Visvesvaraya Technological University

Belagavi, Karnataka-590 018

A

SEMINAR REPORT ON

MILITARY RADAR

Submitted

in partial fulfillment of the requirement for the award of the Degree of

BACHELOR OF ENGINEERING

IN

ELECTRONICS AND COMMUNICATION ENGINEERING

by

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2019-20

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CERTIFICATE

This is to certify Mr Shubodaya H N, 8th semester B.E. in Electronics and Communication Engineering has presented and has successfully completed the seminar titled "**MILITARY RADAR**" in the presence of the undersigned examiners for the partial fulfillment of the award of B.E. Degree under VTU, Belagavi, for the academic year 2019-20

Guide H.O.D

Dr. ------------ Prof. -------------------

DECLARATION

I, **Shubodaya H N**, studying in the 8^{th} semester of Bachelor of Engineering in Electronics & Communication Engineering at Vidyavardhaka College of Engineering, Mysore, hereby declare that this seminar work entitled "Military radar" which is being submitted by me in the partial fulfilment for the award of the degree of Bachelor of Engineering in Electronics & Communication Engineering, from Visvesvaraya Technological University, Belagavi is an authentic record of me carried out during the academic year 2019-2020, under the guidance of Prof. Surekha T P, Department of Electronics & Communication Engineering, Vidyavardhaka College of Engineering, Mysuru.

I further undertake that the matter embodied in the dissertation has not been submitted previously for the award of any degree or diploma by me to any other university or institution.

Place: Mysuru   Shubodaya H N

Date:

ACKNOWLEDGEMENT

It is our proud privilege and duty to acknowledge the kind of help and guidance received from several people in preparation of this report. It would not have been possible to prepare this report in this form without their valuable help, cooperation and guidance.

First and foremost, I wish to record our sincere gratitude to Management of this college and to our beloved Principal, Dr.Sadashive gowda, Principal, Vidyavardhaka College of Engineering, Mysuru for his constant support and encouragement in preparation of this report and for making available library and laboratory facilities needed to prepare this report.

My sincere thanks to Dr.Chandrashekar Head, Department of Electronics and Communication Engineering, VVCE, for his valuable suggestions and guidance throughout the period of this report.

I express my sincere gratitude to my guides, Asst. Prof., Department of Electronics and Communication Engineering, VVCE, Mysuru for guiding us in investigations for this seminar. My discussions with him were extremely helpful. I hold him in esteem for his guidance, encouragement and inspiration.

The seminar on “Title” was very helpful to me in giving the necessary background information and inspiration in choosing this topic for the seminar. My sincere thanks to Prof.

--- and Prof.--- Seminar Coordinator for having supported the work related to this project. Their contributions and technical support in preparing this report are greatly acknowledged.

Last but not the least, I wish to thank my parents for financing my studies in this college as well as for constantly encouraging us to learn engineering. Their personal sacrifice in providing this opportunity to learn engineering is gratefully acknowledged.

Place: Mysuru Shubodaya H N

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CHAPTER 1

1.1. INTRODUCTION

Radar is a detection system that uses radio waves to determine the range, angle, or velocity of objects. It can be used to detect aircraft, ships, spacecraft, guided missiles, motor vehicles, weather formations, and terrain. A radar system consists of a transmitter producing electromagnetic waves in the radio or microwaves domain, a transmitting antenna, a receiving antenna (often the same antenna is used for transmitting and receiving) and a receiver and processor to determine properties of the object(s). Radio waves (pulsed or continuous) from the transmitter reflect off the object and return to the receiver, giving information about the object's location and speed.

Radar was developed secretly for military use by several nations in the period before and during World War II. A key development was the cavity magnetron in the United Kingdom, which allowed the creation of relatively small systems with sub-meter resolution. The term *RADAR* was coined in 1940 by the United States Navy as an acronym for Radio Detection and Ranging. The term *radar* has since entered English and other languages as a common noun, capitalization. The following derivation was also suggested during RAF RADAR courses in 1954/5: at Yates bury Training Camp: Radio Azimuth Direction and Ranging. The modern uses of radar are highly diverse, including air and terrestrial traffic control, radar astronomy, air-defense systems, antimissile systems, marine radars to locate landmarks and other ships, aircraft anti-collision 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 for geological observations. High tech radar systems are associated with digital signal processing, machine learning and are capable of extracting useful information from very high noise levels. Radar is a key technology that the self-driving systems are mainly designed to use, along with sonar and other sensors.

Other systems similar to radar make use of other parts of the electromagnetic spectrum. One example is LIDAR, which uses predominantly infrared light from lasers rather than radio waves. With the emergence of driverless vehicles, radar is expected to assist the automated platform to monitor its environment, thus preventing unwanted incidents.

Fig 1.1. Long-range radar antenna, used to track space objects and ballistic missiles.

Fig 1.2. Radar of the type used for detection of aircraft. It rotates steadily, sweeping the airspace with a narrow beam.

1.2. History

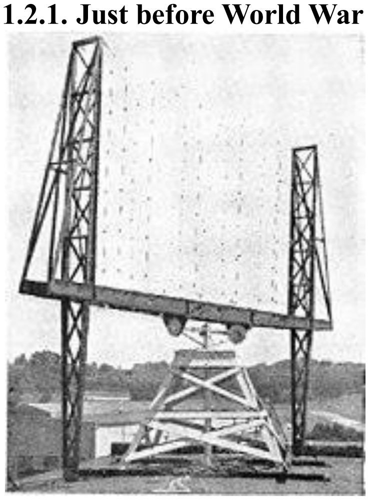
As early as 1886, German physicist Heinrich Hertz showed that radio waves could be reflected from solid objects. In 1895, Alexander Popov, a physics instructor at the Imperial Russian Navy school in Kronstadt, developed an apparatus using a coherer tube for detecting distant lightning strikes. The next year, he added a spark-gap transmitter. In 1897, while testing this equipment for 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 inventor 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 from the transmitter. He obtained a patent for his detection device in April 1904 and later a patent for a related amendment for estimating the distance to the ship. He also obtained a British patent on September 23, 1904 for a full radar system, that he called a *telemobiloscope*. It operated on a 50 cm wavelength and the pulsed radar signal was created via a spark-gap. His system already used the classic antenna setup of horn antenna with parabolic reflector and was presented to German military officials in practical tests in Cologne and Rotterdam harbour but was rejected.

In 1915, Robert Watson-Watt used radio technology to provide advance warning to airmen and during the 1920s went on to lead the U.K. research establishment to make many advances using radio techniques, including the probing of the ionosphere and the detection of lightning at long distances. Through his lightning experiments, Watson-Watt became an expert on the use of radio direction finding before turning his inquiry to shortwave transmission. Requiring a suitable receiver for such studies, he told the "new boy" Arnold Frederic Wilkins to conduct an extensive review of available shortwave units. Wilkins would select a General Post Office model after noting its manual's description of a "fading" effect (the common term for interference at the time) when aircraft flew overhead.

Across the Atlantic in 1922, after placing a transmitter and receiver on opposite sides of the Potomac River, U.S. Navy researchers A. Hoyt Taylor and Leo C. Young discovered that ships passing through the beam path caused the received signal to fade in and out. Taylor submitted a report, suggesting that this phenomenon might be used to detect the presence of ships in low visibility, but the Navy did not immediately continue the work. Eight years later, Lawrence A. Hyland at the Naval Research Laboratory (NRL) observed similar fading effects from passing aircraft; this revelation led to a patent application as well as a proposal for further intensive research on radio-echo signals from moving targets to take place at NRL, where Taylor and Young were based at the time.

1.2.1. Just before World War II



Before the Second World War, researchers in the United Kingdom, France, Germany, Italy, Japan,

Fig 1.3. Experimental radar antenna, US Naval Research Laboratory, Anacostia, D. C., late 1930s

the Netherlands, the Soviet Union, 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's radar development, and Hungary generated its radar technology during the war.

In France in 1934, following systematic studies on the split-anode magnetron, the research branch of the Compagnie Générale de Télégraphie Sans Fil (CSF) headed by Maurice Ponte with Henri Gutton, Sylvain Berline and M. Hugon, began developing an obstacle-locating radio apparatus, aspects of which were installed on the ocean liner *Normandie* in 1935.

During the same period, Soviet military engineer P.K. Oshchepkov, in collaboration with Leningrad Electrophysical Institute, produced an experimental apparatus, RAPID, capable of detecting an aircraft within 3 km of a receiver. The Soviets produced their first mass production radars RUS-1 and RUS-2 Redut in 1939 but further development was slowed following the arrest of Oshchepkov and his subsequent gulag sentence. In total, only 607 Redut stations were produced during the war. The first Russian airborne radar, Gneiss-2, entered into service in June 1943 on Pe-2 dive bombers. More than 230 Gneiss-2 stations were produced by the end of 1944. The French and Soviet systems, however, featured continuouswave operation that did not provide the full performance ultimately synonymous with modern radar systems.

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 following year, the United States Army successfully tested a primitive surface-to-surface radar to aim coastal battery searchlights at night. This design was followed by a pulsed system demonstrated in May 1935 by Rudolf Kühnhold and the firm GEMA [de] in Germany and then another in June 1935 by an Air Ministry team led by Robert Watson-Watt in Great Britain.

In 1935, Watson-Watt was asked to judge recent reports of a German radio-based death ray and turned the

Fig 1.4. The first workable unit built by Robert Watson-Watt and his team

request over to Wilkins. Wilkins returned a set of calculations demonstrating the system was basically impossible. When Watson-Watt then asked what such a system might do, Wilkins recalled the earlier report about aircraft causing radio interference. This revelation led to the Daventry Experiment of 26 February 1935, using a powerful BBC shortwave transmitter as the source and their GPO receiver setup in a field while a bomber flew around the site. When the plane was clearly detected, Hugh Dowding, the Air Member for Supply and Research was very impressed with their system's potential and funds were immediately provided for further operational development. Watson-Watt's team patented the device in GB593017.

Development of radar greatly expanded on 1 September 1936 when Wats on-Watt became Superintendent

Fig 1.5. A Chain Home tower in Great Baddow, Essex, United Kingdom

of a new establishment under the British Air Ministry, Bawdsey Research Station located in Bawdsey Manor, near Felixstowe, Suffolk. Work there resulted in the design and installation of aircraft detection and tracking stations called "Chain Home" along the East and South coasts of England in time for the outbreak of World War II in 1939. This system provided the vital advance information that helped the Royal Air Force win the Battle of Britain; without it, significant numbers of fighter aircraft, which Great Britain did not have available, would always need to be in the air to respond quickly. If enemy aircraft detection relied solely on the observations of ground-based individuals, Great Britain may have lost the Battle of Britain. Also vital was the "Dowding system" of reporting and coordination to provide the best use of radar information during the tests of early radar deployment during 1936 and 1937.

Given all required funding and development support, the team produced working radar systems in 1935 and began deployment. By 1936, the first five Chain Home (CH) systems were operational and by 1940 stretched across the entire UK including Northern Ireland. Even by standards of the era, CH was crude; instead of broadcasting and receiving from an aimed antenna, CH broadcast a signal floodlighting the entire area in front of it, and then used one of Watson-Watt's own radio direction finders to determine the direction of the returned echoes. This fact meant CH transmitters had to be much more powerful and have better antennas than competing systems but allowed its rapid introduction using existing technologies.

1.2.2. During World War II

A key development was the cavity magnetron in the UK, which allowed the creation of relatively small systems with sub-meter resolution. Britain shared the technology with the U.S. during the 1940 Tizard Mission.

In April 1940, *Popular Science* showed an example of a radar unit using the Watson-Watt patent in an article on air defence. Also, in late 1941 *Popular Mechanics* had an article in which a U.S. scientist speculated about the British early warning system on the English east coast and came close to what it was and how it worked. Watson-Watt was sent to the U.S. in 1941 to advice on air defense after Japan's attack on Pearl Harbor. Alfred Lee Loomis organized the secret MIT Radiation Laboratory at Massachusetts Institute of Technology, Cambridge, Massachusetts which developed microwave radar technology in the years 1941–45. Later, in 1943, Page greatly improved radar with the monopulse technique that was used for many years in most radar applications.

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.

CHAPTER 2

2.1. Literature survey

To investigate the exploitation of the polarimetric diversity signal properties in a bistatic polarimetric MIMO radar to improve the performance of joint estimation of direction of arrival (DOA) and direction of departure (DOD) of targets using combined ESPRIT-Root MUSIC technique. Numerical simulations are carried out to illustrate the performance of the proposed approach [1]. The berthing of large ships in inclement weather with frequently poor visibility presents a challenge. To assist with this application, it may be beneficial to utilize standard radar imaging. Whilst this may be achieved using a mechanically-scanned system, reliability, cost and weight issues, coupled with the need to primarily image only a 120± sector on the port and starboard of the ship, make phased array radar an attractive possibility. Multiple-Input Multiple-Output (MIMO) radar, with its ability to enhance the resolution available from a given number of elements, is particularly suited to a short-range application such as this in which there is sufficient time to switch between antenna elements as an alternative to more complex implementations [2]. Identification of time-varying linear systems, which introduce both time-shifts (delays) and frequency shifts (Doppler-shifts), is a central task in many engineering applications. This paper studies the problem of identification of under spread linear systems (ULSs), whose responses lie within a unit-area region in the delay–Doppler space, by probing them with a known input signal. It is shown that sufficiently-under spread parametric linear systems, described by a finite set of delays and Doppler-shifts, are identifiable from a single observation as long as the time–bandwidth product of the input signal is proportional to the square of the total number of delay–Doppler pairs in the system [3]. The first radar has been patented 110 years ago. Meanwhile the applications became numerous and the system concepts have been adopted to the available technologies. Typical applications are speed control, air traffic control, and synthetic aperture radar, airborne and space borne missions, military applications and remote sensing. Research for medical radar applications is well progressing for breast cancer detection and tumor localization. Automobile radar for save and autonomous driving are meanwhile produced in millions per year. In the next years the state-of-the-art radar system concepts will experience almost a revolution. Despite the significant advancements, the radar system technology did not develop like communications or other technologies during the last 20 years. Some of these new technologies will within a few years penetrate radar and revolutionize radar system concepts. This will then allow for new radar features and radar signal processing approaches [4].

The impact of Information innovation on the lead of military activities has developed altogether over the most recent 10 years. Business interests have prompted the fast improvement of the abilities of data frameworks and this pattern is required to proceed. These advancements will permit military to accomplish military prevalence through data predominance by applying them not exclusively to fight the executives yet in addition to readiness, arranging, and coordination's. Direction and control capacities are performed through a game plan of faculty, hardware, offices, and systems that are utilized by administrator in arranging, coordinating, planning, and controlling these powers. This game plan is regularly alluded to as a direction, control, and interchanges framework as it epitomizes useful capacities that give strategic photos of the fight space and interchanges availability [5]. A multi objective optimization (MOO) technique to design an orthogonal-frequency-division multiplexing (OFDM) radar signal for detecting a moving target in the presence of multipath reflections. We employ an OFDM signal to increase the frequency diversity of the system, as different scattering centers of a target resonate variably at different frequencies. Moreover, the multipath propagation increases the spatial diversity by providing extra “looks” at the target. First, to develop a parametric OFDM radar model by reformulating the targetdetection problem as the task of sparse-signal spectrum estimation [6].

Radar data are used to locate areas of interest on images. Vehicle search in these areas is based on vertical symmetry. All vehicles found in different image areas are mixed together and a series of fillters are applied in order to delete false positives. The algorithm analyzes images on a frame by frame basis, without any temporal correlation. Two different statistics, frame-based and eventbased, are computed to evaluate the method efficiency [7].

A sparsity-based approach to track multiple targets in a region of interest using an orthogonalfrequency-division multiplexing (OFDM) radar. To observe that in a particular pulse interval the targets lie at a few points on the delay-Doppler plane and hence we exploit that inherent sparsity to develop a tracking procedure. The use of an OFDM signal not only increases the frequency diversity of our system, as different scattering centers of a target resonate variably at different frequencies, but also decreases the block-coherence measure of the equivalent sparse measurement model. In the tracking filter, to exploit this block-sparsity property in developing a block version of the compressive sampling matching pursuit (CoSaMP) algorithm. To present numerical examples to show the performance of our sparsity-based tracking approach and compare it with a particle filter (PF) based tracking procedure [8].

CHAPTER 3

3.1. Principles

A radar system has a transmitter that emits radio waves known as *radar signals* in predetermined directions. When these signals contact an object they are usually reflected or scattered in many directions, although some of them will be absorbed and penetrate into the target. Radar signals are reflected especially well by materials of considerable electrical conductivity—such as most metals, seawater, and wet ground. This makes the use of radar altimeters possible in certain cases. The radar signals that are reflected back towards the radar receiver are the desirable ones that make radar detection work. If the object is *moving* either toward or away from the transmitter, there will be 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. The reflected radar signals captured by the receiving antenna are usually very weak. They can be strengthened by electronic amplifiers. More sophisticated methods of signal processing are also used in order to recover useful radar signals.

The weak absorption of radio waves by the medium through which they pass 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. Weather phenomena, such as fog, clouds, rain, falling snow, and sleet that block visible light are usually transparent to radio waves. Certain radio frequencies that are absorbed or scattered by water vapor, raindrops, or atmospheric gases (especially oxygen) are avoided when designing radars, except when their detection is intended.

3.1.1. Illumination

Radar relies on its own transmissions rather than light from the Sun or the Moon, or from electromagnetic waves emitted by the target objects themselves, such as infrared radiation (heat). This process of directing artificial radio waves towards objects is called *illumination*, although radio waves are invisible to the human eye as well as optical cameras.

3.1.2. Reflection

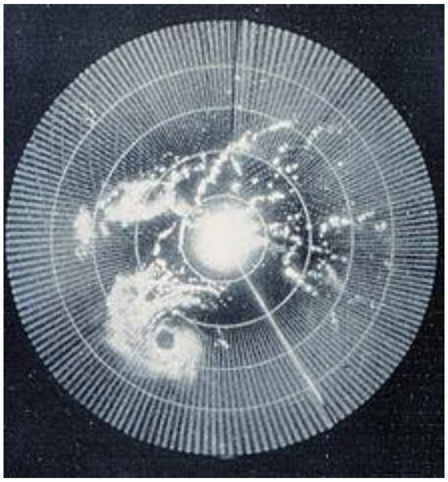


Fig 3.1. Brightness can indicate reflectivity as in this 1960 weather radar image (of Hurricane Abby).

The radar's frequency, pulse form, polarization, signal processing, and antenna determine what it can observe.
If electromagnetic waves travelling through one material meet another material, having a different dielectric constant or diamagnetic constant from the first, the waves will reflect or scatter from the boundary between the materials. This means that a solid object in air or in a vacuum, or a significant change in atomic density between the object and what is surrounding it, will usually scatter radar (radio) waves from its surface. This is particularly true for electrically conductive materials such as metal and carbon fibre, making radar wellsuited 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 by the eye at night.

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 because of 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 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 thus received a vague signal, whereas many modern systems use shorter wavelengths (a few centimeters or less) 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 corner reflector consists of three flat surfaces meeting like the inside corner of a box. The structure will reflect waves entering its opening directly back to the source. They are commonly used as radar reflectors to make otherwise difficult-to-detect objects easier to detect. Corner reflectors on boats, for example, make them more detectable to avoid collision or during a rescue. For similar reasons, objects intended to avoid detection will not have inside corners or 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 range equation

The power P_r returning to the receiving antenna is given by the 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; this can also be expressed as

$$\frac{G_r \lambda^2}{4\pi} \quad ,$$

where

- $\lambda 2$ = transmitted wavelength
- G_r = gain of 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 received power from distant targets is relatively very small.

Additional filtering and pulse integration modifies the radar equation slightly for pulseDoppler radar performance, which can be used to increase detection range and reduce transmit power.

The equation above with F = 1 is a simplification for transmission in a 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, path loss effects should also be considered.

3.1.3. Plot and track extraction

A Track algorithm is a radar performance enhancement strategy. Tracking algorithms provide the ability to predict future position of multiple moving objects based on the history of the individual positions being reported by sensor systems.

Historical information is accumulated and used to predict future position for use with air traffic control, threat estimation, combat system doctrine, gun aiming, and missile guidance. Position data is accumulated by radar sensors over the span of a few minutes.

There are four common track algorithms.[42]

- Nearest neighbor algorithm
- Probabilistic Data Association
- Multiple Hypothesis Tracking
- Interactive Multiple Model (IMM)

Radar video returns from 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.

3.1.4. Components of radar

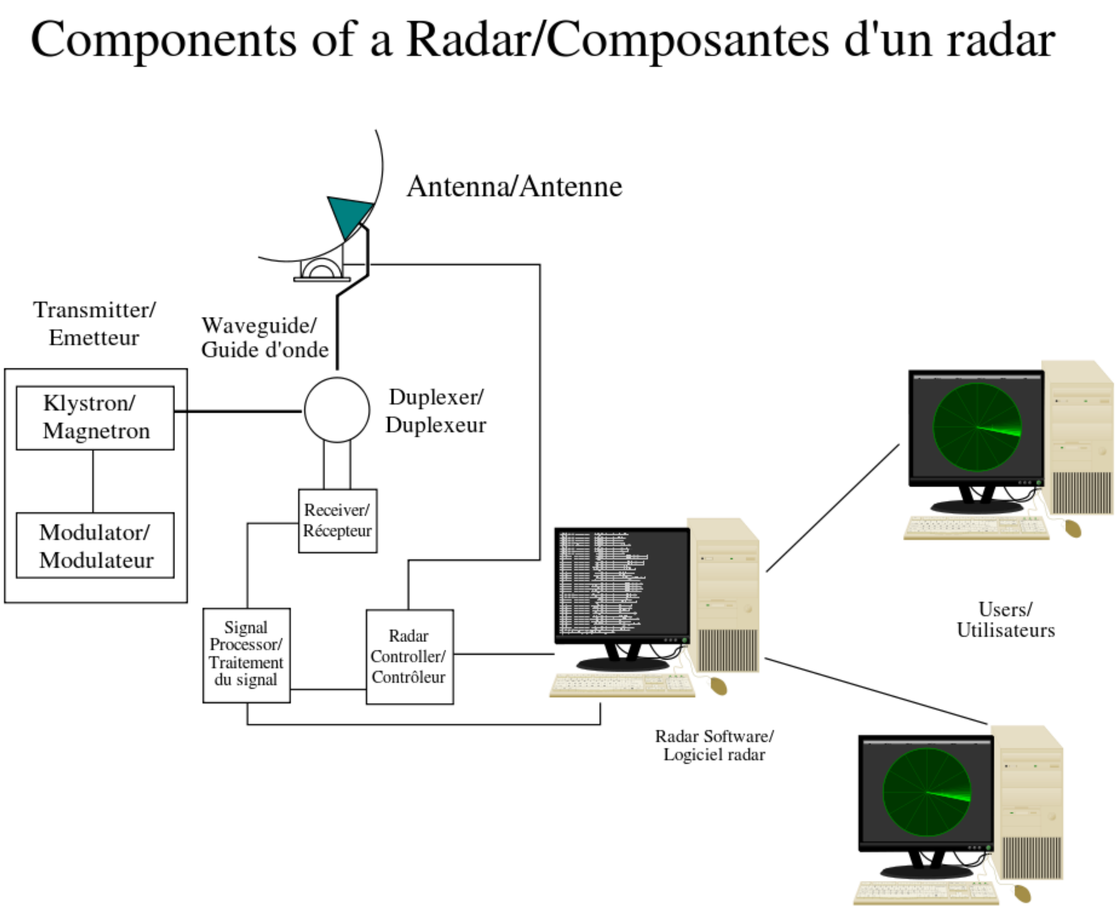


Fig 3.2. Radar components

A radar's 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.
- A display processor to produce signals for human readable output devices.

- An electronic section that controls all those devices and the antenna to perform the radar scan ordered by software.
- A link to end user devices and displays. **3.1.5. Antenna design**

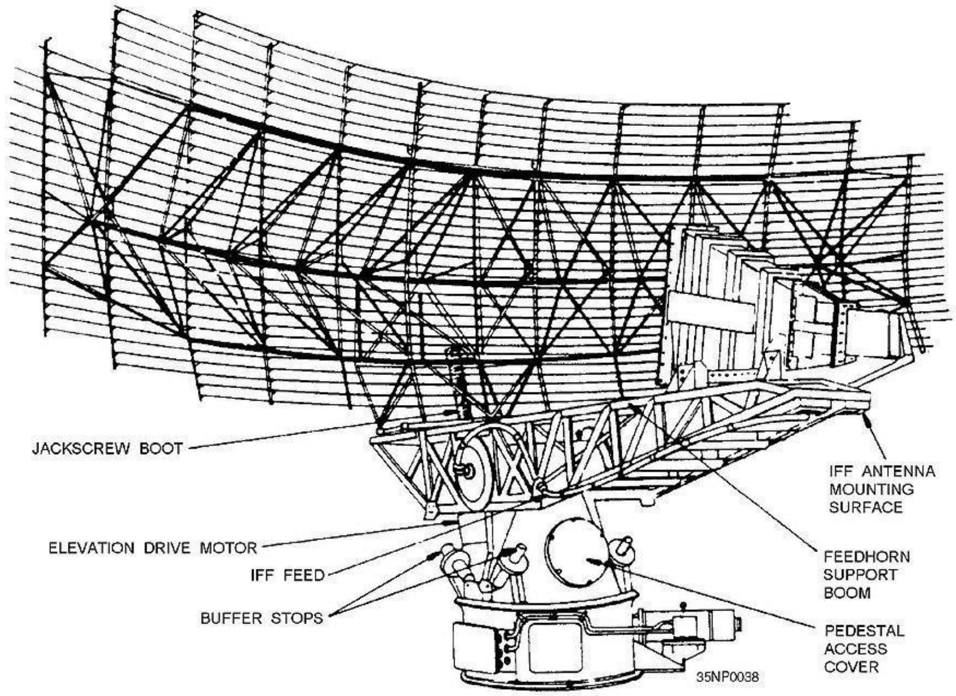


Fig 3.3. AS-3263/SPS-49(V) antenna (US Navy)

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 omnidirectional 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 showed 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.

3.1.6. Parabolic reflector

Fig 3.4. Surveillance radar antenna

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. 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 beam width and wide vertical beam width. 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 beam width and wide azimuthal beam width 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.
- Conical scanning: The radar beam is rotated in a small circle around the "bore sight" axis, which is pointed at the target.

3.1.7. Slotted waveguide

Fig 3.5. 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 harbor surveillance radars now use this approach in preference to a parabolic antenna.

3.1.8. Phased array

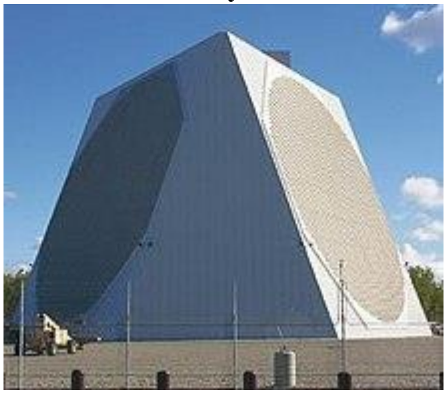


Fig 3.6. Phased array: Not all radar antennas must rotate to scan the sky.

Another method of steering is used in a phased array radar.

Phased array antennas are composed of evenly spaced similar antenna elements, such as aerials or rows of slotted waveguide. Each antenna element or group of antenna elements incorporates a discrete phase shift that produces a phase gradient across the array. For example, array elements producing a 5 degree phase shift for each wavelength across the array face will produce a beam pointed 5 degrees away from the centerline perpendicular to the array face. Signals travelling along that beam will be reinforced. Signals offset from that beam will be cancelled. The amount of reinforcement is antenna gain. The amount of cancellation is side-lobe suppression.[43]

Phased array radars have been in use since the earliest years of radar in World War II (Mammut radar), but electronic device limitations led to poor performance. Phased array radars were originally used for missile defense (see for example Safeguard Program). They are the heart of the ship-borne Aegis Combat System and the Patriot Missile System. The massive redundancy associated with having a large number of array elements increases reliability at the expense of gradual performance degradation that occurs as individual phase elements fail. To a lesser extent, Phased array radars have been used in weather surveillance. As of 2017, NOAA plans to implement a national network of Multi-Function Phased array radars throughout the United States within 10 years, for meteorological studies and flight monitoring.

3.1.9. 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. They have been adopted in the United States by the Institute of Electrical and Electronics Engineers and internationally by the International Telecommunication Union. 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 industries, have replaced the traditional military designations with their own systems.

Table 3.1. Radar frequency bands

Radar frequency bands

Band name	Frequenc range	Wavelengt range	Notes
HF	3–30 MHz	10–100 m	Coastal radar systems, over-the-horizon (OTH) radars; 'high frequency'
VHF	30 – 300 MHz	1–10 m	Very long range, ground penetrating; 'very high frequency'
P	< 300 MHz	> 1 m	'P' for 'previous', applied retrospectively to early radar systems; essentially HF + VHF
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 United States 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, also used for satellite transponders, frequency under K band (hence 'u')
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	1.0–7.5 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.
			Very strongly absorbed by atmospheric oxygen, which resonates at

V	40–75 GHz	4.0–7.5 mm	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.

3.1.10. 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, e.g., the 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 or a solid state transmitter. In this way, the transmitted pulse is intrapulse-modulated and the radar receiver must use pulse compression techniques.

3.1.11. Coolant

Coherent microwave amplifiers operating above 1,000 watts microwave output, like travelling wave tubes and klystrons, require liquid coolant. The electron beam must contain 5 to 10 times more power than the microwave output, which can produce enough heat to generate plasma. This plasma flows from the collector toward the cathode. The same magnetic focusing that guides the electron beam forces the plasma into the path of the electron beam but flowing in the opposite direction. This introduces FM modulation which degrades Doppler performance. To prevent this, liquid coolant with minimum pressure and flow rate is required, and deionized water is normally used in most high power surface radar systems that utilize Doppler processing.

Coolanol (silicate ester) was used in several military radars in the 1970s. However, it is hygroscopic, leading to hydrolysis and 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 eliminate or reduce the volume and toxicity of waste, air emissions, and effluent discharges. Because of this, Coolanol is used less often today.

3.1.12. Regulations

A radio determination system based on the comparison of reference signals with radio signals reflected, or retransmitted, from the position to be determined. Each *radio determination system* shall be classified by the *radio communication service* in which it operates permanently or temporarily. Typical radar utilizations are primary radar and secondary radar, these might operate in the radiolocation service or the radiolocationsatellite service.

CHAPTER 4

4.1. Applications

4.1.1. Terrain-following radar

Terrain-following radar (TFR) is a military aerospace technology that allows a very-low-flying aircraft to automatically maintain a relatively constant altitude above ground level and therefore make detection by enemy radar more difficult. It is sometimes referred-to as *ground hugging* or *terrain hugging* flight. The term *nap-of-the-earth* flight may also apply but is more commonly used in relation to low-flying military helicopters, which typically do not use terrain-following radar. The technology was originally developed by Ferranti for use with the TSR-2 aircraft.[1][2]

Technology

Fig 4.1. TSR-2 *XR220* at RAF Museum Cosford, 2002. Ferranti developed terrain following radar specifically for the TSR-2.

The system works by transmitting a radar signal towards the ground area in front of the aircraft. The radar returns can then be processed to see how the terrain ahead varies, and then used by the aircraft's flight computers to calculate flight-path changes in order to maintain a reasonably constant height above the earth. The computer will consider many factors in determining the flight path for the aircraft, such as distance to the forward terrain, aircraft speed and velocity, angle of attack and quality of signal being returned.

Strike Aircraft Use

Advantages and Disadvantages

Terrain following radar is primarily used by military strike aircraft, to enable flight at very low altitudes (sometimes below 100 feet/30 meters) and high speeds. Since radar detection by enemy radars and interception by anti-aircraft systems require a line of sight to the target, flying low to the ground and at high speed reduces the time that an aircraft is vulnerable to detection to a minimum by hiding the aircraft behind terrain as far as possible. This is known as terrain masking.

However, radar emissions can be detected by enemy anti-aircraft systems with relative ease once there is no covering terrain, allowing the aircraft to be targeted. The use of terrain-following radar is therefore a compromise between the increased survivability due to terrain masking and the ease with which the aircraft can be targeted if it is seen.

Even an automated system has limitations, and all aircraft with terrain-following radars have limits on how low and fast they can fly. Factors such as system response-time, aircraft g-limits and the weather can all limit an aircraft. Since the radar cannot tell what is beyond any immediate terrain, the flight path may also suffer from "ballooning" over sharp terrain ridges, where the altitude becomes unnecessarily high. Furthermore, obstacles such as radio antennas and electricity pylons may be detected late by the radar and present collision hazards.

Integration and Use

On aircraft with more than one crew, the radar is normally used by the navigator and this allows the pilot to focus on other aspects of the flight besides the extremely intensive task of low flying itself. Most aircraft allow the pilot to also select the ride "hardness" with a cockpit switch, to choose between how closely the aircraft tries to keep itself close to the ground and the forces exerted on the pilot.

Some aircraft such as the Tornado IDS have two separate radars, with the smaller one used for terrainfollowing. However more modern aircraft such as the Rafale with phased array radars have a single antenna that can be used to look forward and at the ground, by electronically steering the beams.

Fig 4.2. The F-111C employs TFR

4.1.2. Imaging radar

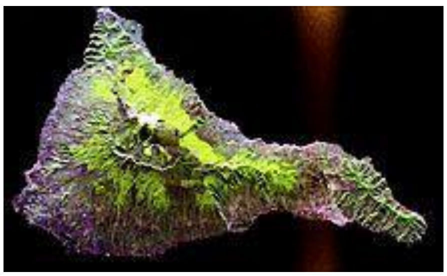


Fig 4.3. Radar imaging

A SAR radar image acquired by the SIR-C/X-SAR radar on board the Space Shuttle Endeavour shows the Teide volcano. The city of Santa Cruz de Tenerife is visible as the purple and white area on the lower right edge of the island. Lava flows at the summit crater appear in shades of green and brown, while vegetation zones appear as areas of purple, green and yellow on the volcano's flanks.

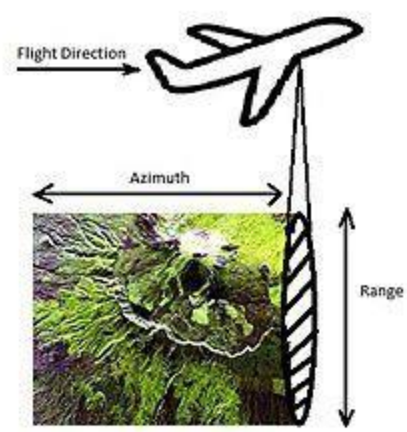


Fig 4.4. Building up a radar image using the motion of the platform

Imaging radar is an application of radar which is used to create two-dimensional images, typically of landscapes. Imaging radar provides its light to illuminate an area on the ground and take a picture at radio wavelengths. It uses an antenna and digital computer storage to record its images. In a radar image, one can see only the energy that was reflected back towards the radar antenna. The radar moves along a flight path and the area illuminated by the radar, or footprint, is moved along the surface in a swath, building the image as it does so.

Digital radar images are composed of many dots. Each pixel in the radar image represents the radar backscatter for that area on the ground: brighter areas represent high backscatter, darker areas represents low backscatter.

The traditional application of radar is to display the position and motion of typically highly reflective objects (such as aircraft or ships) by sending out a radiowave signal, and then detecting the direction and delay of the reflected signal. Imaging radar on the other hand attempts to form an image of one object (e.g. a landscape) by furthermore registering the intensity of the reflected signal to determine the amount of scattering (cf. light scattering). The registered electromagnetic scattering is then mapped onto a twodimensional plane, with points with a higher reflectivity getting assigned usually a brighter color, thus creating an image.

Several techniques have evolved to do this. Generally they take advantage of the Doppler effect caused by the rotation or other motion of the object and by the changing view of the object brought about by the relative motion between the object and the back-scatter that is perceived by the radar of the object (typically, a plane) flying over the earth. Through recent improvements of the techniques, radar imaging is getting more accurate. Imaging radar has been used to map the Earth, other planets, asteroids, other celestial objects and to categorize targets for military systems.

4.1.3. Radar navigation

Fig 4.5. Radar ranges and bearings can be very useful for navigation.

Marine and aviation radar systems can provide very useful navigation information in a variety of situations. When a vessel is within radar range of land or special radar aids to navigation, the navigator can take distances and angular bearings to charted objects and use these to establish arcs of position and lines of position on a chart. A fix consisting of only radar information is called a radar fix.

Some types of radar fixes include the relatively self-explanatory methods of "range and bearing to a single object,"[3] "two or more bearings,"[3] "tangent bearings," and "two or more ranges."

Parallel indexing is a technique defined by William Burger in the 1957 book *The Radar Observer's Handbook*.[4] This technique involves creating a line on the screen that is parallel to the ship's course, but offset to the left or right by some distance. This parallel line allows the navigator to maintain a given distance away from hazards.

Some techniques have been developed for special situations. One, known as the "contour method," involves marking a transparent plastic template on the radar screen and moving it to the chart to fix a position.

Another special technique, known as the Franklin Continuous Radar Plot Technique, involves drawing the path a radar object should follow on the radar display if the ship stays on its planned course.[6] During the transit, the navigator can check that the ship is on track by checking that the pip lies on the drawn line.

After completing the plotting radar technique, the image from the radar can either be displayed, captured or recorded to a computer monitor using a frame grabber.

4.1.4. Wave radar

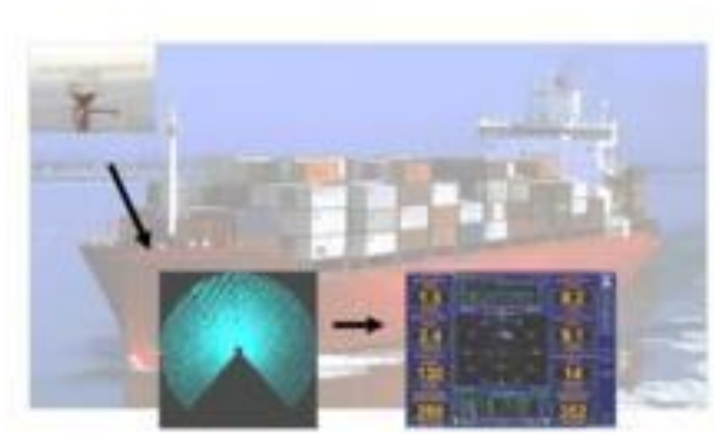


Fig 4.6. Measuring ocean waves by use of marine radars.

Wind waves can be measured by several radar remote sensing techniques. Several instruments based on a variety of different concepts and techniques are available, and these are all often called **wave radars**. This article (see also Grønlie 2004), gives a brief description of the most common ground-based radar remote sensing techniques.

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 water, where swift currents could make mooring a wave buoy enormously difficult. Another interesting case is a ship under way, where having instruments in the sea is highly impractical and interference from the ship's hull must be avoided.

4.1.5. Ground Surveillance Radar

SCANTER 1002 Ground Surveillance Radar (GSR)
Based on thorough know-how and proven Solid State technology from market-leading SCANTER radar systems worldwide, Terma has developed the SCANTER 1002 Ground Surveillance Radar.

The SCANTER 1002 Radar System is specifically tailored to meet today's increasing demands for security optimization and protection of critical infrastructure and installations such as airports, power plants, borders, camps and harbors.

Area surveillance
In the ground surveillance segment where traditional electronic perimeter protection solutions typically only monitor the boundaries and lines, the SCANTER 1002 provides complete meter-by-meter coverage both outside and inside a physical perimeter for detection and tracking of slow (man or animal) and fastmoving objects (landing aircraft) at the same time.

The SCANTER 1002 Radar System is designed for surveillance of areas ranging from small airports to full border size solutions. With 360º surveillance and high update rates, the radar and its embedded tracker deliver constant real-time data that enables evaluation and behavior analysis of potential threats. The unique detection and tracking features of the SCANTER 1002 makes it a highly valued asset to maximize the time available for assessment, decision, and possible intervention.

Fig 4.7. Ground Surveillance Radar on site close to coast line

Operational capabilities
Utilizing advanced signal processing, the SCANTER 1002 provides reliable operation under adverse weather conditions such as rain, fog, dust and snow.

The radar generates tracks with very low probability of false alarms and provides for discrimination between various intrusions, even in complex environments with many obstacles.

System integration
The open architecture design of the SCANTER 1002 facilitates easy integration with cameras and thirdparty surveillance systems, including Terma's intelligent wide-area perimeter detection solution: T.react CIP.

4.1.6. Missile guidance

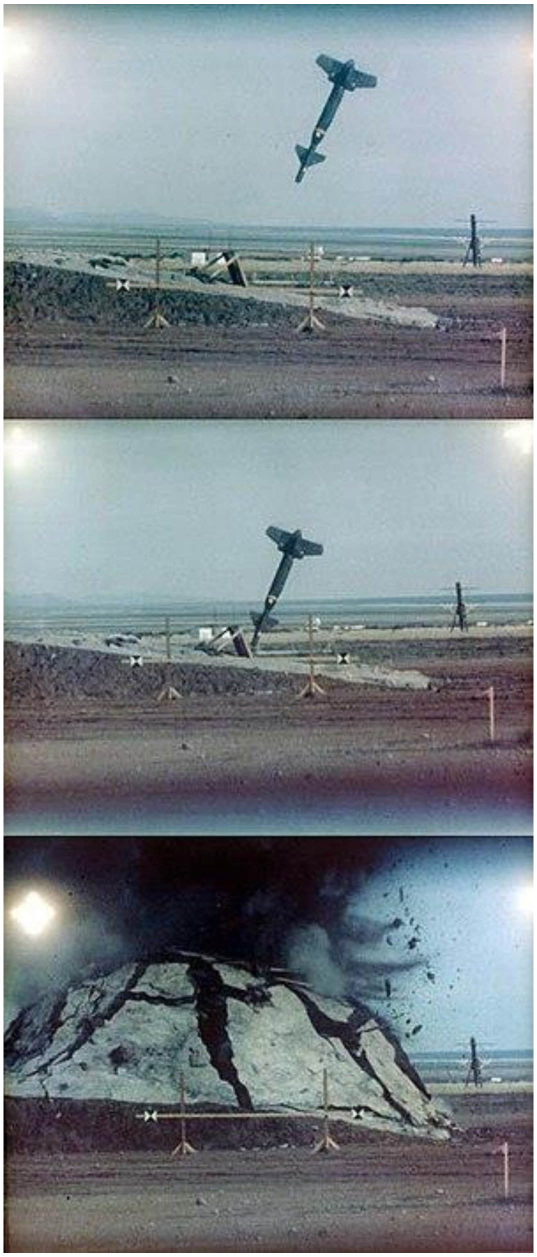


Fig 4.8. A guided bomb strikes a practice target

Missile guidance refers to a variety of methods of guiding a missile or a guided bomb to its intended target. The missile's target accuracy is a critical factor for its effectiveness. Guidance systems improve missile accuracy by improving its "single shot kill probability" (SSKP), which is part of combat survivability calculations associated with the salvo combat model.[1][2]

These guidance technologies can generally be divided up into a number of categories, with the broadest categories being "active," "passive" and "preset" guidance. Missiles and guided bombs generally use similar types of guidance system, the difference between the two being that missiles are powered by an onboard engine, whereas guided bombs rely on the speed and height of the launch aircraft for propulsion.

In every go-onto-target system there are three subsystems:

- Target tracker
- Missile tracker
- Guidance computer

4.1.7. Fire-control radar

A **fire-control radar** (**FCR**) is a radar that is designed specifically to provide information (mainly target azimuth, elevation, range and range rate) to a fire-control system in order to direct weapons such that they hit a target. They are sometimes known as **targeting radars**, or in the UK, **gun-laying radars**. If the radar is used to guide a missile, it is often known as an **illuminator** or **illuminator radar**.

A typical fire-control radar emits a narrow, intense beam of radio waves to ensure accurate tracking information and to minimize the chance of losing track of the target. This makes them less suitable for initial detection of the target, and FCRs are often partnered with a medium-range search radar to fill this role. In British terminology, these medium-range systems were known as tactical control radars.

Most modern radars have a track-while-scan capability, enabling them to function simultaneously as both fire-control radar and search radar. This works either by having the radar switch between sweeping the search sector and sending directed pulses at the target to be tracked, or by using a phased-array antenna to generate multiple simultaneous radar beams that both search and track.

4.1.8. Air traffic control

Fig 4.9. Control tower of Hartsfield-Jackson International Airport (Atlanta)

Air traffic control (ATC) is a service provided by ground-based air traffic controllers who direct aircraft on the ground and through controlled airspace, and can provide advisory services to aircraft in non-controlled airspace. The primary purpose of ATC worldwide is to prevent collisions, organize and expedite the flow of air traffic, and provide information and other support for pilots.[1] In some countries, ATC plays a security or defensive role, or is operated by the military.

Air traffic controllers monitor the location of aircraft in their assigned airspace by radar and communicate with the pilots by radio. To prevent collisions, ATC enforces traffic separation rules, which ensure each aircraft maintains a minimum amount of empty space around it at all times. In many countries, ATC provides services to all private, military, and commercial aircraft operating within its airspace. Depending on the type of flight and the class of airspace, ATC may issue *instructions* that pilots are required to obey, or *advisories* (known as *flight information* in some countries) that pilots may, at their discretion, disregard. The pilot in command is the final authority for the safe operation of the aircraft and may, in an emergency, deviate from ATC instructions to the extent required to maintain safe operation of their aircraft.

4.1.9. Moving target indication

Moving target indication (MTI) is a mode of operation of a radar to discriminate a target against the clutter.[1] It describes a variety of techniques used to find moving objects, like an aircraft, and filter out unmoving ones, like hills or trees. It contrasts with the modern stationary target indication (STI) technique, which uses details of the signal to directly determine the mechanical properties of the reflecting objects and thereby find targets whether they are moving or not.

Early MTI systems generally used an acoustic delay line to store a single pulse of the received signal for exactly the time between broadcasts (the pulse repetition frequency). This stored pulse will be sent to the display along with the next received pulse. The result was that the signal from any objects that did not move mixed with the stored signal and became muted out. Only signals that changed, because they moved, remained on the display. These were subject to a wide variety of noise effects that made them useful only for strong signals, generally for aircraft or ship detection.

The introduction of phase-coherent klystron transmitters, as opposed to the incoherent cavity magnetron used on earlier radars, led to the introduction of a new MTI technique. In these systems, the signal was not fed directly to the display, but first fed into a phase detector. Stationary objects did not change the phase from pulse to pulse, but moving objects did. By storing the phase signal, instead of the original analog signal, or *video*, and comparing the stored and current signal for changes in phase, the moving targets are revealed. This technique is far more resistant to noise, and can easily be tuned to select different velocity thresholds to filter out different types of motion.[1]

Phase coherent signals also allowed for the direct measurement of velocity via the Doppler shift of a single received signal. This can be fed into a bandpass filter to filter out any part of the return signal that does not show a frequency shift, thereby directly extracting the moving targets. This became common in the 1970s and especially the 1980s. Modern radars generally perform all of these MTI techniques as part of a wider suite of signal processing being carried out by digital signal processors. MTI may be specialized in terms of the type of clutter and environment: airborne MTI (AMTI), ground MTI (GMTI), etc., or may be combined mode: stationary and moving target indication (SMTI).

4.1.10. Weapon Locating Radar

Weapon Locating Radars (WLR) are primarily used to detect and locate enemy Artillery units by tracking the trajectory of incoming rounds. They can also provide fire correction of friendly artillery units. WLRs usually can also track mortar shells and unguided rockets. Some WLRs also have limited missile tracking and Air Defence capabilities

CHAPTER 5

5.1. Evaluation

5.1.1. Doppler Effect

Frequency shift is caused by motion that changes the number of wavelengths between the reflector and the radar. This can degrade or enhance radar performance depending upon how it affects the detection process. As an example, Moving Target Indication can interact with Doppler to produce signal cancellation at certain radial velocities, which degrades performance.

Sea-based radar systems, semi-active radar homing, active radar homing, weather radar, military aircraft, and radar astronomy rely on the Doppler effect to enhance performance. This produces information about target velocity during the detection process. This also allows small objects to be detected in an environment containing much larger nearby slow moving objects.

Doppler shift depends upon whether the radar configuration is active or passive. Active radar transmits a signal that is reflected back to the receiver. Passive radar depends upon the object sending a signal to the receiver.

The Doppler frequency shift for active radar is as follows, where is Doppler frequency, is transmit frequency, is radial velocity, and is the speed of light:[38]

$$F_D = 2 \times F_T \times (\frac{V_R}{C})$$

Passive radar is applicable to electronic countermeasures and radio astronomy as follows:

$$F_D = F_T \times (\frac{V_R}{C})$$

Only the radial component of the velocity is relevant. When the reflector is moving at right angle to the radar beam, it has no relative velocity. Vehicles and weather moving parallel to the radar beam produce the maximum Doppler frequency shift.

When the transmit frequency () is pulsed, using a pulse repeat frequency of, the resulting frequency spectrum will contain harmonic frequencies above and below with a distance of. As a result, the Doppler measurement is only non-ambiguous if the Doppler frequency shift is less than half of , called the Nyquist frequency, since the returned frequency otherwise cannot be distinguished from shifting of a harmonic frequency above or below, thus requiring:

Or when substituting with : $$|F_D| < \frac{F_R}{2}$$

As an example, a Doppler weather radar $|V_R| < \frac{F_R \times \frac{C}{F_T}}{4}$ with a pulse rate of 2 kHz and transmit frequency of 1 GHz can reliably measure weather speed up to at most 150 m/s (340 mph), thus cannot reliably determine radial velocity of aircraft moving 1,000 m/s (2,200 mph).

5.1.2. Polarization

In all electromagnetic radiation, the electric field is perpendicular to the direction of propagation, and the electric field direction is the polarization of the wave. For a transmitted radar signal, the polarization can be controlled to yield different effects. 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. **5.1.3. Limiting factors**

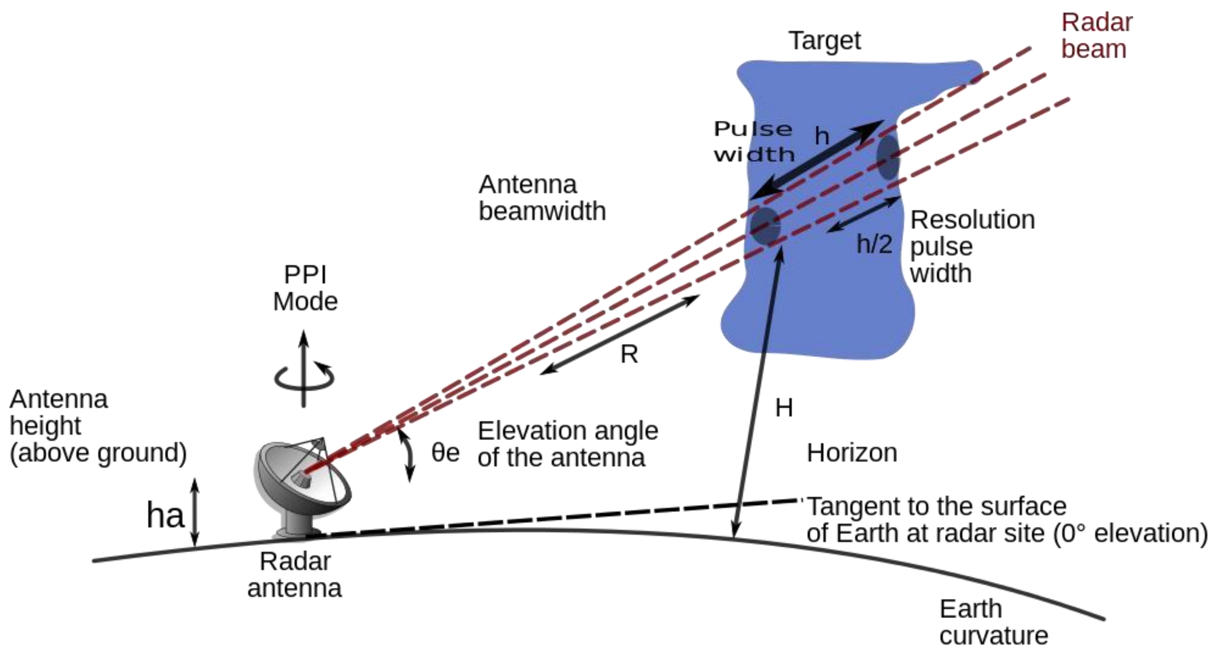


Fig 5.1. Echo heights above ground

Where :
r : distance radar-target
ke : 4/3 ae : Earth radius
θe : elevation angle above the radar horizon ha : height of the feed horn above ground

A radar beam follows a linear path in vacuum but follows a somewhat curved path in atmosphere due to variation in the refractive index of air, which is called the radar horizon. Even when the beam is emitted parallel to the ground, the beam rises above the ground as the curvature of the Earth sinks below the horizon. Furthermore, the signal is attenuated by the medium the beam crosses, and the beam disperses.

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

- Line of sight, which depends on the height above the ground. Without a direct line of sight, the path of the beam is blocked.

- The maximum non-ambiguous range, which is determined by the pulse repetition frequency. The maximum non-ambiguous range is the distance the pulse can travel to and return from before the next pulse is emitted.
- Radar sensitivity and the power of the return signal as computed in the radar equation. This component includes factors such as the environmental conditions and the size (or radar cross section) of the target.

5.1.4. Noise

Signal noise is an internal source of random variations in the signal, which is generated by all electronic components.

Reflected signals decline rapidly as distance increases, so noise introduces a radar range limitation. The noise floor and signal to noise ratio are two different measures of performance that affect range performance. Reflectors that are too far away produce too little signal to exceed the noise floor and cannot be detected. Detection requires a signal that exceeds the noise floor by at least the signal to noise ratio.

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. Noise figure is a measure of the noise produced by a receiver compared to an ideal receiver, and this needs to be minimized.

Shot noise is produced by electrons in transit across a discontinuity, which occurs in all detectors. Shot noise is the dominant source in most receivers. There will also be flicker noise caused by electron transit through amplification devices, which is reduced using heterodyne amplification. Another reason for heterodyne processing is that for fixed fractional bandwidth, the instantaneous bandwidth increases linearly in frequency. This allows improved range resolution. The one notable exception to heterodyne (down conversion) radar systems is ultra-wideband radar. Here a single cycle, or transient wave, is used similar to UWB communications, see List of UWB channels.

Noise is also generated by external sources, most importantly the natural thermal radiation of the background surrounding the target of interest. In modern radar systems, the internal noise is typically about equal to or lower than the external 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. The thermal noise is given by $k_B\,T\,B$, where T is temperature, B is bandwidth (post matched filter) and k_B is Boltzmann's constant. There is an appealing intuitive interpretation of this relationship in a radar. Matched filtering allows the entire energy received from a target to be compressed into a single bin (be it a range, Doppler, elevation, or azimuth bin). On the surface it would appear that then within a fixed interval of time one could obtain perfect, error free, detection. To do this one simply compresses all energy into an infinitesimal time slice. What limits this approach in the real world is that, while time is arbitrarily divisible, current is not. The quantum of electrical energy is an electron, and so the best one can do is match filter all energy into a single electron. Since the electron is moving at a certain temperature (Plank spectrum) this noise source cannot be further eroded. We see then that radar, like all macro-scale entities, is profoundly impacted by quantum theory.

Noise is random and target signals are not. Signal processing can take advantage of this phenomenon to reduce the noise floor using two strategies. The kind of signal integration used with moving target indication can improve noise up to for each stage. The signal can also be split among multiple filters for pulse-Doppler signal processing, which reduces the noise floor by the number of filters. These improvements depend upon coherence.

5.1.5. Interference

Radar systems must overcome unwanted signals in order to focus on the 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 the signal power to the noise power within the desired signal; it compares the level of a desired target signal to the level of background noise (atmospheric noise and noise generated within the receiver). The higher a system's SNR the better it is at discriminating actual targets from noise signals.

5.1.6. 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, and when not being tasked for meteorological purposes, 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 Hail 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. Clutter is considered a passive interference source, since it only appears in response to radar signals sent by the radar.

Clutter is detected and neutralized in several ways. Clutter tends to appear static between radar scans; on subsequent scan 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 (meteorological radars wish for the opposite effect, and therefore use linear polarization to detect precipitation). Other methods attempt to increase the signal-to-clutter ratio.

Clutter moves with the wind or is stationary. Two common strategies to improve measure or performance in a clutter environment are:

- Moving target indication, which integrates successive pulses and
- Doppler processing, which uses filters to separate clutter from desirable signals.

The most effective clutter reduction technique is pulse-Doppler radar. Doppler separates clutter from aircraft and spacecraft using a frequency spectrum, so individual signals can be separated from multiple reflectors located in the same volume using velocity differences. This requires a coherent transmitter. Another technique uses a moving target indicator that subtracts the receive signal from two successive pulses using phase to reduce signals from slow moving objects. This can be adapted for systems that lack a coherent transmitter, such as time-domain pulse-amplitude radar.

Constant false alarm rate, a form of automatic gain control (AGC), is a method that relies on clutter returns far outnumbering 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.

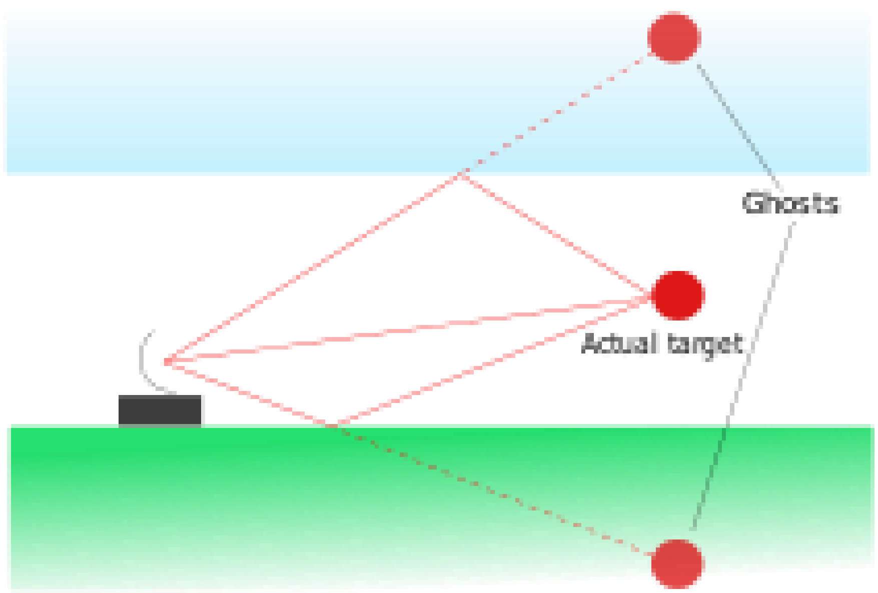


Fig 5.2. Radar multipath echoes from a target cause ghosts to appear.

Clutter may also originate from multipath echoes from valid targets caused by 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. In a typical scenario, an aircraft echo is 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 eliminating it on the basis of jitter or a physical impossibility. Terrain bounce jamming exploits this response by amplifying the radar signal and directing it downward.[39] 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. Monopulse can be improved by altering the elevation algorithm used at low elevation. In newer air traffic control 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.

5.1.7. 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 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 through the radar receiver's sidelobes (*sidelobe jamming*).

Mainlobe jamming can generally only be reduced by narrowing the mainlobe solid angle and cannot 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.

5.1.8. Radar signal processing

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.

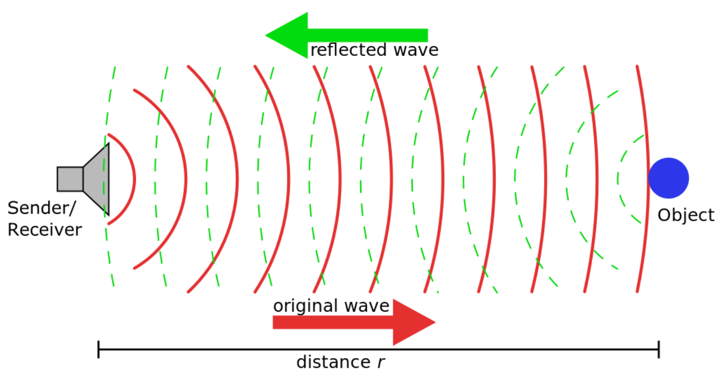


Fig 5.3. Continuous wave (CW) radar

One way to obtain a distance measurement is based on the time-of-flight: 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 round trip time multiplied by the speed of the signal. The factor of one-half comes from the fact that the signal has to travel to the object and back again. Since radio waves travel at the speed of light, accurate distance measurement requires high-speed electronics. In most cases, the receiver does not detect the return while the signal is being transmitted. Through the use of a duplexer, the radar switches between transmitting and receiving at a predetermined rate. A similar effect imposes a maximum range as well. In order to maximize range, longer times between pulses should be used, referred to as a pulse repetition time, or its reciprocal, pulse repetition frequency.

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. 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. As electronics have improved many radars now can change their pulse repetition frequency, thereby changing their range. The newest radars fire two pulses during one cell, one for short range (about 10 km (6.2 mi)) and a separate signal for longer ranges (about 100 km (62 mi)).

The distance resolution and the characteristics of the received signal as compared to noise depends 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 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 1,852 m, then dividing this distance by the speed of light (299,792,458 m/s), and then multiplying the result by 2 yields a result of 12.36 μs in duration.

5.1.9. 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 transmit frequency has changed. The frequency shift is used to measure distance.

The modulation index riding on the receive signal is proportional to the time delay between the radar and the reflector. The frequency shift becomes greater with greater time delay. The frequency shift is directly proportional to the distance travelled. That distance can be displayed on an instrument, and it may also be available via the transponder. 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. This was important in the early development of this type when high frequency signal generation was difficult or expensive.

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 used which allows slow moving objects to be detected as well as largely eliminating "noise" from the surfaces of bodies of water.

5.1.10. 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.

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 into Doppler radar and pulse-Doppler radar systems (weather radar, military 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.

It is possible to make a Doppler 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. CW radar is typically used by traffic enforcement to measure vehicle speed quickly and accurately where range is not important.

When using a pulsed radar, the variation between the phase of successive returns gives the distance the target has moved between pulses, and thus its speed can be calculated. 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 change of frequency of returns from moving targets ("chirp").

5.1.11. Pulse-Doppler signal processing

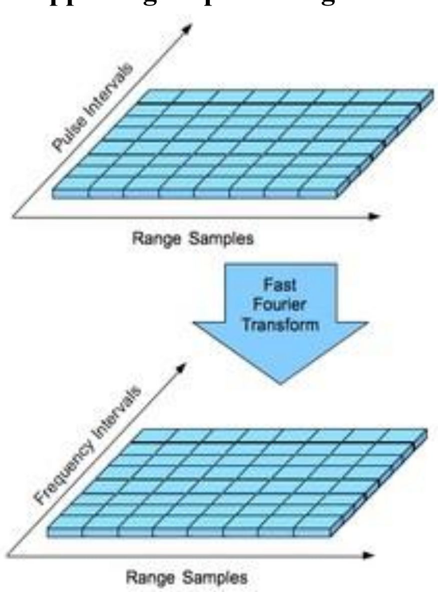


Fig 5.4. Pulse-Doppler signal processing.

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. This is sometimes called the *bed of nails*.

Pulse-Doppler signal processing includes frequency filtering in the detection process. The space between each transmit pulse is divided into range cells or range gates. Each cell is filtered independently much like the process used by a spectrum analyzer to produce the display showing different frequencies. Each different distance produces a different spectrum. These spectra are used to perform the detection process. This is required to achieve acceptable performance in hostile environments involving weather, terrain, and electronic countermeasures.

The primary purpose is to measure both the amplitude and frequency of the aggregate reflected signal from multiple distances. This is used with weather radar to measure radial wind velocity and precipitation rate in each different volume of air. This is linked with computing systems to produce a real-time electronic weather map. Aircraft safety depends upon continuous access to accurate weather radar information that is used to prevent injuries and accidents. Weather radar uses a low PRF. Coherency requirements are not as strict as those for military systems because individual signals ordinarily do not need to be separated. Less sophisticated filtering is required, and range ambiguity processing is not normally needed with weather radar in comparison with military radar intended to track air vehicles.

The alternate purpose is "look-down/shoot-down" capability required to improve military air combat survivability. Pulse-Doppler is also used for ground based surveillance radar required to defend personnel and vehicles.[40][41] Pulse-Doppler signal processing increases the maximum detection distance using less radiation in close proximity to aircraft pilots, shipboard personnel, infantry, and artillery. Reflections from terrain, water, and weather produce signals much larger than aircraft and missiles, which allows fast moving vehicles to hide using nap-of-the-earth flying techniques and stealth technology to avoid detection until an attack vehicle is too close to destroy. Pulse-Doppler signal processing incorporates more sophisticated electronic filtering that safely eliminates this kind of weakness. This requires the use of medium pulserepetition frequency with phase coherent hardware that has a large dynamic range. Military applications require medium PRF which prevents range from being determined directly, and range ambiguity resolution processing is required to identify the true range of all reflected signals. Radial movement is usually linked with Doppler frequency to produce a lock signal that cannot be produced by radar jamming signals. PulseDoppler signal processing also produces audible signals that can be used for threat identification.[40]

5.1.12. Reduction of interference effects

Signal processing is employed in radar systems to reduce the radar interference effects. Signal processing techniques include moving target indication, Pulse-Doppler signal processing, moving target detection processors, correlation with secondary surveillance radar targets, space-time adaptive processing, and trackbefore-detect. Constant false alarm rate and digital terrain model processing are also used in clutter environments.

CHAPTER 6

6.1. Advantages and Disadvantages of RADAR systems

6.1.1. Advantages of RADAR

1. RADAR can penetrate mediums such as clouds, fogs, mist and snow. The signals used by RADAR technology are not limited or hindered by snow, clouds or fogs. This means that even in the presence of these adverse conditions, data will still be collected.

2. RADAR signal can penetrate insulators. Materials that are considered insulators such as rubber and plastic do not hinder RADAR signals from collecting data. The signals will penetrate the materials and capture the necessary data require.

3. It can give the exact position of an object. RADAR systems employ the use of electromagnetic to calculate the distance of an object and its exact position on the earth's surface or space.

4. It can determine the velocity of a target. RADAR systems have the capability of calculating the velocity of an object in motion. Besides knowing its location, you will also have data regarding the velocity of the object.

5. It can measure the distance of an object. RADAR systems work by measuring the exact distance of an object from the transmitter.

6. It can tell the difference between stationary and moving targets. The data collected by RADAR systems is enough to tell whether the object was in motion or it was stationary.

7. RADAR signals do not require a medium of transportation. RADAR employs the use of radio signals that can travel in air or space. They do not require any medium to be transported.

8. RADAR signals can target several objects simultaneously. The radio signals used by RADAR operate on wider area and can target more than one object and return data regarding all the objects targeted.

9. It allows for 3D Imaging based on the various angles of return. The data captured by RADAR systems can be used to map an area and provide 3D images of the area based on the varying angles of return.

10. It is wireless and does not rely on wire connectivity. Radio signals do not require a medium to travel therefore there is no need of wire connectivity.

11. It is cheaper as compared to other systems. RADAR systems are relatively cheaper especially if used for large-scale projects.

12. High operating frequency allows for storage of large amounts of data. The RADAR systems can store large amounts of information that can be used for more than one purpose.

13. It covers a wider geographical area. The radio signals emitted by RADAR systems cover a significantly large geographical area at once.

14. It allows for repetitive coverage. RADAR systems are not limited to single coverage of a target. They can provide the same information multiple times about a target.

15. Easy data acquisition at different scales. It is easier to acquire data and information of a target with various resolutions.

16. It is fast if the area is not too large. RADAR systems return data quite fast if the area under observation is not too wide.

17. It has several industrial applications. RADAR systems provide data that can be used by several industries across the economic spectrum.

18. Cheap and fast method of calculating base maps when no detailed survey is required. The systems can be used to figure out base maps especially if the data being sort is not complicated.

19. It can get data from some of the remotest areas of the planet. RADAR can be used to get data from some of the most unreachable areas of the planet such as active volcanoes.

20. It is economical when doing small-scale map revision. It is a relatively cheaper method for small-scale mapping.

6.1.2. Disadvantages of RADAR systems

1. RADAR takes more time to lock on an object. Since radio signals travel freely in air and space, it takes more time to get to the object and back.

2. RADAR has a wider beam range (Over 50ft Diameter). The beam range for RADAR is quite wide and not target specific.

3. It has a shorter range (200ft). Unlike LiDAR, RADAR signals operate at a limited range of 200ft.

4. It cannot track if an object is decelerating at more the 1mph/s. If an object is in motion, it may be a challenge for RADAR systems to collect data from the object.

5. Large objects that are close to the Transmitter can saturate the receiver. The radio signals work best when the object is further away from the receiver and not closer.

6. Readings may be falsified if the object is handheld. If the target is held in the hand, the data collected may not be accurate.

7. RADAR can be interfered by several objects and mediums in the air. The radio signals face plenty of interference from the air while travelling to and from an object.

8. It cannot distinguish or resolve multiple targets. If there are several targets, the radio signals may not tell the objects apart.

9. It cannot differentiate the color of the object. RADAR systems will get all the information regarding an object but will not provide data regarding color of the target.

10. It cannot resolve targets that are deep in the sea. RADAR systems are not able to penetrate the sea beds to capture data of objects found deep down the sea.

11. It cannot resolve targets that are obstructed by a conducting material. Radio signals have challenges maneuvering materials that are conductors. If an object is behind such material, it is difficult for it to obtain the data regarding the target.

12. It cannot resolve the type of the object. RADAR systems do not provide data regarding the type of the target being resolved. The signals are not intelligent enough to tell the difference in object type.

13. It is not very accurate. The data collected by RADAR systems are accurate only up to a certain extent. Some details may be omitted due to lack of accuracy.

14. It can be interrupted with other signals. Radio signals travel through air and space where it can be combined with other radio signals from other frequency. If not properly directed, the signals can be interrupted by other signals and alter the information being transmitted.

15. It is not very stable and is susceptible to external interference. Since the signals from RADAR systems are not specifically targeted, it is prone to external interference by other mediums.

16. It can be oversensitive. The signals from RADAR systems tend to be oversensitive sometimes which may lead to inaccurate data.

17. It cannot be used beyond the ionosphere. The radio signals emitted by RADAR systems do not work beyond the ionosphere. If they go beyond the ionosphere, they will be deflected back to earth.

18. It can be expensive if used in small areas especially if it is one time use. RADAR systems are effective if used over large geographical areas over long periods of time. However, if it is only used once over a small area, the cost may be relatively expensive.

19. It requires specialized training to analyze the data. The data captured by RADAR system are usually stored in raw format. It requires specialized training to be able to analyze and interpret the data to make sense out of it.

20. The data provided by RADAR systems is usually not complete. The incomplete data is due to the fact that the signals will not report every detail about the target

CHAPTER 7

7.1. Conclusion and future work

The trends in next generation radars have been outlined, from making use of ultra-broadband multifunctional RF-system capabilities, digital frontend AESA antennas with distributed aperture systems in a multiple radar architectures, connectivity via network capable operations up to orthogonal waveforms to parallelize processing in combination with the progression in real-time computing, allows for highly advanced and performance radar applications in the future. They may only be limited by the price for flexibility and processing power, customers are willing to spend.

Early signal digitization enables already today's radars to implement knowledge based processing schemes and self-learning approaches of the environment and thus to improve detection probabilities and reduce false alarms. HENSOLDT is making use of a priori information in its various radar systems, such as ground topology, vegetation, buildings, coastlines, roads, railways, wind mills etc. as well as self-learning maps such as ground und Doppler clutter maps in order to reduce false alarm rates and improve detection probability performance. The use of such a priori and self-learning information is a steadily growing trend towards cognitive radar functionalities.

The variety of new possibilities provided by the future radar trends needs to be optimized by a flexible and modern radar resource management which assigns resources by quality needs of certain radar tasks rather than by fixed rules. One of the latest highly advanced real-time capable Quality of Service (QoS) based resource management schemes which also allows finding globally optimized solutions (under certain conditions) is the Quality of Service Resource Allocation Method called QRAM.

A distributed aperture radar systems there is an emerging trend of MIMO antenna aperture set-ups, using orthogonal waveforms on usually very sparsely populated antenna arrays. This technique may be a costefficient approach for short and medium range applications, where high angular resolutions are required. HENSOLDT has developed a MIMO radar demonstrator as shown in ***Figure*** to investigate the performance of such systems. On the right the built-up of a virtual MIMO array is depicted from the physical arrangement of Tx and Rx radiating elements making use of orthogonal waveforms.

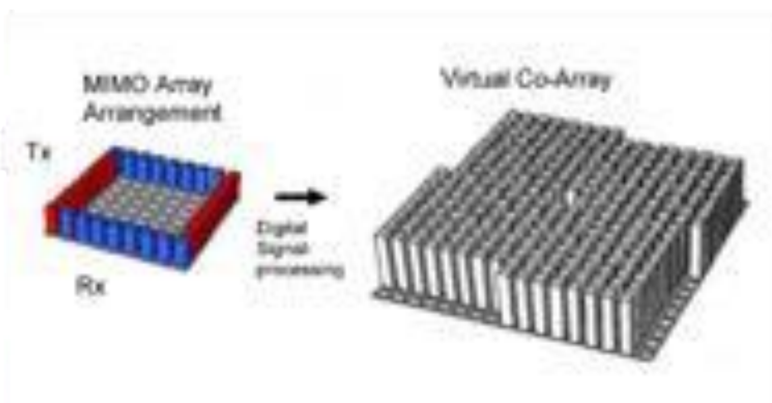


Fig 7.1. Left: HENSOLDT's MIMO demonstrator radar system; Right: Built up of a virtual MIMO array from the physical arrangement of Tx and Rx array elements.

There are several advantages but also restrictions in using MIMO radar for compact multifunction sensors. Apart from the better angular resolution compared to conventionally built radar of equivalent size, the

MIMO approach has the general advantage that an instantaneous Field of View (FoV) can be covered without the need of scanning, disregarding beam focusing in Tx and making use of frequency diverse orthogonal waveforms, so that orthogonal echoes of respective targets can be processed in parallel. On the other hand disregarding beam focusing leads to higher background clutter levels, so that applications are rather constrained to noise limited scenarios of short and medium ranges.

CHAPTER 8

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