracking data from the atmospheric probe during its entry.

1996

February 14 NEAR Shoemaker (Near-Earth Asteroid Rendezvous, USA) launches toward asteroid 253 Mathilde.

November 7 Mars Global Surveyor (USA) launches toward Mars.

December 4 Mars Pathfinder (USA) launches toward Mars.

1997

February 21 Hubble Space Telescope's second refurbishment completed in orbit.

June 27 NEAR Shoemaker flies by asteroid 253 Mathilde at 1,200 kilometers.

July 4 Mars Pathfinder lands in the Ares Vallis region on Mars.

July 6 Mars Pathfinder (USA) rover *Sojourner* rolls off the lander and onto the Martian surface.

September 12 Mars Global Surveyor enters Mars orbit.

October 15 Cassini-Huygens (USA-Europe) launches toward Venus on a gravity-assist trajectory to Saturn.

1998

January 11 Lunar Prospector (USA), launched January 7, enters lunar orbit.

January 23 NEAR Shoemaker flies by Earth at 540 kilometers for gravity-assist, putting it on course for asteroid 433 Eros.

February 17 Voyager 1 exceeds the length of *Pioneer 10*'s flightpath and becomes the most distant human-made object.

April 26 Cassini-Huygens flies by Venus on a gravity-assist trajectory to Saturn.

October 24 Deep Space 1 (USA) technology demonstration spacecraft launches toward asteroid 9969 Braille.

December 11 Mars Climate Orbiter (USA) launches toward Mars.

1999

February 4 Mars Global Surveyor completes aerobraking maneuvers, circularizing its orbit in preparation for science data collection.

February 7 Stardust (USA) launches toward comet Wild 2.

June 24 Cassini-Huygens flies by Venus for the second time on a gravity-assist trajectory to Saturn.

July 29 Deep Space 1 flies by asteroid 9969 Braille at 26 kilometers.

August 18 Cassini-Huygens flies by Earth on a gravity-assist trajectory to Saturn.

September 23 Mars Climate Orbiter unintentionally enters Martian atmosphere and is lost.[3]

2000

February 17 NEAR Shoemaker enters orbit at asteroid 433 Eros.

December 30 Cassini-Huygens flies by Jupiter on a gravity-assist trajectory to Saturn.

2001

January 23 NEAR Shoemaker soft-lands on asteroid 433 Eros, becoming the first spacecraft to land on an asteroid. Operation continued until February 28.

April 7 2001 Mars Odyssey (USA) launches toward Mars.

August 8 Genesis (USA) launches for the L1 Lagrangian Sun-Earth libration point to collect solar wind samples.

September 22 Deep Space 1 flies by comet Borrelly at 2171 kilometers.

October 24 2001 Mars Odyssey enters Mars orbit.

November 16 Genesis arrives at L1 and begins collecting solar wind samples until December 3, 2004, when collection ended and the sample collection canister was sealed.

2002

January 11 *2001 Mars Odyssey* completes aerobraking maneuvers circularizing its orbit in preparation for science data collection.

2003

January 23 *Pioneer 10*'s last signal detected, from about 84 AU.

May 9 *Hayabusa* (Japan) launches toward asteroid 25143 Itokawa.

June 2 *Mars Express* (USA) launches for Mars.

June 10 *Spirit* (USA) Mars Exploration Rover spacecraft launches toward Mars.

8 July *Opportunity* (USA) Mars Exploration Rover spacecraft launches toward Mars.

September 21 *Galileo* enters Jupiter's atmosphere in a procedure to dispose of the spacecraft lest it collide with Europa and introduce Earth microbes to its surface or to its sub-surface saltwater ocean.

October 21 The American astronomers Mike Brown (1965–), Chad Trujillo (1973–), and David Rabinowitz (1960–) discover an object later named Eris in the Kuiper Belt beyond Pluto. Dispute follows among scientists over the definition of the word "planet."

November 13 *SMART 1* technology demonstration spacecraft (Europe), launched September 27, enters lunar orbit.

December 25 *Mars Express* enters Mars orbit.

2004

January 2 *Stardust* flies by comet Wild 2 at 250 kilometers, collecting samples of ejecta.

January 4 *Spirit* Mars Exploration Rover spacecraft arrives in Gusev Crater on Mars.

January 15 *Spirit* (USA) Mars Exploration Rover spacecraft drives onto Martian soil.

January 25 *Opportunity* Mars Exploration Rover spacecraft arrives at Meridiani Planum on Mars.

January 31 *Opportunity* Mars Exploration Rover spacecraft drives onto Martian soil.

March 2 Rosetta (Europe) carrying the *Philae* lander, launches toward Mars on a gravity-assist trajectory to comet Churyumov-Gerasimenko.

May 19 Hayabusa flies by Earth at 3,725 kilometers for gravity assist to asteroid 25143 Itokawa.

July 1 Cassini-Huygens enters Saturn orbit.

August 3 Messenger (Europe) launches toward Venus on a gravity assist trajectory to Mercury.

September 8 Genesis returns to Earth. The parachute fails to deploy because an accelerometer had been installed upside down, and the sample capsule crashes into the Utah desert. The sample fragments are recovered for analysis nonetheless.

December 25 Huygens Titan probe separates from *Cassini* orbiter.

2005

January 12 Deep Impact (USA) launches toward comet Tempel 1.

January 14 Huygens executes parachuted descent through Titan's atmosphere and survives landing.

March 4 Rosetta-Philae (Europe) flies by Earth for the first time on a gravity-assist trajectory to comet Churyumov-Gerasimenko.

May Voyager 1 penetrates the solar termination shock at 94 AU, where the solar wind goes subsonic, and enters the heliosheath behind the heliopause.

July 3 Deep Impact (USA) releases impactor in the path of oncoming comet Tempel 1 from a distance of 880,000 kilometers.

July 4 Deep Impact's impactor strikes comet Tempel 1. Flyby spacecraft observes the event, also widely observed from Earth, while approaching from 10,000 kilometers.

July 4 Deep Impact begins an extended mission named EPOXI (for Extrasolar Planet Observation and Characterization Investigation) using its imager to observe extrasolar planetary occultations. A further extended mission *Deep Impact* Extended Investigation (DIXI), will fly by comet Hartley 2 on October 11, 2010, at 1000 kilometers.

August 2 Messenger flies by Earth at 2,347 kilometers on a gravity assist trajectory to Mercury.

August 12 Mars Reconnaissance Orbiter (USA) launches for Mars, circularizing its orbit in preparation for science data collection.

November 9 *Venus Express* (Europe) launches toward Venus.

November 19 *Hayabusa* settles onto asteroid 25143 Itokawa. On 24 November sample collection was attempted, for a planned return to Earth in June of 2010.

2006

January 15 *Stardust* returns samples of comet and interplanetary material to Earth.

January 19 *New Horizons* (USA) launches toward Jupiter on a gravity assist trajectory to Pluto and other Kuiper belt objects.

March 10 *Mars Reconnaissance Orbiter* enters Mars orbit.

April 11 *Venus Express* enters Venus orbit.

August 24 The International Astronomical Union creates the first scientific definition of the word "planet," and decides that several objects in the solar system, including Pluto, are defined as "dwarf planets."

September 11 *Mars Reconnaissance Orbiter* completes aerobraking maneuvers

October 24 *Messenger* flies by Venus at 2,990 kilometers on a gravity assist trajectory to Mercury.

2007

February 25 *Rosetta-Philae* flies by Mars at 250 kilometers on a gravity-assist trajectory to comet Churyumov-Gerasimenko.

February 28 *New Horizons* flies by Jupiter on a gravity assist trajectory to Pluto, Charon, and other Kuiper belt objects, to continue into the Kuiper belt and beyond.

June 5 *Messenger* flies by Venus for the second time at 337 kilometers on a gravity assist trajectory to Mercury.

August 4 *Phoenix* (USA) Mars Lander launches toward Mars.

September 27 *Dawn* (USA) launches toward Mars on a gravity-assist trajectory to main-belt asteroids and Vesta and Ceres.

October 3 *Kaguya* (Japan), launched September 14, enters lunar orbit.

October 9 *Kaguya* releases companion satellite *Okina* into lunar orbit to participate in radio science experiments.

October 12 *Kaguya* releases companion satellite *Ouna* into lunar orbit to participate in radio science experiments.

November 5 *Chang'e 1*, the first Chinese deep-space mission, launched October 24, enters lunar orbit.

November 13 *Rosetta-Philae* flies by Earth a second time at 5,295 kilometers on a gravity-assist trajectory to comet Churyumov-Gerasimenko.

2008

May 25 *Phoenix lander* lands on Mars and begins observations.

June 5 *Messenger* flies by Mercury the first time at 200 kilometers on a gravity assist trajectory to return to Mercury on its next solar orbit.

July *Voyager 2* penetrates the solar termination shock at 86 AU, where the solar wind goes subsonic, and enters the heliosheath behind the heliopause.

July 1 *Cassini* completes its primary tour of the Saturn system and begins an extended mission in Saturn orbit.

September 5 *Rosetta-Philae* flies by asteroid 2,867 Steins en route to comet Churyumov-Gerasimenko.

October 6 *Messenger* flies by Mercury a second time at 200 kilometers on a gravity assist trajectory to return to Mercury on its next solar orbit.

November 2 Last transmission received from *Phoenix lander.*

November 12 First direct observation of an exoplanet — a planet of another star. The star is Fomalhaut, 25 light-years away, and the planet was detected and confirmed in HST visible-light images (see page 285).

2009

January *Orbiting Carbon Observatory* (USA) planned to launch into Earth orbit.

February *Dawn* to fly by Mars on a gravity-assist trajectory to Vesta and Ceres.

September 29 *Messenger* to fly by Mercury a third time at 200 kilometers on a gravity assist trajectory to return to Mercury on its next solar orbit.

November *Rosetta-Philae* to fly by asteroid 2867 Steins en route to comet Churyumov-Gerasimenko.

November 13 *Rosetta-Philae* to fly by Earth a third time on a gravity-assist trajectory to comet Churyumov-Gerasimenko.

2010

October *Deep Impact* (renamed EPOXI) expected to fly by and observe Comet Hartely 2.

2011

March 18 Messenger expected to enter orbit at Mercury.

August Dawn expected to enter orbit at main-belt asteroid Vesta.

October Mars Science Laboratory (USA) earliest planned launch.

2012

May Dawn expected to leave orbit from Vesta and set off for Ceres.

2013

August BepiColombo (Europe) expected to launch on a six-year mission to orbit Mercury.

2014

May Rosetta-Philae expected to enter a slow orbit at comet Churyumov-Gerasimenko, descending and releasing the lander *Philae*, which is intended to fasten to the comet with harpoons, in November 2014,.

2015

February Dawn expected to enter orbit at main-belt asteroid Ceres.

14 July New Horizons expected to fly by to Pluto at 10,000 kilometers, and by its moon Charon at 27,000 kilometers.

Notes

[1]Spacecraft data selected largely from planetary mission data published online by Dr. David R. Williams of the NASA Goddard Space Flight Center. Complete technical details of any planetary spacecraft and its mission may be found at
http://nssdc.gsfc.nasa.gov/planetary/chronology.html.

[2]Included here to support discussion in Chapter 4. Most other lost missions are not listed in this chronology.

[3]Included here to support discussion in Chapter 2. Most other lost missions are not listed.

Appendix F: Units of Measure, Abbreviations, Greek Alphabet

Units of Measure

There are seven *base units* in the International System of Units (SI). All other SI units are derived from these base units. Many of the derived units have special names and symbols. Most of the units of measure listed here are either SI units — base or derived — or units recognized by SI. The SI base unit definitions listed here are from the U.S. National Institute of Standards *Guide to the SI.*

A Ampere; the SI base unit of electric current. The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.

Å Ångstrom; an internationally recognized non-SI unit of length (typically wavelength or sizes of atoms) equal to 0.1 nanometer.

AU Astronomical Unit; a measure of distance, based on the mean sun-Earth distance. The International Astronomical Union defines the AU as the distance from the Sun at which a particle of negligible mass, in an unperturbed orbit, would have an orbital period of 365.2568983 days (a Gaussian year). The AU is thus defined as $1.4959787066 \times 10^{11}$ m = 149,597,870.66 km.

bel Unit of power ratio; most often expressed as the decibel, dB, 0.1 bel.

bps Bits per second; a measure of data communications rate.

°C Celsius temperature; derived from the SI base unit K –273.15.

c Centi. A multiplier; x 10^{-2} from the Latin "centum" (hundred).

c Speed of light in a vacuum; 299,792,458 m/sec.

cd Candela; the SI base unit of luminous intensity. The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

Da Dalton; a unit of atomic mass approximately equal to the mass of one proton or one neutron (electrons have little mass).

dB Decibel; a base-10 logarithmic expression of power or dimensionless ratio. A number of decibels represents the number of tenths to which the power of ten is raised: 20 dB = $10^{20/10} = 100$.

dBm Decibel referenced to a milliwatt; 30 dBm = $10^{30/10}$ = 1000 mW (1 W).

dBHz Decibel referenced to one hertz; 40 dBHz = $10^{40/10}$ = 10,000 Hz (10 kHz).

dBi Decibel referenced to an isotropic radiator to express gain; 50 dBi = $10^{50/10}$ = 100,000-fold increase (gain).

degree of arc 1° of arc; 1/360 of a circle.

eV Electron volt; a measure of the energy of an electromagnetic wave or photon.

G Giga; a multiplier, x 10^9 from the Latin "gigas" (giant). Note: while Giga means 10^9 everywhere, in the U.S., a *billion* means 10^9, while in other countries using SI, a billion is equal to 10^{12}.

G Gauss; a unit of magnetic flux density equal to 1/10,000 tesla.

g Gram; SI unit of mass.

Hz Hertz; the SI unit of frequency: the number of cycles per second, derived from the SI base unit s^{-1}.

J Joule; the SI unit for energy, work, or quantity of heat, equal to N·m, derived from the base units $m^2 \cdot kg \cdot s^{-2}$.

K Kelvin; the SI base unit of thermodynamic temperature. The kelvin is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water (273.16 K or 0.01 °C).

k Kilo; a multiplier, x 10^3 from the Greek "khilioi" (thousand).

kg Kilogram; the SI base unit of mass. The kilogram is equal to the mass of the international prototype of the kilogram.

LY Light Year; a measure of distance, the distance light travels in one year; about 63,240 AU.

M Mega; a multiplier, x 10^6 from the Greek "megas" (great).

m Milli; a multiplier, x 10^{-3} from the Latin "mille" (thousand).

m Meter; the SI base unit of length (U.S. spelling; elsewhere, metre). The meter is the length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second.

micro A multiplier; x 10^{-6} from the Greek "micros" (small).

μ Symbol for micron (micrometer); one millionth of a meter. Also a multiplier prefix; see micro.

minute of arc 1' of arc = 1/60 of a degree.

mol Mole; the SI base unit for amount of substance. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.

N Newton; the SI unit of force derived from the SI base units $m \cdot kg \cdot s^{-1}$.

n Nano; a multiplier, x 10^{-9} from the Greek "nanoz" (dwarf).

ohm (Symbol Ω) The SI unit of electrical resistance, equal to V/A, derived from the base units $m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$.

Pa Pascal; the SI unit of pressure or stress, equal to N/m^2, derived from the SI base units $m^{-1} \cdot kg \cdot s^{-2}$.

rad Radian; the SI unit of plane angle, derived from $m \cdot m^{-1} = 1$. Equal to $180/\pi$ degrees of arc, about 57.295°.

s Second; the SI base unit of time. The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

second of arc 1" of arc = 1/60 of a minute of arc.

sr Steradian; the SI unit of solid angle, derived from $m^2 \cdot m^{-2} = 1$. This is the solid angle subtended at the center of a sphere of radius R by a portion of the sphere's surface having an area R^2. The area of a sphere is 4π sr.

T Tesla; the SI unit of magnetic flux density equal to 10,000 gauss.

V Volt; the SI unit of electrical potential difference or electromotive force, equal to W/A, derived from the base units: $m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$.

W Watt; an SI unit of power equal to joules per second, derived from the SI base units $m^2 \cdot kg \cdot s^{-3}$.

Conversions

Table F.1. SI to English Unit Conversions

Millimeters to inches:	mm	x	0.0393700787401575	=	in
Centimeters to inches:	cm	x	0.393700787401575	=	in
Meters to feet:	m	x	3.28083989501312	=	ft
Meters to yards:	m	x	1.09361329833771	=	yd
Kilometers to miles:	km	x	0.621371192237334	=	mi
Grams to ounces:	g	x	0.0352739907229404	=	oz
Kilograms to pounds:	kg	x	2.20462262184878	=	lb
Newtons to pounds force:	N	x	0.224809024733489	=	lbf
Kelvin to Celsius:	K	−	273.15	=	°C
Celsius to Fahrenheit:	(°C x 9/5)	+	32.0	=	°F

Abbreviations

3-D Three dimensional
A_e Exhaust area
A_t Throat area
AAAS American Association for the Advancement of Science
AACS Attitude and Articulation Control System
AAS American Astronomical Society
AC Alternating current
ACP Aerosol collector and pyrolizer
Ag Silver
AIAA American Institute of Aeronautics and Astronautics
Al Aluminum
Al_2O_3 Alumina
AMD Angular Momentum Desaturations
Amp Amplifier (see also Units of Measure listed below)
AO Adaptive optics
AO Announcement of opportunity
APL Applied Physics Laboratory, Johns-Hopkins University
APXS Alpha-particle X-ray spectrometer
ARQ Automatic repeat-request
As Arsenic
ASI Agenzia Spaziale Italiana (Italian Space Agency)
ATK Alliant Techsystems, Inc. Previously Thiokol, Inc., now known as ATK Launch Systems Group.
ATLO Assembly, test, and launch operations
AUI Associated Universities, Inc.
BCE Before current era
Be Beryllium
BER Bit error rate
Biprop Bi-propellant
BLF Best-lock frequency
bps Bits per second
BPSK Binary Phase Shift Keying modulation
BVR Block-V (Roman numeral five) Receiver
BWG Beam-waveguide DSN antenna
C Carbon
C_2H_2 Acetylene
$C_2H_8N_2$ Unsymmetrical dimethyl hydrazine, UMDH
C_3 Characteristic energy (intensive quantity)
C_3H_8 Propane
C/A Closest approach
Ca Calcium
C&DH Command and Data Handling subsystem
Caltech California Institute of Technology
CAPS Cassini plasma spectrometer
CCD Charge-coupled device
CCSDS Consultative Committee for Space Data Systems
CD Compact disc
Cd Cadmium
CDA Cosmic dust analyzer
CDR Critical Design Review
CDS Command and Data Subsystem
CEA Cambridge Electron Accelerator
CERR Critical Events Readiness Review
CESR French Centre d'Etude Spatiale des Rayonnements
$CH_3N_2H_3$ Mono-methyl hydrazine, MMH
CIRS Composite IR spectrometer
Cl Chlorine
CLT Command-loss timer
CM Celestial mechanics
Cm Curium
CMC Center Management Council
CMD Command data type (one of seven in DSN)
CME Coronal mass ejection
CMG Control-moment gyro
CNES French National Center of Space Research
CNG Compressed natural gas
Co Cobalt
CO_2 Carbon dioxide
CO_2 Carbon dioxide
COBE COsmic Background Explorer
CTS Command and Telemetry Subsystem
CXC Chandra X-Ray Center
ΔDOR or DDOR Delta dfferenced one-way range
ΔV Delta V; change in velocity
DC Direct current
DDOR or ΔDOR Delta differenced one-way range

DECIGO DECi-hertz Interferometer Gravitational wave Observatory
DN Data number in telemetry
DOF Degree(s) of freedom
Dop (Dopp) Doppler shift
DOR Differenced one-way range
DPS Division for Planetary Science of the American Astronomical
DR Decommissioning Review
DS1 *Deep Space 1* spacecraft
DSCC Deep Space Communications Complex
DSS Deep Space Station
DSL Digital subscriber line
DSM Deep Space Maneuver
DSN Deep Space Network
DSS Deep space station
DVD Digital versatile disc
ECC Error-control coding
EDAC Error detection and correction
EDL Entry, descent, and landing
EDR Experiment Data Record
EDT Eastern daylight time
EGA Engine gimbal assembly
EHF Extremely High Frequency
EIRP Effective isotropic radiated power
ENA Energetic neutral atom
EOPM End of Prime Mission
EPPS Energetic particle and plasma spectrometer
ERT Earth-receive time
ESA European Space Agency
ET Ephemeris time (see Glossary)
EU Engineering unit in telemetry
F&P Fields and particles
F&T Frequency and timing data type (one of seven in DSN)
FEC Forward error-correction
FET Field-effect transistor
FFT Fast Fourier transform
FM Frequency modulation (or modulated)
FRR Flight Readiness Review
g Local gravitational constant
G Universal gravitational constant
g_0 Standard Earth gravity, 9.80665m/s^2
GaAs Gallium arsenide
GC Gas chromatograph
GCMS Gas chromatograph mass spectrometer
Ge Germanium
GEM Graphite-epoxy motor
GMT Greenwich Mean Time
GPMC Governing Program Management Council
GPS Global Positioning System
GR General relativity
GRNS Gamma-ray and neutron spectrometer
GRS Gamma-ray spectrometer
GSFC NASA Goddard Space Flight Center
H_2 Molecular hydrogen
H_2O Water
H_2O_2 Hydrogen peroxide
H_2SO_4 Sulphuric acid
HASI Huygens atmospheric structure instrument
HCN Hydrogen cyanide
HEF High-efficiency (at X-band) DSN antenna
HEMT High-Electron Mobility Transistor
HF High Frequency
HGA High-Gain Antenna
HiRISE High-Resolution Imaging Science Experiment
HRG Hemispherical-resonator gyro
HST *Hubble Space Telescope*
HTPB Hydroxy-terminated polybutadiene binder
I_{sp} Specific impulse (intensive quantity)
IBM International Business Machines
ICRF International Celestial Reference Frame
IEC International Electrotechnical Commission
IEEE Institute of Electrical and Electronics Engineers, Inc. originally (in its modern expanded scope, the name is simply I-triple-E)
IERS International Earth Rotation and Reference Systems Service
INCA Ion and neutral camera
INMS Ion and neutral mass spectrometer
IPU Injection Propulsion Unit
IR Infrared
IRS Infrared Spectrograph
IRU Inertial Reference Unit
ISO Integrated Sequence of Events
I_{sp} Specific impulse
ISS Imaging science subsystem
ISS International Space Station
IUS Inertial upper stage

JAXA Japanese Aerospace Exploration Agency
JHU Johns-Hopkins University
JPL Jet Propulsion Laboratory (Caltech)
JSC NASA Johnson Space Center
Ka Band of microwave radio frequencies (see Appendix D)
KDP Key decision point
KOH Potassium hydroxide
KSC NASA Kennedy Space Center
Ku Band of microwave radio frequencies (see Appendix D)
LANL U.S. Los Alamos National Laboratory
LASCO Large angle spectrometric coronagraph
LBS Linear Boom Actuator
LCD Liquid-crystal display
LDPC Low-density parity-check
LED Light-emitting diode
LGA Low-Gain Antenna
Li Lithium
LIBS laser-induced breakdown spectroscopy
LIGO Laser Interferometer Gravitational Wave Observatory
LINEAR LIncoln Near-Earth Asteroid Research
LISA Laser-Interferometer Space Antenna
LNA Low-Noise Amplifier
LORRI Long-Range Reconnaissance Imager
LRC NASA Lewis Research Center
LV FRR Launch Vehicle Flight Readiness Review
LV LRR Launch Vehicle Launch Readiness Review
LY Light year
MAG Magnetometer
MAG Magnetometer
MARCI Mars Color Imager instrument
MCD Maximum-likelihood Convolutional Decoder
MCO *Mars Climate Orbiter* spacecraft
MCR Mission Concept Review
MDR Mission Definition Review
MEC Mass expulsion control
MEMS Micro-Electro-Mechanical System
MEP Mars Exploration Program
MEPAG Mars Exploration Program Analysis Group
MER Mars Exploration Rover
MGA Mars gravity assist
MGA Medium gain antenna
MIL-STD Military standard
MIMI Magnetospheric imaging instrument
MIMOS Mini-Mössbauer spectrometer
MIT Massachusetts Institute of Technology
MLI Multi-layer insulation
MMH Mono-methyl hydrazine
MMU Mission module unit
MOI Mars Orbit Insertion rocket burn
MOLA Mars Orbiter Laser Altimeter
MON Mixed oxides of nitrogen
MON Monitor data type (one of seven in DSN)
Monoprop Mono-propellant
MPD Magnetoplasmadynamic thruster
MPI German Max Planck Institute
MP P Maximum power point
MRB Mission Readiness Briefing
MRO *Mars Reconnaissance Orbiter*
MRO Memory readout
MS Mass spectrometer
MSL *Mars Science Laboratory*
N_2 Molecular nitrogen
N_2H_4 Hydrazine
N_2O_4 Nitrogen tetroxide (NTO)
NAIF Navigation and Ancillary Information Facility
NASA U.S. National Aeronautics and Space Administration
Nd:YAG Neodymium-doped yttrium aluminum garnet
NEAR *Near-Earth Asteroid Rendezvous* spacecraft (renamed *NEAR-Shoemaker*)
NEO Near-Earth object
NH_3 Ammonia
NH_4CLO_2 Ammonium Perchlorate
NiCd Nickel-cadmium
NIMS Near-IR mapping spectrometer
NIST National Institute of Standards and Technology
NO Nitric oxide
NRAO U.S. National astronomical radio observatory
NRC U.S. National Research Council
NS Neutron spectrometer
NSF U.S. National Science Foundation
NSSDC National Space Science Data Center
NTO Nitrogen tetroxide
O_2 Molecular oxygen

OD Orbit determination
OH Hydroxyl
ORR Operations Readiness Review
OSI Open Systems Interconnection
OSR Optical solar reflector
OTM Orbit Trim Maneuver
P_c Combustion chamber pressure
P_e Exhaust pressure
P&W Pratt and Whitney
Pb Lead
PDR Preliminary Design Review
PDS NASA Planetary Data System
PDT Pacific Daylight Time
PEPSSI Pluto Energetic Particle Spectrometer Science Investigation
PI Principal investigator
PICA Phenolic-impregnated carbon ablator
PIR Proposal Implementation Review
PLAR Post Launch Assessment Review
PLL Phase-locked-loop
PMC Program Management Council
PMSR Project Mission System Review
PN Pseudo-noise code
PNAS Proceedings of the U.S. National Academy of Sciences
PPR Photopolarimeter-radiometer
PRM Periapsis Raise Maneuver
Pu Plutonium
PV Photovoltaic
px Pixel
Q Quantity of electrical charge
QAM Quadrature Amplitude Modulation
QPSK Quadrature Phase Shift Keying modulation
R_J Jupiter radius/radii
RADAR RAdio Detection And Ranging
RAT Rock abrasion tool
RCS Reaction control system
RDR Radar
REX Radio Science Experiment
RFA Request for action
RFI Radio frequency interference
RHU Radioisotope heater unit
RNG Range
RPM Revolutions per minute
RPWS Radio & plasma wave science
RS Radio science data type (one of seven in DSN)
RS Reed-Solomon forward error correction
RSS Radio science system
RTG Radioisotope thermoelectric generator
RWA Reaction wheel assembly
S Band of microwave radio frequencies (see Appendix D)
S33 Saturn-tour Command Sequence number 33
SAF Spacecraft assembly facility
SAO Smithsonian Astrophysical Observatory
SAR Synthetic aperture radar
Sb Antimony
SBC Swing-By Calculator
SCET Spacecraft event time
SDC Student Dust Counter
SEP Sun-Earth-Probe (spacecraft) angle
SET Search for Extraterrestrial Intelligence
SHF Super High Frequency
SI International System of Units
Si Silicon
SiO_2 silicon dioxide, silica
SIR System Integration Review
SIRTF *Spitzer Space Infrared Telescope Facility*
SLA Super light-weight ablator
SMSR Safety and Mission Success Review
SN Supernova
SNR Signal-to-Noise Ratio
SO_2 Sulphur dioxide
SOHO Solar and Heliospheric Observatory
SPC Signal Processing Center
SPICE Spacecraft, Planet, Instruments, C-matrix (camera angles), and Events
SRM Solid-propellant rocket motor
SRPS Stirling Radioisotope Power System
SRR System Requirements Review
SRU Stellar reference unit
SSI Solid-state imager
SSME Space Shuttle main engine
STS Space transportation system (space shuttle)
SWAP Solar Wind Analyzer around Pluto
T_c Combustion chamber temperature
TAI International Atomic Time, from the French “Temps Atomique International”
TCM Trajectory-Correction Maneuver
TCP/IP Transmission Control Protocol and Internet Protocol
TDB Barycentric dynamical time (see Glossary)
TDM Time-division multiplex

TDRSS Tracking and Data Relay Satellite System
TDT Terrestrial dynamical time (see Glossary)
TEGA Thermal evolved gas analyzer
TES Thermal emission spectrometer
TLM Telemetry data type (one of seven in DSN)
TNT Trinitrotoluene
TRK Tracking data type (one of seven in DSN)
TRL Technology readiness level
TT Terrestrial time (see Glossary)
TV Television
TVA Thruster-valve assembly
TWNC Two-way non-coherent
TWTA Traveling-wave tube amplifier
UCLA University of California Los Angeles
UHF Ultra High Frequency
UMDH unsymmetrical dimethyl hydrazine
USNO United States Naval Observatory
USO Ultra-Stable Oscillator
UT Universal Time (see Glossary)
UT0 (see Glossary)
UT1 (see Glossary)
UT2 (see Glossary)
UTC "Temps Universel Coordonné", coordinated universal time
UV Ultraviolet
UVIS UV imaging spectrograph
UVS UV Spectrometer
V_{IN} Inbound velocity
V_{JH} Jupiter's heliocentric velocity
V_{OUT} Outbound velocity
V_e Exhaust velocity
V2 German liquid-propellant rocket 1044–1952
VAC Volts AC
VDC Volts DC
VHF Very High Frequency
VIMS Visible and IR mapping spectrometer
VLBI Very long baseline interferometry
WMAP *Wilkinson Microwave Anisotropy Probe*, and the Planck Surveyor
WWW World-wide web
X Band of microwave radio frequencies (see Appendix D)
XTWTA X-band traveling-wave tube amplifier
YAG Yttrium aluminum garnet
Zn Zinc

The Greek Alphabet

Table F.2. The Greek Alphabet

	Uppercase	Lowercase
Alpha	A	α
Beta	B	β
Gamma	$\varGamma$	γ
Delta	$\varDelta$	δ
Epsilon	E	ϵ
Zeta	Z	ζ
Eta	H	η
Theta	$\varTheta$	θ
Iota	I	ι
Kappa	K	κ
Lambda	$\varLambda$	λ
Mu	M	μ
Nu	N	ν
Xi	$\varXi$	ξ
Omicron	O	o
Pi	$\varPi$	π
Rho	P	ρ
Sigma	$\varSigma$	σ
Tau	T	τ
Upsilon	$\varUpsilon$	υ
Phi	$\varPhi$	ϕ
Chi	X	χ
Psi	$\varPsi$	ψ
Omega	$\varOmega$	ω

Glossary

AACS Attitude and Articulation Control Subsystem; hardware and software responsible for estimating and maintaining a spacecraft's specified orientation, stability, and rotation about one or more axes, and for controlling the pointing of scan platforms, solar arrays, or engine nozzles.

AAS American Astronomical Society; the major organization of professional astronomers in North America, established 1899.

AA Tauri Sun-like star about 450 light years away, with disk of protoplanetary gas and dust, probably forming planetary system. *Spitzer Space Telescope*'s infrared spectrograph revealed signatures of organic compounds in the disk.

A Ring In the Saturnian system, the outermost of three broad main rings visible in a small telescope. Particles in the outer part of the A Ring orbit Saturn once every 14.4 hours, at 16.66 kilometers per second.

Absolute zero Point on the Kelvin scale of absolute thermodynamic temperature at which molecular movement is minimum in relation to the rest of the body.

Absorption Spectrum Electromagnetic radiation wavelengths absorbed by atoms or molecules in a gas. Sunlight passing through a planet's or a satellite's atmosphere exhibits a lack of specific wavelengths corresponding to the amount of their absorption in the atmosphere. Compare reflectance spectrum.

Acceleration The rate of change in velocity, magnitude or direction or both. Expressed in SI as meters per second per second (m/s^2).

Accelerometer AACS input device to measure onboard acceleration.

Acceptance testing Procedures that verify a component works to specifications.

Ace Call sign on voice nets for the single point of contact responsible for a project's realtime operations.

Acetylene Organic compound (C_2H_2) found in outer solar system atmospheres and protoplanetary disks.

Active-sensing Category of science instruments that make observations by supplying the energy needed to probe a target and capture the response, e.g., remote-sensing radar, and direct-sensing alpha-proton x-ray spectrometer (APXS). Compare passive-sensing.

Actuator In control theory, a device that applies an appropriate automated control to a system to change its state, for example reaction wheels on a spacecraft, which affect its attitude.

Adaptive optics System on Earth-based telescopes that uses a deformable mirror to remove distortions due to atmospheric turbulence and improve resolution of a target.

Aerobraking Using an atmosphere to reduce a spacecraft's kinetic energy by converting it to heat via atmospheric friction. Applies to entry and descent via heat-shield, and to modification of a non-shielded spacecraft's orbit, for example to reduce apoapsis altitude.

Aerosol A suspension of fine solid particles or liquid droplets in a gas, such as clouds or smog in an atmosphere.

Aerosol Collector and Pyrolizer (ACP) Active direct-sensing science instrument that admits atmospheric samples, captures aerosols in a filter, then heats the filter's contents to change their state to gas, for further analysis by another instrument (such as a gas chromatograph).

Aerozine-50 A mixture of hydrazine and unsymmetrical dimethyl hydrazine, for use as liquid rocket fuel.

AGU American Geophysical Union; a worldwide scientific community that advances understanding of Earth and space.

AIAA American Institute of Aeronautics and Astronautics; established 1963 to advance the state of aerospace science, engineering, and technological leadership.

Air bags Used by Pathfinder and MER, four bags on the landers' exterior, each having six lobes of Vectran-cloth, inflated by gas generators prior to colliding with the rough Martian surface.

Albedo Measurement of the extent to which an object diffusely reflects sunlight. Geometric albedo measures brightness with illumination from directly behind the observer (phase angle zero), such as from Earth. Bond albedo, named for the American astronomer George Bond (1825–1865), takes into account all wavelengths and all phase angles, and can be observed by spacecraft.

Algorithm Defined sequence of instructions for completing a task, in computer programming or mathematics, which when given an initial state, determines an end state.

Allotrope One of various possible forms an element can take, based on the structural arrangement of its atoms, e.g., amorphous if random, crystal if latticed, coal vs. diamond.

Alpha particle Helium nucleus; two protons and two neutrons.

Alpha-particle X-ray Spectrometer (APXS) Active direct-sensing science instrument which emits alpha particles to probe mineral targets at close range.

Alternating current (AC) Electric current whose direction, and polarity on its conductors, reverses cyclicly.

Alternator Device that converts mechanical energy into the energy of alternating electrical current.

Altimeter On spacecraft, an instrument that measures distance to a body's surface using radar.

Altimetry Science data consisting of measurements from an altimeter showing topographic relief on a body.

Alumina Aluminum oxide (Al_2O_3), a compound widely used as an abrasive. Mechanically supports catalyst material within monopropellant hydrazine thrusters.

Aluminized Having metallic aluminum deposited on a surface, as for example the Kapton film layers of multi-layer insulation.

Aluminum Element, symbol Al, atomic number 13; a lightweight metal at room temperature.

Ammeter Device that registers the quantity of electrical current flowing in a circuit.

Ammonia (NH_3) Compound found extensively in nature.

Ammonium perchlorate (NH_4ClO_4) Compound used widely as oxidizer in solid rocket motors.

Amperage Non-standard term for electrical current.

Ampere-hour (Ah) A measure of battery capacity indicating the number of hours it can supply a current of 1 Ampere.

Amplification In electronics, replicating a low-power signal at higher power.

Amplitude modulation (AM) Modifying a radio signal to carry information by varying the amplitude, or height, of its waves.

Analyte A substance being analyzed in an instrument, typically a gas chromatograph or mass spectrometer.

Angle of attack The angle between an airfoil and the oncoming relative wind.

Angular mass Alternate term for "moment of inertia."

Angular momentum Analog of linear momentum for a rotating or revolving mass, a conserved vector quantity:

$$L = r \times p$$

where

L is an object's angular momentum,
r is its position vector with respect to the origin,
$\times$ indicates vector cross product, and
p is the object's linear momentum.

Angular momentum de-saturation Spacecraft maneuver in which reaction wheels are driven to desired RPMs while the vehicle is held steady by thrusters or magnetic torquers.

Angular velocity Speed at which a body rotates about one of its axes, expressed in SI units radians per second.

Anisotropy Property of being directionally dependent. Opposite of isotropy.

Announcement of Opportunity (AO) Message widely publicized offering details of an opportunity to participate in a project or program.

Anode Electrode through which electric current flow into a device. The negative terminal of a battery as it discharges.

Antarctic Opposite polar region from "arctic."

Antenna A device that converts radio waves into electric current for reception, and vice-versa for transmission. Microwave antennas may also include surfaces that reflect and concentrate radio waves.

Antimony Element, symbol Sb, atomic number 51, semi-metallic, solid at room temperature. Constituent in IR detectors as indium antimonide.

Apastron Apoapsis in stellar orbit.

Aperture An opening, such as for collecting light in an instrument; the diameter of such an opening.

Aphelion Apoapsis in solar orbit.

Apoapsis The high point in an elliptical orbit; the point farthest from the center of attraction.

Apoareion Apoapsis in Mars orbit.

Apocenter Apoapsis.

Apocynthion Apoapsis in lunar orbit.

Apocytherion Apoapsis in Venus orbit.

Apogalacticon Apoapsis in galactic orbit.

Apogee Apoapsis in Earth orbit.

Apohadion Apoapsis in Pluto orbit.

Apohermion Apoapsis in Mercury orbit.

Apojove Apoapsis in Jupiter orbit.

Apokrition Apoapsis in Venus orbit.

Apokrone Apoapsis in Saturn orbit.

Apolune Apoapsis in lunar orbit.

Apoposeidion Apoapsis in Neptune orbit.

Aposelene Apoapsis in lunar orbit.

Apouranion Apoapsis in Uranus orbit.

Apozene Apoapsis in Jupiter orbit.

Arcjet Electrothermal means of propulsion that employs a high-current electric spark to produce high temperature in a rocket chamber, and introduces a fluid propellant, e.g., argon or hydrazine, which expands out the nozzle. High I_{SP}, low thrust. Compare resistojet.

Arctic Region on a planet pole-ward of which the Sun does not set during northern-hemisphere summer if applicable. On Earth, the limit of the midnight sun is 66° 33" north latitude.

Ares Vallis Valley on Mars that appears to have been carved by fluids. 3° N × 342.5° E.

Ariane Expendable launch vehicles produced by Arianespace.

Arianespace World's first commercial launch services provider, founded 1980. As of late 2008, has launched 261 payloads for about seventy customers.

Array, DSN antennas Electronic interconnection of multiple DSSs that serves to increase effective receiving aperture, A_e.

Array, solar panels Two or more solar panels linked mechanically and/or electrically.

Arsenic Element, symbol As, atomic number 33. Semi-metallic substance, solid at room temperature. Important as a doping agent for semiconductors, radiation detectors, and photovoltaics.

Assembly Component of a spacecraft or ground system below the level of subsystem and above the level of subassembly.

Hierarchy is: system, subsystem, assembly, subassembly.

Assigned mission Same as directed mission.

Asteroid A minor planet. Remnant of solar system formation, many of which occupy orbits in the main belt between Mars and Jupiter.

Astromast Deployable fiberglass mast that stows for launch in a small canister, and can become a rigid mast up to a dozen meters or so in length. Produced by Astro Aerospace.

Astrometry Branch of astronomy concerned with precisely determining and explaining the positions and movements of stars.

Astronautics Branch of engineering, science, and technology dealing with space flight.

Astronomy Scientific study of celestial objects.

Astrophysics Branch of astronomy dealing with the physics of stars, galaxies, and the universe.

Asymptote A line whose distance to a given curve tends toward zero; a straight line that approaches a curved trajectory arbitrarily closely.

ATLO Assembly, Test, and Launch Operations. Period in mission Phase D transitioning into Phase E during which a spacecraft is built up, tested, and launched.

Atmosphere A planet's gaseous envelope. The depth of Earth's atmosphere out to the ozone layer is about 0.5 percent the planet's radius.

Atmospheric spacecraft One of eight classifications of spacecraft. Designed to enter and characterize the atmosphere of a celestial body.

Atmospheric structure instrument Passive direct-sensing instrument on atmospheric spacecraft that characterizes the atmosphere's temperature, pressure, or other qualities, as a function of altitude.

Attenuation Reduction in strength, as that of a radio signal passing through a ring system or atmosphere under study.

Audio frequency Frequencies in electronic signals or sound in the range of approximately 10 Hz to 25 kHz.

Audion The first electronic amplifier, a triode vacuum tube invented by Lee DeForrest (1873–1961) in 1906.

Automatic repeat-request or Automatic repeat query (ARQ); error-control protocol for data transmission, typically in Earth-based systems where round-trip light time is not a factor. Messages (data packets) are acknowledged as received intact by the recipient, or else rebroadcast after a certain period of finding no such acknowledgment. Compare forward error correction.

Autonomous navigation Spacecraft hardware and software subsystem that provides the on-board capability to estimate the vehicle's location and path in space, and to execute trajectory corrections automatically to achieve the desired trajectory. Depends upon having a minimum number of natural bodies of known ephemeris within observing range against the background stars, such as exist within the main asteroid belt.

Autumnal equinox Annual equinox (on Earth in the month of September) the beginning of northern-hemisphere autumn. At equinox, the Sun is at a point on the celestial sphere where the celestial equator and ecliptic intersect, and the Sun's center spends nearly equal time above and below the horizon at every location on the planet. Compare vernal (March) equinox.

Azimuth Measurement of the angle on a reference plane, such as the local horizon, of a point along the arc from true north clockwise. Degree of freedom perpendicular to elevation, e.g., on a spacecraft scan platform or DSN antenna drive. Measured in degrees of arc. Compare elevation. Also see Az-el.

Az-el Azimuth-elevation; axes of rotation based on the local horizon and the vertical. Rotation in azimuth varies between north, south, east and west, and rotation in elevation varies between horizon and zenith. Measured in degrees of arc. Compare RA-dec.

B Ring In the Saturnian system, the middle of three main rings visible in a small telescope. Particles in the outer part of the B Ring orbit Saturn once every 5.76 hours, at 17.97 kilometers per second.

Backscatter Light or other electromagnetic wavelengths reflected back toward the observer at low phase angle, such as ambient light from a page in a book.

Bandwidth In signal processing, the number of Hz in a specific range of frequencies, such as at a radio receiver's input. In computing, a rate of data transfer capability.

Barycenter A point about which two massive bodies orbit, e.g., the Sun and Jupiter orbit a barycenter just outside the Sun's photosphere.

Barycentric Coordinate Time (TCB) Defined in 1991 with TT. A time reference based on assumptions not influenced by relativistic time dilation caused by mass in the solar system. TCB therefore ticks faster than a clock on the moving Earth by about 490 milliseconds per year.

Barycentric Dynamical Time (TDB) Depreciated. For ephemerides, TDB is based on the solar system barycenter. Values are within milliseconds of TDT.

Baseline The distance between two optical or radio telescopes that are undertaking an interferometric observation such as a ΔDOR or VLBI.

Battery Grouping of similar objects. In electrical systems, a number of electrochemical cells connected in series and/or parallel to provide primary or secondary source of electrical power.

Bay Equipment rack or cabinet.

Beacon-mode Communications mode based on semaphores represented by the presence or absence of specific subcarriers in a spacecraft's downlink. Small antennas can observe semaphores in comparison with the large apertures required for capturing enough signal power to decode telemetry.

Beryllium Element, symbol Be, atomic number 4, metallic, solid at room temperature, toxic. A lightweight, strong metal used in applications as diverse as optical mirrors (e.g., *Spitzer*, JWST), rocket engine nozzles (e.g., Saturn V), and particle detectors (e.g., Large Hadron Collider).

Best-lock frequency (BLF) "Rest" or "center" frequency that a closed-loop radio receiver, such as that on a spacecraft, naturally returns to after the signal it was tracking ceases. The *Voyager 2* spacecraft lost its ability to track a varying radio signal from Earth shortly after launch, so all uplink to it must be stepped in frequency such that it arrives Doppler-shifted to within a few Hz of its BLF.

Bias A pre-existing, deliberately set condition, such as rotation rate of reaction wheels, or the voltage or current in an electronic circuit.

Big bang The expansive event considered in cosmology at the beginning of spacetime, and evidenced by fossil cosmic background microwave radiation, and the recession of galaxies.

Bimetallic strip A device made with two metals having dissimilar thermal-expansion coefficients, to obtain mechanical motion from temperature changes. Spacecraft thermal-control louvers and residential thermostats are typically driven by bimetallic strips.

Binary Phase Shift Keying (BPSK) radio signal modulation by temporarily advancing or retarding the phase of the carrier wave by a specific angular distance. Illustration p 29.

Biprop engine Bipropellant rocket engine that is fed two different liquid chemicals, a fuel and an oxidizer, to burn and produce thrust.

Biprop thruster Small biprop engine.

Bistatic radio science Observation of radio energy directed from a spacecraft to a natural body surface in such a way that a reflection can be received on Earth and analyzed to help characterize the surface.

Bit Contraction of the words "binary digit." Represents the numeric value 1 or 0.

Black hole Object of immense density and mass whose escape velocity exceeds the speed of light. Observed to exist at galactic centers.

Black powder See gunpowder.

Block-V Receiver (BVR) (Roman numeral five) A highly-evolved software-based microwave radio receiver used by DSN to find, capture, and track a spacecraft's signal, separate subcarriers, and measure Doppler shift.

Blooming In a CCD, the overflow of charge (and image brightness) onto adjacent pixel photo-gates due to overexposure.

Blowdown Mode of operating a spacecraft's propulsion subsystem in which the pressurant gas is not pressure-regulated, but decreases as propellant is used from the tank. Compare pressure-regulated.

Blueberries Small spheroids of hematite revealed on the surface of Mars in Meridiani Planum by the Mars Exploration Rover *Opportunity* in 2004.

Bow shock The boundary between a magnetosphere and the surrounding medium through which it moves. Planets with magnetic fields have bow shocks in the solar wind, and the Sun has a bow shock where the heliopause interfaces with the interstellar medium. Illustration p 337.

B plane Target plane perpendicular to asymptote of the incoming hyperbolic path that passes through target body center. Illustration p 73.

Broadcast Open-loop transmission in virtually all directions to all available receivers.

Bus, electrical Main electrical power distribution circuit.

Bus, serial data Network connecting several peripherals among subsystems and assemblies on a spacecraft, over the same set of wires, typically a single pair of conductors.

Bus, spacecraft A spacecraft's core mechanical housing including all the vehicle's subsystems mounted within or attached to it. Its purpose is to support a payload of scientific instruments reliably with everything they need.

Bus interface unit Electronic communications device that connects a spacecraft subsystem or assembly to the serial data bus, to exchange data with other subsystems or assemblies.

C Ring In the Saturnian system, the innermost of three main rings visible in a small telescope. Particles in the outer part of the C Ring orbit Saturn once every 7.92 hours, at 20.31 kilometers per second.

Cable A wire or bundle of wires. For radio frequency signals, the cable is often a pair of conductors in coaxial arrangement, that is, a single central conductor surrounded in precise circular cross-section by a cylindrical outer conductor.

Cadmium Element, symbol Cd, atomic number 48, metallic, solid at room temperature. Toxic. Used in rechargeable batteries.

Calcium Element, symbol Ca, atomic number 20. Hard metal at room temperature, fairly reactive.

Calibration Operation of an instrument under known conditions with known input, to record data for use in measuring errors inherent to a measuring device, and comparing results obtained when the instrument observes a target.

Calibration curves Equations for converting telemetry values from data numbers, for example 0–255, to their corresponding meaningful readings in engineering units, for example 0-50 volts, based on sensor design and preflight testing.

Callisto Outermost of the four Galilean moons of Jupiter, diameter 5,262.4 kilometers. May have a subsurface water ocean between ice layers.

Call sign Moniker used by a person participating in voice-net or radiotelephone communications. A call sign identifies the job function, rather than the name, of each participant. For example, "Prop" for a propulsion engineer, "Nav" for a navigator, "Telecom" for a telecommunications analyst.

Camera Imaging science instrument whose optical assembly focuses an image onto an image detector for readout and eventual transmission to Earth via telemetry.

Canberra DSCC One of three worldwide Deep Space Communications Complexes in DSN. Near 35°34' S latitude × 148°59' E longitude.

Canopus Supergiant star α Carinae, spectral type F, the second brightest after Sirius, visible from southern latitudes, 350 light years distant.

Capacitor Discrete electronic component that stores energy in the electric field between a pair of conductor plates separated by a dielectric. Also known as *condenser.* Capacity typically measured in micro-farads, μF, or picofarads, pF.

Cape Canaveral Air Force Station; Detachment of U.S. 45th Space Wing at Patrick Air Force Base in Florida. Eastern rocket launch facility. All non-shuttle launches on U.S. east coast are conducted here. Adjacent southeast of NASA Kennedy Space Center, whose Launch Complex 39, with Vehicle Assembly Building, served Apollo and now serves Space Shuttle.

Carbon Element, symbol C, atomic number 6. Found naturally in many allotropes, including amorphous, diamond, graphite, and fullerenes in the form of buckyballs, tubes, fiber, etc.

Carbon dioxide (CO_2) Major constituent of the atmospheres of Venus and Mars. Increasing constituent, unfortunately, in Earth's, as of the twentieth and twenty-first centuries.

Carbonaceous (C-type) Asteroids, mostly in the outer part of the main belt. About 75 percent of the minor planets are this type. Compositions include silicates, oxides, sulfides. Source of carbonaceous chondrite meteorites.

Carbon-carbon Graphite fiber embedded in a carbon matrix. Strong material that can withstand exhaust-nozzle temperature and pressure. Also called 3-D carbon-carbon.

Carbon-fiber epoxy or plastic; strong, low-mass material with many applications in aerospace and elsewhere. Compare fiberglass.

Carrier Unmodulated radio signal from a transmitter. Used for Doppler shift measurement, radio science experiments. Can be modulated to carry telemetry, command, ranging tones, semaphores, etc. either directly or on subcarriers.

Carrier suppression Reduction in the power in a carrier signal along with an increase of power in its modulation.

Cassegrain Optical and radio telescope design comprising parabolic main reflector and a smaller subreflector, which fold a long focal length into a compact structure.

Cassini Division In the Saturnian system, the gap between the outer edge of the B Ring and the inner edge of the A Ring. Clearly visible in a small telescope. Particles in the middle of the Cassini Division orbit Saturn once every 11.76 hours, at 17.8 kilometers per second.

Cassini spacecraft NASA-ESA-ASI Orbiter launched October 15, 1997, entered Saturn orbit July 1, 2004, deployed ESA *Huygens* Probe toward Titan December 25, 2004. Named for Italian-French astronomer Giovanni Domenico (Jean-Dominique) Cassini (1625–1712) who discovered the division between Saturn's A Ring and B Ring.

Cassiopeia A Supernova remnant, strongest interstellar radio source in the sky, about 11,000 LY distant.

Catalyst Substance that accelerates a chemical reaction without being consumed. Hydrazine thrusters use iridium, automotive catalytic converters use platinum and rhodium.

Cathode Electrode through which electric current flows out of a device.

Cathode ray Stream of electrons emitted from a heated cathode in a vacuum tube. Thermionic emission.

Cavity resonator Hollow space inside a device where electromagnetic waves (typically microwave) of specific frequencies are generated or selected. Compare with acoustic wave generation, at desired frequency, in a flute.

Celestial equator Great circle on the imaginary celestial sphere, in Earth's equatorial plane, a projection of the equator out into space. Inclined about 23.5° to ecliptic.

Celestial mechanics See radio science celestial mechanics experiment.

Celestial reference AACS input from Sun sensors, horizon sensors, star trackers, stellar reference units, etc. Compare inertial reference.

Centaur Launch vehicle high-energy upper stage powered by two Pratt and Whitney RL10 engines burning liquid H_2 and liquid O_2, with an I_{SP} of up to 449 s and 146 kN thrust.

Ceramic cloth Fabric made of woven fibers of ceramic material such as Nextel®, a proprietary material made by 3M. Offers resistance to high temperature and particle impact.

Ceres Asteroid (minor planet) about 950 kilometers in diameter. One of five dwarf planets in solar system (count as of 2008) and largest, most massive asteroid in main asteroid belt. One of the targets intended for the *Dawn* spacecraft to orbit in 2015. Compare Vesta.

Chandler wobble Motion of the Earth's rotational axis. Pictured as a point on the arctic/antarctic surface, the pole's location would be seen to move about 15 meters with a period of about 433 days. Illustration p 61.

Chandra X-ray Observatory One of the four NASA Great Observatories. Sensitive to X-ray sources 100 times fainter than previous X-ray telescopes.

Characteristic Energy (C_3) Intensive quantity used in planning interplanetary flights, which gives twice the energy per unit mass required to set off on a particular trajectory, departing a planet's gravitational bond, for a trip to a specific destination. Also called escape energy.

Charge-coupled device (CCD) Image detector, array of isolated silicon capacitors called photogates or wells, each forming one pixel of an image. Charge on every photogate is read out by operating each line of photogates as a shift register.

Charge transfer efficiency The efficiency with which a CCD transfers photogates' electronic charges during readout.

Chemical rocket Rocket engine fed by solid or liquid propellant whose chemical combination or decomposition provides energy for thrust. Compare electric propulsion.

Chemical thermodynamics Branch of science that addresses the interrelation of heat and work with chemical reactions, or with a physical change of state.

Chemistry Branch of science that addresses the composition, structure, and properties of matter, and the changes it undergoes during chemical reactions.

Chlorine Element, symbol Cl, atomic number 17. One of the five halogens.

Choked flow Flow of exhaust gas from rocket combustion chamber into converging throat where its velocity reaches Mach 1 at the narrowest point before diverging and further expanding.

Circuit breaker Electrical device that protects from excessive current by opening the circuit.

Circularize To change an elliptical orbit into a circular orbit, e.g., by reducing the apoapsis altitude through aerobraking during repeated periapsis passages, or by propulsive means, either at apoapsis to raise periapsis, or at periapsis to lower apoapsis altitude.

Class-1 Cleanroom specification in which there is fewer than one airborne particle of size $\geq 0.5\ \mu$ present per cubic foot ($\approx$0.03 m^3). Compare to the millions of particles per ft^3 in an office environment.

Class-100 Cleanroom specification in which there are fewer than one hundred airborne particles of size $\geq 0.5\ \mu$ present per cubic foot ($\approx$0.03 m^3).

Classical mechanics Applications of physics that do not take into account the effects of special or general relativity.

Clean-up TCM Statistical propulsive spacecraft trajectory correction maneuver. Reduces trajectory errors induced during a flyby. May be subject to cancellation depending on magnitude of the errors seen.

Cleanroom An enclosed workspace that has a controlled level of airborne contaminants such as dust, microbes, and aerosol particles.

Clementine Engineering demonstration spacecraft, a joint project of U.S. Ballistic Missile Defense Organization and NASA, Launched in 1994 to test miniature sensors and advanced spacecraft components in flight. In addition to testing, *Clementine* mapped the Moon at various wavelengths in the visible, UV, and IR, obtained laser-ranging altimetry, gravimetry, and charged particle measurements.

Closed loop in control theory, system in which a sensor monitors the system's output, compares it to a desired state, and issues a feedback control signal to adjust the system's performance.

Closed loop radio receiver locks onto the phase of the incoming signal via a phase-locked-loop control system, and tracks the incoming signal as it changes frequency. Useful for extracting telemetry, command, range, and Doppler-shift data.

Cobalt Element, symbol Co, atomic number 27. Metallic, solid at room temperature. The artificially produced isotope ^{57}Co serves as a gamma-ray source in Mössbauer spectrometers.

COBE Cosmic Background Explorer; NASA spacecraft developed and flown by Goddard Space Flight Center to measure diffuse infrared and microwave radiation from the early universe. Launched 1989, operated for four years.

Columbium Element. See niobium.

Comet Halley Periodic comet 1P/Halley, also called Halley's Comet after English polymath Edmond Halley (1656–1742) who predicted its 1758 return. Can be seen from Earth every seventy-five or seventy-six years.

Command data One of the seven DSN data types. Using modulation similar to telemetry, command data sent to a spacecraft can serve the purpose of directing an activity upon receipt, a sequence of time-tagged activities over a period of weeks or months, or software for onboard computers.

Command sequence Set of time-tagged commands, typically numbering in the thousands, uplinked to a spacecraft to direct its activities for a period of weeks or months.

Command-loss timer (CLT) Fault-protection routine, a watchdog timer, which resets to a nominal value every time the spacecraft receives and parses any command. If the timer reaches zero and no command has been received, it will pass control to algorithms that begin to take actions such as to reconfigure the telecommunications subsystem in the assumption that a receiving component on the spacecraft may have failed.

Communications and Navigation One of eight classifications of spacecraft. Designed to relay data among users on the surface, or between surface of a distant planet and Earth. Many examples in Earth orbit. No current examples of dedicated spacecraft of this classification in interplanetary use.

Commutation map In a time-division multiplex system, a map that determines the order of measurements to send via telemetry.

Commutator, data Electronic device for transmitting data across a rotating gap, such as to a de-spun section from a spun section of the spacecraft.

Commutator, power Device, such as a system of brushes, which provides electrical conductivity for power transmission across a rotating gap, such as to a despun section from a spun section of the spacecraft.

Competed Mission Mission offered to the scientific community in an announcement of opportunity (AO) and selected for development and flight from among proposals received. Compare directed mission.

Complemented data Binary data in which all the 1's are changed into 0's and vice-versa. Also called inverted data.

Compression, data Reduction in the number of bits needing to be transmitted, by algorithms which lose no data, or by ones which impose acceptable loss.

Compton Gamma Ray Observatory One of the four NASA Great Observatories. Sensitive to gamma-rays in the range 20 kev to 30 GeV from astronomical sources. Launched April 1991, operated in low Earth orbit until June 2000, conducting all-sky survey and observing individual gamma ray sources including gamma-ray bursts. Named in honor of American physicist Arthur Holly Compton (1892–1962).

Conductive Heat Transfer Transfer of thermal energy from one molecule to another within or between systems without involving material flow.

Conductor Material through which electric current or thermal energy can flow with ease.

Continuous Spectrum Range of wavelengths without gaps, e.g., the unbroken series of visible wavelengths produced by a piece of metal heated to incandescence within a light bulb.

Control theory Branch of engineering and mathematics that deals with the behavior of dynamical systems.

Control-moment gyro (CMG) Spinning-mass device, also called gyrodyne, sometimes called momentum wheel, whose rotor is on the order of 100 kilogram mass, kept at a constant speed by electric motors. The gyroscopic properties of rigidity in space and precession are used to apply torque to the whole spacecraft by rotating the spin axis of a CMG. Used on space stations, not on interplanetary spacecraft. Compare reaction wheels.

Convection Transfer of thermal energy in a combination of conduction and fluid movement.

Convergent-divergent nozzle Rocket engine or thruster nozzle, e.g., De Laval nozzle, in which exhaust gas flows from combustion chamber through a narrowing throat and into a widening bell.

Convolutional coding Forward error correction coding scheme used on spacecraft in creating radio-link symbols, e.g., phase modulations, in response to a pattern of data bits. Viterbi decoding applied upon receipt to regenerate bits.

Cool neutron Neutral nuclear particle having relatively low velocity, e.g., from recent collision with a proton, which has similar mass.

Copper Element, symbol Cu, atomic number 29. Metallic, solid at room temperature. Used in electrical wire. Served as comet-impacting mass for the *Deep Impact* spacecraft.

Coriolis effect A pseudo-force; the apparent deflection of moving objects when they are viewed from a rotating frame of reference, e.g., air masses moving south on the rotating Earth are deflected west, resulting in their rotation.

Coronal mass ejection Eruption of material from the solar corona, at up to 2,700 kilometers per second, consisting of up to 10^{13} kg of plasma (protons and electrons, and other ionized matter such as helium, oxygen, and iron).

Correlator Computer program used in VLBI observations. It analyzes random waves of noise from a quasar, and of pseudo-noise from a spacecraft, received by two DSN stations located on separate continents. It then matches up the wavefronts, i.e. correlates them, and based on the times of each wavefront's arrival, it establishes a precise value for the right ascension and declination of each of the observed objects: quasar and the spacecraft.

Cosmic microwave background (CMB) Fossil radiation pervading the universe with a thermal black body spectrum at 2.725 K with a peak in the microwave frequency 160.2 GHz.

Cosmic ray A high-velocity particle, such as an atomic nucleus. Origin can be solar, or an energetic event such as a supernova within our galaxy, or from a distant galaxy.

Cosmology Theoretical astrophysics at scales larger than individually gravitationally-bound objects in the cosmos.

Critical Commands Sequence of commands stored onboard a spacecraft that operate in critical mode, taking precedence over certain levels of autonomous fault protection. An example is a sequence that controls spacecraft activities during a launch, a landing, or a planetary orbit insertion.

Critical Design Review (CDR) A formal review in which project personnel make presentations to a review board of e.g., NASA experts. The gate a flight project must pass through prior to being given the go-ahead to proceed with Phase D, system assembly, test and launch.

Critical mode Spacecraft CTS mode under which a critical command sequence runs.

Cryogenics Branch of physics concerned with very low temperatures.

Crosslink Communications link between two spacecraft in flight. See Relay.

CTS Command and telemetry subsystem; A spacecraft's computer that stores commands received via the telecommunications subsystem, executes them at their scheduled times or sends them to instruments or other subsystems for execution. It collects, processes, and stores telemetry data for downlink. Named variously on different spacecraft, e.g., command and data subsystem, command and data handling subsystem, etc.

Curium Element, symbol Cm, atomic number 96. Metallic, solid at room temperature. Radioactive element, manufactured via nuclear reactor. Incorporated in alpha-proton x-ray spectrometers as the alpha-particle emitter.

Cycle durability Number of discharge–charge cycles a rechargeable battery can be expected to endure.

D Ring In the Saturnian system, the band of narrow ringlets just inside the C Ring. Particles in the inner part of the D Ring orbit Saturn once every 4.8 hours, at 23.81 kilometers per second. Not visible in a small telescope.

Daily fireing window See launch window.

Data A body of facts, information. Plural of datum, which is a single piece of information. Numbers input to, output from, or operated on by a computer program.

Data management Task of ensuring best available data set is available to users. Includes recovering data that is recoverable, and accounting for unrecoverable data losses.

Data number (DN) Telemetry value, typically between 0 and 255, returned from a transducer, e.g., pressure sensor. Compare engineering unit.

Dawn Ion-engine propelled NASA spacecraft launched September 27, 2007 to enter into orbit around asteroid Vesta and the dwarf planet Ceres, both in the main asteroid belt. *Dawn* is scheduled to explore Vesta between 2011 and 2012, and Ceres in 2015.

De Laval nozzle Convergent-divergent design essential to rocket engines. Consists of a tube that is roughly hourglass shaped, causing gas to achieve supersonic speed at high pressure.

De-spin On a spin-stabilized spacecraft, rotating a platform continuously in the opposite direction of its attitude-stabilizing spin, to use as a stable platform for pointing antennas or optical instruments.

Dead band In a closed-loop control system, a range of system states in which no control action is taken. In thruster-controlled attitude, the time between thruster firings that keep the spacecraft rocking from limit to limit.

Decalibration Transformation of telemetry from data numbers to engineering units.

Deceleration Acceleration in a negative direction.

Declination One of a pair of coordinates in the celestial sphere. Angular distance north or south of the celestial equator. measured in degrees of arc. Compare right ascension. Also see RA-dec.

Decoder Hardware or software that operates on a data stream to effect error correction or parse other coding, producing data identical to its value prior to coding.

Decom map De-commutation map; an algorithm that matches time-division-multiplex downlink telemetry data with its users, e.g., image data to image science team, temperature data to thermal engineers, etc.

Deep Impact NASA spacecraft launched January 12, 2005, to study the composition of the interior of Comet 9P/Tempel by releasing a self-guided projectile spacecraft that impacted the comet on July 4, 2005,

Deep space Realm of interplanetary spacecraft, at lunar distances and beyond.

Deep Space 1 Engineering demonstration spacecraft in the NASA New Millennium Program, launched 1998 and tested eight new technologies, then encountered asteroid Braille in 1999 and Comet Borrelly in 2001.

Deep space maneuver (DSM) Deterministic propulsive spacecraft maneuver that imparts a relatively large ΔV in order to set up for a particular gravity assist flyby during interplanetary cruise that would not be possible to reach otherwise.

Deep space network (DSN) NASA's network, managed by JPL, of deep space stations located at three complexes worldwide: Goldstone, U.S.A.; Madrid, Spain; and Canberra Australia.

Deep space station (DSS) One of the 34–meter or 70–meter diameter radio telescope antennas of the Deep Space Network.

ΔV (Delta-V) Change in velocity, such as via propulsive event or gravity-assist.

Demodulation Process of detecting information that has been imposed onto a carrier signal.

Deterministic maneuver A trajectory correction or orbit trim maneuver that must be performed as part of the original trajectory design. Compare statistical maneuver.

DOR Differenced One-way Range; a DSN VLBI navigation technique that makes radiometric observations of a spacecraft independent of the usual Doppler and range (tracking data type) observables.

Δ DOR Delta Differenced One-way Range; a DSN VLBI navigation technique that makes radiometric observations of a spacecraft and one or more quasars to achieve very accurate right ascension and declination measurement independent of tracking data type observables.

Diffraction Various phenomena that occur when a wave hits an obstacle, such as apparently bending around a small obstacle or spreading out when passing through a small opening.

Diffraction Grating In spectrometers, the wavelength-dispersing element. Slots or scores in a flat plate, arranged in a regular pattern spaced apart on the order of wavelengths of light, produce reflections whose phases variously interfere so the resulting wavelengths vary with viewing angle. Compare with reflections off a compact disk, CD or DVD.

Digit A symbol expressing a numeric value. In the base-10 system, digits range from 0 through 9. In binary (base-2), they range from 0 to 1.

Digitize To represent a continuously variable quantity or phenomenon in samples consisting of discrete numeric digits.

Diode An electronic semiconductor component having two electrodes, e.g., a rectifier with positive and negative terminals.

Direct current (DC) Electric current whose direction, and polarity on its conductors, remains constant.

Direct-sensing Category of science instruments that make observations while admitting, or being immersed in, the phenomenon that they measure, e.g., dust detector, magnetometer. Compare remote-sensing.

Directed mission A mission assigned to an organization by an agency based upon desires of the scientific community, e.g., *Galileo*, *Cassini*. Compare competed mission.

Diurnal Occurring daily.

Doped Having impurities introduced into an otherwise pure material to influence its properties or performance, e.g., Neodymium-doped yttrium aluminum garnet (Nd:YAG) near-IR laser.

Doppler residuals Navigation data comprising the observed Doppler shift in a spacecraft's coherent downlink after accounting for all known motions such as Earth's rotation and revolution, and the spacecraft's nominal orbit.

Doppler shift Change in received frequency due to relative motion between source and receiver.

Downlink Radio communications received from a spacecraft.

DSN Pass Space-link session. Tracking period during which a spacecraft passes across the sky.

Dual-mode propulsion system Spacecraft propulsion system designed to use hypergolic bi-propellants together, e.g., for TCMs, and the hypergolic fuel alone in catalyst-based thrusters, e.g., for attitude control.

Dust Particles of matter ranging in size from a few molecules to about 0.1 millimeter. Can be distinguished by location; circumplanetary (e.g., in ring systems), circumstellar (interplanetary), interstellar (e.g., in nebulae), and intergalactic.

Dust analyzer Direct-sensing science instrument on spacecraft capable of measuring the incidence of dust impacts, and characterizing properties of the incident dust, e.g., mass, direction of flight, velocity, chemical composition, electric charge.

Dust detector Direct-sensing science instrument on spacecraft capable of counting dust impacts.

Dwarf planet A celestial body in solar orbit that is massive enough to be rounded by its own gravity (in hydrostatic equilibrium) but which has not cleared its neighboring region of planetesimals and is not a satellite. Defined 2006 by International Astronomical Union; five identified in solar system as of press time.

E Ring The outermost ring in the Saturnian system; a sparse collection of fine ice particles that issue from geysers on Saturn's moon Enceladus. Particles in the middle part of the E Ring orbit Saturn once every 32.88 hours, at 12.63 kilometers per second. Not visible in a small telescope.

Earth Third planet from the Sun, one of the four terrestrial planets. Equatorial diameter 12,756.2 kilometers. Dense N_2/O_2 atmosphere with variable H_2O cloud cover, liquid saltwater oceans, water-ice polar caps. The only known habitat for life as of late 2008. Mean distance from Sun 1 AU = 14.960×10^7 km.

Echo A 180-kilogram passive communications test and geodetic satellite balloon placed in Earth orbit in 1960. Used to test communications by bouncing radio signals off its reflective surface, and to measure the shape of the Earth to a new level of precision.

Eclipse Passage into the shadow of a solar system body.

Ecliptic Plane in Earth's sky in which the Sun appears to remain during the year, and in which eclipses of the Moon occur.

EDAC Error-detection and correction; process of detecting errors in a data stream and reconstructing the original data. Interplanetary spacecraft use forward error correction (FEC) schemes, which add additional bits to the data instead of depending on Automatic repeat-request, which requires a short round-trip light time.

Edison effect Thermionic emission; cathode ray.

Elastic collision Exchange of momentum experienced by bodies passing one another at close range, interacting via gravitation rather than physical collision. Total kinetic energy of the colliding bodies remains the same after as before the interaction.

Electric propulsion Use of electric or magnetic fields to accelerate mass in a thruster or rocket engine, rather than chemical means. Capable of high I_{SP} but low thrust.

Electro-explosive device Pyrotechnic device to operate a single-use component e.g., propulsion-subsystem valve, parachute mortar, or exploding bolt.

Electrolyte Substance containing free ions that conducts electricity, e.g., in an electrical battery.

Electromagnetic wave Wave — e.g., light, radio, etc. — comprising an electric field that rises and collapses, which in turn creates a magnetic wave, which rises and collapses, producing an electric wave, and so propagating itself forever without any medium but spacetime.

Electromagnetic spectrum All possible electromagnetic radiation frequencies, (or wavelengths, or energies). See Appendix D, p 342.

Electron Low-mass subatomic particle with negative electric charge. When an atom is deprived of an electron (or gains an extra one) it is said to be ionized. Electrons are essential for chemical bonds, and for electricity and magnetism.

Electrostatic propulsion Thrust produced by accelerating ions with an electrically charged grid.

Electrothermal propulsion Thrust produced by heating a gas with an electric arc.

Elevation Degree of freedom perpendicular to azimuth, e.g., in a DSN antenna drive or spacecraft scan platform. Also see az-el.

Ellipse Conic section, the locus of points in a plane such that the sum of the distances to two fixed foci is constant. The shape of any orbit. Note that a circle is an ellipse whose eccentricity is zero.

Emission spectrum Wavelengths at various intensities produced by an excited gas. Each element's atomic emission spectrum is unique and can be used to detect the element in an unknown compound.

Emissivity Ratio of energy a particular material radiates to energy radiated by a (fictitious) black body at the same temperature. A measure of a material's ability to radiate energy it has absorbed, expressed numerically between 0 and 1.

Enceladus Icy moon of Saturn, 500 kilometers in diameter, the surface of which exhibits a range of ages, from old and heavily cratered to present-day geologic activity. It orbits within the densest part of Saturn's E Ring, which is created by geysers of water ice and other compounds from its south polar region.

Encoder, data Hardware or software that modifies a data stream for some purpose, e.g., forward error correction, on a spacecraft. Most interplanetary spacecraft encode data using Reed-Solomon, Golay, turbo, and/or convolutional encoding.

Encounter Spacecraft's close approach to a solar system body during which it makes observations to be telemetered to Earth, and/or carries out radio science experiments.

Endothermic A chemical reaction that requires thermal energy to be supplied. Compare Exothermic.

Energetic neutral atom camera
Passive remote-sensing science instrument capable of creating images of magnetospheres, e.g., in *Cassini*'s magnetospheric imaging instrument, MIMI.

Energetic neutral atom (ENA)
Fast-moving atom. In a magnetosphere, ions and electrons are trapped by magnetic field lines, which they move about or along. When an ion collides in the

right way with one or more electrons needed to neutralize the atom, it becomes free of the magnetic field and flies away.

Energy Scalar physical quantity that is a property of objects and systems, which is by nature conserved. Often defined as the ability to do work. Equivalent to mass as in $E=mc^2$.

Energy density Amount of energy stored per unit mass, e.g., electrical energy in a battery.

Engine gimbal actuator AACS output device that aims a rocket engine or nozzle while it is operating, to align its thrust vector along the spacecraft's center of mass.

Engineering data Telemetry that details a spacecraft's state and condition, such as temperatures, pressures, computer states, propellant quantities, voltages, currents, and switch positions.

Engineering demonstration spacecraft One of eight classifications of spacecraft. Designed to test new technologies in flight and advance their technology readiness level (TRL) for subsequent use on scientific spacecraft.

Engineering unit (EU) Unit of measure such as volt, ampere, newton, degree Celsius, etc., which are output from the process of decalibration from data numbers in telemetry.

Enthalpy Description of a system's thermodynamic potential, e.g., amount of thermal energy released in a specific exothermic chemical reaction.

Ephemeris (plural ephemerides) Numeric representation of the positions of astronomical objects at any given time.

Ephemeris Time (ET) Obsolete, replaced in 1984 by TDT and TBT.

Epoch In astronomy, a precise moment in time for which celestial coordinates or orbital elements are specified by international agreement.

Equator and equinox J2000.0 Coordinate system basis (mean equator and equinox) and epoch (J2000.0, which is 12:00 TT January 1 of the Julian year 2000). The coordinate system is used for expressing positions of objects as solar system ephemerides. Oriented with its xy-plane parallel to the mean Earth equator at the given epoch (J2000.0), and its z-axis pointing toward the mean north celestial pole of that epoch. The x-axis points toward the mean equinox of the epoch.

Equinox See vernal or autumnal equinox.

Escape energy See characteristic energy.

Eris Dwarf planet, about 2,600 km in diameter, orbiting the Sun in the Kuiper belt. Has a moon named Dysnomia.

Ethane Hydrocarbon (C_2H_6), liquid in lakes on the surface of Saturn's moon Titan and a component of natural gas, with methane, on Earth. Melting point –182.76 °C, 90.34 K, boils at –88.6°C, 184.5 K.

Euler angle Notation that gives the rotation of one spatial frame with respect to another. Illustration p 95.

Europa One of the four Galilean moons of Jupiter, second out from the planet, diameter 3,121.6 kilometers. Most likely has a warm saltwater ocean beneath a relatively thin icy shell and above a layer of rock.

Exciter Part of the DSN Block-V receiver that builds a carrier signal based on a highly stable hydrogen maser frequency reference, adds modulation for any required subcarriers such as for range (tracking data) or command data, and then delivers it to the input of a high power amplifier (klystron).

Exoplanet Extra-solar planet.

Exothermic Chemical reaction that releases heat. Compare Endothermic.

Exploding bolt A hollow metal bolt that contains an explosive charge strong enough to break its walls, which are typically thinnest where the break is desired.

Extra-solar planet Body orbiting a star other than the Sun.

F Ring In the Saturnian system, the narrow ring just outside the broad A Ring. Particles in the outer part of the F Ring orbit Saturn once every 14.88 hours, at

16.45 kilometers per second. Not visible in a small telescope.

Fail-safe Spacecraft component or trajectory design which, if it were to fail, will fail in a safe manner, i.e. without catastrophic result.

Fairing Aerodynamic capsule that protects a spacecraft atop its launch vehicle while in the dense parts of Earth's atmosphere.

Fault-protection monitor Spacecraft software routine that periodically checks a specific condition or conditions to determine whether a fault exists.

Fault-protection response Prescribed action to be taken autonomously by spacecraft subsystem or main computer, e.g., CTS, to mitigate a fault that has been detected.

Feed horn Conical waveguide that interfaces with antenna reflectors.

Fiber optics Technology of transmitting and receiving signals via modulated light through optical fibers, which due to total internal reflection, act as waveguides. Fiber optic communication has largely replaced copper wire in major networks.

Field effect transistor (FET) Solid-state amplifier discrete component. An electric *field* at the gate terminal controls the flow of electric current through a channel between the source terminal and the drain terminal. Compare with transistors that operate based on a small *current* to control the output current.

Figure of merit A quantity that characterizes the performance of a device or system relative to other similar ones.

Flight readiness review (FRR) Formal examination of a spacecraft's readiness for flight, in a meeting held shortly before the launch period opens.

Flight software (FSW) Software for the computers on a spacecraft in flight.

Flight system Spacecraft.

Fluorine Element, symbol F, atomic number 9, the most highly reactive of all elements. One of the five halogens.

Flux-gate Technology in which a magnetometer uses alternating electric currents in coils of wire to continuously magnetize, de-magnetize, and re-magnetize a susceptible core. The amount of current needed to change the core's state of magnetization varies when it is in an ambient magnetic field, and can serve as an indicator of the field.

Flyby Spacecraft One of eight classifications of spacecraft. Designed for long cruise period and brief, passing encounters.

Focal ratio An optical instrument's focal length divided by its effective aperture. Expressed "$f/\#$" where # is the ratio. Also called "f-number" or "f-ratio."

Focus Point in an optical instrument where gathered light rays converge.

Force Influence which, when applied to a free mass, causes it to accelerate. Expressed as a vector quantity.

Forward Error Correction (FEC) System of error control that adds redundant bits to a data stream prior to transmission, e.g., convolutional coding, Reed-Solomon coding. Compare with automatic repeat-query (ARQ).

Forward scatter Light scattering at high illumination phase angle, by particles whose dimensions approach the wavelength of light, into the hemisphere of space bounded by a plane normal to the direction of the incident radiation.

Fossil radiation Radiation left over from the "Big Bang," which has red-shifted into the microwave region of the spectrum.

Frame In telemetry, an organized group of bits that may contain packets or portions of packets, e.g., transfer frame.

Frame tie DSN observation using VLBI of a planetary spacecraft and quasars, to reconcile frames of reference, e.g., planetary ephemerides, with the International Celestial Reference Frame (ICRF).

Frangible nut Explosive nut. Illustration p 175.

Free-fall Condition in orbit in which an observer senses no gravitational acceleration.

Free-molecular flow Fluid dynamics regime in which aerobraking of planetary orbiter spacecraft is executed, where the atmospheric molecules' mean free path is larger than the spacecraft.

Free-return trajectory Trajectory in which a spacecraft traveling away from the primary body, e.g., Earth, is modified by the gravitation of a secondary body, e.g., the Moon, causing the spacecraft to return to the primary body without requiring additional rocket thrust.

Free-space optical Telecommunications carried out over the channel of empty space between transmitter and receiver using, e.g., IR or visible-light laser transmitters and Cassegrain telescope light "antennas."

Frequency Number of cycles per second, stated in hertz (Hz).

Frequency and timing One of the seven DSN data types. Based on a frequency standard such as a hydrogen maser, reference frequencies and clock time are maintained and distributed to all DSN subsystems. John Harrison showed the importance to navigation of having an accurate clock in 1761 (see longitude). The DSN frequency and timing system is an accurate chronometer that enables interplanetary navigation.

Frequency band A named range of frequencies such as S-band (around 2 GHz) or visible light. See Appendix D, p 342.

Frequency modulation Means of imposing information onto a carrier signal by slightly changing its frequency.

Frequency stability In a radio signal, consistency in the amount of time between peaks in its electromagnetic waves. Expressed as Allen deviation.

Fuel Liquid or solid chemical that decomposes explosively in a catalytic thruster or combines with another chemical in a bipropellant engine or solid rocket motor to produce thermal energy for converting to rocket thrust.

G Ring In the Saturnian system, the narrow ring between the F Ring and the E Ring. Particles in the outer part of the G Ring orbit Saturn once every 20.88 hours, at 14.69 kilometers per second. Not visible in a small telescope.

Gain Increase in signal strength obtained, e.g., by collecting a weak incoming signal over a large area, or by actively amplifying it.

Galaxy Massive, gravitationally bound system of stars, interstellar gas, dust, and dark matter, often orbiting a supermassive black hole at its center. Our home galaxy is the Milky Way, about 100,000 LY in diameter. Nearest galaxy is the spiral in Andromeda, about 2.5×10^6 LY distant and on a collision course with us. Most distant known galaxy is 2.8×10^9 LY away.

Galileo spacecraft NASA orbiter launched October 18, 1989, entered Jupiter orbit December 7, 1995, having deployed its atmospheric probe toward Jupiter July 13, 1995, which entered Jupiter's atmosphere while being tracked by the orbiter during its Jupiter orbit insertion critical sequence. Named for Tuscan astronomer Galileo Galilei (1564–1642) who discovered clear evidence that Earth is not the center of everything. The four Galilean moons are named in his honor for his having first observed them on January 7, 1610.

Gallium Element, symbol Ga, atomic number 31; a metal that melts slightly above room temperature. Gallium arsenide is an important photovoltaic.

Galvanometer Voltmeter.

Gamma ray (γ-ray) Electromagnetic radiation in the region above about 10^5 ev. See Appendix D, p 342. Produced in nature by highly energetic events, e.g., compression of matter at the threshold of a supermassive black hole.

Gamma-ray spectrometer Passive remote-sensing science instrument that measures the distribution of photon energies in the most energetic parts of the electromagnetic spectrum (see Appendix D, p 342). On planet-orbiting spacecraft, the instrument is useful for identifying the abundance and distribution of roughly twenty different elements on the surface, based on the energies of gamma radiation they emit as they are bombarded by cosmic rays from natural sources.

Ganymede One of the four Galilean moons of Jupiter, third out from the planet, diameter 5,262.4 kilometers, largest moon in solar system. Most likely has a subsurface water ocean between ice layers.

Gas chromatograph Direct-sensing science instrument that separates a sample of mixed gases into a sequentially ordered stream of gases, e.g., for further analysis by a mass spectrometer.

Geocentric Having Earth's center as reference. Compare topocentric.

Geometric albedo See albedo.

Geostationary orbit Circular geosynchronous orbit in which the spacecraft does not wander significantly north and south by virtue of its equatorial inclination.

Geosynchronous altitude About 36,000 kilometers above Earth's sea level.

Geosynchronous orbit Spacecraft orbit about Earth having a period equal to one sidereal day, which is 23 hours 56 minutes. In a geosynchronous orbit, a spacecraft appears to maintain a fixed position above a point on Earth.

Germanium Element, symbol Ge, atomic number 32. Semi-metallic, solid at room temperature. An important semiconductor in its pure crystalline form.

Giotto ESA spacecraft flown to Comet Halley in 1986.

GMT Greenwich Mean Time, a time scale based on Earth's minutely variable rotation rate and the passage of a fictitious "mean" Sun — one whose rate of passage through the sky daily is an average of its values over Earth's annual motions through perihelion and aphelion.

Golden record *Voyager 1* and *Voyager 2* spacecraft each carry a gold-plated copper phonograph-style record, containing images and sounds representing life on Earth, into interstellar space. *Pioneer 10* and *Pioneer 11* each carried a gold-anodized aluminum plate etched with artwork reflective of the human-inhabited planet and star-system from which the vessel came. These records and plaques will probably survive the interstellar dust impacts for many hundreds of millions of years, while they orbit the center of our galaxy, having escaped the Sun's gravitational bond.

Goldstone DSCC One of three worldwide Deep Space Communications Complexes in DSN. Near 35°15' N latitude × 116°48' W longitude.

Graphite Electrically conductive allotrope of carbon.

Graphite fiber Carbon fiber or plastic reinforced with carbon fiber. Strong, low-mass material with many applications in aerospace and elsewhere. Compare fiberglass.

Grating See diffraction grating.

Gravitation The natural acceleration of one mass toward another, described in the general theory of relativity as stemming from the curvature of spacetime governing the motion of inertial objects.

Gravitational radiation Fluctuations, or gravitational waves, in the curvature of spacetime predicted by general relativity, which are generated by very massive objects accelerating, e.g., neutron stars orbiting one another, or coalescing. Not yet directly detected, but it has been indirectly observed in the orbital decay in a binary system comprising a pulsar and a star.

Gravitational wave General-relativistic phenomenon, see above. Compare gravity wave.

Gravity field mapping Science investigation in which a planet-orbiting spacecraft's speed is tracked via Doppler shifts in its radio link as the spacecraft's speed increases slightly when approaching an area of concentrated mass on the planet, and slows slightly when receding from the area. Characterizes the planet's distribution of mass on and below its surface.

Gravity assist Intentional interaction between a spacecraft and a natural body it passes. Called an elastic collision, some of the natural body's orbital momentum is decreased or increased, and in the exchange the spacecraft's velocity changes substantially, as measured from the system's center, e.g., the Sun.

Gravity gradient The difference in gravitational attraction felt at one side of, e.g., a spacecraft from that felt at its other side when in the presence of a substantial gravitational mass, e.g., a planet. The difference is due to the force of gravity decreasing as the square of the distance from the planet. Gravity gradient can produce a torque on the object. It causes the Moon to keep one side toward Earth.

Gravity wave Hydrodynamic wave, e.g., in an atmosphere, oscillating as the planet's gravity causes the air to respond to a disturbance. Compare gravitational wave.

Ground system DSN and all ground-based communications and computing hardware, software, and workforce that acts as the counterpart to a flight system (spacecraft).

Ground truth Directly measured quantities at the surface of a planet, e.g., made by a lander or rover, which correspond with and serve to calibrate remote-sensing measurements made from orbit. Helps investigators interpret remote-sensing data.

Guillotine Cable-cutting device on spacecraft, typically driven by pyrotechnic charges.

Gunpowder Early solid-rocket propellant used by the Chinese, invented in China in the ninth century. Granular mixture of sulfur, charcoal and potassium nitrate, which releases oxygen to burn the other ingredients. Low explosive.

Gyro Short for gyroscope.

Gyroscope A device that senses an object's rotation. AACS inertial reference input device. Gyro technology can employ a small spinning mass, a vibrating reed, a vibrating hemisphere, or a coil of fiber optic cable.

Gyroscopic effect With regard to a spinning mass, the rigidity in space of its axis, and/or the precession that results from applying torque to the axis.

Hale Telescope The largest instrument atop Mt. Palomar in California, a 200-inch (5.1–meter) aperture reflecting telescope. Named in honor of the American astronomer George Ellery Hale (1868–1938). At first light in 1948 it was the world's largest telescope, and is still a first-rate scientific asset today.

Haumea Dwarf planet, dimensions about $1960 \times 1518 \times 996$ km, orbiting the Sun in the Kuiper belt. Rotates rapidly, with a period under four hours, causing its elongated shape. Has two moons, named Hi'iaka and Namaka.

Hayabusa JAXA spacecraft that rendezvoused with asteroid Itokawa September 2005. Expected to return a sample-canister to Earth in 2010.

Heliocentric orbit An orbit that has the Sun at one focus of its ellipse, e.g., Earth's orbit, *Ulysses* spacecraft orbit, *Spitzer* spacecraft orbit.

Heliopause Outer boundary of the heliosphere, which creates a bow shock external to it, at the turbulent interface with the interstellar medium. See Appendix C, p 337.

Heliosheath Region of space outside the Sun's termination shock and inside the heliopause.

Heliosphere Bubble of plasma inflated by the solar wind and confined by the solar magnetic field and the interstellar medium.

Helium Element, symbol He, atomic number 2, gaseous at room temperature; one of the six noble gases. Named for the Sun, where it was first discovered.

Helium magnetometer Passive direct-sensing science instrument that uses high-frequency alternating electric current discharges and infrared optical pumping to excite ionized helium in a cell. Measuring changes in energy the helium absorbs indicates the effects of an external magnetic field.

Hematite Iron-bearing mineral (Fe_2O_3). Typically formed or altered on Earth in aqueous conditions. Abundant on the surface of Mars.

Hemispherical resonator gyro (HRG) AACS inertial reference input device. Senses rotation about an axis using no moving parts. Relies on measuring precession of nodes on the rim of a small, vibrating fused quartz hemisphere, via piezoelectric effects.

HEMT High-electron mobility transistor; a special field-effect transistor. Low-noise amplifier, typically the first stage of amplification for a received microwave signal, e.g., in residential television dish antennas. DSN HEMTS are cryogenically cooled to reduce contribution of noise.

High-gain antenna (HGA) Microwave antenna on a spacecraft consisting of the largest practical main-reflector aperture. For reference, *Voyager*'s 3.7–meter diameter HGA provides a 63,000-fold increase in signal strength at X-band frequencies, or about 48 dB.

High-inclination orbit Orbit whose plane forms a large angle with the ecliptic, or with a planet's equator. An orbit with maximum inclination (90°) is called a polar orbit.

HiRISE High-resolution imaging science experiment on *Mars Reconnaissance Orbiter*. Can achieve 30-centimeter pixel size images of the Martian surface in visible light. Its telescope aperture is 50 centimeters, focal length 12,000 millimeters.

Hill sphere Area of greater gravitational influence around a body, when compared to the influence of another body's gravitation.

Hohmann transfer Portion of a solar orbit that a spacecraft can attain given an impulse of thrust (of appropriate C_3) at the transfer orbit's perihelion. Would return the spacecraft toward the Sun in elliptical orbit were it not to encounter its target planet at apoapsis. Variations of this ideal minimum-energy transfer are adapted as needed for timing, out-of plane inclinations, and other planning issues. Named for German engineer Walter Hohmann (1880–1945).

Horizon sensor AACS celestial reference input device on some spacecraft, particularly planet-orbiting surface-observing missions.

Hot neutron Neutral nuclear particle having relatively high velocity, e.g., from recent collision with a much more massive atom.

Housekeeping data Engineering telemetry from a science instrument that reports on the instrument's state, e.g., temperature, configuration, electrical power levels, etc.

HST Hubble Space Telescope; one of the four NASA Great Observatories. Launched April 24, 1990. A 11,110-kilogram spacecraft with 2.4–meter aperture Ritchey-Chrétien reflecting telescope and multiple instruments. Primary mirror manufactured with spherical aberration error, accommodated by corrective optics installed December 1993 by Space Shuttle astronauts. A total of four such servicing missions have been accomplished as of press time. Named for American astronomer Edwin P. Hubble (1889–1953), who, working at Mt. Wilson with assistant Milton Humason (1891–1972), measured spectra of distant galaxies and discovered in 1929 that the amount of redshift is proportional to their distance, establishing the expansion of the universe.

Huygens ESA atmospheric spacecraft. Released by *Cassini* December 25, 2004, entered Titan's atmosphere January 14, 2005 and returned telemetry to *Cassini* that was relayed to Earth. *Cassini* measured Doppler shift on the *Huygens* carrier, which was also received directly on Earth where its Doppler shift, later correlated with *Cassini* data, traced the parachuting probe's wind-driven movements. *Huygens* survived touchdown and reported on the methane-soggy sand in which it landed. Named for Dutch astronomer Christiaan Huygens (1629–1695) who discovered this largest moon of Saturn in 1655.

Hydrazine (N_2H_4) Liquid monopropellant rocket fuel that decomposes explosively on contact with a heated catalyst in rocket thrusters.

Hydrofluoric acid Solution of hydrogen fluoride (HF) in water, a corrosive acid that dissolves glass.

Hydrogen Element, symbol H, atomic number 1, commonly found as the diatomic H_2 molecule, gaseous at room temperature. Most abundant element in the universe. Named in 1783 for its ability to generate water by burning in the air.

Hydrogen maser Frequency standard that employs hydrogen's physical properties and a tuned cavity to generate and maintain a highly stable microwave frequency (near 1,420 MHz). Used in DSN to generate uplink carrier signals and provide system-wide frequency and timing references.

Hydrogen peroxide (H_2O_2) Unstable compound that decomposes in contact with a catalyst in relatively low-power rocket engines.

Hypergolic Either of two rocket propellants that ignite spontaneously when mixed, e.g., monomethyl hydrazine or nitrogen tetroxide.

Iapetus One of Saturn's moons, the third largest, diameter 1,436 kilometers. Orbits 3.561×10^6 km from Saturn. Leading hemisphere has a high equatorial ridge and is covered in (probably exogenic) dark organic matter. Trailing hemisphere exhibits high-albedo water ice.

IMC Image-motion compensation; rotation of a spacecraft or its instruments to keep a target centered in optical fields of view during a flyby encounter.

Imaging radar See SAR, synthetic aperture radar.

Imaging science Discipline concerned with planning, capturing, compressing and transmitting, analyzing, modifying, and visualizing images obtained by passive remote-sensing instruments, e.g., at visible-light wavelengths.

Imaging spectrometer or spectrograph; passive remote-sensing instrument having multiple pixels that make up an image, which is captured all at once (rather than via an internal scanning mechanism), each pixel revealing the intensity of each of a number of wavelengths observed. Compare mapping spectrometer. Data output is called a "cube" rather than a two-dimensional image.

Impact detector Passive direct-sensing instrument that measures the incidence of dust particle impacts, and may also do some characterization of them. Compare dust analyzer.

Impact radius Circle drawn on a B-plane chart inside of which a spacecraft's aim point will cause it to impact the target body's surface.

Impulse Change in momentum (mass $\times$ velocity) brought about by force, e.g., from a rocket's thrust.

Impulse turbine Device that changes the velocity (rather than pressure) of a jet, e.g., of steam from a divergent-convergent nozzle, impacting and resulting in change of momentum (impulse) on a turbine's blades, which do not require submersion.

Incandescence Emission of visible light from an object, e.g., rocket nozzle or tungsten filament, due to its temperature.

Index of refraction Measure of how much the speed of a wave, e.g., light, is reduced when passing through a medium. Liquid water's index is 1.33, meaning light slows to 1/1.33 c. Responsible for bending light rays where density of a medium varies.

Indium Element, symbol In, atomic number 49. Soft metal, solid at room temperature. Constituent in IR detectors such as indium antimonide.

Indium antimonide (InSb) Semiconductor used in detectors, e.g., photodiodes, sensitive to IR wavelengths around 1 μ to 6 μ.

Indium-gallium phosphide (InGaP) Semiconductor useful in high-frequency and high-power applications, in HEMTs, and in multi-junction solar cells.

Inertia Intrinsic property of mass that demonstrates Newton's first law of motion. The fundamental nature of inertia and of mass are subjects of investigation.

Inertial reference AACS input device that registers change in spacecraft orientation based on internal gyroscopes and without external (celestial) reference.

Inertial vector propagator Algorithm in AACS that maintains knowledge of the directions (vectors) from spacecraft to specified targets of interest, based on current ephemerides. Computes (propagates) changes to the vectors into the future.

Inferior conjunction Conjunction (coincidence of right ascension) of an interior planet or spacecraft with the Sun when the Earth and the planet are on the same side of the Sun. Compare superior conjunction.

Infrared (IR) Electromagnetic radiation in wavelengths from about 1 millimeter to 380 nanometers. See Appendix D, p 342. Produced in nature by, e.g., animals and stars.

Integrated sequence of events (ISOE) Time-ordered list of spacecraft events and DSN events.

Intensive quantity Physical quantity that expresses units of A per units of B, e.g., density (mass per unit volume), specific energy (energy per unit mass), specific impulse (impulse per unit of propellant).

Interferometry Technique of interpreting the pattern of interference created by the superposition of two or more waves, e.g., microwave, radio, or light, to determine properties of the waves' source, e.g., position in the sky through VLBI, or rotation rate in a laser gyro.

Intergalactic space Space between the galaxies, i.e., outside the Milky Way.

Internet protocol (IP) See TCP/IP.

Interplanetary flight Movement of a spacecraft which has departed Earth's gravitational bond, having characteristic energy, C_3, greater than zero.

Interplanetary space Space between the planets and Sun within the solar system.

Interplanetary spacecraft Vehicle designed to leave Earth's gravitational bond. All are robotic as of today.

Interstellar space Space between the stars, which begins outside the heliosphere.

Inverted data See complemented data.

Inverter, power See power inverter.

Io Innermost of the four Galilean moons of Jupiter, diameter 3,643.2 kilometers. Most volcanically active body known, constantly being resurfaced in the present.

Ion An atom missing one or more of its electrons. The solar wind fills interplanetary space with these. Also, an atom with an excess of electrons, e.g., in a chemical solution.

Ion engine Means of electrostatic propulsion that employs high-voltage grids to accelerate ions to high velocity and generate thrust. High I_{SP}, low thrust. Compare MPD thruster.

Ionization The process of electrons being removed from their atoms, e.g., by absorption of electromagnetic energy.

Ionosphere Highest layer in a body's atmosphere, ionized by solar radiation.

IR spectrometer See spectrometer. Measures invisible "colors" in the IR.

Iridium Element, symbol Ir, atomic number 77. Solid at room temperature. Very hard, dense, brittle, corrosion-resistant metal. Found in meteorites at higher relative abundance than typically found in the Earth's crust.

Iridium Earth-orbiting U.S. communications spacecraft with large planar solar arrays that show bright specular flashes, called "Iridium flares," in the local sky at times published online.

Iron Element, symbol Fe, atomic number 26. Strong metal at room temperature, made stronger by alloying with carbon to make steel. Major constituent of the terrestrial planets' cores.

Isotropy Condition of being homogenous in all directions. Compare anisotropy.

I_{sp} See specific impulse.

Julian year Definition of the year as 365.25 days, or 31,557,600 seconds. Named after the Julian calendar that came into use in 45 BCE.

Juno Jupiter polar orbiter project in the NASA New Frontiers Program that began preliminary design, Phase A of its mission, in June 2005. Planned to launch in August 2011. Cost capped at \$700M.

Jupiter Fifth planet from the Sun, one of the four gas giants or Jovian planets. Equatorial diameter 11.209 times Earth's. H_2 atmosphere with about 10 percent He and traces of other gases. Mean distance from Sun 5.2 AU.

Jupiter radius 1 R_J = 71,492 km.

Ka-band Range of microwave frequencies around 26.5 to 40 GHz.

Kapton Polyimide film proprietary to DuPont, Inc., used for its high durability performance in extreme temperatures, electrical properties, and low mass.

Kepler's first law of planetary motion: The planets' orbits are ellipses with the Sun at one focus.

Kepler's second law of planetary motion: A line joining the planet to the Sun sweeps out equal areas in equal amounts of time.

Kepler's third law of planetary motion: The square of a planet's period of revolution about the Sun is proportional to the cube of the semimajor axis of the planets elliptical orbit.

Kinetic energy The energy a body possesses due to its motion, expressed as:

$$\frac{1}{2}mv^2$$

where m is its mass and v its velocity.

Klystron High-power microwave amplifier used in DSN transmitters, output of which is measured in kilowatts, e.g., 18 kW at X-band for telecommunications, to 400 kW for radar astronomy.

Ku-band Range of microwave frequencies around 12 to 18 GHz.

Kuiper belt Region in the solar system beyond Neptune's orbit, 30 AU, extending to about 55 AU from the Sun. Populated with icy bodies including Pluto.

Lagrange point Any of five orbital positions at which an object can in theory remain stationary with respect to two massive objects, e.g., Sun and Earth. Labelled L1 through L5.

Lander and Penetrator Spacecraft One of eight classifications of spacecraft. Designed to encounter the surface of a solar system body.

Laser Electro-optical device that produces a coherent source of light by emission of stimulated radiation.

Laser gyro AACS inertial reference input device. Senses rotation about an axis using no moving parts. Relies on measuring Doppler-shifted light via interferometry to measure rotation about an axis.

Laser-Induced Remote-sensing Spectrograph. An active remote sensing instrument. Bombards target, e.g., rock, with focused high-energy infrared light, causing part of the target to vaporize, and observes spectra of emissions from the resulting hot gas. Named ChemCam on *Mars Science Laboratory*.

Latitude North-south coordinate measurements on a globe, given by parallel lines measured from 0° at the equator to 90° north and south at the poles. Compare longitude.

Launch period Range of days during which a launch with a nominal energy (C_3) and arrival time can be attempted.

Launch window Period during a day in the launch period when launch is possible. Also called daily firing window.

Launch-arrival plot See porkchop plot.

Lead Element, symbol Pb, atomic number 82. Soft metal, solid at room temperature.

Light time Time it takes radio communications to propagate, e.g., from DSN to spacecraft and back.

Light See visible light.

Light-emitting diode (LED) Semiconductor diode that exhibits electroluminescence, emitting narrow-spectrum, non-coherent IR, visible light, or UV when electrical current flows through its p-n junction. LEDs are more efficient in converting electrical power to light than are incandescent or fluorescent devices.

Light-induced degradation Reduction in a solar cell's electrical power output in its first few weeks in operation.

Limb Visible edge of a body such as the Sun or a planet.

LINEAR Acronym for "Lincoln near-Earth asteroid research." MIT Lincoln Laboratory program funded by U.S. Air Force and NASA to demonstrate application of technology originally developed for surveillance of Earth orbiting satellites, to the problem of detecting and cataloging near-Earth asteroids.

Link Communications path between spacecraft engineers and their subsystems in flight, and between science teams and their payload of instruments on the craft. Includes spacecraft's communications equipment, intervening interplanetary space, DSN equipment, earth-based communications systems, computers, and routers that participate in the communications path. Usually instantiated for hours at a time.

Liquid ethane (C_2H_6) Constituent of lakes on the surface of Saturn's moon Titan. Boils at 184.5 K (standard pressure).

Liquid helium Liquified helium gas, useful as a refrigerant for low-noise amplifiers and infrared instruments. Boils at 4.2 K (standard pressure).

Liquid hydrogen Liquified hydrogen gas, useful as rocket propellant. Boils at 23 K (standard pressure).

Liquid oxygen Liquified oxygen gas, useful as rocket propellant. Boils at 90.19 K (standard pressure).

Liquid-propellant Liquid chemical for rocket engine or thruster. Called monopropellant if the engine uses only one chemical, e.g., hydrazine, or bipropellants if two chemicals, fuel and oxidizer, are required.

LISA Laser-Interferometer Space Antenna; proposed gravitational wave observatory.

Lithium Element, symbol Li, atomic number 3, alkali metal; a low-density solid at room temperature.

Local Civil Time (LCT) Statutory time designated by civilian authorities, a fixed offset from UTC, possibly adjusted seasonally for daylight saving time.

Local mean time (LMT) Mean solar time at a planet's local meridian (based on the angle of the Sun).

Lock In telecommunications, state of a closed-loop radio receiver in which a phase-locked-loop circuit has acquired the incoming signal and is following it, along with its every shift in phase. With telemetry data, state of a DSN telemetry subsystem in which it is successfully predicting and finding in a data stream the codeword (pseudo-noise, PN code) that identifies the start of a transfer frame. Command lock on a spacecraft means its command data decoder is decoding binary digits from the uplink carrier signal's phase shift symbols.

Log In space flight operations, a chronology of realtime events kept by, e.g., an Ace. Includes such events as beginning of a DSN track, acquisition of signal, telemetry lock, spacecraft activities observed, descriptions of anomalies or discrepancies, and references to their documentation.

Longitude East-west coordinate measurements on a globe. Half great circles called meridians intersecting both opposite rotational poles of a planet or other body. British inventor John Harrison (1693–1776) first successfully demonstrated longitude determination on Earth with his long-sought accurate, seaworthy chronometer in 1761. Compare latitude.

Lorentz force Force on a point charge due to electromagnetic fields. The basis of motor and generator design. Named for named for the Dutch physicist Hendrik Lorentz (1853–1928), Louvers Mechanical devices on a spacecraft bus that autonomously open to permit IR to radiate, and close to contain IR, to maintain desired temperature within. Driven by ambient thermal energy on bimetallic strips.

Low-density parity-check (LDPC) Forward error-correction coding system first described 1960 by American grad student Robert Gallager (1931–). Gallager codes, used today in digital satellite TV, reach within a fraction of a dB of the Shannon limit. LDPC uses a decoder for each bit in a message.

Low-gain antenna (LGA) Small, nearly omnidirectional microwave antenna on a spacecraft, with gain of perhaps 1 dB or so.

Low-Noise Amplifier (LNA) DSN microwave subsystem component downstream of the antenna's Cassegrain reflector and feed. Either a high-electron-mobility transistor, HEMT, or a maser. Typically cooled with liquid helium to a few kelvins.

Luminosity Quantity of energy a body, e.g., a star, radiates per unit time. Apparent luminosity refers to visible light radiated. Bolometric luminosity refers to all wavelengths.

Lunar Prospector Project in NASA's Discovery Program that flew a polar orbit around the Moon for 1.5 years beginning in January 1998 to map elements near the surface and refine the gravity field map.

Mach 1.0 The speed of sound, which varies according to the medium's density and temperature. Named for the Czech-Austrian physicist Ernst Mach (1838–1916).

Madrid DSCC One of three worldwide Deep Space Communications Complexes in DSN. Near 40°26' N latitude × 002°00' W longitude.

Magellan NASA Planetary orbiter that mapped the surface of Venus to high resolution using synthetic aperture radar imaging, altimetry, and radiometry, and carried out atmospheric investigations including the first aerobraking to change orbital parameters. Operated at Venus 1990 through 1994.

Magnesium Element, symbol Mg, atomic number 12, a strong, lightweight metal at room temperature. Readily burns in oxygen, giving off a bright white light.

Magnetic torquers AACS output devices, electromagnets that interact with Earth's magnetic field to manage spacecraft attitude.

Magnetometer Passive direct-sensing instrument that measures the magnetic field of a planet or in interplanetary or interstellar space.

Magnetosphere Magnetized region generated by and surrounding an astronomical object, e.g., Sun, Earth, Jupiter. Typically formed into tear shapes by pressure from external forces such as the solar wind or interstellar medium.

Main asteroid belt Region between the orbits of Mars and Jupiter populated by debris remaining after solar system formation.

Makemake Dwarf planet, about 1,500 km in diameter, orbiting the Sun in the Kuiper belt.

Mapping spectrometer or spectrograph. Passive remote-sensing instrument having multiple pixels that make up an image, which is captured via an internal scanning mechanism (rather than all at once), each pixel revealing the intensity of each of a number of wavelengths observed. Compare imaging spectrometer.

Mars Fourth planet from the Sun, one of the four terrestrial planets. Diameter 0.532 of Earth's. Surface temperature ranges from about –120 °C to 15°C.

Mars Climate Orbiter NASA Planetary orbiter spacecraft lost during its orbit insertion burn in 1998 due to buildup of navigation error stemming from metric-English unit confusion during interplanetary cruise.

Mars Exploration Rover (MER) Twin NASA rover spacecraft, named *Spirit* and *Opportunity*, which landed in 2003 on opposite sides of Mars.

Mars Express ESA Planetary orbiter spacecraft that began orbiting Mars in 2003.

Mars Global Surveyor (MGS) NASA Planetary orbiter spacecraft that operated at Mars from September 1997 until November, 2006.

Mars Observer NASA Planetary orbiter lost August, 1993, during bipropellant tank pressurization in preparation for orbit insertion.

Mars Pathfinder (MPF) NASA Discovery-program planetary lander that landed July, 1997. Deployed *Sojourner,* the first operable rover on another planet.

Mars Polar Lander (MPL) Lander spacecraft in the NASA Mars Surveyor '98 program that failed during atmospheric entry, descent, and landing in the high southern latitudes in December 1999.

Mars Reconnaissance Orbiter (MRO) NASA Planetary orbiter that entered Mars orbit in March, 2006.

Mars Science Laboratory (MSL) NASA Rover due to launch in 2011.

Maser Low-noise amplifier that multiplies the strength of a microwave signal by emission of stimulated radiation, while contributing little noise. Compare laser.

Maser frequency standard Microwave frequency resonant-cavity oscillator based on stimulated emissions of, e.g., hydrogen, used in DSN to generate uplink signal and other references with extremely high frequency stability. See frequency and timing.

Mass Intrinsic quality of matter that causes it to have momentum, and respond to gravitation. Equivalent to energy as in $E=mc^2$.

Mass-expulsion control (MEC) Attitude control via rocket thrusters.

Mass spectrometer Active direct-sensing instrument that analyzes a sample of ionized gas to determine the range of atomic or molecular masses (thereby the chemical species) it contains.

Mass-expulsion device A rocket engine or thruster.

Maximum power point (MPP) Combination of voltage and current that produces the most power out of a solar panel under varying conditions of temperature and illumination. MPP tracking circuitry computes and utilizes the MPP.

MCD Maximum-likelihood Convolutional Decoder. DSN electronic assembly that runs a Viterbi algorithm in hardware to apply forward error correction and convert radio symbols to data bits.

Mean Sun Fictitious body whose rate of daily passage through the sky is an average of the Sun's motion across the sky throughout the entire year. Basis of Greenwich Mean Time (GMT).

Mechanical devices Subsystem on a spacecraft that incorporates deployable and mechanically operable assemblies, e.g., instrument booms and landing struts.

Medium-gain antenna (MGA) Assembly in a spacecraft's telecommunications subsystem capable of higher gain than LGA, and wider area coverage at lower gain than HGA.

Megapixel One million picture elements (photogates), as in CCDs.

Memory effect Loss of ability of a NiCd battery to recharge completely if repeatedly discharged and recharged only to a fraction of its capacity.

MEMS gyros Micro-electromechanical system that senses rotation. Used in handheld remote controllers and Segway® personal transporters. Beginning to come into use on spacecraft.

Mercury First planet from the Sun, one of the four terrestrial planets. Diameter 0.383 of Earth's. Mean distance from Sun 0.387 AU. Surface temperatures range from –183°C to 427°C.

Mercury Element, symbol Hg, atomic number 80; a liquid metal at room temperature. Vapor emits strongly at UV wavelengths when excited. Toxic.

Meridian A line of longitude, from pole to pole.

Messenger Mercury-orbiter spacecraft planned to enter orbit about the planet on March 18, 2011.

Metallic (M-type) Asteroid M-type asteroids comprise about 8 percent of main-belt types and are found mostly in the middle of the main belt. Their reflectance spectra generally indicate a composition of metallic iron, matching the spectra of iron meteorites.

Meteor An object in the process of entering the atmosphere from outer space, or falling through it. Compare meteorite, meteoroid.

Meteorite An object from outer space found on the planet's surface.

Meteoroid An object in interplanetary space that may be on a planet- (or spacecraft-) impacting trajectory.

Meteorological station Direct-sensing instrument or suite of instruments that measure atmospheric conditions such as wind speed and direction, temperature, pressure, humidity, e.g., on the *Phoenix* Mars lander.

Methane (CH_3) gas at room temperature on Earth. Constituent of outer planet atmospheres, and of clouds and liquid lakes on Saturn's moon Titan.

Microwave Region of electromagnetic spectrum with wavelengths measured in centimeters. See Appendix D, p 342.

Minor planet Asteroid.

MIssion An operation designed to carry out the goals of a project. Often used interchangeably with *project.*

Mission phase Period in the life of a project, typically denoted as pre-Phase-A initial studies, and Phase-A through-D development, assembly and testing, and then Phase E operations.

Mission plan Detailed document that serves as a central reference for carrying out every aspect of mission operations.

MMH Mono-methyl hydrazine ($CH_3N_2H_3$) liquid rocket fuel used in bipropellant systems, hypergolic with nitrogen tetroxide.

MO&DA Mission operations and data analysis; Phase E in a mission's lifetime, during which it carries out its intended data collection, and at least an initial analysis is performed.

Modulation Technology of imposing information onto a telecommunications channel, e.g., phase variations on a microwave radio signal.

Modulation index In phase modulation, the number of degrees or radians a wave is shifted to constitute an information symbol.

Momentum, linear The product of an object's mass and velocity.

Momentum thrust The major component of force in a rocket engine, which comes from acceleration of mass out the nozzle. Terms to the left of the + sign (see description on p 127) in:

$$F = \dot{m}v_e + p_e A_e$$

Compare pressure thrust.

Momentum wheel See reaction wheel.

Monitor data One of the seven DSN data types. Indications of DSN station equipment performance, such as received signal levels, transmitter power, and antenna pointing angles.

Monocoque Structural design in which loads are supported by an external skin. From French for "single shell."

Monoprop thruster Small rocket engine that uses a single liquid propellant, e.g., hydrazine, which comes in contact with an electrically heated catalyst to initiate explosive decomposition of the liquid.

Moon Capitalized, the Earth's natural satellite. Otherwise, any object's natural satellite.

Moore's Law Conjecture by Gordon Moore, cofounder of Intel Corporation, which states that the number of transistors on an integrated-circuit chip will double about every two years. This has held true for forty years or more. First published in "Cramming more components onto integrated circuits" in *Electronics* magazine, April 19, 1965.

Mössbauer Spectrometer Active direct-sensing science instrument good at measuring iron-bearing minerals, e.g., in rocks.

MPD thruster Magnetoplasmadynamic means of electric propulsion that employs the force resulting from interaction between a magnetic field and an electric current (Lorentz force) to accelerate ions to high velocity and generate thrust. High I_{SP}, low thrust. Compare ion engine.

Multijunction solar cell Also called Multibandgap, a solar cell made of multiple thin-film layers of semiconductors, each of which is responsive to a different range of wavelengths of light.

Multiplex (MUX) Technology of combining multiple signals or measurements into a single telecommunications channel.

Nadir The point directly below the observer. Compare zenith.

NEAR-Shoemaker (Near-Earth Asteroid Rendezvous) NASA spacecraft that orbited near-Earth asteroid Eros beginning February 2000, then touched down on its surface at end of mission in February 2001.

Neon Element, symbol Ne, atomic number 10, gaseous at room temperature; one of the six noble gases. When excited, strongly emits characteristic orange, red, and other wavelengths.

Nephlometer An active remote-sensing science instrument that illuminates cloud particles in an atmosphere and observes light reflected from them.

Neptune Eighth planet from the Sun, one of the four gas giants or Jovian planets. Equatorial diameter 3.883 times Earth's. Atmosphere of predominantly H_2 with about 19 percent He and 1.5 percent methane. Mean distance from Sun 30.07 AU.

Neptunium Element, symbol Np, atomic number 93. Metallic, solid at room temperature. Not occurring naturally, this radioactive element is manufactured in a nuclear reactor.

Neutron The neutral nuclear subatomic particle, similar in mass to the proton.

Neutron radiation Ionizing radiation consisting of moving neutrons. Emitted by nuclear fission and fusion, etc.

Neutron Spectrometer Passive direct-sensing science instrument that uses scintillators to measure energy distribution of free neutral subatomic particles. Geometry of multiple detector elements allows separation of background neutron radiation from that being emitted from target surface. Useful in identifying water on target's surface.

New Horizons NASA flyby spacecraft launched January 19, 2006, to encounter Pluto and its moon Charon on July 14, 2015, and then continue into the Kuiper belt for possible additional but as yet unidentified object encounters Passed Jupiter February 28, 2007 for gravity assist and instrument checkout.

Newton's first law An object at rest tends to stay at rest, and an object in motion tends to stay in motion with the same speed and in the same direction, unless acted upon by an unbalanced force.

Newton's second law The acceleration of an object as produced by a net force is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass of the object.

Newton's third law For every action there is an equal, but opposite, reaction.

Nickel Element, symbol Ni, atomic number 28; metallic, solid at room temperature. Used in rechargeable batteries.

Nickel-cadmium batteries (NiCd) Rechargeable battery having a high cycle durability. Under some circumstances they exhibit "memory effect" reducing their ability to cycle deeply. Toxic due to their cadmium content.

Nickel-hydrogen (NiH_2) Rechargeable battery having a high cycle durability and well-proven performance on spacecraft. Enclosed in pressure vessels.

Niobium (also called columbium). Element, symbol Nb, atomic number 41. Metallic, solid at room temperature, high melting point (2,477°C). Steel alloyed with niobium is used in rocket engines.

Nitrogen Element, symbol N, atomic number 7, commonly found as the diatomic molecule N_2, gaseous at room temperature. Major constituent of the atmospheres of Earth and Titan.

Non-coherent Communications mode in which spacecraft downlink radio signal is not in phase-coherence with an uplink.

NTO Nitrogen tetroxide oxidizer (N_2O_4); powerful oxidizer, highly toxic and corrosive. Hypergolic with various forms of hydrazine.

Nutation Irregular nodding motion or wobble in the rotation axis of a largely axially symmetric object, such as a planet or a spinning spacecraft.

Observable A parameter input to the navigation orbit determination process, such as a spacecraft's range, right ascension, declination, Doppler shift, or optical navigation data.

Observatory spacecraft One of eight classifications of spacecraft. Designed to carry out observations of typically deep-space phenomena from above the Earth's atmosphere, e.g., *Spitzer*, *SOHO*, *Chandra*.

Occultation zone Area behind a planet or other body as viewed from Earth or Sun.

Ohm's Law Relation between voltage, current, and resistance (see description p 145):

$$V = IR$$

Omnidirectional Quality of an antenna denoting its ability to receive from, or transmit in all directions, or at least a large part of the sky surrounding the antenna.

One-way Communications mode in which a DSN station is receiving a spacecraft's downlink, and the spacecraft has not (yet) received the station's uplink.

Ontario Lacus Lake on the surface of Titan, Saturn's largest moon, where the terrain is largely made of water ice at around 90 K, filled with liquid ethane and (perhaps) methane, as confirmed by *Cassini* in 2008.

Open loop in control theory, a system that runs without self-adjustment.

Open loop radio Receiver that observes a band of frequencies, usually to record samples of them, and perform fast Fourier transforms to display power levels at all received frequencies. Useful for radio science and very-long baseline interferometry.

OSI Open systems interconnection; an early basic reference model for network communications. Superseded by TCP/IP.

Opnav Image for use in optical navigation, typically of a target body, overexposed to show the background stars.

Opportunity Name of the Mars Exploration Rover that landed at Meridiani Planum in 2004, three weeks after its twin, *Spirit*, landed on the opposite side of Mars.

Opposition effect Apparent brightening of an object, e.g., the Moon, when at opposition (illumination phase angle near zero).

Optical modulator Device placed in a fiber-optic link that varies its opacity over time to vary the intensity of light in the link.

Optical navigation The process of acquiring opnav images on a spacecraft, and after receiving them in telemetry on Earth, or an onboard Autonav engine, processing them to provide information on the spacecraft's location in relation to the target against stars recognized in the image background.

Optical Solar Reflector Mirror-like cell on a spacecraft designed to reject solar heating.

Orbit Gravitationally bound path of one object around another, or of both about a barycenter.

Orbit determination (OD) Computer program suite that describes a spacecraft's orbit given observables and laws of motion.

Orbit insertion burn Rocket engine operation upon arrival at target object, e.g., planet, that decelerates the spacecraft from interplanetary cruise so it will be trapped in orbit about the object.

Orbital Tour Mission of an orbiter spacecraft that includes encounters with objects other than the primary body being orbited, e.g., *Galileo* observations of Jupiter's satellites as well as Jupiter itself.

Orbiter One of eight classifications of spacecraft. Spacecraft designed to enter into orbit at a destination body and conduct observations of the body and/or of its environment and associated bodies.

Oscillation Repetitive variation, e.g., in the field strength of an electromagnetic wave.

Oscillator A device that sets up and maintains an oscillation, e.g., circuitry in a radio transmitter.

OTM Orbit trim maneuver. Spacecraft propulsive maneuver that makes a small adjustment in its orbit about its target body.

Outer space Space exceeding 100 kilometers above Earth's surface.

Oxygen Element, symbol O, atomic number 8, found in Earth's atmosphere as the diatomic molecule O_2, gaseous at room temperature. O_2 is not expected to be found in any other planet's atmosphere since it is highly reactive, unless some process, e.g., photosynthesis, continually replenishes it.

Oxidizer A chemical that readily transfers oxygen in a chemical reaction, or a different substance that gains electrons in a redox (reduction–oxidation) chemical reaction.

Packet Formatted group of bits.

Packet-mode Modern means of data communication wherein formatted groups of bits are routed according to information contained in their headers. Compare time-division multiplex.

Pandora Moon of Saturn that orbits just outside the narrow F Ring and one of the ring's "shepherd" moons (the other is Prometheus). Mostly water ice, about 114 kilometers in length.

Parachute mortar Pyrotechnic device that fires a parachute out of its storage canister for deployment.

Parallel connection Electrical arrangement in which similar devices, e.g., batteries or solar cells, have all their positive terminals tied together and all their negative terminals tied together. Increases current, maintains voltage. Compare series connection.

Pass DSN space-link session. Tracking period during which a spacecraft passes across the sky.

Passive-sensing Category of science instruments that make observations without supplying the main probing energy, e.g., remote-sensing cameras and spectrometers, and direct-sensing dust detectors and magnetometers. Compare active-sensing.

Payload On a launch vehicle, the interplanetary spacecraft mission module and any of its own propulsion stages, e.g., *Voyager*'s mission module and injection propulsion unit. On a spacecraft bus, the science instruments.

Periapsis raise maneuver Propulsive maneuver conducted at or near apoapsis to increase orbital energy, thus raising the altitude of subsequent periapses.

Periapsis Low point in elliptical orbit; the point closest to the center of attraction.

Periareion Periapsis in Mars orbit.

Periastron Periapsis in stellar orbit.

Pericenter Periapsis.

Pericynthion Periapsis in lunar orbit.

Pericytherion Periapsis in Venus orbit.

Perigalacticon Periapsis in galactic orbit.

Perigee Periapsis in Earth orbit.

Perihelion Periapsis in solar orbit.

Perihadion Periapsis in Pluto orbit.

Perihermion Periapsis in Mercury orbit.

Perijove Periapsis in Jupiter orbit.

Perikrition Periapsis in Venus orbit.

Perikrone Periapsis in Saturn orbit.

Perilune Periapsis in lunar orbit.

Periposeidion Periapsis in Neptune orbit.

Periselene Periapsis in lunar orbit.

Periuranion Periapsis in Uranus orbit.

Perizene Periapsis in Jupiter orbit.

Phase angle Angle of illumination on a body, 0° being from directly behind the observer, around to 180° in which the observer is behind the target looking toward the source of illumination. Spoken of as "low phase" when closer to 0° and "high phase" when closer to 180°.

Phase coherence Condition in which two or more electromagnetic waves bear an unchanging relation in the timing of their peaks and troughs.

Phase modulation Imposition of information, such as telemetry, on a carrier signal (or subcarrier) by stepping the phase of the carrier in predetermined ways.

Phase, project Period in the life of a project, typically denoted as pre-Phase-A initial studies, and Phase-A through-D development, assembly and testing, and then Phase E operations.

Phase, wave Fraction of a complete cycle corresponding to an offset from a reference time, measured in degrees from 0° through 360°.

Phase-locked-loop (PLL) Closed-loop control system, e.g., in a radio receiver that tracks an incoming signal as its frequency changes.

Phoenix lander Spacecraft in NASA's Mars Scout Program that landed in the Martian arctic on May 25, 2008, and conducted surveillance and analysis of the icy soil. Mission ended November 11, 2008 near the onset of Martian autumn.

Photoelectric effect Quantum electronic phenomenon in which electrons are emitted from matter upon absorption of energy from electromagnetic radiation, e.g., light.

Photogate An isolated photosensitive silicon capacitor that makes up one pixel in a CCD image detector.

Photography Chemical-based method of capturing an image on film. The French artist and chemist Louis Daguerre (1787–1851) developed a practical means of preparing, exposing, developing, and fixing a plate to capture an image, called a Daguerreotype. He made a photograph of the Moon in 1838. Early in the space age before electronic imaging, canisters of exposed film were returned from a series of Earth-orbiters in the Corona project, from 1959 until 1972, in capsules that were recovered in mid-air by a specially equipped aircraft during their parachute descent.

Photometer Passive remote-sensing optical science instrument used to measure illuminance or irradiance.

Photometry Type of science data concerned with the quantity or power of electromagnetic radiation, e.g., light, a target naturally radiates or reflects, captured using photometers. Field of science that studies this phenomenon, such as in analyzing target surface composition. Compare radiometry.

Photon A quantum (particle) of light or other electromagnetic phenomenon.

Photovoltaic (PV) Describes a material that is capable of converting light to electric current with substantial efficiency.

PICA Phenolic impregnated carbon ablator; modern thermal protection system material for atmospheric-entry heat shields that has advantages of low density and efficient ablative capability at high heat flux.

Piezoelectric Describes a material that can generate an electric potential in response to applied mechanical stress, and/or change shape upon the application of an electric current. Examples include crystal (or ceramic) microphones and earphones.

Pioneer spacecraft NASA series of spacecraft that performed first-of-their-kind explorations of the Sun, Jupiter, Saturn and Venus. The different missions had little in common except that they all paved the way for later in-depth investigations, and all used spin-stabilized spacecraft.

Pitch Rotation about a spacecraft's lateral axis.

Planck constant Constant of proportion between a photon's energy and its frequency: 6.626068×10^{-34} J s.

Planck Surveyor Observatory spacecraft due to launch in 2009 to image the anisotropies of the cosmic microwave background radiation field over the whole sky with unprecedented sensitivity and angular resolution.

Planet A celestial body in solar orbit that is massive enough to be rounded by its own gravity (in hydrostatic equilibrium), and has cleared the neighborhood around its orbit. Defined in 2006 by the International Astronomical Union. See also Dwarf planet.

Planetary Radio Astronomy Science concerned with observing radio-frequency emissions from planetary systems and outer heliospheric phenomena. On *Voyager*, the passive direct-sensing PRA instrument shares a 10-meter long dipole antenna with the plasma wave instrument.

Plasma State of matter as charged gas consisting of ions and electrons.

Plasma spectrometer Passive direct-sensing science instrument that measures qualities in ambient plasma such as chemical composition, density, flow, velocity, and temperature of ions and electrons.

Playback Readout from a spacecraft's mass data storage device being telemetered to Earth.

Pluto Dwarf planet, Kuiper belt object, whose highly elliptical orbit takes it 30 to 49 AU from the Sun, causing it to occasionally come closer to the Sun than Neptune. Discovered by American astronomer Clyde Tombaugh (1906–1997) in 1930. Diameter 0.187 of Earth's. Surface temperature measured from Earth at –382°C. Three satellites known at press time. Just as the first of many asteroids was discovered in 1801 (Ceres) and declared a new planet, Pluto was the first of many Kuiper belt objects to be discovered. Ranked then as a planet, it was re-classified in 2006 when more and more similar objects were being discovered.

Plutoid An object similar to Pluto, e.g., other large Kuiper belt objects.

Plutonium Element, symbol Pu, atomic number 93. Metallic, solid at room temperature. Radioactive element, not occurring naturally, manufactured via nuclear reactor.

Plutonium dioxide (PuO_2) Form of the radioisotope used in RTGs on interplanetary spacecraft.

PMD Propellant management device; vanes or baffles within a propellant tank that use surface tension to bring liquid to the tank exit port in the absence of powered or gravitational acceleration.

Polarimeter Passive remote-sensing science instrument that measures the polarization of light reflected or emitted by a target.

Polarization Specific orientation of the electric field component of an electromagnetic wave such as microwave or light, e.g., left-circular, right circular, linear.

Polarizer A device that selects desired polarization of light or microwave radio by filtering out unwanted polarizations.

Polar orbit An orbit whose inclination is near 90°.

Porkchop plot Launch-arrival plot; computer-generated contours of characteristic energy C_3 on an x-y grid of launch and arrival dates. Often the contours take on the shape of a porkchop.

Potassium Element, symbol K, atomic number 19. Alkali metal, soft solid at room temperature, highly reactive.

Potassium hydroxide (KOH) Strongly basic compound used in aqueous solution as alkaline battery electrolyte.

Power flux density Quantity of energy transport through a unit of area, times time. Intensive quantity.

Power inverter Electronic device that converts direct current (DC) to alternating current (AC).

Power margin Difference between electrical power generated and that actually used.

Power transient Sudden, temporary increase in electrical power consumption, e.g., due to inrush current when a device first turns on and warms up.

Precession Property of a spinning mass wherein the direction of the axis changes, e.g., at right angles to an applied torque.

Preliminary Design Review (PDR) An important step in the life of a mission in which the review board determines whether a project is approved for final design and fabrication, Phase C.

Pressurant Gas head, e.g., helium, inside a tank of liquid propellant that provides the force to push the liquid propellant toward an engine or thruster.

Pressure thrust Component of force in a rocket engine that comes from exhaust pressure against the nozzle's interior surface. Terms to the right of the + sign (see description on p 127) in:

$$F = \dot{m}v_e + p_e A_e$$

Compare momentum thrust.

Pressure-regulated Mode of propulsion system operation in which pressurant is admitted through a regulator into the propellant tank during a rocket burn to maintain constant pressure and constant propellant flow rate. Compare blowdown.

Primary battery Spacecraft battery that supplies all the electrical power for a spacecraft's operation, e.g., *Sputnik*'s silver oxide-zinc battery, *Huygens*'s lithium-sulphur dioxide.

Principal investigator Professional scientist who leads the experiments and/or observations in one or more fields being carried out by a spacecraft. Typically at the level of an academic professor, with a team including grad students in the PI's discipline and staff scientists, engineers, and technicians.

Program Level of administration above the project level in a mission, e.g., a series of spacecraft having similar cost constraints or broad objectives, such as the NASA Mars Scout program. Characterized by a defined architecture and/or technical approach, requirements, funding level, and a management structure that initiates and directs one or more projects.

Program Instructions for a computer. Compare data.

Project Administrative level below the program level e.g., the *Phoenix* Mars lander flight project. Characterized by defined requirements, a life-cycle cost, a beginning, and an end.

Prometheus Innermost of the two "shepherd" moons straddling Saturn's F Ring (the other is Pandora). About 145 kilometers in length, mostly water ice.

Propane (C_3H_8) One of the hydrocarbons found in the outer solar system.

Propellant The reactant in a rocket engine or thruster, e.g., the xenon gas that is ionized and accelerated in an ion engine, the hydrazine that decomposes in a monopropellant thruster, or the granular mixture that burns in a solid rocket motor.

Proton The positively charged nuclear subatomic particle, similar in mass to the neutron.

Pseudo-noise code (PN) Pattern of bits that identifies the start of each telemetry transfer frame.

Pulsed plasma thruster Variation of the MPD thruster that uses solid propellant that ablates when the spark operates.

Push-broom Imaging technique using a detector consisting of a line of photogates. A two-dimensional image is built up by spacecraft motion, e.g., *Mars Reconnaissance Orbiter*'s HiRISE camera. The same technique is used in office photocopiers.

Pyrotechnic Device on a spacecraft that uses an explosive charge to power a one-time operation, e.g., shutting a valve, cutting a cable, releasing a bolt.

Quadrapod Four-legged support, e.g., holding a subreflector above a main reflector in a DSN antenna. Comparable to a tripod.

Qualification testing Procedures that determine a component's characteristics in operations to the extremes of envelopes such as temperature or pressure.

Quartz Mineral abundant on Earth consisting of silicon dioxide, SIO_2 in a tetrahedral lattice crystal.

Quasar Originally, quasi-stellar radio source. Now known to be an extremely distant, extremely powerful active galactic nucleus where matter enters a supermassive black hole. From Earth, quasars appear as a point source. Positions of some quasars in the sky form the basis of the International Celestial Reference Frame (ICRF).

Quaternion Mathematical construct that describes rotation in three dimensions. An algebra in which each object contains four scalar variables and objects can be operated on as single entities.

Radar Active remote sensing technique, originally "radio detection and ranging." Used for science observations in modes such as synthetic-aperture imaging, scatterometry, and altimetry, in which brief pulses of relatively high power radio energy are directed toward a target. In some modes these pulses are modulated with identifying tags. In all active modes, the echoes collected and analyzed.

Radar astronomy Branch of astronomy in which very high-power radio pulses, e.g., S-band or X-band frequencies, are transmitted from a DSN station toward a target of interest, e.g., a planet, an asteroid, or a moon. Reflected signal is captured typically by widely separated receiving stations on Earth, and correlated to form images, or extract other data from the echoes.

RA-dec Right ascension-declination; axes of rotation based on the celestial equator. Rotation in RA varies between east and west, and rotation in declination, normal to the celestial equator, varies north and south of it. RA is measured in hours, minutes, and seconds, tied to Earth's rotation, and declination is measured in degrees of arc N or S. Compare. Az-el.

Radiation Energy in the form of electromagnetic waves (see Appendix D, p 342), or moving subatomic particles.

Radio and plasma waves
Subject of scientific study concerning waves of audio frequency through radio frequencies up to the tens of MHz generated in plasma or emitted by natural processes in the magnetic environments of the Sun and planets.

Radio astronomy The study of celestial objects at radio frequencies.

Radio science celestial mechanics
Experiment in which a natural object's mass is determined by measuring the velocity changes the object induces in the spacecraft via gravitation. Velocity measurement is via Doppler shift evident in the frequency of the spacecraft's two-way coherent carrier signal.

Radio science data One of the seven DSN data types. Uses the spacecraft radio transmitter(s) and the DSN as a science instrument system to help characterize a target or phenomenon in any of several modes. During ring or atmospheric occultation experiments, the spacecraft's signal passes through the subject of study, and effects on the received signal, such as attenuation, scintillation, polarization, are recorded and studied. Other modes include celestial mechanics experiments, gravitational wave searches, bistatic radio, relativistic effects of the Sun, and solar corona characterization.

Raw image An image, e.g. from a spacecraft's CCD, to which calibrations have not yet been applied to yield highest scientific quality. Not contrast enhanced, or combined into a color image, etc. See page 193.

RHU Radioisotope heater unit; device containing a small amount of encapsulated radioisotope that constantly emits heat typically at about 1 watt. Situated within spacecraft bus or appendages as needed for thermal control.

Radioisotope An element that has an unstable nucleus, which emits radiation as it breaks down.

Radiometer Passive remote-sensing science instrument used to measure the natural radio emission, e.g., microwave frequency, from a target. Compare photometer.

Radiometric Type of navigation observable data acquired by DSN, e.g., Doppler shift of a spacecraft carrier signal, range measurement, or VLBI observation. Compare optical navigation.

Radiometry Science or science data concerned with the quantity or power of electromagnetic radiation, e.g., microwave radio energy that a target naturally radiates, measured using radiometers. Field of science that studies this phenomenon, e.g., in analyzing target surface composition. Compare photometry.

Range data Tracking data acquired by DSN that measures round-trip line-of-sight distance between DSN antenna and spacecraft.

Ranging tone Modulation applied to DSN uplink and subsequently spacecraft downlink carrier signal used by navigators to determine round-trip line-of-sight distance to the spacecraft.

Reaction control system (RCS) Spacecraft propulsion system thrusters used for attitude control and the occasional TCM or OTM.

Reaction wheel AACS output device for applying torque to a spacecraft. Small, electrically driven wheel, with mass typically on the order of 10 kilograms, the rotational axis of which is fixed in the spacecraft's body. Typically arranged in a set of three or more with orientations that permit applying torque, in positive and negative directions, to the spacecraft in all three axes. Also called momentum wheels. Compare control-moment gyro.

Real time Operations in which there is minimum delay (even if round-trip light time is measured in hours or days) between the ends of a system, e.g., in a control system where a sensor's input is processed immediately into outputs that automatically change the system's state (e.g., anti-lock brakes) or which humans observe and optionally make control inputs. By comparison, non-real time would describe operation of ground-based data storage facility that users can access at their convenience.

Receiver Radio device that selects a desired frequency, amplifies it, and harvests information, e.g., music or spacecraft telemetry, from it. Compare transceiver.

Red alarm Visual and/or audio alert, e.g., on computer screen and pager, highlighting a telemetry measurement that exceeds limits set by engineers. Represents a condition that threatens or would tend to threaten spacecraft health or safety.

Reed-Solomon Forward error-correction coding scheme in which blocks of data in the spacecraft's computer are rendered into polynomials whose evaluation at various points become the data to be transmitted.

Reflectance Spectrum Wavelengths of light reflected by an object's surface. Because the target may absorb some of the incident light's wavelengths, the reflected spectrum may be diminished in those wavelengths, providing information about the surface's composition. A flower that appears red to the eye has absorbed blue wavelengths of light.

Reflection Change in a wave's direction at an interface between two different media. Includes scattering and/or specular returns.

Refraction Change in a wave's direction due to a change in its speed, e.g., when it passes from one medium to another.

Regolith Blanket of dust, soil, or broken rock covering a rocky surface.

Relay Electromechanical device in which electrical contacts, e.g., in a power distribution circuit, are operated by an electromagnet whose coil is energized by a smaller current, e.g., from a computer.

Relay Radio communications from Earth to one spacecraft which transmits to another or vice-versa, e.g., command and telemetry data communications between Earth, a Mars orbiter, and a Mars rover. The spacecraft-to-spacecraft leg is called *crosslink*.

Remote-sensing Category of science instruments that make observations of phenomena at a distance, such as passive-sensing cameras, or active-sensing imaging radars. Compare direct-sensing.

Resistojet Electrothermal means of propulsion that employs a high-current electric resistance heating unit such as a wire, that causes high temperature in a rocket chamber, and introduces a fluid propellant, e.g., argon or hydrazine, which expands out the nozzle. High I_{SP}, low thrust.

Right ascension One of a pair of coordinates in the celestial sphere. Measured in the east-west arc. Compare declination.

Roll Rotation about a spacecraft's vertical (Z) axis.

Room temperature For scientific applications, an average of 21°C, or 294 K.

Rover One of eight classifications of spacecraft. Spacecraft designed to land on a body's surface and travel to gather science data, e.g., to place direct-sensing science instruments in contact with selected targets.

RTG Radioisotope thermoelectric generator; spacecraft electric power supply that uses heat produced by the natural decay of a radioisotope, thermocouples, and radiator fins, to generate current using thermal gradient and Seebeck effect, with no moving parts.

S-band Range of microwave frequencies around 2 to 4 GHz.

Safing Spacecraft condition, typically in response to an anomaly detected by a fault protection monitor, in which the spacecraft's normal operations are suspended, and its attitude, electrical power, and other factors are driven to states that will keep the spacecraft and its instruments from suffering damage.

Sagittarius A* (asterisk pronounced *star*) Point in the sky where lies the supermassive black hole at our galaxy's center. Time-lapse observations (see Internet) reveal high-velocity proper motion of stars orbiting the mass.

SAR Synthetic aperture radar; imaging radar technique in which radio signals reflecting back from a transmitted pulse are captured along the distance the physical receiving antenna travels during reception. Image pixels are made up of lines of equal reflected distance intersecting with lines of equal Doppler shift.

SAR swath Relatively narrow strip of radar image data acquired along the surface of a body.

Saturation (light) The point at which the electronic charge on a CCD pixel is maximum and will overflow into adjacent pixels.

Saturation (angular momentum) The point at which a reaction wheel's RPM can no longer be safely increased.

Saturn Sixth planet from the Sun, one of the four gas giants or Jovian planets. Equatorial diameter 9.449 times Earth's. H_2 atmosphere with about 3 percent He and trace amounts of other substances, including ammonia and water-ice clouds. Mean distance from Sun 9.58 AU.

Saturn radius 1 R_S = 60,330 kilometers at the equator.

Scan platform Articulated spacecraft appendage that can point instruments independently of spacecraft attitude.

Scatterometry Radar investigation in which a signal is transmitted to a surface and the amount of reflected energy is measured. Noise is also recorded between transmit pulses, for subtraction from the reflected signal. Can be used to infer wind direction and speed over an ocean due to variations in reflected energy from waves of various heights and orientations.

Science data Telemetry returned from a spacecraft's science instruments, e.g., cameras, spectrometers, etc., or measurements of the spacecraft's carrier signal in a radio science experiment such as atmospheric occultation. Compare engineering data.

Scintillation Twinkling; rapid variations in apparent intensity, e.g., of a spacecraft's radio signal as it passes through a ring system or an atmosphere. Also, a flash of light produced in a transparent material by an event of ionization, used in some high-energy particle detectors.

Scintillator A transparent material used in some high-energy particle detectors to reveal passage of particles by flashes of light produced in the material.

Secondary battery Rechargeable battery in a system that is primarily powered by another source. Supplies electrical power during relatively short periods when primary source is unavailable, e.g., solar panels in shadow.

Seebeck effect Thermoelectric effect. Conversion of temperature difference directly to electrical current. Principle of RTG operation.

Selenium Element, symbol Se, atomic number 34, a non-metal, solid at room temperature. Photovoltaic.

Semaphore A rudimentary signal sent without telemetry, such as via a subcarrier modulated onto a carrier to indicate spacecraft health or presence of an anomaly, or by interruptions of the carrier to indicate events such as parachute deployment.

Semiconductor Substance that conducts electric current in one direction only, e.g., crystalline silicon. Used to create electronic components.

Semi-monocoque Structural design in which a vehicle's skin supports part of its structural load, e.g., aircraft fuselage.

Sequence See command sequence.

Series connection Electrical arrangement in which each of several units, e.g., cells in a battery, has its positive terminal tied to the next unit's negative terminal. Increases voltage, maintains current. Compare parallel connection.

SETI Search for extraterrestrial intelligence; Scientific investigation that examines radio and light received from sources among the stars for evidence of communications between intelligent lifeforms.

Shannon limit Theoretical upper limit to rate of data communications in a noisy physical channel such as radio or light. Given as C, by:

$$C = B \log_2(1 + \tfrac{S}{N})$$

where

B is the channel bandwidth in hertz.

S is the signal power

N is the noise power

($\frac{S}{N}$ is the signal-to-noise ratio)

Shear plate Spacecraft structural member that typically closes the inboard and outboard faces of a bay, bearing load in the shear direction.

SI International System of Units; Metric system universally used in science, and dominant in international commerce and trade.

Signal Radio waves generated by spacecraft or DSN station for communications. Also, an electromagnetic phenomenon sought out, e.g., by some science instruments.

Signal level Amount of power in a signal.

Signal-to-noise ratio (SNR) Ratio of the signal power to the ambient noise power in the frequencies of interest.

Silicaceous (S-type) Asteroids Asteroids made of stony material, similar to ordinary chondrite meteorites. S-type asteroids comprise about 17 percent of known asteroids and typically occupy main belt's inner regions.

Silicon Element, symbol Si, atomic number 14. An important semiconductor and photovoltaic material.

Silver Element, symbol Ag, atomic number 47. Metallic, solid at room temperature.

Single-fault tolerant State of being able to continue to operate after having experienced the failure of one component in a subsystem, e.g., through redundant hardware.

Sky crane Liquid-propellant spacecraft module designed to lower *Mars Science Laboratory* to the surface.

SLA Super light weight ablator; cork-like proprietary thermal protection system material made by Lockheed Martin Corporation used to coat the forward surface of atmospheric heat shields. When heated by atmospheric friction, it forms an IR-opaque gas layer between the hot shock wave and the spacecraft.

Sodium Element, symbol Na, atomic number 11, an alkali metal. Salts impart a characteristic yellow color to a flame. Vapor strongly emits yellow wavelengths close to 589 nm.

SOHO Solar and Heliospheric Observatory; spacecraft in Earth's L1 Lagrange point making continuous, multispectral observations of the Sun, its solar wind emissions and background stars, and the occasional nearby planet or comet. (Images and movies are easily found online.)

Sojourner Mars rover deployed on July 4, 1997 by *Pathfinder* lander. First successful rover on another planet. Length, width, height: 65×48×30 cm. Mass: 10.6 kilograms. Returned 550 images and analyzed mineralogy of sixteen locations near the lander during an 83-sol lifetime.

Solar array drive Electric motor driven actuator that orients a solar panel or array in one or more degrees of freedom and provides feedback to its controller.

Solar cell Piece of photovoltaic material with conductors attached to provide electric current when illuminated.

Solar occultation Passage of a spacecraft behind an object as viewed from the Sun.

Solar panel Array of solar cells on a substrate.

Solar photon pressure Also called solar radiation pressure. Constant small force due to incident sunlight. Useful for solar-sailing. While Earth-orbiting spacecraft feel other small forces that might drown out its effect, it is a dominant small force for interplanetary spacecraft to accommodate, such as by frequent reaction wheel momentum desaturation maneuvers, if the spacecraft presents an asymmetric profile, e.g., *Mars Climate Orbiter* (p 49).

Solar sailing Method of harnessing solar photon pressure (not to be confused with solar wind) as a propulsive force for navigating a spacecraft in interplanetary, and perhaps interstellar flight. To date, no dedicated spacecraft has succeeded in demonstrating its use, although the *Messenger* spacecraft used its large solar shade in 2008 to skip a planned TCM by solar-sailing closer to its aim-point. While previous spacecraft have used solar photon pressure for attitude control, e.g., *Mariner 10* in 1974, the *Messenger* team developed a sequence of body and shade attitude, and solar-array orientations, which affect orbital parameters, and should reduce the number of TCMs needed in the future.

Solar wind Plasma, largely of hydrogen nuclei (protons) and electrons, which the Sun continuously emits, inflating the heliosphere. *Ulysses* spacecraft determined that its speeds are much higher at high solar latitudes.

Solid rocket motor (SRM) Simple propulsion system comprising a mixture of granular fuel, oxidizer, and combustible binding agent, which do not react until they are ignited. Molded into a low mass shell equipped with nozzle. Once ignited, solid propellant continues burning until exhausted, providing all its impulse in one application.

Solid-state data recorder Mass data storage device on interplanetary spacecraft that uses dynamic random-access memory — the commercial DRAM devices that are used in personal computers — in bulk. Protected from bit-flips caused by radiation in interplanetary space by error-detection and correcting "scrubbing" algorithms and by physical radiation hardening and shielding. Typical capacity around 2 Gbits (despite enormous advances in consumer products that have not been space-qualified as of press time).

Solid-state power switch Electronic assembly that provides electric power to selected spacecraft components on command. Replaces electro-mechanical relays and thermal fuses with more reliable solid-state devices, which have the capability to detect, control, and isolate faults in flight, and provide individual-line reset capability.

Space weathering Erosion of the surface of airless bodies in the solar system caused by cosmic ray collisions, solar irradiation, sputtering and implantation of solar wind particles, and bombardment by meteors of all sizes.

Spacecraft Vehicle designed for flight outside Earth's atmosphere. Singular and plural.

Space-link session DSN pass. Tracking period during which a spacecraft passes across the sky.

Specific energy Energy per unit mass, expressed as Joules/kilogram. In SI base units, m^2/s^2.

Specific impulse Written I_{sp}, impulse per unit propellant, an intensive quantity describing rocket efficiency. Based on propellant mass or propellant *weight,* (mass affected by Earth standard gravity). In the latter usage, units of I_{sp} are seconds. Simplified form (see description on page 124):

$$I_{sp} = \frac{v_e}{g_0}$$

Spectral density Power per unit frequency, expressed as dBm/Hz or W/Hz.

Spectrograph See spectrometer. "Graph" refers to drawing or recording data vs measuring. Early instruments made *spectrographs* on film (compare *photograph*). Instruments have evolved over time and the "-graph" and "-meter" suffixes overlap.

Spectrometer Passive remote-sensing optical science instrument that disperses incident light (or IR, UV, X-ray, etc.) and measures the intensity of each of a number of wavelengths observed.

Spectrophotometer See spectrometer.

Spectroscope See spectrometer. "Scope" implies the instrument is fitted with an eyepiece for visual observation.

Spectroscopy Branch of science involving measurement of a quantity as function of its wavelength or frequency or energy. See Appendix D, p 342. Applies to any part of the electromagnetic spectrum.

Spectrum, electromagnetic All possible electromagnetic radiation frequencies, (or wavelengths, or energies). See Appendix D, p 342.

Specular reflection Mirror-like reflection at microwave through optical wavelengths, in which a ray from a single incoming direction is reflected to a single outgoing direction. Compare backscatter.

Sphere-cone shape Form of atmospheric entry heat shields, with spherical component at front, trailing back in a cone whose appropriate angle depends on medium and conditions of entry. Illustration p 172.

SPICE file Acronym for "Spacecraft, Planet, Instruments, C-matrix (camera angles), and Events" file; a file that provides context for such science observations as spacecraft and planetary ephemerides, instrument mounting alignments, spacecraft orientations, sub-spacecraft coordinates, distance to target, illumination geometry, sequences of events, and data for time conversions.

Spin bearing assembly Interface between a spinning spacecraft and its de-spun section, typically accommodating the transfer of mechanical loads, electrical power, radio signals, and/or data.

Spin stabilization Mode in which a spacecraft's attitude is maintained by setting the whole spacecraft spinning about one axis. Compare three-axis stabilization.

Spirit Name of the Mars Exploration Rover that landed at Gusev crater in 2004, three weeks before its twin, *Opportunity*, landed on the opposite side of Mars.

Spitzer Space Telescope One of the four NASA Great Observatories. Sensitive to IR sources. Launched August 25, 2003, *Spitzer* occupies a heliocentric orbit, trailing Earth's position. Telescope is 85-centimeter aperture Ritchey-Chrétien optical design. Instruments and telescope are cooled by evaporation of liquid helium to minimize IR noise. The coolant is expected to run out in early 2009, but operation of one of its instruments in warm mode has been funded. Originally called *Space Infrared Telescope Facility (SIRTF)*, renamed *Spitzer Space Telescope* after launch.

Sputnik Series of Soviet Earth-orbiting spacecraft, including the world's first, launched October 4, 1957.

Standard deviation Root-mean-square (RMS) deviation of values from their mean, noted as sigma, σ.

Standard gravity Acceleration at Earth's surface, 9.80665 meters per second per second (m/s^2).

Star scanner AACS celestial reference input device that estimates attitude about three axes by timing the passage of stars through each of two slits as the spacecraft rotates.

Star tracker AACS celestial reference input device that provides information about excursions in attitude about a single axis, by measuring angular movement of a single bright star that is constantly held in its field of view.

Star A massive, luminous ball of plasma, e.g., the Sun. Others are enormously distant and therefore appear much dimmer.

Stardust NASA Spacecraft that captured and returned particles from comet tail and interplanetary dust to Earth January 15, 2006.

Statistical maneuver A trajectory correction or orbit trim maneuver that compensates for the variations that are a normal part of the navigation process, such as a small adjustment following a flyby.

Stefan-Boltzman constant Relates energy emission to temperature as (K is temperature in kelvins):

$$E = 5.67x10^{-8}W/m^2/K^4$$

Stellar occultation Passage of a star behind an object of interest. Often used to search for or measure an atmosphere or ring system.

Stellar reference unit (SRU) AACS celestial reference input device with a telescopic field of view and star recognition system, which can provide attitude reference information in all three axes whether the spacecraft's orientation is rotating or not.

Stirling Radioisotope Power System (SRPS) Mechanical device whose Stirling engine obtains power from a thermal gradient to run an alternator and generate electrical power. Thermal gradient set up by hot radioisotope at one end and cooling fin at the other.

Stratosphere Atmospheric layer above a troposphere and below a mesosphere. Temperature is stratified, cooling with altitude.

Structure subsystem Spacecraft low-mass skeleton that provides mechanical support and alignment for the other subsystems.

Strut Structural system member, often set in triangles to support instruments or rocket thruster clusters. Often made of carbon fiber tube with metallic end fittings.

Subassembly Component of a spacecraft or ground system below the level of assembly. Hierarchy is: system, subsystem, assembly, subassembly.

Subsystem Component of a spacecraft or ground system below the level of system and above the level of assembly. Hierarchy is: system, subsystem, assembly, subassembly.

Subcarrier Tone modulated onto a carrier. May represent a semaphore or carry its own modulation.

Sublimation Change of state from solid directly to gas.

Submillimeter Typically describes a radio signal less than 1 millimeter in wavelength.

Subreflector Secondary reflector on a Cassegrain HGA or DSN antenna, smaller than the main reflector, mounted on a tripod or quadrapod above the main reflector. Comparable to the secondary mirror in a Cassegrain telescope.

Sufficiently-stable oscillator (SSO) Assembly in a telecommunications subsystem that achieves good frequency stability as a reference for generating the downlink carrier signal, typically on the order of less than 10^{-11} (Allen deviation) over a period of up to 1,000 seconds. This is useful for some radio science experiments, such as occultations, and can support a link carrying telemetry and range modulation. Navigation requires typically better stability.

Sulphur Element, symbol S, atomic number 16. A yellow non-metallic solid at room temperature.

Sun Center of mass of the solar system. G2 in stellar spectral class. Inflates bubble of plasma called the heliosphere, which collides along a bow-shock in the interstellar medium. Solar-generated radiation and magnetic field dominates the heliosphere.

Sun sensor AACS celestial reference input device that provides information on attitude excursions, e.g., in pitch and yaw.

Sun-Earth-probe angle (SEP) Angle between the Sun, the Earth, and the spacecraft (probe). Approaches zero at superior conjunction each year for spacecraft operating near the ecliptic.

Sun-synchronous orbit Spacecraft orbit about a planet in which the orbit plane is maintained in an orientation that provides a desired solar illumination of the surface around spacecraft periapsis, e.g., 2 P.M. local solar time, to take advantage of a desired length of shadows on the surface.

Superior conjunction Conjunction (coincidence of right ascension) of a planet or spacecraft with the Sun when the Earth and the planet are on opposite sides of the Sun. This period may pose difficulties communicating with a spacecraft due to the Sun's radio noise. Compare opposition.

Supernova Explosion of a dying star that releases a burst of radiation that can briefly outshine an entire galaxy, while creating heavy elements and ejecting matter into interstellar space.

Swing-by Flyby of a planet by a spacecraft for the purpose of obtaining a gravity assist.

Symbol Unit of modulation, e.g., in microwave binary phase key shift, in which the phase of the carrier signal is stepped back and forth between two predetermined values. In interplanetary application, a number of symbols greater than one constitute a single bit of data.

Synchronous rotation Rotation of a natural or artificial satellite as it keeps one side toward the primary body due to gravity gradient, as the Moon is in synchronous rotation with the Earth.

System noise temperature Contribution of radio noise from the receiving antenna, its reflectors, and waveguides, low-noise amplifier, etc., measured in kelvins.

System A flight system (spacecraft) or a ground system (DSN etc.). Hierarchy is: system, subsystem, assembly, subassembly.

TAI Temps Atomique International; the weighted average of the time kept by hundreds of atomic clocks in over fifty national laboratories worldwide. TAI minus UT1 was approximately 0 on January 1, 1958.

Tantalum Element, symbol Ta, atomic number 73. Dense metal, solid at room temperature. Used in high-performance capacitors, and as radiation shielding for sensitive electronics in interplanetary space.

Target plane See B-plane.

Target-motion compensation See image motion compensation.

TCG Geocentric Coordinate Time; defined in 1991 with TT.

TCM Trajectory correction maneuver; spacecraft propulsive maneuver that makes a small adjustment in targeting and/or arrival time. Compare OTM.

TCP/IP Transmission control protocol, Internet protocol; suite of communications protocols in use on the Internet and other networks, named for two of its significant protocols. Designed as a system of layers, each with well-defined activities and interfaces with adjacent layers.

TDT Terrestrial dynamic time; obsolete, replaced by TT in 2001.

Telecommunications channel A band of frequencies used for communications.

Telemetry channel A series of repeating measurements in telemetry such as the temperature at a specific point. Illustration p 40.

Telemetry data One of the seven DSN data types. Symbols modulated on a spacecraft's downlink carrier are reconstituted into digital bits representing science instrument observations such as images, spacecraft engineering conditions such as pressures and temperatures, and optical navigation observations.

Telepresence Technologies that allows a person to feel present, or to have an effect, at a location other than their true location.

Termination shock Region in the outer heliosphere where the solar wind slows to subsonic speed and bunches up. *Voyager 1* and *Voyager 2* have penetrated this region while measuring and telemetering ambient conditions to Earth.

Thermal emission spectrometer Passive remote sensing far-IR optical science instrument that captures spectra naturally emitted or reflected from targets. Can be used to identify mineral composition.

Thermal energy Difference between the internal energy of an object (due to motion of its molecules, chemical bonds, etc.) and that which it would have at absolute zero, 0 K. Increased or decreased by heating or cooling.

Thermionic emission Electrons expelled from a hot material in vacuum. Cathode rays. Edison effect.

Thermocouple Union of two dissimilar metals that generates electric current proportional to temperature gradient.

Thermopile Collection of multiple thermocouples into a single unit.

Thermometer Instrument which measures temperature, e.g. as part of a suite of atmospheric structure instruments.

Three-axis stabilization Mode in which a spacecraft has individual control over its attitude in pitch, yaw, and roll. Compare spin-stabilization.

Three-way coherent Telecommunications mode in which a spacecraft receives an uplink from DSN station A, while DSN station B is in lock with the spacecraft's downlink. The downlink is phase-coherent with the uplink, creating the substantial frequency stability of a massive ground-based maser.

Thrust Force of reaction, e.g. upon operating a rocket.

Thruster Small liquid-propellant rocket engine.

Thruster-valve assembly Small liquid-propellant rocket engine with integral electrically controlled valve to admit propellant(s) on demand.

Thrust-vector control Mechanical means of changing direction of a rocket nozzle and/or its exhaust stream direction.

Time-division multiplex (TDM) Scheme for transmitting more than one measurement over a single telecommunications channel, by arranging for each measurement to take turns over time.

Titan Largest satellite of Saturn and second largest moon in solar system after Jupiter's Ganymede. Discovered 1655 by Christiaan Huygens. Diameter 5,150 kilometers, larger than the planet Mercury. Nitrogen atmosphere has methane and ethane clouds and probably rain, surface pressure 146.7 kPa ($\approx$1.5 bar). Lakes on surface are filled with liquid ethane and probably methane. Bulk of Titan is about half water ice and half rocky material, density 1.88 g/cm^3. Explored by *Cassini* and *Huygens* spacecraft 2004 through present.

Titanium Element, symbol Ti, atomic number 22. A strong, lightweight metal at room temperature.

Topocentric Relative to a point on a body's surface rather than its center. Compare geocentric.

Total impulse Integral of a rocket's thrust over time.

Tracking data One of the seven DSN data types. Provides radiometric measurement of a spacecraft signal's Doppler shift, the line-of-sight range or distance, and its right ascension and declination.

Trajectory A path through space. An orbit or a portion of an orbit.

Transceiver Radio device that combines receiver and transmitter.

Transfer frame Formatted group of bits, defined by CCSDS within the data link layer, which groups telemetry data into units for transmission to Earth. May contain many packets, or one packet may span transfer frames.

Transformer Electrical device that uses induction to transfer electrical energy from one circuit to another. Can step voltage up or down across circuits.

Transistor Semiconductor device used to amplify a signal or switch electrical current.

Transmitter Electronic component that amplifies a radio frequency signal to high power, e.g., for concentration by an antenna in a beam aimed toward a spacecraft or the Earth.

Trans-Neptunian object An object that orbits the Sun at greater distance than Neptune, e.g. in the Kuiper belt.

Traveling-wave tube amplifier Electronic vacuum-tube on a spacecraft that inputs a low-power microwave signal and outputs a high-fidelity replica of the signal at a suitable power level for sending across interplanetary space.

Triode Electronic vacuum tube amplifier with three elements: heated cathode, grid, and anode plate.

Triple-point Temperature and pressure conditions at which a substance can exist at solid, liquid, or gas. This exists for water on Earth's surface, and for methane on or near the surface of Saturn's moon Titan.

Triton Largest natural satellite of Neptune. In a retrograde orbit. Diameter 2,706.8 kilometers. Nitrogen snow covered large areas at the time of *Voyager 2*'s encounter in 1989, when active nitrogen geysers were also observed.

Troposphere Atmospheric layer above a body's surface. Often turbulent.

Truss Structural element made up of triangular supports.

TT Terrestrial time; defined in 1991 to be consistent with the SI second and general relativity.

Tungsten Element, symbol W, atomic number 74. Metal, solid at room temperature, has the highest melting point of all metals (3,421.85°C), and highest tensile strength at elevated temperature.

Turbo code Forward error correction system in which encoding occurs in parallel. At the receiving end, each of two decoders is given a different encoded version of the original data. The algorithms collaborate to decode the message, iterating several times and comparing notes to reach a consensus on a correctly decoded result.

Turing test Proposal, by English mathematician Alan Turing (1912–1954), for a test of a machine's ability to demonstrate intelligence in which a human judge engages in a natural language conversation with one human and one machine. If the judge cannot reliably tell which is which, the machine is said to pass the test.

2001 Mars Odyssey NASA Planetary orbiter spacecraft, investigating Mars since 2001.

Two-way Communications mode in which a spacecraft receives an uplink from DSN, and the same DSN station receives a downlink from the spacecraft. Can be either coherent or non-coherent.

Two-way coherent Telecommunications mode in which a spacecraft receives an uplink from DSN, while the same DSN station is in lock with the spacecraft's downlink and the downlink is phase-coherent with the uplink, enjoying the substantial frequency stability of a massive ground-based frequency reference.

Two-way non-coherent (TWNC) Telecommunications mode in which a spacecraft receives an uplink from DSN, and the same DSN station is in lock with the spacecraft's downlink, but the downlink is not phase-coherent with the uplink. Instead, an on-board oscillator generates the downlink frequency.

Ultra-stable oscillator (USO) Assembly in a telecommunications subsystem that achieves good frequency stability as a reference for generating the downlink carrier signal. This is useful for some radio science experiments, such as occultations, and can support a link carrying telemetry modulation, although navigation requires better stability.

Ultraviolet (UV) Electromagnetic radiation in wavelengths of about 400 nanometers to 10 nanometers, or energies of about 3.1 eV to 124 eV. See Appendix D, p 342. Produced in nature by stars.

Ultraviolet Spectrometer See spectrometer. Measures invisible "colors" in the UV.

Ulysses ESA spacecraft launched 1990, which increased its solar orbit inclination to 80.2° via Jupiter gravity assist, and observed the inner heliosphere at high latitudes. Mission ending at press time.

UMDH Unsymmetrical dimethyl hydrazine ($C_2H_8N_2$), liquid rocket fuel.

Universal time (UT) Defined by the Earth's rotation, formerly determined using astronomical observations. GPS serves today. Refer to TAI and UTC.

Universe Everything that exists, including space-time, energy, and matter.

Uplink Signal sent from DSN to spacecraft. May be pure carrier, or carrier modulated with ranging tones and/or command data, on the carrier or on subcarrier(s).

Uranium Element, symbol U, atomic number 92. Metallic, radioactive, solid at room temperature.

Uranus Seventh planet from the Sun, one of the four gas giants or Jovian planets. Equatorial diameter 4.007 times Earth's. Atmosphere of H_2 with about 15 percent He and 2 percent methane. Discovered by William Herschel (1738–1822) in 1781. Mean distance from Sun 19.2 AU.

UT Universal Time, the new name proffered in 1928 for GMT by the International Astronomical Union. See also its variations UT0, UT1, and UT2, below.

UT0 Uncorrected UT as obtained from meridian circle observations or via GPS.

UT1 UT corrected for polar motion.

UT2 Largely obsolete. UT1 corrected for seasonal variations in the Earth's rotational speed.

UTC Temps Universel Coordonne. Coordinated universal time; introduced in 1972, UTC differs from TAI by an integral number of seconds. Leap seconds are introduced in UTC as needed, typically on January 1, to keep the difference between UTC and GMT less than 0.9 s.

Vacuum tube Sealed envelope, typically glass, evacuated to about 1 μP, inside of which thermionic emission moves from a heated cathode toward a target having opposite polarity.

Vaporization Change of state from liquid to gas via evaporation or boiling.

Vector System of notation for any quantity that has both magnitude and direction, such as spacecraft velocity, angular or linear momentum, magnetic fields, etc. Notation includes arrows.

Vectran Manufactured fiber that forms the cloth used in space suits and Mars lander airbags. Stronger than Kevlar.

Vega Soviet program that included two flyby spacecraft, each of which encountered Venus, dropped off landers and atmospheric spacecraft, and then encountered Comet Halley.

Velocity Vector quantity of speed and direction.

Venera Soviet program that included sixteen orbiter, lander, and atmospheric missions to Venus. Thirteen were successful.

Venturi effect Reduction of fluid pressure at increased speed, e.g., over an airfoil.

Venus Second planet from the Sun, one of the four terrestrial planets. Diameter 0.949 of Earth's. Dense, high-pressure CO_2 atmosphere overcast with SO_2 clouds. Mean distance from Sun 0.723 AU. Mean surface temperature 460°C.

Venus Express ESA's follow-on from its *Mars Express*. Many instruments are simply upgraded versions of those on the Mars platform. After a 153-day cruise to Venus, the spacecraft entered Venusian orbit on April 11, 2006.

Vernal equinox Annual equinox (on Earth, in the month of March), the beginning of northern-hemisphere spring. On an equinox, the Sun's center spends nearly equal time above and below the horizon at every location on Earth. At equinox, the Sun is at a point on the celestial sphere where the celestial equator and ecliptic intersect. Compare autumnal (September) equinox.

Vesta Asteroid (minor planet) in main asteroid belt, about 530 kilometers in diameter. Brightest asteroid, second most massive in belt. One of the targets intended for the *Dawn* spacecraft to orbit in 2011. Compare Ceres.

Vidicon Image sensor based on vacuum tube incorporating phosphor-scanning electron beam. Older technology, replaced by CCD image detectors.

Viking NASA mission to Mars with two orbiters and two landers, which touched down June and July 1976 and returned imaging and other science data for years via telemetry.

Visible light Electromagnetic waves in the wavelength range of about 380 nanometers to 750 nanometers, to which the human eye is sensitive — about one octave.

Viterbi algorithm in information theory serves to discover the most likely sequence of hidden states. Applied to decode modulated radio symbols into telemetry bits in the DSN's maximum-likelihood convolutional decoder.

VLBI data Very long baseline interferometry data, one of the seven DSN data types, comprises sampled, time-tagged, packetized representations of incoming microwave signals from a single source, collected by two widely separated antennas. Transmitted to a correlator for processing. Useful for spacecraft navigation, study of Earth's crustal dynamics, and radio and radar astronomy.

Voice net Used in realtime flight operations, one of a set of several live conversations using telephone technology. Each of a dozen or so nets can be enabled for listening, muted, or selected for transmitting. Voice protocol adheres to international standard phraseology similar to air traffic control radio communications.

Voice-over-Internet-protocol (VOIP) Process wherein audio-frequency waves are sampled many times per wave, represented numerically, and sent via Internet-protocol packet-mode communications. Upon receipt, packets are sorted into correct order, missing packets retrieved if possible, and audio waveforms reproduced, all at high-enough speed to be virtually undetectable in real time.

Volatiles Substances that evaporate, e.g., when exposed to vacuum or increased temperature.

Voltage converter A device that outputs a specific AC or DC voltage from an AC or DC input at higher or lower voltage than the device produces. Any deficit of source voltage is accommodated, at the expense of increased current draw, by elaborate circuitry. Excess energy converted to heat.

Voltage regulator Device that produces a steady DC voltage, regardless of current draw, from an input of unsteady but higher voltage. Excess energy converted to heat, which can be used for specific purposes on a spacecraft.

Voltage Electromotive force; electrical tension; difference of electrical potential. Analogous to the pressure of water in a pipe.

Voltaic pile Crude electrochemical battery made, e.g., of copper and zinc discs separated by brine-soaked paper.

Voyager 1 spacecraft Launched September 5, 1977 after *Voyager 2*, returned observations of the heliosphere, and the Jovian and Saturnian systems. Penetrated Sun's termination shock July 2008 at 94 AU on northerly trajectory. Operations continue at press time.

Voyager 2 spacecraft Launched August 20, 1977, before *Voyager 1*, returned observations of the heliosphere, and the Jovian, Saturnian, Uranian, and Neptunian systems. Penetrated Sun's termination shock July 2008 at 86 AU on southerly trajectory. Operations continue at press time.

Watchdog timer Software algorithm that regularly checks a situation, and decrements a counter when a check returns a negative result, then passes information or control to a different algorithm if or when the count reaches zero (or a preset value). Positive results of check will normally reset the counter to a default value.

Wave-front Leading edge of an expanding sphere of electromagnetic energy, a surface of points having the same phase, as its electric field and magnetic field propagate one another at the speed of light.

Waveguide Pipe-like structure usually rectangular in cross section with smoothed interior walls, which guides the propagation of microwave radio signals with low loss of signal strength. Compare with fiber-optic filament that guides light.

Wavelength The physical distance between subsequent peaks (or troughs) in the electric or magnetic field strength of a propagating electromagnetic wave, symbol λ.

WMAP Wilkinson Microwave Anisotropy Probe. Project in NASA Explorer Program. Launched 2001, produced first microwave full-sky map at resolution $< 1°$. Named for American cosmologist David Wilkinson (1935–2002). Operations continue as of late 2008

Wolter telescope Configuration that gathers high-energy photons using grazing-incidence mirrors, e.g., in concentric arrangement. Illustration p 197. See also *Chandra,* p 300.

X-band Range of microwave frequencies around 8 to 12 GHz.

Xenon Element, symbol Xe, atomic number 54, gaseous at room temperature, one of the six noble gases. Used in strobe lamps due to its bright emission of light when excited. Serves as propellant in ion engines on spacecraft.

X-ray Electromagnetic radiation in the region from about 10^2 to about 10^5 ev. See Appendix D, p 342. Produced in nature by highly energetic events, e.g., compression of matter at the threshold of a supermassive black hole.

X-ray fluorescence spectrometer Direct-sensing science instrument. In active-mode, illuminates target at close range with built-in x-ray or γ-ray source and observes secondary, fluorescent, lower-energy x-rays from the target, to identify chemical elements. Passive mode would observe fluorescence from targets illuminated by natural source such as Sun.

Yaw Vehicle rotation about (typically) its longitudinal Y axis.

Yttrium Element, symbol Y, atomic number 39. Metallic, solid at room temperature. Used as the phosphor that produces red color in a television cathode ray tube. Constituent in the yttrium-aluminum garnet (YAG) laser.

Yo-yo Spacecraft despin mechanism that unreels and releases two tethered masses to dissipate its angular momentum, and reduce the spin rate of a spacecraft.

Zenith The point directly above an observer. Compare nadir.

Zinc Element, symbol Zn, atomic number 30. Metallic, solid at room temperature.

Index