sign "has got a lot of challenges," observes Mark R. Oderman, managing director of CSP Associates in Cambridge, Mass., who has surveyed new rocket technologies. Oderman says the Roton has many features "that imply high levels of technical or financial risk."

Space Access in Palmdale, Calif., is designing an altogether different but equally daring craft. Its heavy space plane would take off and land horizontally under the power of a proprietary engine design called an ejector ramjet. This novel engine, which has been tested on the ground, will propel the craft from a standstill to Mach 6, according to Space Access's Ronald K. Rosepink—a performance well beyond anything in service today. Rosepink says the engine is almost 10 times more efficient than existing engines.

At Mach 6, the plane will fire up two

Space Tethers

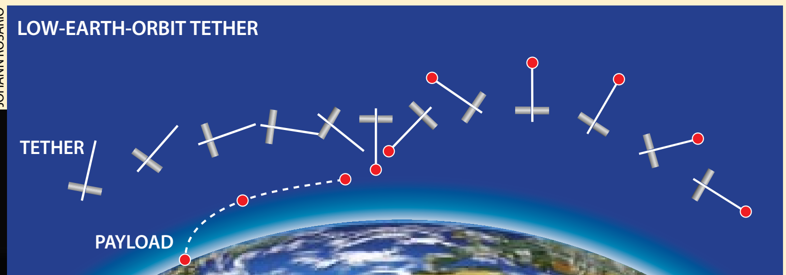
by Robert L. Forward and Robert P. Hoyt

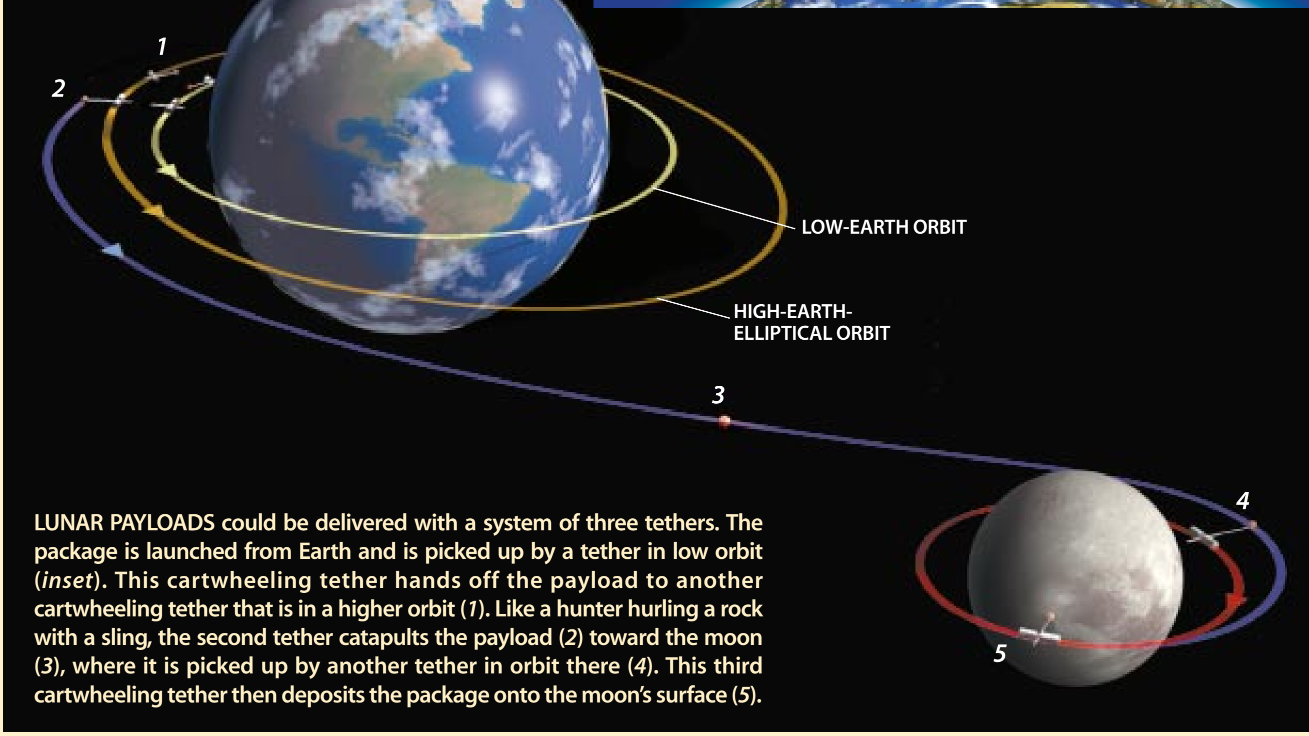
When humans begin to inhabit the moon and planets other than Earth, they may not use the modern technology of rockets. Instead space travel and settlement may depend on an ancient technology invented long before recorded history—string.

How can mere string propel objects through space? Consider two scenarios. First, a thick strand connecting two satellites can enable one to "throw" the other into a different orbit, much like a hunter casting a stone with a sling. Such a concept could be adapted for transporting payloads to the moon and beyond. Second, if the string is a conductive wire, electricity flowing through it will interact with Earth's magnetic field to generate propulsive forces. The great advantage of both types of tethers—momentum transfer and electrodynamic—is their economical operation. Instead of consuming huge quantities of propellant, they work by simply draining a little momentum from a body already in orbit or by using electrical energy supplied from solar panels.

To date, 17 space missions have involved tethers. Most of these missions have been successful, but the general public has heard mainly about two failures. In 1992 a satellite built by the Italian Space Agency was to be released upward, away from Earth, from the space shuttle *Atlantis* at the end of a long tether made of insulated copper wire. But the spool mechanism jammed, halting the experiment.

Four years later the National Aeronautics and Space Administration tried again. In that mission, as the tether approached its full 20-kilometer (12-mile) length, the motion of the shuttle through Earth's magnetic field generated 3,500 volts in the tether.





LUNAR PAYLOADS could be delivered with a system of three tethers. The package is launched from Earth and is picked up by a tether in low orbit (*inset*). This cartwheeling tether hands off the payload to another cartwheeling tether that is in a higher orbit (*1*). Like a hunter hurling a rock with a sling, the second tether catapults the payload (*2*) toward the moon (*3*), where it is picked up by another tether in orbit there (*4*). This third cartwheeling tether then deposits the package onto the moon's surface (*5*).

liquid-hydrogen-fueled rockets. At Mach 9, its nose will open like the jaws of a crocodile to release the second and third stages plus the payload. All the stages have wings and will fly back and land horizontally at the launch strip. Space Access's plane will handle payloads of around 14,000 kilograms, as big as those carried by the shuttle. Commercial service could start in 2003, Rosepink claims.

The most prominent launch vehicle in development, the X-33, is under construction at Lockheed Martin's Skunk Works in Palmdale, Calif., as part of a joint industry-NASA effort to reduce launch costs 10-fold. The X-33 is a roughly half-size experimental craft intended to test a type of rocket engine known as a linear aerospike, as well as various other technologies. On paper the linear aerospike can power a fully reusable, vertical takeoff

Electronic devices on the shuttle and the Italian satellite provided an electrical conduit to the ionosphere, allowing ampere-level currents to flow through the tether. The experiment demonstrated that such electrodynamic tethers can convert shuttle momentum into kilowatts of electrical power, and vice versa.

Unfortunately, a flaw in the insulation allowed a high-power electric arc to jump from the tether to the deployment boom, and the arc burned through the tether. But although the break aborted the electrodynamic part of the project, it inadvertently triggered a spectacular display of momentum transfer. At the time, the Italian satellite was 20 kilometers above the shuttle and was being pulled along faster than the orbital speed for that higher altitude. Consequently, when the tether broke, the excess momentum made the satellite soar to seven times the tether length, or 140 kilometers, above the shuttle.

Other work has had greater success. In 1993, to test an idea proposed by Joseph A. Carroll of Tether Applications in San Diego, a payload attached to a 20-kilometer tether was deployed downward from a large satellite. Because the speed of the payload was then slower than that required for an object at that reduced orbital altitude, cutting the tether at the right moment caused the package to descend toward a predetermined point on Earth's surface. Tether Applications is now developing a reentry capsule and tether that the International Space Station could use to send urgent deliveries to Earth, including scientific payloads that cannot wait for the next shuttle pickup.

In a related mission in 1994, a payload was left hanging at the end of a 20-kilometer tether to see how long the connection—as thick as a kite string—would survive collisions with micrometeors and space debris. The expected lifetime of the tether, which could readily be cut by a particle the size of a sand grain traveling at high speed, was a meager 12 days. As things turned out, it was severed after only four.

The experiment demonstrated the need to make tethers out of many lines, separated so that they cannot all be cut by the same particle yet joined periodically so that when one line fails, the others take up the load. With that in mind, the Naval Research Laboratory (NRL) and the National Reconnaissance Office (NRO) fabricated a 2.5-millimeter-diameter hollow braid of Spectra fiber (a high-strength polymer used in fishing lines) loosely packed with yarn. A four-kilometer length linking two satellites that was launched in June 1996 has remained orbiting in space uncut for almost three years.

In a follow-up experiment last October, NRL and NRO tested a tether with a different design: a thin plastic tape three centimeters wide with strong fiber strands running along its length. The six-kilometer tether should survive for many years in space, but the tape makes it heavy. Our company, Tethers Unlimited in Clinton, Wash., is working with Culzean Fabrics and Flemings Textiles, both in Kilmarnock, Scotland, to fabricate multiline tethers with an open, fishnetlike pattern that will weigh less and should last in space for many decades.

Other tether demonstrations are scheduled. The Michigan Technic Corporation in Holland, Mich., has plans in 2000 for a shuttle to release two science packages joined by a two-kilometer tether.

In addition, the NASA Marshall Space Flight Center is investigating the use of electrodynamic tethers for propellantless space propulsion. In mid-2000 a mission will demonstrate that a conducting tether can lower the orbit of a Delta 2 upper stage. At Tethers Unlimited, we are developing a commercial version of the NASA concept: a small package that would be attached to a satellite or upper stage before launch. When the spacecraft completed its mission or malfunctioned, the conducting tether would unfurl and drag against Earth's magnetic field, causing the craft to lose altitude rapidly until it burned up in the upper atmosphere. We will test such a tether de-orbit device in late 2000 on an upper stage built by the Lavochkin Association of Russia.

NASA is also considering such electrodynamic tethers for upward propulsion. In the system, solar panels would supply a flow of electricity through the tether to push against Earth's magnetic field. The resulting force could haul payloads around Earth indefinitely. This approach might be used to keep the International Space Station in orbit without refueling.

How far can tethers take humankind in the future? We and others have analyzed a system of rapidly cartwheeling, orbiting tethers up to hundreds of kilometers long for delivering payloads to the moon and ever farther. The idea is simple—think of Tarzan swinging from one vine to the next. First, a low-Earth-orbit tether picks up a payload from a reusable launch vehicle and hands the delivery to another tether in a more distant elliptical-Earth orbit. The second tether then tosses the object to the moon, where it is caught by a Lunavator tether in orbit there.

The Lunavator would be cartwheeling around the moon at just the right velocity so that, after catching the payload, it could gently deposit the object onto the lunar surface a half-rotation later. Simultaneously, the tether could pick up a return load. No propellant would be required if the amount of mass being delivered and picked up were balanced. Such a transportation mechanism could become a highway to the moon that might make frequent lunar travel commonplace.

Obviously, there are many technological challenges that must be overcome before such a system becomes a reality, but its potential for opening up an economical expressway in space is tremendous. Perhaps someday there will be numerous cartwheeling tethers around many of the planets and their moons, carrying the hustle and bustle of interplanetary commerce. And it all will have begun with a piece of string.

ROBERT L. FORWARD and ROBERT P. HOYT are the founders of Tethers Unlimited, a start-up aerospace company based in Clinton, Wash., that specializes in developing space tether systems for commercial applications.