Handbook of

Radar Systems and Technology

Mackenzie Carlos

Shawn Sandoval

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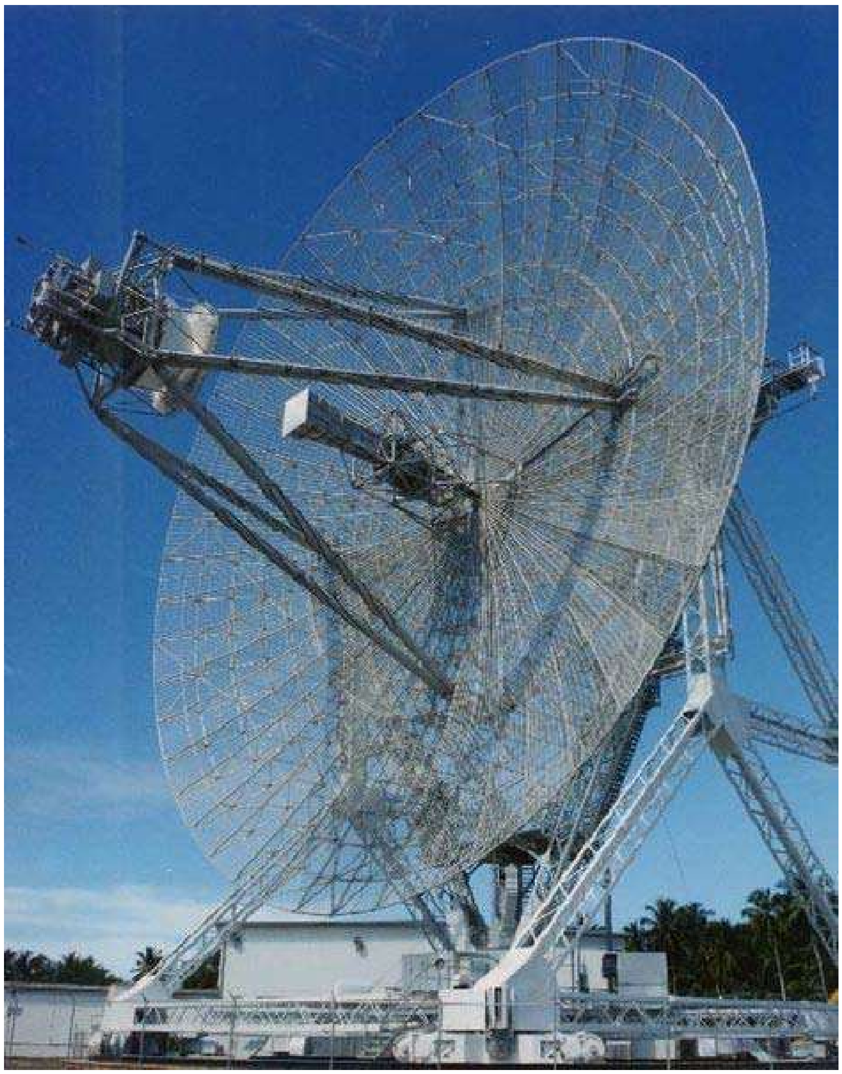
Radar



A long-range radar antenna, known as *ALTAIR*, used to detect and track space objects in conjunction with ABM testing at the Ronald Reagan Test Site on Kwajalein Atoll.

Israeli military radar is typical of the type of radar used for air traffic control. The antenna rotates at a steady rate, sweeping the local airspace with a narrow vertical fan-shaped beam, to detect aircraft at all altitudes.

Radar is an object-detection system which uses electromagnetic waves—specifically radio waves—to determine the range, altitude, direction, or speed of both moving and fixed objects such as aircraft, ships, spacecraft, guided missiles, motor vehicles, weather formations, and terrain. The radar dish, or antenna, transmits pulses of radio waves or microwaves which bounce off any object in their path. The object returns a tiny part of the wave's energy to a dish or antenna which is usually located at the same site as the transmitter.

Practical radar was developed in secrecy during World War II by Britain and other nations. The term *RADAR* was coined in 1940 by the U.S. Navy as an acronym for ***ra****dio* ***d****etection* ***a****nd* ***r****anging*. The term *radar* has since entered the English and other languages as the common noun *radar*, losing all capitalization. In the United Kingdom, the technology was initially called RDF (*range and direction finding*), using the same initials used for radio direction finding to conceal its ranging capability.

The modern uses of radar are highly diverse, including air traffic control, radar astronomy, air-defense systems, antimissile systems; nautical radars to locate landmarks and other ships; aircraft anticollision systems; ocean-surveillance systems, outer-space surveillance and rendezvous systems; meteorological precipitation monitoring; altimetry and flight-control systems; guided-missile target-locating systems; and ground-penetrating radar geological observations.

Other systems similar to radar have been used in other parts of the electromagnetic spectrum. One example is "lidar", which uses visible light from lasers rather than radio waves.

History

Several inventors, scientists, and engineers contributed to the development of radar.

As early as 1886, Heinrich Hertz showed that radio waves could be reflected from solid objects. In 1895 Alexander Popov, a physics instructor at the Imperial Russian Navy school in Kronstadt, developed an apparatus using a coherer tube for detecting distant lightning strikes. The next year, he added a spark-gap transmitter. During 1897, while testing this in communicating between two ships in the Baltic Sea, he took note of an interference beat caused by the passage of a third vessel. In his report, Popov wrote that this phenomenon might be used for detecting objects, but he did nothing more with this observation.

The German Christian Hülsmeyer was the first to use radio waves to detect "the presence of distant metallic objects". In 1904 he demonstrated the feasibility of detecting a ship in dense fog, but not its distance. He received Reichspatent Nr. 165546 for his detection device in April 1904, and later patent 169154 for a related amendment for also determining the distance to the ship. He also received a British patent on September 23, 1904 for the first full Radar application, which he called *telemobiloscope*.

A Chain Home tower in Great Baddow, United Kingdom

In August 1917 Nikola Tesla outlined a concept for primitive radar units. He stated, "[...] *by their* [standing electromagnetic waves] *use we may produce at will, from a sending station, an electrical effect in any particular region of the globe;* [with which] *we may determine the relative position or course of a moving object, such as a vessel at sea, the distance traversed by the same, or its speed*."

In 1922 A. Hoyt Taylor and Leo C. Young, researchers working with the U.S. Navy, discovered that when radio waves were broadcast at 60 MHz it was possible to determine the range and bearing of nearby ships in the Potomac River. Despite Taylor's suggestion that this method could be used in darkness and low visibility, the Navy did not immediately continue the work. Serious investigation began eight years later after the discovery that radar could be used to track airplanes.

Before the Second World War, researchers in France, Germany, Italy, Japan, the Netherlands, the Soviet Union, the United Kingdom, and the United States, independently and in great secrecy, developed technologies that led to the modern version of radar. Australia, Canada, New Zealand, and South Africa followed prewar Great Britain, and Hungary had similar developments during the war.

In 1934 the Frenchman Émile Girardeau stated he was building an obstacle-locating radio apparatus "conceived according to the principles stated by Tesla" and obtained a patent (French Patent n° 788795 in 1934) for a working system, a part of which was installed on the Normandie liner in 1935. During the same year, the Soviet military engineer P.K.Oschepkov, in collaboration with Leningrad Electrophysical Institute, produced an experimental apparatus, RAPID, capable of detecting an aircraft within 3 km of a receiver. The French and Soviet systems, however, had continuous-wave operation and could not give the full performance that was ultimately at the center of modern radar.

Full radar evolved as a pulsed system, and the first such elementary apparatus was demonstrated in December 1934 by the American Robert M. Page, working at the Naval Research Laboratory. The year after the US Army successfully tested a primitive surface to surface radar to aim coastal battery search lights at night. This was followed by a pulsed system demonstrated in May 1935 by Rudolf Kühnhold and the firm GEMA in Germany and then one in June 1935 by an Air Ministry team led by Robert A. Watson Watt in Great Britain. Later, in 1943, Page greatly improved radar with the monopulse technique that was then used for many years in most radar applications.

The British were the first to fully exploit radar as a defence against aircraft attack. This was spurred on by fears that the Germans were developing death rays. The Air Ministry asked British scientists in 1934 to investigate the possibility of propagating electromagnetic energy and the likely effect. Following a study, they concluded that a death ray was impractical but that detection of aircraft appeared feasible. Robert Watson Watt's team demonstrated to his superiors the capabilities of a working prototype and then patented the device (British Patent GB593017). It served as the basis for the Chain Home network of radars to defend Great Britain. In April 1940, *Popular Science* showed an example of a radar unit using the Watson-Watt patent in an article on air defence, but not knowing that the U.S. Army and U.S. Navy were working on radars with the same principle, stated under the illustration, "This is not U.S. Army equipment."

The war precipitated research to find better resolution, more portability, and more features for radar, including complementary navigation systems like Oboe used by the RAF's Pathfinder. The postwar years have seen the use of radar in fields as diverse as air traffic control, weather monitoring, astrometry, and road speed control.

Applications of radar

Commercial marine radar antenna. The rotating antenna radiates a vertical fan-shaped beam.

The information provided by radar includes the bearing and range (and therefore position) of the object from the radar scanner. It is thus used in many different fields where the need for such positioning is crucial. The first use of radar was for military purposes: to locate air, ground and sea targets. This evolved in the civilian field into applications for aircraft, ships, and roads.

In aviation, aircraft are equipped with radar devices that warn of obstacles in or approaching their path and give accurate altitude readings. They can land in fog at airports equipped with radar-assisted ground-controlled approach (GCA) systems, in which the plane's flight is observed on radar screens while operators radio landing directions to the pilot.

Marine radars are used to measure the bearing and distance of ships to prevent collision with other ships, to navigate and to fix their position at sea when within range of shore or other fixed references such as islands, buoys, and lightships. In port or in harbour, vessel traffic service radar systems are used to monitor and regulate ship movements in busy waters. Police forces use radar guns to monitor vehicle speeds on the roads.

Meteorologists use radar to monitor precipitation. It has become the primary tool for short-term weather forecasting and to watch for severe weather such as thunderstorms, tornadoes, winter storms, precipitation types, etc. Geologists use specialised ground-penetrating radars to map the composition of the Earth's crust.

Principles

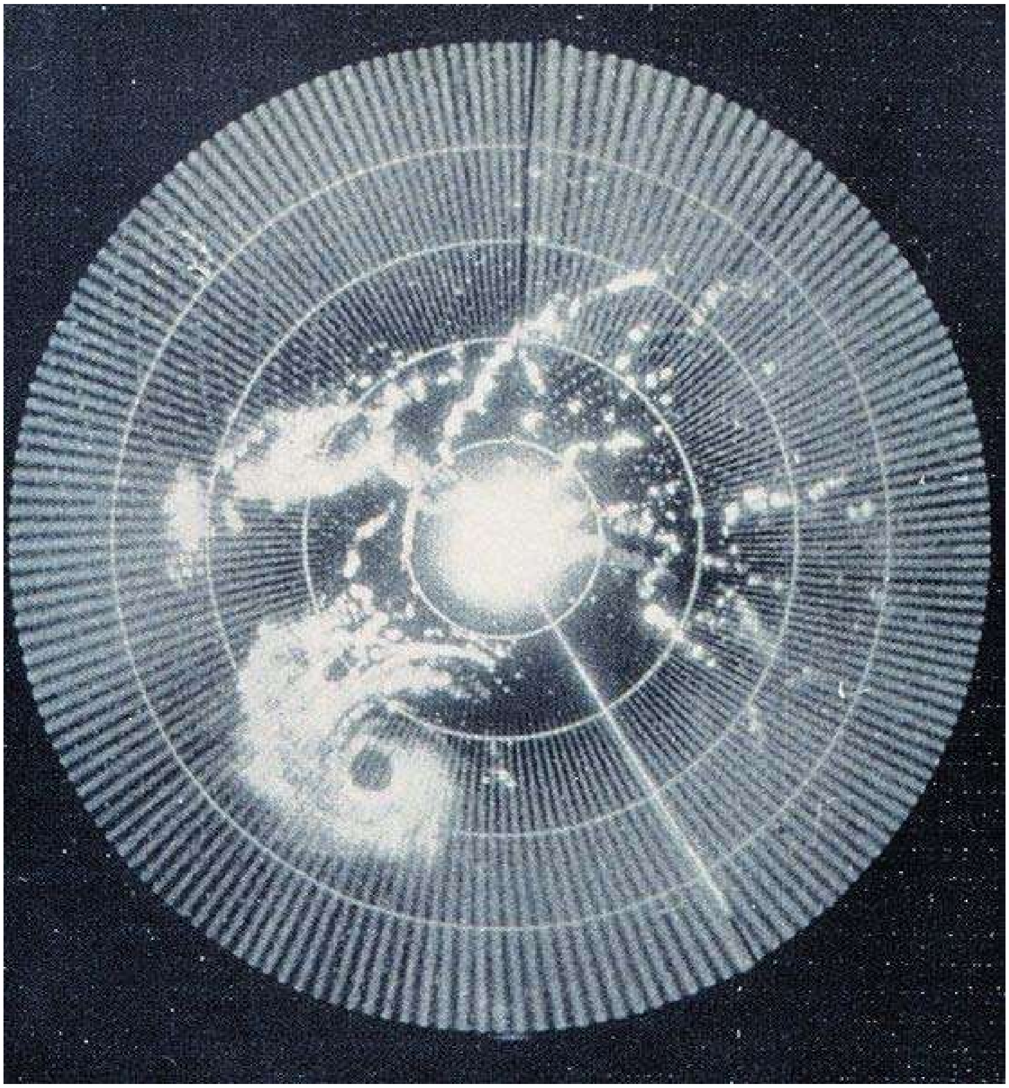
A radar system has a transmitter that emits radio waves called *radar signals* in predetermined directions. When these come into contact with an object they are usually reflected and/or scattered in many directions. Radar signals are reflected especially well by materials of considerable electrical conductivity—especially by most metals, by seawater, by wet land, and by wetlands. Some of these make the use of radar altimeters possible. The radar signals that are reflected back towards the transmitter are the desirable ones that make radar work. If the object is *moving* either closer or farther away, there is a slight change in the frequency of the radio waves, due to the Doppler effect.

Radar receivers are usually, but not always, in the same location as the transmitter. Although the reflected radar signals captured by the receiving antenna are usually very weak, these signals can be strengthened by the electronic amplifiers that all radar sets contain. More sophisticated methods of signal processing are also nearly always used in order to recover useful radar signals.

The weak absorption of radio waves by the medium through which it passes is what enables radar sets to detect objects at relatively-long ranges—ranges at which other electromagnetic wavelengths, such as visible light, infrared light, and ultraviolet light, are too strongly attenuated. In particular, there are weather conditions under which radar works well regardless of the weather. Such things as fog, clouds, rain, falling snow, and sleet that block visible light are usually transparent to radio waves. Certain, specific radio frequencies that are absorbed or scattered by water vapor, raindrops, or atmospheric gases (especially oxygen) are avoided in designing radars except when detection of these is intended.

Finally, radar relies on its own transmissions, rather than light from the Sun or the Moon, or from electromagnetic waves emitted by the objects themselves, such as infrared wavelengths (heat). This process of directing artificial radio waves towards objects is called *illumination*, regardless of the fact that radio waves are completely invisible to the human eye or cameras.

Reflection



Brightness can indicate reflectivity as in this 1960 weather radar image (of Hurricane Abby). The radar's frequency, pulse form, polarization, signal processing, and antenna determine what it can observe.

Electromagnetic waves reflect (scatter) from any large change in the dielectric constant or diamagnetic constants. This means that a solid object in air or a vacuum, or other significant change in atomic density between the object and what is surrounding it, will usually scatter radar (radio) waves. This is particularly true for electrically conductive materials, such as metal and carbon fiber, making radar particularly well suited to the detection of aircraft and ships. Radar absorbing material, containing resistive and sometimes magnetic substances, is used on military vehicles to reduce radar reflection. This is the radio equivalent of painting something a dark color so that it cannot be seen through normal means.

Radar waves scatter in a variety of ways depending on the size (wavelength) of the radio wave and the shape of the target. If the wavelength is much shorter than the target's size, the wave will bounce off in a way similar to the way light is reflected by a mirror. If the wavelength is much longer than the size of the target, the target may not be visible due to poor reflection. Low Frequency radar technology is dependent on resonances for detection, but not identification, of targets. This is described by Rayleigh scattering, an effect that creates the Earth's blue sky and red sunsets. When the two length scales are comparable, there may be resonances. Early radars used very long wavelengths that were larger than the targets and received a vague signal, whereas some modern systems use shorter wavelengths (a few centimeters or shorter) that can image objects as small as a loaf of bread.

Short radio waves reflect from curves and corners, in a way similar to glint from a rounded piece of glass. The most reflective targets for short wavelengths have 90° angles between the reflective surfaces. A structure consisting of three flat surfaces meeting at a single corner, like the corner on a box, will always reflect waves entering its opening directly back at the source. These so-called corner reflectors are commonly used as radar reflectors to make otherwise difficult-to-detect objects easier to detect, and are often found on boats in order to improve their detection in a rescue situation and to reduce collisions.

For similar reasons, objects attempting to avoid detection will angle their surfaces in a way to eliminate inside corners and avoid surfaces and edges perpendicular to likely detection directions, which leads to "odd" looking stealth aircraft. These precautions do not completely eliminate reflection because of diffraction, especially at longer wavelengths. Half wavelength long wires or strips of conducting material, such as chaff, are very reflective but do not direct the scattered energy back toward the source. The extent to which an object reflects or scatters radio waves is called its radar cross section.

Radar equation

The power P_r returning to the receiving antenna is given by the radar equation:

$$P_r = \frac{P_t G_t A_r \sigma F^4}{(4\pi)^2 R_t^2 R_r^2}$$

where

- P_t = transmitter power
- G_t = gain of the transmitting antenna
- A_r = effective aperture (area) of the receiving antenna
- σ = radar cross section, or scattering coefficient, of the target
- F = pattern propagation factor
- R_t = distance from the transmitter to the target
- R_r = distance from the target to the receiver.

In the common case where the transmitter and the receiver are at the same location, $R_t = R_r$ and the term $R_t^2 R_r^2$ can be replaced by R^4, where R is the range. This yields:

$$P_r = \frac{P_t G_t A_r \sigma F^4}{(4\pi)^2 R^4}.$$

This shows that the received power declines as the fourth power of the range, which means that the reflected power from distant targets is very, very small.

The equation above with $F = 1$ is a simplification for vacuum without interference. The propagation factor accounts for the effects of multipath and shadowing and depends on the details of the environment. In a real-world situation, pathloss effects should also be considered.

Doppler effect

Ground-based radar systems used for detecting speeds rely on the Doppler effect. The apparent frequency (f) of the wave changes with the relative position of the target. The doppler equation is stated as follows for v_{obs} (the radial speed of the observer) and v_s (the radial speed of the target) and f_0 frequency of wave :

$$f = \frac{v + v_{obs}}{v - v_s} f_0$$

However, the change in phase of the return signal is often used instead of the change in frequency. It is to be noted that only the radial component of the speed is available. Hence when a target is moving at right angle to the radar beam, it has no velocity while one parallel to it has maximum recorded speed even if both might have the same real absolute motion.

Polarization

In the transmitted radar signal, the electric field is perpendicular to the direction of propagation, and this direction of the electric field is the polarization of the wave. Radars use horizontal, vertical, linear and circular polarization to detect different types of reflections. For example, circular polarization is used to minimize the interference caused by rain. Linear polarization returns usually indicate metal surfaces. Random polarization returns usually indicate a fractal surface, such as rocks or soil, and are used by navigation radars.

Limiting factors

Beam path and range

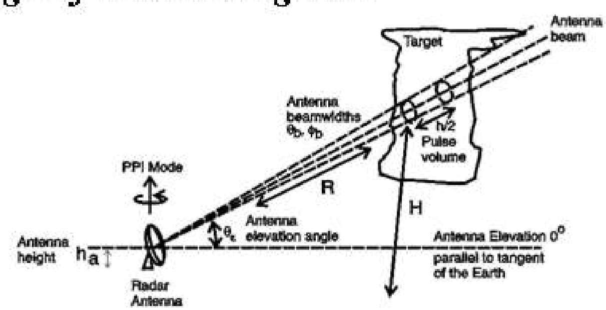
BEAM HEIGHT WITH DISTANCE (AGL)

$$H=\left(\sqrt{r^2+(k_e a_e)^2+2r k_e a_e \sin(\theta_e)}\right)-k_e a_e+h_a$$

***r* : distance** ***k_e* : 4/3 (Standard refraction coefficient)**

***a_e* : Earth radius** ***θ_e* : Elevation angle**

***h_a* : Height of radar above ground**



Echo heights above ground

The radar beam would follow a linear path in vacuum but it really follows a somewhat curved path in the atmosphere due to the variation of the refractive index of air. Even when the beam is emitted parallel to the ground, it will raise above it as the Earth curvature sink below the horizon. Furthermore, the signal is attenuated by the medium it crosses and the beam disperse as its not a perfect pencil shape.

The maximum range of a conventional radar can either be limited by a number of factors:

1. Line of sight, which depends on height above ground.
2. The maximum non-ambiguous range (MUR) which is determined by the Pulse repetition frequency (PRF). Simply put, MUR is the distance the pulse could travel and return before the next pulse is emitted.
3. Radar sensitivity and power of the return signal as computed in the radar equation. This includes factors such as environmentals and the size (or radar cross section) of the target.

Noise

Signal noise is an internal source of random variations in the signal, which is generated by all electronic components. Noise typically appears as random variations superimposed on the desired echo signal received in the radar receiver. The lower the power of the desired signal, the more difficult it is to discern it from the noise (similar to trying to hear a whisper while standing near a busy road). Noise figure is a measure of the noise produced by a receiver compared to an ideal receiver, and this needs to be minimized.

Noise is also generated by external sources, most importantly the natural thermal radiation of the background scene surrounding the target of interest. In modern radar systems, due to the high performance of their receivers, the internal noise is typically about equal to or lower than the external scene noise. An exception is if the radar is aimed upwards at clear sky, where the scene is so "cold" that it generates very little thermal noise.

There will be also flicker noise due to electrons transit, but depending on 1/f, will be much lower than thermal noise when the frequency is high. Hence, in pulse radar, the system will be always heterodyne.

Interference

Radar systems must overcome unwanted signals in order to focus only on the actual targets of interest. These unwanted signals may originate from internal and external sources, both passive and active. The ability of the radar system to overcome these unwanted signals defines its signal-to-noise ratio (SNR). SNR is defined as the ratio of a signal power to the noise power within the desired signal.

In less technical terms, SNR compares the level of a desired signal (such as targets) to the level of background noise. The higher a system's SNR, the better it is in isolating actual targets from the surrounding noise signals.

Clutter

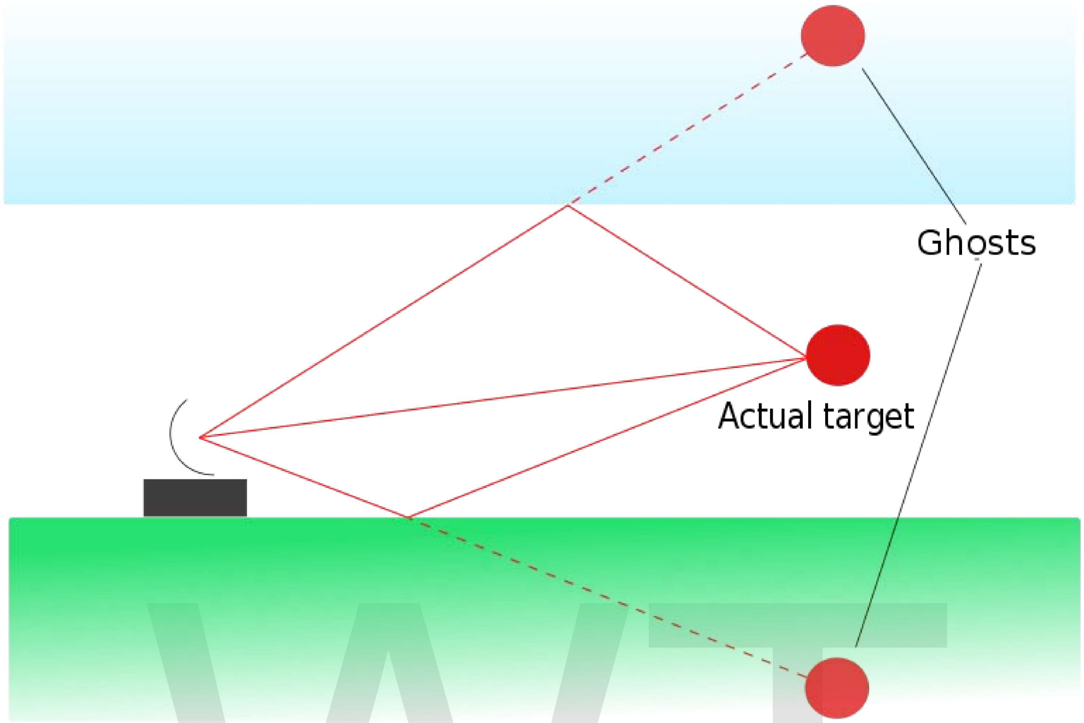
Clutter refers to radio frequency (RF) echoes returned from targets which are uninteresting to the radar operators. Such targets include natural objects such as ground, sea, precipitation (such as rain, snow or hail), sand storms, animals (especially birds), atmospheric turbulence, and other atmospheric effects, such as ionosphere reflections, meteor trails, and three body scatter spike. Clutter may also be returned from man-made objects such as buildings and, intentionally, by radar countermeasures such as chaff.

Some clutter may also be caused by a long radar waveguide between the radar transceiver and the antenna. In a typical plan position indicator (PPI) radar with a rotating antenna, this will usually be seen as a "sun" or "sunburst" in the centre of the display as the receiver responds to echoes from dust particles and misguided RF in the waveguide. Adjusting the timing between when the transmitter sends a pulse and when the receiver stage is enabled will generally reduce the sunburst without affecting the accuracy of the range, since most sunburst is caused by a diffused transmit pulse reflected before it leaves the antenna.

While some clutter sources may be undesirable for some radar applications (such as storm clouds for air-defence radars), they may be desirable for others (meteorological radars in this example). Clutter is considered a passive interference source, since it only appears in response to radar signals sent by the radar.

There are several methods of detecting and neutralizing clutter. Many of these methods rely on the fact that clutter tends to appear static between radar scans. Therefore, when comparing subsequent scans echoes, desirable targets will appear to move and all stationary echoes can be eliminated. Sea clutter can be reduced by using horizontal polarization, while rain is reduced with circular polarization (note that meteorological radars wish for the opposite effect, therefore using linear polarization the better to detect precipitation). Other methods attempt to increase the signal-to-clutter ratio.

Constant False Alarm Rate (CFAR, a form of Automatic Gain Control, or AGC) is a method relying on the fact that clutter returns far outnumber echoes from targets of interest. The receiver's gain is automatically adjusted to maintain a constant level of overall visible clutter. While this does not help detect targets masked by stronger surrounding clutter, it does help to distinguish strong target sources. In the past, radar AGC was electronically controlled and affected the gain of the entire radar receiver. As radars evolved, AGC became computer-software controlled, and affected the gain with greater granularity, in specific detection cells.



Radar multipath echoes from a target cause ghosts to appear

Clutter may also originate from multipath echoes from valid targets due to ground reflection, atmospheric ducting or ionospheric reflection/refraction (e.g. Anomalous propagation). This clutter type is especially bothersome, since it appears to move and behave like other normal (point) targets of interest, thereby creating a ghost. In a typical scenario, an aircraft echo is multipath-reflected from the ground below, appearing to the receiver as an identical target below the correct one. The radar may try to unify the targets, reporting the target at an incorrect height, or—worse—eliminating it on the basis of jitter or a physical impossibility. These problems can be overcome by incorporating a ground map of the radar's surroundings and eliminating all echoes which appear to originate below ground or above a certain height. In newer Air Traffic Control (ATC) radar equipment, algorithms are used to identify the false targets by comparing the current pulse returns, to those adjacent, as well as calculating return improbabilities due to calculated height, distance, and radar timing.

Jamming

Radar jamming refers to radio frequency signals originating from sources outside the radar, transmitting in the radar's frequency and thereby masking targets of interest. Jamming may be intentional, as with an electronic warfare (EW) tactic, or unintentional, as with friendly forces operating equipment that transmits using the same frequency range. Jamming is considered an active interference source, since it is initiated by elements outside the radar and in general unrelated to the radar signals.

Jamming is problematic to radar since the jamming signal only needs to travel one-way (from the jammer to the radar receiver) whereas the radar echoes travel two-ways (radar-target-radar) and are therefore significantly reduced in power by the time they return to the radar receiver. Jammers therefore can be much less powerful than their jammed radars and still effectively mask targets along the line of sight from the jammer to the radar (*Mainlobe Jamming*). Jammers have an added effect of affecting radars along other lines of sight, due to the radar receiver's sidelobes (*Sidelobe Jamming*).

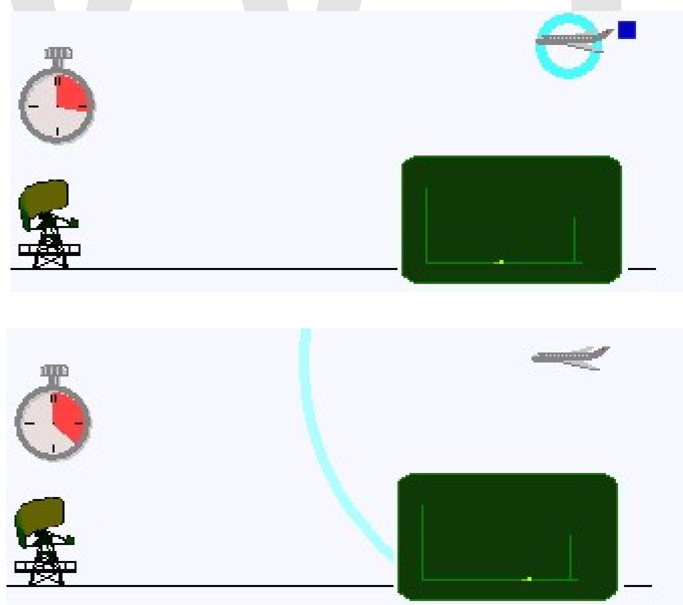
Mainlobe jamming can generally only be reduced by narrowing the mainlobe solid angle, and can never fully be eliminated when directly facing a jammer which uses the same frequency and polarization as the radar. Sidelobe jamming can be overcome by reducing receiving sidelobes in the radar antenna design and by using an omnidirectional antenna to detect and disregard non-mainlobe signals. Other anti-jamming techniques are frequency hopping and polarization.

Interference has recently become a problem for C-band (5.66 GHz) meteorological radars with the proliferation of 5.4 GHz band WiFi equipment.

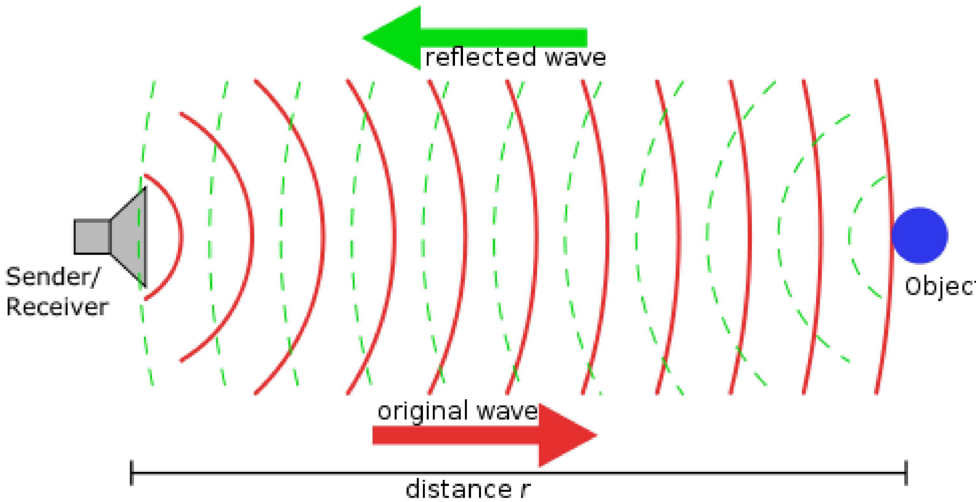
Radar signal processing

Distance measurement

Transit time



Pulse radar: The round-trip time for the radar pulse to get to the target and return is measured. The distance is proportional to this time.



Continuous wave (CW) radar

One way to measure the distance to an object is to transmit a short pulse of radio signal (electromagnetic radiation), and measure the time it takes for the reflection to return. The distance is one-half the product of the round trip time (because the signal has to travel to the target and then back to the receiver) and the speed of the signal. Since radio waves travel at the speed of light (186,000 miles per second or 300,000,000 meters per second), accurate distance measurement requires high-performance electronics.

In most cases, the receiver does not detect the return while the signal is being transmitted. Through the use of a device called a *duplexer*, the radar switches between transmitting and receiving at a predetermined rate. The minimum range is calculated by measuring the length of the pulse multiplied by the speed of light, divided by two. In order to detect closer targets one must use a shorter pulse length.

A similar effect imposes a maximum range as well. If the return from the target comes in when the next pulse is being sent out, once again the receiver cannot tell the difference. In order to maximize range, longer times between pulses should be used, referred to as a pulse repetition time (PRT), or its reciprocal, pulse repetition frequency (PRF).

These two effects tend to be at odds with each other, and it is not easy to combine both good short range and good long range in a single radar. This is because the short pulses needed for a good minimum range broadcast have less total energy, making the returns much smaller and the target harder to detect. This could be offset by using more pulses, but this would shorten the maximum range again. So each radar uses a particular type of signal. Long-range radars tend to use long pulses with long delays between them, and short range radars use smaller pulses with less time between them. This pattern of pulses and pauses is known as the pulse repetition frequency (or PRF), and is one of the main ways to characterize a radar. As electronics have improved many radars now can change their PRF thereby changing their range. The newest radars fire 2 pulses during one cell, one for short range 10 km / 6 miles and a separate signal for longer ranges 100 km /60 miles.

The distance resolution and the characteristics of the received signal as compared to noise depends heavily on the shape of the pulse. The pulse is often modulated to achieve better performance using a technique known as pulse compression.

Distance may also be measured as a function of time. The radar mile is the amount of time it takes for a radar pulse to travel one nautical mile, reflect off a target, and return to the radar antenna. Since a nautical mile is defined as *exactly* 1,852 meters, then dividing this distance by the speed of light (*exactly* 299,792,458 meters per second), and then multiplying the result by 2 (round trip = twice the distance), yields a result of approximately 12.36 microseconds in duration.

Frequency modulation

Another form of distance measuring radar is based on frequency modulation. Frequency comparison between two signals is considerably more accurate, even with older electronics, than timing the signal. By measuring the frequency of the returned signal and comparing that with the original, the difference can be easily measured.

This technique can be used in continuous wave radar, and is often found in aircraft radar altimeters. In these systems a "carrier" radar signal is frequency modulated in a predictable way, typically varying up and down with a sine wave or sawtooth pattern at audio frequencies. The signal is then sent out from one antenna and received on another, typically located on the bottom of the aircraft, and the signal can be continuously compared using a simple *beat frequency* modulator that produces an audio frequency tone from the returned signal and a portion of the transmitted signal.

Since the signal frequency is changing, by the time the signal returns to the aircraft the broadcast has shifted to some other frequency. The amount of that shift is greater over longer times, so greater frequency differences mean a longer distance, the exact amount being the "ramp speed" selected by the electronics. The amount of shift is therefore directly related to the distance traveled, and can be displayed on an instrument. This signal processing is similar to that used in speed detecting Doppler radar. Example systems using this approach are AZUSA, MISTRAM, and UDOP.

A further advantage is that the radar can operate effectively at relatively low frequencies, comparable to that used by UHF television. This was important in the early development of this type when high frequency signal generation was difficult or expensive.

A new terrestrial radar uses low-power FM signals that cover a larger frequency range. The multiple reflections are analyzed mathematically for pattern changes with multiple passes creating a computerized synthetic image. Doppler effects are not used which allows slow moving objects to be detected as well as largely eliminating "noise" from the surfaces of bodies of water. Used primarily for detection of intruders approaching in small boats or intruders crawling on the ground toward an objective.

Speed measurement

Speed is the change in distance to an object with respect to time. Thus the existing system for measuring distance, combined with a memory capacity to see where the target last was, is enough to measure speed. At one time the memory consisted of a user making grease-pencil marks on the radar screen, and then calculating the speed using a slide rule. Modern radar systems perform the equivalent operation faster and more accurately using computers.

However, if the transmitter's output is coherent (phase synchronized), there is another effect that can be used to make almost instant speed measurements (no memory is required), known as the Doppler effect. Most modern radar systems use this principle in the pulse-doppler radar system. Return signals from targets are shifted away from this base frequency via the Doppler effect enabling the calculation of the speed of the object relative to the radar. The Doppler effect is only able to determine the relative speed of the target along the line of sight from the radar to the target. Any component of target velocity perpendicular to the line of sight cannot be determined by using the Doppler effect alone, but it can be determined by tracking the target's azimuth over time. Additional information of the nature of the Doppler returns may be found in the radar signal characteristics article.

It is also possible to make a radar without any pulsing, known as a continuous-wave radar (CW radar), by sending out a very pure signal of a known frequency. CW radar is ideal for determining the radial component of a target's velocity, but it cannot determine the target's range. CW radar is typically used by traffic enforcement to measure vehicle speed quickly and accurately where range is not important.

Other mathematical developments in radar signal processing include time-frequency analysis (Weyl Heisenberg or wavelet), as well as the chirplet transform which makes use of the fact that radar returns from moving targets typically "chirp" (change their frequency as a function of time, as does the sound of a bird or bat).

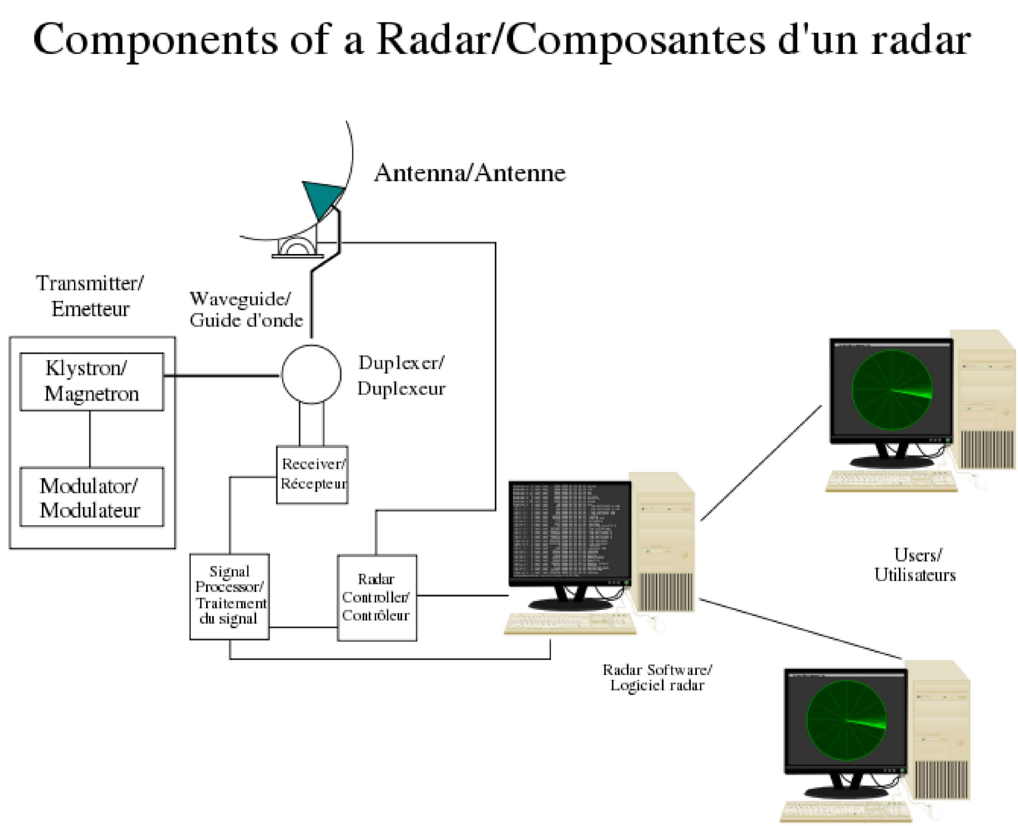
Reduction of interference effects

Signal processing is employed in radar systems to reduce the radar interference effects. Signal processing techniques include moving target indication (MTI), pulse doppler, moving target detection (MTD) processors, correlation with secondary surveillance radar (SSR) targets, space-time adaptive processing (STAP), and track-before-detect (TBD). Constant false alarm rate (CFAR) and digital terrain model (DTM) processing are also used in clutter environments.

Plot and track extraction

Radar video returns on aircraft can be subjected to a plot extraction process whereby spurious and interfering signals are discarded. A sequence of target returns can be monitored through a device known as a plot extractor. The non relevant real time returns can be removed from the displayed information and a single plot displayed. In some radar systems, or alternatively in the command and control system to which the radar is connected, a radar tracker is used to associate the sequence of plots belonging to individual targets and estimate the targets' headings and speeds.

Radar engineering



Radar components

A radars components are:

- A transmitter that generates the radio signal with an oscillator such as a klystron or a magnetron and controls its duration by a modulator.
- A waveguide that links the transmitter and the antenna.
- A duplexer that serves as a switch between the antenna and the transmitter or the receiver for the signal when the antenna is used in both situations.

- A receiver. Knowing the shape of the desired received signal (a pulse), an optimal receiver can be designed using a matched filter.
- An electronic section that controls all those devices and the antenna to perform the radar scan ordered by a software.
- A link to end users.

Antenna design

Radio signals broadcast from a single antenna will spread out in all directions, and likewise a single antenna will receive signals equally from all directions. This leaves the radar with the problem of deciding where the target object is located.

Early systems tended to use omni-directional broadcast antennas, with directional receiver antennas which were pointed in various directions. For instance the first system to be deployed, Chain Home, used two straight antennas at right angles for reception, each on a different display. The maximum return would be detected with an antenna at right angles to the target, and a minimum with the antenna pointed directly at it (end on). The operator could determine the direction to a target by rotating the antenna so one display showed a maximum while the other shows a minimum.

One serious limitation with this type of solution is that the broadcast is sent out in all directions, so the amount of energy in the direction being examined is a small part of that transmitted. To get a reasonable amount of power on the "target", the transmitting aerial should also be directional.

Parabolic reflector

More modern systems use a steerable parabolic "dish" to create a tight broadcast beam, typically using the same dish as the receiver. Such systems often combine two radar frequencies in the same antenna in order to allow automatic steering, or **radar lock**.

Parabolic reflectors can be either symmetric parabolas or spoiled parabolas:

- Symmetric parabolic antennas produce a narrow "pencil" beam in both the X and Y dimensions and consequently have a higher gain. The NEXRAD Pulse-Doppler weather radar uses a symmetric antenna to perform detailed volumetric scans of the atmosphere.

Surveillance radar antenna

- Spoiled parabolic antennas produce a narrow beam in one dimension and a relatively wide beam in the other. This feature is useful if target detection over a wide range of angles is more important than target location in three dimensions. Most 2D surveillance radars use a spoiled parabolic antenna with a narrow azimuthal beamwidth and wide vertical beamwidth. This beam configuration allows the radar operator to detect an aircraft at a specific azimuth but at an indeterminate height. Conversely, so-called "nodder" height finding radars use a dish with a narrow vertical beamwidth and wide azimuthal beamwidth to detect an aircraft at a specific height but with low azimuthal precision.

Types of scan

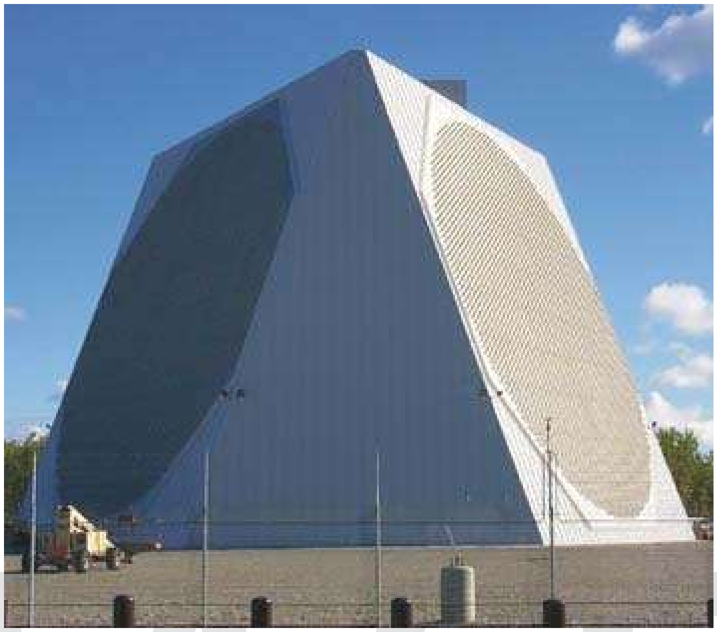
- Primary Scan: A scanning technique where the main antenna aerial is moved to produce a scanning beam, examples include circular scan, sector scan etc.
- Secondary Scan: A scanning technique where the antenna feed is moved to produce a scanning beam, examples include conical scan, unidirectional sector scan, lobe switching etc.
- Palmer Scan: A scanning technique that produces a scanning beam by moving the main antenna and its feed. A Palmer Scan is a combination of a Primary Scan and a Secondary Scan.

Slotted waveguide

Slotted waveguide antenna

Applied similarly to the parabolic reflector, the slotted waveguide is moved mechanically to scan and is particularly suitable for non-tracking surface scan systems, where the vertical pattern may remain constant. Owing to its lower cost and less wind exposure, shipboard, airport surface, and harbour surveillance radars now use this in preference to the parabolic antenna.

Phased array



Phased array: Not all radar antennas must rotate to scan the sky

Another method of steering is used in a phased array radar. This uses an array of similar aerials suitably spaced, the phase of the signal to each individual aerial being controlled so that the signal is reinforced in the desired direction and cancels in other directions. If the individual aerials are in one plane and the signal is fed to each aerial in phase with all others then the signal will reinforce in a direction perpendicular to that plane. By altering the relative phase of the signal fed to each aerial the direction of the beam can be moved because the direction of constructive interference will move. Because phased array radars require no physical movement the beam can scan at thousands of degrees per second, fast enough to irradiate and track many individual targets, and still run a wide-ranging search periodically. By simply turning some of the antennas on or off, the beam can be spread for searching, narrowed for tracking, or even split into two or more virtual radars. However, the beam cannot be effectively steered at small angles to the plane of the array, so for full coverage multiple arrays are required, typically disposed on the faces of a triangular pyramid.

Phased array radars have been in use since the earliest years of radar use in World War II, but limitations of the electronics led to fairly poor accuracy. Phased array radars were originally used for missile defense. They are the heart of the ship-borne Aegis combat system, and the Patriot Missile System, and are increasingly used in other areas because the lack of moving parts makes them more reliable, and sometimes permits a much larger effective antenna, useful in fighter aircraft applications that offer only confined space for mechanical scanning.

As the price of electronics has fallen, phased array radars have become more and more common. Almost all modern military radar systems are based on phased arrays, where the small additional cost is far offset by the improved reliability of a system with no moving parts. Traditional moving-antenna designs are still widely used in roles where cost is a significant factor such as air traffic surveillance, weather radars and similar systems.

Phased array radars are also valued for use in aircraft, since they can track multiple targets. The first aircraft to use a phased array radar is the B-1B Lancer. The first aircraft fighter to use phased array radar was the Mikoyan MiG-31. The MiG-31M's SBI-16 Zaslon phased array radar is considered to be the world's most powerful fighter radar . Phased-array interferometry or, aperture synthesis techniques, using an array of separate dishes that are phased into a single effective aperture, are not typically used for radar applications, although they are widely used in radio astronomy. Because of the Thinned array curse, such arrays of multiple apertures, when used in transmitters, result in narrow beams at the expense of reducing the total power transmitted to the target. In principle, such techniques used could increase the spatial resolution, but the lower power means that this is generally not effective. Aperture synthesis by post-processing of motion data from a single moving source, on the other hand, is widely used in space and airborne radar systems.

Frequency bands

The traditional band names originated as code-names during World War II and are still in military and aviation use throughout the world in the 21st century. They have been adopted in the United States by the IEEE, and internationally by the ITU. Most countries have additional regulations to control which parts of each band are available for civilian or military use.

Other users of the radio spectrum, such as the broadcasting and electronic countermeasures (ECM) industries, have replaced the traditional military designations with their own systems.

Radar frequency bands

Band name	Frequency range	Wavelength range	Notes
HF	3–30 MHz	10–100 m	coastal radar systems, over-the-horizon radar (OTH) radars; 'high frequency'
P	< 300 MHz	1 m+	'P' for 'previous', applied retrospectively to early radar systems
VHF	30–300 MHz	1–10 m	Very long range, ground penetrating; 'very high frequency'
UHF	300–1000 MHz	0.3–1 m	Very long range (e.g. ballistic missile early warning), ground penetrating, foliage penetrating; 'ultra high frequency'

L	1–2 GHz	15–30 cm	Long range air traffic control and surveillance; 'L' for 'long'
S	2–4 GHz	7.5–15 cm	Moderate range surveillance, Terminal air traffic control, long-range weather, marine radar; 'S' for 'short'
C	4–8 GHz	3.75–7.5 cm	Satellite transponders; a compromise (hence 'C') between X and S bands; weather; long range tracking
X	8–12 GHz	2.5–3.75 cm	Missile guidance, marine radar, weather, medium-resolution mapping and ground surveillance; in the USA the narrow range 10.525 GHz ±25 MHz is used for airport radar; short range tracking. Named X band because the frequency was a secret during WW2.
K_u	12–18 GHz	1.67–2.5 cm	high-resolution
K	18–24 GHz	1.11–1.67 cm	from German *kurz*, meaning 'short'; limited use due to absorption by water vapour, so K_u and K_a were used instead for surveillance. K-band is used for detecting clouds by meteorologists, and by police for detecting speeding motorists. K-band radar guns operate at 24.150 ± 0.100 GHz.
K_a	24–40 GHz	0.75–1.11 cm	mapping, short range, airport surveillance; frequency just above K band (hence 'a') Photo radar, used to trigger cameras which take pictures of license plates of cars running red lights, operates at 34.300 ± 0.100 GHz.
mm	40–300 GHz	7.5 mm – 1 mm	millimetre band, subdivided as below. The frequency ranges depend on waveguide size. Multiple letters are assigned to these bands by different groups. These are from Baytron, a now defunct company that made test equipment.
V	40–75 GHz	4.0–7.5 mm	Very strongly absorbed by atmospheric oxygen, which resonates at 60 GHz.
W	75–110 GHz	2.7–4.0 mm	used as a visual sensor for experimental autonomous vehicles, high-resolution meteorological observation, and imaging.
UWB	1.6–10.5 GHz	18.75 cm – 2.8 cm	used for through-the-wall radar and imaging systems.

Radar modulators

Modulators act to provide the waveform of the RF-pulse. There are two different radar modulator designs:

- high voltage switch for non-coherent keyed power-oscillators These modulators consist of a high voltage pulse generator formed from a high voltage supply, a pulse forming network, and a high voltage switch such as a thyratron. They generate short pulses of power to feed the e.g. magnetron, a special type of vacuum tube that converts DC (usually pulsed) into microwaves. This technology is known as Pulsed power. In this way, the transmitted pulse of RF radiation is kept to a defined, and usually, very short duration.

- hybrid mixers, fed by a waveform generator and an exciter for a complex but coherent waveform. This waveform can be generated by low power/low-voltage input signals. In this case the radar transmitter must be a power-amplifier, e.g. a klystron tube or a solid state transmitter. In this way, the transmitted pulse is intrapulsemodulated and the radar receiver must use pulse compression technique mostly.

Radar coolant

Coolanol and PAO (poly-alpha olefin) are the two main coolants used to cool airborne radar equipment today.

Coolanol (silicate ester) was used in several military radars in the 1970s, for example the AN/APG-63 in the F-15. However, it is hygroscopic, leading to formation of highly flammable alcohol. The loss of a U.S. Navy aircraft in 1978 was attributed to a silicate ester fire. Coolanol is also expensive and toxic. The U.S. Navy has instituted a program named Pollution Prevention (P2) to reduce or eliminate the volume and toxicity of waste, air emissions, and effluent discharges. Because of this Coolanol is used less often today.

PAO is a synthetic lubricant blend of a polyol ester admixed with effective amounts of an antioxidant, yellow metal pacifier and rust inhibitors. The polyol ester blend includes a major proportion of poly (neopentyl polyol) ester blend formed by reacting poly(pentaerythritol) partial esters with at least one C7 to C12 carboxylic acid mixed with an ester formed by reacting a polyol having at least two hydroxyl groups and at least one C8-C10 carboxylic acid. Preferably, the acids are linear and avoid those which can cause odours during use. Effective additives include secondary arylamine antioxidants, triazole derivative yellow metal pacifier and an amino acid derivative and substituted primary and secondary amine and/or diamine rust inhibitor.

A synthetic coolant/lubricant composition, comprising an ester mixture of 50 to 80 weight percent of poly (neopentyl polyol) ester formed by reacting a poly (neopentyl polyol) partial ester and at least one linear monocarboxylic acid having from 6 to 12 carbon atoms, and 20 to 50 weight percent of a polyol ester formed by reacting a polyol having 5 to 8 carbon atoms and at least two hydroxyl groups with at least one linear monocarboxylic acid having from 7 to 12 carbon atoms, the weight percents based on the total weight of the composition.

Radar configurations and types

Radars configurations include Monopulse radar, Bistatic radar, Doppler radar, Continuous-wave radar, etc.. depending on the types of hardware and software used. It is used in aviation (Primary and secondary radar), sea vessels, law enforcement, weather surveillance, ground mapping, geophysical surveys, and biological research.

Chapter 2

Air Traffic Control Radar Beacon System

The **air traffic control radar beacon system** (**ATCRBS**) is a system used in air traffic control (ATC) to enhance surveillance radar monitoring and separation of air traffic. ATCRBS assists ATC surveillance radars by acquiring information about the aircraft being monitored, and providing this information to the radar controllers. The controllers can use the information to identify radar returns from aircraft (known as *targets*) and to distinguish those returns from ground clutter.

Parts of the system

The system consists of transponders, installed in aircraft, and secondary surveillance radars (SSRs), installed at air traffic control facilities. The SSR is co-located with the **primary surveillance radar**, or PSR. These two radar systems work in conjunction to produce a synchronized surveillance picture. The SSR transmits interrogations and listens for any replies. Transponders that receive an interrogation decode it, decide whether to reply, and then respond with the requested information when appropriate. Note that in common informal usage, the term "SSR" is sometimes used to refer to the entire ATCRBS system, however this term (as found in technical publications) properly refers only to the ground radar itself.

The antenna system of a typical ground radar. The ladder-like top section is the SSR directional antenna, and the remainder of the assembly makes up the PSR antenna.

Ground Interrogation Equipment

An ATC ground station consists of two radar systems and their associated support components. The most prominent component is the PSR. It is also sometimes referred to as *skin paint radar* because it operates using traditional radar principles, transmitting radio pulses and listening for and timing the reflections from the skin or other metal components of aircraft. The primary surveillance radar is subject to the radar equation that says signal strength drops off as the fourth power of distance to the target. Objects detected using the PSR are known as **primary targets.**

The second system is the **secondary surveillance radar**, or SSR, which depends on a cooperating transponder installed on the aircraft being tracked. The transponder emits a signal when it is swept by the secondary radar. In a transponder based system signals drop off as the inverse square of the distance to the target, instead of the fourth power in primary radars. As a result, effective range is greatly increased for a given power level. The transponder can also send encoded information about the aircraft, such as identity and altitude.

The SSR is equipped with a main antenna, and an omnidirectional "Omni" antenna at many older sites. Newer antennas (like the picture to the right), are grouped as a left and right antenna, and each side connects to a hybrid device which combines the signals into sum and difference channels. Still other sites have both the sum and difference antenna, and an Omni antenna. Surveillance aircraft, e.g. AWACS, have only the sum and difference antennas, but can also be space stabilized by phase shifting the beam down or up when pitched or banking. The SSR beam antenna is typically fitted to the PSR antenna, so that they point in the same direction as the antennas rotate. The omnidirectional antenna is mounted near and high, and usually on top of the radome if equipped. Mode-S interrogators require the sum and difference channels to provide the monopulse capability to measure the off-boresight angle of the transponder reply.

The SSR repetitively transmits interrogations as the rotating radar scans the sky. The interrogation specifies what type of information a replying transponder should send by using a system of modes. There have been a number of modes used historically, but four are in common use today: mode 1, mode 2, mode 3/A, and mode C. **Mode 1** is used to sort military targets during phases of a mission. **Mode 2** is used to identify military aircraft missions. **Mode 3/A** is used to identify each aircraft in the radar's coverage area. **Mode C** is used to request an aircraft's altitude.

Two other modes, mode 4 and mode S, are not considered part of the ATCRBS system, but they use the same transmit and receive hardware. **Mode 4** is used by military aircraft for the Identification Friend or Foe (IFF) system. **Mode S** is a discrete selective interrogation rather than a general broadcast, that facilitates TCAS for civil aircraft. Mode S transponders ignore interrogations not addressed with their unique identity code, reducing channel congestion. At a typical SSR radar installation, ATCRBS, IFF, and mode S interrogations will all be transmitted in an interlaced fashion.

Returns from both radars at the ground station are transmitted to the ATC facility using a microwave link, a coaxial link, or (with newer radars) a digitizer and a modem. Once received at the ATC facility, a computer system known as a **radar data processor** associates the reply information with the proper primary target and displays it next to the target on the radar scope.

Airborne Transponder Equipment

The equipment installed in the aircraft is considerably simpler, consisting of the transponder itself, usually mounted in the instrument panel or avionics rack, and a small L band UHF antenna, mounted on the bottom of the fuselage. Many commercial aircraft also have an antenna on the top of the fuselage, and either or both antennas can be selected by the flight crew.

Typical installations also include an altitude encoder, which is a small device connected to both the transponder and the aircraft's static system. It provides the aircraft's pressure altitude to the transponder, so that it may relay the information to the ATC facility. The encoder uses 11 wires to pass the height information to the transponder in the form of a Gillham Code, a modified binary Gray code.

A light aircraft transponder

The transponder has a small required set of controls and is simple to operate. It has a method to enter the four-digit transponder code, also known as a *beacon code* or *squawk code*, and a control to transmit an *ident*, which is done at the controller's request. Transponders typically have 4 operating modes: Off, Standby, On (Mode-A), and Alt (Mode-C). On and Alt mode differ only in that the On mode inhibits transmitting any altitude information. Standby mode allows the unit to remain powered and warmed up but inhibits any replies, since older transponders incorporate transmitters which must be warmed up before they will function.

Theory of operation

The steps involved in performing an ATCRBS interrogation are as follows: First, the ATCRBS **interrogator** periodically interrogates aircraft on a frequency of 1030 MHz. This is done through a rotating or scanning antenna at the radar's assigned Pulse Repetition Frequency (PRF). Interrogations are typically performed at 450 - 500 interrogations/second. Once an interrogation has been transmitted, it travels through space in the direction the antenna is pointing at the speed of light until an aircraft is reached. When the aircraft receives the interrogation, the aircraft **transponder** will send a reply on 1090 MHz after a 3.0 μs delay indicating the requested information. The interrogator's processor will then decode the reply and identify the aircraft. The range of the aircraft is determined from the delay between the reply and the interrogation. The azimuth of the aircraft is determined from the direction the antenna is pointing when the first reply was received, until the last reply is received. This window of azimuth values is then divided by two to give the calculated "centroid" azimuth. The errors in this algorithm cause the aircraft to jitter across the controllers scope, and is referred to as "track jitter." The jitter problem makes software tracking algorithms problematic, and is the reason why monopulse was implemented.

The interrogation

Interrogations consist of three pulses, 0.8 μs in duration, referred to as P1, P2 and P3. The timing between pulses P1 and P3 determines the mode (or question) of the interrogation, and thus what the nature of the reply should be. P2 is used in side-lobe suppression, explained later.

Mode 3/A uses a P1 to P3 spacing of 8.0 μs, and is used to request the *beacon code*, which was assigned to the aircraft by the controller to identify it. Mode C uses a spacing of 21 μs, and requests the aircraft's pressure altitude, provided by the altitude encoder. Mode 2 uses a spacing of 5 μs and requests the aircraft to transmit its Military identification code. The latter is only assigned to Military aircraft and so only a small percentage of aircraft actually reply to a mode 2 interrogation.

The reply

Replies to interrogations consist of 15 time slots, each 1.45 μs in width. The reply is encoded by the presence or absence of a 0.45 μs pulse in each slot. These are labeled as follows:

F1 C1 A1 C2 A2 C4 A4 X B1 D1 B2 D2 B4 D4 F2 SPI

The F1 and F2 pulses are framing pulses, and are always transmitted by the aircraft transponder. They are used by the interrogator to identify legitimate replies. These are spaced 20.3 μs apart.

The A4, A2, A1, B4, B2, B1, C4, C2, C1, D4, D2, D1 pulses constitute the "information" contained in the reply. These bits are used in different ways for each interrogation mode.

For mode A, each digit in the transponder code (A, B, C, or D) may be a number from zero to seven. These octal digits are transmitted as groups of three pulses each, the A slots reserved for the first digit, B for the second, and so on.

In a mode C reply, the altitude is encoded by a *Gillham interface*, Gillham Code, which uses gray code. The Gillham interface is capable of representing a wide range of altitudes, in 100-foot (30 m) increments. The altitude transmitted is pressure altitude, and corrected for altimeter setting at the ATC facility. If no encoder is attached, the transponder may optionally transmit only framing pulses (most modern transponders do).

In a mode 3 reply, the information is similar to the mode A reply in that there are 4 digits transmitted between 0 and 7. The mode 3 reply differs from the mode A reply in that the transmitted code is assigned by a military air traffic controller, not a civilian air traffic controller.

The X bit is currently only used for test targets. This bit was originally transmitted by BOMARC missiles that were used as air launched test targets. This bit may be used by drone aircraft.

The SPI pulse is positioned 4.35μs past the F2 pulse (3 time slots) and is used as a "Special Identification Pulse". The SPI pulse is turned on by the "identity control" on the transponder in the aircraft cockpit when requested by air traffic control. The air traffic controller can request the pilot to ident, and when the identity control is activated, the SPI bit will be added to the reply for about 20 seconds (two to four rotations of the interrogator antenna) thereby highlighting the track on the controllers display.

Side lobe suppression

The SSR's directional antenna is never perfect; inevitably it will "leak" lower levels of RF energy in off-axis directions. These are known as side lobes. When aircraft are close to the ground station, the side lobe signals are often strong enough to elicit a reply from their transponders when the antenna is not pointing at them. This can cause *ghosting*, where an aircraft's target may appear in more than one location on the radar scope. In extreme cases, an effect known as *ring-around* occurs, where the transponder replies to excess resulting in an arc or circle of replies centered on the radar site.

To combat these effects, **side lobe suppression** (SLS) is used. SLS employs a third pulse, P2, spaced 2μs after P1. This pulse is transmitted from the omnidirectional antenna (or the antenna difference channel) by the ground station, rather than from the directional antenna (or the sum channel). The power output from the omnidirectional antenna is calibrated so that, when received by an aircraft, the P2 pulse is stronger than either P1 or P3, *except* when the directional antenna is pointing directly at the aircraft. By comparing the relative strengths of P2 and P1, airborne transponders can determine whether or not the antenna is pointing at the aircraft when the interrogation was received. The power to the difference antenna pattern (for systems so equipped) is not adjusted from that of the P1 and P3 pulses. Algorithms are used in the ground receivers to delete replies on the edge of the two beam patterns.

To combat these effects more recently, side lobe suppression (SLS) is still used, but differently. The new and improved SLS employs a third pulse, spaced 2μs either before P3 (a new P2 position) or after P3 (which should be called P4 and appears in the Mode S radar and TCAS specifications). This pulse is transmitted from the directional antenna at the ground station, and the power output of this pulse is the same strength as the P1 and P3 pulses. The action to be taken is specified in the new and improved C74c as:

2.6 Decoding Performance.

c. Side-lobe Suppression. The transponder must be suppressed for a period of 35 ±10 microseconds following receipt of a pulse pair of proper spacing and suppression action must be capable of being reinitiated for the full duration within 2 microseconds after the end of any suppression period. The transponder must be suppressed with a 99 percent efficiency over a received signal amplitude range between 3 db above minimum triggering level and 50 db above that level and upon receipt of properly spaced interrogations when the received amplitude of P2 is equal to or in excess of the received amplitude of P1 and spaced 2.0 ±0.15 microsecond from P3.

Any requirement at the transponder to detect and act upon a P2 pulse 2μs after P1 has been removed from the new and improved TSO C74c specification.

Most "modern" transponders (manufactured since 1973) have an "SLS" circuit which suppresses reply on receipt of any two pulses in any interrogation spaced 2.0 microseconds apart that are above the MTL Minimum Triggering Level threshold of the receiver amplitude descriminator (P1->P2 or P2->P3 or P3->P4). This approach was used to comply with the original C74c and but also complies with the provisions of the new and improved C74c.

The FAA refers to the non-responsiveness of new and improved TSO C74c compliant transponders to Mode S compatible radars and TCAS as "The Terra Problem", and has issued Airworthiness Directives (ADs) against various transponder manufacturers, over the years, at various times on no predictable schedule. The ghosting and ring around problems have recurred on the more modern radars.

To combat these effects most recently, great emphasis is placed upon software solutions. It is highly likely that one of those software algorithms was the proximate cause of a mid-air collision recently, as one airplane was reported at showing its altitude as the pre-flight paper filed flight plan, and not the altitude assigned by the ATC controller.

Radar display

The beacon code and altitude were historically displayed verbatim on the radar scope next to the target, however modernization has extended the radar data processor with a **flight data processor**, or FDP. The FDP automatically assigns beacon codes to flight plans, and when that beacon code is received from an aircraft, the computer can associate it with flight plan information to display immediately useful data, such as aircraft callsign, the aircraft's next navigational fix, assigned and current altitude, etc. near the target in a *data block*.

Mode S

Mode S, or *mode select*, despite also being called a mode, is actually a radically improved system intended to replace ATCRBS altogether. A few countries have mandated mode S, and many other countries, including the United States, have begun phasing out ATCRBS in favor of this system. Mode S is designed to be fully backward compatible with existing ATCRBS technology.

Mode S, despite being called a replacement transponder system for ATCRBS, is actually a data packet protocol which can be used to augment ATCRBS transponder positioning equipment (radar and TCAS).

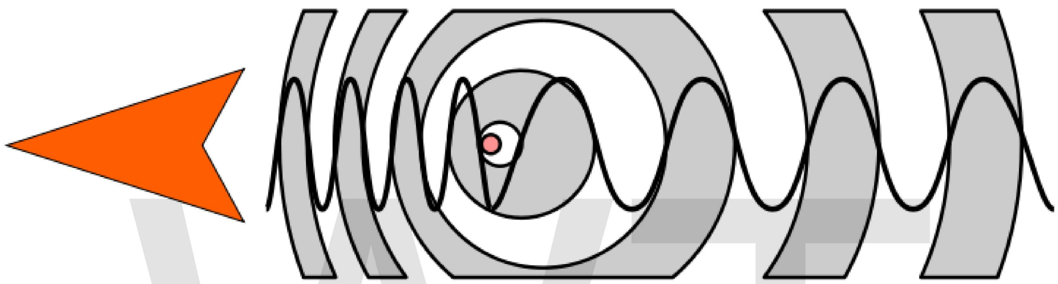
One major improvement of Mode S, is the ability to interrogate a single aircraft at a time. With old ATCRBS technology, all aircraft within the beam pattern of the interrogating station will reply. In an airspace with multiple interrogation stations, ATCRBS transponders in aircraft can be overwhelmed. By interrogating one aircraft at a time, workload on the aircraft transponder is greatly reduced.

The second major improvement is increased azimuth accuracy. With PSRs and old SSRs, azimuth of the aircraft is determined by the half split method. The half split method is computed by recording the azimuth of the first and last replies from the aircraft, as the radar beam sweeps past its position. Then the mid-point between the start and stop azimuth is used for aircraft position. With Mode S, the radar can use the information of one reply to determine azimuth. This is calculated based on the RF phase of the aircraft reply, as determined by the sum and difference antenna elements, and is called monopulse. This monopulse method results in superior azimuth resolution.

The Mode S system also includes a more robust communications protocol, for a wider variety of information exchange. At this time, this capability is becoming mandatory across Europe with some states already requiring its use.

Chapter 3

Doppler Radar



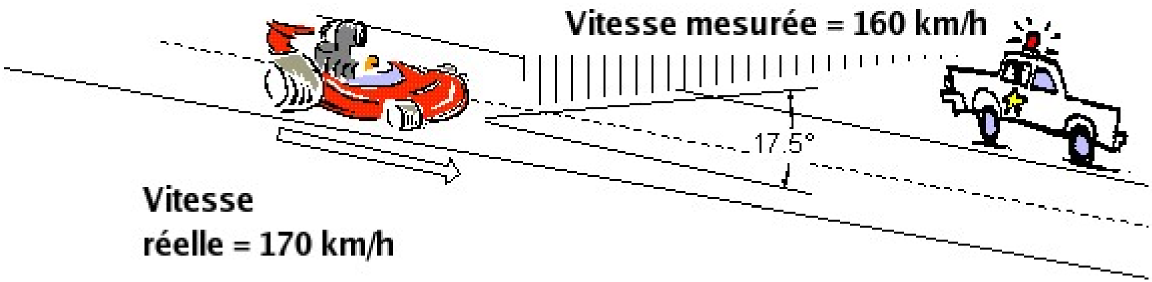
Doppler effect

A **Doppler radar** is a specialized radar that makes use of the doppler effect to produce velocity data about objects at a distance. It does this by beaming a microwave signal towards a desired target and listening for its reflection, then analyzing how the frequency of the returned signal has been altered by the object's motion. This variation gives direct and highly accurate measurements of the radial component of a target's velocity relative to the radar. Doppler radars are used in aviation, sounding satellites, meteorology, police speed guns, and radiology.

The specific term "*Doppler Radar*", due in part to its extremely common use by television meteorologists in on-air weather reporting, has erroneously become popularly synonymous with the type of radar used in meteorology. Most modern weather radars use the pulse-doppler technique to examine the motion of precipitation, but it is only a part of the processing of their data. So, while these radars use a highly specialized form of *doppler radar*, the term is much broader in its meaning and its applications.

Concept

Doppler Effect



The emitted signal toward the car is reflected back with a variation of frequency that depend on the speed away/toward the radar (160 km/h). This is only a component of the real speed (170 km/h).

The Doppler effect (or Doppler shift), named after Austrian physicist Christian Doppler who proposed it in 1842, is the change in frequency of a wave for an observer moving relative to the source of the waves. It is commonly heard when a vehicle sounding a siren approaches, passes and recedes from an observer. The received frequency is increased (compared to the emitted frequency) during the approach, it is identical at the instant of passing by, and it is decreased during the recession. This variation of frequency also depends on the direction the wave source is moving with respect to the observer; it is maximum when the source is moving directly toward or away from the observer, and diminishes with increasing angle between the direction of motion and the direction of the waves, until when the source is moving at right angles to the observer, there is no shift.

An analogy would be pitcher throwing one ball every second in a person's direction (a frequency of 1 ball per second). Assuming that the balls travel at a constant velocity, if the pitcher is stationary, the man will catch one ball every second. However, if the pitcher is jogging towards the man, he will catch balls more frequently because the balls will be less spaced out (the frequency increases). The inverse is true if the pitcher is moving away from the man; he will catch balls less frequently due to the pitcher's backward motion (the frequency decreases). If the pitcher were to move at an angle but with the same speed, the variation of the frequency at which the receiver would catch the ball would be less as the distance between the two would change more slowly.

Note that, from the point of view of the pitcher, the frequency remains constant (whether he's throwing balls or transmitting microwaves). Since with electromagnetic radiation like microwaves frequency is inversely proportional to wavelength, the wavelength of the waves is also affected. Thus, the relative difference in velocity between a source and an observer is what gives rise to the doppler effect.

Frequency variation

The exact formula for radar doppler shift is the same as that for reflection of light by a moving mirror. There is no need to invoke Einsteins' theory of special relativity, because all observations are made in the same frame of reference. The exact result derived with c as the speed of light and v as the target velocity gives the shifted frequency (F_r) as a function of the original frequency (F_t) :

$$F_r = F_t(\frac{1 + v/c}{1 - v/c})$$

The exact "beat frequency", aka Doppler Frequency (F_d), is thus:

$$F_d = F_r - F_t = 2v\frac{F_t}{(c - v)}$$

Since for most all practical applications of radar, $v \ll c$, so $(c - v) \to c$. We can then write:

$$F_d \approx 2v\frac{F_t}{c}$$

Technology

U.S. Army soldier using a radar gun, an application of Doppler radar, to catch speeding violators.

There are three ways of producing the Doppler effect. Radars may be Coherent pulsed (CP), Continuous wave (CW), or Frequency modulated (FM). CW doppler radar only provides a velocity output as the received signal from the target is compared in frequency with the original signal. Early doppler radars were CW, but these quickly led to the development of frequency modulated continuous wave(FM-CW) radar, which sweeps the transmitter frequency to encode and determine range.

The CW and FM-CW radars can normally only process one target, which limits their use. With the advent of digital techniques, Pulse-Doppler radars (PD) were introduced, and doppler processors for coherent pulse radars were developed at the same time. The advantage of combining doppler processing with pulse radars is to provide accurate velocity information. This velocity is called Range-Rate. It describes the rate that a target moves towards or away from the radar. A target with no range-rate reflects a frequency near the transmitter frequency, and cannot be detected. The classic zero doppler target is one which is on a heading that is tangential to the radar antenna beam. Basically, any target that is heading 90 degrees in relation to the antenna beam cannot be detected by its velocity (only by its conventional reflectivity).

History

FM radar was highly developed during World War II for the use by US Navy aircraft. Most used the UHF spectrum, and had a transmit yagi antenna on the port wing, and a receiver yagi antenna on the starboard wing. This allowed bombers to fly an optimum speed when approaching ship targets. Later when magnetrons and microwaves became available, the use of FM radar fell into disuse.

When the digital Fast Fourier transform became available, it was immediately connected to Coherent Pulsed radars, where velocity information was extracted. This quickly proved useful in both weather and air traffic control radars. The velocity information provided another input to the software tracker, and improved computer tracking. Due to the low *pulse repetition frequency* (PRF) of most coherent pulsed radars, which maximizes the coverage in range, the amount of doppler processing is limited. The doppler processor can only process velocities up to ±1/2 the PRF of the radar. This was not a problem for weather radars.

Specialized radars quickly were mechanized when digital techniques became affordable. Pulse-Doppler radars combine all the benefits of long range, and high velocity capability. Pulse-Doppler radars use a medium to high PRF (on the order of 30 kHz). This high PRF allows for the detection of either high speed targets, or high resolution velocity measurements. Normally it is one or the other, that is, a radar designed for detecting targets from zero to Mach 2, does not have a high resolution in speed, while a radar designed for high resolution velocity measurements does not have a wide range of speeds. Weather radars are high resolution velocity radars, while air defense radars have a large range of velocity detection, but the accuracy in velocity is in the 10's of knots.

Antenna designs for the CW and FM-CW started out as separate transmit and receive antennas before the advent of affordable microwave designs. In the late 1960s traffic radars began being produced which used a single antenna. This was made possible by the use of circular polarization, and a multi-port waveguide section operating at X band. By the late 1970s this changed to linear polarization and the use of ferrite circulators at both X and K bands. PD radars operate at too high a PRF to use a Transmit-Receive gas filled switch, and most use solid-state devices to protect the receiver Low Noise Amplifier when the transmitter is fired.

Chapter 4

Pulse-Doppler Radar

Pulse-Doppler is a radar system capable of not only detecting target location (bearing, range, and altitude), but also measuring its radial velocity (range-rate). It uses the Doppler effect to determine the relative velocity of objects; pulses of RF energy returning from the target are processed to measure the phase shift between carrier cycles successive pulses at the transmitted frequency. To achieve this, the transmitter frequency source must have very good phase stability and the system is said to be coherent.

They are used in different fields. In meteorological radars, pulse-Doppler measures instantaneous speed at discrete range intervals to detect wind field in weather as the beam is slewed across the sky. Doppler On Wheels, NEXRAD, Terminal Doppler Weather Radar, and ARMOR Doppler Weather Radar are examples. In search and track radars, the purpose is to measure the speed of all targets and eliminate environmental reflections from weather, the surface of the earth, and biological objects like birds, which hides target signals, by their characteristic velocity.

Pulse repetition frequency

Pulse-Doppler typically uses medium Pulse repetition frequency (PRF) from about 3 kHz to 30 kHz. Systems using PRF below 3 kHz are considered low PRF because direct range can be measured to a range of 50 km, and Doppler processing becomes an increasing challenge due to coherency limitations as PRF falls below 3 kHz. Systems using PRF above 30 kHz function better as interrupted CW radar because direct velocity can be measured up to 4.5 km/s at L band, and range measurement becomes more of a challenge as PRF increases above 30 kHz. Range and velocity cannot be measured directly using medium PRF, and a technique called ambiguity resolutions is used to identify range.

Underlying principle

Pulse-Doppler radar is based on the Doppler effect, where movement in range produces frequency shift on the signal reflected from the target.

$$DopplerFrequency = 2F_o\left(\frac{RangeVelocity}{C}\right)$$

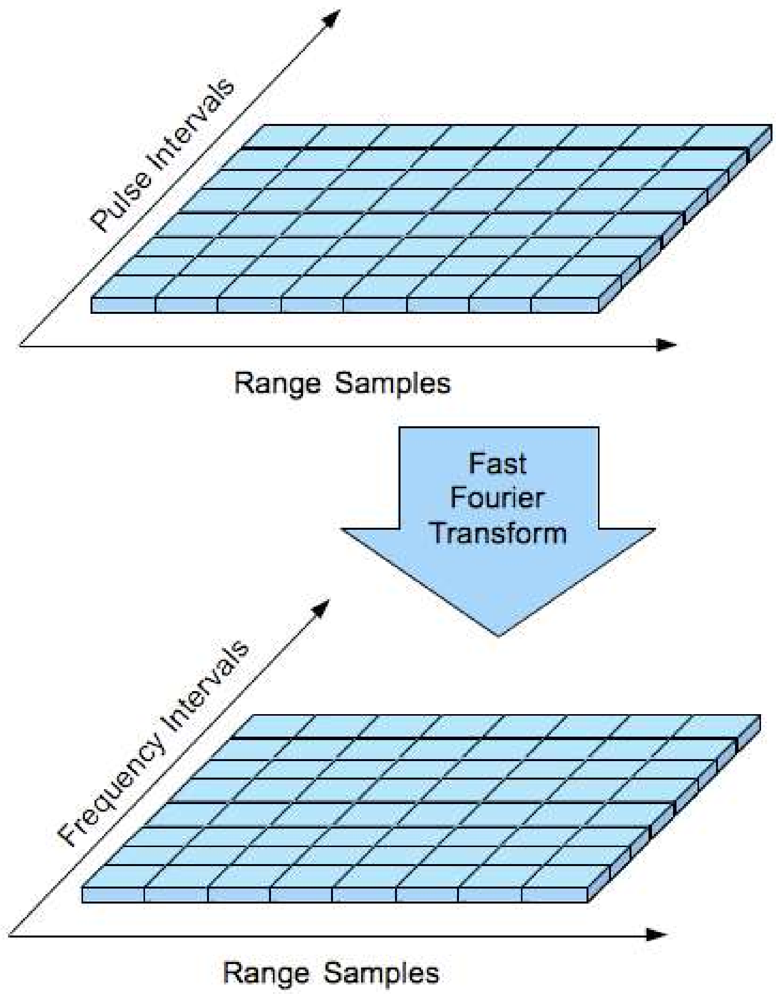
In some systems, the velocity measurement is compared to the change in range to determine if the detected signal is an airborne vehicle or an electronic artifact. Angular measurement is made using monopulse scanning and sidelobe blanking as the radar beam is scanned across the sky.

Multiple receive samples are taken between transmit pulses. Each sample includes an in-phase (I) value and a quadrature (Q) value. I an Q are the real and imaginary component of a complex number.

A spinning wheel, mirror and strobe-light can be used to visualize I and Q. The mirror is placed at a 45 degree angle above the wheel so that you can see the front and top of the wheel at the same time. The strobe-light is attached to the wheel so that you can see the wheel spin when the room lights are turned off. You sit directly in front of the wheel while a friend spins the wheel. The view of the front of the wheel (I) and the top of the wheel (Q) tell you whether your friend has spun the wheel clockwise or counterclockwise. Clockwise is like inbound Doppler. Counterclockwise is like outbound Doppler.

Pairs of I and Q values form a complex number explained as real and imaginary parts. I is the real components. Q is the imaginary component.

Signal Processing



Pulse-Doppler signal processing. The *Range Sample* axis represents individual samples taken in between each transmit pulse. The *Range Interval* axis represents each successive transmit pulse interval during which samples are taken. The Fast Fourier Transform process converts time-domain samples into frequency domain spectra.

I(t) and Q(t) are both required during the sampling process so that radar signal processing can include information about closing (approaching) versus opening (leaving) Doppler velocities. This is crucial for proper operation of pulse-Doppler systems.

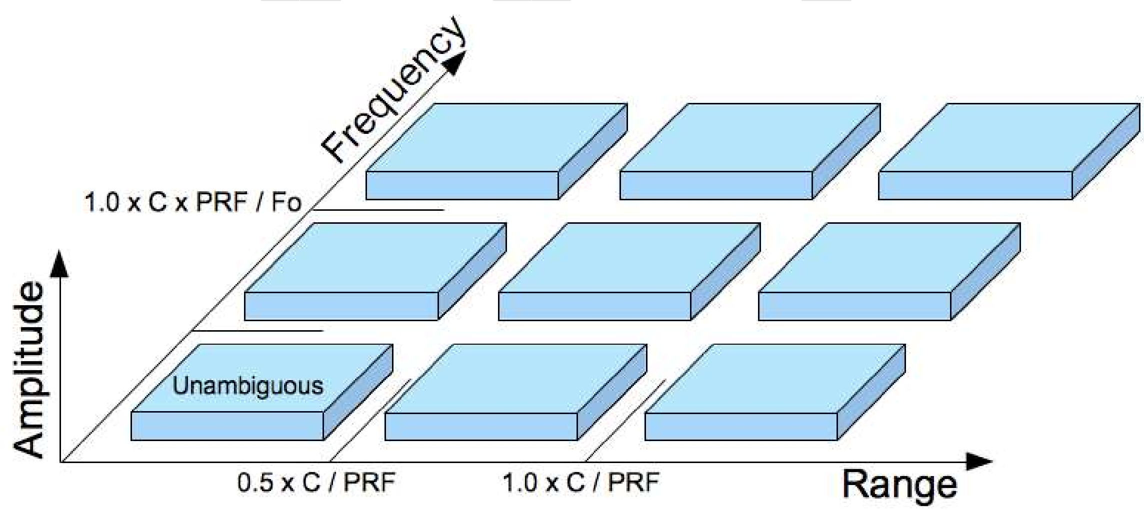
Pulse-Doppler relies on taking up to a few dozen individual I and Q samples in between each transmit pulse. Each different range sample has its own separate processing, and these time samples are converted to frequency domain using a digital filter, usually involving a fast Fourier transform (FFT). Side-lobes are produced during signal processing and a side-lobe suppression strategy, such as Dolph-Chebyshev Windowing, is commonly used to reduce false alarms.

The digital filter produces as many frequency outputs as there are time inputs. Production of one FFT requires as many samples as the number of points in the FFT (a 256 point FFT requires 256 transmit pulses). Each separate spectrum undergoes separate detection processing.

Pulse-Doppler typically uses a form of constant false alarm rate detection processing to identify target signals. Detection processing for pulse-Doppler produces an ambiguous range and ambiguous velocity corresponding to one of the FFT outputs from one of the range samples. The reflection from clutter falls into filters corresponding to a different frequency than the filter corresponding to most aircraft. Sub-clutter visibility in a pulse-Doppler radar is a measure of the power difference between the smallest signals that can be detected in the presence of a large signal at a different frequency. This Measure of Performance is called Sub-clutter Visibility. Sub-clutter visibility for pulse-Doppler is typically over 50dB. Conventional non-coherent radar using Moving target indication provides up to about 25dB sub-clutter visibility. Pulse-Doppler is used in many military applications for this reason.

Pulse-Doppler signals are audible, so a helicopter sounds like a helicopter and a jet sounds like a jet. The actual size of the target can be calculated using these audible signals, which is impossible with pulse compression and low PRF systems. Audible Doppler and target size support passive vehicle type classification when identification friend or foe is not available. This is another reason pulse-Doppler has military applications.

Ambiguity Resolution



Pulse-Doppler ambiguity zones. Each blue zone with no label represents a velocity/range combination that will be folded into the unambiguous zone. Areas outside the blue zones are blind ranges and blind velocities. Blind velocities correspond with the clutter notch.

Pulse Doppler relies on medium pulse repetition frequency (PRF) from about 3 kHz to 30 kHz. Each transmit pulse is separated by between 5 km and 50 km of distance. Operation in an environment larger than 5 km to 50 km means reflections arrive at the antenna from multiple ranges simultaneously. The true range and speed of the target is effectively folded by a modulo operation produced by the transmit and receive process.

Range Ambiguity Resolution

True range is found using two different PRF. Each pair of PRF is a separate detection scheme with unique mathematical properties that are configured into the radar. Target detection requires samples from both PRF, which are transmitted alternating back and forth rapidly during the search process.

The time between transmit pulses is split into several range samples. Each range sample contains the receive signal from a specific range interval. This is called sampling.

This is explained best using the following example, where PRF A produces a transmit pulse every 6 km and PRF B produces a transmit pulse every 5 km.

Transmit Sample 1   Sample 2   Sample 3   Sample 4   Sample 5

Target PRF A

Target PRF B

The apparent range for PRF A falls in the 2 km sample, and the apparent range for PRF B falls in the 4 km sample. This combination places the true target distance at 14 km (2x6+2 or 2x5+4). This can be seen graphically when range intervals are stacked end-to-end as shown below.

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 29 29

A A A A A

B B B B B B

"A" represents target range possibilities for PRF A, and "B" represents target range possibilities for PRF B.

This process is usually automated with a look-up table, and the size of this table limits the maximum range. A convolution algorithm may be used instead of a table.

Each individual PRF has blind ranges, where the transmitter pulse occurs at the same time as the target reflection signal arrives back at the radar. A third and fourth PRF are required to complete a detection by repeating the process described above. PRF alternates rapidly while scanning to fill in any blind ranges.

Multiple target reflections can corrupt the range ambiguity resolution process. Frequency ambiguity resolution improves performance for multiple target scenarios by separating target signals using speed differences.

Frequency Ambiguity Resolution

Each range samples is converted from time domain I/Q samples into frequency domain. Older systems use individual filters for this. Newer systems use digital sampling and a Fast Fourier transform or Discrete Fourier transform instead of physical filters. Each filter converts time samples into a frequency spectrum. Each spectrum frequency corresponds with a different speed. The ambiguous velocity is as follows.

$$AmbiguousVelocity = -0.5\left(\frac{DopplerFrequency * C}{TransmitFrequency}\right)$$

Frequency is folded for high speed targets where radial velocity produces a frequency shift above the Nyquist frequency. The true speed of the target may be folded by a modulo operation produced by the sampling process.

$$TrueVelocity = AmbiguousVelocity + 0.5N\left(\frac{PRF * C}{TransmitFrequency}\right)$$

$$N = IntegerBetween \pm \left(\frac{0.5Bandwidth}{PRF}\right)$$

The Nyquist frequency will also change when the PRF is changed. The target frequency will shift if the speed is greater than the Nyquist frequency. This shift can be used to establish the frequency interval, much the same way as described above for range ambiguity resolution.

A blind velocity occurs when Doppler frequency falls close to the PRF. This folds the return signal into the same filter as stationary clutter reflections. Rapidly alternating different PRF while scanning eliminates blind frequencies.

Special Consideration

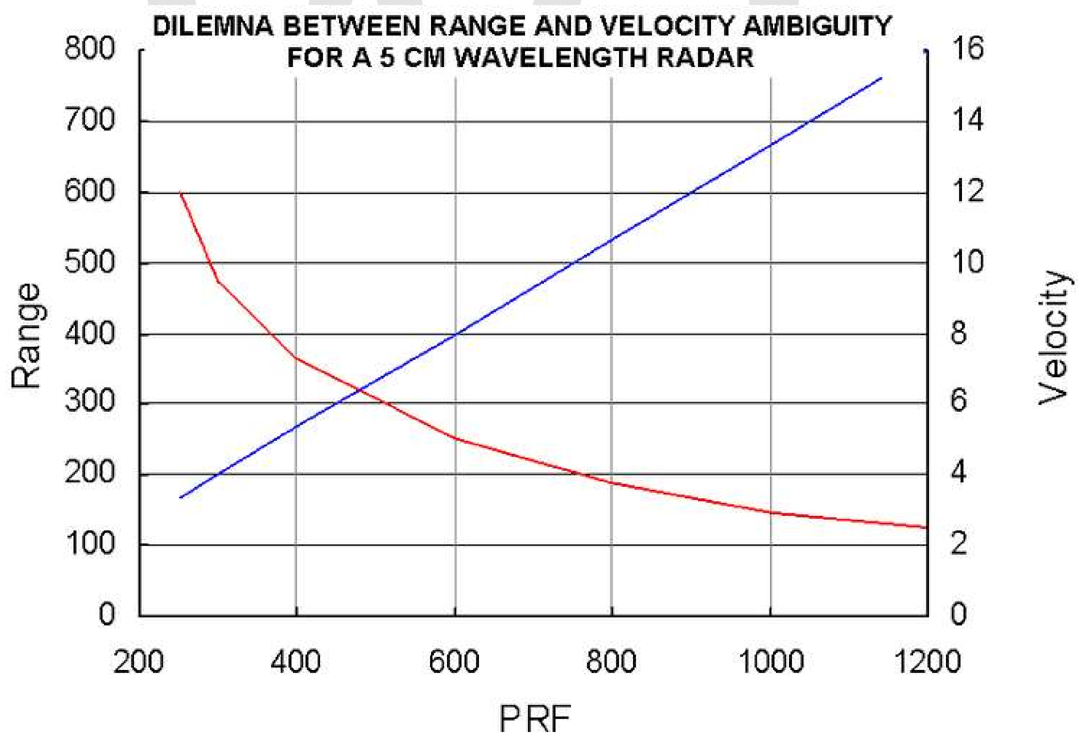
Pulse-Doppler radar has special requirements that must be satisfied to achieve acceptable performance.

Coherency

Pulse-Doppler radar requires an oscillator with very little noise. The amount of tolerable FM or phase noise depends upon the size of the filters used for signal processing. If range samples are split into 100 different frequencies using a PRF of 10 kHz, then the tolerable limit for FM transmit noise requires signal no greater than the sub-clutter visibility reduction factor 100 Hz away from the carrier frequency, and this must be maintained over a time span of no less than 10ms.

FM noise above this threshold paints stationary objects with false Doppler signal, which reduces sub-clutter visibility performance. Noise reduction includes shaping the transmit pulse to reduce ringing artifacts. Pulse Doppler requires coherent amplifiers, like solid state, klystron or traveling wave tube. Extra FM noise originating from transmitter amplification will induce apparent motion on stationary objects which will reduce performance, so magnetron and crossed-field amplifier are not appropriate because noise introduced by these devices interfere with detection performance.

In order for Pulse-Doppler radar to be effective, it is essential that the received echoes are coherent with the carrier signal, at least during the sampling period. To achieve this, a number of techniques are employed, the most common being that the transmitter signal is derived from a highly stable oscillator (the COHO) and the received signal is demodulated using an equally stable local oscillator (the STALO), which is phase locked to it. Doppler shift may then be accurately resolved by comparing the frequency components of the returned echo with the frequency components of the transmitted signal.



Maximum range from reflectivity (red) and unambiguous Doppler velocity range (blue) with a fix pulse repetition rate.

Scalloping

Scalloping is a phenomenon unique to two-PRF detection schemes. This creates **detection gaps** with a pattern of discrete ranges, each of which has a blind velocity.

Objects moving at the radial velocity that produces a harmonic of the PRF produce zero Doppler at the receiver. This is the blind velocity for a PRF. The target will become invisible in a two PRF detection scheme when the target reflection arrives during the transmit pulse on the other PRF.

Assume two pulse frequencies PRF-A and PRF-B. There will be blind zones at every range for PRF-A where there is a transmit pulse at the same time as when a signal is arriving. PRF-B will produce detections in those blind ranges, except that PRF-B will have blind velocities different from PRF-A.

This leaves intermittent detection gaps at discrete velocities in each blind range. Aircraft with a Doppler frequency that is a harmonic of PRF-B will not be detectable at blind ranges for PRF-A. Aircraft with a Doppler frequency that is a harmonic of PRF-A will not be detectable at blind ranges for PRF-B.

These detection gaps are filled in by using three or more alternating PRF in the detection scheme. The other alternative is to increase the pulse rate high enough to eliminate frequency ambiguity.

Velocity becomes ambiguous at a 3 kHz PRF for an L band radar at 300 m/s (near the speed of sound). Velocity becomes ambiguous at a 3 kHz PRF for an X band radar at 30 m/s (speed of a fast car).

Increasing PRF increases the Nyqist frequency. Velocity becomes ambiguous at a 30 kHz PRF for an L band radar at 3000 m/s (about half the velocity of low earth orbit). Velocity becomes ambiguous at a 30 kHz PRF for an X band radar at 300 m/s (speed of sound).

Alternating PRF requires a minimum level of complexity that depends upon maximum radial velocity of the object. The maximum radial velocity is determined by the environment. Objects moving inside earth's atmosphere are limited to about 1 km/s due to thermal heating caused by shock wave physics. Space begins above about 20miles, and objects in low earth orbit travel about 8 km/s. There is no velocity limit in space.

Modeling and simulation is required used to evaluate performance for the chosen PRF combination to ensure no detection gaps for all possible range and velocity combination.

Range Performance

The theoretical range performance is as follows.

$$R = \left(\frac{P_t G_t A_r \sigma F^4 D}{16\pi^2 K_b T B N} \right)^{-4}$$

where

- R = distance to the target
- P_t = transmitter power
- G_t = gain of the transmitting antenna
- A_r = effective aperture (area) of the receiving antenna
- σ = radar cross section, or scattering coefficient, of the target
- F = pattern propagation factor
- D = number of discrete Doppler filters for each range sample
- R = distance to the target
- K_b = Boltzmann's constant
- T = Temperature (kelvin)
- B = Receiver Bandwidth (band pass filter)
- N = Noise Factor

This is derived by combining the Radar equation with the Noise equation and accounting for in-band noise distribution across multiple detection filters. The value D is added to the standard radar range equation to account for noise power that arrives at the receiver being distributed equally among each of the Doppler filters.

Angular movement of the antenna must be slow enough so each volume of space remains within the main antenna lobe no less than the duration of three full PRF samples to achieve the level of performance described by this equation. Increasing the value of D will increase detection range at the expense of requiring more time to complete a full scan. It is impractical to increase D to a value that that requires phase noise lower than the transmitter specification.

Detection range is increased by the number of filters. For example, use of 100 filters will reduce noise contribution in each filter 20dB below the level of noise (electronics) begin sampled in the receiver. Each filter holds a small amount of the total noise arriving at the receiver but all of the signal arriving from the target goes into no more than two filters. This reduces the bandwidth associated with the detection process. A 20dB improvement corresponds with the ability to detect a target 100 times smaller than with conventional pulse-amplitude radar, all else being equal.

Active RF phase shifters commonly used with electronically steered phased array antenna normally have a phase settling time that exceeds the coherency limit needed for pulse-Doppler. This limits pulse-Doppler antennas to a mechanically steered configuration.

Application considerations

Type of Radar

The maximum velocity that can be unambiguously measured is inherently limited by the PRF, as discussed above. The PRF-value must therefore be chosen carefully, based on a tradeoff between maximum velocity resolution and the reduction of velocity aliasing and range ambiguity problems. This tradeoff is highly application dependent, as e.g. weather radars measure velocities at a totally different scale as compared to radars designed to detect supersonic missiles and aircraft.

Moving targets

Stationary targets such as earth ground clutter (land, buildings, etc.) will be dominant in the low doppler frequencies, while moving targets will produce much higher doppler shifts. The radar processor can be designed to mask out clutter by the use of doppler filters (digital or analogue) around the main spectral line (called the clutter-notch), which will result in the display of moving targets only (in relation to the radar). If the radar itself is moving, such as on a fighter aircraft, or a surveillance aircraft, then much more processing will be required, as the clutter in the filters will be based on platform speed, terrain under the radar, antenna depression angle, and antenna rotation/steered angle.

Monopulse radar

Doppler signal processing improves performance of monopulse radar systems by reducing or eliminating signals from slow object, like the earth surface, trees, buildings, and weather.

Chapter 5

Active Electronically Scanned Array

APAR AESA onboard *Hamburg* (F220), a *Sachsen*-class frigate of the German Navy

An **Active Electronically Scanned Array** (AESA), also known as **active phased array radar** is a type of phased array radar whose transmitter and receiver functions are composed of numerous small solid-state transmit/receive modules (TRMs). AESAs aim their "beam" by broadcasting radio energy that interfere constructively at certain angles in front of the antenna. They improve on the older passive electronically scanned radars by spreading their broadcasts out across a band of frequencies, which makes it very difficult to detect over background noise. AESAs allow ships and aircraft to broadcast powerful radar signals while still remaining stealthy.

Basic concept

Radar systems generally work by connecting an antenna to a powerful radio transmitter to broadcast a short pulse of signal. The transmitter is then disconnected and the antenna is connected to a sensitive receiver which amplifies any echos from target objects. By measuring the time it takes for the signal to come back, the radar receiver can determine the distance to the object. The receiver then sends the resulting output to a display of some sort. The transmitter elements were typically klystron tubes or magnetrons, which are suitable for amplifying or generating a narrow range of frequencies to high power levels. In order to scan a portion of the sky, the radar antenna has to be physically moved to point in different directions.

Starting in the 1960s new solid-state devices capable of delaying the transmitter signal in a controlled way were introduced that led to the first practical large-scale passive electronically scanned array (PESA), or simply phased array radar. PESAs took a signal from a single source, split it up into hundreds of paths, selectively delayed some of them, and sent them to individual antennas. The resulting broadcasts overlapped in space, and the interference patterns between the individual signals was controlled in order to reinforce the signal in certain directions, and mute it down in all others. The delays could be easily controlled electronically, allowing the beam to be steered very quickly without having to move the antenna. A PESA can scan a volume of space much more quickly than a traditional mechanical system. Additionally, as the electronics improved, PESAs added the ability to produce several active beams, allowing them to continue scanning the sky while at the same time focusing smaller beams on certain targets for tracking or guiding semi-active radar homing missiles. PESAs quickly became widespread on ships and large fixed emplacements in the 1960s, followed by airborne sensors as the electronics shrank.

AESAs are the result of further developments in solid-state electronics. In earlier systems the broadcast signal was originally created in a klystron or traveling wave tube or similar device, which are relatively large. Receiver electronics were also large due to the high frequencies that they worked with. The introduction of gallium arsenide microelectronics through the 1980s served to greatly reduce the size of the receiver elements, until effective ones could be built at sizes similar to those of handheld radios, only a few cubic centimeters in volume. The introduction of JFETs and MESFETs did the same to the transmitter side of the systems as well. Now an entire radar, the transmitter, receiver and antenna, could be shrunk into a single "transmitter-receiver module" (TRM) about the size of a carton of milk.

The primary advantage of a AESA over a PESA is that the different modules can operate on different frequencies. Unlike the PESA, where the signal was generated at single frequencies by a small number of transmitters, in the AESA each module broadcasts its own independent signal. This allows the AESA to produce numerous "sub-beams" and actively "paint" a much larger number of targets. Additionally, the solid-state transmitters are able to broadcast effectively at a much wider range of frequencies, giving AESAs the ability to change their operating frequency with every pulse sent out. AESAs can also produce beams that consist of many different frequencies at once, using post-processing of the combined signal from a number of TRMs to re-create a display as if there was a single powerful beam being sent.

Advantages

In addition to the advantages offered by PESAs, notably the lack of mechanical steering and the ability to form multiple beams, AESAs add many capabilities of their own. Among these are the ability to use some of the TRMs for "other purposes", like radar detection, and more importantly, the difficulties that AESAs cause for radar detectors.

Low Probability of Intercept

Radar systems work by sending out a signal and then listening for its echo off distant objects. Each of these paths, to and from the target, is subject to the inverse square law of propagation. That means that a radar's received energy drops with the fourth power of distance, which is why radar systems require high powers, often in the megawatt range, in order to be effective at long range.

The radar signal being sent out is a simple radio signal, and can be received with a simple radio receiver. It is common to use such a receiver in the targets, normally aircraft, to detect radar broadcasts. Unlike the radar unit, which has to send the pulse out and then receive its reflection, the target's receiver does not need the reflection and thus the signal drops off only as the square of distance. This means that the receiver is always at an advantage over the radar in terms of range - it will always be able to detect the signal long before the radar can see the target's echo. Since the position of the radar is extremely useful information in an attack on that platform, this means that radars generally have to be turned off for lengthy periods if they are subject to attack; this is common on ships, for instance.

Turning that received signal into a useful display is the purpose of the "radar warning receiver" (RWR). Unlike the radar, which knows which direction it is sending its signal, the receiver simply gets a pulse of energy and has to interpret it. Since the radio spectrum is filled with noise, the receiver's signal is integrated over a short period of time, making periodic sources like a radar add up and stand out over the random background. Typically RWRs store the detected pulses for a short period of time, and compare their broadcast frequency and pulse repetition frequency against a database of known radars. The rough direction can be calculated using a rotating antenna, or similar passive array, and combined with symbology indicating the likely purpose of the radar - airborne early warning, surface to air missile, etc.

This technique is much less useful against AESA radars. Since the AESA can change its frequency with every pulse, and generally does so using a pseudo-random sequence, integrating over time does not help pull the signal out of the background noise. Nor does the AESA have any sort of fixed pulse repetition frequency, which can also be varied and thus hide any periodic brightening across the entire spectrum. Traditional RWRs are essentially useless against AESA radars.

High jamming resistance

Jamming is likewise much more difficult against an AESA. Traditionally, jammers have operated by determining the operating frequency of the radar and then broadcasting a signal on it to confuse the receiver as to which is the "real" pulse and which is the jammer's. This technique works as long as the radar system cannot easily change its operating frequency. When the transmitters were based on klystron tubes this was generally true, and radars, especially airborne ones, had only a few frequencies to chose among. A jammer could listen to those possible frequencies and select the one being used to jam.

Since an AESA changes its operating frequency with every pulse, and spreads the frequencies across a wide band even in a single pulse, jammers are much less effective. Although it is possible to send out broadband white noise against all the possible frequencies, this means the amount of energy being sent at any one frequency is much lower, reducing its effectiveness. Moreover, AESAs can be switched to a receive-only mode, and use the jamming signals as a powerful source to track its source, something that required a separate receiver in older platforms.

AESAs are so much more difficult to detect, and so much more useful in receiving signals from the targets, that they can broadcast continually and still have a very low chance of being detected. This allows the radar system to generate far more data than if it is being used only periodically, greatly improving overall system effectiveness.

Other advantages

Since each element in a AESA is a powerful radio receiver, active arrays have many roles besides traditional radar. One use is to dedicate several of the elements to reception of common radar signals, eliminating the need for a separate radar warning receiver. The same basic concept can be used to provide traditional radio support, and with some elements also broadcasting, form a very high bandwidth data link. The F-35 uses this mechanism to send sensor data between aircraft in order to provide a synthetic picture of higher resolution and range than any one radar could generate.

AESAs are also much more reliable than either a PESA or older designs. Since each module operates independently of the others, single failures have little effect on the operation of the system as a whole. Additionally, the modules individually operate at low powers, perhaps 40 to 60 watts, so the need for a large high-voltage power supply is eliminated.

Replacing a mechanically scanned array with a fixed AESA mount (such as on the F/A-18E/F Super Hornet) can help reduce an aircraft's overall radar cross-section (RCS), but some designs (such as the Eurofighter Typhoon) forgo this advantage in order to add the limits of mechanically scanning to the limits of electronic scanning and provide a larger angle of coverage.

List of existing systems

US based manufacturers of the AESA radars used in the F22 and Super Hornet include Northrop Grumman and Raytheon. These companies also design, develop and manufacture the transmit/receive modules which comprise the 'building blocks' of an AESA radar. The requisite electronics technology was developed in-house via Department of Defense research programs such as MIMIC Program.

Airborne systems

- Northrop Grumman/Raytheon AN/APG-77, for the F-22 Raptor
- Northrop Grumman AN/APG-80, for the F-16E/F Block 60 Fighting Falcon
- Northrop Grumman AN/APG-81, for the F-35 Joint Strike Fighter
- Northrop Grumman Multirole AESA, for the Boeing Wedgetail (AEW&C)
- Northrop Grumman APY-9, for the E-2D Advanced Hawkeye
- Northrop Grumman SABR, for F-16 Fighting Falcon upgrades
- Raytheon AN/APG-63(V)2 and AN/APG-63(V)3, for the F-15C Eagle and Republic of Singapore's F-15SG
- Raytheon APG-79, for the F/A-18E/F Super Hornet and EA-18G Growler
- Raytheon AN/APQ-181 (AESA upgrade currently in development), for the B-2 Spirit bomber
- AMSAR, research from the European GTDAR consortium, for Eurofighter and Rafale fighter Radar
- Captor-E CAESAR (CAPTOR Active Electronically Scanning Array Radar)
- RBE2-AA Radar à Balayage Electronique 2 - Active Array
- SELEX Seaspray 7000E, for helicopters
- SELEX Vixen 500E
- Mitsubishi Electric Corporation J/APG-1, AESA for the Mitsubishi F-2 fighter
- Ericsson Erieye AEW&C
- Ericsson PS-05/A MK-5 for JAS 39 Gripen. Will be available by 2012.
- Phazotron NIIR Zhuk-AE, for MiG-35
- Tikhomirov NIIP Epaulet-A
- Elta EL/M-2083 aerostat-mounted air search radar
- Elta EL/M-2052, for fighters. Interim candidate for HAL Tejas. Also, suitable for F-15, MiG-29 & Mirage 2000
- Elta EL/M-2075 radar for the IAI Phalcon AEW&C system
- NRIET-designed (Nanjing Research Institute of Electronic Technology) radar mounted on the KJ-2000 AEW&C system
- Toshiba HPS-106, air & surface search radar, for the Kawasaki P-1 maritime patrol aircraft, four antenna arrays.
- Mitsubishi Electric Corporation HPS-104, for the Mitsubishi SH-60

Ground and sea-based systems

- APAR (Active Phased Array Radar): Thales' multifunction radar is the primary sensor of the Royal Netherlands Navy's De Zeven Provinciën class frigates, the

German Navy's Sachsen class frigates, and the Royal Danish Navy's Ivar Huitfeldt class frigates. APAR is the first Active Electronically Scanned Array multifunction radar employed on an operational warship.

- Selex EMPAR (European Multifunction Phased Array Radar)
- Elta EL/M-2080 *Green Pine* ground-based early warning AESA radar
- Elta EL/M-2248 *MF-STAR* multifunction naval radar
- Northrop Grumman AN/TPS-80 Ground/Air Task Oriented Radar (G/ATOR)
- AN/SPY-3 multifunction radar for U.S. DD(X), CG(X) and CVN-21 next-generation surface vessels
- Raytheon U.S. National Missile Defense X-Band Radar (XBR)
- MEADS's fire control radar
- THAAD system fire control radar
- Type-03 Medium Range Surface-to-Air MissileSystem (Chu-SAM,SAM-4) multifunction radar
- BAE Systems Insyte SAMPSON multifunction radar for UK Type 45 destroyers
- FCS-3 Mitsubishi Electric Corporation (Melco)
- OPS-24 Mitsubishi Electric Corporation (The world's first Naval Active Electronically Scanned Array radar)
- J/FPS-3 Japanese main ground-based air defense Radar produced by Melco
- J/FPS-4 Cheaper than J/FPS-3, produced by Toshiba
- J/FPS-5 Japanese ground-based next generation Missile Defense Radar
- J/TPS-102 Self-propelled ground-based radar, cylindrical array antenna, NEC
- JMPQ-P13 Counter-battery radar, Toshiba
- JTPS-P14 Transportable air defence radar, Melco
- JTPS-P16 Firefinder radar, Melco
- CEAFAR CEA Technologies A 4th generation multifunction digital active phased array radar, installed on HMAS Perth and to be installed on all ANZAC class frigates.

Chapter 6

Clutter

Clutter is a term used for unwanted echoes in electronic systems, particularly in reference to radars. Such echoes are typically returned from ground, sea, rain, animals/insects, chaff and atmospheric turbulences, and can cause serious performance issues with radar systems.

Backscatter coefficient

What is considered to be clutter by one user may be a target for another. Usually targets may be considered to be a point scatterer and clutter as extended, covering many range, angle and Doppler cells. The clutter may fill a volume (rain) or be confined to a surface (land). In principle all that is required to estimate the return (backscatter) is a knowledge of the volume or surface illuminated and the echo per unit volume, η, or per unit surface area, $\sigma°$, (the backscatter coefficient).

Clutter or Noise limited radar

In addition to any possible clutter there will also always be noise. The total signal competing with the target return is thus clutter plus noise. In practice there is often either no clutter or clutter dominates and the noise can be ignored. In the first case the radar is said to be Noise Limited, in the second it is Clutter Limited.

Volume Clutter

Rain, hail, snow and chaff are examples of volume clutter. An airborne target, at range R, is within a rainstorm. What is the effect on the detectability of the target?

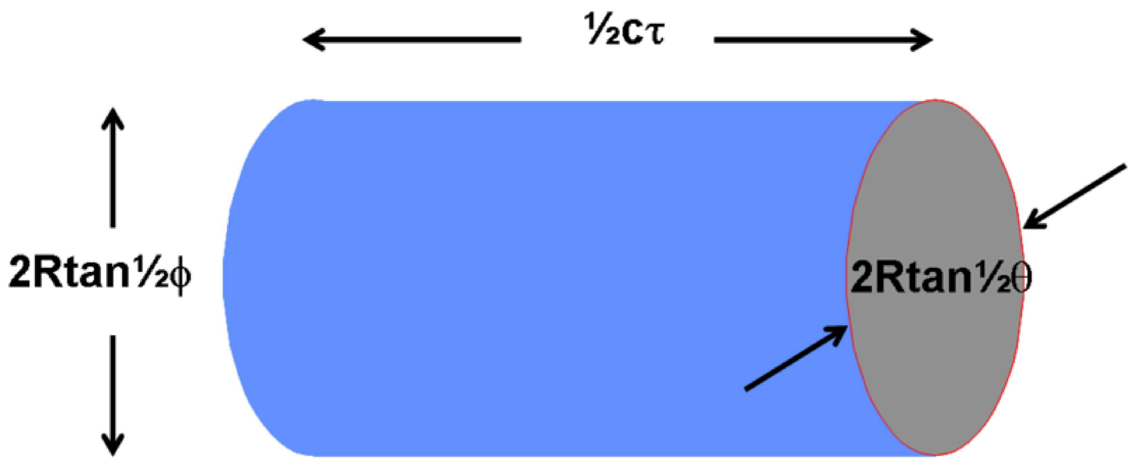


Figure 1. Illustration of illuminated Rain Cell

First find the magnitude of the clutter return. Assume that the clutter fills the cell containing the target, that scatterers are statistically independent and that the scatterers are uniformly distributed through the volume. The clutter volume illuminated by a pulse can be calculated from the beam widths and the pulse duration, Figure 1. If *c* is the velocity of light and τ is the time duration of the transmitted pulse then the pulse returning from a target is equivalent to a physical extent of *c*τ, as is the return from any individual element of the clutter. The azimuth and elevation beamwidths, at a range *R*, are θ / 2 and φ / 2 respectively if the illuminated cell is assumed to have an elliptical cross section.

The volume of the illuminated cell is thus:

$$V_m = \pi R \tan(\theta/2) R \tan(\phi/2)(c\tau/2)$$

For small angles this simplifies to:

$$V_m \approx \frac{\pi}{4}(R\theta)(R\phi)(c\tau/2)$$

The clutter is assumed to be a large number of independent scatterers that fill the cell containing the target uniformly. The clutter return from the volume is calculated as for the normal radar equation but the radar cross section is replaced by the product of the volume backscatter coefficient, η, and the clutter cell volume as derived above. The clutter return is then

$$C = \frac{P_t G_t A_r}{(4\pi)^2 R^4} \frac{\pi}{4}(R\theta)(R\phi)(c\tau/2)\eta \text{ Watts}$$

where

- P_t = transmitter power (Watts)
- G_t = gain of the transmitting antenna
- A_r = effective aperture (area) of the receiving antenna
- R = distance from the radar to the target

A correction must be made to allow for the fact that the illumination of the clutter is not uniform across the beamwidth. In practice the beam shape will approximate to a sinc function which itself approximates to a Gaussian function. The correction factor is found by integrating across the beam width the Gaussian approximation of the antenna. The corrected back scattered power is

$$C = \frac{P_t G_t A_r}{2\log 2 (4\pi)^2 R^4} \frac{\pi}{4} (R\theta)(R\phi)(c\tau/2)\eta \text{ Watts}$$

A number of simpliflying substitutions can be made. The receiving antenna aperture is related to its gain by:

$$A_r = \frac{G\lambda^2}{4\pi}$$

and the antenna gain is related to the two beamwidths by:

$$G = \frac{\pi^2}{\theta\phi}$$

The same antenna is generally used both for transmission and reception thus the received clutter power is:

$$C = \frac{P_t G^2 \lambda^2}{1024(\log 2)\pi^2 R^2} c\tau\eta \text{ Watts}$$

If the Clutter Return Power is greater than the System Noise Power then the Radar is clutter limited and the Signal to Clutter Ratio must be equal to or greater than the Minimum Signal to Noise Ratio for the target to be detectable.

From the radar equation the return from the target itself will be

$$S = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4} \sigma \text{ Watts}$$

with a resulting expression for the signal to clutter ratio of

$$\frac{S}{C} = \frac{1024(\log 2)G\sigma}{(4\pi)^3 R^2 c\tau\eta}$$

The implication is that when the radar is noise limited the variation of signal to noise ratio is an inverse fourth power. Halving the distance will cause the signal to noise ratio to increase (improve) by a factor of 16. When the radar is volume clutter limited, however, the variation is an inverse square law and halving the distance will cause the signal to clutter to improve by only 4 times.

Since

$$G = \frac{\pi^2}{\theta\phi}$$

it follows that

$$\frac{S}{C} = \frac{16(\log 2)G\sigma}{(4\pi)^3 R^2 \theta\phi c\tau\eta}$$

Clearly narrow beamwidths and short pulses are required to reduce the effect of clutter by reducing the volume of the clutter cell. If pulse compression is used then the appropriate pulse duration to be used in the calculation is that of the compressed pulse, not the transmitted pulse.

Problems in calculating Signal to Volume Clutter Ratio

A problem with volume clutter, e.g. rain, is that the volume illuminated may not be completely filled, in which case the fraction filled must be known, and the scatterers may not be uniformly distributed. Consider a beam 10^{o} in elevation. At a range of 10 km the beam could cover from ground level to a height of 1750 metres. There could be rain at ground level but the top of the beam could be above cloud level. In the part of the beam containing rain the rainfall rate will not be constant. One would need to know how the rain was distributed to make any accurate assessment of the clutter and the signal to clutter ratio. All that can be expected from the equation is an estimate to the nearest 5 or 10 dB.

Surface clutter

The surface clutter return depends upon the nature of the surface, its roughness, the grazing angle (angle the beam makes with the surface), the frequency and the polarisation. The reflected signal is the phasor sum of a large number of individual returns from a variety of sources, some of them capable of movement (leaves, rain drops, ripples) and some of them stationary (pylons, buildings, tree trunks). Individual samples of clutter vary from one resolution cell to another (spatial variation) and vary with time for a given cell (temporal variation).

Beam Filling

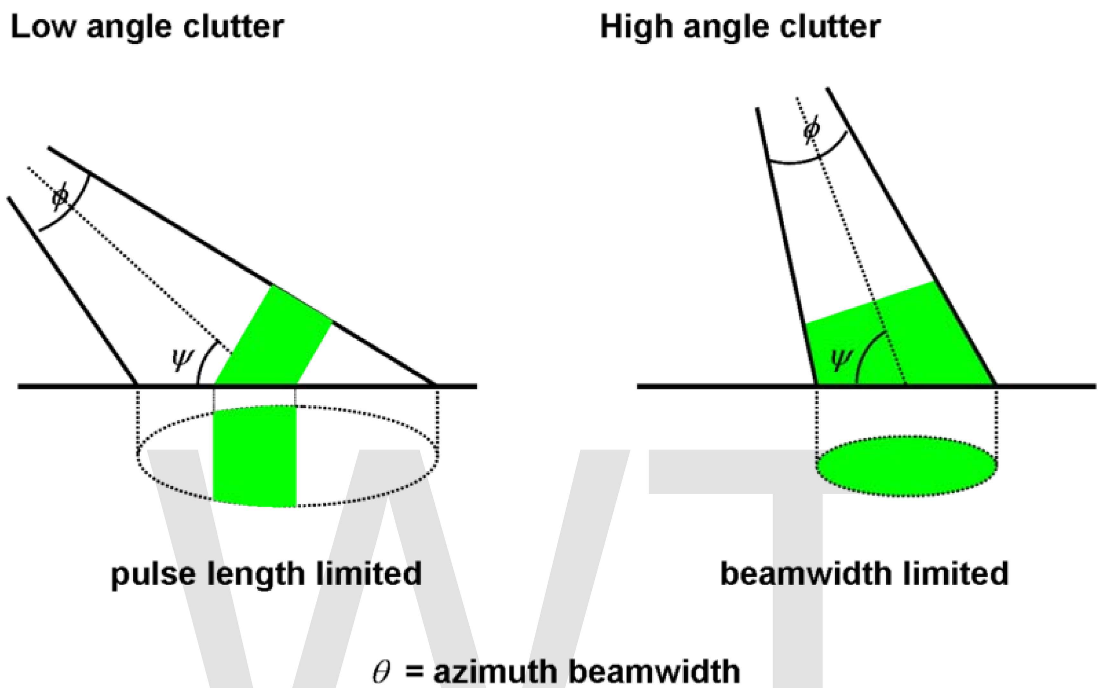


Figure 2. Illustration of High and Low Angle Surface Clutter Illumination

For a target close to the Earth's surface such that the earth and target are in the same range resolution cell one of two conditions are possible. The most common case is when the beam intersects the surface at such an angle that the area illuminated at any one time is only a fraction of the surface intersected by the beam as illustrated in Figure 2.

Pulse Length Limited Case

For the pulse length limited case the area illuminated depends upon the azimuth width of the beam and the length of the pulse, measured along the surface. The illuminated patch has a width in azimuth of

$$2R\tan\theta/2.$$

The length measured along the surface is

$$(c\tau/2)\sec\psi.$$

The area illuminated by the radar is then given by

$$A = 2R(c\tau/2)(\tan\theta/2)\sec\psi$$

For 'small' beamwidths this approximates to

$$A = R(c\tau/2)\theta\sec\psi$$

The clutter return is then

$$C = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4} A\sigma^o \text{ Watts}$$

Substituting for the illuminated area *A*

$$C = \frac{c}{2^7\pi^3}\frac{P_t G^2 \lambda^2}{R^3}\tau\theta\sec\psi\sigma^o \text{ Watts}$$

where σ^o is the back scatter coefficient of the clutter. Converting θ to degrees and putting in the numerical values gives

$$C = 1300\frac{P_t G^2 \lambda^2}{R^3}\tau\theta^o\sec\psi\sigma^o \text{ Watts}$$

The expression for the target return remains unchanged thus the signal to clutter ratio is

$$\frac{S}{C} = \frac{1}{1300}\frac{R^3}{P_t G^2 \lambda^2}\frac{1}{\tau\theta\sec\psi\sigma^o}\frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4}\sigma \text{ Watts}$$

This simplifies to

$$\frac{S}{C} = 4\times 10^{-7}\frac{\cos\psi}{R\tau\theta}\frac{\sigma}{\sigma^o}$$

In the case of surface clutter the signal to clutter now varies inversely with R. Halving the distance only causes a doubling of the ratio (a factor of two improvement).

Problems in calculating clutter for the Pulse length Limited Case

There are a number of problems in calculating the signal to clutter. The clutter in the main beam is extended over a range of grazing angles and the backscatter coefficient depends upon grazing angle. Clutter will appear in the antenna sidelobes, which again will involve a range of grazing angles and may even involve clutter of a different nature.

Beam Width Limited case

The calculation is similar to the previous examples, in this case the illuminated area is

$$A = \pi R^2 \tan^2 \theta/2$$

which for small beamwidths simplifies to

$$A \approx \pi R^2 \theta^2 / 4$$

The clutter return is as before

$$C = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4} A \sigma^o \text{ Watts}$$

Substituting for the illuminated area *A*

$$C = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4} \pi R^2 (\theta/2)^2 \sigma^o \text{ Watts}$$

This can be simplified to:

$$C = \frac{P_t G^2 \lambda^2}{4^4 \pi^2 R^2} \theta^2 \sigma^o \text{ Watts}$$

Converting θ to degrees

$$C = \frac{P_t G^2 \lambda^2}{4^4 R^2} (\theta^o/180)^2 \sigma^o \text{ Watts}$$

The target return remains unchanged thus

$$\frac{S}{C} = \frac{4^4 R^2}{P_t G^2 \lambda^2} (180/\theta^o)^2 \frac{1}{\sigma^o} \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4} \sigma$$

Which simplifies to

$$\frac{S}{C} = 5.25 \times 10^4 \frac{1}{\theta^{o2} R^2} \frac{\sigma}{\sigma^o}$$

As in the case of Volume Clutter the Signal to clutter ratio follows an inverse square law.

General problems in Calculating Surface Clutter

The general significant problem is that the backscatter coefficient cannot in general be calculated and must be measured. The problem is the validity of measurements taken in one location under one set of conditions being used for a different location under different conditions. Various empirical formulae and graphs exist which enable an estimate to be made but the results need to be used with caution.

Chapter 7

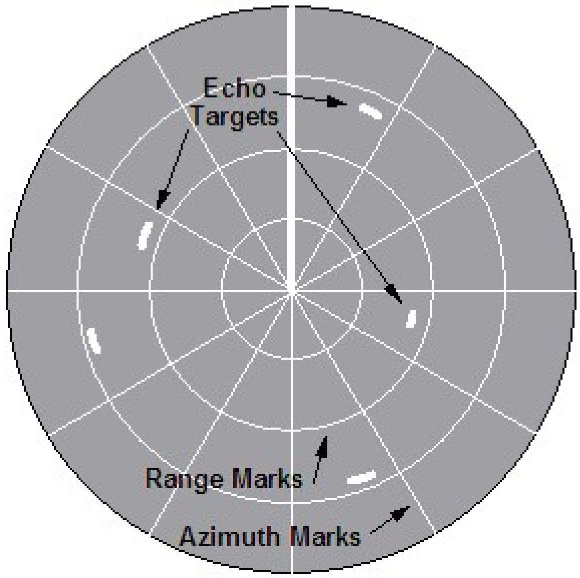
Geo Warping

Here we, explains a technology called **Geo Warping** in the context of real time visualization of geo-referenced radar video data. **Geo Warping** allows displaying radar video consistently with any geographical projection and thus avoids any restrictions when displaying it together with video from multiple radar sources or together with any other geographical data like scanned maps or satellite images which are provided in a particular projection. There are many areas where **Geo Warping** has unique benefits:

- One radar video signal displayed together with maps of different geographical projections. E.g.
  - Mercator
  - UTM
  - stereographic
- Multiple radar video signals displayed simultaneously:
  - Having the computing power to do so on one computer.
  - Adapting the projection of all radar signals allowing the geographically correct display and accurate superimposition of those videos.
- Slant range Correction: a modern 3D radar system can measure the height of a target and hence it is possible to correct the radar video by the real corrected range of the target. Slant Range Correction also allows to compensate the radar tower height e.g. for maritime surveillance radars.

Introduction

Radar video presents the echoes of electromagnetic waves a radar system has emitted and received as reflections afterwards. These echoes are typically presented on a computer screen with a color coding scheme depicting the reflection strength. Two problems have to be solved during such a visualization process. The first problem arises from the fact that typically the radar antenna turns around its position and measures the reflection echo distances from its position in one direction. This effectively means that the radar video data are present in polar coordinates. In older systems the polar oriented picture has been displayed in so called plan position indicators (PPI). The PPI-scope uses a radial sweep pivoting about the center of the presentation. This results in a map-like picture of the area covered by the radar beam. A long-persistence screen is used so that the display remains visible until the sweep passes again. Bearing to the target is indicated by the target's angular position in relation to an imaginary line extending vertically from the sweep origin to the top of the scope. The top of the scope is either true north (when the indicator is operated in the true bearing mode) or ship's heading (when the indicator is operated in the relative bearing mode).

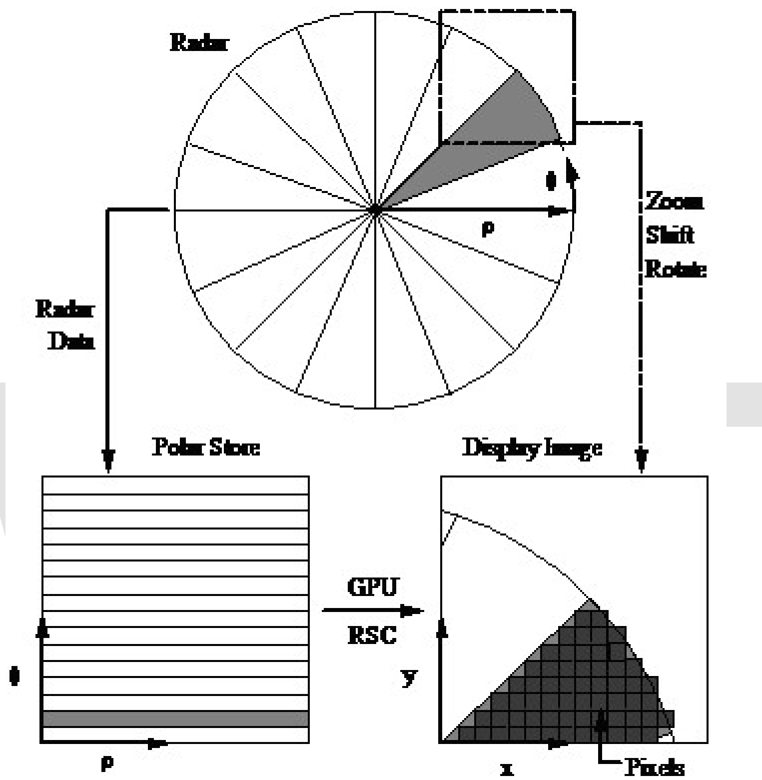


This is a typical plan position indicator (PPI)

For visualization on a modern computer screen the polar coordinates have to be converted into Cartesian coordinates. This process called radar scan conversion is presented with more detail in the next section. The second problem to solve arises from the fact that a radar system is placed in the real world and measures real world echo positions. These echoes have to be displayed together with other real world data like object positions, vector maps and satellite images in a consistent way. All this information refers to the curved earth surface but is dis-played on a flat computer display. Building a link from real world earth positions to dis-play pixels is commonly called geographical referencing or in short geo-referencing. Part of the geo-referencing process is to map the 3D earth surface onto a 2D display. This process of a geographical projection can be performed in many ways, but different data sources have their own 'natural' projection. E.g. Cartesian radar video data from a radar source on the earth surface are geo-referenced by a so called radar projection. When using this radar projection the Cartesian radar video pixels can directly displayed on a computer screen (only being linearly transformed according to the current position on the screen and e.g. the current zoom level). A problem now arises if e.g. also a satellite map shall be shown together with the radar video data. The 'natural' geographical projection of a satellite image would be a satellite projection which depends on the satellite orbit, position and further parameters. Now either the satellite image has to be reprojected to a radar projection or the radar video has to use the satellite projection. This geographical re-projection is also called **geographical warping** or **Geo Warping** where each image pixel has to be transformed from one projection into another. Here we, describes in further detail the Geo Warping of radar video images in real time. It will also show that radar video Geo Warping is done most efficiently when it is integrated with the radar scan conversion process.

Radar Scan Conversion

Here we, describes the principles of the radar scan conversion (RSC) process.



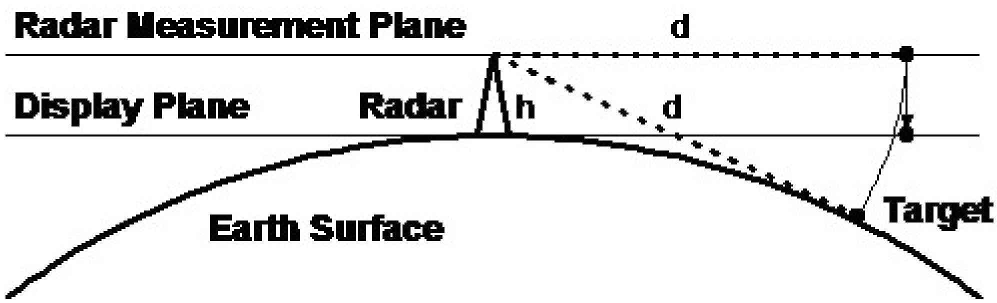
The radar scan conversion process in general as its is done by the OpenGL RSC

The radar supplies its measured data in polar coordinates (ρ,θ) directly from the rotating antenna. ρ defines the target/echo distance and θ the target angle in polar world coordinates. These data are measured, digitized and stored in a polar coordinate *polar store* or *polar pixmap*. The main RSC task is to convert these data to Cartesian (x, y) display coordinates, creating the necessary display pixels. The RSC process is influenced by the current zoom, shift and rotation settings defining which part of the 'world' shall be visible in the display image. As detailed later the RSC process also takes the currently used geographical projection into account when the radar video images are Geo Warped.

The OpenGL RSC is implemented using a reverse scan conversion approach which calculates for every image pixel the most appropriate radar amplitude value in the polar store. This approach generates an optimal image without any artifacts known from forward *spoke fill* algorithms. By applying bi-linear filtering between adjacent pixels in the *polar store* during the conversion process the OpenGL RSC finally achieves a very high visual quality radar display image for every zoom level, creating smooth images of the radar echoes.

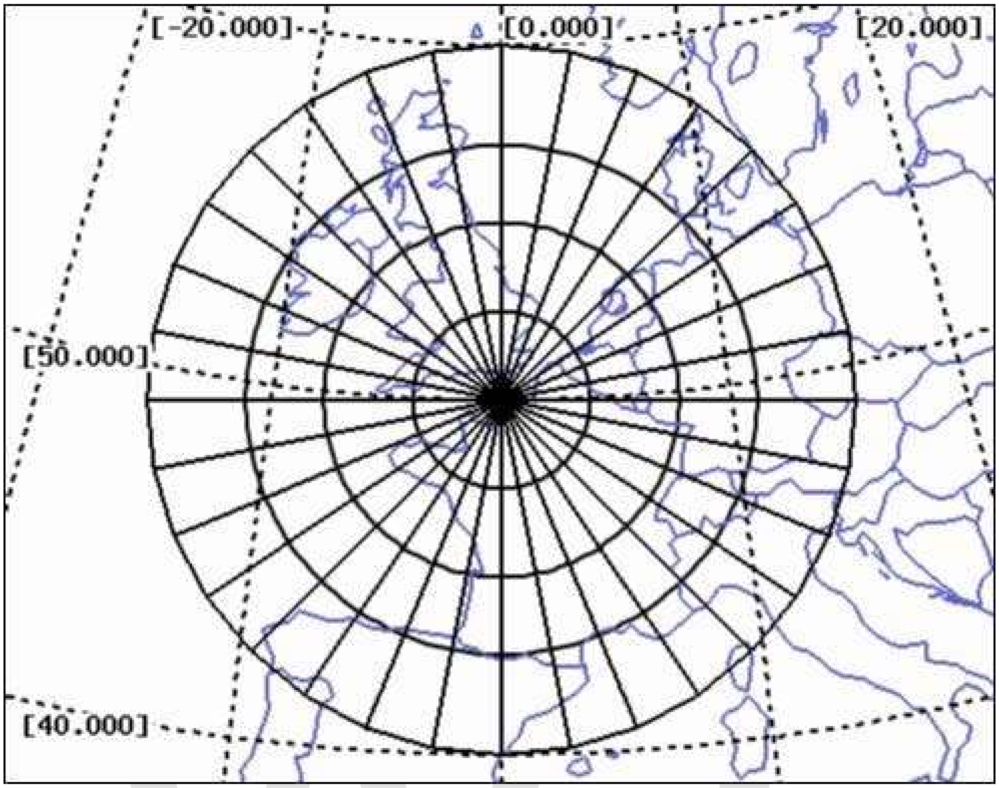
The Radar Projection

After the previous section has explained the radar scan conversion process from real world polar coordinates to cartesian display coordinates, here we will explain how radar video data are geo referenced and displayed on a computer screen.



This figure shows the principles of a radar measurement

The radar sensor is positioned on the earth surface with a height **h** above the ground. It measures the direct distance **d** to the target (and not e.g. the distance the target is away from the radar if one would move on the earth surface). This distance is then used in the display plane after adjustment to the current display zoom level by the radar scan converter (RSC). Now it has to be clarified how the radar video data is geo referenced. This basically means, that if we want to display a geographical real world object (like e.g. a light house) which is at the same real world position as the radar target, that it also shall appear at the same position in the display plane. This is realized by calculating the distance from the radar sensor to the respective real world object and use that distance in the display plane. The position of the real world object is typically given in geographical coordinates (latitude, longitude and height above the earth surface). In other words, using a radar projection with geographical data is done by *simulating* a radar measurement process with the real world objects and use the resulting range and azimuth in the display plane.

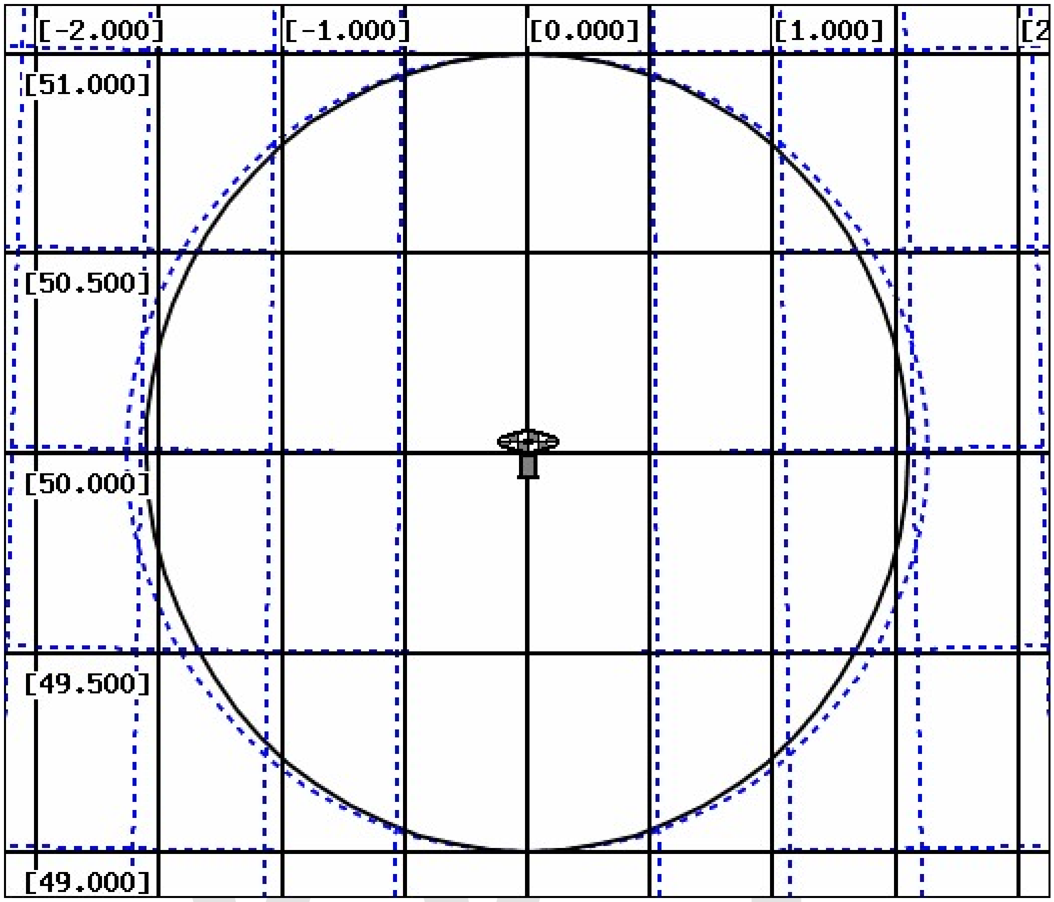


This figure shows an example radar projection with the center of projection (COP) at latitude 50.0° and longitude 0.0° which is also the radar position.

The picture to the right shows an example radar projection with the center of projection (COP) at latitude 50.0° and longitude 0.0° which is also the radar position. The dashed lines are the equal-latitude and equal-longitude lines on top of the background map. The solid lines show equal-range and equal-azimuth with the respect to the radar position. It is a feature of the radar projection that equal-range lines are circles and equal-azimuth lines are straight lines. This is necessary to display radar video consistently with other map data when using a radar projection where the projection center has to be the radar position.

Geo Warping

Here we, explains the actual Geo Warping or re-projection process when applied to radar video in real time. Assume we want to display radar video on top of a satellite image. As an example we use the CIB projection which is used to display satellite data in CIB (Controlled Image Base) format.



Geo Warping Radar to CIB Projection

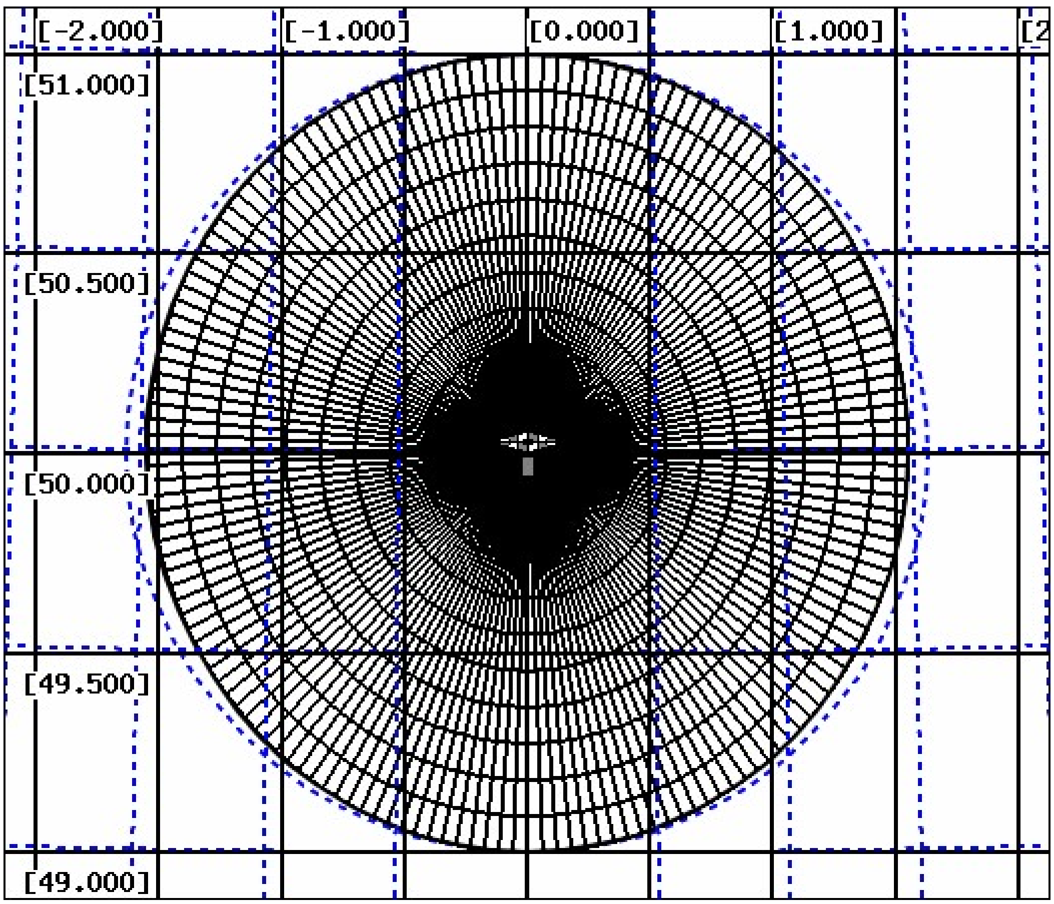
The Figure *Geo Warping Radar to CIB Projection* shows dashed the maximal range circle for a range of 111 km or 60 miles using the radar projection. Such a range is typical for long range coastal surveillance radars. As stated in the last section this is a perfect circle also on the computer screen. The solid line ellipse shows the same range circle for the CIB projection.

Typically the errors occurring without Geo Warping are smallest near the radar position if at least the projection center (COP) coincides with the radar position, as realized in our example. Otherwise the error distribution depends both on the used projection and also on the projection parameters. Thus, in our case the errors are most significant near the maximum radar range. The CIB projection error corrected in east-west direction at half the radar range is 2.6 km and is 5.3 km at the full radar range of 111 km. An error of 5.3 km is quite significant compared to a typical radial radar measurement resolution of 15m.

Coordinate Re-projection

The Figure *Coordinate Re-projection* explains how the radar coordinates have to be transformed to match the CIB projection coordinates. The radar world coordinates correspond to the Cartesian version of the data measured by the radar sensor. Using an inverse radar projection these coordinates are converted into geographic coordinates which represent the radar data posi-tions on the earth surface. These coordinates are then finally projected by the CIB (or any other) projection for displaying on the computer screen.

A problem which arises is that Geo Warping all measured radar video pixels is far too computing resource consuming as to be performed in real time. A possible solution is to use lookup tables for all points on the screen, but the lookup table re-computation after e.g. a display zoom operation still causes a noticeable delay for radar video visualization.



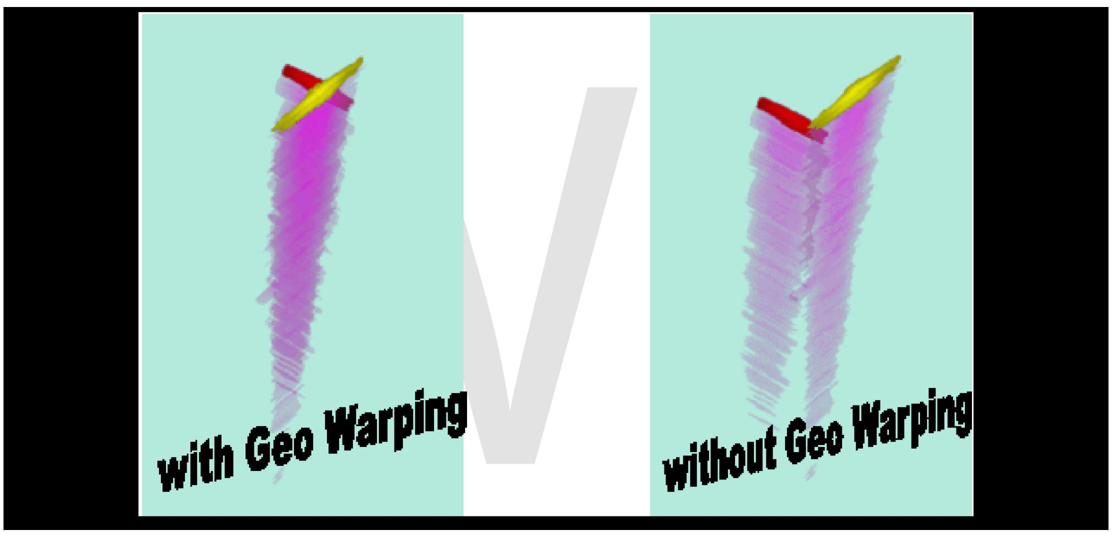
Geo Warping Grid

The Figure *Geo Warping Grid* depicts the solution to the problem. The circular radar coverage area is divided into a circular grid. Only the corner points of the grid are geo warped which drastically reduces the computation time. Coordinates within a grid tile are computed by a weighted bilinear interpolation of the grid corner points. As geographical projections are typically non-linear functions this introduces a certain error for the radar video display position. Keeping this error sufficiently below the radar measurement resolution makes sure that this is no restriction for the radar video display quality. The grid tile size has to be computed once for a radar position and a given projection. Thus, the grid is typically computed once for a static radar and only more often for moving radars e.g. on ships.

The OpenGL radar scan converter does its scan conversion computations on the graphics processor (GPU) to achieve high performance and visual quality. The bi-linear coordinate interpolation mentioned above is done in dedicated hardware on the GPU and therefore causes no overhead for the scan converter.

Example

This example demonstrates how Geo Warping helps to consistently display multiple radar videos.



Example of a radar target shown with and without the effects of Geo Warping

This figure shows the visual effects on the right side without Geo Warping that targets seen by two radars cannot be correctly displayed and it is unclear where the target is actually positioned. The red and yellow target echoes are seen be radars which are about 50km away. The radars are also about 50km away from each other. The semi-transparent pink color depicts the track history.

In this scenario even a radar projection is used but of course the radar projection center (COP) can be only at the position of one of the radars. Even larger inconsistencies can arise if a projection different from a radar projection is used. The geo warped view on the left side shows the consistently displayed radar echoes where both radar echoes are exactly at the real target's position.

Chapter 8

Blip-to-scan Ratio and Conical Scanning

Blip-to-scan ratio

In radar systems, the **blip-to-scan ratio**, or **blip/scan**, is the ratio of the number of times a target appears on a radar display to the number of times it *could* have been seen. Alternately it can be defined as the ratio of the number of scans in which a return is received to the total number of scans.

"Blip" refers to the dots drawn on early warning radars based on plan position indicator (PPI) displays. "Scan" is a single search of the entire sky made by rotating the antenna. Radars with a low blip-to-scan ratio draw only a few reflections from the aircraft, making them more difficult to detect. By flying high and fast the ratio can be further reduced, rendering the aircraft almost invisible. This fact was the primary reason the Lockheed U-2 was replaced by the much faster Lockheed A-12, although upgrades to Soviet radar systems rendered the A-12 vulnerable as soon as it was available.

Radar basics

Early warning radars of the 1950s were little changed from the earliest examples operated by Germany and England during World War II. A radar antenna rotated around its vertical axis to allow it to scan the sky in azimuth (side to side). The antenna is shaped to produce a beam that is narrow from side-to-side to allow it to locate objects accurately in angle, but quite broad vertically, 30 to 40 degrees, in order to scan the entire sky from the horizon up to high altitudes.

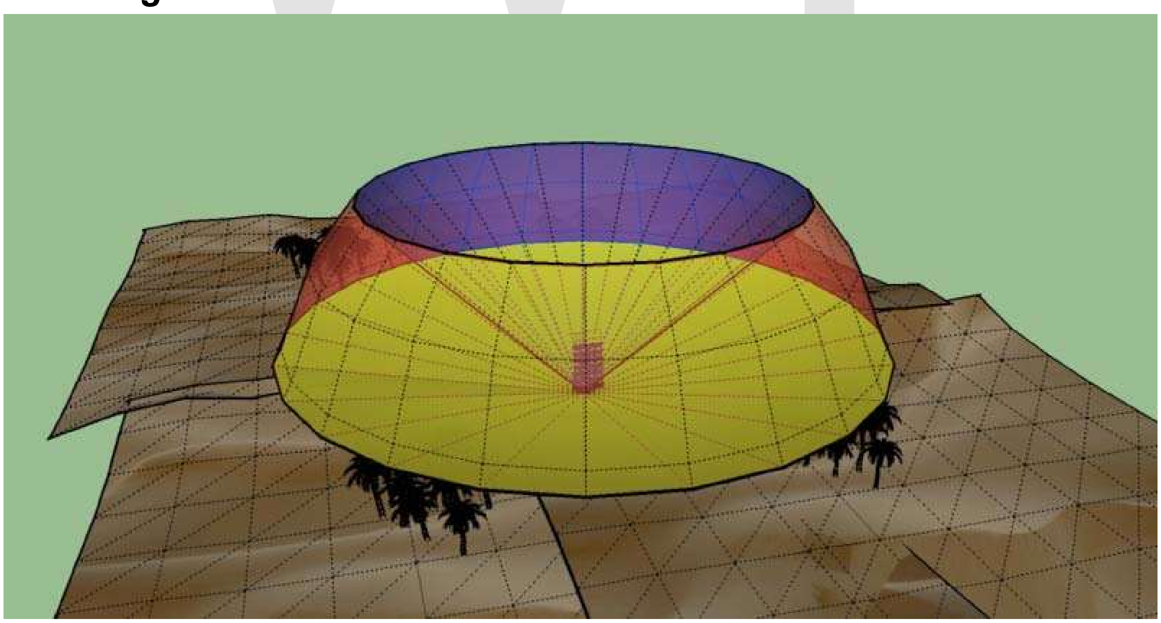
The radar electronics produce a series of pulses of radio energy. These are sent out of the antenna, which then listens for a short period for any reflections before sending out the next pulse. Reflections are amplified and sent to an oscilloscope for display, causing a "blip" on the screen. An encoder in the antenna mount sends the current direction of the antenna to the display, rotating the blips around the face of the display. Distances, determined by the time between sending and receiving the pulses, were displayed with longer ranges being further from the center of the scope. The result is a 2D top-down image of the airspace around the radar.

One key characteristic of any radar is the *pulse repetition frequency* (PRF). Since the radio pulse travels at a finite speed, the speed of light, the time you have to wait for a reflection to return is a function of the range to the target. For instance, a radar designed to have a range of 300 km needs to wait 2 milliseconds (300 km / 300,000 km/s times 2 for there and back) in order to see a reflection at its maximum range. This implies that such a radar can send out at most 500 pulses per second, the PRF. For instance, if it sent out 1000 pulses, it would be impossible to determine if a particular reflection was a target at 150 km from the pulse just sent out, or 300 km from one pulse ago.

Intertwined with the PRF is the length of the pulse, or duty cycle. Longer pulses mean that more energy will be reflected from the target, making it easier to amplify and display. However, the radar system cannot listen for reflections while the pulse is being sent. This means that a radar also has a minimum range, the time it takes for reflections to travel back to the antenna while the pulse is being broadcast. A radar with a 30 km minimum range, for instance, can have pulses no longer than 0.1 ms in duration. For an early warning radar the minimum range is generally not important, so longer pulses are used to maximize the returns.

Further assume that the horizontal beamwidth is one degree, and the antenna rotates once every ten seconds, or 36 degrees a second. An aircraft will be "painted" by the beam for only 1/36 th of a second, as the one degree beam sweeps over it. With a PRF of 500, that means the aircraft will be hit with less than 14 pulses. To become visible on the "slow" displays of the era, a number of these pulses will have to be returned and drawn on the screen. If a number of these pulses are "lost", due to electronics noise or other reasons, the blip may never become visible. This is the blip-to-scan ratio.

Avoiding detection



Radars paint only a portion of the sky with their signal. In this image, the yellow surface represents the lowest angles the radar can aim, based on the need to avoid reflections from local terrain. The purple surface is the maximum angle the antenna can reach, often around 30 to 45 degrees. The red surface is the maximum range of the radar, which is a factor of many design decisions. In this example, an aircraft flying at high altitude would only be detectable for a short time, in the small annular ring between the red and purple surfaces. An aircraft can also approach the radar below the yellow surface.

Consider the target aircraft after the antenna has completed one rotation and returned to the same area of the sky ten seconds later. An aircraft traveling at 1000 km/h will have moved almost three kilometers in that time (1000 km/h = 278 m/s). On a display showing the example radar's entire 300 km radius this represents movement of only 0.5% across the display's face (600 km diameter), producing a tiny line segment between the two dots.

The small movement can aid the operator in interpreting the display. Radars are often filled with dots of random noise known as "clutter", but rarely do they produce the same slowly-moving line as an aircraft. Additionally, the phosphor coatings on the displays are deliberately chosen to have a half life on the order of a few scans, allowing the returns from any one target to "add up" and make them much more obvious on the display.

But if the target speed is increased its movement becomes more pronounced. At Mach 3 (3500 km/h at 25,000 m) the same ten seconds of movement represents over 1.5% of the display's face. At this point the slowly moving dot turns into a series of individual spots, which can easily be mistaken for clutter. Additionally, since the spots are separated by a distance on the tube, the returns no longer "add up" on the display, making them as dim as the other noise.

Of course an operator seeing a straight line of small dots across their screen might eventually "see" the target. To frustrate even this, aircraft were designed to fly as high as possible. Recall that the radar's scanning beam is fan-shaped and spread vertically across an angle. The beam only scans high altitudes at long ranges, and a large volume of airspace above the radar is out of sight. This means that there is only a ring-shaped area at long range where a high-altitude aircraft would be visible. Crossing this area quickly would result in only a few dots, hopefully not enough to become obvious.

And thus the concept of using the blip/scan to avoid detection. A high-speed, high-altitude aircraft could fly over early warning radars and never be seen. Even if it became visible, the small number of returns and fast movement across the operator's display would make manual calculation of an intercept extremely difficult.

Aircraft projects

Blip/scan spoofing was discovered during the late 1950s at a time when ground-controlled interception of manned interceptors was the only practical anti-bomber technique. Before the U-2 became operational in June 1956, CIA officials had estimated that its life expectancy for flying safely over the Soviet Union would be between 18 months and two years. After overflights began and the Soviets demonstrated the capability of tracking and attempting to intercept the U-2, this estimate was adjusted downward; in August 1956, Richard Bissell reduced the number to six months.

A replacement for the U-2 had been under consideration even before their operational missions began. Originally these studies focused entirely on the reduction of the radar cross section, but after the idea of spoofing the blip/scan was introduced in 1957, the plans were changed to study high-speed designs instead. Lockheed calculated that in order to be effective against known Soviet radars, an aircraft would have to travel between Mach 2 and Mach 3 at 90,000 ft and have an RCS of about 10 square meters. This led to a number of proposals which were down-selected to the Lockheed A-12 and Convair KINGFISH.

It was during the development of these aircraft that it was realized that using blip/scan avoidance was problematic. It was discovered that the high-temperature exhaust of these aircraft engines reflected radar energy at certain wavelengths, and persisted in the atmosphere for some time. It would be possible for the Soviets to modify their radars to use these frequencies, and thereby track the targets.

It was also realized that since blip/scan avoidance relied on a problem in the *displays*, changing these displays could render the technique moot. This was particularly worrying, because the USAF was in the process of introducing precisely this sort of display as part of their SAGE project. SAGE recorded the radar returns in a computer, which then drew the targets on the display as an icon, whose brightness was independent of the physical return.

Finally, the introduction of the first effective anti-aircraft missiles dramatically changed the entire concept. Radars for plotting an air intercept were generally made as long-range as possible, in order to give the operators ample time to guide their aircraft as the targets slowly moved across the display. This led to low blip/scan ratios. Missiles, on the other hand, had radars with maximum ranges only slightly longer than the missile's range, about 40 km in the case of the SA-2 Guideline. They had much higher PRF's, and as a result the blip/scan problems were greatly reduced. They still had the problem of finding the target in time to prepare for an attack and launch, but this was by no means as difficult as guiding a manned aircraft onto the same target. This point was alarmingly demonstrated in the U-2 Crisis of 1960.

By the time the A-12 was operational in the early 1960s the blip/scan technique was no longer considered useful. The A-12 never flew over the USSR (although it came close to doing so) and was limited to missions against other countries, like Vietnam. Even here the performance of the aircraft proved questionable, and A-12s were attacked by SA-2 missiles on several occasions, receiving minor damage in one case.

Conical scanning

Conical scanning is a system used in early radar units to improve their accuracy, as well as making it easier to steer the antenna properly to point at a target. Conical scanning is similar in concept to the earlier lobe switching concept used on some of the earliest radars, and many examples of lobe switching sets were modified in the field to conical scanning during World War II, notably the German Würzburg radar. With simple electronics, antenna guidance can be made entirely automatic, although potential failure modes and susceptibility to deception jamming led to the replacement of conical scan systems with monopulse radar sets.

Concept

A basic radar antenna commonly has a beam width of a few degrees. While this is fine for locating the target in the early warning role, it is not nearly accurate enough for gun laying, which demands accuracies on the order of 0.1 degrees. It is possible to improve the beam width through the use of larger antennas, but this is often impractical.

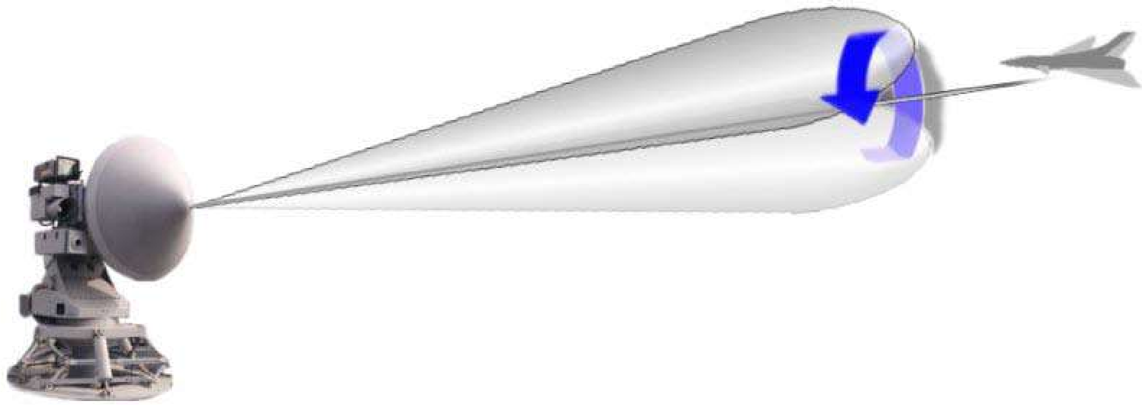
In order to monitor the direction of a designated target, it is only necessary to keep the aerial pointing directly at the target. Knowledge of the pointing direction of the aerial then naturally gives knowledge of the target direction. In order to keep a single target tracker staring at the designated target automatically, it is necessary to have a control system that keeps the aerial beam pointing at it regardless of the target motion. An apparently obvious method for doing this is to utilise the idea that the radar will get maximum received power when the target is in the beam centre. Circuitry designed to monitor any fall off in received signal strength could be used to control a servo motor that steers the aerial to follow the target motion. There are three difficulties with this method:

a. The radar will have no information as to which direction the target has moved, and therefore no indication as to which way to drive the aerial.

b. As the target moves away from the beam centre, the received power changes only very slowly at first. Thus the system is rather insensitive to aerial pointing errors.

c. Real variations in target echo power caused by scintillation will be interpreted as target motion.

Conical Scanning



Conical scanning concept. The radar beam is rotated in a small circle around the "boresight" axis, which is pointed at the target. The circle is small enough so the target is within the edge of the "lobe" of the radar beam and reflects a weak signal back. If the target is in the center of the circle, on the boresight axis, the reflected signal will have a constant strength as the beam rotates around it. However, if the target moves to one side of the circle the reflected signal will be stronger when the beam reaches that side of the circle, and weaker when the beam is on the other side, so the return signal strength will oscillate as the beam is rotated. For example, if the target moves up, when the beam reaches the top of its circle the target will be closer to the center of the lobe and will reflect a stronger signal than when the beam is at the bottom of its circle. From this changing return signal the direction the target has moved is electronically calculated, and the boresight axis is automatically moved to follow the target.

Conical scanning addresses this problem by "moving" the radar beam slightly off center from the antenna's midline, and then rotating it. Given an example antenna that generates a beam of 2 degrees width – fairly typical – a conical scanning radar might move the beam 1.5 degrees to one side of the centerline by offsetting the feed slightly. The resulting pattern, at any one instant in time, covers the midline of the antenna for about 0.5 degrees, and 1.5 degrees to the side. By spinning the feed horn with a motor, the pattern becomes a cone centered on the midline, extending 3 degrees to the sides in our example.

The key concept is that a target located at the midline point will generate a constant return no matter where the lobe is currently pointed, whereas if it is to one side it will generate a strong return when the lobe is pointed in that general direction and a weak one when pointing away. Additionally the portion covering the centerline is near the edge of the radar lobe, where sensitivity is falling off rapidly. An aircraft centered in the beam is in the area where even small motions will result in a noticeable change in return, growing much stronger along the direction the radar needs to move. The antenna control system is arranged to move the antenna in azimuth and elevation such that a constant return is obtained from the aircraft being tracked. Whilst use of the lobe alone might allow an operator to "hunt" for the strongest return and thus aim the antenna within a degree or so in that "maximum return" area at the center of the lobe, with conical scanning much smaller movements can be detected, and accuracies under 0.1 degree were possible.

Construction

There are two ways to cause the redirection of the beam from the antenna's midline. The first is referred to as a ***rotated*** feed. As its name suggests, a feed horn is set just off the parabolic focal point which causes the energy to focus slightly off the antenna midline. The feed is then rotated around the focal point of the paraboloid to produce the conical rotation. The other system is a ***nutated*** feed. A nutated feed offsets the antenna at an angle to a fixed feed horn, and then rotates the antenna. A variation of a nutated feed makes the feed move in a small circle, rapidly and continuously changing the pointing direction of the beam. In this latter type, neither the feed nor the antenna revolves around the pointing axis of the antenna; only the pointing direction changes, tracing out a narrow cone.

The primary difference between the two basic schemes is in polarization. As the feed horn in the rotated process spins, the polarization changes with the rotation and will thus be 90 degrees off in polarization when the feed is 90 degrees off its initial axis. As the feed horn is fixed in nutated feeds, no polarization changes occur. Most early systems used a rotated feed, due to its mechanical simplicity, but later systems often used nutated feeds in order to use the polarization information.

In the U.S. Navy Mk. 25 gun fire control radar, spiral scan mode aided target acquisition. Basically conical scan (of the non-revolving nutating feed type), the size of the scan cone cyclically increased and decreased roughly twice a second. The scanned area was several degrees, in all. (Once the target was acquired, the operator switched to conical scan for tracking.)

Since the lobe is being rotated around the midline of the antenna, conical scanning is only really appropriate for antennas with a circular cross section. This was the case for the Würzburg, which operated in the microwave region. Most other forces used much longer-wavelength radars that would require paraboloid antennas of truly enormous size, and instead used a "bedspring" arrangement of many small dipole antennas arranged in front of a passive reflector. To arrange conical scanning on such a system would require all of the dipoles to be moved, an impractical solution. For this reason the US Army simply abandoned their early gun laying radar, the SCR-268. This was not particularly annoying, given that they were in the process of introducing their own microwave radar in the aftermath of the Tizard Mission, the SCR-584.

Automatic guidance for the antenna, and thus any slaved guns or weapons, can be added to a conical scan radar without too much trouble. The control system has to steer the antenna such that a constant amplitude return is received from the target.

Unfortunately there are a number of factors that can dramatically change the reflected signal. For instance, changes in the target aircraft's direction can present different portions of the fuselage to the antenna, and dramatically change the amount of signal being returned. In these cases, a conical scan radar might interpret this change in strength as a change in position. For instance, if the aircraft were to suddenly "brighten" when it was off-axis to the left, the circuitry might interpret this as being off to the right if the change occurs when the lobe is aligned in that direction. This problem can be solved by using two simultaneous overlapping receiver beams leading to the monopulse radar, so-named because it always compares signal strength from a single pulse against itself, thereby eliminating problems with all but impossibly fast changes in signal strength.

Conical Scan Receive Only (COSRO)

COSRO systems do not modify the transmit signal sent from the antenna.

Antenna waveguide in COSRO systems includes an RF received feedhorn structure that produces a left/right RF receive sample and an up/down RF receive sample. These two signals are multiplexed inside a waveguide device that has a rotating vane. The output of the multiplex device is a single RF signal and two position signals that indicate left/right and up/down.

The COSRO technique does not transmit any signals that indicate the position of the rotating vane.

Antenna Sampling

RF receive signals from multiple transmit pulses are combined mathematically to create a vertical and horizontal signal. The vertical signal is created by adding RF samples when the vane/feedhorn is in the up direction and subtracting RF samples when the vane/feedhorn is in the down direction. The horizontal signal is created by adding RF samples when the vane/feedhorn is in the left direction and subtracting RF samples when the vane/feedhorn is in the right direction.

This produces a pair of angle error signals used to drive antenna positioning drive motors.

Jamming

Conical scan radars can be easily jammed. If the target knows the general operating parameters of the radar, it is possible to send out a false signal timed to grow and fade in the same pattern as the radar lobe, but inverted in strength. That is, the false signal is at its strongest when the radar signal is the weakest (the lobe is on the "far side" of the antenna compared to the aircraft), and weakest when the signal is the strongest (pointed at the aircraft). When added together with the "real" signal at the radar receiver, the resulting signal is "always strong", so the control system cannot make an accurate estimate as to where in the lobe pattern the target is located.

Actually accomplishing this in hardware is not as difficult as it may sound. If one knows that the signal is rotated at 25 RPM, as it was in the Würzburg radar, the jammer is built to fade from maximum to zero at the same speed, 25 times a second. Then all that is needed is to sync the signals up, which is accomplished by looking for the low point in the signal (which is generally easier to find) and triggering the pattern at that point. This system, known as **inverse gain jamming**, was used operationally by the Royal Air Force against the Würzburg radar during WWII.

It is possible to arrange a radar so the lobes are not being moved in the broadcaster, only the receiver. To do this, one adds a second antenna with the rotating lobe for reception only, a system known as **COSRO**, for *Conical Scan on Receive Only* (compare to **LORO**, a similar system used against lobe switching radars). Although this denied lobing frequency information to the jammer in the aircraft, it was still possible to simply send out random spikes and thereby confuse the tracking system (or operator). This technique, called **SSW** for *Swept Square Wave*, doesn't protect the aircraft with the same sort of effectiveness as inverse gain, but is better than nothing and often fairly effective.

Chapter 9

Frequency Agility and Bistatic Radar

Frequency agility

Frequency agility is the ability of a radar system to quickly shift its operating frequency to account for atmospheric effects, jamming, mutual interference with friendly sources, or to make it more difficult to locate the radar broadcaster through radio direction finding. The term can also be applied to other fields, including lasers or traditional radio transceivers using frequency-division multiplexing, but it remains most closely associated with the radar field and these other roles generally use the more generic term "frequency hopping".

Description

Jamming

Radar systems generally operate by sending out short pulses of radio energy and then turning off the broadcaster and listening for the returning echoes from various objects. Because efficient signal reception requires careful tuning throughout the electronics in the transceiver, each operating frequency required a dedicated transceiver. Due to the size of the tube-based electronics used to construct the transceivers, early radar systems, like those deployed in World War II, were generally limited to operating on a single frequency. Knowing this operating frequency gives an adversary enormous power to interfere with radar operation or gather further intelligence.

The British used the frequency information about the Würzburg radar gathered in Operation Biting to produce "Window", aluminum foil strips cut to 1/2 the length of the wavelength of the Würzburg, rendering it almost useless. They also produced jammer units, "Carpet" and "Shivers", that broadcast signals on the Würzburg's frequency, producing confusing displays that were useless for aiming. Post-war calculations estimated these efforts reduced the combat effectiveness of the Würzburg by 75%. These countermeasures forced the Germans to upgrade thousands of units in the field to operate on different frequencies.

Knowing the frequency of the Würzburg also helped the British in their attempts to locate the systems using radio direction finders, allowing aircraft to be routed around the radars, or at least be kept at longer distances from them. It also helped them to find new operating frequencies as they were introduced, by selecting the location of known installations when they disappeared and singling them out for further study.

Agility

A radar system that can operate on several different frequencies makes these countermeasures more difficult to implement. For instance, if a jammer is developed to operate against a known frequency, changing that frequency in some of the in-field sets will render the jammer ineffective against those units. To counter this, the jammer has to listen on both frequencies, and broadcast on the one that particular radar is using.

To further frustrate these efforts, a radar can rapidly switch between the two frequencies. No matter how quickly the jammer responds, there will be a delay before it can switch and broadcast on the active frequency. During this period of time the aircraft is unmasked, allowing detection. In its ultimate incarnation, each radar pulse is sent out on a different frequency and therefore renders single-frequency jamming almost impossible. In this case the jammers are forced to broadcast on every possible frequency at the same time, greatly reducing its output on any one channel. With a wide selection of possible frequencies, jamming can be rendered completely ineffective.

Additionally, having a wide variety of frequencies makes ELINT much more difficult. If only a certain subset of the possible frequencies are used in normal operation the adversary is denied information on what frequencies might be used in a wartime situation. This was the idea behind the Type 85 radar in the Linesman/Mediator network in the United Kingdom. The Type 85 had twelve klystrons that could be mixed to produce sixty output frequencies, but only four of the klystrons were used in peacetime, in order to deny the Soviet Union any information about what signals would be used during a war.

Improving electronics

One of the primary reasons that early radars did not use more than one frequency was the size of their tube based electronics. As their size was reduced through improved manufacturing, even early systems were upgraded to offer more frequencies. These, however, were not generally able to be switched on the fly through the electronics itself, but were controlled manually and thus were not really agile in the modern sense.

"Brute force" frequency agility, like the Linesman, was common on large early warning radars but less common on smaller units where the size of klystrons remained a problem. In the 1960s solid state components dramatically decreased the size of the receivers, allowing several solid-state receivers to fit into the space formerly occupied by a single tube-based system. This space could be used for additional broadcasters and offer some agility even on smaller units.

Passive electronically scanned array (PESA) radars, introduced in the 1960s, used a single microwave source and a series of delays to drive a large number of antenna elements (the array) and electronically steer the radar beam by changing the delay times slightly. The development of solid-state microwave amplifiers, JFETs and MESFETs, allowed the single klystron to be replaced by a number of separate amplifiers, each one driving a subset of the array but still producing the same amount of total power. Solid-state amplifiers can operate at a wide range of frequencies, unlike a klystron, so solid-state PESAs offered much greater frequency agility, and were much more resistant to jamming.

The introduction of active electronically scanned arrays (AESAs) further evolved this process. In a PESA the broadcast signal is a single frequency, although that frequency can be easily changed from pulse to pulse. In the AESA, each element is driven at a different frequency (or at least a wide selection of them) even within a single pulse, so there is no high-power signal at any given frequency. The radar unit knows which frequencies were broadcast, and amplifies and combines only those return signals, thereby reconstructing a single powerful echo on reception. An adversary, unaware of which frequencies are active, has no signal to see, making detection on radar warning receivers extremely difficult.

Modern radars like the F-35's AN/APG-81 use thousands of broadcaster/receiver modules, one for each antenna element.

Other advantages

The reason that several cell phones can be used at the same time in the same location is due to the use of frequency hopping. When the user wishes to place a call, the cell phone uses a negotiation process to find unused frequencies among the many that are available within its operational area. This allows users to join and leave particular cell towers on-the-fly, their frequencies being given up to other users.

Frequency agile radars can offer the same advantages. In the case of several aircraft operating in the same location, the radars can select frequencies that are not being used in order to avoid interference. This is not as simple as the case of a cell phone, however, because ideally the radars would change their operating frequencies with every pulse. The algorithms for selecting a set of frequencies for the next pulse cannot be truly random if one wants to avoid all interference with similar systems, but a less-than-random system is subject to ELINT methods to determine the pattern.

Another reason for adding frequency agility has nothing to do with military use; weather radars often have limited agility to allow them to strongly reflect off rain, or alternately, to see through it. By switching the frequencies back and forth, a composite image of the weather can be built up.

Bistatic radar

Bistatic radar is the name given to a radar system which comprises a transmitter and receiver which are separated by a distance that is comparable to the expected target distance. Conversely, a radar in which the transmitter and receiver are collocated is called a **monostatic radar**.

Specific classes of bistatic radar

Pseudo-monostatic radars

Some radar systems may have separate transmit and receive antennas, but if the angle subtended between transmitter, target and receiver (the bistatic angle) is close to zero, then they would still be regarded as monostatic or **pseudo-monostatic**. For example, some very long range HF radar systems may have a transmitter and receiver which are separated by a few tens of kilometres for electrical isolation, but as the expected target range is of the order 1000-3500 km, they are not considered to be truly bistatic and are referred to as pseudo-monostatic.

Forward scatter radars

In some configurations, bistatic radars may be designed to operate in a fence-like configuration, detecting targets which pass between the transmitter and receiver, with the bistatic angle near 180 degrees. This is a special case of bistatic radar, known as a **forward scatter radar**, after the mechanism by which the transmitted energy is scattered by the target. In forward scatter, the scattering can be modeled using Babinet's principle and is a potential countermeasure to stealth aircraft as the radar cross section (RCS) is determined solely by the silhouette of the aircraft seen by the transmitter, and is unaffected by stealth coatings or shapings. The RCS in this mode is calculated as $\sigma=4\pi A^2/\lambda^2$, where A is the silhouette area and λ is the radar wavelength. However, target location and tracking is very challenging in forward scatter radars, as the information content in measurements of range, bearing and Doppler becomes very low (all these parameters tend to zero, regardless of the location of the target in the fence).

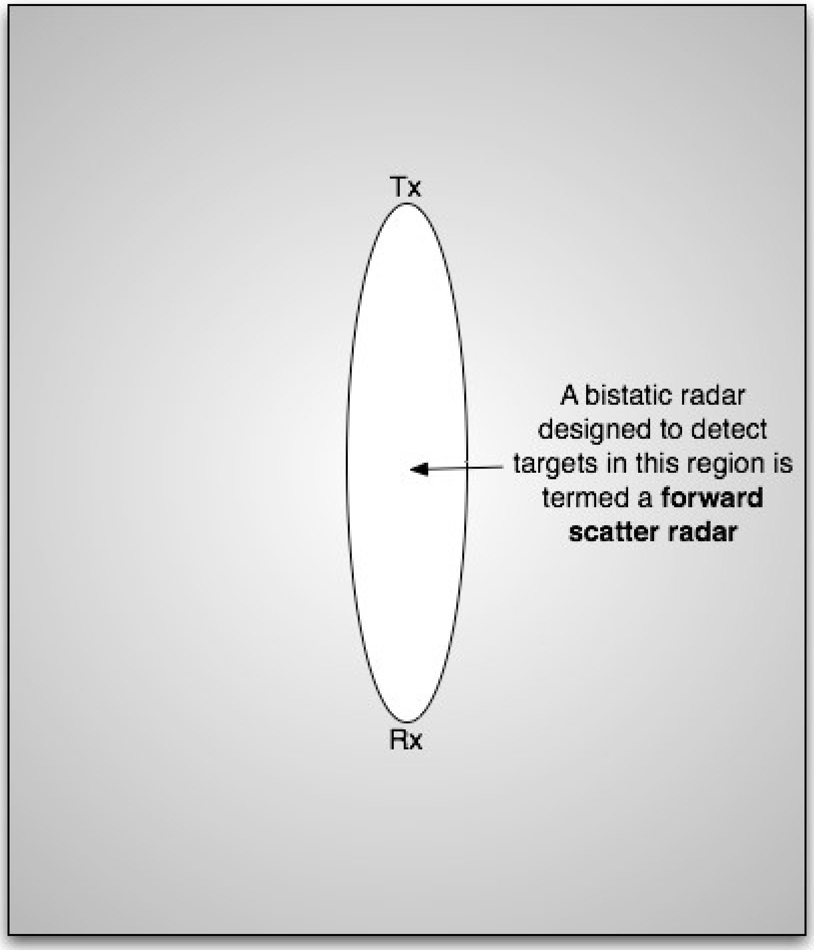


Illustration of forward scatter geometry

Multistatic radar

A multistatic radar system is one in which there are at least three components - for example, one receiver and two transmitters, or two receivers and one transmitter, or multiple receivers and multiple transmitters. It is a generalisation of the bistatic radar system, with one or more receivers processing returns from one or more geographically separated transmitters.

Passive radar

A bistatic or multistatic radar that exploits non-radar transmitters of opportunity is termed a **passive radar** or **passive coherent location** system or **passive covert radar**.

Advantages and disadvantages

The principal advantages of bistatic and multistatic radar include:

- Lower procurement and maintenance costs (if using a third party's transmitter)
- Operation without a frequency clearance (if using a third party's transmitter)
- Covert operation of the receiver
- Increased resilience to electronic countermeasures as waveform being used and receiver location are potentially unknown
- Possible enhanced radar cross section of the target due to geometrical effects

The principal disadvantages of bistatic and multistatic radar include:

- System complexity
- Costs of providing communication between sites
- Lack of control over transmitter (if exploiting a third party transmitter)
- Harder to deploy
- Reduced low-level coverage due to the need for line-of-sight from several locations

Chapter 10

Racon and Ground-penetrating Radar

Racon

Racon signal as seen on a radar screen. This beacon transmits the letter "Q" in Morse code.

A **Racon** is a radar transponder commonly used to mark maritime navigational hazards. The word is a portmanteau of RAdar and beaCON.

When a racon receives a radar pulse, it responds with a signal on the same frequency which puts an image on the radar display. This takes the form of a short line of dots and dashes forming a Morse character radiating away from the location of the beacon on the normal plan position indicator radar display. The length of the line usually corresponds to the equivalent of a few nautical miles on the display.

Within the United States, the United States Coast Guard operates about 80 racons, and other organisations also operate them, for example the owners of oil platforms. Their use for purposes other than aids to navigation is prohibited, and they are used to mark:

- lighthouses and navigation buoys

    - by far the majority are on buoys rather than lighthouses. For example, at Boston Harbor, only the Boston Lighted Whistle Buoy B and the North Channel Entrance Lighted Whistle Buoy NC have racons (showing "B" and "N", respectively)
- navigable spans under bridges such as
    - Arthur Ravenel Bridge
    - Golden Gate Bridge
    - San Francisco – Oakland Bay Bridge (three racons)
- to identify centre lines and turning points
- offshore oil platforms and other structures
    - including approximately 35 in the Gulf of Mexico
- environmentally-sensitive areas such as coral reefs

In other parts of the World they are also used to indicate:

- temporary, new and uncharted hazards (with a Morse character "D")
- as leading line racons

A United States Coast Guard technician prepares a racon beacon for installation at Fowey Rocks Light southeast of Miami.

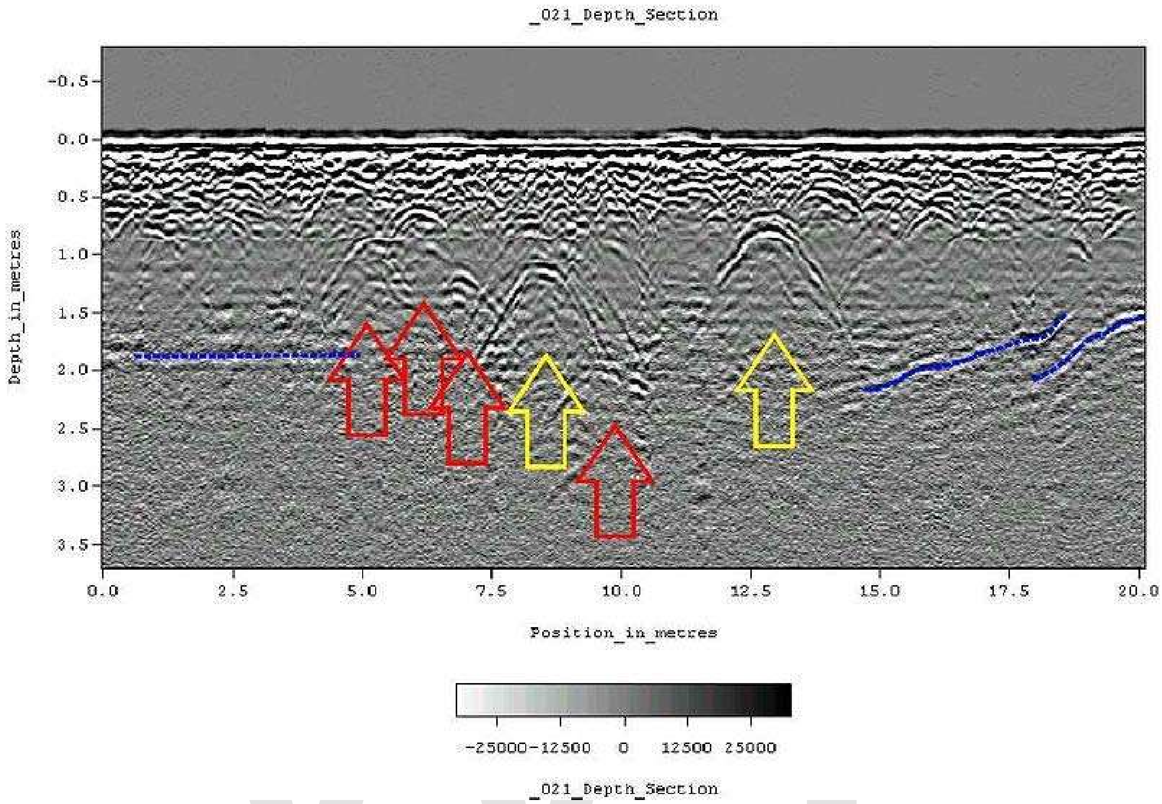
Their characteristics are defined in the *ITU-R Recommendation M.824, Technical Parameters of Radar Beacons (RACONS)*. Racons usually operate on the 9320 MHz to 9500 MHz marine radar band (X-band), and most also operate on the 2920 MHz to 3100 MHz marine radar band (S-band). Modern racons are frequency-agile; they have a wideband receiver that detects the incoming radar pulse, tunes the transmitter and responds with a 25 microsecond long signal within 700 nanoseconds.

Older racons operate in a slow sweep mode, in which the transponder sweeps across the X-band over 1 or 2 minutes. It only responds if it happens to be tuned to the frequency of an incoming radar signal at the moment it arrives, which in practice means it responds only around 5% of the time.

To avoid the response masking important radar targets behind the beacon, racons only operate for part of the time. In the United Kingdom, a duty cycle of about 30% is used — usually 20 seconds in which the racon will respond to radar signals is followed by 40 seconds when it will not, or sometimes 9 seconds on and 21 seconds off (as in the case of the Sevenstones Lightship). In the United States a longer duty cycle is used, 50% for battery-powered buoys (20 seconds on, 20 seconds off) and 75% for on-shore beacons.

Ramarks are wide-band beacons which transmit continuously on the radar bands without having to be triggered by an incoming radar signal. The transmission forms a line of Morse characters on the display radiating from the centre of the display to its edge. They are not used in the United States.

Ground-penetrating radar



A ground-penetrating radargram collected on an historic cemetery in Alabama, USA. Hyperbolic reflections indicate the presence of reflectors buried beneath the surface, possibly associated with human burials.

Ground-penetrating radar (**GPR**) is a geophysical method that uses radar pulses to image the subsurface. This nondestructive method uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum, and detects the reflected signals from subsurface structures. GPR can be used in a variety of media, including rock, soil, ice, fresh water, pavements and structures. It can detect objects, changes in material, and voids and cracks.

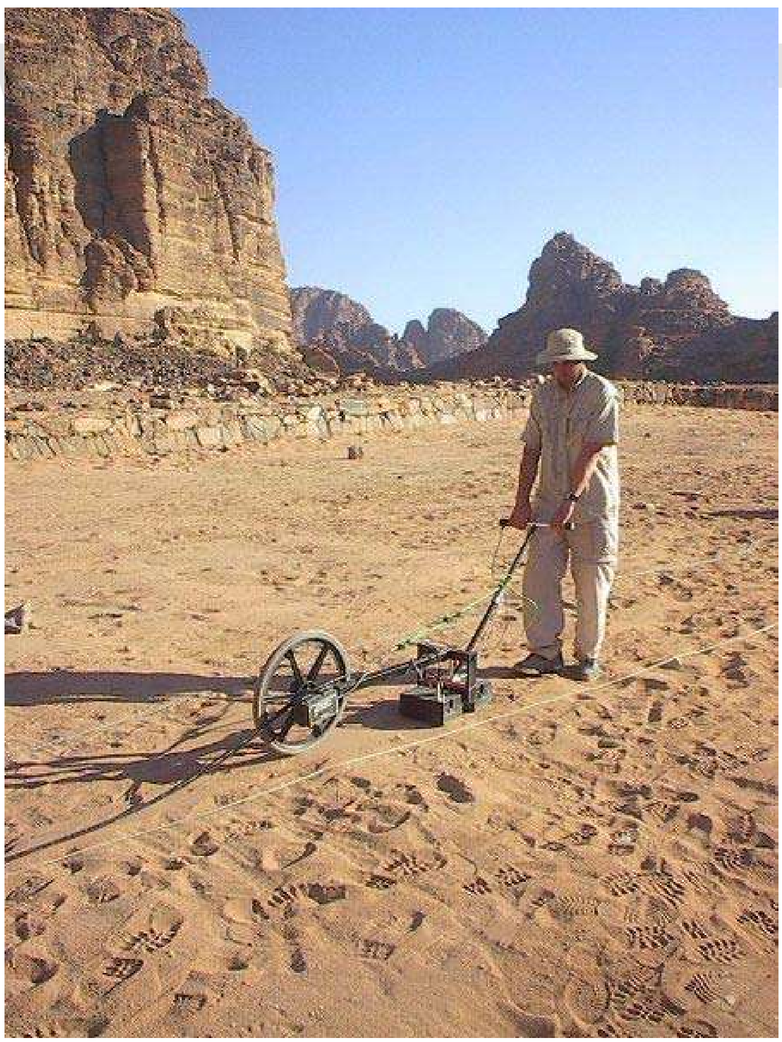
GPR uses high-frequency (usually polarized) radio waves and transmits into the ground. When the wave hits a buried object or a boundary with different dielectric constants, the receiving antenna records variations in the reflected return signal. The principles involved are similar to reflection seismology, except that electromagnetic energy is used instead of acoustic energy, and reflections appear at boundaries with different dielectric constants instead of acoustic impedances.

The depth range of GPR is limited by the electrical conductivity of the ground, the transmitted center frequency and the radiated power. As conductivity increases, the penetration depth decreases. This is because the electromagnetic energy is more quickly dissipated into heat, causing a loss in signal strength at depth. Higher frequencies do not penetrate as far as lower frequencies, but give better resolution. Optimal depth penetration is achieved in ice where the depth of penetration can achieve several hundred meters. Good penetration is also achieved in dry sandy soils or massive dry materials such as granite, limestone, and concrete where the depth of penetration could be up to 15 m. In moist and/or clay-laden soils and soils with high electrical conductivity, penetration is sometimes only a few centimetres.

Ground-penetrating radar antennas are generally in contact with the ground for the strongest signal strength; however, GPR air launched antennas can be used above the ground.

Cross borehole GPR has developed within the field of hydrogeophysics to be a valuable means of assessing the presence and amount of soil water.

Applications



Ground penetrating radar survey of an archaeological site in Jordan

GPR has many applications in a number of fields. In the Earth sciences it is used to study bedrock, soils, groundwater, and ice. Engineering applications include nondestructive testing (NDT) of structures and pavements, locating buried structures and utility lines, and studying soils and bedrock. In environmental remediation, GPR is used to define landfills, contaminant plumes, and other remediation sites, while in archaeology it is used for mapping archaeological features and cemeteries. GPR is used in law enforcement for locating clandestine graves and buried evidence. Military uses include detection of mines, unexploded ordnance, and tunnels.

Before 1987 the Frankley Reservoir in Birmingham, England UK was leaking 540 litres of drinking water per second. In that year GPR was used successfully to isolate the leaks.

Borehole radars utilizing GPR are used to map the structures from a borehole in underground mining applications. Modern directional borehole radar systems are able to produce three-dimensional images from measurements in a single borehole.

One of the other main applications for ground penetration radars to locate underground utilities, since GPR is able to generate 3D underground images of pipes, power, sewage and water mains.

Three-dimensional imaging

Individual lines of GPR data represent a sectional (profile) view of the subsurface. Multiple lines of data systematically collected over an area may be used to construct three-dimensional or tomographic images. Data may be presented as three-dimensional blocks, or as horizontal or vertical slices. Horizontal slices (known as "depth slices" or "time slices") are essentially planview maps isolating specific depths. Time-slicing has become standard practice in archaeological applications, because horizontal patterning is often the most important indicator of cultural activities.

Limitations

The most significant performance limitation of GPR is in high-conductivity materials such as clay soils and soils that are salt contaminated. Performance is also limited by signal scattering in heterogeneous conditions (e.g. rocky soils).

Other disadvantages of currently available GPR systems include:

- Interpretation of radargrams is generally non-intuitive to the novice.
- Considerable expertise is necessary to effectively design, conduct, and interpret GPR surveys.
- Relatively high energy consumption can be problematic for extensive field surveys.

Recent advances in GPR hardware and software have done much to ameliorate these disadvantages, and further improvement can be expected with ongoing development.

Power regulation

In 2005, the European Telecommunications Standards Institute introduced legislation to regulate GPR equipment and GPR operators to control excess emissions of electromagnetic radiation . The European GPR association (EuroGPR) was formed as a trade association to represent and protect the legitimate use of GPR in Europe.

Similar technologies

Ground penetrating radar uses a variety of technologies to generate the radar signal, these are impulse, stepped frequency, FMCW and noise. Systems on the market in 2009 also use DSP to process the data, while survey work is being carried out rather than off line.

GPR is used on vehicles for close-in high speed road survey and landmine detection as well as in stand-off mode.

Pipe Penetrating Radar (PPR) is an application of GPR technologies applied in-pipe where the signals are directed through pipe and conduit walls to detect pipe wall thickness and voids behind the pipe walls.

Wall-penetrating radar can read through walls and even act as a motion sensor for police.

GPR is used for hand held landmine detection to reduce the false alarms experienced by the standard metal detector and systems are available off the shelf (Vallon and L3Com Cyterra)

The "Mineseeker Project" seeks to design a system to determine whether landmines are present in areas using ultra wideband synthetic aperture radar units mounted on blimps.

Chapter 11

AN/FPS-16

The FPS-16 radar sits atop Tranquillon Peak overlooking all of Vandenberg Air Force Base in California, including Space Launch Complex-6, and the shoreline. Tranquillon Peak's elevation of 2,126 feet (648 m) is the highest point on Vandenberg AFB. The radar provides data and range safety for missile launches. This radar, along with its data system, is used for tracking the Minuteman III ICBM.

The **AN/FPS-16** is a highly accurate ground-based monopulse single object tracking radar (SOTR), used extensively by the NASA manned space program and the U.S. Air Force. The accuracy of Radar Set AN/FPS-16 is such that the position data obtained from point-source targets has azimuth and elevation angular errors of less than 0.1 milliradian (approximately 0.006 degree) and range errors of less than 5 yards (5 m) with a signal-to-noise ratio of 20 decibels or greater.

FPS-16 Monopulse Tracking Radar

The first monopulse radar was developed at the Naval Research Laboratory (NRL) in 1943 to overcome the angular limitations of existing designs. The monopulse technique makes angular determinations simultaneously on each individual received pulse. This improvement in radar technology provides a tenfold increase in angular accuracy over previous fire and missile control radars at longer ranges. The monopulse radar is now the basis for all modern tracking and missile control radars. Although monopulse radar was developed independently and secretly in several countries, Robert Morris Page at the NRL is generally credited with the invention and holds the U.S. patent on this technique.

The monopulse technique was first applied to the Nike-Ajax missile system, an early U.S. continental air defense weapon. Many improvements were made to provide a more compact and efficient monopulse antenna feed and lobe comparison waveguide circuitry, such that monopulse tracking radar became the generally accepted tracking radar system for military and civilian agencies, such as NASA and the FAA.

The NRL's work on monopulse radars eventually led to the AN/FPS-16, developed jointly by NRL and RCA as the first radar designed especially for missile ranges. The AN/FPS-16 was used to guide the first U.S. space satellite launches, Explorer 1 and Vanguard 1, at Cape Canaveral in 1958.

FPS-16 and Project Mercury

The FPS-16 radar at Vandenberg AFB, California has been used for tracking NASA space vehicles since the 1960s.

The C-band monopulse tracking radar (AN/FPS-16) used in the Project Mercury was inherently more accurate than its S-band conically-scanned counterpart, the Very Long Range Tracking (VERLORT) radar system. The AN/FPS-16 radar system was introduced at the Atlantic Missile Test Range with installations including Cape Canaveral, Grand Bahama, San Salvador, Ascension and East Grand Bahama Island between 1958 and 1961. The FPS-16 located on the Australian Weapons Research Establisnment Range at Woomera, in South Australia was also linked to the NASA network for Mercury and later missions. NASA Acq aid and telelmetry systems were co-located with the Australian radar.

To obtain reliability in providing accurate trajectory data, the Mercury spacecraft was equipped with C-band and S-band cooperative beacons. The ground radar systems had to be compatible with the spacecraft radar beacons. The FPS-16 radar in use at most national missile ranges was selected to meet the C-band requirement. Although it originally had a range capability of only 250 nautical miles (460 km), most of the FPS-16 radar units selected for the project had been modified for operation up to 500 nautical miles (900 km), a NASA requirement, and modification kits were obtained for the remaining systems. In addition to the basic radar system, it was also necessary to provide the required data-handling equipment to allow data to be transmitted from all sites to the computers.

The FPS-16 system originally planned for the Project Mercury tracking network did not have adequate displays and controls for reliably acquiring the spacecraft in the acquisition time available. Consequently, a contract was negotiated with a manufacturer to provide the instrumentation radar acquisition (IRACQ)[Increased RAnge Acquisition] modifications. For the near earth spacecraft involved a major limitation of the FPS-16 was its mechanical range gear box, a wonderful piece of engineering. However, for a target at a range typically, say, 700 nautical miles (1,300 km; 810 mi) at acquisition of signal [AOS], the radar was tracking second time around, that is, the pulse received in this interpulse period was that due to the previously transmitted pulse, and it would be indicating a range of 700 nmi (1,300 km; 810 mi). As the range closed the return pulse became closer and closer to the time at which the next transmitter pulse should occur. If they were allowed to coincide, remembering that the transmit-receive switch disconnected the receive (Rx) and connected the transmit (Tx) to the antenna at that instant, track would be lost. So, IRACQ provided an electronic ranging system, the function of which was to provide the necessary gating pulses to the Az and El receiver channels so that the system would maintain angle track. The system utilized a voltage controlled crystal oscillator [VCXO] as the clock generator for the range counters. An early/late gate system derived an error voltage which either increased [for a closing target] or decreased [for an opening target] the clock frequency, thus causing the gates to be generated so as to track the target. It also, when the target reached an indicated range of less than 16,000 yd (15 km), took over the generation of transmitter trigger pulses and delayed these by 16,000 yd (15 km), thus enabling the received pulses to pass through the Big Bang, as it was called, of normally timed Tx pulses. The radar operator, would, while IRACQ maintained angle track be slewing the range system from minimum range to maximum so as to regain track of the target at its true range of <500 nmi (900 km). As the target passed through point of closest approach (PCA) and increased in range the process was repeated at maximum range indication. The most difficult passses were those in which the orbit was such that the target came to PCA at a range of, say 470 nmi. That pass required the radar operator to work very hard as the radar closed, and then opened in range through the Big Bang in short order. The IRACQ Console contained a C-scope associated with which was a small joy stick which gave C-scope operator control of the antenna angle servo systems so that he could adjust the pointing angle to acquire the signal. IRACQ included a scan generator which drove the antenna in one of several pre-determined search patterns around the nominal pointing position, it being desirable that IRACQ acquire the target as early as possible. An essential feature of this modification is that it allows examination of all incoming video signals and allows establishment of angle-only track. Once the spacecraft has been acquired, in angle range. Other features of the IRACQ system included additional angle scan modes and radar phasing controls to permit multiple radar interrogation of the spacecraft beacon. The addition of a beacon local oscillator wave meter permitted the determination of spacecraft-transmitter frequency drift.

Early in the installation program, it was realized that the range of the Bermuda FPS-16 should be increased beyond 500 miles (800 km). With the 500-mile (800 km)-range limitation, it was possible to track the spacecraft for only 30 seconds prior to launch-vehicle sustainer engine cut-off (SECO) during the critical insertion phase. By extending the range capability to 1,000 miles (2,000 km), the spacecraft could be acquired earlier, and additional data could be provided to the Bermuda computer and flight dynamics consort This modification also increased the probability of having valid data available to make a go/no-go decision after SECO.

The VERLORT radar fulfilled the S-band requirement with only a few modifications. Significant ones were the addition of specific angle-track capability and additional angular scan modes. At Eglin Air Force Base in Florida, the MPQ-31 radar was used for S-band tracking by extending its range capability to meet Project Mercury requirements. The data-handling equipment was essentially the same as for the FPS-16. Coordinate conversion and transmitting equipment was installed at Eglin to allow both the MPQ-31 and the FPS-16 to supply three-coordinate designate data to the Atlantic Missile Range (AMR) radars via central analog data distributing and computing (CADDAC) .

C-Band Radar Transponder

The C-Band Radar Transponder (Model SST-135C) is intended to increase the range and accuracy of the radar ground stations equipped with AN/FPS-16, and AN/FPQ-6 Radar Systems. C-band radar stations at the Kennedy Space Center, along the Atlantic Missile Range, and at many other locations around the world, provide global tracking capabilities. Beginning with Vehicles 204 and 501, two C-band radar transponders will be carried in the instrumentation unit (IU) to provide radar tracking capabilities independent of the vehicle attitude. This arrangement is more reliable than the antenna switching circuits necessary if only one transponder would be used.

Transponder operation

The transponder receives coded or single pulse interrogation from ground stations and transmits a single-pulse reply in the same frequency band. A common antenna is used for receiving and transmitting. The transponder consists of five functional systems: superheterodyne receiver, decoder, modulator, transmitter, and power supply. The duplexer (a 4-port ferromagnetic circulator) provides isolation between receiver and transmitter. Interrogating pulses are directed from the antenna to the receiver, and reply pulses are directed from the transmitter to the antenna. The preselector, consisting of three coaxial cavities, attenuates all RF signals outside the receiving band. The received signal is heterodyned to a 50 MHz intermediate frequency in the mixer and amplified in the IF amplifier which also contains the detector. In case of coded transmission, the decoder module provides a pulse output only if the correct spacing exists between pulse pairs received. The shaped-pulse output of the decoder is directed to the modulator which converts it into a high-power, precisely shaped and precisely delayed pulse which is applied to the magnetron to produce the reply pulse. Six telemetry outputs are provided: input signal level, input pulse repetition frequency (PRF), temperature, incident power, reflected power, and reply PRF.

Semiconductors are used in all circuitry, with the exception of the local oscillator and magnetron.

Radar ground station operation

The radar ground stations determine the position of the vehicle C-band transponder by measuring range, azimuth angle, and elevation angle. Range is derived from pulse travel time, and angle tracking is accomplished by amplitude-comparison monopulse techniques. As many as four radar stations may track the beacon simultaneously.

NASA Manned Space Flight Network (MSFN) C-band Radar

The NASA Manned Space Flight Network (MSFN) land based C-band pulse radar types consist of the AN/FPS-16, AN/MPS-39, AN/FPQ-6 and the AN/TPQ-18. The MPS-39 is a transportable instrument using space-fed-phased-array technology; the TPQ-18, a transportable version of the FPQ-6. The indicator AN (originally "Army–Navy") does not necessarily mean that the Army, Navy or Air Force use the equipment, but simply that the type nomenclature was assigned according to the military nomenclature system. The meaning of the three letter prefixes; FPS, MPS, FPQ and TPQ are:

- FPS - fixed; radar; detecting and/or range and bearing
- MPS - ground, mobile; radar; detecting and/or range and bearing
- FPQ - fixed; radar; special, or combination of purposes
- TPQ - ground, transportable; radar; special, or combination of purposes.

AN/FPS-16 RADAR SET

TYPICAL TECHNICAL SPECIFICATIONS

Type of presentation: Dual-trace CRT,
A/R and R type displays.

Transmitter data -
Nominal Power: 1 MW peak (fixed-frequency magnetron);
250 kW peak (tunable magnetron).
Frequency
Fixed: 5480 plus or minus 30 MHz
Tunable: 5450 to 5825 MHz

Pulse repetition frequency (internal):
341, 366, 394, 467, 569, 682, 732, 853,
1024, 1280, 1364 or 1707 pulses per second

Pulse width: 0.25, 0.50, 1.0 μs

Code groups: 5 pulses max, within 0.001 duty cycle limitation of transmitter.

Radar receiver data -
Noise Figure: 11 dB
Intermediate Frequency: 30 MHz
Bandwidth: 8 MHz
Narrow Bandwidth: 2 MHz
Dynamic Range of Gain Control: 93 dB

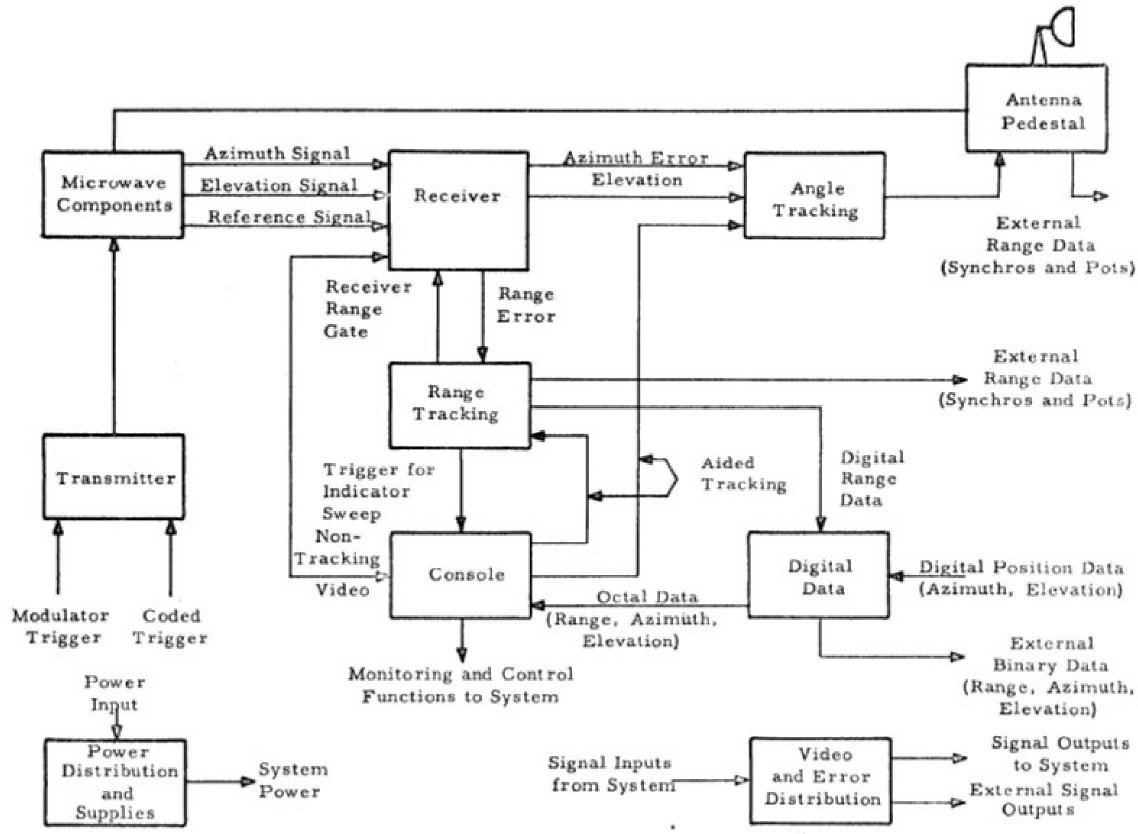
Gate width
Tracking: 0.5 μs, 0.75 μs, 1.25 μs
Acquisition: 1.0 μs, 1.25 μs, 1.75 μs

Coverage
Range: 500 to {{convert|400000|yd|m|-5|abbr=on}}
Azimuth: 360° continuous
Elevation: minus 10 to plus 190 degrees

Servo bandwidth
Range: 1 to 10 Hz (var)
Angle: 0.25 to 5 Hz (var)

Operating power requirements: 115 V AC,
60 Hz, 50 kV·A, 3 phase

Principles of operation



AN/FPS-16 Radar Set block diagram

The AN/FPS-16 is a C-band monopulse radar utilizing a waveguide hybrid-labyrinth comparator to develop angle track information. The comparator receives RF signals from an array of four feed horns which are located at the focal point of a 12-foot (4 m) parabolic reflector. The comparator performs vector addition and subtraction of the energy received by each horn. The elevation tracking data is generated in the comparator as the difference between the sums of the top two horns. The azimuth tracking error is the difference between the sums of the two vertical horn pairs. The vectorial sums of all four horns is combined in a third channel. Three mixers with a common local oscillator, and three 30 MHz IF strips are used; one each for the azimuth, elevation, and sum signals.

The same four-horn cluster is used for RF transmission. The transmitter output is delivered to the comparater labyrinth, which now acts to divide the outgoing power equally between all four horns. The receivers are protected by TR tubes during the transmit time.

The horn cluster is located approximately at the focal point of a 12-foot (4 m) parabolic reflector. During the transmission cycle, the energy is distributed equally among the four horns. During the receive cycle, the outputs of the elevation and azimuth comparator arms represent the amount of angular displacement between the target position and electrical axis. Consider an off-axis target; the image is displaced from the focal point, and the difference in signal intensity at the face of the horns is indicative of angular displacement. An on-target condition will cause equal and in-phase signals at each of the four horns and zero output from the elevation and azimuth arms.

The sum, azimuth, and elevation signals are converted to 30 MHz IF signals and amplified. The phases of the elevation and azimuth signals are then compared with the sum signal to determine error polarity. These errors are detected, commutated, amplified, and used to control the antenna-positioning servos. A part of the reference signal is detected and used as a video range tracking signal and as the video scope display. A highly precise antenna mount is required to maintain the accuracy of the angle system.

The FPS-16 antenna pedestal is a precision-machined item which is engineered to close tolerances and is assembled in dust-free, air-conditioned rooms to prevent warping during mechanical assembly. The pedestal is mounted on a reinforced concrete tower to provide mechanical rigidity. The electronic equipment is mounted in a two-story concrete building, which also surrounds the tower to decrease tower warpage due to solar radiation.

The radar utilizes a 12-foot (4 m) parabolic antenna giving a beamwidth of 1.2 degrees at the half-power points. The range system utilizes either a 1.0, 0.5, or 0.25-microsecond pulse and the prf can be set by pushbuttons. Twelve repetition frequencies between 341 and 1707 pulses per second can be selected. A jack is provided through which the modulator can be pulsed by an external source. By means of external modulation, a code of from 1 to 5 pulses may be used.

Data rake-offs are provided for potentiometer, synchro, and digital information in all three coordinates. The azimuth and elevation digital data is derived from optical-type analog-to-digital encoders. Two geared coders with ambiguity resolution are used for each parameter. The data for each angle is a Gray code 17-bit word in serial form. The overlapping ambiguity bits are removed, and the data is transformed from cyclic Gray code to straight binary before recording for transmission to the computer. The range servo presents a 20-bit straight binary word in serial form after ambiguity resolution and code conversion. The same type optical encoders are used.

The AN/FPS-16 antenna pedestal is mounted on a 12-by-12-foot (4 by 4 m) concrete tower which extends 27 feet (8 m) above grade level. The center of the emplaced antenna is approximately 36 feet (11 m) above grade level. The electronic equipment, auxiliary system, maintenance section, etc., are housed in a 66 by 30 by 24 ft (20×9×7 m) two-story concrete block building. The building surrounds, but is not attached to, the pedestal tower. This method of construction places the tower within the air conditioned environment of the equipment building and provides protection from solar radiation and other weather effects which would dilute the inherent accuracy of the system. Power requirements for each station are: 120/208 volts, ±10 volts, 4-wire, 60 Hz; 175 kV·A.

Models of the AN/FPS-16

The AN/FPS-16 and AN/FPQ-6 are C-band tracking radar systems. Their key characteristics are compared in the following table.

Radar Ground Station Characteristics

	AN/FPS-16	AN/FPQ-6
Frequency band (MHz) . .	5400-5900	5400-5900
Peak power (mW)	1.3	3.0
Antenna size (meters)	3.9	9.2
Antenna gain (dB)	47	52
Receiver noise figure (dB)	6.5	8
Angle precision (units) . . .	0.15	0.1
Range precision (meters)..	4.5	3.0

AN/FPS-16 (XN-I)

The first experimental model was made with an X-band RF system and a lens-type antenna. It later was changed to C-band with a reflector antenna. This radar was further modified for use on Vanguard and is now installed at the Atlantic Missile Range, Patrick AFB, Florida.

AN/FPS-16 (XN-

Two of this model were made. One was installed on Grand Bahama Island, BWI, and one remained at RCA, Moorestown, N.J. These radars are almost identical to later production models.

AN/FPS-16 (XN-3)

This was an experimental version of AN/FPS-16 (XN-2) that includes a 3-megawatt modification kit, a circular polarization kit, a data correction kit, and a boresight television kit. This radar was installed at RCA, Moorestown, N.J.

AN/FPS-16AX

This is a production AN/FPS-16 modified according to (XN-3). Three radars located at White Sands Missile Range, and one located at Moorestown, New Jersey, have been so modified. AN/MPS-25 is the nomenclature of a trailer-mounted production model AN/FPS-16.

AN/FPQ-4

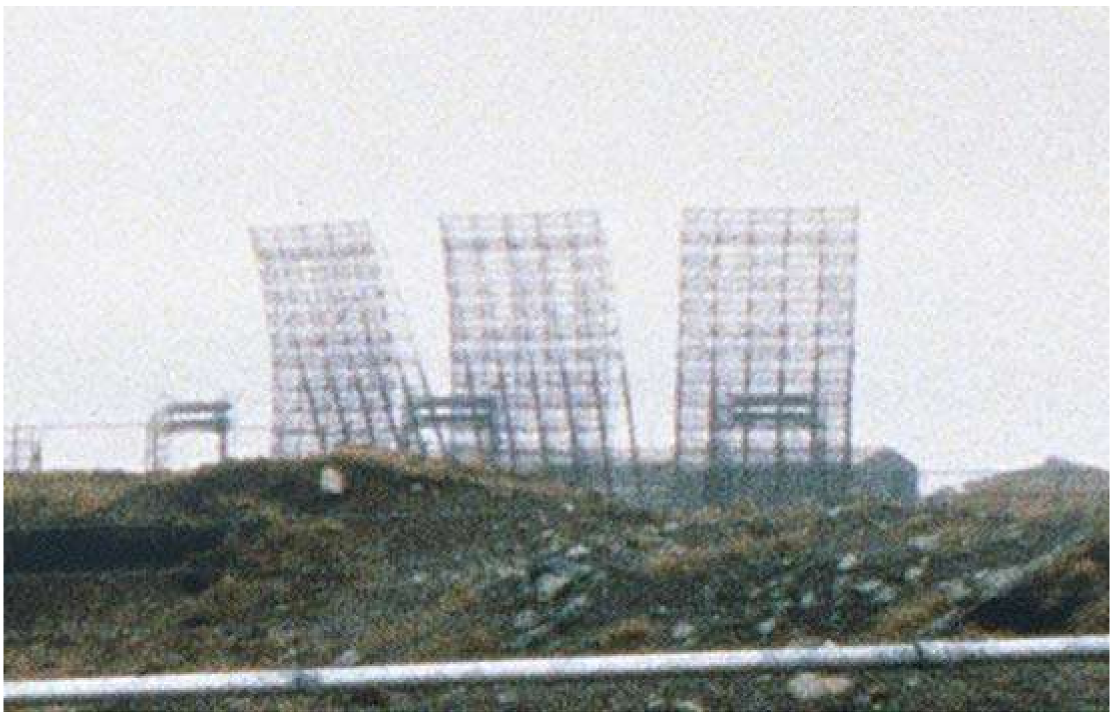
This is an adaptation of AN/FPS-16 that was made for use as a target tracker in the land-based Talos system. Two models were installed at WSMR. Two more models, with modifications, were installed on a ship for use in the Atlantic Missile Range on the Project DAMP. A fifth such radar was installed at RCA, Moorestewn, N.J. as a part of the Project DAMP research facility.

AN/FPS-16 RADAR SET
PRINCIPAL COMPONENTS AND PHYSICAL DATA

COMPONENTS	QTY	OVERALL DIMENSIONS (Inches)	UNIT WT. (Pounds)
Amplifier Electronic Control AM-1751/FPS-16	1	3.1 x 3.7 x 10.4	6
Tuning Drive TG-55/FPS-16	1	3.1 x 3.i x 10	3
Control Electrical Frequency C-2278/FPS-16	1	3.7 x 4.7 x 19.2	6
Control Amplifier C-2276/FPS-16	1	3.7 x 1.7 x 17.2	5
Air Conditioner	1	32 x 56 x 73	1500
Air Conditioner	1	18 x 72 x 76	1500
Amplifier Filament Supply	13	3.7 x 3.7 x 5	1
Angle Compensation Amplifier (Azimuth & Elevation)	2	8.2 x 15.5 x 19.5	24
Angle Control Unit AM-1760/FPS-16	1	8.2 x 15.5 x 19.5	20
Angle Error Amplifier (Azimuth & Elevation)	2	8.2 x 13.7 x 19.5	21
Angle Servo Preamplifier (Azimuth Servo; Elevation Servo)	2	2.5 x 6 x 19.5	10
Angle Summing Amplifier (Azimuth & Elevation)	2	12.2 x 15.5 x 19.5	24
Azimuth Driver Amplifier AM-1759/FPS-16	1	8.2 x 13.7 x 19.5	21

Chapter 12

AN/FPS-17



AN/FPS-17 antennas at Shemya, Alaska

The **AN/FPS-17** is a ground-based fixed-beam radar system that was installed at Pirinçlik Air Base in south-eastern Turkey.

This system was deployed to satisfy scientific and technical intelligence collection requirements during the Cold War. The first installation (designated AN/FPS-17, XW-1) at Diyarbakir was originally intended to provide surveillance of the USSR's missile test range at Kapustin Yar south of Stalingrad - especially to detect missile launchings. The data it produced, however, exceeded surveillance requirements, permitting the derivation of missile trajectories, the identification of earth satellite launches, the calculation of a satellite's ephemeris (position and orbit), and the synthesis of booster rocket performance. The success achieved by this fixed-beam radar led to the co-location of a tracking radar (AN/FPS-79), beginning in mid-1964. Together, these radars had the capability for estimating the configuration and dimensions of satellites or missiles and observing the reentry of manned or unmanned vehicles.

Genesis

Experimentation with the detection of missiles by a modified SCR-270 radar in 1948 and 1949 at Holloman Air Force Base, New Mexico along with U.S. experience in the use of high-power components on other radars, created a basis for believing that a megawatt-rated radar could be fabricated for operation over much longer ranges than ever before. The need for intelligence on Soviet missile activity being acute, a formal requirement for such a radar was established, and Rome Air Development Center was given responsibility for engineering the system.

In October 1954 General Electric, which had experience in producing high-power VHF equipment and radars, was awarded a contract for the fabrication, installation, and testing of what was to be at the time the world's largest and most powerful operational radar. The contract stipulated that the equipment was to be in operation at Site IX near Diyarbakir within nine months: by 1 June 1955. Construction began in February, and the scheduled operational date was missed by fifteen minutes.

The original antenna installation was a large D.S. Kennedy parabolic reflector, 175 feet (53 m) high by 110 feet (34 m) wide, radiating in the frequency range 175 to 215 megacycles. Standard GE high-power television transmitters, modified for pulse operation, were used initially.

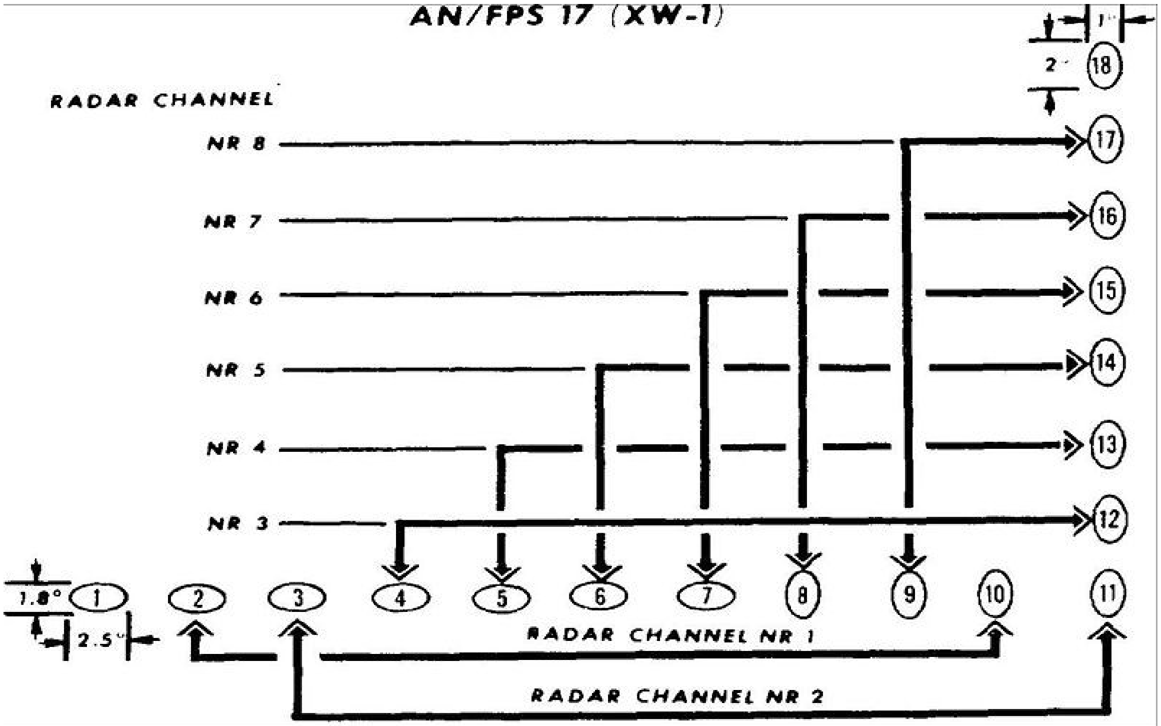
Surveillance was carried out by six horizontal beams over the Kapustin Yar area. In 1958 a second antenna, 150 feet (46 m) high by 300 feet (90 m) long, and new 12-megawatt transmitters were installed as part of a modification kit which provided three additional horizontal beams, a seven-beam vertical fan, and greater range capability.

The elaborated system includes automatic alarm circuitry, range-finding circuitry, and data-processing equipment; it is equipped to make 35 mm photographic recordings of all signals received. A preliminary reduction of data was accomplished on-site, but the final processing was done in the Foreign Technology Division at Wright Patterson Air Force Base.

From 15 June 1955, when the first Soviet missile was detected, to 1 March 1964, 508 incidents (sightings) were reported, 147 of them during the last two years of the period.

Operation

The system has eight separate radar sets or channels, each with its own exciter, transmitter, duplexer, receiver, and data display unit. These eight channels feed electromagnetic energy into sixteen fixed beams formed by the two antennas, each channel, or transmitter-receiver combination, being time-shared between two beams. Pneumatically driven switches operate on a three-second cycle to power each beam alternately for 1.5 seconds. There are antenna feeds for two additional beams which could be made to function with some patchwork in the wiring.

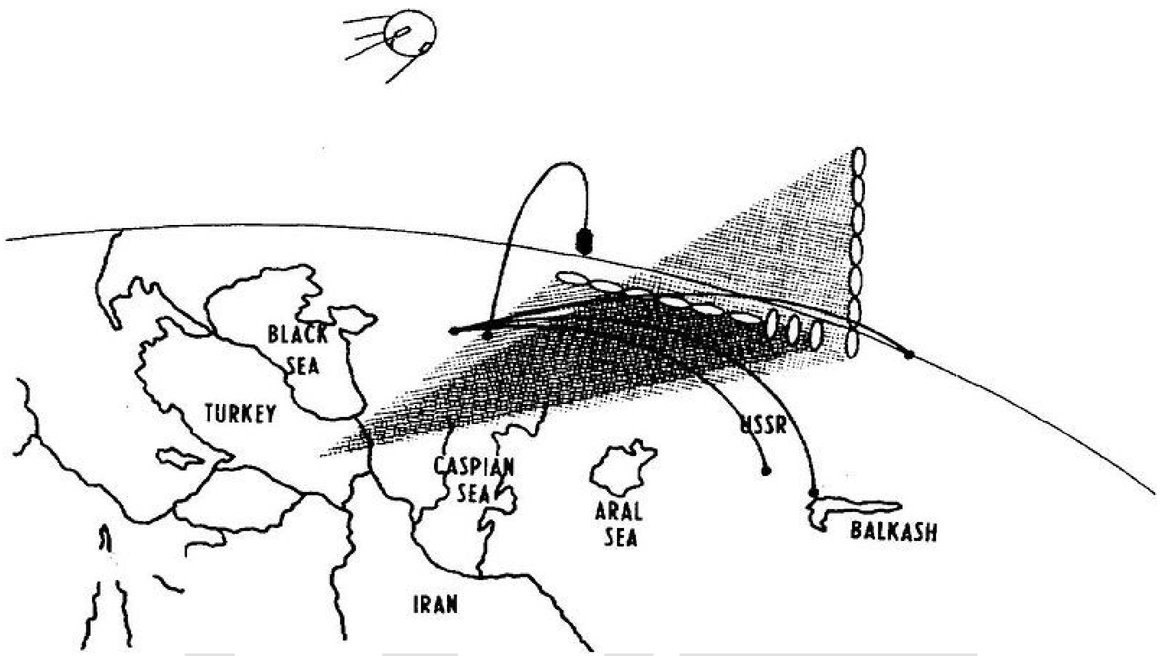


Beam pattern

The antenna feeds are positioned to produce in space the beam pattern depicted in the figure. Beams 1 and 18 are those not ordinarily energized. Beams 1 through 7 use the older of the two antennas; 8 through 18 are formed by the newer, "cinerama" antenna, whose 300-foot (90 m) width gives them their narrow horizontal dimension.

Beams 2 through 9 are projected in horizontal array; 10 through 17 (although 10 actually lies in the horizontal row) are grouped as the vertical component. All beams of each group are powered simultaneously. Except for being controlled by a master timing signal, each of the eight channels operates independently of the others. Each transmitter is on a slightly different frequency to prevent interaction with the others. The transmitted pulse, 2000 microseconds long, is coded, or tagged, by being passed through a tapped delay line which may reverse the phase at 20-microsecond intervals. Upon reception the returned signal is passed through the same tapped delay line and compressed 100:1, to 20 microseconds in order to increase the accuracy and resolution of the range measurement, which is of course a function of the interval between transmission and return.

A delay line is an artificial transmission detour that serves to retard the signal, made up with series inductances and parallel capacitances that yield a constant delay. Pick-off points at 20-microsecond intervals permit these sub-pulses to be extracted in such sequence that they all arrive together, to achieve the compression effect.



This diagram shows the beam pattern superimposed on the target area

The total azimuthal coverage is from 18° to 49.7°. The system normally detects missiles or satellites launched from Kapustin Yar at a nominal range of 800 nautical miles (1,500 km); it tracks one type of missile out as far as 1,625 nautical miles (3,010 km). The missiles and satellites are not sensed at their maximum detectable range because the coverage of the fixed beam configuration does not conform with the test range layout.

The electrical characteristics of each of the channels are:

Frequency	175-215 megacycles
Peak power per beam	1.2 megawatts
Pulse length	2000 microseconds
Pulse repetition rate	30 cycles per second
Duty cycle (portion of time transmitting)	0.06
Beam width (horizontally elongated)	2.5° x 1.8°
Beam width (vertically elongated)	1° x 2°
Pulse compression ratio	100:1
Range accuracy	within 5 nmi (9 km)

To illustrate how the capability of the system is calculated, we can take typical logs which show channel 4, for example, operating with the following parameters:

Peak power output	1.0 megawatt
Minimum discernible signal	130 decibels below one milliwatt
Frequency	192 megahertz

Channel 4's maximum range of intercept capability for a target one square meter in cross section is then determined by using these parameters in the radar range equation

$$R = \left[\frac{P_t G^2 \lambda^2 A}{(4\pi)^3 \sigma_{min}}\right]^{\frac{1}{4}}$$

where:

- R is the range in meters
- P_t is the peak power transmitted in watts
- G is the antenna gain over isotropic (omnidirectional) radiator
- λ is the wavelength in meters
- σ_{min} is the minimum discernible signal in watts
- A is the target size in square meters

Substituting,

$$\lambda = \frac{c}{f}$$

where:

- c is the speed of light in meters per second
- f is the frequency in hertz (1/s)

$$\lambda = \frac{3 \times 10^8\,\mathrm{m/s}}{192 \times 10^6\,\mathrm{Hz}} = 1.56\,\mathrm{m}$$

converting.

$$\sigma_{min} = -130\,\mathrm{dBm} = 10^{-130/10}\,\mathrm{mW} = 10^{-16}\,\mathrm{W}$$

and

$$R = \left[\frac{10^6\,\mathrm{W} \times 5000^2 \times (1.56\,\mathrm{m})^2 \times 1\,\mathrm{m}^2}{12.57^3 \times 10^{-16}\,\mathrm{W}}\right]^{\frac{1}{4}}$$

Range = 4,184 kilometres (2,260 nmi).

Sightings made by the fixed-beam system include vertical firings (for upper-atmosphere research vehicles or booster checkout), ballistic missiles fired to the nominal 650-nautical-mile (1,200 km), 1,050-nautical-mile (1,940 km), and 2,000-nautical-mile

(3,700 km) impact areas, launches of Cosmos satellites, orbiting satellites, and natural abnormalities such as ionospheric disturbances or aurora.

Measurements and processing

Data on target missiles or satellites are recorded in each radar channel by photographing a five-inch (127 mm) intensity-modulated oscilloscope with the camera shutter open on a 35 mm film moving approximately five inches per minute. The range of an individual target is represented by its location across the width of the film, the time by a dotdash code along the length. In addition to this positional information, the target's approximate radial velocity (velocity in the direction of observation) was determined by measuring the Doppler frequency shift in the radar signal when it is returned. The doppler shift is found to within 500 cycles by determining which of eighteen frequency filters covering successive bands 500 cycles per second wide will pass the return signal. This measurement of radial velocity runs from -4 to -f-4 nautical miles (7 km) per second in increments of 0.219-nautical-mile (0.406 km). All these data, together with the elevation and azimuth of the observing beam, are automatically converted to serial form, encoded in standard teletype code, and punched on paper tape for teletype transmission.

Data was thus received at Wright-Patterson Foreign Technology Division (FTD) first by teletype and then on film, the latter accompanied by logs giving data on the target as read by site personnel and data on equipment performance such as peak transmitted power, frequency, and receiver sensitivity. Upon arrival, the film when was edited and marked to facilitate reading on the "Oscar" (preliminary processing) equipment. Targets are sorted by differences in range and rate of range change, and the returns on each were numbered in time sequence.

The FTD Oscar equipment consisted of a film reader which gave time and range data in analog form, a converter unit which changed them to digital form, and an IBM printing card punch which received the digital data. The Oscar equipment and human operator thus generated a deck of IBM cards for computer processing which contains the history of each target's position through time.

The first step in the computer processing is to translate Oscar units into actual radar range, "Z" (Greenwich mean) time, and beam number, the latter fixing the azimuth and elevation of the return. During this first step, three separate quality-control checks are made on each IBM card to eliminate erroneous data.

Those observations that succeed in passing all these tests are taken to the second step of computer processing, with fitting of a second-degree polynomial curve to the raw range/time data in accordance with least squares criteria. In this method, a mathematical function is fit to best approximate a series of observations where the sum of squares of its residuals (deviations from the raw data) is least. If there is systematic irregularity in the reliability of the data, the residuals are weighted accordingly.

A standard deviation from this curve is established, and any raw datum point showing a deviation as large as three times the standard is discarded. Then second-degree curves are similarly fitted to the azimuth/time and elevation/time data. The three second-degree polynomials - for range/time, azimuth/time, and elevation/time - are used to generate a value for position and velocity at mean time of observation, and on the basis of these values an initial estimate of the elliptical trajectory is made.

In computing the elliptical path, the earth is physically considered a rotating homogeneous sphere and geometrically considered an ellipsoid -that is, its equatorial bulge is ignored in the gravitational computation but not with respect to intersections of its surface. An ellipse not intersecting the Earth's surface represents a satellite orbit; one intersecting the Earth's surface describes a trajectory above the point of intersection.

The parameters of the ellipse are iterated with the computer, establishing a best-fit ellipse constrained by a weighted least-squares criterion. Along this ellipse the target's track is computed -the history through time of latitude, longitude, altitude, and such velocity and angular parameters as may be of interest. A missile's actual range is probably shorter than that of its computed trajectory because of its non-elliptical thrusting path and atmospheric drag after its reentry. The difference is on the order of 10-nautical-mile (19 km) to 25 nautical miles (46 km) for short and medium range missiles, 50-nautical-mile (93 km) for ICBM's.

Shemya Island, Alaska

Soviet rocket tests to Kamchatka during the late 1950s increased interest in Shemya Island, Alaska at the western Aleutians as a location for monitoring missile tests from the far northeastern Soviet Union. Old facilities were rehabilitated and new ones constructed on the island, including a large detection radar (AN/FPS-17), which went into operation in 1960. In 1961, the AN/FPS-80 tracking radar was constructed nearby. Blue Fox refers to a modification of the AN/FPS-80 tracking radar to the AN/FPS-80(M) configuration in 1964. These radars were closed in the 1970s when the Cobra Dane phased array radar was built to monitor missile tests. Shemya was redesignated from an Air Force station to an Air Force base in 1968.

The AN/FPS-17 Detection Radar at the Shemya AFB became operational in May 1960, and the AN/FPS-80 Tracking Radar became operational on April 1, 1962.

Blue Nine refers to the project which produced the AN/FPS-79 Tracking Radar Set built by General Electric, used with the Air Force 466L Electromagnetic Intelligence System (ELINT).

Aftermath

The Diyarbakir space surveillance site operated a detection radar (FPS-17) and a tracking radar (FPS-79) throughout the 1960s and 1970s. If a new space object is sensed by the detection radar's fans, then the tracking radar can be oriented to achieve lockon. The orientation is governed by knowledge of the appropriate "normal" object's astrodynamic laws of motion, or by an assumption as to launch point. Thus, if an unknown is detected, and if it follows an unusual path, it is unlikely that it could, or would, be tracked. Furthermore, the director of the radar may make a decision that the unknown object detected is not of interest (because of the location of the FPS-17 fan penetration or because of the lack of prior information on a possible new launch). In the absence of detection fan penetration (the fan has a rather limited coverage), the FPS-79 tracking radar is tasked to follow other space objects on a schedule provided by the Space Defense Center, and again there is almost no likelihood that an anomalistic object could, or would, be tracked.

Chapter 13

AN/FPQ-6 and Airport Surveillance Radar

AN/FPQ-6

The **AN/FPQ-6** is a fixed, land-based C-band radar system used for long-range, small-target tracking. The AN/FPQ-6 Instrumentation Radar located at the NASA Kennedy Space Center was the principal C-Band tracking radar system for Apollo program.

RCA's Missile and Surface Radar Division developed the FPQ-6 skin tracking C-Band radar as a successor to the AN/FPS-16 radar set. The AN/FPQ-6 can provide continuous spherical coordinate information at ranges of 32,000 nautical miles (59,000 kilometers) with an accuracy of plus and minus 6 ft (1.8 m). The AN/FPS-16 has range limited to 500 nmi (930 kilometers) with an accuracy of 15 feet (5 m), although it could be modified to a maximum range of 5,000 nmi (9,300 kilometers).

Radar Ground Station Characteristics

	AN/FPS-16	AN/FPQ-6
Frequency band (MHz) . .	5400-5900	5400-5900
Peak power (MW)	1.3	3.0
Antenna size (m)	3.9	9.2
Antenna gain (dB)	47	52
Receiver noise figure (dB)	6.5	8
Angle precision (units) . . .	0.15	0.1
Range precision (m)......	4.5	3.0

The AN/FPQ-6 radar employed a 2.8 megawatt peak power (4.8 kilowatt average), broad banded (5400–5900 MHz) transmitter with a frequency stability of 1×10^{8}.

The 8.8 meter diameter parabolic antenna, using a Cassegrain antenna feed, had a 0.4° beamwidth and a gain of 51 dB. Its monopulse, 5 horn feed system permitted the reference and error antenna patterns to have their gains independently established as well as the slope of the error patterns optimized while supplying target return signals to the receiving system with a minimum of insertion loss.

The three channel signal outputs of the antenna feed system were supplied directly to the receiving system without undergoing any additional loss-inducing signal manipulation with bandwidths optimized for the specified pulse widths of 0.5, 0.75, 1.0 and 2.4 microseconds and the receiver noise figure of 7.5 dB was improved to 3.5 dB through the addition of closed-cycle parametric RF amplifiers. This system ensured a dynamic range in excess of 120 dB.

The receiving system provided simultaneous presentation of the skin and beacon returns to the console operator so that skin tracking could be used if the beacon signal was lost.

The antenna pedestal was a high precision, two axis mount, using a hydrostatic bearing in azimuth and phase roller bearings in elevation to provide mobility and support to the counterbalanced, solid surface antenna. The antenna was positioned through anti-backlash dual drive pedestal gearing via a high torque-to-inertia electro-hydraulic valve motor system. A viscous coupler located between the valve motor and pedestal drive gearing damped out undesired mechanical resonances.

The AN/FPQ-6 had a self contained digital computer, an RCA FC-4101, whose primary purpose was to correct dynamic lag in the angular output data. As designed, both the AN/FPQ-6 and AN/TPQ-l8 radars were provided with a built-in data processor referred to as the RCA 4101 Computer.

The ground floor of the two story building contained the air-conditioning, transmitter heat exchanger controls, equipment load center data input junction box and ex-Mercury atomic time standard. The first floor contained the 8 equipment racks, the console, and the 3 megawatt transmitter.

Functional description

The AN/FPQ-6 Missile Range Instrumentation Set is a fixed station long-range precision tracking set to be used for tracking intercontinental ballistic missiles for range safety and range user's trajectory measurement data. It will also be used for tracking during staging and parking orbit (trilateration) of a synchronous satellite, The operational objective is to provide a fixed station radar capable of skin tracking a square meter target to ranges in excess of 300 nmi (560 km).

The specifications for the FPQ-6 radar installation at Patrick Air Force Base, Florida, are shown in the following table.

```
Apollo Land-Based C-Band Radar Characteristics


Station    Station        Radar     Antenna      Peak    Receiver
Receiver    Unambiguous
```

	Location	Type	Diam. (ft)	Gain (dB)	Power (MW)	Noise Figure (dB)	Bandwidth (MHz)	Range capability (nmi)
PAFB	Patrick Air Force Base, FL	FPQ-6	29	51	3	4	1.6	32,000

NOTE:
The nominal frequency range is 5.4 to 5.9 GHz.
Receiver bandwidth is for 1 microsecond pulsewidth.
FPS-6 radars have circular polarization capability.

Some notes on the AN-FPQ 6 Radar

The AN-FPQ 6 radar was built by RCA and was, effectively, a development of the AN-FPS 16. The Q6, as it was known by those who worked on it, was an amplitude comparison monopulse C-band radar, with a 2.8 MW peak klystron transmitter tunable from 5.4 to 5.8 GHZ, which had a 9 meter parabolic antenna, having 52 dB gain, a 0.6 degree beam width, utilizing a Cassegrainian feed with a five horn monopulse comparator. This radar had an unambiguous maximum range of 2^{15} or 32,768 nautical miles (60,686 km), and employed uncooled parametric amplifiers with a system noise temperature of 440 K, [a noise figure of 4 dB].

A major features of the radar was its maximum unambiguous range of 32,768 nautical miles (60,686 km) despite a pulse repetition frequency [PRF]of some hundreds of pulses per second. To combine these two features requires that the radar carry out *n*th time around tracking, that is, it had to be able to track an echo resulting from a transmitted pulse other than that sent as the start of the same PRF period in which the echo was received. In order to do so the range system employed a 2 second time base which allowed the system to determine the number of PRF periods elapsing before an echo, resulting from a particular transmit (Tx) pulse was received. The range system carried out a find process, then a verify process before entering the auto-tracking mode. [Note: All the following discussion uses ranges in yards—the radar was designed to work in those units and converting them to metric units would not add any clarity to this description.] The FIND process is first carried out. In this process two successive Tx trigger pulses are delayed by a time equivalent to an RF wave go and return distance of 16,000 yd. Then the range gate triggers are delayed by an equivalent time. The delayed Tx trigger pulses are counted in an auxiliary counter, the zone counter, until target video pulses are detected in the delayed range gates. At this point the zone counter contains the number of PRF periods corresponding to the *n*th time around. The VERIFY process is then entered. In this mode one Tx pulse is delayed for a 16,000 yd equivalent distance. The range gate in the zone determined in the FIND mode is also delayed to match the TX delay. This sequence is repeated until four video returns, from eight attempts, are received. When the four returns are detected automatic tracking is maintained. The contents of the zone counter are added to the apparent range, that is the range reported in the current PRF period, to determine the actual range of the target. If, during the Verify process four returns are not found after eight tries the Find process is re-initiated. Take this example, in which a PRF of 142 PPS is assumed: A target at a range of 4,883,072 yd is to be acquired. At the radar console the operator initiates the FIND mode, and the system carries out that process by delaying triggers, counting zones etc., as described above, and finds that the zone counter has stored a count of four. The VERIFY mode then takes place, resulting in confirmation of the zone count. The target will appear, on the radar display to be at a range of 265,200 yd, that is the difference between, in this case, four PRF period equivalents, plus the additional range. The range reported will be the actual target range of 4,883,072 yd, the figure displayed on the range read-out. As the radar was designed to track moving objects the need arose to handle targets which, in closing or opening range, during *n*th time around tracking, came into coincidence with the next Tx pulse. So, in the jargon, the radar had to be capable of tracking "through the Big Bang." This arises from the fact that the antenna serves both the Tx and Rx. To allow this to happen a device called the Transmit-Receive Switch [T-R Switch]is used. The antenna is connected to the Rx until the Tx is pulsed. The T-R Switch detects the Tx pulse and transfers the antenna to the Tx for the duration of the pulse, say, 1 microsecond. [That period is that in which a radio wave would travel 164 yd. Remember we are talking here of radar ranges, the total go and return distance.] At the instant the Rx is disconnected from the antenna the range system will lose track. In order for an Nth time around tracking system to work there has to be some arrangement to cover the loss of Rx signal for the Tx pulse period. In the radar under discussion this is achieved as follows. When the target pulse reaches an apparent range of ±16,000 yd of the Tx pulse a number of Tx pulse, the number being the zone count, are delayed by a time equivalent to 32,000 yd. Take our example above. When the range of the target reduces to 4,633,872 yd-that is 16,000 yd greater than the 4 zones, the 32,000 yd delay is introduced into the Tx system. After 4 pulses the delay is transferred into the range gate generation system, and the target continues to be tracked. After the target has reached a range of 4,601,872 yd, 4 zones minus 16,000 yd, the delay is removed from the system. At that point the range is such that the zone counter will have been decremented by 1 and the apparent range will be 1,138,468 yd, but with the target at a real range of 3 zones plus the apparent range. Obviously, for an opening target the zone counter will be incremented and the apparent range will be slightly more than 16 yd.

Airport surveillance radar

Airport Surveillance Radar (KDAB, Daytona Beach, FL)

An **airport surveillance radar (ASR)** is a radar system used at airports to detect and display the position of aircraft in the terminal area.

Digital Airport Surveillance Radar (DASR)

The Digital Airport Surveillance Radar (DASR) is a new terminal air traffic control radar system that replaces current analog systems with new digital technology. The United States Air Force Electronics Systems Center, the US Federal Aviation Administration, and the US Navy are in the process of procuring DASR systems to upgrade existing radar facilities for US Department of Defense (DoD) and civilian airfields. The DASR system detects aircraft position and weather conditions in the vicinity of civilian and military airfields. The civilian nomenclature for this radar is the ASR-11. The ASR-11 will replace existing ASR-7, ASR-8, and ASR-9 models. The military nomenclature for the radar is the AN/GPN-30. The older radars, some up to 20 years old, are being replaced to improve reliability, provide additional weather data, reduce maintenance cost, improve performance, and provide digital data to new digital automation systems for presentation on air traffic controller displays. The Iraqi Air Force has received the DASR system.

ASR 910, a German derivate of AN/TPN-24, Radartower in Neubrandenburg (Western-Pommerania/ Germany)

Display systems

ASR data is displayed on Automated Radar Terminal System (ARTS) display consoles in control towers and Terminal Radar Approach Control (TRACON) rooms, usually located at airports. These were being replaced with STARS however the FAA has ceased all new installations of STARS due to hardware issues. Currently there is no new radar system ready to be installed in the near future.

The Standard Terminal Automation Replacement System (STARS) was a joint Federal Aviation Administration (FAA) and Department of Defense (DoD) program to replace Automated Radar Terminal Systems (ARTS) and other capacity-constrained, older technology systems at 172 FAA and up to 199 DoD terminal radar approach control facilities and associated towers.

STARS will be used by controllers, at facilities who already have it installed, to provide air traffic control (ATC) services to aircraft in terminal areas. Typical terminal area ATC services are defined as the area around airports where departing and arriving traffic are served. Functions include aircraft separation, weather advisories, and lower level control of air traffic. The system is designed to accommodate air traffic growth and the introduction of new automation functions which will improve the safety and efficiency of the US National Airspace System (NAS) as the legacy systems are replaced.

Chapter 14

EL/M-2080 Green Pine and GIRAFFE Radar

EL/M-2080 Green Pine

Green Pine radar antenna

The EL/M-2080 **Green Pine** is an Israeli ground-based missile-defense radar produced by Elta, a subsidiary of Israel Aerospace Industries, to operate mainly with the Arrow theater missile defense system of Israel, which is jointly funded and produced with the United States. Green Pine was exported to India, and its advanced version, the Super Green Pine, is also to be delivered to South Korea at a cost of $83 million apiece. The Israeli Air Defense Network within the Israeli Air Force (IAF) of the Israel Defense Forces (IDF) operates both Green Pine radars and Super Green Pine radars as an integral part of the Arrow system.

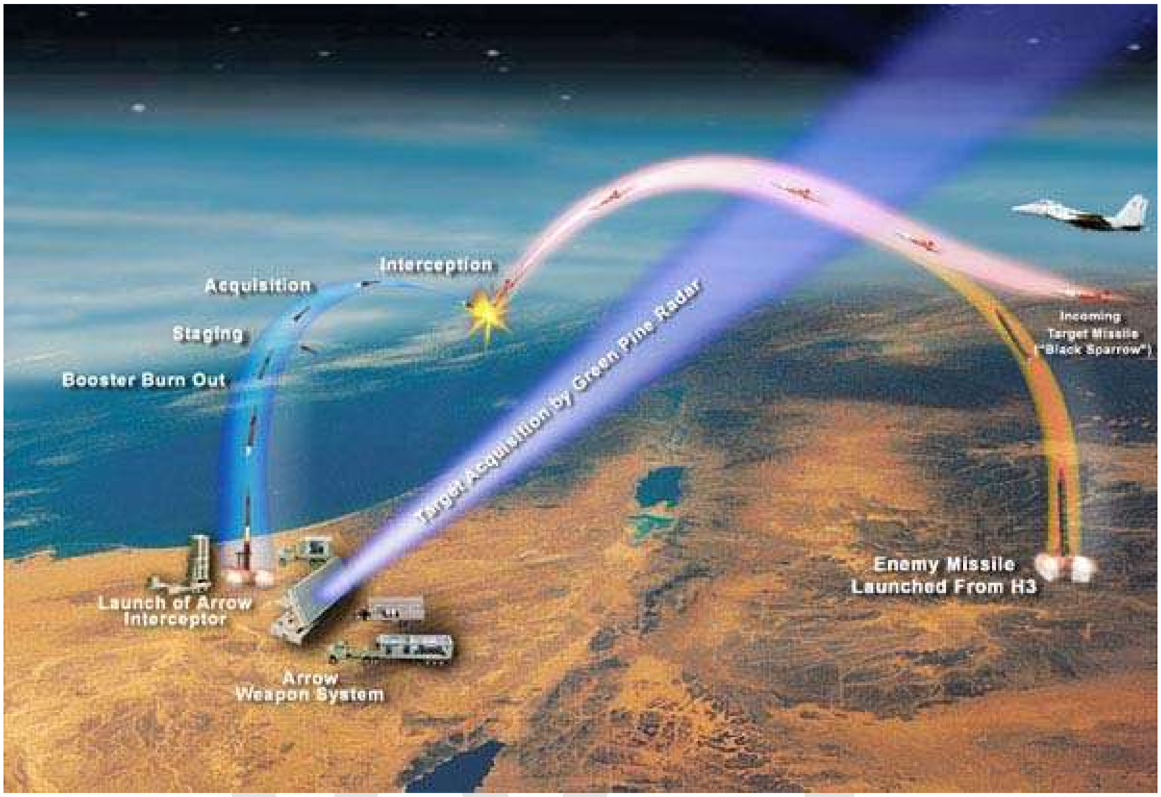
History

The Arrow program was launched as a response to the acquisition by Arab states of long range surface-to-surface missiles. The United States and Israel signed a memorandum of understanding to co-fund it in 1986, and in 1988 the United States Department of Defense Strategic Defense Initiative Organization (SDIO) placed an order with Israel Aircraft Industries for the Arrow 1 technology demonstrator. Over the years SDIO was renamed to Ballistic Missile Defense Organization (BMDO), and later to Missile Defense Agency (MDA), while Israel Aircraft Industries was renamed to Israel Aerospace Industries. The Gulf War, which exposed the controversial performance of the Patriot missile against Iraqi "Al Hussein" missiles, gave further impetus to the development of the Arrow. It was initially designed to intercept missiles such as the SS-1 "Scud", its "Al Hussein" derivative, the SS-21 "Scarab" operated by Syria, and the CSS-2 operated by Saudi Arabia. The Arrow evolved also with an eye on the advanced missile programs of Iran.

Elta was awarded the contract to develop and manufacture the EL/M-2080 Green Pine radar in 1992. The Green Pine was developed from the Elta Music phased array radar, presented in November 1994, rolled out in 1995, and turned operational in November 1998. The Green Pine has since been used in dozens of tests of the Arrow system. In 2000 it was revealed that the Green Pine detected the launch of a Syrian Scud-D missile from its base outside Aleppo in northern Syria, and tracked its full trajectory until its impact point, some 700 km (430 mi) in the southern desert. In 2005, and in 2008, Green Pine detected and tracked similar drills of Syrian Scuds.

On July 29, 2004, Israel and the United States carried out a joint test at the Naval Air Station Point Mugu (NAS Point Mugu) Missile Test Center in California, in which the Arrow interceptor was launched against a real Scud-B missile. The test represented a realistic scenario that could not have been tested in Israel due to test-field safety restrictions. To enable the test a full battery was shipped to Point Mugu. The Green Pine radar and command-and-control systems were deployed at the base, while the Arrow launcher was installed 100 km (60 mi) offshore on an island that forms part of the test range. The test was a success, with the interceptor destroying the Scud that flew a 300 km (190 mi) trajectory at an altitude of 40 km (25 mi), west of San Nicolas Island. This was the seventh test of the complete system, the first interception of a real Scud.

Specifications



Stages of missile interception by the Arrow system, using Green Pine radar

In contrast to the older AN/MPQ-53 Passive Electronically Scanned Array (PESA) radar set of the MIM-104 Patriot PAC-2, the Green Pine is an Active Electronically Scanned Array (AESA) solid state radar. Unlike the advanced AN/TPY-2 X band radar of the Terminal High Altitude Area Defense system, Green Pine operates at L band - in the range 500 MHz to 1,000 MHz, or 1,000 MHz to 2,000 MHz.

Green Pine reportedly operates in search, detection, tracking, and missile guidance modes simultaneously, capable of detecting targets at ranges of up to about 500 km (300 mi), and is able to track up to 30 targets at speeds over 3,000 m/s (10,000 ft/s). It discriminates targets from natural clutter and countermeasures, illuminates the true target and guides the missile to within 4 m (13 ft) of the target.

The effective radiated power (ERP) of the Green Pine also makes it a possible candidate for conversion into a directed-energy weapon, by focusing pulses of radar energy on target missiles. The energy spikes are tailored to enter missiles through antennas or sensor apertures where they can fool guidance systems, scramble computer memories or even burn out sensitive electronic components.

The radar system includes a 9 m (30 ft) wide by 3 m (10 ft) high trailer-mounted rotatable antenna array, a power system, a cooling system and a radar control center. The power system has both no-break and transformer containers, with the former including a diesel generator, an inductive clutch control module and a diesel fuel tank. The transformer container houses transformers, a service generator, a direct current converter and switching racks. The radar's cooling system is a heat exchanger that makes use of inherently redundant cascade cooling machines and incorporates an integral coolant tank and control panels. The radar is made up of 2,000–2,300 transmit–receive modules and weighs 60 tonnes (130,000 lb). The system is transportable rather than mobile, as it can be moved to other prepared sites, but cannot be set up just anywhere. According to its developer, Green Pine's deployment at a new operational site takes "less than 24 hours".

Super Green Pine

Super Green Pine radar antenna

An advanced version of the radar, called Super Green Pine, Green Pine Block-B, or Great Pine is to take the place of the original Green Pine. It is composed of smaller transmit–receive modules with better capabilities than those of the Green Pine, and is believed to produce double the power output, extending detection range to about 800–900 km (500–560 mi). In October 2010 IDF decided to be put another Arrow 2 battery into operational use in the coming months. The new battery will receive the new radar - "Super Green Pine".

Users

Israel

Israel had deployed at least 2 Green Pine radars as an integral part of the Arrow system. As of 2008 an unknown number of both Green Pine and Super Green Pine versions were active. United States European Command (EUCOM) has deployed to Israel a Raytheon-built AN/TPY-2 X band radar to increase the range at which Israel can detect incoming ballistic missiles beyond the abilities of Green Pine.

India

India had acquired and deployed two Green Pine radars around July 2002 and another one in August 2005. The Swordfish Long Range Tracking Radar of the Indian Defence Research and Development Organisation is an acknowledged derivative of the original Green Pine. The Indian government has sought to purchase the complete Arrow system since 1999, but in early 2002 the U.S. vetoed Israel's request to sell the Arrow 2 missiles to India, exercising its right as a major funding contributor. U.S. officials argued that the sale would violate the Missile Technology Control Regime (MTCR).

South Korea

South Korea was also considering buying two Green Pine radars, which would become operational in 2012. Reportedly, they preferred two Super Green Pine radars, at a cost of $83 million each, to its counterpart – ThalesRaytheonSystems' M3R radars.

GIRAFFE Radar

A Giraffe AMB radar display at Le Bourget Air Show on 2007

The Saab (formerly Ericsson Microwave Systems AB) **GIRAFFE Radar** is a family of land and naval two- or three-dimensional G/H-band (4 to 8 GHz) radar-based surveillance and air defense command and control systems tailored for operations with medium- and Short Range Air Defense (SHORAD) missile or gun systems or for use as gap-fillers in a larger air defense system. The radar gets its name from the distinctive folding mast which when deployed allows the radar to see over nearby terrain features such as trees, extending its effective range against low-level air targets. The first systems were produced in 1977. By 2007 some 450 units of all types are reported as having been delivered.

Description

Giraffe is a family of G/H (formerly C-band) frequency agile, low to medium altitude pulse doppler air search radars and combat control centers which can be used in mobile or static short to medium range air defense applications. Giraffe is designed to detect low-altitude, low cross-section aircraft targets in conditions of severe clutter and electronic countermeasures. When equipped as an air-defense command center Giraffe provides an air picture to each firing battery using manpack radio communication.

GIRAFFE uses Agile Multi-Beam (AMB), which includes an integrated Command, control and communication (C_3) system. This enables GIRAFFE to act as the command and control center in an air defense system, it can also be integrated into a sensor net for greater coverage. It is normally housed in a single 6m long shelter mounted on an all-terrain vehicle for high mobility. Additionally the shelter can be augmented with Nuclear, Biological and Chemical protection and light layers of armor to protect against small arms and fragmentation threats.

Manufacturers

- Ericsson (Telefonaktiebolaget L. M. Ericsson)
- Saab Microwave Systems

Variants

- Giraffe 40: This is a short-range (40 km instrumented) air defense radar with command and control capability. It employs a folding antenna mast that extends to a height of 13 meters when deployed and can be integrated with an Interogation Friend or Foe (IFF) capability. Coverage is stated to be from ground level to 10,000 meters in altitude. In Swedish service the radar is designated PS-70 and PS-701 and provides target data to RBS-70 SHORADS missiles and 40mm Bofors guns. A more powerful version with a 60 kW transmitter is known commercially as Super Giraffe and in Swedish service as PS-707. These radars are no longer marketed.

- Giraffe 50AT: This is the model used in the Norwegian NALLADS air defense system which combines the radar and RBS-70 missiles with 20 mm anti-aircraft guns to provide low-level air defense for the combat brigades of the Norwegian army. Mounted on a BV-202 all-terrain tracked vehicle this version has an instrumented range of 50 km. The antenna extends to a height of 7 meters and the system can control up to 20 firing units of guns or missiles or a combination of both. The Command and Control system features fully automatic track initiation, target tracking, target identification (IFF), target classification and designation, hovering helicopter detection threat evaluation and handling of "pop-up" targets.

It can also exchange data with Giraffe 75 or AMB systems as part of a larger network.

- Giraffe 75: This features a 13 meter antenna mast and is normally carried on a 6x6 5-ton cross-country truck which carries the radar and command and control shelter. Instrumented range is 75 km and altitude coverage extends from ground-level to 10,000 meters. An optional add-on unit extends the radars coastal defense capabilities. In Swedish service the radar is designated PS-90. In the Greek Air Force Giraffe 75 is used in combination with Contraves (now Rheinmetall defense) Skyguard/Sparrow fire control systems. 1 Giraffe typically controls 2 Skyguard systems each with 2 twin 35 mm GDF-005 guns and 2 Sparrow surface-to-air missile launchers.

- ARTE 740: This is a coastal defense radar based on the Giraffe 75 antenna and Giraffe AMB processing system optimized for surface and low-altitude coverage for the Swedish Amphibious Forces (formerly the Coastal Artillery). It is mounted on a MOWAG Piranha 10x10 armored vehicle. 6 systems are in service.

- Giraffe S: Optimized as a mobile radar for un-manned remote-controlled applications as a "gap-filler" in air defense early warning systems concentrating on small, low-flying targets over a long distance. It can also be employed as a coastal surveillance radar where targets are small surface vessels and sea-skimming missiles or aircraft. A new antenna extends range coverage to 180 km with altitude coverage from ground level to 6,000 meters. The antenna mast extends to 8 meters.

- GIRAFFE AMB: This newest member of the family, providing multi-beam 3-Dimensional air coverage at 5.4 to 5.9 GHz with instrumented ranges of 30, 60 and 100 km and altitude coverage extended from ground-level to 20,000 meters with 70-degree elevation coverage. Data rate is 1-scan per-second. Its maintained pulse density suppresses high cluttering in adverse weather conditions. Ultra-low antenna side-lobes combined with pulse-to-pulse and burst-to-burst frequency agility provides some resistance to jamming. As in previous Giraffe radars automatic hovering helicopter detection is provided as is an artillery and mortar locating function, allowing the radar to detect incoming rounds and give 20 seconds or more of warning before impact. Giraffe AMB is the principal sensor of the Swedish RBS 23 BAMSE air defense missile system but is available for many other applications. A skilled crew can deploy the radar in around 10 minutes and recover it in around 6 minutes.

Sea GIRAFFE

Sea GIRAFFE 3 D radar on Polish Corvette

Sea GIRAFFE is the naval variant of the GIRAFFE radar with AMB technology. It is specialized for rapidly detecting small, fast moving targets at all altitudes and small surface targets in severe clutter. Its roles include :

- Air surveillance and tracking
- Surface surveillance and tracking
- Target identification for weapon systems
- High-resolution splash spotting

Sea GIRAFFE can detect air and surface targets from the horizon to an altitude of 20,000 m (65,000 ft) at elevations up to 70º. It can simultaneously handle multiple threats approaching from different directions and altitudes, including diving anti-ship missiles.

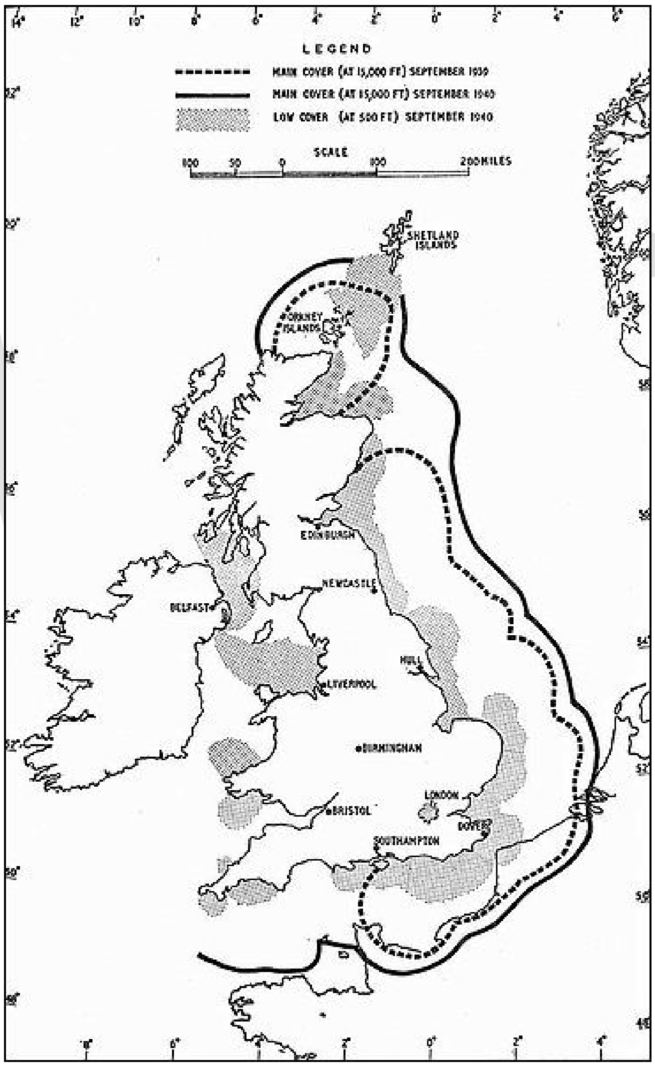
Users

- Australia: Installed on Anzac-class frigates. Recently ordered as a ground-based system, too.

- Brazil: In use by the Marine Corps since 1989, in the 50AT version, with a BV-206D tractor. To be replaced by the Saber M60.
- Canada: Sea Giraffe is used on Halifax class frigates.
- Estonia
- Finland
- Latvia
- Greece
- Malaysia; Sea Giraffe is installed on Lekiu class frigate.
- Norway
- Poland
- Serbia
- Sweden: used in coastal defence. Visby class corvettes also use Sea Giraffe.

Chapter 15

Chain Home



Radar Coverage 1939-1940

Chain Home was the codename for the ring of coastal Early Warning radar stations built by the British before and during the Second World War. The system otherwise known as AMES Type 1 (Air Ministry Experimental Station) consisted of radar fixed on top of a radio tower mast, called a 'station' to provide long-range detection of aircraft. This system had shortcomings in not being able to detect aircraft at lower altitudes and thus was used in conjunction with the **Chain Home Low** system, or AMES Type 2 which could detect aircraft flying at minimum altitude level of 500 ft.

Development

The Chain Home system was fairly primitive, since — in order to be battle-ready — it had been rushed into production by Sir Robert Watson-Watt's Air Ministry research station near Bawdsey. Watson-Watt, a pragmatic engineer, believed that "third-best" would do if "second-best" would not be available in time and "best" never available at all. Chain Home certainly suffered from glitches and errors in reporting.

It was in many ways technically inferior to German radar developments, but the better German technology came at a cost. The simpler Chain Home stations provided comprehensive coverage by the start of the Battle of Britain, whereas the Germans had only commissioned around 8 of their Freya stations by this time. Although simple, Chain Home could determine distance and direction of incoming aircraft formations. The method was called Radio Direction Finding (RDF), later called 'radar' (RADio direction And Ranging) in the U.S. Most stations were also able to measure the angle of elevation of the formation which, together with the range, gave the height; local geography prevented some stations from measuring elevation. Although not originally a design goal, the operators became very adept at estimating the size of detected formations from the shape of the displayed returns.

Chain Home looked nothing like later radar equipment. The antenna did not rotate: the transmitting array was formed of fixed wires strung between 110 m (360 ft)-high metal towers which sent out a "floodlight" beam of radio energy about 100° wide. The receiving array was on wooden towers about 73 m (240 ft) high, and consisted of two antennas at right angles to each other. The receiving antennas were directional, so the signal strength received by each depended on the angle between it and the target. An operator would manually adjust a comparator device to find what angle to the target best matched the relative strengths of the two received signals. The angle of elevation to the target was estimated by similar comparison of the signal strengths from a second pair of receiving antennas closer to the ground, which produced a different sensitivity in elevation. The time delay of the echo determined the range to the target.

The Chain Home stations were designed to operate at 20-50 MHz, the "boundary area" between high frequency and VHF bands at 30 MHz, although typical operations were at 20-30 MHz (the upper end of the HF band), or about a 12 m wavelength. The availability of multiple operating frequencies gave some protection from jamming. The detection range was typically 120 mi (190 km; 100 nmi), but could be better.

The Chain Home Low stations operated at 200 MHz on the VHF band, or about a 1.5 m wavelengh. Technically, they were not closely related to Chain Home, and they employed a rotating antenna.

Freya, by contrast, operated in the 2.5 to 2.3 m (120 to 130 MHz) band, with a maximum range of only 100 miles (160 km), and could not accurately determine altitude.

From May to August 1939 the German Zeppelin LZ130 *Graf Zeppelin II* made flights along Britain's North Sea coast to investigate the 100 m-high radio towers the British had erected from Portsmouth to Scapa Flow. LZ130 performed a series of radiometric tests and took photographs. German sources report the 12 m Chain Home signals were detected and suspected to be radar; however, the chief investigator was not able to prove his suspicions, so Germany went to war uncertain of British radar defences. Other sources are said to report different results.

The Germans observed 12 m pulse signals at the western front without being able to recognize their origin and purpose. In mid-June 1940, the German Aeronautic Research Institute (DVL) set up a special group under the direction of Professor von Handel and found out that the signals originated from radar installations on the coast of the English Channel. They pinpointed the location of the 12 m CH installations that up to then had been thought to be coastal radio stations. The observation that the transmissions of the individual stations were pulse-modulated, in order to avoid mutual interference, was exploited in July 1940 to put the CH out of service for some time.

Operations

The Chain Home stations were arranged around the British coast, initially in the South and East but later the entire coastline, including the Shetland Islands. They were first tested in the Battle of Britain in 1940 when they were able to provide adequate early warning of incoming *Luftwaffe* raids. Their early deployment had allowed the U.K. time to develop a well-integrated communication system to direct responses to enemy formations detected.

Chain Home had many limitations. With fixed antennae facing the sea, the Observer Corps had to be employed to report aircraft movements once the coast was reached. With detection poor below 5,000 ft (1,500 m), Chain Home Low stations were placed between Chain Home stations to detect aircraft down to 2,000 ft (610 m) but only out to 35 mi (56 km) from the coast, about one third the range of Chain Home.

Calibration of the system was carried out initially using a flight of mostly civilian-flown, impressed Avro Rota autogyros flying over a known landmark, the radar then being calibrated so that the position of a target relative to the ground could be read from the position on the display CRT. The Rota was used because of its ability to maintain a relatively stationary position over the ground, the pilots learning to fly in small circles while remaining heading into the wind.

During the battle, Chain Home stations — most notably the one at Ventnor, Isle of Wight — were attacked several times between 12 and 18 August 1940. On one occasion a section of the radar chain in Kent, including the Dover CH, was put out of action by a lucky hit on the power grid. However, though the wooden huts housing the radar equipment were damaged, the towers survived owing to their open steel girder construction. Because the towers were untoppled and the signals soon restored, the *Luftwaffe* concluded the stations were too difficult to damage by bombing and left them alone for the remainder of the war. Had the *Luftwaffe* realised just how essential the radar stations were to British air defences, it is likely that they would have expended great effort to destroy them.

The Chain Home system was dismantled after the war, but some of the tall steel radar towers remain, converted to new uses. One such 360-foot (110 m) high transmitter tower (picture below) can now be found at the BAE Systems facility at Great Baddow in Essex (2008). It originally stood at Canewdon, and is said to be the only Chain Home tower still in its original, unmodified form.

Among the tallest timber structures ever built in the United Kingdom, at least two of the wooden reception towers were still standing in 1955, at Hayscastle Cross. Unlike the transmitter tower pictured here, those at Hayscastle Cross were guyed.

Use by the Germans

The Germans deployed a passive radar system, the Kleine Heidelberg Parasit or Heidelberg-Gerät, which allowed them to track British aeroplanes using the radio signals from the Chain Home radars. The "floodlight" nature of the Chain Home transmissions provided a pair of signals which could be used to locate aircraft. The primary signal was received directly by the German receiver from the Chain Home transmitter; the second, weaker, signal was that reflected from the aircraft. The time delay between these two signals established how much longer was the reflected path compared to the direct path, and from geometry this longer path described an ellipse on which the aircraft must lie. The focal points of this ellipse were the transmitting and receiving antennas, and the Germans knew the location of both. A direction-finding antenna searching for the echo could be used to establish where on the ellipse the aircraft was. This system gave the Germans a radar with a range of up to 400 km (250 mi; 220 nmi), and an accuracy in range of 1–2 km (0.62–1.2 mi; 0.54–1.1 nmi) and in bearing of about 1°. The Heidelberg Parasit was not affected by window.

Chain Home sites

A chain home tower in Great Baddow

- Bawdsey: Suffolk (grid reference TM336380)
- Branscombe: Devon (SY1988)
- Brenish: Western Isles (NA9910024250)
- Bride: Isle of Man (NX4604)
- Broadbay: Western Isles (NB5314034470)
- Canewdon: Essex (TQ9094)
- Castell Mawr: Near Llanrhystud, Ceredigion, AMES No. 67 (SN5369)
- Dalby: Isle of Man (SC2178)
- Danby Beacon: Lealholm, North Yorkshire (NZ732097)
- Douglas Wood: Monikie, Angus (NO4862041515)
- Dover (Swingate): Kent (TR335429)
- Downderry: Cornwall
- Drone Hill: Near Coldingham, Borders (NT8447066535)
- Drytree: Goonhilly Downs, Cornwall (SW723218)
- Dunkirk, Kent (TR076595)
- Folly: Nolton, Pembrokeshire (SM858195)
- Great Bromley: Essex (TM104265)

- Greystone: County Down, Northern Ireland, AMES No. 61
- Hawks Tor: Plymouth, Devon
- Hayscastle Cross: Pembrokeshire (SM920256)
- High Steet, Darsham, Saxmundham, Suffolk, IP17 3QD (TM411720)
- Hillhead: Memsie, Aberdeenshire (NJ9430061700)
- Kilkeel: County Down, Northern Ireland AMES No. 78
- Kilkenneth: Tiree, Argyll and Bute (NL9408045570)
- Loth: Helmsdale, Sutherland (NC9590009600)
- Netherbutton: Holm, Orkney (HY4621104396)
- Nefyn: Gwynedd, AMES No. 66 (SH2704037575)
- Newchurch: Kent (TR0531)
- North Cairn: Near Stranraer, Dumfries, AMES No. 60 (NW97107074)
- Northam: Devon (SS4529)
- Noss Hill: Shetland Islands (HU3613015575)
- Ottercops Moss: Otterburn, Northumberland (NY944896)
- Pevensey: East Sussex (TQ644073)
- Poling: West Sussex (TQ043052)

Chapter 16

Counter-battery Radar and SLC-2 Radar

Counter-battery radar

A **counter-battery radar** detects artillery projectiles fired by one or more guns, howitzers, mortars and rocket launchers and from their trajectories locates the position on the ground of the gun, etc., that fired it. Alternatively, or in addition, it may determine where the projectile will land. The normal purpose of a counter-battery radar is to locate hostile batteries up to about 50 km away depending on the radar's capabilities.

If the radar is fast and has fast communications, then it may be possible to provide some warning to troops targeted by the incoming projectiles. However, many projectiles have a time of flight under a minute, which makes it difficult to give warnings without a highly automated communication system, unless the target is in the vicinity of the radar. Counter-battery radars can also be used to observe the fire of friendly artillery and calculate corrections to adjust its fire onto a particular place.

Radar is the most recently developed means of locating hostile artillery. The emergence of indirect fire in World War 1 saw the development of sound ranging, flash spotting and air reconnaissance, both visual and photographic. Radars, like sound ranging and flash spotting, require hostile guns, etc., to fire before they can be located.

History

The first radars were developed for anti-aircraft purposes just before World War 2. These were soon followed by fire control radars for ships and coastal artillery batteries. The latter observed the fall of shot enabling corrections to be plotted. It was also found that some radars could detect large projectiles in flight.

However, radar operators in light anti-aircraft batteries close to the front line found they were able to track mortar bombs. Probably helped by the fins of a mortar bomb producing a stronger return signal. This led to their dedicated use in this role, with special secondary instruments if necessary, and development of radars designed for mortar locating.

Locating mortars was relatively easy because their trajectory was sufficiently close to parabolic that the simple mathematics of parabolas could be used with analogue computers. Better radars were also able to detect howitzers when firing in high angle (elevation greater than 45 degrees), although in reality such use was quite rare.

Low angle trajectories normally used by guns, howitzers and rockets were more difficult. They could be detected but their shape, a segment of an ellipse, was impossible to resolve until efficient algorithms were developed and digital computers, usable on the battlefield, had achieved the necessary performance.

By the early 1970s radar systems capable of locating guns appeared possible, and many European members of NATO embarked on the joint Project Zenda. This was short-lived for unclear reasons, but the US embarked on Firefinder program and Hughes developed the necessary algorithms, although it took two or three years of difficult work.

The next step forward was European when in 1986 France, Germany and UK agreed the 'List of Military Requirements' for a new counter-battery radar. The distinguishing feature was that instead of just locating individual guns, etc., the radar was able to locate many simultaneously and group them into batteries with a centre point, dimensions and attitude of the long axis of the battery. This radar eventually reached service as EuroART's COBRA system.

However, operations in Iraq and Afghanistan led to a new need for a small counter-mortar radar, given 360 degree coverage and requiring a minimal crew, for use in forward operating bases. In another back to the future step it has also proved possible to add counter-battery software to battlefield airspace surveillance radars.

Description

The basic technique is to track a projectile for sufficient time to record a segment of the trajectory. This is usually done automatically, but some early and not so early radars required the operator to manually track the projectile. Once a trajectory segment is captured it can then be processed to determine its point of origin on the ground. Before digital terrain databases this involved interaction with a paper map to check the altitude at the coordinates, change the location altitude and recompute the coordinates until a satisfactory location was found.

The additional problem was finding the projectile in flight in the first place. The conical shaped beam of a traditional radar had to be pointing in the right direction, and to have sufficient power and accuracy the beam couldn't have too large an angle, typically about 25 degrees, which made finding projectile quite difficult. One technique was to deploy listening posts that told the radar operator roughly where to point the beam, in some cases the radar didn't switch on until this point to make it less vulnerable to electronic counter-measures (ECM). However, conventional radar beams were not notably effective.

Since a parabola is defined by just two points then tracking a segment of the trajectory was not notably efficient. The Royal Radar Establishment in UK developed a different approach. The Foster scanner converted the conical beam into one about 40 degrees wide and 1 degree vertical with an antenna that had only two predefined vertical positions. A mortar bomb was plotted as it passed through each of the beam positions to provide the necessary two points that could be processed by an analogue computer.

However, once phased array radars compact enough for field use and with reasonable digital computing power appeared they offered a better solution. A phased array radar has many transmitter/receiver modules. These are electronically controlled and cover a 90 degree arc without moving the antenna. They can detect and track anything in their field of view, providing they have sufficient computing power. They can filter out the targets of no interest (e.g.: aircraft) and depending on their capability track a useful proportion of the rest.

Counter battery radars are mostly X band because this offers the greatest accuracy for the small radar targets. However, C and Ku bands have also been used. Projectile detection ranges are governed by the radar cross section (RCS) of the projectiles. Typical RCS are:

-
    - Mortar bomb 0.01 m
    - Artillery shell 0.001 m
    - Light rocket (e.g. 122 mm) 0.009 m
    - Heavy rocket (e.g. 227 mm) 0.018 m

The best modern radars can detect shells at around 30 km and the others at 50+ km. Of course the trajectory has to be high enough to be seen by the radar at these ranges, and since the best locating results for guns and rockets are achieved with a reasonable length of trajectory segment close to the gun, long range detection does not guarantee good locating results. The accuracy of location is typically given by a circular error probable (CEP) (the circle around the target in which 50% of locations will fall) expressed as a percentage of range. Modern radars typically give CEPs around 0.3 - 0.4% of range. However, with these figures long range accuracy may be insufficient to satisfy the Rules of Engagement for counter-battery fire in counter insurgency operations.

Radars typically have a crew of 4 – 8 soldiers, although only one is needed to actually operate the radar. Older types were mostly trailer mounted with a separate generator, so took several minutes to bring into action and need a larger crew. However, self-propelled ones have been used since the 1960s. To produce accurate locations radars have to know their own precise coordinates and be precisely oriented. Until about 1980 this relied on conventional artillery survey, although gyroscopic orientation from the mid 1960s helped. Modern radars have an integral Position and Azimuth Determining System and GPS.

Radars can detect projectiles at considerable distances, and larger projectiles give stronger reflected signals. Detection ranges depend on capturing at least several seconds of a trajectory and can be limited by the radar horizon and the height of the trajectory. For non-parabolic trajectories it is also important to capture a trajectory as close as possible to its source in order to obtain the necessary accuracy.

Action on locating hostile artillery depends on policy and circumstances. It some armies radars may have authority to send target details to counter-battery fire units and order them to fire, in others they may merely report data to an HQ that then takes action. Modern radars usually record the target as well as the firing position of hostile artillery. However, this is usually for intelligence purposes because there is seldom time to alert the target with sufficient warning time in a battlefield environment, even with data communications. However, there are exceptions. The new Lightweight Counter Mortar Radar (LCMR – AN/TPQ 48) is crewed by two soldiers and designed to be deployed inside forward positions, in these circumstances it can immediately alert adjacent troops as well as pass target data to mortars close by for counter-fire.

Threats

Radars are vulnerable and high value targets; they are easy to detect and locate if the enemy has the necessary ELINT/ESM capability. The consequences of this detection are likely to be attack by artillery fire or aircraft (including anti-radiation missiles) or ECM. The usual measures against detection are using a radar horizon to screen from ground based detection, minimising transmission time and using alerting arrangements to tell the radar when hostile artillery is active. Deploying radars singly and moving frequently reduces exposure to attack.

However, in low threat environments, such as the Balkans in the 1990s, they may transit continuously and deploy in clusters to provide all-around surveillance.

In other circumstances, particularly counter-insurgency, where ground attack with direct fire or short range indirect fire is the main threat radars deploy in defended localities but do not need to move, unless they need to cover a different area.

Counter Battery Radar Systems

- Radar FA No 8 (Green Archer) (mortar locating)
- Radar FA No 15 (Cymbeline) (mortar locating)
- AN/MPQ 10 (mortar locating)
- AN/MPQ 4 (mortar locating)
- AN/KPQ 1 (mortar locating)
- AN/TPQ-36 Firefinder radar
- AN/TPQ-37 Firefinder radar
- AN/TPQ-48 Lightweight Counter Mortar Radar
- COBRA
- ARTHUR
- BEL Weapon Locating Radar
- Red Color
- MAMBA
- EL/M-2084 combined air surveillance and counter-battery radar
- Giraffe AMB combined air surveillance and counter-battery radar
- SNAR 1, SNAR 2 - NATO reporting name PORK TROUGH (Mortar Locating)

- ARSOM 2P - NATO reporting name SMALL YAWN
- NATO reporting name LITTLE FRED

SLC-2 Radar

SLC-2 counter battery radar

The **SLC-2 Radar** is a counter-battery radar designed to accurately locate hostile artillery, rocket and ground-to-ground missile launchers immediately after enemy firing, and to support friendly artillery by providing guidance of counter-fire.

SLC-2 radar can also be applied in adjusting firing of friendly weapons or rockets. With slight modification to software parameters, SLC-2 radar can also be used to detect and track low flying targets such as light aircraft, helicopters and RPVs.

SLC-2 systems have sometimes been mounted on a Dongfang EQ2102 3.5 ton truck.

Development

Four AN/TPQ-37 Firefinder radar have been sold to China and this had become the foundation of SLC-2 radar development. Aside from political reasons, the US$ 10 million plus unit price tag of TPQ-37 (including after sale logistic support) was simply too costly for Chinese. Decision was made to develop a domestic equivalent after mastering the technologies of TPQ-37. After the initial test of TPQ-37 in Tangshan (汤山) Range near Nanjing in 1988, and in Xuanhua District in October of the same year, several shortcomings of TPQ-37 were discovered and further intensive tests were conducted and completed in 1994.

The requirement of the Chinese domestic equivalent was subsequently modified to address these issues revealed in trials. Due to the limitation of the Chinese industrial capability at the time, decision was made to develop the Chinese domestic equivalent in several steps. The first step was to develop a smaller one, which would result in the Chinese equivalent of AN/TPQ-36 Firefinder radar, and based on the experience gained from this program, a more capable larger version in the same class of AN/TPQ-37 Firefinder radar would be developed, which eventually resulted in SLC-2 series.

Type 373 Radar

This is the predecessor of SLC-2 radar. Type 373 radar is fielded after the Type 704 Radar series, which Type 373 radar is based on. Type 373 radar is designed to specifically improve the performance of TPQ-37 by solving the shortcoming revealed in tests. One of limitations of TPQ-37 revealed in tests was that the it was less effective against projectiles with flat trajectory, so it is much more effective against howitzer and mortar rounds than rounds from 130 mm towed field gun M1954 (M-46) and its Chinese derivative Type 59-1. Type 373 radar is designed to improve the capability against rounds with flat trajectory.

Another problem revealed in the tests was that the reliability of TPQ-37 is much lower than what was claimed. The reason was that when TPQ-37 was deployed in environments with high humidity and high level of rainfall (southern China), high salinity (coastal regions), high altitude (southwestern China), and subjected to daily high temperature differences (northwestern China), malfunctions occurs more frequently. Type 373 radar was designed specifically to improve the reliability against these harsh environmental factors.

SLC-2

As Chinese capability in microelectronics matured, an updated version of passive phased array Type 373 radar is developed, designated as SLC-2. This is a fully solid-state, highly digitized version that adopts planar active phased array antenna.

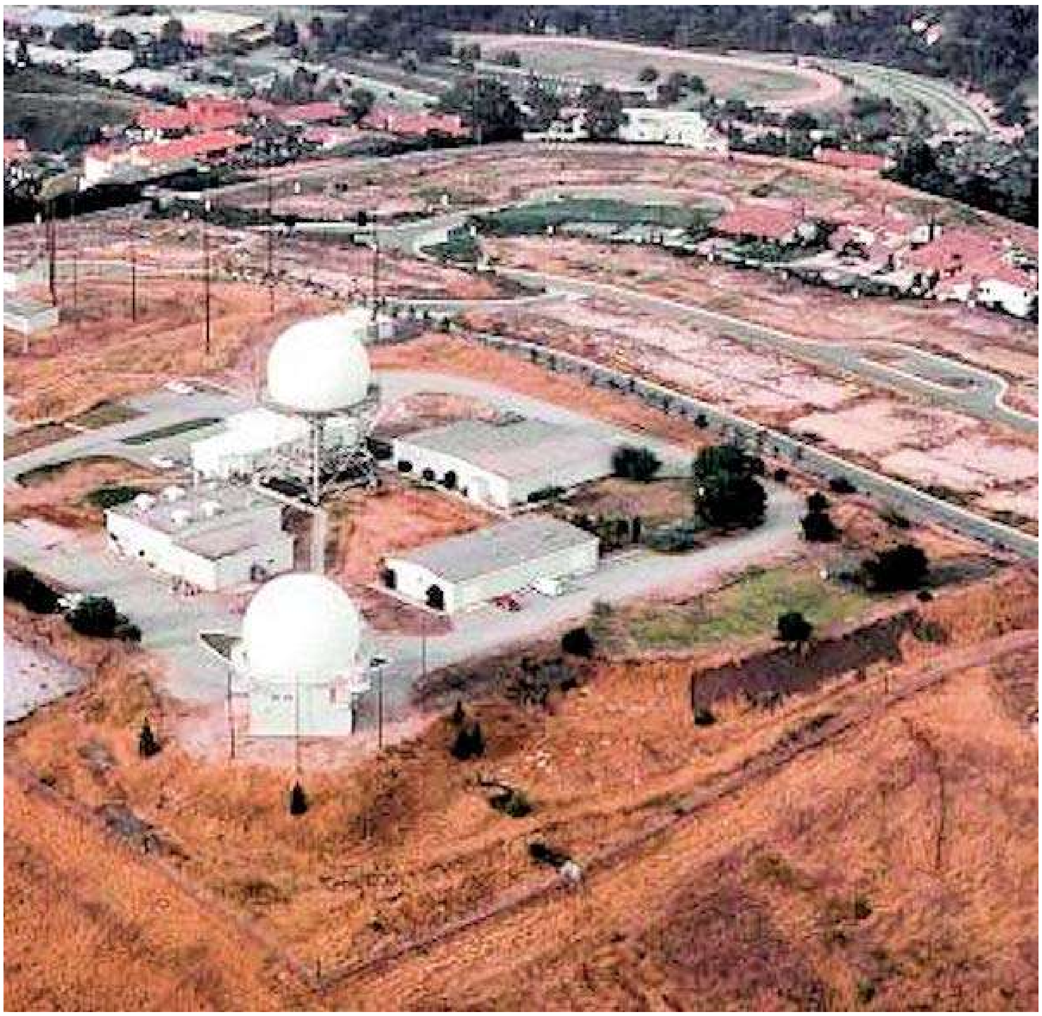
One of the shortcomings of TPQ-37 revealed in tests was in its multi-targeting capability. When enemy artillery batteries located more than two hundred meters apart fires simultaneously, TPQ-37 could provide accurate coordinate for distance, but coordinates for positions were less accurate. This would not be a problem for most users because TPQ-37 can be used in pairs in conjunction, provide accurate coordinates for locations. However, these costly radars could not be purchased in large numbers and China thus developed the capability for SLC-2 to provide accurate coordinates for both distance and position.

Specifications

- S - band
- Detection range: (for 80% detection probability against 81-mm mortar rounds sized target)
    - For artillery—35 km
    - For rockets—50 km
- Accuracy: 0.35% of range (for range more than 10 km)
    - 35 m (for range less than 10 km)
- Peak power: 45 kW
- Noise: 3dB
- Clutter improvement factor: 55 dB
- Other features:
    - Active phased array antenna with electronic scanning both in azimuth and elevation
    - Sophisticated computer-controlled digital signal processing
    - Comprehensive online or offline BITE
    - Automatic/manual height correction with digital/video map
    - Various effective ECCM

Chapter 17

Joint Surveillance System



The former J-31 San Pedro JSS ARSR-1 radar site, California

USAF Battle Control System operators monitor the skies from the floor of the program's Eastern Air Defense Sector location.

The **Joint Surveillance System (JSS)** is a joint United States Air Force and Federal Aviation Administration system for the atmospheric air defense of North America. It replaced the Semi Automatic Ground Environment (SAGE) system in 1983.

Overview

The JSS consists of long range surveillance radars, primarily operated and maintained by the Federal Aviation Administration (FAA), but providing communication and radar data to both FAA and United States Air Force control centers.

Air Route Surveillance Radar

FAA equipment is a primarily a mixture of Long Range Air Route Surveillance Radars (ARSR) of various types, although some use legacy AN/FPS radars. They are co-located with UHF ground-air-ground (G/A/G) transmitter/receiver (GATR) facilities at many locations. Fourteen sites have VHF radios as well. The GATR facility provides radio access to fighters and Airborne early warning and control (AEW&C) aircraft from the SOCCs. The JSS has been enhanced under the FAA/Air Force Radar Replacement Program with 44 ARSR-4/FPS-130 radars to replace some of the many previous long-range radars. This provides common, high-performance, unattended radars. The ARSR-4/FPS-130 is a 3-D long range radar with an effective detection range of some 250 miles and has been fully integrated with JSS at all joint use sites.

These radars are generally unattended except for periodic FAA maintenance crews which visit the sites as necessary.

Sector Operations Control Centers

The USAF Air Combat Command portion of the JSS is composed of three Continental United States (CONUS) Sector Operations Control Centers (SOCC) equipped with Battle Control System-Fixed (BCS-F) displays. Three of the SOCCs are located in the Continental United States (CONUS) at the following locations:

- Rome, New York 43°13′00″N 075°24′21″W / 43.2166667°N 75.40583°W (Eastern Air Defense Sector)
- Tyndall AFB, Florida 30°04′30″N 085°35′39″W / 30.075°N 85.59417°W (Air Operations Center for AFNORTH)
- McChord Field, Washington 47°07′18″N 122°30′14″W / 47.12167°N 122.50389°W (Western Air Defense Sector)

A SOCC is located in Alaska at Elmendorf AFB, in Hawaii at Wheeler Field and two in Canada at CFB North Bay, Ontario. The mission of the SOCC network is peacetime air sovereignty and surveillance. Wartime functions are available if necessary. The SOCCs accept data from multiple sensors, automatically process this data and display data for detection, tracking and identification of air targets, and the assignment and direction of interceptor aircraft to ensure peacetime air sovereignty.

Each SOCC functions as the primary command and control center in each NORAD region during crisis or attack as long as they are capable.

CONUS SOCCs receive data from 46 radar sites. Some 14 more sites feed data to Elmendorf AFB, Alaska and two radar sites supply data for the SOCC at Hickam Field, Hawaii. A total of 24 air surveillance radar networks in Canada feed data to two SOCCs located at CFB North Bay, Ontario.

Command and control can be transitioned to the E-3AAirborne early warning and control (AEW&C) for survivability as the tactical situation warrants. In peacetime, six of these aircraft are assigned to co-operate with the JSS. ROCC information is also passed to the North American Air Defense Command (NORAD) Combat Operations Centre (COC) at Colorado Springs, Colorado.

Radar stations

Site Number	NORAD-ID	Name	State	Radar Type	Location	USAF Sector	FAA Sector	Notes
QPC		Haleyville	AL	AN/FPS-67B	34°24′56″N 087°32′23″W / 34.41556°N 87.53972°W	EADS	ASO Southern	Radar developed by Raytheon for SAGE system
MGM		Montgomery	AL	ARSR-1D	32°12′42″N 086°10′06″W / 32.21167°N 86.16833°W	EADS	ASO Southern	In rural area, 13.2 miles (21.2 km) southeast of Montgomery.
QXR	Z-237	Russellville	AR	AN/FPS-64A	35°24′10″N 092°59′39″W / 35.40278°N 92.99417°W	WADS	ASW Southwest	Former ADCOM SAGE radar site, still uses the FPS-64A.
TXK		Texarkana	AR	AN/FPS-67B	33°21′35″N 093°55′22″W / 33.35972°N 93.92278°W	WADS	ASW Southwest	Replaced ADCOM SAGE Texarkana AFS M-91 site
J-29	Z-247	Humboldt Mountain	AZ		33°58′53″N 111°47′53″W / 33.98139°N 111.79806°W		ASW Southwest	Opened 1992 at former ADCOM Mount Lemmon AFS site. Closed 2000, replaced by J-29A
J-29A		Ajo	AZ	ARSR-4	32°25′52″N 112°56′42″W / 32.43111°N	WADS	ASW Southwest	Opened 2000 at former ADCOM Ajo AFS site,

					112.945°W			replaced J-29 near Phoenix
QXP		Seligman	AZ	ARSR-3	35°21′10″N 112°56′59″W / 35.35278°N 112.94972°W	WADS	AWP Western Pacific	Remote site on top of mountain peak.
J-83	Z-33	Crescent City	CA		41°33′33″N 124°05′10″W / 41.55917°N 124.08611°W		AWP Western Pacific	Former ADCOM Klamath AFS, Closed 1995, replaced by J-83A
J-83A		Rainbow Ridge	CA	ARSR-4	40°23′39″N 124°09′58″W / 40.39417°N 124.16611°W	WADS	AWP Western Pacific	Replaced J-83 and J-34. Remote site on top of mountain peak.
J-34	Z-37	Point Arena	CA		38°53′35″N 123°32′40″W / 38.89306°N 123.54444°W		AWP Western Pacific	Former ADCOM SAGE Point Arena AFS, closed 1995. Replaced by J-83A
J-33	Z-38	Mill Valley	CA	ARSR-4	37°55′26″N 122°35′51″W / 37.92389°N 122.5975°W	WADS	AWP Western Pacific	Former ADCOM SAGE Mill Valley AFS, inactivated 1980. Now FAA site.
J-32	Z-236	Paso Robles	CA	ARSR-4	35°23′41″N 120°21′15″W / 35.39472°N 120.35417°W	WADS	AWP Western Pacific	FAA site since 1960. Former USAF SAGE site Z-236, replacing Cambria AFS, Became JSS site in 1980

J-31	Z-39	San Pedro	CA		33°44′46″N 118°20′10″ W / 33.74611°N 118.33611° W		AWP Western Pacific	Former ADCOM San Pedro Hill AFS inactivated 1995. JSS site closed, replaced by Navy ARSR-4 site J-36A on San Clemente Island.
J-36A		San Clemente Island (USN)	CA	ARSR-4	32°53′03″N 118°27′03″ W / 32.88417°N 118.45083° W	WADS	AWP Western Pacific	New site established in late 1990s located on very remote location.
J-30	Z-76	Mount Laguna	CA	ARSR-4	32°52′34″N 116°24′54″ W / 32.87611°N 116.415°W	WADS	AWP Western Pacific	Replaced ADCOM Mount Laguna AFS inactivated 1991. Second ARSR-4 installation
J-35		Vandenburg AFB	CA	ARSR-4	34°35′13″N 120°35′41″ W / 34.58694°N 120.59472° W	WADS		USAF JSS site (not used by the FAA)
DNV	Z-212	Denver	CO	ARSR-1D	39°35′39″N 104°41′35″ W / 39.59417°N 104.69306° W	WADS	ANM Northwest Mountain	Opened in 1963 by FAA, was data tied-into the ADCOM SAGE network.
GJC	Z-215	Grand Junction	CO	ARSR-2	39°38′19″N 108°45′45″ W / 39.63861°N 108.7625°W	WADS	ANM Northwest Mountain	Opened in 1963 by FAA, was data tied-into the ADCOM

								SAGE network.
TCO	Z-222	Trinidad	CO	ARSR-2	37°32′49″N 104°00′50″ W / 37.54694°N 104.01389° W	WADS	ANM Northwest Mountain	Opened in 1963 by FAA, was data tied-into the ADCOM SAGE network.
J-04	Z-327	Whitehouse NOLF	FL	ARSR-4	30°20′45″N 081°52′25″ W / 30.34583°N 81.87361°W	EADS	ASO Southern	Replaced ADCOM M-114 SAGE site at NAS Jacksonville inactivated 1981.
J-05	Z-211	Patrick AFB	FL		28°12′50″N 080°35′57″ W / 28.21389°N 80.59917°W		ASO Southern	Former ADCOM SAGE site, inactivated 1988. Used until 1996 by FAA.
J-05A		Melbour-e	FL	ARSR-4	28°05′03″N 080°47′53″ W / 28.08417°N 80.79806°W	WADS	ASO Southern	Replaced J-05 with new ARSR-4 installation.
J-06	Z-210	Richmond	FL	ARSR-1F	25°37′24″N 080°24′16″ W / 25.62333°N 80.40444°W		ASO Southern	Former ADCOM Richmond AFS, closed 1992, destroyed by Hurricane Andrew
J-06A		Tamiami	FL	ARSR-4	25°38′50″N 080°30′19″ W / 25.64722°N 80.50528°W	EADS	ASO Southern	Replaced destroyed J-06 by FAA at new location with ARSR-4 radar.
J-07	Z-209	NAS Key West	FL	ARSR-4	24°35′04″N 081°41′21″ W /	EADS	ASO Southern	ADCOM SAGE site closed 1979,

					24.58444°N 81.68917°W			now joint-use Navy/FAA radar
J-09	Z-330	Fort Lonesome	FL		27°38′44″N 082°07′58″ W / 27.64556°N 82.13278°W		ASO Southern	Opened in 1980 replacing ADCOM SAGE site M-129 at MacDill AFB. Closed 1998
J-09A		Fort Green	FL	ARSR-4	27°42′02″N 082°00′25″ W / 27.70056°N 82.00694°W	EADS	ASO Southern	In agricultural area 32.9 miles (52.9 km) east-southeast of Tampa.
J-10	Z-333	Cross City	FL	ARSR-4	29°44′38″N 083°00′03″ W / 29.74389°N 83.00083°W	EADS	ASO Southern	New site opened in 1980 replaced ADCOM SAGE Cross City AFS TM-200.
J-11	Z-198	Tyndall AFB	FL	ARSR-4	30°04′33″N 085°36′39″ W / 30.07583°N 85.61083°W	EADS	ASO Southern	Opened in 1983, replaced ADCOM TM-198 site on the base.
QHN		Ashburn	GA	ARSR-1E	31°41′45″N 083°45′01″ W / 31.69583°N 83.75028°W	EADS	ASO Southern	In rural location, 25.2 miles (40.6 km) east-northeast of Albany, GA
QNK		Lincolnton	GA	ARSR-3	33°45′35″N 082°28′01″ W / 33.75972°N 82.46694°W	EADS	ASO Southern	Replaced ADCOM SAGE site at Aiken AFS, South Carolina (SM-159)

QJO		Arlington	IA	ARSR-3	42°46′06″N 091°36′55″ W / 42.76833°N 91.61528°W	WADS	ACE Central	In rural location, 41.7 miles (67.1 km) east-northeast of Waterloo, IA
QVA		Ashton	ID	ARSR-2	44°33′45″N 111°26′41″ W / 44.5625°N 111.44472° W	WADS	ANM Northwest Mountain	Opened 1963. On mountain peak 2.3 miles (3.7 km) south-southewest of Yellowstone National Park Airport, ID
BOI	Z-223	Boise	ID	ARSR-2	44°26′33″N 116°08′13″ W / 44.4425°N 116.13694° W	WADS	ANM Northwest Mountain	Opened in 1963 by FAA. Located atop Snowbank Mountain. Vegan feeding information into the ADCOM SAGE network in 1963.
JOL		Elwood	IL	ARSR-3	41°25′22″N 088°03′30″ W / 41.42278°N 88.05833°W	EADS	AGL Great Lakes	In rural location, 7.2 miles (11.6 km) south of Joilet, IL
IND		Indianapolis	IN	ARSR-1E	39°44′46″N 086°17′05″ W / 39.74611°N 86.28472°W	EADS	AGL Great Lakes	In urban area, 2.3 miles (3.7 km) north of Indianapolis International Airport; 7102 Howard St,

								Indianapolis, IN 46241
QTZ		La Grange	IN	ARSR-1E	41°37′52″N 085°24′53″ W / 41.63111°N 85.41472°W	EADS	AGL Great Lakes	Located in suburbs, 1 mile (1.6 km) south of La Grange, IN.
GCK	Z-226	Garden City	KS	ARSR-2	37°39′51″N 100°52′18″ W / 37.66417°N 100.87167° W	WADS	ACE Central	FAA site since 1964 in highly agricultural area, , was data tied-into the ADCOM SAGE network. 21.3 miles (34.3 km) south of Garden City, KS.
QBZ		Oskaloosa	KS	ARSR-2	39°13′19″N 095°14′46″ W / 39.22194°N 95.24611°W	WADS	ACE Central	In rural area, 17.3 miles (27.8 km) north of Larwence, KS.
J-14	Z-248	Lake Charles AFS	LA		30°11′05″N 093°10′30″ W / 30.18472°N 93.175°W		ASW Southwest	Former ADCOM SAGE site at former Lake Charles AFB. Closed in the 1990s and moved to J-14A
J-14A		Lake Charles	LA	ARSR-4	30°21′38″N 093°30′41″ W / 30.36056°N 93.51139°W	WADS	ASW Southwest	New site located in rural area 23.5 miles (37.8 km) east-northeast of former site.
J-13	Z-246	Slidell	LA	ARSR-4	30°20′53″N	EADS	ASW	Former

					089°46′46″ W / 30.34806°N 89.77944°W		Southwest	ADCOM SAGE site, on north side of Lake Pontchartrain, 32.5 miles (52.3 km) north-northeast of New Orleans
QHA		Cummington	MA	AN/FPS-66B	42°28′29″N 072°58′05″ W / 42.47472°N 72.96806°W	EADS	ANE New England	Located atop Bryant Mountain. Using ADCOM SAGE radar.
J-53	Z-10	North Truo	MA	ARSR-4	42°02′03″N 070°03′15″ W / 42.03417°N 70.05417°W	EADS	ANE New England	On former ADCOM North Truro AFS closed in 1994.
J-54	Z-110	Bucks Harbor	ME	ARSR-4	44°37′46″N 067°23′43″ W / 44.62944°N 67.39528°W	EADS	ANE New England	On former ADCOM Bucks Harbor AFS closed in 1979
J-63		Caribou	ME	ARSR-4	46°53′09″N 067°58′17″ W / 46.88583°N 67.97139°W	EADS	ANE New England	Former Army Nike IFC L-58C of Loring AFB Defense Area
CPV		Coopersville	MI	AN/FPS-66	43°02′44″N 085°59′32″ W / 43.04556°N 85.99222°W	EADS	AGL Great Lakes	Using ADCOM SAGE Radar
J-58	Z-34	Empire	MI	ARSR-4	44°48′07″N 086°03′05″ W / 44.80194°N 86.05139°W	EADS	AGL Great Lakes	Former ADCOM Empire AFS. Became a USAF-FAA joint-use site in 1964, USAF inactivated

								1978
J-62	Z-397	Canton	MI	ARSR-4	42°16′36″N 083°28′27″ W / 42.27667°N 83.47417°W	EADS	AGL Great Lakes	First, was a temporary data-tie (Z-61 radar change-out). Now a permanent data-tie site in the JSS, replacing Port Austin AFS (Z-61/J-57).
QJE		Minneapolis	MN	ARSR-1E	44°45′09″N 093°13′40″ W / 44.7525°N 93.22778°W	WADS	AGL Great Lakes	Located 10.8 miles (17.4 km) south-southwest of Minneapolis-Saint Paul International Airport in urban area. Address is 13591 Harwell Path Apple Valley, MN 55124
J-60	Z-306	Nashwauk	MN	ARSR-4	47°23′51″N 093°10′13″ W / 47.3975°N 93.17028°W	WADS	AGL Great Lakes	New FAA/USAF JSS radar site; replaced Finland AFS, MN (Z-69) and Baudette AFS, MN (Z-132).
QJC		Tyler	MN	ARSR-2	44°11′37″N 096°12′15″ W / 44.19361°N 96.20417°W	WADS	AGL Great Lakes	In rural area of southwest Minnesota, 154.7 miles (249.0 km) west-southwest of Minneapolis.
STL		St. Louis	MO	ARSR-	38°42′03″N	WADS	ACE	In urban area,

				1E	090°23′26″ W / 38.70083°N 90.39056°W		Central	address is 2310 Ashby Rd St Louis, MO 63114
QMH		Newport	MS	ARSR-3	32°56′51″N 089°50′41″ W / 32.9475°N 89.84472°W	EADS	ASO Southern	In very rural area
J-77	Z-147	Malmstrom AFB	MT		47°30′05″N 111°12′11″ W / 47.50139°N 111.20306° W		ANM Northwest Mountain	ADCOM site closed 1996, Moved to J-77A.
J-77A		Bootlegger Ridge	MT	ARSR-4	47°36′49″N 111°17′25″ W / 47.61361°N 111.29028° W	WADS	ANM Northwest Mountain	Replacement JSS site for Malmstrom AFB radar site (Z-147 / J-77); Bootlegger Ridge ARSR-4 site is about 7 miles northeast of Great Falls.
J-78	Z-179	Lakeside (Kalispell)	MT	ARSR-4	48°00′41″N 114°21′54″ W / 48.01139°N 114.365°W	WADS	ANM Northwest Mountain	Located at former ADCOM Kalispell AFS.
QRL		Benson	NC	ARSR-1E	35°30′40″N 078°32′56″ W / 35.51111°N 78.54889°W	EADS	ASO Southern	FAA long-range radar site. Also known as Raleigh. Once considered as the JSS replacement for the ADCOM SAGE Fort Fisher AFS, NC (Z-115).

QRM		Charlotte	NC	ARSR-1	35°36′39″N 081°14′18″ W / 35.61083°N 81.23833°W	EADS	ASO Southern	In rural area, 10.2 miles (16.4 km) southeast of Hickory, NC
J-02	Z-115	Fort Fisher	NC	ARSR-4	33°58′38″N 077°54′56″ W / 33.97722°N 77.91556°W	EADS	ASO Southern	Fort Fisher AFS was an active ADCOM site until 1988; FAA site at former GATR faciity.
J-75	Z-303	Finley	ND	ARSR-4	47°31′42″N 097°54′03″ W / 47.52833°N 97.90083°W	WADS	AGL Great Lakes	Opened November 1979 at new JSS site, replacing the original Finley AFS, ND (Z-29). [Located at old GATR site, ~ a mile or so WNW of the former USAF radar site.]
J-76	Z-300	Watford City	ND	ARSR-4	47°40′44″N 103°46′50″ W / 47.67889°N 103.78056° W	WADS	AGL Great Lakes	New FAA/USAF JSS radar site; replaced Fortuna AFS, ND (Z-27), Minot AFS, ND (Z-28), & Opheim AFS, MT (Z-26). Site is located at the former Alexander, ND, gap-filler radar site, Z-177B / Z-28E.

NPL	Z-217	North Platte	NE	ARSR-2	40°49′58″N 100°44′53″ W / 40.83278°N 100.74806° W	WADS	ACE Central	FAA site since 1963, Former ADCOM SAGE site Z-217
J-51	Z-63	Gibbsboro	NJ	ARSR-4	39°49′29″N 074°57′15″ W / 39.82472°N 74.95417°W	EADS	AEA Eastern	Former ADCOM Gibbsboro AFS. USAF site closed 1984
GAL	Z-221	Gallup	NM	ARSR-2	36°04′33″N 108°51′37″ W / 36.07583°N 108.86028° W	WADS	ASW Southwest	Opened 1963 by FAA. Former ADCOM SAGE site Z-221. Also known as Farmington, NM; located above Washington Pass, north of Gallup.
QWC	Z-234	Mesa Rica	NM	ARSR-1E	35°14′15″N 104°12′16″ W / 35.2375°N 104.20444° W	WADS	ASW Southwest	Former ADCOM SAGE site Z-234.
J-28	Z-245	Silver City	NM		32°59′21″N 108°57′38″ W / 32.98917°N 108.96056° W		ASW Southwest	Closed 1990s Located atop Brushy Mountain. Part of the 1972 Southern Air Defense System. Now replaced by new ARSR-4 JSS site at Deming, NM (J-28A).

J-28A		Deming	NM	ARSR-4	32°29′30″N 107°09′59″ W / 32.49167°N 107.16639° W	WADS	ASW Southwest	Replaced JSS site at Silver City, NM (Z-245 / J-28).
BTM	Z-214	Battle Mountain	NV	ARSR-2	40°24′11″N 116°52′04″ W / 40.40306°N 116.86778° W	WADS	AWP Western Pacific	Located on top of Mt. Lewis, south of town. Earlier known as *Elko*.
J-52	Z-315	Riverhead	NY	ARSR-4	40°52′43″N 072°41′14″ W / 40.87861°N 72.68722°W	EADS	AEA Eastern	'New' FAA/USAF JSS radar site; replaced Montauk AFS, LI, NY (Z-45).
J-55	Z-312	Remsen	NY	ARSR-4	43°20′43″N 075°14′56″ W / 43.34528°N 75.24889°W	EADS	AEA Eastern	New FAA/USAF JSS radar site; replaced Watertown AFS, NY (Z-49). Also called 'Starr Hill.
J-56	Z-309	Dansville	NY	ARSR-1E	42°38′18″N 077°39′10″ W / 42.63833°N 77.65278°W	EADS	AEA Eastern	Replaced Lockport AFS, NY (Z-21).
CLE		Cleveland	OH	ARSR-1E	41°18′08″N 081°41′01″ W / 41.30222°N 81.68361°W	EADS	AGL Great Lakes	Located 13.7 miles (22.0 km) miles south of Cleveland.
QWO		London	OH	ARSR-1E	39°50′46″N 083°28′54″ W / 39.84611°N 83.48167°W	EADS	AGL Great Lakes	Located 3.3 miles (5.3 km) miles southwest of London, OH.
OEX		Oklahoma	OK	ARSR-4	35°24′11″N	WADS	ASW	FAA ARSR-4

		City			097°37′42″ W / 35.40306°N 97.62833°W		Southwest	Training Site. Located about a mile west of the Will Rogers World Airport.
QVN		Fossil	OR	ARSR-3	44°57′37″N 119°57′06″ W / 44.96028°N 119.95167° W	WADS	ANM Northwest Mountain	138.3|mi|km} east-southeast of Portland, OR
J-81	Z-345	Salem	OR	ARSR-4	44°55′22″N 123°34′25″ W / 44.92278°N 123.57361° W	WADS	ANM Northwest Mountain	Former ADCOM SAGE site. Also known as Laurel Mtn. and Dallas, OR. New FAA/USAF JSS radar site; replaced Mount Hebo AFS, OR (Z-100). FPS-90 came from Keno AFS, OR (Z-180); modified to FPS-116. First operational JSS site in the 25th NORAD Region, 1 May 1979, as OL AJ / 25th ADS.
QCF		Clearfield	PA	ARSR-3	41°04′13″N 078°33′01″ W / 41.07028°N 78.55028°W	EADS	AEA Eastern	Located 6.1 miles (9.8 km) west of Clearfield, PA in rural area.

J-61		Trevose	PA	ARSR-1	40°08′03″N 074°59′13″ W / 40.13417°N 74.98694°W		AEA Eastern	Temporary data-tie (during the Gibbsboro AFS {Z-63} JSS radar change-out). Then became a 'permanent' replacement for Z-63 until Gibbsboro re-opened with its ARSR-4 and closed in mid 1990s.
J-03	Z-324	Jedburg	SC	ARSR-4	33°04′11″N 080°13′14″ W / 33.06972°N 80.22056°W	EADS	ASO Southern	Replaced North Charleston AFS, SC (Z-113).
QOJ	Z-235	Joelton	TN	ARSR-1E	36°20′10″N 086°51′41″ W / 36.33611°N 86.86139°W	EADS	ASO Southern	Former ADCOM Joelton AFS closed in 1961 and taken over by FAA.
QYB	Z-233	Memphis	TN	ARSR-1	34°51′10″N 089°45′57″ W / 34.85278°N 89.76583°W	EADS	ASO Southern	Former ADCOM SAGE Site Z-233.
QYS		Rogers	TX	ARSR-1E	30°56′38″N 097°16′07″ W / 30.94389°N 97.26861°W	WADS	ASW Southwest	In rural area, 2.7 miles (4.3 km) west-northwest of Rogers, TX
J-27	Z-244	El Paso	TX		31°40′51″N 106°11′50″ W / 31.68083°N 106.19722° W	WADS	ASW Southwest	Located in Horizon City, TX. Activated in 1963 part of Southern Air Defense

								System. Closed in 1997, replaced by new ARSR-4 JSS sites at Eagle Peak, TX (J-27A) and at Deming, NM (J-28A).
J-27A		Eagle Peak	TX	ARSR-4	30°55′13″N 105°05′09″ W / 30.92028°N 105.08583° W	WADS	ASW Southwest	New site opened in late 1990s replacing J-27, 101.1 miles (162.7 km) SE of El Paso, TX in remote location on top of mountain.
J-15	Z-240	Ellington AFB	TX		29°36′56″N 095°10′23″ W / 29.61556°N 95.17306°W	WADS	ASW Southwest	ADCOM SAGE site closed in 1979. FAA took over, closed 1997. Now replaced by new ARSR-4 JSS site at Morales, TX (J-15A).
FTW	Z-231	Keller	TX	ARSR-1D	32°56′40″N 097°13′13″ W / 32.94444°N 97.22028°W	WADS	ASW Southwest	Also known as Fort Worth. Opened in 1960s, still using ARSR-1D.
J-15A		Morales	TX	ARSR-4	29°20′29″N 096°52′18″	WADS	ASW Southwest	Replaced Ellington

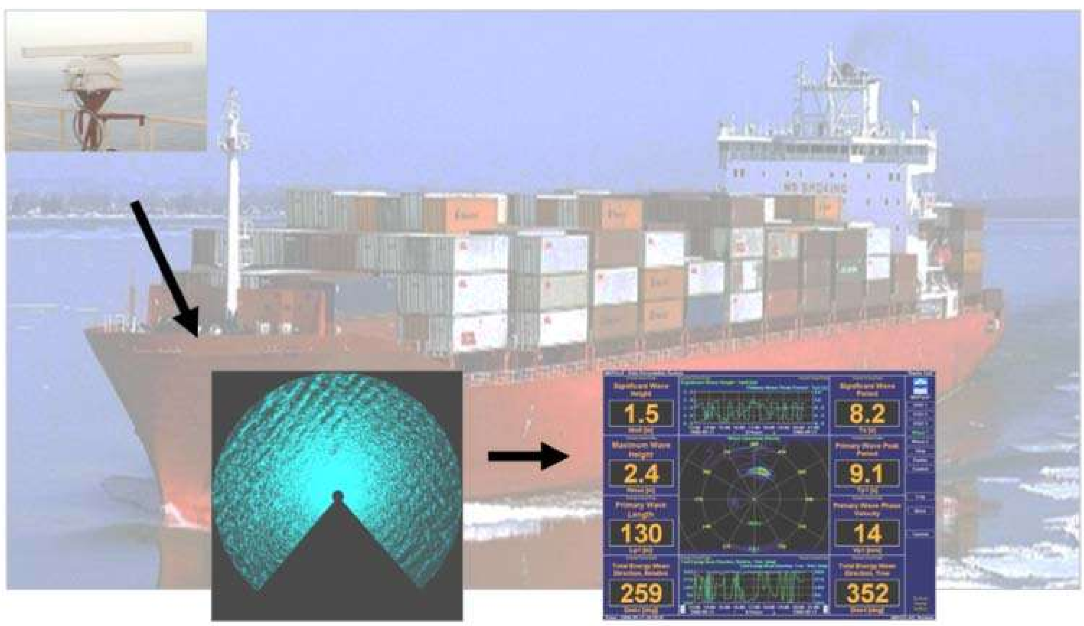
					W / 29.34139°N 96.87167°W			ANGB, TX, radar site (Z-240/J-15), 111.3 miles (179.1 km) north-northeast of Corpus Christi, TX
J-26	Z-242	Odessa	TX		32°33′15″N 102°25′40″ W / 32.55417°N 102.42778° W		ASW Southwest	Closed 1995, replaced by new ARSR-4 JSS site at King Mountain, TX (J-26A).
J-26A		King Mountain	TX	ARSR-4	31°17′06″N 102°16′24″ W / 31.285°N 102.27333° W	WADS	ASW Southwest	Replaced JSS site at Odessa / Andrews, TX (Z-243/J-26); located in remote West Texas.
J-16	Z-242	Oilton	TX	ARSR-4	27°29′56″N 098°58′10″ W / 27.49889°N 98.96944°W	WADS	ASW Southwest	Opened in 1972 as part of the Southern Air Defense System (SADS); Later ADCOM site 630th RADS OL-B, inactivated 31 December 1977.
J-25	Z-339	Sonora	TX	ARSR-3	30°28′16″N 100°33′29″ W / 30.47111°N 100.55806° W		ASW Southwest	Former ADCOM SAGE site, closed 1995, Now replaced by Rocksprings, TX, ARSR-4

								JSS site (J-25A).
J-25A		Rocksprings	TX	ARSR-4	30°02′48″N 100°16′04″ W / 30.04667°N 100.26778° W	WADS	ASW Southwest	Replaced JSS Site at Sonora, TX (J-25).
CDR	Z-216	Cedar City	UT	ARSR-2	37°35′35″N 112°51′49″ W / 37.59306°N 112.86361° W	WADS	ANM Northwest Mountain	Opened in 1962 by FAA
SLC	Z-213	Francis Peak	UT	ARSR-1E	41°01′58″N 111°50′18″ W / 41.03278°N 111.83833° W	WADS	ANM Northwest Mountain	Opened in 1962 by FAA. Also called "Salt Lake City"
QHZ		Horicon	WI	ARSR-2	43°26′45″N 088°29′32″ W / 43.44583°N 88.49222°W	EADS	AGL Great Lakes	In central Wisconsin in primarily agricultural area.
QBN		Binns Hall	VA	ARSR-3	37°22′58″N 076°59′55″ W / 37.38278°N 76.99861°W	EADS	AEA Eastern	Once considered as the JSS replacement for Cape Charles AFS, VA (Z-56).
J-01	Z-321	NAS Oceana	VA	ARSR-4	36°49′38″N 076°00′49″ W / 36.82722°N 76.01361°W	EADS	AEA Eastern	Former ADCOM SAGE site, now FAA/USAF/Navy JSS radar site; replaced Cape Charles AFS, VA (Z-56).
J-50	Z-318	The Plains	VA	ARSR-3	38°52′57″N 077°42′10″ W /	EADS	AEA Eastern	Opened in 1980. Replaced the

					38.8825°N 77.70278°W			ADCOM radar site at Fort Meade, MD (Z-227) and the FAA radar site at Suitland, MD.
J-79	Z-151	Mica Peak	WA	ARSR-4	47°34′26″N 117°04′52″ W / 47.57389°N 117.08111° W	WADS	ANM Northwest Mountain	Former ADCOM Mica Peak AFS (SM-151), deactivated in July 1975. Site transferred to FAA.
J-80	Z-44	Makah	WA	ARSR-4	48°22′18″N 124°40′30″ W / 48.37167°N 124.675°W	WADS	ANM Northwest Mountain	Former ADCOM Makah AFS (P-44), closed in 1982. Now USAF/FAA JSS site.
QSI	Z-224	Lovell	WY	ARSR-2	44°49′01″N 107°54′08″ W / 44.81694°N 107.90222° W	WADS	ANM Northwest Mountain	Located on Medicine Mountain. Earlier known as *Cody*.
LSK	Z-219	Lusk	WY	ARSR-2	42°35′38″N 104°35′18″ W / 42.59389°N 104.58833° W	WADS	ANM Northwest Mountain	Opened in 1963 by FAA
RKS	Z-218	Rock Springs	WY	ARSR-2	41°26′05″N 109°07′03″ W / 41.43472°N 109.1175°W	WADS	ANM Northwest Mountain	Opened in 1962 by FAA

Chapter 18

Wave Radar



Measuring ocean waves by use of marine radars

Wind waves can be measured by several radar remote sensing techniques. Several instruments based on a variety of different concepts and techniques are available to the user and these are all often called **wave radars**.

Instruments based on radar remote sensing techniques have become of particular interest in applications where it is important to avoid direct contact with the water surface and avoid structural interference. A typical case is wave measurements from an offshore platform in deep waters with the presence of high currents making the mooring of a wave buoy enormously difficult. Another interesting case is a ship in transit where having instruments in the sea is highly impractical and interference from the ships hull must be avoided.

Radar remote sensing

Terms and definitions

Basically there are two different *classes* of radar remote sensors for ocean waves.

- **Direct sensor** measures directly some relevant parameter of the wave system (like surface elevation or water particle velocity).
- **Indirect sensors** observe the surface waves via the interaction with some other physical process as for example the radar cross section of the sea surface.

Microwave radars may be used in two different *modes*;

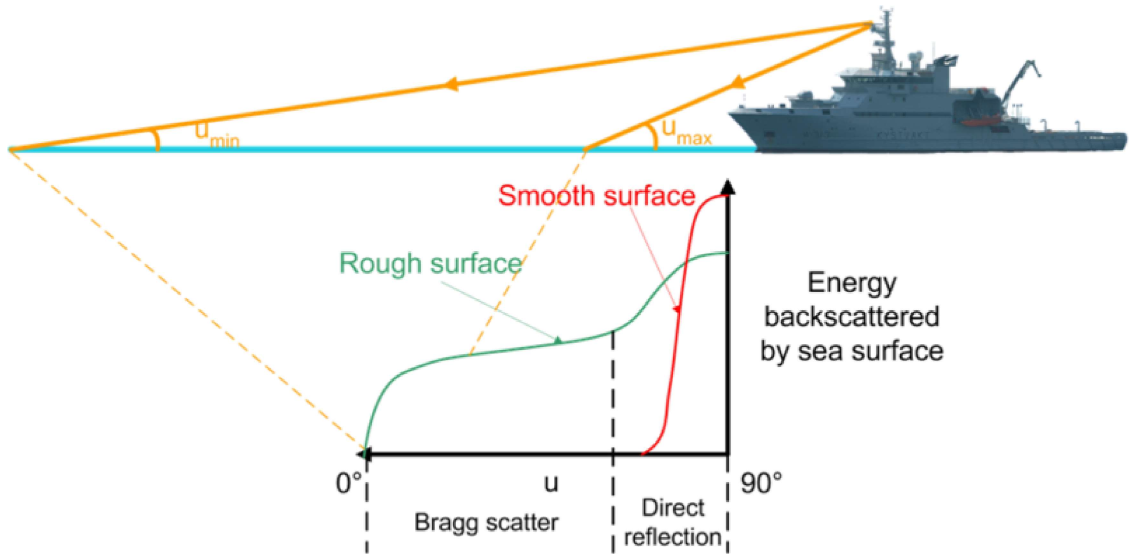
- The near **vertical mode**. The radar echo is generated by specular reflections from the sea surface.
- The **low grazing angle mode**. The radar echo is generated by Bragg scattering, hence wind generated surface ripple (capillary waves)must be present. The backscattered signal will be modulated by the large surface gravity waves and the gravity wave information is derived from the modulation of the backscattered signal. An excellent presentation of the theories of microwave remote sensing of the sea surface is given by Plant and Shuler (1980).

The radar footprint (the radial and azimuthal extent of the surface area to be illuminated by the radar) must be small in comparison with all ocean wavelength of interest. The radar spatial resolution is determined by the bandwidth of the radar signal and the beamwidth of the radar antenna.

The beam of a microwave antenna is dispersive, consequently the resolution becomes a function of range. The beam of an IR radar (laser) is non dispersive, the radar footprint is therefore independent of range.

HF radars utilize the Bragg scattering mechanism and do always operate at very low grazing angles. Due to the low frequency of operation the radar waves are backscattered directly from the gravity waves and surface ripple need not be present.

Radar transceivers may be coherent or non-coherent. Coherent radars measure Doppler-modulation as well as amplitude modulation, while non-coherent radars only measure amplitude modulation. Consequently, a non-coherent radar echo contains less information about the sea surface properties. Examples of non-coherent radars are conventional marine navigation radars.



Energy backscattered from sea surface as a function of angle

The radar transmitter waveform may be either unmodulated continuous wave, modulated or pulsed. An unmodulated continuous wave radar has no range resolution, but can resolve targets on the basis of different velocity, while a modulated or pulsed radar can resolve echoes from different ranges. The radar waveform plays a very important role in radar theory (Plant and Shuler, 1980)).

The wave radar performance is highly dependent on

- Mode of operation or measurement geometry (vertical or grazing)
- Class of system (direct or indirect)
- Frequency of operation
- Radar waveform (unmodulated CW or modulated/pulsed)
- Type of transceiver (coherent or non-coherent)
- Radar antenna properties

Remote sensing techniques

An excellent survey of different radar techniques for remote sensing of waves is given by Tucker (1991).

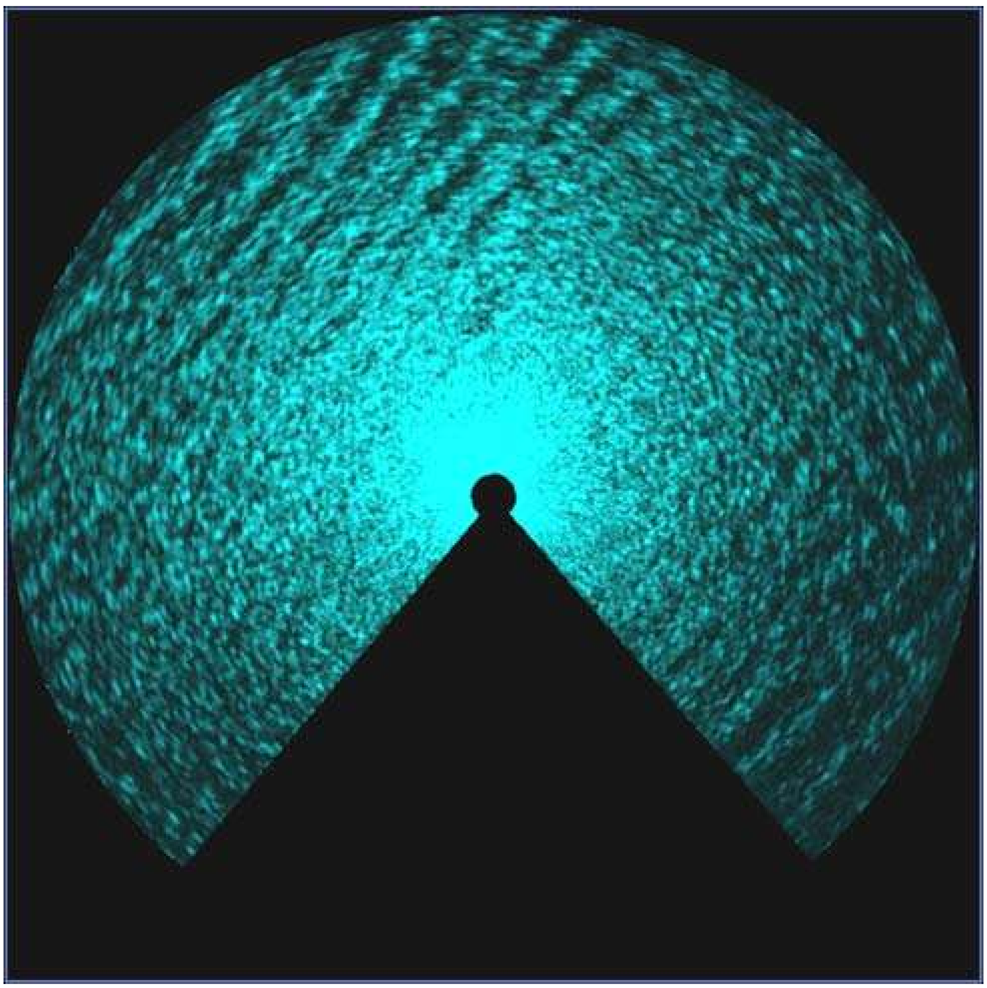
Laser altimeters

Laser altimeters are small and light weight and operate in the infra-red (IR) frequency band. They operate in vertical mode and normally use pulsed waveforms to perform direct measurements of sea surface elevation which easily can be converted to wave amplitude.

Microwave range finders

Microwave range finders also operate in vertical mode at GHz frequencies and is not as affected by fog and water spray as the laser altimeter. A continuous wave frequency modulated (CWFM) or pulsed radar waveform is normally used to provide range resolution. The beam is dispersive, hence the size of the footprint increases linearly with range.

One example of a microwave range finder is the Miros SM-094 which is designed for wave and water level (and tide) measurements. This sensor is applied as air gap (bridge clearance) sensor in NOAAs PORTS system. Another example is the Saab wave radar REX which is a derivative of a Saab tank radar.

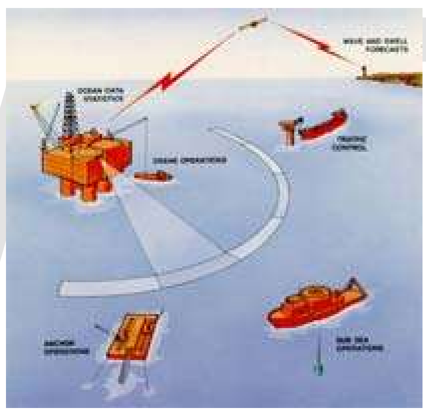


Digitized sea clutter image

An array of three vertical radars in a triangular configuration can be used to measure a directional wave spectrum. Algorithms and signal processing software similar to what is used in the processing of heave, pitch, roll buoys. A commercial system called "Directional WaveGuide" is available from the Dutch companies Enraf and Radac.

Marine navigation radars

Marine navigation radars (X band) provide sea clutter images which contain a pattern resembling a sea wave pattern. By digitizing the radar video signal it can be processed by a digital computer. Sea surface parameters may be calculated on the basis of these digitized images. The marine navigation radar operates in low grazing angle mode and wind generated surface ripple must be present. The marine navigation radar is non-coherent and is a typical example of an indirect wave sensor, because there is no direct relation between wave height and radar back-scatter modulation amplitude. An empirical method of wave spectrum scaling is normally employed. Marine navigation radar based wave sensors are excellent tools for wave direction measurements. A marine navigation radar may also be a tool for surface current measurements. Point measurements of the current vector as well as current maps up to a distance of a few km can be provided (Gangeskar, 2002). Miros WAVEX has its main area of application as directional wave measurements from moving ships. Another example of a marine radar based system is OceanWaves WaMoS II.



Measurement geometry of pulsed Doppler wave and current radar

The range gated pulsed Doppler microwave radar

The range gated pulsed Doppler microwave radar operates the in low grazing angle mode. By using several antennas it may be used as a directional wave sensor, basically measuring the directional spectrum of the horizontal water particle velocity. The velocity spectrum is directly related to the wave height spectrum by a mathematical model based on linear wave theory and accurate measurements of the wave spectrum can be provided under most conditions. As measurements are taken at a distance from the platform on which it is mounted, the wave field is to a small degree disturbed by interference from the platform structure.

Miros Wave and current radar is the only available wave sensor based on the range gated pulsed Doppler radar technique. This radar also uses the dual frequency technique to perform point measurements of the surface current vector

The dual frequency microwave radar

The dual frequency microwave radar transmits two microwave frequencies simultaneously. The frequency separation is chosen to give a “spatial beat” length which is in the range of the water waves of interest. The dual frequency radar may be considered a microwave equivalent of the high frequency (HF) radar. The dual frequency radar is suitable for the measurement of surface current. As far as wave measurements are concerned, the back-scatter processes are too complicated (and not well understood) to allow useful measurement accuracy to be attained.

The HF radar

The HF radar is well established as a powerful tool for sea current measurements up to a range of about 30 km. It operates in the MHz frequency band corresponding to a radar wavelength in the range of 10 to 300m. The Doppler shift of the first order Bragg lines of the radar echo is used to derive sea current estimates in very much the same way as for the dual frequency microwave radar. Two radar installations are normally required, looking at the same patch of the sea surface from different angles. CODAR Ocean Sensors (COS). The latest generation of shore-based ocean radar can reach more than 200 km for ocean current mapping and more than 100 km for wave measurements Helzel WERA. For all ocean radars, the accuracy in range is excellent. With shorter ranges, the range resolution gets finer. The angular resolution and accuracy depends on the used antenna array configuration and applied algorithms (direction finding or beam forming). The WERA system provides the option to use both techniques; the compact version with direction finding or the array type antenna system with beam forming methods.

Chapter 19

Active Phased Array Radar

Rear side of APAR onboard the German Navy Sachsen class frigate *Hessen*

APAR mounted on top of the German Navy Sachsen class frigate *Hamburg'*s superstructure

APAR (Active Phased Array Radar) is a shipborne multifunction radar (MFR) developed and manufactured by Thales Nederland. It is the first Active Electronically Scanned Array MFR employed on an operational warship.

Characteristics

APAR has four fixed (i.e., non-rotating) sensor arrays (faces), fixed on a pyramidal structure. Each face consists of 3424 transmit/receive (TR) modules operating at X band frequencies.

The radar provides the following capabilities:

- air target tracking of over 200 targets out to 150 km
- surface target tracking of over 150 targets out to 32 km
- horizon search out to 75 km
- "limited" volume search out to 150 km (in order to back up the volume search capabilities of the SMART-L)
- cued search (a mode in which the search is cued using data originating from another sensor)
- surface gunfire support
- missile guidance using the Interrupted Continuous Wave Illumination (ICWI) technique, thus allowing guidance of 32 semi-active radar homing missiles in flight simultaneously, including 16 in the terminal guidance phase
- "innovative" Electronic Counter-Countermeasures (ECCM)

Note: all ranges listed above are instrumented ranges.

Mountings

APAR aboard the Royal Netherlands Navy De Zeven Provinciën class frigate HNLMS *Tromp*

APAR aboard the German Navy Sachsen class frigate *Hessen* at Kiel Week 2007

APAR is installed on four Royal Netherlands Navy (RNLN) LCF De Zeven Provinciën class frigates and three German Navy F124 Sachsen class frigates. In August 2006, the Royal Danish Navy selected an anti-air warfare system designed around APAR and SMART-L over the competing BAE Systems SAMPSON Integrated Weapon System (SIWS) for their three new frigates, known as the Ivar Huitfeldt class, which is currently under construction. SIWS is based on SAMPSON multi-function and CEA-MOUNT fire control radars.

Live Missile Firings

APAR's missile guidance capability supports the Evolved Sea Sparrow Missile (ESSM) and the SM-2 Block IIIA missile. In November 2003, approximately 200 nautical miles (370 km) from the Azores, the missile guidance capabilities were tested with live firings for the first time. The firings were performed by the RNLN's HNLMS *De Zeven Provinciën* and involved the firing of a single ESSM and a single SM-2 Block IIIA. These firings were the first ever live firings involving a full-size ship-borne Active Electronically Scanned Array guiding missiles using the ICWI technique in an operational environment. As related by Jane's Navy International:

During the tracking and missile-firing tests, target profiles were provided by Greek-built EADS/3Sigma Iris PVK medium-range subsonic target drones. [...] According to the RNLN, ... "APAR immediately acquired the missile and maintained track until destruction". [...] These ground-breaking tests represented the world's first live verification of the ICWI technique.

In August 2004, a German Navy Sachsen class frigate completed a series of live missile firings at the Point Mugu missile launch range off the coast of California that included a total of 11 ESSM and 10 SM-2 Block IIIA missiles. The tests included firings against target drones such as the Northrop Grumman BQM-74E Chukkar III and Teledyne Ryan BQM-34S Firebee I, as well as against missile targets such as the Beech AQM-37C and air-launched Kormoran 1 anti-ship missiles.

Further live firings were performed by the RNLN's HNLMS *De Zeven Provinciën* in March 2005, again in the Atlantic Ocean approximately 180 nautical miles (330 km) west of the Azores. The tests involved three live-firing events including firing a single SM-2 Block IIIA at an Iris target drone at long range, a single ESSM at an Iris target drone, and a two-salvo launch (with one salvo comprising two SM-2 Block IIIAs and the other comprising two ESSMs) against two incoming Iris target drones. The long-range SM-2 engagement apparently resulted in an intercept at a range of greater than 100 km from the ship, with a missile-target miss distance of 8 feet (the warhead's proximity fuse having been disabled for the purposes of the test).

Operational Concept

APAR is typically paired with Thales Nederland's SMART-L radar (which operates at L band frequencies). SMART-L is a long-range Volume Search Radar (VSR) that is able to provide volume search and tracking out to 480 km. The whole system is called Anti-Air Warfare Systems (AAWS), and is based on the NATO Anti-Air Warfare (NAAWS) concept of the late 1980s. The principle behind this concept is that an X band MFR coupled with an L band VSR provides the optimal combination of complimentary capabilities: the VSR is optimized for long range detection and tracking of targets, while the MFR is optimized for medium range high accuracy tracking of targets, as well as horizon search and missile guidance functions.

As discussed below, some have questioned the optimality of separate MFR/VSR installations on-board ship. However, the wisdom of NATO's concept is evident to this author:

BAE Systems have also claimed that Sampson eliminates the need for several separate systems. They suggest that on the Type 45 destroyer, the Alenia Marconi Systems/Signaal [now Thales Nederland] S1850M long-range 3D radar that is designed to work in partnership with Sampson "really is superfluous and is not needed to perform the mission of the ship". BAE Systems believes that the reason the large volume search radar has been incorporated in to PAAMS is "more of a historic nature, associated with [the] work sharing issues" that were a huge problem during the trilateral Project Horizon.

Some tasks are difficult to combine, for example (long range) volume search takes a lot of radar resources, leaving little room for other tasks such as targeting. Combining volume search with other tasks also results either in slow search rates or in low overall quality per task. Driving parameters in radar performance is time-on-target or observation time per beam. This is perhaps a the [sic] key reason why the Royal Navy selected the S1850M Long Range Radar to complement Sampson on the Type 45 destroyers. It is also a reason why NATO in its NATO Anti-Air Warfare System study (NAAWS) defined the preferred AAW system as consisting of a complementary Volume Search Radar and MFR. This - as NATO points out - gives the added advantage that the two systems can use two different radar frequencies; one being a good choice for long range search, the other a good choice for an MFR (which is especially nice as physics makes both tasks difficult to combine).

Counter-Piracy Operations

Ships of the RNLN's De Zeven Provinciën class have been involved in counter-piracy operations off the Horn of Africa. The untraditional target set (i.e., small slow-moving or even static surface targets) can apparently be challenging for doppler radars designed to take on "high end" threats. However, according to Jane's International Defence Review:

[The RNLN has] reported great success using tailored surface-search software for the APAR sets fitted to the De Zeven Provinciën-class frigates deployed on anti-piracy roles. By sacrificing some of APAR's high-end anti-air warfare capabilities, which were deemed unnecessary for the anti-piracy role, its performance and resolution were improved in the surface-search role.