Electromagnetic Surveillance

6

Radar

1. Introduction

Radar is an acronym for *ra*dio *d*irection *a*nd *r*anging as well as *ra*dio *d*etection *a*nd *r*anging. It is a remote-sensing technology in which radio signals, usually in the microwave range, are detected and interpreted. In *active* radar systems, radio signals are emitted toward an object or structure with the intent of intercepting and interpreting the reflected signals (incident electromagnetic energy). The examples that follow can help make this clearer.

Imagine it's foggy and you can't move forward, but you have a bag of tennis balls and you want know if there's anything ahead of you. Throwing a ball and noting whether it returns can help you get an idea if there's anything there. Imagine that the tennis balls can be thrown at a constant rate of speed; it would then be possible to time the rate at which a ball returns and use the information to calculate the distance. By throwing many balls you can even get some idea of where the boundaries of the object might be. This is the general idea behind radio detection and radio ranging.

Now imagine you're a bat or a dolphin, and you can send out clicks and chirps and ultra-

U.S. Air Force airborne surveillance, command, control, and communications staff monitoring the radar scopes on an E-3 Sentry aircraft. [U.S. DoD News Photo 1992, released.]

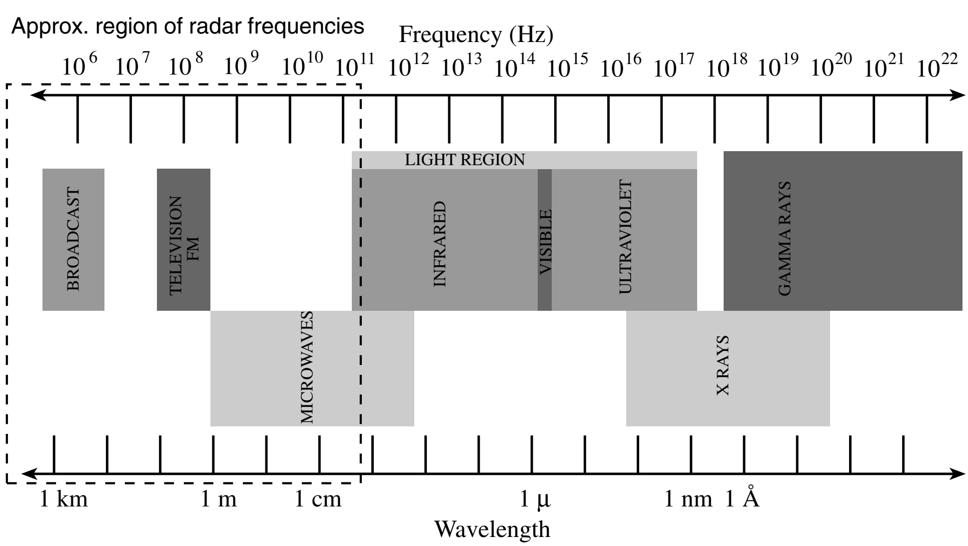
sonic vocalizations to bounce off the rocks or sand or trees that might be nearby. As the different echoes come back, you build up a picture in your mind of what the surrounding terrain looks like, even if it's dark and you have your eyes closed. This is the general idea behind radar imaging, except that instead of imagining the terrain in your mind, it is electronically interpreted into a grayscale image resembling a photograph.

Radar is similar to animal sonar in many ways, but it differs in that it uses radio waves–a type of electromagnetic radiation–rather than sound. Radio energy travels at the speed of light, much faster than sound, and radio 'waves' and other electromagnetic energies have particle-like qualities that allow them to travel in a vacuum.

The radar signals used in most surveillance technologies are electronically synthesized, and are invisible to humans, but can be sent and sensed with devices designed for the purpose, and translated into visual or auditory information that can be more easily understood. Radar is a very useful technology for surveillance applications.

Radar Basics

Radio waves are considered to be at the lower end of the electromagnetic energy spectrum because the wavelengths are longer. For the purposes of illustration, let's accept that electromagnetic waves travel 300,000 kilometers (km) per second in a vacuum. They are known to travel more slowly when impeded by water or thick particulate matter, but the differences are slight, or can be calculated in order to compensate for them. By relating time and the speed of the wave, the distance can be calculated. When radio waves are used to sense radio-reflective objects, in order to calculate their distance or direction, we call it *radar*.



When symbolically represented on a chart, radio waves are illustrated as the longer-wave region next to the optical region. The wavelengths used for most broadcast applications range from around one meter to one kilometer. Those used for radar vary, but are typically in the microwave frequencies which are closer to the infrared portion of the optical spectrum, up to about one meter in length. [Classic Concepts ©1999 diagram, used with permission.]

When radar signals are emitted from a radio wave transmitter, they will continue away from the source indefinitely (gradually diminishing through *attenuation*) unless they encounter obstructions. An obstruction reflects the signals in various directions returning some to the radar receiver (which is usually near the transmitter). They can yield information about the deflecting object or structure, usually termed the *target*. If the obstruction is very smooth in relation to the length of the wavelengths, the scattering of the radio waves will be minimal (assuming it is not a highly absorbant material). If the obstruction is very rough or convoluted (as in rough terrain or radar-defeating chaff), the signals will be scattered in many directions and only a small portion of the signal may reflect back to the receiving antenna. If the object is very small and longer wavelengths are being used, the signals may pass right by, making it 'invisible' to the radar. This is useful for sensing large objects in fog or rain.

The reflected signals are collectively called the radar *echo*. When intercepted and correctly interpreted, different aspects of the echo, such as polarization, spectral reflectivity, and time of arrival can be visually interpreted, and displayed and mathematically analyzed to yield information about the size, shape, location, and velocity of the radar target. If the radar is mounted on a moving object, like an aircraft, the angle of the radar signal, relative to the trajectory of the aircraft and the velocity of the aircraft, is considered in the calculations.

Sending out a radar signal does not guarantee its return, even if it hits the desired target. Radar signals are affected by terrain, some types of weather (depending on the frequencies used), radar-absorbing or -jamming systems, and other sources of *attenuation* (gradual diminution of the signal). Factors that interfere with radar signals are discussed in detail in Section 7 (Problems and Limitations).

Visualizing Radar Signals

We cannot see radio waves, but radar echoes can be intercepted, interpreted, and displayed in a number of ways. When a radar receiver intercepts incoming radio waves, they can be converted to electrical impulses which can then power a number of other electronic devices including radar displays. Specialized cathode-ray tubes (CRTs) intended for displaying radar 'blips' or *pips,* and computer monitors, are commonly used to represent ground-based radar target data. Digital or film images taken from aircraft or satellites using radar imaging sensors are similar to traditional grayscale photographs and are discussed further in Chapter 9. This chapter focuses mainly on ground-based radar data that are displayed symbolically, rather than photographically, on traditional cathode-ray tubes or digital viewing systems.

Radar systems range from small, portable devices to large Earth or marine stations. They can be deployed on the ground, from high-altitude planes, or orbiting satellites.

Radar was invented in the early part of the 20th century for marine navigation and adapted for air navigation by 1936, at about the same time that commercial availability of cathode-ray tubes was increasing. Because the concepts of radar ranging and sound ranging (sonar) are similar, radar and sonar technologies share some common history and terminology. Like sonar, radar came into regular military use during World War II and was further enhanced for various applications when the development of the transistor in 1947 introduced solid-state technology. Radar is now an essential tool of marine and air navigation and is widely used in aerial and planetary imaging.

Surveillance Applications

Radar is extensively used in surveillance activities, including military targeting, tracking, and defense, and civilian monitoring of moving vessels, hazards, threats, environmental changes, and weather systems. Radar is popular because of its versatility. Certain short-range, low-power systems for specialized purposes are priced in the consumer range. They can be used in light or dark and in many kinds of weather (some frequencies work better in wet weather than others). More expensive medium- and long-range radar tracking stations are stationed throughout the world and are used regularly for navigation, international surveillance, and defense.

Economics of Radar Systems

Compared to other surveillance technologies such as video surveillance, genetic surveillance, or audio surveillance, high-end radar surveillance can be expensive. Video surveillance systems can now be installed for a few thousand dollars or a few tens of thousands of dollars. DNA profiles can cost as little as $30 for a basic dog-breeder's canine DNA profile and a commercial human DNA workup is now less than two thousand dollars. The cost of tapping a phone for employer monitoring of telemarketing calls ranges between a few hundred and a few thousand dollars.

High-end radar systems, in contrast, often cost millions of dollars, depending on their complexity, range, and the extent of computer processing incorporated into the systems. They are mainly used in law enforcement, weather forecasting, military surveillance, and astronomical research. Because radar systems tend to be commissioned by large corporations, universities, and government agencies, this chapter has a stronger emphasis on companies and contractors than in other chapters. If you desire more detailed information on radar you can contact the organizations listed in the *Resources* section at the end of this chapter, most of which have Web sites on the Internet.

2. Types and Variations

There are many types of radar systems but they all work on similar general principles. The cost associated with radar systems varies according to the range and variety of frequencies that can be transmitted, the strength of the pulse, and the complexity of the receiving system. The most expensive systems are those which have high-power, long-range transmitters and computerized artificial intelligence-equipped (expert system) receivers.

Radar signals travel in two general directions, assuming that a target is encountered, from the sender toward the target and then away from the target (ideally, back to the sender, depending on the angle of reflection). Radar systems can be *send-and-receive*, *receive-only*, or *send-only*. Send-and-receive systems and receive-only systems are the ones most often used for surveillance activities.

- ***Send-and-receive* systems** represent the great majority of surveillance-related radar systems. These are *active* systems, consisting of aiming a signal at a target and interpreting the returning signal in order to derive information about the target. Send-and-receive systems are sometimes used in receive-only or send-only modes.
- ***Receive-only* systems** are usually defensive or covert systems in which the stealth vessel or target has a receiver equipped to detect an incoming radar signal, but no transmitter to betray its presence with radar signals that can, in turn, be detected by others. Car-mounted radar detectors are examples of small-scale receive-only systems. Most of them beep and/or blink when a radar signal is detected. Receive-only systems, in general, are the least expensive type of radar since they do not require the specialized electronics or power needed to send out radar pulses. However, more sophisticated receive-only systems may be used on stealth vessels that have radar-defeating features such as chaff or radar-resistant paint, to absorb, avoid, or scramble the incoming signal by deflecting it in many directions. In that way, the signal is detected, but the reflected signal gives an obscured 'picture' of the vessel that was

encountered by the radar probe. Stealth vessels are designed to look 'smaller' and decoys are often designed with reflectors to look bigger. Receive-only systems are *passive* systems.

- ***Send-only* systems** are usually *beacons*, to provide warnings or location information, or *decoys* for use in situations of armed conflict. As a decoy, a radar signal may be sent out to simulate a significant vessel or force stationed at the source of the signal when in fact it may just be a portable transmitter or an unstaffed, automated system. The decoy is intended to confuse, to draw fire, or to draw attention away from other forces or installations. Send-only systems are *active* systems, because they generate radio energy, but they don't use receiving components.

Most of the systems discussed in this chapter are send-and-receive, which can be designed with single antennas or with multiple antennas. When the same antenna is used for both transmitting and receiving, it is called *monostatic radar*. Monostatic systems are very common. If there are two antennas, it is called a *bistatic radar*. If there are more than two antennas, it is usually called a *polystatic radar* or *radar array*. The antennas must be spaced to minimize interference with one another.

Radar Sending

Radar signals can be *pulsed* or *continuous*, with the vast majority being pulsed. A pulse is a discreet burst of radio waves. The pulses are repeated at carefully timed intervals. The *pulse-repetition rate* is a count of the number of successive pulses per unit of time. Since radar waves travel at a more-or-less constant speed (most synthetic radar signals are sent through the Earth's atmosphere), it takes more time for radar signals to travel longer distances. Thus, longer radar ranges typically require slower pulse-repetition rates.

Radar Receiving

Radar sensors are categorized in a number of ways, and there are many hybrids and variations. The basic types include altimeters, scatterometers, and *synthetic-aperture radars* (SARs). Radar altimeters are commonly used in aircraft. Additional information about SAR and airborne radar systems is provided in the Aerial Surveillance chapter. Radar data are often used in conjunction with data from other technologies, including cameras, sonar, and seismic detectors. Since radio energy doesn't travel as effectively as sound through water, it's not typically used for below-water sensing applications.

Modulation

Frequency modulation is a means of sending radio signals by altering their frequency. It is based on the same general principles as public FM broadcasting (the main difference is that broadcast frequencies use longer wavelengths than most radar applications). In radar, if frequency modulation is used in conjunction with continuous signals, then more information, including the distance to the target, can be calculated.

Variations

There are many different varieties of radar systems. Here are some common schemes and concepts that are of interest:

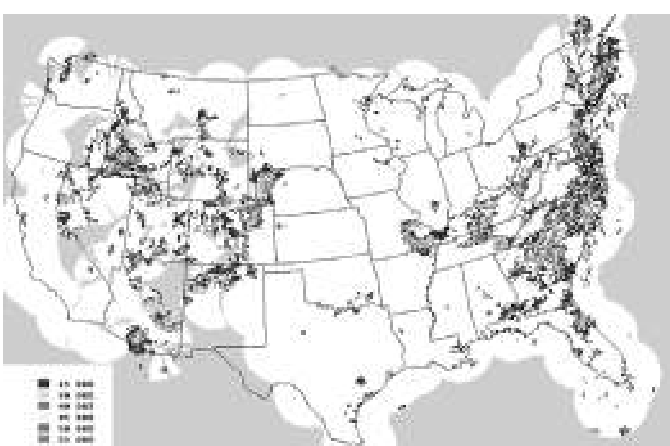
automatic detection and tracking radar (ADT) - This is a form of track-while-scanning system in which each rotation of the antenna yields data on the targets within its range. The visual display shows 'streaks' to represent the paths of the objects (assuming that they are moving) rather than blips. The movement and direction of vehicles or marine vessels can be monitored on this type of system.

phased-array radar (PA) - Not all antennas are designed to rotate while transmitting radar beams. For example, electronic phased-array radars can scan the radar beam back and forth within a certain *swath* to provide rapid updates of events within the sweep of the beam.

synthetic-aperture radar (SAR) - SAR is a more recently developed system, now commonly used in aerial and satellite sensing, in which one dimension represents the *range* (the *along-track* distance from the radar transmitter to the target) and the other dimension represents the *azimuth* (the *cross-track* perpendicular to the range). The distance traveled by the craft using the radar becomes the 'synthetic' aperture instead of using a very long physical antenna.

continuous-wave radar (CW) - the majority of radar systems are pulsed, but some specialized radars, such as weapons or scientific research systems, use continuous-wave technologies. CW radar transmits and receives at the same time, taking advantage of the Doppler effect, in which frequencies shift and thus are different for outgoing and incoming waves. This contrasts with pulsed radar which receives between transmission pulses to prevent interference.

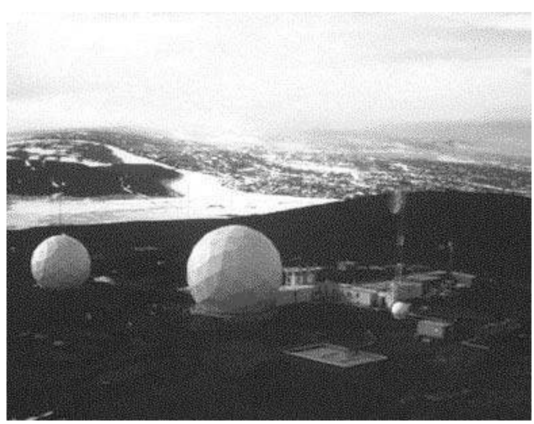
Doppler radar - The Doppler principle is widely used in designing radar systems and evaluating radar signals. A *Doppler shift* occurs when an object is in motion relative to a reference point such as a radar receiver. If you are standing near a moving train that's blowing a whistle at an unchanging frequency, the pitch that you hear will change as the train approaches and passes you. This is due to compression and expansion of the sound waves relative to your position. Similarly, a tracked object which is moving toward or away from a radar receiver will cause a shift in the transmitted frequency that subsequently reaches the receiver. By measuring the frequency, information about the velocity of the object can be calculated, thus Doppler radar typically scans a target in terms of speed rather than range. Doppler concepts are widely used in weather-tracking and traffic radar systems. Sometimes two Doppler radar systems are used in tandem for calculating additional spatial information.



An example of a radar weather map from the *U.S. National Weather Service*. Areas of precipitation are indicated with color coding. Higher levels of precipitation are expressed with hotter colors. The state lines have been added for reference. [National Weather Service summer 2000 weather photo, released.]

Radar is used throughout the transportation industry for homing, tracking, determining altitude, detecting and identifying objects, and land-, sea-, and air-traffic monitoring and enforcement. Radar antennas can readily be seen mounted on the decks and masts of water craft, especially ferries and coast guard vessels. Radar systems on aircraft are usually enclosed and may be located in the nose (especially receiving systems), in a radome (a large, streamlined, rotating antenna cover), or under the belly of the plane (side-looking radar).


Left: A weather officer with the All Weather Service (AWS) demonstrates weather surveillance systems in 1980. She is pointing out views of severe storms that were photographed from ground level and imaged with a Doppler radar system. Right: The P-3C Orion aircraft is equipped with several surveillance systems including an AN/APN-227 Doppler radar system and sonar tracking system (shown here in a counter-narcotics flight, in 1995). [U.S. DoD 1980 news photos by William D. Boardman and Paul J. Spiotta, released.]

Left: Contractors to the U.S. Air Force lift a Next Generation radar transmitter/receiver trailer for installation at the NEXRAD site in the Azores. Right: Domes protect radar antennas from weather damage in a U.S. Navy installation in Antarctica. [U.S. DoD 1996 news photo by Lemuel Casillas, 1995 photo by Edward G. Bushey, Jr., released.]

Identification Systems

The terminology and procedures for training radar engineers and operators were developed in the late 1930s, and evolved considerably in the 1940s when commercialization of radar and military use of radar increased. One important development was the creation of *identification friend or foe* (IFF) and later *identification friend, foe, or neutral* (IFFN) systems. These made it possible to distinguish various radar targets.

An IFF system is like a password system. A signal 'query' is transmitted to the radar target, which in turn transmits back a coded pulse. The code can be prearranged or dynamically assigned during operation. Commercial airlines and military aircraft are equipped to transmit various basic identifiers plus, as systems became more sophisticated, information such as origin, airline, flight number, mission, etc. On symbolic radar displays, this information can be assigned to an individual target so it can be identified by name, shape, or color. Thus, an aircraft carrier might be assigned a blue rectangle, while a foreign submarine might be assigned a red circle, thus easing the jobs of tracking and interpretation. Symbolic systems can be particularly important in the identification and tracking of fast-flying surveillance craft that have small radar signatures intentionally designed to avoid identification on radar.

Visual Displays

There are many types of radar displays and the visual interpretation of the images requires various degrees of training and skill. Radar is used by air traffic controllers to guide the take-offs and landings of commercial and military aircraft. It is used by aircraft and marine vessels to detect hazards or incoming projectiles. Clearly, since many lives may be at stake, good training and skill are necessary for personnel to evaluate three-dimensional air traffic or various navigational hazards based on their interpretation of blips or symbols on a two-dimensional screen. Radar display systems are described in more detail in Section 3 (Context).

Traditionally, radar technology has depended on frequencies associated with radio waves, but the invention of lasers has provided other ways to apply the basic concepts associated with radar technology. An optical radar, called *lidar* (*li*ght ra*dar*) or *ladar* (laser radar), transmits very narrow, coherent light beams rather than radio waves, which can be used to create high resolution images. (See the Infrared Surveillance chapter for related information.)

3. Context

A radar beam is essentially cone-shaped, like the light from a flashlight. It becomes broader as it moves away from the source and gradually 'fades' or *attenuates* as various particles and objects absorb or reflect the beam. Newer, higher-frequency narrow-beam radar systems have been developed that do not spread in the same way, which can provide more precise targeting. However, there is usually a trade-off that limits the range. The high-frequency beams don't usually travel as far when they have to pass through Earth's atmosphere, which contains particles and vapor. An unobstructed radar beam travels in a straight line (on a cosmic scale, gravitational forces can bend the path of electromagnetic waves, but for terrestrial purposes, assume the line of travel is straight).

A radar beam is *absorbed* by 'spongy' objects (dirt, leaves, fog), *refracted* (bent) by materials with different densities (e.g., as it passes from air into water), and is *reflected* by reasonably solid objects. Some of the reflected beam is *scattered* in various directions and some of it is reflected back to the source. It is the reflected signals that are called the returning *echoes.*

Very short electromagnetic wavelengths, which include ultraviolet, X-rays, and gamma rays, can be harmful to humans as shorter wavelengths are associated with higher energy levels than longer ones. Ultraviolet can cause sunburn and sometimes cancer. X-rays can cause substantial damage to human tissue and are used very carefully in order to avoid causing harm. However, the relatively long wavelengths of radio waves, when used in normal ways in broadcasting and remote sensing, do not harm human tissues, as far as we know.*

Radar is valuable because it can be used day or night in a variety of weather conditions and, depending on the transmitter and the frequencies used, the signals can travel great distances.

3.a. Range

Radar range to a target is somewhat limited by *line of sight*. Certain reflective objects can interfere with both the outgoing and returning radar signals. When the signal deflects off of many objects other than the *target*, not only does it attenuate more quickly, but relevant targets also become more difficult to distinguish from the radar *clutter*.

Higher frequencies (shorter wavelengths) tend to have shorter ranges, as they can be scattered by atmospheric moisture and particles. Lower frequencies (longer wavelengths) tend to have longer ranges. However, the power of the transmitter is also a factor, so these are only general guidelines.

There are many varieties of radar systems, but a general rule within categories of radar systems is the longer the radar range the more power the system must generate. Most radar systems are surface-based (land, air, and water), in the sense that they are used within the Earth's atmosphere; however, a number of radar systems are now installed in probes, orbiting satellites, and high-flying aircraft. These typically send and receive signals through the Earth's atmospheric envelope, though some also send signals out into space. Atmospheric particles reduce radar range through attenuation (scattering and absorption). Adjustments for rotation, angle, and time of day are made on space-based systems to maximize performance from limited power sources (satellites are dependent upon limited-power batteries and solar energy converters).

Interference from other sources of radio waves at or near the same frequencies as a specific radar may occur and may further limit range.

Very short-range radars, e.g., those used in traffic enforcement, may scan up to a few miles or a few hundred feet, depending on terrain. With a clear line-of-sight, short-range radars may scan up to about 50 miles. Long-range radars may scan up to a few hundred miles, and very long-range radars, such as those used on satellite systems, may scan in excess of 500 miles. There are also very long-range radars used in radio astronomy that send signals out into space where there are vast areas without atmospheric particles to attenuate the signals; these may travel for millions of miles. One of the first times radar was used for exploring and mapping the heavens was when experimenters bounced a signal off the Moon in the mid-1940s.

3.b. Radar Receivers

Our environment is full of radio signals of different frequencies that travel constantly through air and walls (and our bodies) outside of our awareness. Consumer radio broadcasts that are sent through the air as inaudible waves, are converted to audio frequencies so we can enjoy them in our homes. Similarly, traditional TV aerials or satellite dishes capture invisible television broadcasts that are converted by a TV tuner and displayed on a monitor. Since humans cannot see or hear radar pulses, which are a type of radio wave, these signals must be converted to a form that enables us to interpret the information. The most common means of

*There are some concerns that microwave frequencies in radio-based communications devices (e.g., cell phones) could be harmful, but there isn't firm evidence to substantiate these concerns at this time. However, high-power microwave communications systems are dangerous, as are unshielded microwave ovens.

‘viewing’ radar echoes is on a radar scope where bright areas indicate the presence of a reflected signal. Auditory signals are sometimes used for less sophisticated applications like vehicle radar detectors.

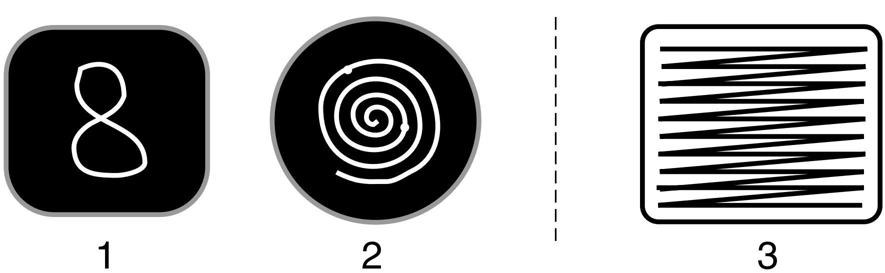
A radar *scope* provides an *image* of the radar echo at the moment the signal is apprehended by the receiver. Since most radars are pulsed (a signal is sent and the system waits for its return before sending the next one), there are ‘blank’ moments between pulses in which echoes will not be displayed on the scope. Since the mid-1930s, most radar systems have been designed to display on cathode-ray tubes (CRTs) in which the inside of the viewing surface (the inside front glass portion of the monitor) is coated with phosphors which are excited when the beam emitted from the back of the CRT hits the front. When they get excited they glow, creating an image on the radar screen. On many systems, the brightness of the glow can be controlled. In pulsed radar, this glow gradually fades and is replaced by the image from the next signal from the receiver, providing the illusion of a continuous signal.

If the radar system uses a low pulse rate, in which there is a longer time delay between radar signals, a *long-persistence-phosphor* CRT can be used. On these displays, the phosphors glow longer to maintain the image longer. This helps provide a sense of the target image as long as the viewer remembers that it is a stop-action picture with a built-in delay. In other words, the lingering glow shows the scene as it ‘was,’ not as it ‘is,’ but that is usually more useful to the operator than a blank screen.

Vector and Raster Displays

There is more than one way to control the travel of a CRT beam, so display devices are further divided into *vector* displays, in which the beam is aimed only at the part of the screen which is illuminated, and *raster* displays, in which the beam sweeps continuously across the full screen surface as on television sets or computer monitors, creating a *frame*.

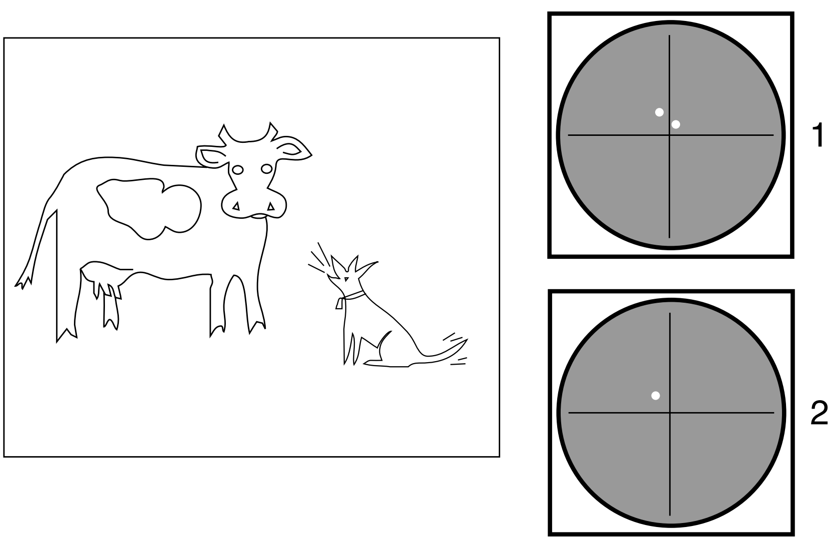
Traditional ‘pip’ radars have *vector displays* similar to those used in traditional oscilloscopes. The beam becomes a visual reference by tracing a predetermined path that is altered from its course in one or two directions by a signal coming from a radar receiver. Thus, a repeating beam traveling from left to right may be altered in the vertical direction to indicate the presence of a signal representing a radar echo. Similarly, a circular beam following a spiral path from the center to the outside might exhibit ‘bright spots’ to represent radar echoes, thus providing a two-dimensional representation of a three-dimensional space being scanned by the radar. Vector displays have been in use for several decades.



Vector displays commonly trace a single beam at whatever portion of the screen needs to be lit at a particular time (1) or, on some radar scopes, trace a predetermined path and illuminate relevant targets (2) if they are present. *Raster displays* trace a *frame* that covers every part of the screen, usually from left to right and top to bottom. The *frame refresh rate* is usually about 60 times per second and is continuous, whether or not a target is detected (3). Raster displays are used on many computer-based radar systems with resolution typically expressed in *pixels* (e.g., 1024 *x* 768).

In monochrome displays, the beam is turned on to illuminate the screen when ‘cued’ by a signal. In color displays, the signal may be displayed as another color or another intensity against a selected background. Computer-controlled raster displays provide great flexibility in the types of images that can be displayed, and symbols can be dynamically substituted by the system or the operator to represent objects or situations. Raster computer displays have been in common use for about 20 years (and have been used for TV displays for half a century).

Blip and *brightness* radar displays are always providing ‘approximate’ images due to delays and the limits of spatial resolution. The range of sizes of objects in the real world is much greater than the range of sizes of objects that can be represented on a small screen. Since nothing can be displayed smaller than the blip or pixel itself, or bigger than the total area of the screen, compensations in interpretation must be made. In other words, if the imaging resolution of the display is such that a blip symbolizes something the size of a horse, then smaller objects such as bicycles or go-carts would appear to be as big as a horse, or won’t show up at all.



The spatial resolution of a TV-sized radar display cannot match the spatial resolution of acres of land so operators must learn to adjust their thinking to interpret the images. Depending on the distance and resolution of the system, the dog in the scene will either appear to be the same size as the cow (1) or will not be displayed at all (2) because it is too small to register. ‘Tuning’ the system to display smaller objects doesn’t solve the problem because too many objects on the screen clutter the image and large objects would be so large they would fill up the screen or overpower the smaller ones. Thus, a radar system must be set up to balance the spatial relationships of the target and background, an example of the context-sensitive nature of radar system design, tuning, and interpretation.

It should be noted that despite the limitations in operator interpretation and resolution, radar detection systems can still be remarkably accurate. Radar systems are capable of tracking fast-moving aircraft and incoming projectiles using computer processing to correlate the data and may even be set up to control the launch of a countermeasures device.

In portable systems, cathode-ray-tube (CRT) displays are impractical unless the viewing screen is very small. The electron beams in a CRT need to travel some distance in order to illuminate the full surface of a screen, so traditional CRT monitors are long and bulky. Newer display systems, especially those used with portable computers, utilize a number of technologies to reduce the bulk of the screen, including display systems such as *gas plasma* or *transistors* at each pixel location. While not as crisp as CRT displays, these more recent display technologies are very practical in the field, as the monitors may be only about 1/2" thick, weighing less than two pounds for a 14" viewing area.

The most common categories of display systems are

- *A-scope* - displays a signal as a time-varied *blip*, suitable for monitoring the progress of a moving target.
- *B-scope* - displays range and bearing information in rectangular coordinates.
- *plan-position indicator* (PPI) - displays part or all of an arc, as the radar antenna rotates through some portion of an arc, up to 360°. The echoes appear as bright spots on a long-persistence monitor (a monitor in which the lighted areas retain their intensity for some time before fading). The fade can be minimized with computer processing, but it is important for the operator to remember that the image is only current at the moment it displays, like a stop action photo that is retained until the next photo is snapped [Beam, 1989]. The revolution of the antenna may be as slow as six revolutions per minute. The refresh rate of the radar image is related to the speed of revolution of the scanning antenna and the refresh rate of the image display. There is a relationship between the pulse rate and the scanning speed of the radar. If the scanning rate is high and the pulse rate is low, fast-moving objects might evade detection. The radar range, in turn, will impact the pulse rate.

Photographs of different radar displays and operations consoles in use by air traffic controllers and military personnel are included later in this chapter to give the reader a sense of the variety of radar terminals that are in existence.

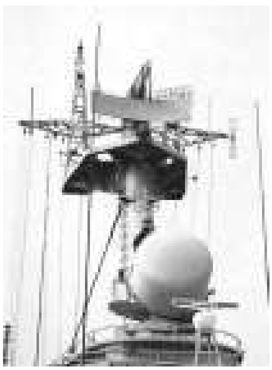
Radar Antennas

Since the directional character of radar beams is important, both for targeting and interpretation, most radar antennas are mounted on movable mechanisms. Radar antennas typically can rotate around their vertical axes, and some can be angle-adjusted as well.

The SPS-49 radar antenna (left) and a radar dome (right) are just two of several systems used on board the aircraft carrier USS Abraham Lincoln (CVN-72). Military marine vessels are also routinely equipped with a variety of radar countermeasures devices which may include noise and jamming systems and *chaff* (a type of thread-like reflective material) to scatter incoming signals. [U.S. DoD 1990 news photo by Don S. Montgomery, released.]

Most ground-based aerial tracking radar systems use a *conical scan*. Because this type of system can be jammed, multi-input *monopulse tracking* radars were developed to receive data as a single pulse, which resists detection [Beam, 1989].

Military ground equipment with scanning radar antennas are incorporated into IFFN systems (Identification Friend Foe or Neutral). Identification systems are also used in civilian applications, but are less likely to incorporate key-coding to prevent imposters.



Left: A variety of types of radar antennas are visible on the Soviet-built USNS Hiddensee, including a High Pole-B EW antenna, a Square Head Identification Friend or Foe (IFF) receiver on the back, a Plank Shave missile-targeting antenna on the front, a Kivach 3 surface-search antenna on the bridge, and a radome with a Bass Tilt gunfire control antenna to control two types of gun systems. Right: The U.S. Navy cruiser USS Normandy (CG-60) is equipped with a cone-shaped SPQ-9A surface gun control radar on the fore mast, an SPG-62 radar illuminator to the left, an SPS-29(V)6 air-security radar on the main mast with a small dome-shaped SPS-64(V)9 navigational radar above and forward on the mast. On the top aft deck are two SPG-62 radar illuminators and on the right is a QE-82 antenna for WSC-3 UHF Satcomm. On the aft deck house are two panels of the SPY-1A fixed antenna radar array. [U.S. DoD 1993 and 1994 news photos by Don S. Montgomery, released.]

The U.S. Navy guided-missile destroyer USS Scott (DDG-995) is equipped (left) with an SPG-51 missile radar illuminator on top of the bridge, above which is a dome-shaped SPQ-9A surface gunfire-control radar, above which is an SPS-49(V)5 EW air search radar. Near the top of the mast is the SPG-55 surface-search antenna. To the aft end of the bridge is the SLQ-32(V)5 EW. The large screen (right) is the SPS-48E 3D search radar, below which is the SPG-60 gun/missile control. On the far right is a QE-82 antenna for WSC-3 UHF Satcomm. [U.S. DoD 1994 news photos by Don S. Montgomery, released.]

Radar Frequencies

Radar operates in a wide variety of frequency ranges with the choice of frequencies related to the character of the application, the cost, and whether the sensing is of a covert nature. Civilian radar applications often operate at fixed-center frequencies, whereas covert applications may use frequency-hopping schemes to escape attention or interference.

As the wavelengths become shorter, they suffer more from attenuation, and consequently tend to be used for short-range applications, such as commercial automobile radar detectors. Detectors tuned for specific frequencies can generally be designed for better sensitivity. For broadband detectors, that detect over a range of frequencies, there is usually a sensitivity trade-off. There is also a trade-off between stationery radars (which are usually ground-based) and moving radars. Moving radars usually have about a 25% loss in range, depending on the system and the frequency used. However, if they gain a clearer line of sight between the transmitter and the target, as on an aircraft, it more than compensates for the loss in range.

It took a while for electronics engineers to figure out how to use the higher frequencies for radar applications, just as it took time to figure out how to generate ultrasound radiation for sonar applications. Consequently, many early radar systems emitted energy in the high frequency (HF) and very-high frequency (VHF) ranges. As the science of electronics has improved, radar has been applied to L-band frequencies and beyond. Each frequency range has its advantages and disadvantages.

Note, the following frequency ranges are not 'fixed.' They are administrative designations that sometimes change (or are subdivided) as radio science advances and new applications emerge to take advantage of their various properties. The designations are relatively stable at the longer wavelengths, but are still being developed at the higher energy microwave frequencies and have changed somewhat over the last several years.

3 to 30 MHz, high frequency (HF or *shortwave*)

Suitable for long-range applications; can be 'bounced' off the Earth's ionosphere to extend the range, allowing for *over-the-horizon* radar signals. Attenuation from particulate matter in the atmosphere is minimal. However, HF also requires long antennas and has to compete with a lot of other radio wave traffic. HF waves are more economical to generate than microwaves.

30 to 300 MHz, very-high frequency (VHF)

The pros and cons of VHF for radar transmissions are similar to those for HF, although the antennas don't need to be quite as long. VHF waves are more economical to generate than microwaves. Some satellite imaging radars are in this region, including some environment sensing SAR applications.

300 to 1,000 MHz, ultra-high frequency (UHF)

A large number of surveillance activities, including air traffic control and many military applications, are conducted in UHF frequencies. UHF is suitable for long-range radar applications, has moderate attenuation, and is moderately economical.

400 MHz to 1 GHz (P-band)

A long-distance experimental radar band which has been used for a variety of applications including radar interferometers and synthetic-aperture radar. There are a variety of weather, satellite, military and forest service radar applications that operate within the 1200 to 1700 MHz frequency range. It is also used for astronomical radar sensing. Interference from certain of the applications that have been approved to use these frequencies (e.g., certain satellites with strong signals) makes it difficult for them to be used for anything else.

1 to 2 GHz (L-band)

A long-distance frequency range used for experimental, satellite, weather, and military operations. The NASA/JPL synthetic-aperture imaging satellites do much of their imaging in L-band and C-band frequency ranges.

2 to 4 GHz (S-band)

A medium-high-distance frequency range used for air traffic control, weather monitoring, consumer short-range transmitters, and consumer cordless telephones. There are some three-dimensional radar imaging applications carried out at this frequency range and also at higher frequency ranges. Some identification systems work at this range, as do some atmospheric boundary-layer radars.

4 to 8 GHz (C-band)

A medium-high-distance frequency range used in a variety of surveillance activities and military operations, including weapons control systems. This range has medium-long-range capabilities and is also reasonably good for precision applications. Some synthetic-aperture radars that are used for remote sensing operate in this region. A number of air-traffic control and air defense applications operate within about 3 to 6 GHz. Some altimeters operate in this region.

8 to 12 GHz (X-band)

A medium-distance, higher-precision range used in professional applications, traffic radars, military applications, civilian marine applications, weather forecasting. X-band radar is used to assess sea-surface characteristics, including temperature and air disturbances. Missile-targeting radars operate in this region. Most synthetic-aperture radars operate in this frequency range. Nose-mounted aerial radar systems often operate in the X-band and K-band regions. The surveillance of airport runways is carried out in this range (and in the K-band range). Some vehicle radar detectors work at about 10.5 GHz, as do some focused phased-array imaging radars.

above 12 GHz

The frequency designations above this region are currently somewhat fluid, and different maximum and minimum ranges have been published by various organizations, depending on their specific applications needs. In general, these higher frequencies are used for shorter-distance, high-precision detection systems, landing systems, and airborne radar. Some special-purpose weather radars operate in this region, e.g., air particle sensors. Some vehicle radar detectors operate at about 24 GHz with some of the wide-band radar detectors at about 34 GHz. The designations found in this higher-frequency region include K-band, Ku-band, Ka-band, Q-band, V-band, and W-band (around 100 GHz) in that general order, almost all of which are used for satellite radar, although some frequencies at the lower end (e.g., around 20 GHz) have been set aside for mobile voice communications and guidance systems and there is an allocation within the Ka-band for non-geostationary fixed-orbit satellite services as well as subregions for various satellite and multipoint communications distribution services.

infrared (optical region)

Portions of the infrared region use a specialized very-short-distance, high-precision, optical radar mainly used for distance-determination and weapons control systems.

As the wavelengths become progressively smaller, they become more subject to attenuation from particles and vapors. Some scientists have capitalized on this 'limitation' by using high-frequency radar to map the structure and shape of cloud formations.

4. Origins and Evolution

There is a widespread misconception, even among professionals, that radar was invented during World War II. This is probably because U.K. military strategists in World War II recognized the importance of radar and developed and used it extensively, influencing the outcome of the war. However, radar didn't originate in the U.K. or during wartime. It was invented in Germany more than thirty years earlier, at the turn of the century, for the purpose of preventing marine collisions. Radar evolved gradually and became an important marine and aerial navigation technology by the mid-1930s. With the outbreak of World War II, radar became one of the significant technologies used to defeat the German forces, which is ironic, considering the German military administration rejected the first radar inventions by German scientists.

Basic Concepts

One of the most important scientific concepts that has been applied to modern radar was developed in 1842, by Johann Christian Doppler (1803-1853), who studied the way in which motion could compress sound waves and thus alter the frequency of sound relative to the perspective of the observer. This principle was later found to apply to other wavelike phenomena, like light. Since radio energy has wavelike properties, Doppler's observations would eventually be used to design radar systems that could use the Doppler effect to judge speed.

In essence, radar involves the sending and receiving of reflected electromagnetic waves. Thus, initial discoveries which led to the development of radar were made in the 19th century by inventors such as Heinrich R. Hertz (1857-1894), a German physicist employed at the University of Karlsruhe. Hertz demonstrated the reflection of electromagnetic waves by other electric inductors in 1886.

Radar Ranging

In the late 1800s and early 1900s, searchlights were being used on marine craft to help prevent collisions with other vessels and to illuminate hazardous obstacles and floating debris. This system was severely limited by range and weather. Christian Hülsmeyer (1881-1957) sought a way to improve navigation by using radio waves, and on 30 April 1904, registered patent DRP #165546 for a *Telemobiloskop* (far-moving scope), a radio device to aid marine craft in preventing collisions. Hülsmeyer's use of radio waves as a remote-sensing technology was a significant advancement. His invention provided greater range and utility in bad weather than searchlight systems. The German engineer's device, the first to fully embody the basic principles of radar, was demonstrated on 18 May 1904.

Amateur radio broadcasting flourished between 1906 and 1920 and many hobbyists were eager to study the characteristics of radio transmissions and to experiment with practical applications. Their experiments included bouncing radio signals off various surfaces to further study phenomena such as reflection, refraction, and attenuation.

During the early century in Europe, Hans Dominik, a science fiction writer, and Richard Scherl, developed the *Strahlenzieler* (raypointer), which used radio wave echoes as a detection system. Scherl produced a working model and offered it to the Germans for use in World War I in February 1916, but it was rejected by German administrators as 'unimportant' to the war effort. Soon after, in the United States, Nicola Tesla, an eccentric genius who did hundreds of experiments with electricity and radio technology, described radar concepts in the Electrical Experimenter (1917).

In the 1920s, military personnel began taking an interest in applying radar technology to navigation and remote sensing. A. H. Taylor of the U.S. Naval Research Laboratory observed in 1922 that a radio echo from a steamer could be used to locate a vessel. He may have independently come up with the idea, or he may have had conversations with colleagues resulting from the lectures given that year by Guglielmo Marconi, a radio pioneer, who described the use of radar for navigation.

Up to this time, radar was used to sense the presence of an object, but it was not yet used for deriving further information about the object. In 1926, American researchers Gregory Breit (1899-1981) and Merle Anthony Tuve (1901-1982) bounced a pulse-modulated radio signal off the conducting layer of Earth's high atmosphere (termed the ionosphere by R. Watson-Watt) in order to determine its distance. While the high frequencies commonly used for radar would not be practical for measuring the ionosphere (high-frequency waves pass right through it), this experiment nevertheless demonstrated concepts fundamental to radar, i.e., bouncing a signal off a wave-reflecting object and analyzing the resulting echo to calculate the distance.

In the 1920s and 1930s, radar technology was put to wider practical use. Radio signals were bounced off marine vessels to detect their presence. Ships show up well on radar, in contrast to their water environment, and they move slowly, in contrast to aircraft. However, as the technology was improved, aircraft were tracked as well, and surveillance radars began to gradually evolve into other areas. In Italy, during this time, pioneer experiments in weapons-detection were carried out. While these early systems didn't yield sophisticated information, due to the lack of display devices and analytic methods and equipment, they did embody basic radar detection and ranging capabilities by sensing the presence and approximate direction of movement of a vessel or weapons charge.

Radar Display Devices

Karl Ferdinand Braun (1850-1918), a German physicist, developed a number of technologies that were later to become important in radio communications and radar systems. He created a crystal rectifier which was used in early crystal radio sets, and in 1897, he developed the oscilloscope, which had a cathode-ray display system that was later adapted for imaging radar signals.

In the late 1920s, the research of Vladimir Kosma Zworykin (1889-1982) led to significant improvements in radar technology. Zworykin, a Russian-born American researcher, experimented with beams emitted in an electron tube, and in 1923 patented the *Iconoscope* television tube, a variation on the cathode-ray tube. Display tubes have been an indispensable component in radar scopes ever since the early 1930s, and modern versions are regularly used in vector displays and computerized raster display systems.

The three-element electron tube was a mainstay of electronics from the early 1900s until the transistor age emerged in the late 1940s. Based on the two-element Fleming tube, Lee de Forest added a third element, a controlling grid, to create the *Audion* in 1906. Thus electron tubes could now be used to build transmitters, amplifiers, receivers, and many other electronic components.

Practical Radar Systems

Robert Watson-Watt (1892-1973), a Scottish physicist, is credited as a radar technology pioneer for a patent for a device he called a *radiolocator* (1935), designed to detect aircraft. Early systems were known as radio direction finders (RDFs). Watson-Watt was an advocate for narrow-beam radar designs. Based on his research, by the following year, the British Royal Air Force (RAF) was operating a radar-based air warning network for aircraft detection.

By 1937, radio waves were being used for direction-finding, homing, and ranging for commercial aircraft and marine vessels, and were well-documented in engineering texts (e.g., Terman's "Radio Engineering"). Direction-finding was used to help aircraft and marine vessels stay to a course. Homing devices came to be used to guide various craft to a specific location, like guiding an aircraft to a landing base on the ground or on an aircraft carrier. Radio-ranging systems consisting of beacons designed to lay in a course in a predetermined direction were implemented to mark primary air routes throughout the U.S.

A letter to the Chief Signal Officer in Washington, D.C. on 5 May 1937, requesting radio equipment "...to detect the presence of aircraft by reflected signals..." was penned by Lt. Col. M. F. Davis, Air Corps, who was stationed in the Panama Canal Zone at the time. By summer, negotiations with RCA and Westinghouse for high-power VHF triode tubes were underway, with Westinghouse eventually winning a bid to supply radar systems to the U.S. military [Helgeson, http://www.bwcinet.com/acwrons/equip/SCR-270.html].

Experimental designs, improved electronics, and more comprehensive radar systems incorporating CRT technology were in development in a number of locations by the late 1930s. Leo Young developed a radar duplexer, with an integrated antenna for transmitting and receiving. A 200-MHz version was completed late in 1937 and tested on the USS Leary. An improved version was demonstrated on the battleship USS New York in 1939, heralding the age of marine radar for strategic warfare and defense. In 1942, the USS New York was used for a time as a radar training vessel.

As might be expected for machines developed prior to the invention of microelectronics, early radar systems were bulky and limited in frequency and range. Marcus Laurence Elwin Oliphant (1901- ?), a physicist in the labs of the University of Birmingham, secured a grant to build Europe's biggest cyclotron. It was in these labs that a significant development in radar was invented, the first electron-tube *cavity magnetron*, built by British physicist Henry Boot (1917-1983) and biophysicist John T. Randall (1905-1984). The magnetron led to significant improvements in radar accuracy in the early 1940s, when high-power magnetrons capable of generating microwaves suitable for radar transmissions were developed.

Zworykin's cathode-ray tube display technology coupled with Boot and Randall's transmission systems provided key elements in the design and manufacture of improved, modern radar systems. By 1940, the British east and south coasts had been installed with high-tower transmitting aerials. Given the German aircraft superiority in World War II, these radar improvements and installations were important to the outcome of the Battle of Britain.

Military Development and Use of Radar

With the War raging in Europe and fears of it spreading, the early 1940s became a time of intense military development and deployment of radar in the United States.

In June 1940, the U.S. President established the National Defense Research Committee (NDRC) to support scientific research on military technology, which included contributions to the development of airborne radar systems. In July, the NDRC Radar Division held its first meeting, defining its mission and embarking on the development of microwave technologies for radar-based aircraft early warning systems and interception. The exchange of information with the British, generally remembered as the Tizard mission, resulted in many new ideas and advancements. In August, information was exchanged on important developments including British detection of German aircraft, British ship and airborne radar systems, identification systems, and news of the cavity magnetron, an advanced means of generating radio waves in the microwave range. The Chief of Naval Operations subsequently requested samples of various British radar systems.

With a clear goal, and information on British systems, the Navy began developing identification systems, including airborne surface-detection radar, and ship-based detection radar.

In November 1940, the Massachusetts Institute of Technology (MIT) Radiation Laboratory was the site for the first general meeting of the Radar Division and became involved in many of the development projects that resulted from the meeting. The Chief of Naval operations authorized the use of the acronym "RADAR," and consolidated the various radio ranging names that were being used into "Radio Detection and Ranging Equipment."

By March 1941, the Navy was reporting that they were able to track aircraft up to a distance of about 100 miles, and recommended the installment of aircraft identification devices. By May, Project Roger had been established at the Naval Aircraft Factory to support the MIT Radiation Lab and the Naval Research Laboratory radar projects. Project Roger aided in the installation and testing of the systems, which included aircraft radio control and search and blind bombing capabilities. In July, the first Identification Friend Foe (IFF) systems were installed in aircraft, along with some British ASV radar systems. Radar Plot systems for shipborne air warning were approved for installation into aircraft carriers.

In August 1941, the first modern-style radars were being installed in U.S. aircraft. The AI-10, a microwave radar developed by the MIT Radiation Lab, was tested in an XJO-3 aircraft.* The tests led to the development of the ASG and the AN/APS-2. The success of the radar projects led the Bureau of Aeronautics to request radar guidance equipment for their assault drones. They were interested in having automatic homing devices and a means to transmit target information to a control operator. The homing devices were an important concept that could potentially be used to guide missiles to their targets. The Bureau established a plan for the installation of long-range radar into patrol planes and short-range search radar in a torpedo plane. The installation of radio altimeters was also planned. By November, intercept radars had been successfully designed and were eventually installed in some of the F4Us.

Left: This F4U-5P "Corsair" aerial reconnaissance plane was equipped with radar and aerial surveillance equipment (there is a camera hatch below the cockpit). It was a variant on the F4U-5. The F4U-1P was equipped for photo-reconnaissance. This image was taken around the summer of 1950. The earlier F4U was one of the first aircraft to be equipped with *interception radar*, in the summer of 1941. Right: The USS Valley Forge transporting aircraft in April 1949. Some of the aft planes are F4Us. [U.S. Navy All Hands and Historical Center Collection historical archives photos, public domain.]

*The XJO-3 was among the first twin-engine aircraft to successfully execute aircraft carrier take-offs and landings with tricycle wheels, in August 1939. and could detect surface ships at up to about 40 miles.

Toward the end of the year, the Navy was contracting out the construction of airborne search radars that had been developed by the Naval Research Lab, while research and development of other innovations continued. One of the most important of these was a transceiving antenna. Up to this time conventional, separate, Yagi-Uda antennas (a common branching type) had been used for the transmitting and receiving of radar pulses. This system was cumbersome, so research on a ‘duplex’ system, in which a switch could toggle between the input and the output, allowed a single antenna to be used where two had been previously necessary, making the radar systems more streamlined and reliable.

Improvements in radar were having an important impact on strategy and the administration of military resources, and changes were now rapidly made in how personnel and equipment were deployed to take advantage of the new capabilities.

Overseas Developments

Letters from RCAF Overseas Headquarters indicate that Canada, too, had been establishing radar surveillance posts. Some of these were overseas, where it was not easy to hide and haul around bulky radar equipment. By the time the U.S. entered the War in December 1941, there was a secret Canadian radar installation north of Singapore which detected an incoming enemy raid and provided warning of the impending attack. When threatened, the radar post was moved to Singapore Island and later relocated to another part of the island. The members are reported to have improvised when necessary, sometimes using palm trees instead of masts for installing their radar antennas.

By December 1941, when the United States entered the War, some radar defense systems had been put into service in the Continental U.S. and some of the U.S. possessions. Not surprisingly, these early installations have been described as ineffective by U.S. Army personnel and historians:

> “These [radar defense systems] consisted mainly of obsolete SCR 268 searchlight control sets, sited to attempt to utilize it [them] for early warning and also the original version of the SCR 270 early warning set. The coverage provided was inadequate for two reasons. One was a misconception at first of the technical qualifications of a good radar site. This conception was that generally the more altitude the radar was set on, the greater the coverage. This proved false and practically all the radars had to be relocated on new sites. The other reason for the weakness of the system and one difficulty faced by the entire program of radar development, was the lack of trained operating personnel and technicians immediately available. An extensive and intensive training program was under away [sic] both in the United States and the United Kingdom but initially the quantity and quality of personnel could not be produced fast enough. Another difficulty encountered was the maintenance and constant modifications to the design of the sets. Spare parts could not keep up with aqnd [sic] ground observer units....”

Technology and trained operators were not the only important aspects of early warning systems. The effective use of radar warning systems was hindered by the lack of effective administrative channels for conveying the warnings that resulted from radar and radio comunications data. For example, radio messages had been intercepted by American forces that indicated a break in Japanese diplomatic relations, but the intelligence wasn’t processed in time to establish defenses against the attack on Pearl Harbor.

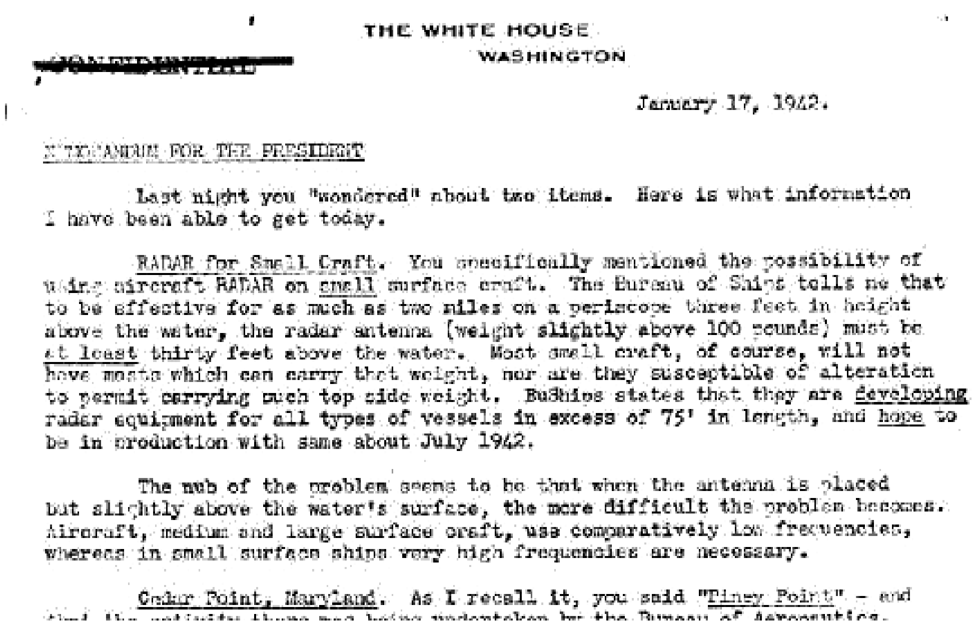
Radar systems improved substantially during the course of the War and thereafter. The historian quoted above continues on to describe improvements and how they could be used on the front lines during and after wars.

"... as the war progressed more and more thought was given to the offensive use of radar.... This made it possible to effect interception of Stuka raids well before the enemy reached the front line. Interceptions were controlled and made from radar plots by a ground controller and visual contact by the pilot with the enemy flight....

The Navy is a great user of radar and control both offensively and defensively. Ships carry radar and control equipment for detecting enemy flights and making the interception. Their control ships controlled all army air activity initially in the island operations. They also use it for control of all types of automatic and heavy gun firing, detection of enemy and identification of friendly shipping.

Strategic air operations use radar extensively. They do not, however, incorporate the use of ground control such as does the Tactical Air. They are linked to the ground as their airborne radar APQ-13, APS-15 and others all pierce the clouds and reveal the landfalls and terrain features over which they fly.... One of the mostly highly prized activities utilizing radar and control is that of GCA, Ground Control Approach. This equipment has demonstrated its effectiveness in both ETO and in the Pacific areas. It picks up aircraft which are either in distress and in overcast, or lost in zero conditions and guides...."

[Colonel Rex J. Elmore, "Development of Radar and Control in Air Operations," *Military Review*, August 1946, unclassified.]



THE WHITE HOUSE
WASHINGTON

[redacted]

January 17, 1942.

MEMORANDUM FOR THE PRESIDENT

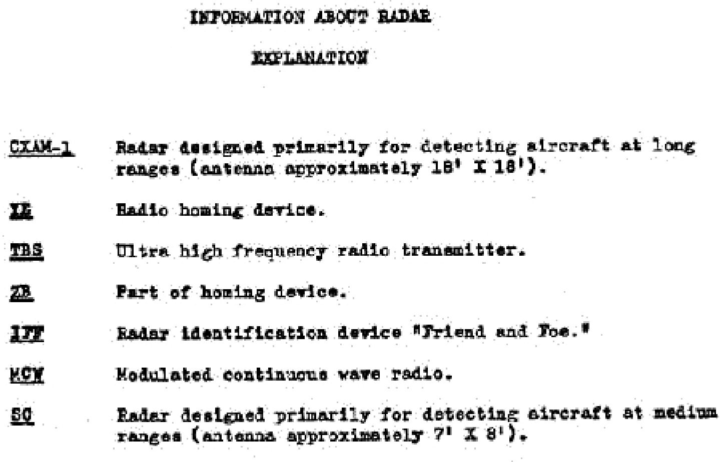
Last night you "wondered" about two items. Here is what information I have been able to get today.

RADAR for Small Craft. You specifically mentioned the possibility of using aircraft RADAR on small surface craft. The Bureau of Ships tells me that to be effective for as much as two miles on a periscope three feet in height above the water, the radar antenna (weight slightly above 100 pounds) must be at least thirty feet above the water. Most small craft, of course, will not have masts which can carry that weight, nor are they susceptible of alteration to permit carrying such top side weight. BuShips states that they are developing radar equipment for all types of vessels in excess of 75' in length, and hope to be in production with same about July 1942.

The nub of the problem seems to be that when the antenna is placed but slightly above the water's surface, the more difficult the problem becomes. Aircraft, medium and large surface craft, use comparatively low frequencies, whereas in small surface ships very high frequencies are necessary.

Cedar Point, Maryland. As I recall it, you said "Piney Point" – and

This January 1942 Memorandum for the President from John L. McCrea to President Franklin D. Roosevelt responds to the President's inquiries about placing radar on small craft. It explains, in simple terms, some of the difficulties with installing radar systems on small craft, including weight and height requirements that are impractical for small craft. [National Archives historical documents, declassified public domain.]


INFORMATION ABOUT RADAR

EXPLANATION

CXAM-1	Radar designed primarily for detecting aircraft at long ranges (antenna approximately 18' X 18').
YE	Radio homing device.
TBS	Ultra high frequency radio transmitter.
ZB	Part of homing device.
IFF	Radar identification device "Friend and Foe."
MCW	Modulated continuous wave radio.
SC	Radar designed primarily for detecting aircraft at medium ranges (antenna approximately 7' X 8').

An excerpt from a February 1942 letter from J. B. Dow to President Roosevelt indicates that FDR was interested in keeping up to date on how radar technology was being used during World War II. This excerpt lists a few of the common codes in use at the time. [National Archives historical documents, declassified public domain.]

Communications terminology and protocols evolved substantially in the 1940s with the war (and the following Cold War) as motivating factors. Identification friend or foe (IFF) systems improved at this time as well. Homing devices, based on homing in on a radar beam reflected from the intended target, came into use around the summer of 1942. Discussions about the establishment of early warning radar stations began about this time as well, based on the desire to extend the range of 'sight' to beyond the horizon.

The aviation industry scored one especially big bonus from radar research and development in January 1943, when a new aircraft approach radar that had barely been tested prevented an emergency situation. A snowstorm shut down an airfield at NAS Quonset Point before the arrival of a flight of PBYs. The ground-control approach crew were able to detect the incoming planes on the search radar and relayed landing instructions through the control tower to the aircraft for contact landing, thus bringing in the planes with the first Ground Control Approach (GCA) system.

New Strategies for Warfare

As it evolved, radar supplemented hydrophones in the detection of submarines and other underwater targets. Helicopters were equipped with radar and dipping sonar systems to aid in submarine detection. In the Battle of the Atlantic, radar provided a way to locate surfaced U-boats from the water or from the air.

In November 1943, new strategies were employed when a radar-equipped Avenger was used to guide two Hellcat fighter planes to enemy aircraft during nighttime. On the second reconnaissance, the team successfully detected and engaged the enemy.

Warfare changed as radar provided a way to 'see' in the dark and at distances not previously possible. But as radar evolved, so did anti-radar technologies. Materials with lower radar 'signatures' and radar-jamming techniques were developing alongside the radar technologies, creating a competitive environment in which scientists were always trying to keep one step ahead of the opposing technology.

Aerial Early Warning Systems

Until the war in the 1940s, World War I had been known as the Great War. After the eruption of yet another world war, less than a generation later, it was retroactively called World War I and the second global conflict then became World War II. Concerns about preventing a third war were probably already surfacing before the conclusion of World War II, and effort was put into establishing early warning systems using the new radar technologies.

Stationary radar warning platforms were effectively used during the War, but military planners felt there was a need for radar-equipped aircraft early warning systems. In 1944, the U.S. Navy established such a program through the Naval Research Lab and the Radiation Laboratory (later known as the Lincoln Lab). Experimenting with a combination of radio ranging and radio communications technologies, scientists developed an airborne radar system which could transmit radar video data to sea or ground platforms. Thus, aircraft carriers, for example, could dispatch a reconnaissance aircraft which could subsequently transmit the data to the combat information center (CIC) on board ship. The concept was sound, but the technology was lacking. The range of the video data link just wasn't long enough at the time to provide the desired early warning capabilities. The solution proposed in 1945 was to establish the CIC on board the aircraft [Bouchard, 1999].

The honor guard from the 11th Airborne Division Reconnaissance Battalion presents arms as Allied representatives arrive for the ceremonies commemorating the surrender of Japan in Tokyo Bay, 2 September 1945. Reconnaissance and surveillance of Japanese radio communications and marine vessels were significant factors in countering Japanese offensives in the Pacific during the War. [U.S. Army Signal Corp Collection, public domain.]

When World War II ended, scientists looked for new ways to exploit radar technology. In 1946, radio waves were bounced off the Moon and back, demonstrating that the energy not only could penetrate the ionosphere, but that FM modulation, developed by Armstrong, had great potential as a measurement and communication technology. That same year, a group of engineers from Douglas Aircraft proposed the use of satellites as observation posts, though actual implementation did not occur until many years later.

Following the War, the Federal Communications Commission (FCC) allocated certain frequency bands for radar, including X-band and K-band frequencies for commercial use, and other bands for commercial aviation and military use.

The development of airborne radar systems led to the modification of a number of land-based aircraft to accommodate air search radar systems, which were put into service in 1946. Later that year the Patrol Bomber Squadron flying the planes was transfered to Rhode Island and redesignated the Airborne Early Warning Development Squadron Four (VX 4). Another move to Maryland in 1948 established it as the center for airborne naval early warning. The result of equipping and flying the modified aircraft led to the subsequent development of specialized radar-equipped reconnaissance planes.

Radar had proved its worth as a detection and navigational tool and was expected to continue to be used for other purposes at the conclusion of the War.*

Gradually, destroyers were being outfitted with radar systems, with some of the ships being specifically assigned as *radar pickets*. The Sullivans (DD-537), for example, served on radar picket duty in the Pacific in 1945.

During the summer and fall of 1948, a U.S. submarine, the Spinax, was modified for radar and communications capabilities by adding equipment such as was used in the naval destroyers. It thus became the first radar picket submarine, redesignated SSR 489. The Spinax Electronic Counter-Measures (ECM) equipment was used to detect radar or similar electronic radiation. On the port side of the periscope wells was the submarine-spotting radar.

The Sullivans, was one of the earliest U.S. naval destroyers assigned to radar picket duty in the Pacific region in the mid-1940s, shown here in October 1962. Right: The USS Valley Forge is shown in April 1949. Also note atop the tripod mast there is a large SX radar antenna. [U.S. Navy historical photos, released.]

In the late 1940s, Arthur C. Clarke predicted and described in detail the process of putting geostationary satellites in orbit around the Earth. His predictions were not only remarkably accurate, but probably in part inspired the development of satellite technology.

The Transistor Revolution

The invention of the transistor in 1947 at Bell Laboratories heralded the next significant stage of growth in surveillance technologies and, once the technology became established,

*There are many books that provide histories and details on Allied radar installations in World War II, some of which are listed in the *Resources* section at the end of the chapter.

had a dramatic effect on the evolution of radar devices. Transistors and the evolution of semiconductor technology represented an important shift from mechanical to electronic components and systems, and from large-scale to small-scale radar sets which were equal to or better than their older large-scale counterparts. That is not to say that transistors completely superseded tubes. For certain high-frequency radar applications, vacuum tubes continued to be important system components, but overall, the design and efficiency of radar systems were improved with transistorized parts.

In 1947, the scientists at Bell Laboratories introduced a historic development in electronics, the transistor, which made microminiaturization and a new generation of devices possible. [U.S. Postal Service first day cover from the author's collection, used with permission.]

Adding Radar to the Fleets

As radar technology advanced, and became more practical and affordable with the addition of transistor technologies, planes and ships were increasingly outfitted with a variety of types of radar systems.

By the early 1950s, a number of planes had evolved from the original B-25 Mitchell bombers that were first flown in 1940. These descendants included the TV-25K and TB-25M which were subsequently modified to serve as training aircraft for teaching Hughes E-1 and E-5 *fire control radar* operation skills. The addition of radar to many aircraft and ships continued through the 1950s along with training of the radar operators, prompted in part by the Korean War.

Sikorski helicopters from the First Marine Division Reconnaissance Company in Korean operations, September 1951. Helicopters were first equipped with some of the modern radar technologies in the mid-1940s. [U.S. Navy All Hands Collection photo, public domain.]

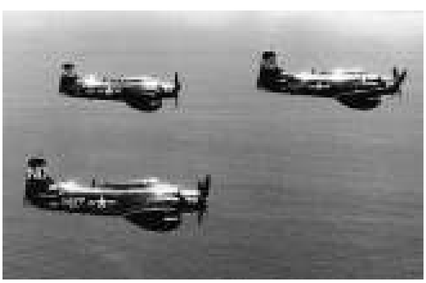
By the 1950s, new radar technologies were spreading around the globe. Australia, for example, shifted its defense policies to become more self-sufficient, adding to its air force and establishing its own system of air defense and air traffic control radars.

The Establishment of Early Warning Systems

The beginnings of extensive U.S. early warning radar in Canadian territory began with the "Pine Tree Line." This was an air surveillance radar system that was intended to safeguard the northern approach to the U.S. It stretched across southern Canada, becoming operational in 1951. However, due to its proximity to the U.S. border, it was considered to be insufficient warning and patrols off the coasts continued to supplement the Line.

In 1952, to further address the desire for early warning systems for national defense, Project Lincoln was initiated at MIT, which had been an important center for radar development during the War. The result of the Lincoln research was the recommendation that the early warning system be established across northern Canada. However, the difficulties of establishing and maintaining radar stations in the cold northern reaches of Canada were raised as objections to the concept. In spite of the inherent difficulties, it was initiated as Project 572 and became the Distant Early Warning (DEW) Line.

Radar picket lines along the coasts were established in the 1950s, including the Inshore and Contiguous Barriers. Extensions of the DEW Line were also planned. The radar picket stations were originally patrolled by radar picket destroyer escorts, but gradually became patrolled by radar picket ships and later were supplemented by airborne early warning craft.



Left: Early warning radar picket aircraft flying near Korea in August 1951. These Douglas AD-3W "Skyraider" planes were based aboard the USS Boxer (CV-21) as Squadron VC-11. Right: Ships supporting the Alaska DEW Line in September 1955. The USS Harris County and the USS San Bernardino County are shown unloading at Point Barrow, Alaska. Bottom: The USS San Bernardino County supporting the DEW Line operations in an ice belt of the shore of Alaska in September 1955. [U.S. Navy historical photos, public domain.]

The Alaskan portion of the northern DEW Line was completed in 1953, and was extended across northern Canada by 1956, coming into operation the following year. The DEW Line had been extended into the Atlantic as well, and test patrols of the Atlantic Barrier began in the summer of 1956.

Radar Automation

In spite of all the advancements in radar during the War and following the invention of the transistor in 1947, there were still many aspects of radar that were manually handled. One of these was the plotting of trajectories. Since bright blips on a radar screen are only there for as long as the target can be seen and resolved by the radar, the radar operator had to have a good memory and sense of what was happening to track activities within a region under surveillance. Hence, manual plotting systems were developed, in which the status was marked and tracked on accompanying charts, providing a picture of what was happening to analysts and strategists who might also be evaluating the information. With aircraft and other vessels becoming progressively faster, due to improvements in technology, this system was fast becoming obsolete.

IBM was one of the companies working on solutions to automate plotting and introduced its Semi-Automatic Ground Environment (SAGE) system in the 1950s, continuing development on the system into the 1960s. Since the changeover from vacuum tubes to transistors was not yet complete, SAGE's brain consisted of a gigantic, old-style computer. By the time SAGE was fully functional, however, the new, smaller electronics had become established and SAGE became an expensive, less-efficient behemoth.

Establishing Surveillance Systems

With America building radar stations across northern Canada, it became clear that better coordination between the defense forces of the two nations was needed. As a result, the North American Air Defense Command (NORAD) was established in September 1957.

In the summer of 1957, the Russian Federation announced in print to the world's radio technologists that they would be launching a satellite into orbit to study the ionosphere. They provided information on the radio wave frequencies that would be used for the satellite broadcasts so that communications received by listeners around the world could be reported, in order to track the progress of the satellite. The frequencies selected were just above those used for global standard time signals. In October 1957, the Federation successfully launched Sputnik I, the world's first artificial satellite. A month later, they launched Sputnik II, with a passenger, a dog named Laika, to test radiation levels and to investigate the feasibility of putting a human in space. The craft was equipped with a slow-scan TV camera for broadcasting images to ground-based receivers. Space programs and modern surveillance and communications satellites arose from these momentous events in the 1950s and early 1960s. As a competitive response to the launch of Sputnik, America planned to be the first nation to put a man on the Moon.

In the late 1950s, a Minitrack system was developed for the National Research Laboratory (NRL) Vanguard Satellite Program which detected signals from Sputnik and subsequent satellites to monitor their orbital positions. Since not all satellites would necessarily broadcast signals that could be interpreted by American systems, the idea of reflecting signals off the satellites to track their positions was born and eventually led to a more elaborate system called the Space Surveillance System (SPASUR) which became operational in 1961, using a frequency of 108 MHz.

In January 1959, Fidel Castro seized power in Cuba and established ties with the Soviet

Union, raising U.S. concerns over national security. A number of U.S. destroyers were converted to radar pickets and surveillance efforts increased overall. U.S. intelligence agents reported the installation of Soviet missiles in Cuba. In 1960, the Central Intelligence Agency was involved in a plot against Fidel Castro. Meanwhile, Americans had been flying spy missions over Soviet territory and in May 1960, Khruschev announced having shot down an American plane. (This is described further in the Aerial Surveillance chapter.)

In January 1961, President Eisenhower's administration broke off relations with Castro when Castro ordered a reduction in U.S. embassy staff.

In 1961, an invasion of Cuba at the Bay of Pigs was planned, and only days later aborted. A U.S. radar picket station was established at the southern tip of Florida, to monitor the region between the U.S. and Cuba. Political negotiations and military pressure on shipping and submarine activity in the vicinity of Cuba eventually resulted in the withdrawal of Soviet offensive weapons, closely monitored by U.S. forces in the area. In November and December 1962, the political situation with Cuba was very unstable and many reconnaissance, patrol, minesweeping, and anti-submarine ships were dispatched to the region. The event, which fortunately didn't erupt into a major nuclear war, has been remembered as the Cuban Missile Crisis. Radar was extensively used to patrol the region.

By the early 1960s, radar technology had advanced to the point where it could be used to remotely land an aircraft. At about the same time, satellite technology had taken to the skies and radar was used not just to warn of impending enemies in wartime, but to conduct global surveillance in peacetime as well. One of the early radar surveillance systems was a U.S. installation in Japan that scanned adjoining Soviet territory.

Space Surveillance

In 1965, the U.S. SPASUR system was upgraded to the Naval Space Surveillance System (NAVSPASUR) and the transmissions frequency was changed from 108 MHz to 216.88-217.08 MHz. The system was essentially a high-powered, continuous-wave, bistatic radar which sent out a latitudinally fanned radar beam which is often referred to as a 'fence.' When the beam encountered a reflective object in orbit, the returning beam could be intercepted and analyzed by ground receiving stations, providing information on the existence of a satellite and a collective calculation of its position. The receiving stations used interferometers, Doppler data, and triangulation to calculate information about the orbiting object detected by the sensors. Once a general position was known, more targeted surveillance could be conducted with other sensors if desired, to determine the location and characteristics of the satellite.

By the late 1960s and early 1970s, radar imaging was contributing to our ability to map terrain and investigate the unique 'signatures' of various types of materials. Radar frequencies suitable for probing beneath the Earth in soil and sand were being studied and certain lower frequencies were found to be capable of deeper penetration (with some trade-offs in resolution).

Multisensor surveillance vessels began to be developed in the early 1970s, first by converting existing systems, and then by designing specialized stealth and surveillance craft that could carry several sensing systems. One of the early multisensor platforms was based on a modified B-25 "Mitchell" (a common World War II bomber plane) which was outfitted with side-looking radar (SLAR), an infrared scanner, radiometers, and aerial cameras. Many of the B-25s were modified to become training craft in the 1950s. Radomes were fitted in the noses and radar equipment was installed in the bomb bays.

A series of reconnaissance and fighter aircraft were developed over the next three decades, starting with early achievements such as the highly classified U-2 to more recent designs like the F-18 Super Hornet and the F-22 Raptor. These fast, high-flying aircraft gathered information from out of the reach of conventional weapons. The U-2 was equipped with long-rang cameras, radar-intercept receivers, and recording equipment in order to gather information on missile sites, troop deployment, and nuclear installations, especially in the U.S.S.R. during the Cold War years [Rowan and Deindorfer, 1967].

In October 1983, the Naval Space Command (NSC), a component of USSPACECOM (the U.S. Space Command), began operations. The NSC, among other things, handles satellite-based space surveillance and early warning systems for defense.

Technological Advancements

Computer technology and microminiaturization were well established by the mid-1980s and the components were beginning to be used in many types of radar systems, making them smaller, more economical, and more powerful.

By the late 1980s, digital signal processing (DSP) was being incorporated into radar systems to aid in automation and signal interpretation [Mardia 1987]. Miniaturization was also improving, allowing smaller, lower power-consumption systems to be developed. It was also becoming more practical to use higher frequencies, broadening the range of products and improving consumer radar products.

In the early 1990s, many of the new microelectronics technologies that had been developing over the last decade were tested in military situations. Homing devices, missile-seeking systems, radar imaging systems, and countermeasures had all evolved significantly and were being gradually incorporated into the military arsenal.

Radar systems along borders were continually monitored and gradually updated (and sometimes renamed) as the technology evolved. The NAVSPASUR warning system came to be known as the NAVSPACECOM 'fence' in 1993, though many continued to called it by the NAVSPASUR name even into the year 2000.

In Operation Desert Storm, Navy EA-6B Prowler aircraft used reconnaissance and sensing devices to determine the location of a threat. They would then jam and destroy the enemy radar systems. In early 1991, the Prowlers damaged enemy early warning systems and attacked critical radar sites with high-speed anti-radiation missiles (HARM).

Left: Naval F-14 "Tomcat" aircraft were equipped with long-range AWG-9 radar systems which, when engaged, would apparently cause Iraqi MiGs to turn away. The Tomcat is shown here launching from an aircraft carrier in August 1999. Right: A Tactical Air Reconnaissance Pod System (TARPS) being removed from an F-14. [U.S. Navy news photos, released.]

Left: The EA-6B Prowler was used for reconnaissance missions in Operation Desert Storm. Shown here are Prowlers patroling the “No Fly” zone over southern Iraq in February 1998. The Prowlers provide ‘cover’ for accompanying planes and ships by jamming enemy radar systems, data links, and communications. Middle and Right: The *radome,* a protective radar cover, is clearly visible on this E2-C Hawkeye Airborne Early Warning aircraft. Hawkeyes provide long-range radar and communications support for aircraft carriers. [U.S. Navy photos by Chuck Radosta and Tedrick Fryman, III, Johnny Grasso, released.]

During hostilities, fire-control radars were used by the Iraqis along with Silkworm missiles in Kuwait. The Gulf marine region was defended by several underwater mine fields that were located by American intelligence and surveillance devices. Extensive mine-clearing operations were carried out and the Silkworm radar systems targeted to disable them.

Electronic reconnaissance was performed by specially equipped EP-3Es. An S-3B worked in conjunction with the USS Valley Forge (CG 50) in the Persian Gulf, using forward-looking infrared and *inverse synthetic-aperture radar* (ISAR). Left: An S-3B Viking and ES-3A Shadow. The Shadow is with the Fleet Air Reconnaissance Squadron shown here in support of Operation Southern Watch over the Gulf. Right: An S-3B Viking conducting air operations with the Japanese Maritime Self-Defense Force in the Sea of Japan in November 1999. [U.S. Navy 1999 photo by Michael Pendergrass, released.]

The RIM-7 NATO Sea Sparrow *air-to-air missiles* are designed with *radar guidance systems* to counter offensive missiles. In other words, the air-to-air missile is used to track and destroy a previously fired incoming missile. Note the various radomes on the ship’s tower (left). [U.S. Navy 1999 and 2000 photos by Johnnie Robbins and Brett Dawson, released.]

Mapping the Earth from Space

One of the most significant aerial mapping missions using radar was the spring 2000 flight of the U.S. Space Shuttle *Endeavour*. This mission was designed to obtain 3D topographical images of about 80% of the Earth's terrain using two large radar antennas. One was located in the shuttle, the other on a 197-foot mast. The area covered was about 43.5 million square miles extending from Canada to Cape Horn. Over 300 digital tapes (about 12 terabytes) of radar data resulted from the mission. The tapes were copied for study and evaluation by NASA and the National Imagery and Mapping Agency, with the originals stored in environmental chambers for safekeeping and backup. The data were gathered for military navigation and targeting, with less precise charts available to scientists, pilots, and search and rescue groups. (Charts are degraded to make them less useful if they are acquired by hostile forces.)

Radar is now routinely used in navigation, geographical surveying, law enforcement, international surveillance, air traffic control, intruder security systems, missile tracking, scientific research, especially astronomy, and the forensic sciences.

5. Description and Functions

5.a. Basic Radar Systems

The basic concepts associated with radar have been described in the introductory sections of this chapter. This section fills in a few gaps and provides some sample images of radar console operators at work in a number of different environments.

A typical radar send-and-receive system consists of radio wave-generating equipment, an antenna to direct the waves, an antenna to receive the returning waves (which may be the same as the sending antenna, or separate), a receiver to interpret the waves, and a display system which may or may not include computer algorithms for plotting movement over time, iconizing the data, or storing it for subsequent replay.

Most radar systems are pulse systems in which a series of pulses follows one after another, each carefully timed before the next pulse is transmitted.

In its most basic form, a send-and-receive radar consists of:

- A transmitting system with a *generator* to create a pulse, a *modulator* to process the pulse, an *oscillator* (usually a vacuum tube) to create high frequencies, an *amplifier* to 'enlarge' the signal and an *antenna* to focus and direct the pulse outward toward the intended target(s).
- A receiving system with an *antenna* to intercept and direct the returning pulse, an *amplifier* to increase the strength of the signal by increasing the voltage, a *processor* to automate aspects of data processing, and a *display device* to convert the signal into a visual representation that indicates the presence and relationships of reflective objects encountered by the transmitted beam.

Radar displays can be roughly grouped into *range indicators* and *plan-position indicators*. There are hybrid systems as well.

Radar systems can range in size from handheld, to large-scale arrays covering a few acres. Ground-penetrating radars are one of the more interesting technologies being used in law enforcement and archaeological investigations.

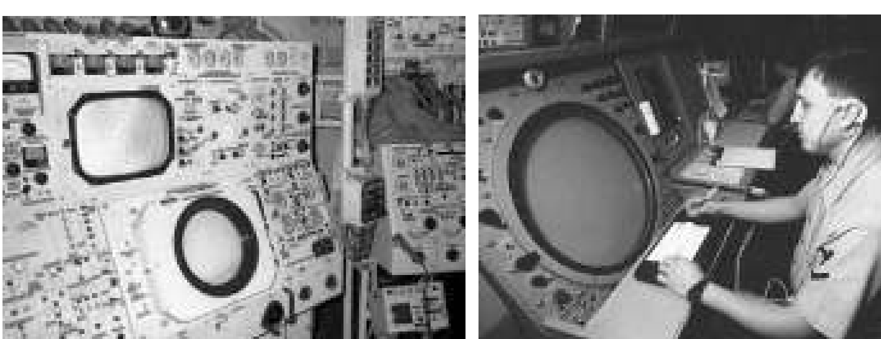
Radar-based landing systems for planetary probes can help provide data on elevations, roughness, distribution of slopes, and bulk density of the surface in order to carry out a landing. A reflective surface is necessary for a good landing using this type of system.

In the U.S., radar frequencies are allocated and monitored by the Federal Communications Commission (FCC). In Europe cooperative arrangements between nations have existed over the decades and are gradually being brought under the umbrella of the European Union. Frequencies of 2.7 to 3.4 GHz are used in civil and military radar applications in Europe. This allocation has recently been under discussion and review, with some concerns about changes expressed by NATO.

5.b. Radar Displays

As introduced earlier, the most common way to represent and display radar signals is on a specialized cathode-ray tube (CRT) called a *radar scope* though, increasingly, radar signals are being imaged on various types of computer monitors including transistor- or gas plasma-based portable display systems. Radar scopes generally have alignment and measurement references superimposed over the display field to help the operator interpret the information. Since radar signals travel through three-dimensional space, and a CRT represents the signal symbolically on a two-dimensional coordinate system, various means of symbolic representation and interpretation are used. Depending on what type of information is sought, different aspects of the echo are selected or emphasized.

Different types of radar console stations in the *combat information center* (left) and the *combat direction center* (right) of the aircraft carrier USS Kitty Hawk (CV-63). [U.S. DoD 1987 and 1991 news photos by James R. Gallagher, released.]



Left: A radar plot station on the Soviet-built USNS Hiddensee acquired by the Federal German Navy in 1991. Right: An air traffic control surveillance radar console on which Lou Scarozza monitors approaching aircraft at a U.S. Naval Air Station. [U.S. DoD 1993 photos by Eric A. Clement and by Don S. Montgomery, released.]

Radar is an essential tool for navigation on ferries, commercial tankers, cruise liners, larger boats, and military vessels. On aircraft carriers, they are also used for monitoring the aircraft that are associated with the carrier and foreign vessels (both surface and airborne). At times, they are used for directing combat operations. Due to the versatility of radar, aircraft carriers are equipped with many different radar antennas and usually have several radar console centers.

5.c. Digital Technology

Traditionally, most radar screens display sweeping or bouncing lines or bright blips, but radar display technology is changing with the introduction of computer electronics.

Computer technology now makes it possible to take traditional radar bouncing lines and bright blips and assign symbols or icons to individual aspects of the display. This can make the information more user-friendly by, for example, assigning a boat symbol to a large, slow object, and a plane symbol to a fast-moving target, once the source of the data has been determined. Radar operators must understand that symbolic mapping is never a perfect match with the original three-dimensional space, as the proportions may still be misleading, and must be monitored for errors as carefully as any traditional display.

Analysis and evaluation of the information by a human operator are still essential aspects of radar technology and a radar operator requires training, practice, and the ability to concentrate and interpret visual information. On iconic systems, in order to provide checks and balances for ambiguous signals, the blip images and the symbolic images may be displayed side-by-side (on a split screen or on separate monitors), or the display may be toggled from one to the other. On some computerized systems, the 'raw' radar blips may not be accessible.

Computer technology has provided other improvements to radar displays besides iconic representations of information. Here are some of the digital processing and display innovations provided by computerization:

tracking and plotting - This can be used to analyze the progress of targets over time, somewhat like the radar weather maps that are shown on TV, in which the successive images of a storm are played one after another in rapid sequence to make a segment that looks like an animation. This was a task that used to be done by hand using a pencil and graph paper.

storage and replay - Digital radar systems with memory caches and hard drives can be used to 'replay' previous image segments, or to freeze or analyze a particular segment of information, if a review of recent or past events is desired.

comparison and analysis - Expert systems can provide a means to simultaneously compare current information against past events, to look for patterns or changes that might be significant, and to call attention to situations that might be important.

display customization - Computer displays can also provide dynamic assignment of colors, or selective display of information, to aid in interpretation and representation.

As with all technologies, there are trade-offs. A traditional display, used well, may still be better than a computerized display used by an inexperienced operator. A computerized display with a lot of processing will have trade-offs in terms of speed, and a symbolic display is only as good as the symbol assignments provided by the operators. Nevertheless, in spite of limitations (and complications) provided by computers, their storage, replay, and signal processing capabilities have improved radar and the improvements are not limited to the display systems. The capability to send out carefully timed beams to create sophisticated radar arrays is just one of the benefits of computer technology as the science continues to advance.

5.d. Synthetic-Aperture Radar

There are many types of radar, but one of the more recent and important is synthetic-aperture radar (SAR), a technology capable of resolving a fairly broad area of terrain in high resolution, making it suitable for radar imaging applications like mapping the Earth's terrain, tracking ships, or monitoring weather systems. Satellite SAR scans of the ocean, for example, can create images about 100 kilometers square, providing good coverage of coastal features or shipping traffic.

The basic idea of a *synthetic* aperture is that distance can be 'substituted' for the length of an antenna. Radio waves can be a kilometer in length or more and antennas have been traditionally constructed so they are mathematically proportionate to the length of the wave so they will resonate in tune with the signal. Since there are practical limits on the size of antennas, especially when they are mounted on aircraft or small ships, some clever substitutions have been developed.

SAR involves a lot of calculations, which are not discussed here, but in simple terms, SAR typically provides a 2D image, in which one dimension represents the *range* (the *along-track* distance from the radar transmitter to the target) and the other dimension represents the *azimuth* (the *cross-track* perpendicular to the range). These concepts of range and azimuth are also used in sonar.

Now imagine that a SAR is mounted on an aircraft moving in a straight line. Since long antennas are needed to resolve long wavelengths and the length and shape of antenna transmitters and receivers are related to the dimensions of the radio wave (and associated frequency), a 'synthetic' aperture can be achieved by associating *the distance flown* with what would normally be the physical antenna length, thus creating a *synthetic apertur*e. In other words, the distance flown (as opposed to a physical aperture) makes it possible to create the effect of a long antenna.

The Doppler effect, described earlier, is used in SAR to resolve the shifted frequencies associated with the movement of the craft. Like other aspects of radar, there are trade-offs between resolution, speed, and the length of the radar pulses, but some of the most interesting radar images are generated with this technology.

5.e. Magnetrons

While microprocessors have replaced many types of vacuum-tube technologies, tubes are still important components in high-frequency applications, and radar transmitters commonly use vacuum-tube pulsed oscillators called *magnetrons,* developed in the late 1930s by Boot and Randall. A high-voltage pulse is applied to the magnetron which, in turn, emits a microwave-frequency radar pulse. While the noncoherent pulse of a crystal-controlled system cannot be perfectly locked, it has the advantages of small size and conversion efficiency. Coherent systems, which may be more costly and less efficient than a magnetron, are still useful, however, for special applications.

5.f. Space Systems

Radar signals on Earth are monitored with specialized fast, high-altitude planes and orbiting satellites. These systems are commonly used in surveillance because they are too distant to be shot down with conventional missile systems. Information can be sent through radio frequencies, but since these signals can be intercepted, physical storage media such as cassette tapes or film in protective wrappings, are sometimes ejected and intercepted as they fall to Earth. In case they miss their landing targets, they are sometimes equipped with dyes or transmitters to aid in their recovery. Since the recovery of physical storage media may be costly and somewhat hit-or-miss, it is more common now to use radio communications protected by spread-spectrum and encryption technologies (these are discussed in more detail in the Radio and Cryptologic Surveillance chapters).

One nation's satellite is another nation's reflector. In the late 1950s and early 1960s, when Earth-orbiting satellite technology began to evolve, unsettled political relations between the U.S. and the U.S.S.R. motivated military and scientific personnel to make use of opposing forces' space technology whenever possible. The interception of signals from a transmitting satellite was an obvious objective, but engineers didn't overlook the fact that an orbiting body, even if it was not actively transmitting, could provide a reflective surface useful for calculating positional information. Ground-tracking stations were developed to transmit signals to both passive and active objects and receivers were used to intercept the information and make it available for interpretation. Thus, a 'picture' of objects in the sky could be created from this information and new or unusual movements or objects could be detected and, if significant, scrutinized more closely.

5.g. Ground-Penetrating Radar

Most radar is used through Earth's atmosphere from ground stations and aircraft, although satellite radar from orbiting platforms is becoming more prevalent. However, ground-penetrating radar (GPR) has been found to be a useful technology for detecting the composition of the environment for a short distance under the ground.

Ground-penetrating radar was originally developed as a way to measure depths through ground structures such as glacier ice; this was easier than trying to drill hundreds of holes to try to assess depths of a particular region of ice. However, it was found that radar could yield more than just depth information. It could also be used to image areas with varying dielectric properties, yielding a highly useful set of data that aids in locating geophysical structures (water, silt, rock strata, etc.) and synthetic objects buried underground.

6. Applications

As has already been shown, radar has many commercial, scientific, and political applications. The examples in the previous sections clearly show that it is an integral tool in military surveillance. This section seeks to present a broader view of radar, describing a few more of the scientific and civilian uses and some of the interesting experimental radars that may become more common in the future.

6.a. Traffic Enforcement

Radar has been used in traffic enforcement for several decades and during that time, systems have become smaller and more accurate. Radar detectors have also been evolving in step with the traffic radar systems in a cat-and-mouse game that has caused the regulations regarding radar and radar detectors to be scrutinized and adjusted on a regular basis.

One of the more common technologies for speed enforcement is a single-shot radar 'gun' which only sends a signal at the time the vehicle is in visual range of the operator and the trigger is pulled. Radar detectors don't protect from this type of instrument. However, low power, semiconductor radar-jamming dash-mounted transmitters have been designed by some manufacturers to interrupt the signal, sending back unusable data. These incorporate a cavity resonator to generate microwave signals using a car's 12V battery system.

On the left is an older gun-style police radar system, on the right a somewhat newer one, though speed radar systems are upgraded every few years to take advantage of new technologies. A typical system consists of one or two radar transmitters, a controlling console, tuning forks (for calibrating the system), and a remote control. [Classic Concepts photos copyright 1999, used with permission.]

Police radar detectors generally operate in the X-band at about 10.5 GHz or the K-band at about 22 GHz. They are directional, but since many of the gun-style radar systems used in law enforcement are used from in front or behind, it handles most applications. There is some potential for spurious signals, as reflections off large reflective objects may trigger other radar devices in the vicinity, but the problem is not serious.

Certification is necessary to operate and calibrate radar speed control devices. Courses are offered which usually require about four hours of classroom and hands-on instruction.

This Speed Watch vehicle-monitoring system, set up by local police in a 25 MPH zone two blocks from a school zone, shows how an unstaffed radar traffic monitoring system can provide a visual reminder to speeding drivers. Over the half hour period during which these photos were taken, the average speed at which motorists approached the system was 33 MPH (with highs of 37) but the motorists consistently dropped to 22 MPH by the time they passed the unit. [Classic Concepts photos copyright 2000, used with permission.]

Photoradar, in which the radar system senses an approaching or retreating vehicle and snaps a picture of the license plate, has been in use in Asia and Europe since the 1980s, and has been implemented in British Columbia and a number of states in the U.S. It is primarily used for speed monitoring, though it has also been used for traffic light enforcement in some areas. Commercial photoradar systems use radio waves in the Ka-band. Traffic enforcement tickets are sent to the owner of the vehicle, as determined by the number on the plate, regardless of who was driving the vehicle at the time of the infraction. The choice of the Ka-band was made in part to help defeat radar detection systems.

Those seeking to avoid being prosecuted for speeding have come up with various schemes to interrupt this system, including sprays and plastic covers that allow the license number to be seen, but which scatter the light so that it cannot be effectively photographed. These systems are generally illegal.

Another traffic enforcement strategy is to inform motorists of their speed so they can make adjustments voluntarily. These systems are usually placed in locations where there is a habitual speeding problem in areas where there are particular hazards such as a blind intersection or curve or children playing near parks or schools. As motorists approach the system, the radar sends out a series of pulses to detect the vehicle speed and updates a large sign to display the speed. As the motorist's speed changes, so does the display.

6.b. Civilian Applications

The capability of radar to 'see in the dark' and 'peer into structures' allows it to be used for many security and diagnostic applications. Computerization has made it possible to design smaller, less expensive, more powerful devices that can now be marketed for smaller-scale commercial uses. It is likely that these uses will increase over the next several years.

Left: A concealable *radar security detector* can sense intruders up to a distance of six meters. Designed at the Lawrence Livermore National Laboratory (LLNL), the repeat radar signal from this *micropower impulse radar* (MIR) detects motion in the room by responding to changes in the returning echo. Right: The same impulse radar technology can be used to peer into novel places, as shown with this *micropulse radar stethoscope* used by Elaine Ashby, M.D., to measure inventor Tom McEwan's heart rate. [LLNL news photos by Jacqueline McBride and James E. Stoots, Jr., released]

6.c. Scientific Research

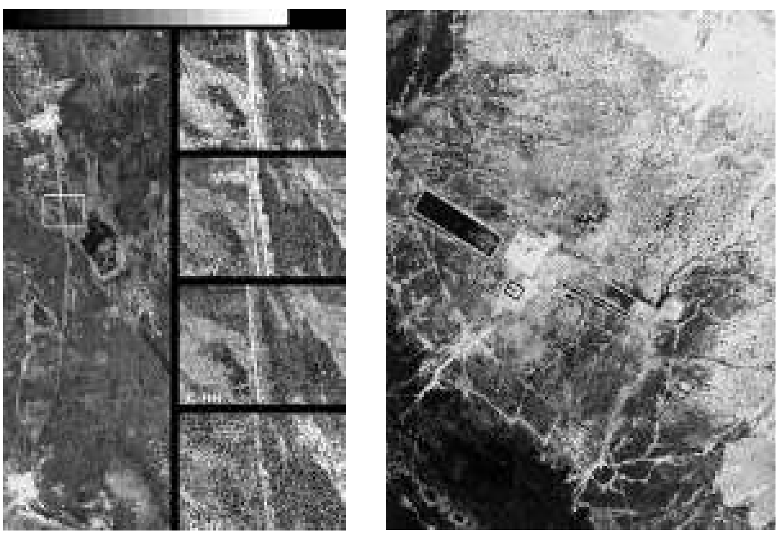
Radar has been a great boon to scientists studying almost every branch of science, but especially environmental studies, geology, archeology, anthropology, and astronomy.

Archaeology and Anthropology

Radar can often detect physical features, patterns, and trends that can't be seen any other way. It has helped us to locate ancient burial sites and villages, unusual rock formations, and changing geological formations. Recent radar images have aided archaeologists and historians in finding out more about the technology and habits of ancient civilizations.

The impressions of old villages and cities may not be noticed with the unaided eye, but when you image them with radar from the air or with ground-penetrating radar on the surface, suddenly building foundations, fields, squares, and other structures can be distinguished from more recent structures because they differ in composition or density. In some cases, radar images have revealed structures for the first time, as in archaeological finds in the Sahara Desert.

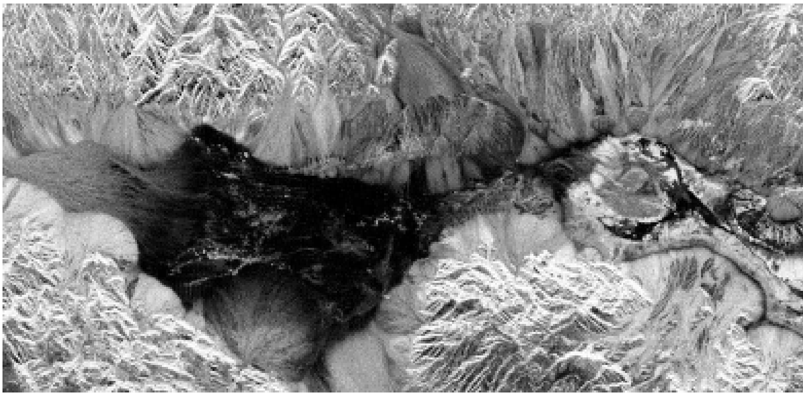
The Great Wall of China has been constructed and reconstructed over a period of many centuries, giving a glimpse into the turbulent political history of the region, its battles, its wall-builders, its economy, and its industry. Visual and radar aerial imaging of the wall has revealed that its boundaries have changed many times and have helped scientists discover regions of the wall that could not be seen from the ground.



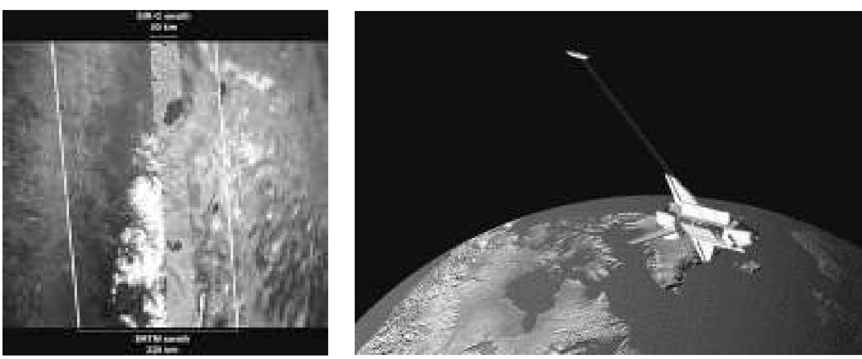
Left: This is an aerial view of a segment of the Great Wall of China in north-central China. The details on the right show close-ups of particular sections of the wall. The satellite photos were taken by the Jet Propulsions Lab Spaceborne Imaging Radar-C (SIR-C) in the L-band. The image shows the younger portion of the wall, built during the Ming Dynasty (about 600 years ago) and also the ruins of the older wall, built 900 years early, during the Sui Dynasty. The L-band can also reveal vegetation as bright areas. The images are aiding researchers in tracing the path of the old sections of the wall, providing a glimpse into the turbulent political history of China. Right: This satellite image of Angkor, Cambodia, taken in 1994 from the Space Shuttle Endeavor, shows 60 temples, some dating back as far the 800s. Apparently undiscovered structures were revealed by this image which combines L-band and C-band radar data. At one time, Angkor had a million residents before it was abandoned in the 1400s. [NASA/JPL news photos, 1996, released.]

Earth Monitoring and Mapping

A large proportion of the airborne images of the Earth are created with radar technologies. From weather-mapping to Space Shuttle-based terrestrial mapping, radar has contributed important information to our understanding of our planet.



This image of Death Valley, California was imaged with the SIR-C/X-SAR NASA Spaceborne Imaging Radar. The synthetic-aperture system is equipped with L-band, C-band, and X-band microwave radar capabilities. The picture above was imaged by the Jet Propulsion Lab using the L-band instrument. It shows how radar imaging is not only useful but often very beautiful. [NASA/JPL 1995 news photo, released.]



Left: A digital radar image of the Sierra Nevada Mountains acquired during a 1994 NASA Space Shuttle Mission using the Spaceborne Imaging Radar C/X-Band Synthetic Aperture Radar system. It has been superimposed with a photograph taken by the astronauts on the Space Shuttle. Color values are added to the grayscale radar images to aid in interpretation. Right: This computer-generated simulation of the spring 2000 Shuttle Radar Topography Mission (SRTM) shows how the Space Shuttle is used to collect 3D measurements of about 80% of the Earth's land surface (excluding the poles) using radar sensing equipment with a resolution of about 16 meters. A 60-meter mast was installed on the shuttle, along with a C-band radar imaging antenna. The mission used the same radar system that was twice flown in the Space Shuttle Endeavour missions in 1994, called the Spaceborne Imaging Radar-C (SIR-C). This is a cooperative project between the Defense Mapping Agency of the U.S. Department of Defense and NASA's Jet Propulsion Laboratory (JPL). [NASA/JPL 1996 and 1994 news photos, released.]

Human-related and natural environmental changes are now monitored with radar by many organizations, such as the Space Radar Laboratory (SRL), which has carried out space shuttle missions since the early 1990s. The systems are versatile, with the ability to take radar measurements of any type of region in any kind of weather. They are used to study geographic features such as rock formations, volcanic activity, ocean currents, vegetations, snow and ice packs, and wetlands. By comparing and contrasting data collected on different missions, small and large-scale changes and patterns may be discerned. The payloads have included the Spaceborne Imaging Radar *Synthetic-Aperture Radar* (SAR), which used C-band and X-band frequencies (SIR-C/X-SAR), and the *Measurement of Air Pollution from Satellite* system (MAPS). The data from the missions are distributed by NASA to the international scientific community.

Oil Spill Detection and Monitoring

Radar is used to detect whether tankers stray or deliberately move into restricted zones. It can also be used to detect unauthorized dumping or spills if the substance coats the water (e.g., oil) and is thick enough to alter the radar-scattering pattern of the surface of the water. The radio waves may be impeded, however, if the water currents are especially rough. Side-looking radar (SLAR) systems mounted on aircraft have been found useful for this type of surveillance.

Underground Investigations

Ground-penetrating radar has many uses. It can be used to measure the depths of glaciers and ice floes. It can aid in locating old septic tanks, oil drums, and wells. It can help to assess and study geophysical structures and mineral veins. It can even be used to help detect underground bunkers or covert storage facilities.

Ground-penetrating radar provides a way to initially survey a site without digging things up and disturbing the area. This not only saves time and money that might be spent on extensive excavations, but can help protect gravesites, private property, or sensitive environmental areas.

Surveillance with ground-penetrating radar is suitable for scientific geophysical research, resource exploration, forensic searches for old gravesites or possible victims of homicide, and hunting for fossils and artifacts. The radar probe, which resembles a large handheld metal detector, can create an image that shows changes in density at different depths up to several feet. On a computer display, a grid may be overlaid on the radar pattern to further aid in interpreting the information.

Space Exploration and Astronomy

Radio waves can travel for vast distances through space and radar is an important component of astrophysics. It has been used, for example, as a measurement tool to pinpoint distances between the Earth and solid celestial bodies like planets and asteroids. There are many uses of radar in astronomy and interplanetary exploration and the reader is encouraged to consult other resources as well as the National Aeronautics and Space Administration (NASA) at http://www.nasa.gov/ for information on radar technologies and pictures of radar imaging.

Weather Monitoring and Forecasting

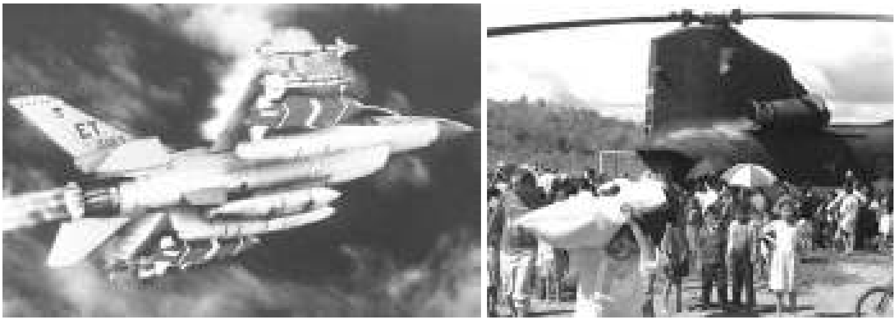
Weather forecasting, an important application of radar, has already been mentioned and illustrated in earlier sections.

6.d. Instrumentation and Navigation

Navigation

Radar is widely used for marine and air navigation and experimental vehicle navigation systems are under development that may aid in autonomous vehicles and collision-avoidance systems.

Radar is used in marine navigation to locate landmasses, harbors, and docking areas, potentially dangerous obstacles, and moving surface-marine or sub-marine craft.



Left: The F-16 Fighting Falcon is equipped with a Dispenser Weapons System 39 (DWS) which includes an onboard computer and a *radar altimeter* to automatically guide it to its target with data transmitted from the aircraft. Right: A Chinook (CH-47) helicopter brings in relief supplies to victims of Hurricane Mitch in Honduras. The Chinook "Super D" models are being equipped with a number of new instruments, including radar altimeters. [U.S. DoD 1994 news photo by Cindy Farmer, 1998 news photo by Thomas Cook, released.]

Radar is also used in the aviation industry to safely get aircraft on and off the ground without colliding with other aircraft, buildings, or terrain that might be obscured by severe rain, snow, or fog. The radar systems used in air traffic control are almost entirely pulsed systems divided further into *primary radar* and *secondary surveillance radar* (SSR).

- High-resolution *primary radar systems* are used to track the movement of airport ground traffic, aircraft approaches, and en route air travel. They developed from military Identification Friend or Foe (IFF) systems, adding the Selective Identification Feature (SIF), a code that was crucial to tracking individual aircraft.
- *Secondary surveillance radar* (SSR) can intercept and interpret more information than a primary system, including altitude, hijacking, communications difficulties, and unspecified emergencies. The ground interrogator and the aircraft transponder communicate on different frequencies in order to reduce interference of incoming and outgoing signals. SSR systems are beginning to use tracking systems derived from missile guidance technologies for angle measurement.

Radar altimeters are used for both ground and air applications including navigation and weather monitoring. They are also used for extraterrestrial applications, such as interplanetary space exploration equipment such as the Mars lander.

Personal Navigation

Solid-state miniaturization has resulted in smaller and smaller radar systems, to the point where a type of radar system has been incorporated into canes for the blind. For covert operations, such a system could presumably be used for navigating in areas without light, or where light might increase the possibility of detection.

6.e. Security, Surveillance, and Defense

Radar is used in many ways to provide warning of movement, vessels, projectiles, and unidentified objects. From commercial security systems to satellite early warning, and ballistic missiles defense, radar is a versatile technology that can provide good information without a lot of interference from other types of signals.

Left: A synthetic-aperture radar (SAR) receiving information from the airborne Joint Surveillance Target Attack Radar System (J-STARS). A J-STARS Boeing E-8 aircraft was used to monitor vehicle and troop movements and relay them to stations in Hungary as part of the NATO Implementation Force (IFOR) in Bosnia and Herzegovina. Right: A navigation officer on a Boeing 707 plots a course on a laptop computer as part of J-STARS. In flight, the radar can detect and track more than 120 miles of terrain. A 40-foot radome under the forward fuselage houses a phased-array radar antenna which feeds information to Army and Air Force operators with access to realtime large-screen graphics consoles. [U.S. DoD 1996 news photo by L. Aaron, released.]

Left: On a goodwill visit in 1989, various radar systems could be seen on the Soviet Slava-class cruiser Marshall Ustinov (CG-088). A Top Steer surveillance radar is mounted on top of the bridge. A Top Pair (Top Sail and Big Net) surveillance radar is situated further aft. Right: A U.S. Navy *Aircraft Approach Controller* monitoring an aircraft marine carrier radar display on the USS George Washington. The radar console aids the controller in managing air traffic flow and takeoffs and landings in the vicinity of the carrier. This mission to the Adriatic Sea was in support of the NATO Implementation Force (IFOR). [U.S. DoD 1989 news photo by Don S. Montgomery, 1996 news photo by Joe Hendricks, released.]

Long-range radar systems warn of incoming missiles and aircraft. SPADATS (Space Detection and Tracking System) is a joint program of the United States and Canada used to monitor artificial satellites.

Much radar plotting is still done by hand but, gradually, some of the plotting activities associated with radar monitoring are being automated by computer systems. Computerization allows the creation of ‘animations’ that can illustrate movement over time and the monitoring of individual targets (much the same way weather radar can show a storm system approaching the coast of Florida by quickly playing a series of stop-action frames).

Aircraft patrols and satellite links have become an intrinsic part of early warning and defense systems utilizing radio waves for communications and radar systems for specific sighting and imaging tasks.

Left: A U.S. Navy Mobile Inshore Undersea Warfare Unit being set up in Jordan for radar surveillance, in 1985. Right: Inside a Mobile Unit control van, an Operations Specialist plots the location and progress of enemy ship contacts during an exercise in North Carolina in 1992. [U.S. DoD news photos by Mike Moore and William G. Davis, III, released.]

Left: An Air Defense Command radar tracking station is located in Trinidad. Right: An Air Defense Command radar on a snow-covered vantage point in Nova Scotia, Canada. [U.S. DoD 1968 news photos by Ken Hackman, released.]

Left: A Joint Service team assembles an Army-Navy Transportable Ground 75-Air Control and Warning Radar System on the McGregor Test Range in New Mexico. Right: An Airborne Early Warning E-2C Hawkeye lands on an aircraft carrier. Note the streamlined radar-protecting radome on top of the craft. [U.S. DoD 1996 news photo by Regina Height and 1990 news photo by Don S. Montgomery, released.]

Pave Paws, an Early Warning phased-array radar system designed to detect incoming sea-launched ballistic missiles (left, in 1995). The display console (middle) and computer room (right) of the An/FPS-115 Pave Paws system in 1986. Data storage and analysis are important aspects of radar monitoring and imaging. High-storage-capacity hard drive and tape systems have now superseded most of the older computer formats. In 1986, Random-Access Memory (RAM) sold for $700 MByte compared to $1.50 MByte in 1999 and hard drives sold in 1986 for hundreds of dollars for only 20 megabytes whereas $200 now buys over 4 GBytes. Thus, substantial changes in capabilities have occurred not only in storage capacity and data access, but in the speed and size of display consoles (especially raster-based digital consoles). [U.S. DoD news photos by Ken Wright and Don Sutherland, released.]

Projectile Detection and Guidance

Radar is used to both to detect and track incoming missiles and to guide outgoing missiles. Radar was used to counter Iraqi Patriot missiles after they had been fired. The Patriot missiles themselves were guided by radar and used a local radar to increase the targeting precision.

Fire-control computers are used to help determine the path of a guided missile and Missile Guidance Radar (MGR) is used for homing guidance. Missile Tracking Radar (MTR) can be replaced or supplemented by a high-power continuous-wave illuminator (CWI) radar which is interfaced with the Target Tracking Radar (TTR) to home in on the Doppler frequencies generated by the target.

An AN/MPQ-53 radar set for the MIM-104 Patriot tactical air defense system deployed during Operation Desert Shield. It uses a multifunction, phased-array device for surveillance, tracking, and guidance. Note that the sandy ‘terrain’ around the radar unit is actually camouflage. [U.S. Air Force news photo, released.]

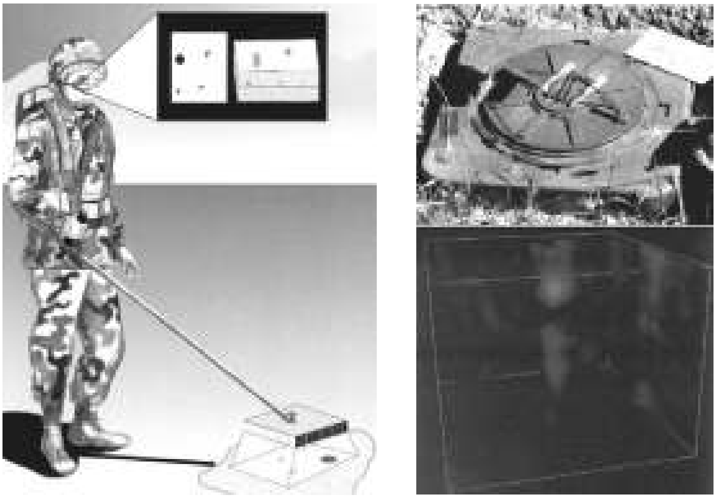
Radar can be used to track avariety of incoming projectiles, including hostile fire.


The *AN/TPQ-36 Fire Finder radar system* is used by the U.S. Army to determine information on incoming projectiles (rockets and mortars as small as .50-caliber), calculating their origin and possible landing location. The Target Acquisition Battery Bravo 25th Field Artillery Regiment shown here was deployed as part of a NATO Implementation Force (IFOR) in Bosnia and Herzegovina. Similar *AN/TPQ-27 Fire Finding radars* were also used. [U.S. DoD 1996 news photos by Lisa Zunzanyika-Carpenter, released.]

Mine detection

In spite of technological evolution and implementation in the developed nations, there are still many places in the world where the chief mine-detection tool is a long stick. Success at finding the mine often results in severe consequences for the person carrying the stick. The technique is inefficient, and impractical in regions of active combat. The next best commonly available, low-cost tool, a metal detector, is not suitable for locating plastic explosives. As a consequence, a number of low- to medium-cost solutions have been proposed, some of them incorporating radar technology. Ground-penetrating radar (GPR) systems have been tested in a number of soil types using a variety of frequencies, including frequencies in the X-band, C-band, and L-band ranges [Hanson et al., 1992].

One mine-detection strategy of interest is a micropower impulse radar (MIR) developed by Lawrence Livermore National Laboratory (LLNL). A self-contained, compact, low power, ultra-wideband radar impulse can be assembled into arrays and used to create two-dimensional and three-dimensional images of objects in sand, soil, or even concrete. Both metallic and plastic landmines have been detected in 5 to 10 cm of moist soil in test runs, with depths of up to 30 cm for dry soils. Other researchers, investigating the utility of radar technology to detect mines have suggested that winter conditions may significantly hinder mine detection, depending on the type of road surface. Radar sensor data can be combined with infrared sensor data to provide a more complete picture of the topography with multi-sensor readings. Mine-detection technology can also be applied to other ground-penetration surveillance activities, such as bunker or structure detection. The systems can be aircraft- or vehicle-mounted, depending on the circumstances. GPR technology is somewhat generic and can be applied to other fields of study, including archaeological exploration.



Left: A handheld radar-based mine detector being developed by the Lawrence Livermore National Laboratory. It employs micropower impulse radar technology to provide three-dimensional images of underground objects. Objects are intended to be identified by the size, shape, and mixture of reflected microwave frequencies. More than a dozen radars can be incorporated into the system, which also includes a waist-mounted computer and a 'heads-up' display for viewing the radar images. Top Right: One of several types of land mines. Bottom Right: A computer image showing lighter areas that indicate objects buried beneath the surface that might be mines. [LLNL news photo by Marsha Bell, released.]

6.f. Commercial Products

There are thousands of different radar products ranging from tiny car-mounted or handheld radar detectors to acreage-wide, large-scale array, transceiver radar stations. There isn't room to catalog them all here, so instead, here is an annotated selection of some major companies supplying some representative products, especially medium- and large-scale national and international radar surveillance systems. These companies can help answer questions about more specific types of radar technologies, their applications, and their cost.

ARCTEC (a joint venture of ATCO Frontec Services Inc. and Arctic Slope World Services, Inc.) - Selected by the U.S. Air Force to manage the strategic northern network stations known collectively as the *Alaska Radar System* (ARS). The ARS control center is located in Anchorage. ARCTEC develops and operates the Solid State Phased Array Radar System (SSPARS), a group of international stations that track and monitor orbiting satellites and ballistic missiles and Canada's North Warning System which stretches east and west across the Canadian arctic. The system is used for surveillance and tracking of commercial aircraft.

BAe Australia - Development, maintenance, and operations of Jindalee's Over The Horizon Radar (OTHR). This system, supplied to the Australian Defence Force (ADF), currently represents the only operational wide-area surveillance system.

The Boeing Company - Boeing is well-known for aircraft design and manufacture, but it also oversees multifirm contracts which include aircraft radar design and installation.

British Aerospace Defence Systems in collaboration with the U.K. Defence Evaluation and Research Agency - Developers of the SAMPSON multi-function, active-array radar which can be used in ground-based missile defence systems and in advanced air defence systems on naval destroyers.

The SAMPSON can handle both tracking and surveillance with data from multiple incoming sources, and is highly resistant to interference from sea clutter and jamming.

California Microwave - Contracted by the U.S. Army Communications & Electronics Command for A-Kit surveillance equipment for Airborne Reconnaissance Low Multi-function (ARL-M) aircraft, to be completed by 2001.

Celsius Group - The Celsius Tech Electronic division supplies chaff, flare dispensers, and second generation radar warning receiver systems such as are being installed in the JAS 39 Gripen multirole combat aircraft. The systems are designed to detect, analyze, and evaluate hostile radar threats.

Hughes Aircraft Compay - Provides APG-73 radars to projects led by The Boeing Company. See next listing.

Hughes International Corporation - This company is well-known for the design and manufacture of radar systems for command, control, and communications, including the AN/MPQ-64 Sentinel Air Defense Systems 3-D air defense radars which assist the U.S. Military in locating and identifying hostile targets such as aircraft, unstaffed air vehicles and cruise missiles. Designed with radiation and electronic countermeasures, these systems began production in the mid-1990s. Hughes has been involved with satellite sensing systems for many years.

Japan Radio Co., Ltd. (JRC.Co) - Established 1915, Japan Radio is a supplier of marine electronics and communications equipment, including radar, ground surveillance radars, radar simulators, wireless systems, mobile earth stations, GPS-based vehicle location systems, graphic workstations, direction finders, Doppler sounders and current meters. Tokyo, Japan.

Lockheed Martin Corporation - A well-known aerospace contractor, the Ocean, Radar & Sensor Systems division provides radar systems for the APS 145 radar system which is installed in E2-C aircraft. Lockheed Martin, in conjunction with Boeing and Pratt & Whitney, under contract to the U.S. Air Force, rolled out the first F-22A Raptor fighter jet in spring 1997. The F-22 is scheduled to gradually replace the F-15.

Nav Canada - Provides products to Canada's civil air navigation services, including air traffic control systems, electronic navigation aids, and various computer and radar systems.

Northrup Grumman Corp. - Well-known in aerospace, the company was contracted by the Wright-Patterson Airforce Base in 1997 to supply a radar microwave automatic test equipment shop for testing and repairing APG-68 fire control radar used in F-16 aircraft which are vended to foreign nations. Northrup Grumman also manufactures radar system improvement program (RSIP) kits through Boeing contracts.

Raytheon Company - Contracted by The Boeing Company to provide F-15 C/D aircraft radar upgrades as well as F/A-18E/F Super Hornet active electronically scanned array (AESA) radar systems. These systems are intended to increase detection and tracking ranges and to improve image resolution in phased steps up to about 2004. Raytheon has cooperated on a number of radar-related projects with Northrup Grumman Corporation and Boeing. Raytheon has been contracted to provide ALR-67(V)3 radar warning receiver systems for F/A-18E/F Super Hornet aircraft including countermeasures receivers. Features include advanced threat-detection capabilities, pulse Doppler and continuous-wave tracking, and identification of radio frequency and millimeter-wave threat emitters.

Textron Systems - Developers of ladar, laser radar systems for long-range detection, tracking, and imaging of a variety of types of targets.

Thomson-CSF Airsys - Developers of RAC 3D multimode, warning and coordination radar systems for use with very-short-range to medium-range surface-to air weapons systems. The system can also be used as a defense surveillance system for troops and conflict zones. It can be used in marine, land, and airforce operations. The RAC 3D system is operational in a number of NATO member nations.

7. Problems and Limitations

Attenuation (the gradual loss of signal) is an integral limitation of radar systems used over land through our atmosphere. Severe weather conditions, mountains, intervening buildings or vessels other than the target vessel, etc. are all obstacles that may degrade or deflect the signal before it reaches its target or its return destination. Attenuation tends to increase as the length of the waves decreases while the corresponding frequency increases.

Interpretation of Displays and Radar Data

The effective use of radar displays takes training and experience. The interpretation of a radar signal is largely dependent on the mode of representation (rectangular grid, conical scan, etc.), the type of display (raster or vector), the speed with which the display is updated, and the resolution of the display. The quantity of objects on the display and their speeds can also influence how easy or difficult it might be to assess radar targets. Here are some of the more common concerns in interpreting radar data:

- The actual size of objects relative to one another cannot be fully represented on a small screen. The difference in size between the smallest pixel or blip on a radar screen and the entire screen image is much less than the difference in size between a dog and a house. Even common objects, if they are small, require a resolution of about 300 dots per inch to clearly represent details and relative sizes, whereas most raster monitors used on computerized radar systems have a resolution of about 72 or 96 dots per inch.
- Fast movement can be missed on a radar display. For example, movie film frame rates that simulate 'natural' movement range from about 24 to 30 frames per second (about 1600 per minute). In other words, 24 to 30 still frames presented in succession can simulate a horse running or a plane flying through the clouds so they appear natural to us. Since most radar systems are pulsed, a radar 'frame' is similar to a film frame, in that it is a 'snapshot' of a moment in time. It would seem logical to pulse the radar at a rate of 24 to 30 frames per second, but this is technologically difficult and expensive. The rate of the pulse is related to the signal range and the speed of movement of the transmitting unit, which may be a rotating antenna in some systems. An antenna rotation may be as low as six revolutions per minute.
- A radar display is typically 2D (although 3D systems are becoming more prevalent with computer technology). There are always trade-offs when 3D information is represented on a 2D display.
- Radars can be 'fooled' by objects made with highly absorbant materials or materials that scatter the radio waves in many directions. Chaff is a long, stringy, reflective material that flutters in the wind as a radar countermeasure intended to confuse the sensor and, in particular, to influence the homing direction of incoming projectiles.
- Radar data can provide erroneous information if the target is deliberately using highly reflective materials spaced out over an area to make something look bigger than it actually is. For example, reflecting posts and surfaces can be put outside the corners of a small encampment to make it appear larger.
- While radio waves travel quite readily through air and space, they are refracted and impeded in water. Sonar, using acoustical waves rather than radio waves, is usually used in liquid environments.

Antennas

Since the length or diameter of an antenna is directly related to the length of the radio wave that is being apprehended, longer radio waves typically require larger antennas. In domestic defense installations, large antenna arrays can be installed on domestic or foreign ally property. But, since many surveillance activities require that the sensing system be hidden, not easily recognized, or mounted on a moving vehicle, a smaller antenna is generally preferred. Thus, the frequencies which can be used will in part be limited by the size and shape of the transmitting and receiving antennas.

Since antenna size and frequency are closely related, and most antennas are of a fixed size, many radar systems will operate on only one frequency, or on a limited number of frequencies. This imposes a further limitation on the covert nature of radar use. When scanning repeatedly on the same frequency, it is harder to hide the signal, and there are more opportunities for someone to detect the presence of the signal and subject it to jamming.

Radar Countermeasures

There are many ways in which to counter a radar probe, including radar-reflecting barricades, radar-absorbent or radar-scattering paints and materials, and frequency jamming. All are used to one extent or another in military operations.

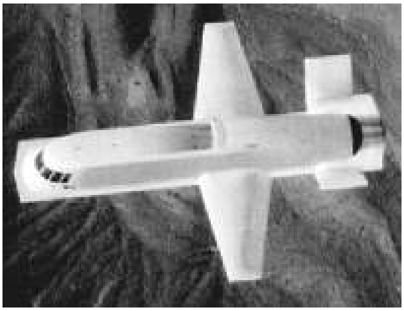
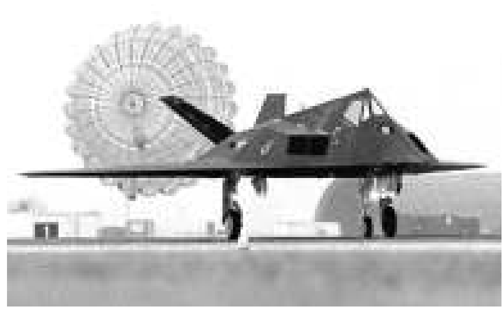
Countermeasures to radar will depend on the type of radar, the frequency, and the type(s) of antennas used. Monopulse tracking radar antennas are designed with multiple inputs to the receiver so that calculations can be derived from signal pairs. Thus, a single unobtrusive pulse, aimed at a target, can provide information about that target. This is especially valuable in covert operations where transmitted signals are best kept to a minimum. However, because it depends on a minimum level of transmissions, without repeat verification pulses, this type of system, if detected, is easily countered with a series of pulses designed to confuse the receiving system [Beam 1989].

The Blackbird SR-71, developed in the late 1950s and flown in 1964, is still one of the most unique, fastest, highest-flying stealth aircraft in the world. The Blackbird, or "habu" as it is sometimes called, was the first generation of U.S. military "stealth" aircraft utilizing radar-absorbent materials to yield a radar cross-section or *signature* of less than ten square meters.

Radar-resistant design characteristics, including absorbent and reflective materials, were also used on the classified F-117 Nighthawk fighter bomber plane which was developed in the 1970s but not shown to the public until the late 1980s. Similarly, the Tacit Blue Technology Demonstration Program stealth aircraft with a low radar signature was flown in the early 1980s and unveiled to the public in 1996.

The B-2 ‘batwing’ stealth bomber is another U.S. military craft which is radar-resistant. The B-2 was used in combat in March 1999.

F-22 Raptor fighter jet is a recently released stealth aircraft with a low radar signature. The figher is not designed to be a bomber plane. It uses a radar-resistant ‘skin’ to lower its radar signature. Manufacturing these new stealth aircraft is a high-precision job. Tolerances for attaching the skin are very fine, 0.009 inches. The Raptor has a passive radar receiver in order not to provide a transmission signature, and the active transmitter is operated offboard. This aircraft is intended to replace older F-15 models and several hundred will be purchased by the U.S. Air Force. The F-22s will use radar systems that are similar to those being retrofitted into the older F-15s.

Left: The Tacit Blue program was created to demonstrate low-detection properties of stealth aircraft. The Tacit Blue aircraft was designed with low-detection-probability structure and materials and a low-probability-of-intercept radar and other sensors. From the side, it resembles an aerodynamically-sleek motorhome with very thin, tapered wings and tail. It was intended to covertly monitor battle lines to provide intelligence and target information in realtime to ground command centers. This aircraft flew for three years, beginning in February 1982. Right: The F-117 "Nighthawk" was designed as a stealth plane with a particular type of design and radar-absorbing materials built into the structure of the plane to significantly lower the radar signature (the infrared signature is lowered as well). There are a few aperture openings for sensors, but the apertures are basically hidden in this model. [U.S. DoD 1996 news photo and 1999 news photo by Mitch Fuqua, released.]

More and more, as the technology evolves, automatic countermeasure capabilities are being built into radar systems. For example, under Northrop Gumman, the Signal Technology Corporation is contracting to build internally installed Tactical Electronic Warfare systems for the AN/ALQ-135(V) which are intended to automatically detect and jam hostile radar signals.

Bandwidth and Frequency

In the early days of radio wave experimentation and broadcasting, frequency overlap and crowding weren't significant problems, but as the technology improved and was adapted to commercial enterprises, the limitations of the airwaves began to become apparent. High-power stations began to overpower signals from low-power stations and amateur radio operators, signals transmitted at the same frequency interfered with one another, and other problems arose. The Federal Communications Commission (FCC) is a U.S. regulatory agency created as a result of the Communications Act of 1934. It was implemented to regulate the broadcast industry by allotting frequencies, time slots, and call signs. Later, it was further charged with controlling emissions from consumer items such as computers, telephones, etc. which might interfere with radio wave transmissions.

Anyone manufacturing or operating radar devices must comply with the restrictions set out by the FCC. Certain low-power, short-range devices may be used in certain circumstances, but these are generally in the hobbyist/educational category and not appropriate for surveillance activities, and most low-powered devices that are suitable for surveillance are regulated by various privacy laws, even if the frequencies are loosely enforced. As a result of federal regulation, the bandwidths assigned to radar are defined, with adjustments made from time to time, usually when technologies improve and formerly 'useless' frequencies become valuable commodities.

In addition to regulatory limitations, radar frequencies have inherent physical limitations. Radar operates over a wide variety of frequencies, but not all are suitable for use in adverse weather conditions. In long-range surveillance activities, scattering can be a significant problem in wet conditions if frequencies above 10 GHz are used. Then again, what limits one application might benefit another. If you are specifically trying to detect turbulent weather conditions, then scattering becomes a useful detection device rather than a liability, and frequencies below 10 GHz would be inappropriate because they would pass right through the storm without echoing back.

Incursions/Interference with Amateur Radio

Amateur radio enthusiasts have been instrumental in many of the technological advances that have occurred in remote-sensing applications. They launched some of the first satellites, developed some of the telemetry technologies, and showed how former 'junk' wavelengths could be used in practical applications. As a consequence, there have been many debates between the amateur radio operators and the FCC over the years regarding radio frequency allocations.

The military and commercial satellite industries have shown tremendous growth since the mid-1990s, but they require radio bandwidth in order to control their systems' locations and orientations through *telemetry* and they also need it to communicate their data back to Earth. The developers of low-orbit satellites (LEOs), for example, wanted frequencies set aside for their use which were already in use by amateur radio operators.

Wind-profiler radar systems operating near 50, 449, and 1000 MHz have the potential to interfere with amateur radio. These systems are used by weather forecasters to chart wind patterns in the higher atmosphere. Another problem for amateur radio operators (called 'hams') is increased interference on some amateur UHF allocations from Earth Exploration Satellites (EES) which are used for mapping by synthetic-aperture radars (SARs).

8. Restrictions and Regulations

Radio frequency resources are already severely stretched. They aren't just used for radar; they are also used by television and radio networks, by ham radio operators, by educational institutions, and scientific research labs. They are increasingly used for cordless phones, cell phones, personal radios, and for many types of intercoms and security systems.

Because radar is based on the use of radio waves, nearly all aspects of radar are regulated in the U.S. by the Federal Communications Commission (FCC). There may be a few short-range hobby and educational applications that are loosely regulated but, for the most part, FCC approval must be obtained before radar units can be sold commercially and FCC broadcast regulations must be followed, including appropriate FCC licensing, for their use.

A stronger radio signal will overpower a weaker signal if they are at or near the same frequency. AM stations can overlap and interfere with listening. FM stations use 'guard bands,' unused frequencies on each side of the transmission frequencies, to provide a clean signal. For these reasons, specific frequencies are designated for particular types of tasks, licenses are allocated by the FCC for broadcast stations, and the whole industry must be carefully organized and monitored to make sure there are enough radio frequencies to go around. With the steadily increasing world population, now over six billion, this is becoming more difficult than ever.

FCC licensing is required for the calibration of radar units and radar operator training and certification programs are in place to provide minimum competency skills for the use of radar (particularly for traffic or air navigation radar systems).

The Institute of Electrical and Electronic Engineers (IEEE) has established standards for the letter-band terminology used with reference to radar (Standard 521-1984) and the U.S. Department of Defense (DoD) lists the letter-band terminology in its Index of Specifications and Standards.

International regulations also apply to radio frequencies used by commercial and military aircraft and various satellite transmitters and receivers.

Vehicle Radar Detectors

The use of vehicle radar detectors is prohibited or strictly regulated in many parts of the world. In general, speeding is seen as a danger to innocent victims, including passengers and other motorists, and law enforcement officers are hired to uphold traffic laws. Radar is one of the tools commonly used to detect and record excessive vehicular speed. Speeding is also seen as a problem by insurance companies, who have to pay out large sums of money as a result of damage caused by speeding, a cost that is partially borne by other drivers. Since speeding is a voluntary action, accidents due to speeding are considered by insurance and law enforcement agents (and innocent victims) to be unnecessary and preventable.

There have been a number of laws and guidelines established for how police radar must be calibrated, used, and maintained, along with regulations on the use or prohibition of radar detectors. By the mid-1960s, it was generally accepted that stationary traffic radar, when properly calibrated and operated, could yield accurate vehicle speeds. By the mid-1970s operating guidelines for moving radar were being established and minimum training standards for operators were gradually being established.

Vehicle radar systems are not used just for traffic enforcement. Newer technologies are being applied to navigation systems for surface vehicles. As a result of requests for bandwidth for experimental systems, in 1998 the FCC temporarily restricted amateur access to 76 to 77 GHz to provide bandwidth for commercial development and use of frequencies for applications such as vehicle radar collision-avoidance systems. This occurred to the dismay of amateur radio operators, in spite of reports that incompatibility would not be a problem.

The FCC often applies compensatory trade-offs when bandwidth is taken from one set of applications and reallocated for others. One example is when it upgraded amateur and amateur-satellite allocation of 77.5 to 78 GHz from secondary to coprimary.

9. Implications of Use

Since radar cannot be seen or heard, it is widely used as a surveillance technology, but it is rarely used in the day-to-day surveillance of personal or business activities in the same way that audio or video surveillance devices are used. For this reason, there is much less controversy over the use of radar than over many other technologies. Radar has been applied in many safety and security applications, particularly air navigation and weather forecasting, and we all benefit from the technology in these ways. FCC regulation of radio frequencies has helped to prevent unethical uses of the technology by requiring that radio devices be approved before sale and that specific frequencies be used for specific types of tasks.

On the whole, up to this point, we appear to have received more benefits than negative consequences from radar technologies.

10. Resources

Inclusion of the following companies does not constitute nor imply an endorsement of their products and services and, conversely, does not imply their endorsement of the contents of this text.

10.a. Organizations

Army Research Office (ARO) - This North Carolina-based U.S. Department of Army office considers funding bids for research and development in leading-edge fields such as communications, surveillance and countersurveillance, including radar and lidar technologies.
http://www.aro.ncren.net/research/baa99-1/baa99.htm

ATC Radar Tracker and Server system (ARTAS) - A EUROCONTROL project involved in the development of ARTAS V3U installed at Schiphol in use as a primary surveillance data source since 1998 with further versions in development since December 1997 the most current being ARTAS 1 V5. ARTAS comprises tracker, server, recorder, and system manager stations along with associated FDDI-ring computer network architectures. A router bridge is used to interface with external sources of data, including radar data sources.

Automatic Dependent Surveillance (ADS) - A EUROCONTROL project for implementation and operation of ADS in Europe, including evaluation of ADS-B and ADS-C technologies in terms of cost efficiency and safety.

Defence Evaluation and Research Agency (DERA) - A U.K. Ministry of Defence agency involved with non-nuclear research, technology, testing, and evaluation. DERA, with a staff of about 12,000, is one of Britain's largest research facilities, involved with research and testing of aviation technologies, electronics, command and information systems, sensors, weapons systems, and space technologies. DERA provides research data on airborne radar, target recognition techniques and active/passive microwave ground radar systems. http://www.dra.hmg.gb/

EUROCONTROL - *European Organisation for the Safety of Air Navigation*. An international organization founded in 1960 for overseeing air traffic control in the upper airspace of almost 30 European member states. http://www.eurocontrol.be/

EUROCONTROL Surveillance Team - A working team of EUROCONTROL since 1998 for the development of long-term surveillance strategies which include evaluation of Mode S Surveillance strategy/technology. Meets primarily in Brussels, but there have been meetings in Italy and Germany as well.

The Federation of American Scientists - A privately funded, nonprofit research, analysis, and advocacy organization focusing on science, technology, and public policy, especially in matters of global security, weapons science and policies, and space policies. Sponsors include a large number of Nobel Prize Laureates. FAS evolved from the Federation of Atomic Scientists in 1945. The site contains numerous surveillance, guidance systems, U.S. Naval documentation, and other radar-related information. http://www.fas.org/index.html

High Frequency Active Auroral Research Program (HAARP) - Studies the properties and behavior of the ionosphere, with particular emphasis on communications and surveillance systems for civilian and defense purposes.

Joint Surveillance and Target Attack Radar System (J-STARS) - A joint effort of the U.S. Air Force and Army program. The goal is common battle management and targeting capability for detecting, locating, classifying, and tracking stationary and moving targets. Thus, radar-based craft transmitting to ground stations via secure surveillance and control data links can serve as warning systems, and as a means to attack long-range targets. Test systems were deployed starting in the mid-1990s.

Surveillance Analysis Support System (SASS-C) - An ATC center-based Surveillance Analysis Workbench for ATC Radar and Tracker performance measurement. A EUROCONTROL project, SASS-C embodies radar data acquisition, classification, and object detection. It also includes other radar-related technology including radar plot feeders and radar plot filters.

U.K. Defence Research Agency - Includes Naval Radar Research division. Involved in the development of multifunction radar systems for weapons systems.

U.S. Naval Space Command - This arm of the military includes a Fleet Surveillance Support Command and a Satellite Operations Center which are involved in surveillance and warning activities through the monitoring of sea and airspace and orbiting satellites. Field stations along the U.S. southern regions, along with tracking and communications systems, comprise an electronic 'fence.' Data are gathered, cataloged, and evaluated on a more-or-less continuous basis.

10.b. Print Resources

Barton, David K.; Ward, Harold R., "Handbook of Radar Measurement," Dedham, Ma.: Artech House, 1984, 426 pages.

Beam, Walter R., "Command, Control, and Communications Systems Engineering," New York: McGraw-Hill Publishing, 1989, 339 pages.

Blackman, Samuel S., "Multiple-Target Tracking with Radar Applications," Artech House, 1986, 449. While a little out of date, this is still considered a good reference for those needing to understand and solve target tracking problems.

Brown, R. Hanbury, "Boffin: A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics," Bristol, New York: Adam Hilger, 1991, 192 pages. A personal account of the development of ground and airborne detection radar, and early radar applications in astronomy.

Buderi, Robert, "The Invention that Changed the World: How a Small Group of Radar Pioneers Won the Second World War and Launched a Technical Revolution," New York: Touchstone Books, 1998, 576 pages. A lively, detailed account of radar as it was used in World War II.

Chrzanowski, Edward J., "Active Radar Electronic Countermeasures," Artech House, 1990, 246 pages. Written to accompany an intensive course on the subject, this book describes radar systems designed to interfere with hostile radar systems.

Curlander, John C.; McDonough, Robert N., "Synthetic Aperture Radar: Systems and Signal Processing," New York: John Wiley & Sons, 1991, 647 pages. Handbook for SAR imaging systems theory and design.

de Arcangelis, Mario, "Electronic Warfare: From the Battle of Tsushima to the Falklands," Poole, Dorset, U.K.: Blandford, 1985. Discussions of electronic intelligence (ELINT) and electronic countermeasures (ECM) with an introductory history.

Devereux, Tony, "Messenger Gods of Battle. Radio, Radar, Sonar: The Story of Electronics in War," London: Brassy's, 1991. Historical information and basic physical principles of electronics used in warfare.

Dillard, Robin A.; Dillard, George M., "Detectability of Spread-Spectrum Signals," Artech House, 1989, 149 pages. Reference for engineering designers for intercept-reduced communications.

Hovanessian, S. A., "Radar Detection and Tracking Systems," Dedham, Ma.: Artech House, 1978.

Jelalian, Albert Y. (editor), "Laser Radar Systems," Artech House, 1992, 292 pages. Engineering design reference.

Levanon, Nadav, "Radar Principles," New York: John Wiley & Sons, 1988, 320 pages. Includes technical theory, techniques, practical examples, and academic exercises.

Long, Maurice W., "Airborne Early Warning System Concepts," Artech House, 1992, 519 pages. General reference on systems and trends.

Lothes, Robert N.; Wiley, Richard G.; Szymanski, Michael B., “Radar Vulnerability to Jamming,” Artech House, 1990, 247 pages. Engineering course on jamming, deception, and radar analysis.

Mardia, Hemant Kumar, “Digital Signal Processing for Radar Recognition in Dense Radar Environments,” Ph.D. thesis, The University of Leeds, 1987. Discusses the use of DSP in radar surveillance systems and describes the design of a radar warning receiver and an electronic surveillance measures receiver.

Price, Alfred, “The History of U.S. Electronic Warfare: The Renaissance Years, 1946 to 1964,” Alexandria, VA: Association of Old Crows, 1989. History of the development and application of U.S. electronic warfare, including the gathering of electronic intelligence and countermeasures.

Rowan, Richard Wilmer; Deindorfer, Robert, “Secret Service: 33 Centuries of Espionage,” New York: Hawthorn, 1967, 786 pages.

Skolnik, Merrill I., “Introduction to Radar Systems,” New York: McGraw-Hill, 1986 (2nd edition). In spite of being somewhat dated, this text is considered to have good coverage of radar technology at a high undergraduate or beginning graduate level.

Skolnik, Merrill I., “Radar Handbook,” New York: McGraw-Hill, 1989 (2nd edition). A comprehensive updated version of a 1970 reference for radar engineers which includes digital and Doppler radar, radar subsystems, and more.

Stevens, Michael, “Secondary Surveillance Radar,” Artech House, 1988, 300 pages.

Stimson, George W., “Introduction to Airborne Radar,” El Segundo, Ca.: Hughes Aircraft Company. There is also a second edition by Scitech Pub., 584 pages. Lucid, updated, well-illustrated text of radar techniques.

Wehner, Donald R., “High-Resolution Radar,” Norwood, Ma.: Artech House, 1994 (2nd edition), 593 pages. Spatial radar systems theory and design.

Wiley, Richard G., “Electronic Intelligence: The Analysis of Radar Signals,” Dedham, Ma.: Artech House, 1993 (2nd edition), 337 pages. Practical reference for systems design.

Wiley, Richard G., “Electronic Intelligence: The Interception of Radar Signals,” Norwood, Ma.: Artech House, 1985, 284 pages.

Articles

Bouchard, Joseph F., “Guarding the Cold War Ramparts: The U.S. Navy’s Role in Continental Air Defense,” *Military Review*, Summer 1999. An interesting brief history of the establishment of early warning radar systems in air and ground stations during and following World War II.

Easton, R.L.; Fleming, J.J., “The Navy Space Surveillance System,” *Proceedings IRE*, April 1960, Vol. 48, p. 663-669.

Grossnick, Roy, “Naval Aviation? A Century of Evolution,” on the U.S. Navy site NANews. This is not specifically about radar, but it discusses the impact of technology on naval strategy and technological developments over the years. The author is head of the Aviation History Branch of the Naval Historical Center and Hal Andrews serves as technical advisor.

Hanson, J. V.; Evans, T. D.; Hevenor, R. A.; Ehlen, J., “Mine Detection in Dry Soils Using Radar,” *U.S. Army Topographic Engineering Center Report No. R-163,* March 1992.

McDonell, Michael, “Lost Patrol,” *Naval Aviation News*, June 1973, pp. 8-16. This is a sort-fact-from-fiction story about five TBM Avengers that disappeared in 1945 somewhere in the “Bermuda Triangle.”

McLean, J.W.; Murray, J.T., “Streak tube lidar allows 3-D surveillance,” *Laser Focus World,* Jan. 1998, p. 171-176.

Journals

IEEE has a number of collections of articles in proceedings from various engineering conferences, including *Radar and Signal Processing* and *Radar, Sonar, and Navigation*.

"Journal of the Optical Society of America," includes articles on optical simulations of radar and other topics.

"Quarterly Journal of the Royal Astronomical Society," includes articles on radar research on the upper atmosphere and ionosphere.

See also the journal listings for Radio Surveillance and Sonar Surveillance as there is considerable overlap in the topics.

10.c. Conferences and Workshops

Many of these conferences are annual events that are held at approximately the same time each year, so even if the conference listings are outdated, they can still help you determine the frequency and sometimes the time of year of upcoming events. It is very common for international conferences to be held in a different city each year, so contact the organizers for current locations.

Many of these organizations describe the upcoming conferences on the Web and may also archive conference proceedings for purchase or free download.

The following conferences are organized according to the calendar month in which they are usually held.

"IMDEX Asia 97" Includes multifunction radar and surveillance keynotes and seminars, spring 1997. Sponsored by EDS.

European Radiocommunications Committee (ERC) - Held in Poland in 1998 at the invitation of the National Radiocommunications Agency of Poland.

International Radar Symposium (IRS), Germany, 1998. Includes radar surveillance topics.

EUSAR - European Conference on Synthetic Aperture Radar, Germany, March 1996. All aspects of SAR, including sensors, signal processing, data management, and imaging.

"IEEE International RADAR Conference," 7-12 May 2000.

"International Conference on Radar Systems," 5th annual conference, Brest, France, 17-21 May 1999.

"International Conference on Microwaves, Radar, and Wireless Communications," 13th annual conference, Poland, 22-24 May 2000.

"GPR 2000," International Conference on Ground-Penetrating Radar, held every other year, Queensland, Australia, 23-26 May 2000.

"International Laser Radar Conference," 20th annual conference, Vichy, France, 10-14 July 2000.

"European Conference on Radar Meteorology," 1st annual, Bologna, Italy, 4-8 Sept. 2000.

"International Military Operations and Law Conference," Australia, March 1996. This year for the first time merged with the USPACOM Legal Conference. Topics included the discussion of international rules for reconnaissance and surveillance of the coasts of other nations near military establishments.

"ATCA '98," The Air Traffic Control Association annual meeting, New Jersey, November 1998. Numerous topics of radar use in air traffic services were included, especially upgrades and expansions in numerous countries. The use of satellite technology for safety and navigation, in expanses where radar surveillance is impractical or impossible, were also discussed.

10.d. Online Sites

Defence Systems Daily: The Internet Defence & Aerospace News Daily (DSD). Topical articles and searchable archives with numerous news items on specific commercial products utilizing radar technologies. http://defence-data.com/

The Federation of American Scientists' Military Analysis Network. This site has Navy documents online which can be read on the Web. Two sections in particular, Fundamentals of Naval Weapons Systems, and Laser Fundamentals are of interest to surveillance. http://www.fas.org/man/dod-101/navy/docs/index.html

The Radar Operator Course. This is a 100-image traffic radar slide show summarizing radar history, legal issues, Doppler principles, radar theory, beam reflection, shadowing, and phenomena that can interfere with the radar signals. The course was organized by Ian Wallace of the Washington State Criminal Justice Training Commission, based on the national Highway Traffic Safety Administration radar courses. http://www.wa.gov/cjt/radar/index.htm

The USS Spinax (SSR 489). This site is devoted to stories and pictures (lots of pictures) about the crew and the operations of the Spinax, the first U.S. radar picket submarine. http://www.spinax.com/

10.e. Media Resources

"Air Defense," from the *History Channel* Weapons at War series. The story of radar, rockets, and anti-aircraft guns that defend against airborne attacks. Shows the British labs where radar was developed during the War. Includes combat footage shot aboard ships in the Pacific. Shows anti-aircraft technology in the Korean, Vietnam, and Gulf wars. VHS, 50 minutes, cannot be shipped outside the U.S. and Canada.

"Radar," from the *History Channel* Modern Marvels series. Radar as a pivotal technology in World War II, particularly the Battle of Britain. Shows the cavity magnetron and provides inside accounts on the development of radar during the War. VHS, 50 minutes, cannot be shipped outside the U.S. and Canada.

"Stealth Technology," from the *History Channel* Modern Marvels series. Introduces the stealth technology of the F-117 "Nighthawk" and larger B-2 bomber aircraft. Describes how these stealth planes avoid detection by radar and other technologies. VHS, 50 minutes, cannot be shipped outside the U.S. and Canada.

11. Glossary

In the field of radar, which is used throughout military operations, acronyms and abbreviations are so numerous, they cannot all be included here, but there are some of interest.

Titles, product names, organizations, and specific military designations are capitalized; common generic and colloquial terms and phrases are not.

AASR	advanced airborne surveillance radar
ABF	adaptive beam-forming. An error-compensation system for antenna arrays.
ADAR	air defense radar
ADS-B	Automatic Dependent Surveillance - Broadcast
AESA	active electronically scanned array. A type of radar array being adapted for use in stealth fighter jets.
AEW	Airborne Early Warning
ARS	airborne radar system, aerial reconnaissance and surveillance
ASARS	advanced synthetic aperture radar system
ASR	airport surveillance radar

ATAR	advanced tactical radar, automatic target recognition
AWACS	Airborne Warning and Control System. Electronic surveillance aircraft. In 1999, The Boeing Company retrofitted a number of the aircraft through Daimler-Chrysler Aerospace with Radar System Improvement Program (RSIP) kits. These kits upgrade the radar computers and control maintenance panels to detect smaller, stealthier craft. In E-3 aircraft, the upgrade improves the sensitivity of the pulse Doppler radar and provides greater anti-jamming capabilities. RSIP kits have also been used to upgrade U.K. Sentry AEW1 aircraft. Upgrades to older aircraft also often include GPS improvements as this technology has evolved substantially in the last 5 years. See Joint STARS.
Bragg scatter	Scatter of radar echoes resulting from very small fluctuations relative to the length of the radar waves, usually occurring in the atmosphere.
BRWL	bistatic radar for weapons location
BMEWS	Ballistic Missile Early Warning System. A U.S. government radar-based missile warning system installed along the arctic from Greenland to England.
BWER	bounded weak echo region. A region of weak radar reflectivity which is bounded by a differently reflecting environment, as might occur in a storm with variations in updraft and precipitation.
CANOPUS	Canadian satellite observing systems incorporating advance imaging radar, optical, and sensing instruments.
CANTASS	Canadian Surveillance Towed Array Sonar System. A long array of small hydrophones which is towed. Used in submarine sensing and warfare.
chaff	stringy materials, often made of metal, designed to influence radar probes, often as a radar countermeasure. Naval ships often have chaff 'tubs' on their decks. Chaff is sometimes also dropped by balloons. It is sometimes used to test radar systems. A chaff 'corridor' is sometimes called 'confetti.'
DAR	defense acquisition radar
EA-6B Prowler	U.S. Air and Naval electronic warfare aircraft equipped with radar communications jamming systems. However, new technologies are always being developed, and enemy use of frequencies beyond those of the EA-6B is likely.
EFIS	electronic flight instrument system
ESM	electronic surveillance measures
ETRAC	enhanced tactical radar correlator
FAAR	forward area alerting radar
FFR	fire finder/finding radar
FIRESTORM	Federation of Intelligence, Reconnaissance, Surveillance, and Targeting, Operations and Research Models
FLIR	forward-looking infrared radar
FLTTD	Field Ladar Technical Transition Demonstration. A laser radar program of the U.S. Army.
FOPEN	foliage penetration
FOSIC	Fleet Ocean Surveillance Information Center
FSS	frequency surveillance system
GBR, GSR	ground-based radar, ground surveillance radar
GCA	ground control approach. Aircraft landing systems which typically include radar systems monitored by air traffic controllers.
GPR	ground-penetrating radar
GSTS	ground-based surveillance and tracking system
HIPAR	high power acquisition radar

IES	A machine vision, radar signal detection, and military reconnaissance system which interprets imagery to provide information on movement, as of troops and other objects (Matzkevich, 1995).
IFSAR	interferometric synthetic-aperture radar
ISAR	inverse synthetic-aperture radar
ISTA	intelligence, surveillance, and target acquisition
Joint STARS, J-STARS	Joint Surveillance and Target Attack Radar System. An air-to-ground E-8C aircraft surveillance system for locating, classifying, and tracking ground targets. See AWACS.
JTIDS	Joint Tactical Information Display System. Tactical information provided through a digital link. This is a passive display system that can provide information about the surrounding environment without generating a transmissions signature. Suitable for use in stealth and fighter aircraft to indicate the positions of other aircraft or proximate objects.
ladar/lidar	laser radar/light radar. Can be used for weather information and for the detection of airborne chemical and biological agents. Suitable for long-range applications such as detection, tracking, and imaging hard and soft objects. In addition to the range and velocity information provided by traditional radar, ladar can be used to calculate length through a 'soft' object, for example, and can provide information about complex motion. The length-measuring capabilities are highly valuable in studying and imaging specific objects in order to determine their type and dimensions (tanks, helicopters, decoys, etc.).
LOPAR	low power acquisition radar
LRS	long-range surveillance
MIR	micropower impulse radar
MSTAR	man-portable surveillance and target acquisition radar
NASOG	North American Special Operations Group
NAVSPASUR	Naval Space Surveillance System. NAVSPASUR makes use of continuous wave (CW) multistatic radar systems to reflect energy beams to receiving stations where position and trajectory information is calculated. In 1965 the frequency was changed from the SPASUR system's 108 MHz to 216.9-217.1 MHz. Called NAVSPACECOM fence since the early 1990s.
NORAD1	North American Aerospace Defense Command
OTHR	over-the-horizon radar
PAR	precision-approach radar
PHALCON	phased-array L-band conformal radar. A commercial aircraft long-range radar system manufactured in Israel. Diplomatic feathers were ruffled when Israel offered this system to the Chinese for use in their Air Force. U.S. officials were concerned about the use of U.S. technology in products being sold to other foreign powers.
Radio Electronic Combat	An information warfare strategy which aims at disabling an enemy command and control infrastructure.
racon	radar beacon. A safety, homing, or location signal which transmits a particular signal which identifies the beacon. Beacons are intended to provide information to navigators of various types of moving vessels, such as ships, aircraft, and ground troop vehicles.
radar picket	A radar-equipped unit stationed some distance from a protected force to increase radar detection ranges.
RADINT	radar intelligence

RALT	radar altimeter
radome	a covering that protects radar equipment from weather and vandalism but which does not impede the travel of radio waves
RCS	radar cross-section. A measure of visibility on radar as based on theoretically perfect reflectance. Stealth vessels are designed to have a minimum RCS or radar 'signature.' The RCS represents the apparent radar reflectivity of an object or structure and may be larger or smaller than the actual object. The RCS can be manipulated by application of special paints or skins, nonmetallic composites, and by particular shapes that tend to scatter or have a low profile to the radar. Smooth contours or certain low profile rippled surfaces tend to lower the RCS, depending on the angle of reflection and the radar frequencies used.
RISTA	reconnaissance, intelligence, surveillance, and target acquisition
RSIP	radar system improvement kits. Technology to upgrade aging radar systems, especially on aircraft. Improvements usually include greater range and higher resolution radar imaging.
RSTA	reconnaissance, surveillance, and target acquisition
RSTER	Radar Surveillance Technology Experimental Radar. Originally a ground-based volume search radar which has since been used in the Mountaintop Program (mid-1990s) for studying technologies for airborne early warning systems (AEW). One of the goals of the Mountaintop Program has been to simulate an airborne surveillance environment. Data from the project are hosted in the CREST database.
SAGE	Semi-Automatic Ground Environment, a system for air-defense radar processing
SAR	small-aperture radar
SPADATS	Space Detection and Tracking System. A joint effort of the U.S. and Canada which tracks Earth-orbiting satellites.
SPASUR	U.S. Navy Space Surveillance system. Evolved in the early 1960s from the Vanguard Satellite Program which used a combination of intercepted and bounced signals from orbiting bodies to provide tracking and positioning information. This later was integrated into Naval Space and Command and NORAD. See NAVSPASUR.
SRIG	Surveillance, Reconnaissance, and Intelligence Group
SSR	Secondary Surveillance Radar
TCAS	Traffic Alert Collision Avoidance System. A commercial, on-board aircraft radar system that queries the transponders of nearby craft and reports identification and location information.
TASR	terminal area surveillance radar
TMD	Theater Missile Defense. Ship-borne radars are one of the technologies used to carry out TMD missions.
TRACON	Terminal Radar Approach Control
TTR	target-tracking radar
VISTA	Very Intelligent Surveillance and Target Acquisition
WSR-88D	Weather Surveillance Radar 1988 Doppler, a component of the U.S. National Weather Service (NWS) located in the mountains of Puerto Rico since the mid-1990s. Doppler radar can be used to detect and track tornados and to help determine their velocities. Better definition and greater variety of information than previous conventional WSR-74S radar, especially for short-fuse warnings.