Chapter 1
Introduction and Radar Overview

1.1 Introduction

Radar systems have evolved tremendously since their early days when their functions were limited to target detection and target range determination. In fact, the word "radar" was originally an acronym that stood for radio detection and ranging. Modern radars, however, are sophisticated transducer/computer systems that not only detect targets and determine target range, but also track, identify, image, and classify targets while suppressing strong unwanted interference such as clutter and countermeasures (jammers). Modern systems apply these major radar functions in an ever-expanding range of applications, from the traditional military and civilian tracking of aircraft and vehicles, to two- and three-dimensional mapping, collisions avoidance, earth resources monitoring, and many others.

The goal of Vol. I of *Principles of Modern Radar* is to provide newcomers to radar and current practitioners a comprehensive introduction to the functions of a modern radar system, the elements that comprise it, and the principles of their operation and analysis. In this chapter, an overview of the basic concepts of a radar system is given. The intent is to give the reader a fundamental understanding of these concepts and to identify the major issues in radar system design and analysis. Later chapters then expand on these concepts.

1.2 The Radar Concept

A radar is an electrical device that *transmits* radio frequencdy (RF) electromagnetic (EM) waves towards a region of interest and *receives* and *detects* these EM waves when *reflected* from objects in that region. Figure 1-1 shows the major elements involved in the process of transmitting a radar signal and receiving the reflected signals. The element of the radar that generates these EM waves is the *transmitter*. The *antenna* is the element of the radar that takes as input these EM waves from the transmitter and introduces them into the propagation medium (normally the atmosphere). The transmitter is connected to the antenna through a transmit-receive (TR) device (usually a *circulator* or a switch). The transmitted signal propagates through the environment to the target. Propagation effects of the atmosphere and earth on the waves may alter the strength of the EM waves at the target, as will the phenomenology of the reflection of these EM waves from objects of interest (*targets*).

The antenna also receives the EM waves again from the propagation medium when reflected from an object. The portion of the signal reflected from the target that propagates back to the radar antenna is "captured" by the antenna and applied to the *receiver* circuits. The components in the receiver amplify the received signal, convert the RF signal to an *intermediate frequency* (IF) and subsequently apply the signal to an analog-to-digital (A/D) converter, and then to the signal/data processor. The *detector* is the device that transforms the received EM waves into electrical signals that are then sorted and analyzed by the radar's *signal processor.* The coherent *exciter* generates the transmitted waveform and provides the reference signals to the receiver for coherent detection of the received signal.

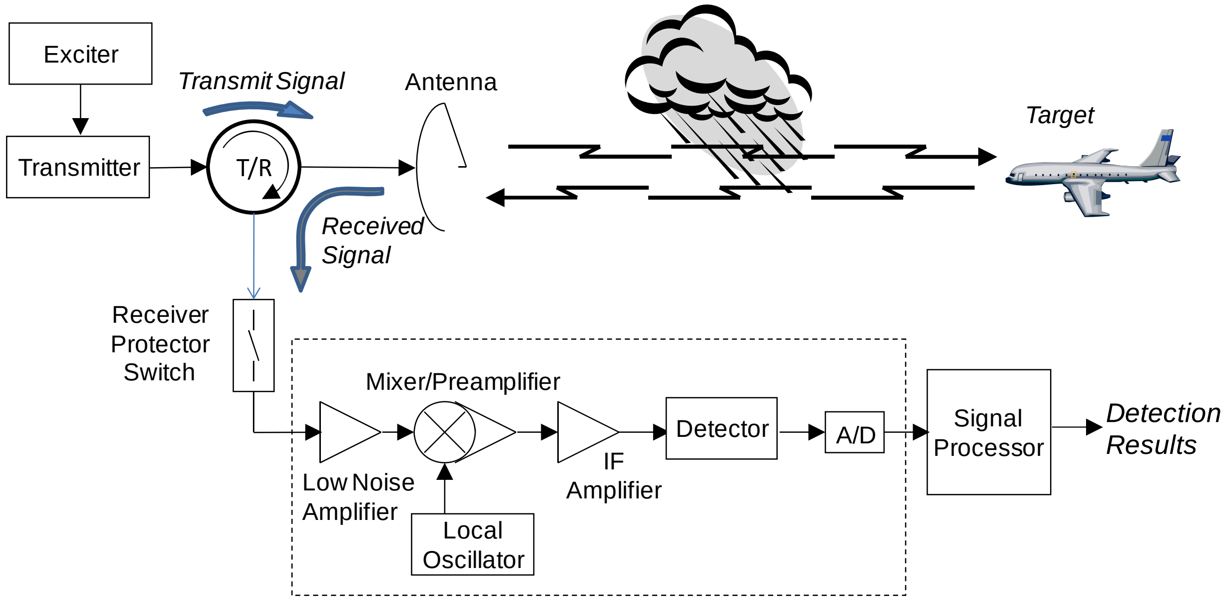


Figure 1-1. Major elements of the radar transmission/reception process.

The propagation of EM waves and their interaction with the atmosphere, clutters, and targets are discussed in Section 2 of this text (Chapters 4 - 8), while the major subsystems of a radar are described in Section 3 (Chapters 9 – 13).

The range, R, to a detected object can be measured from the time, T, it takes the EM waves to propagate to the object and back. Since cT must be the round-trip distance between the radar and the object, half that distance is the one-way range from the radar to the object:

$$R = \frac{cT}{2} \tag{1.1}$$

Here c is the speed of the EM wave ($c \approx 3\times10^8$ m/s in free space)[1].

Signals from targets (objects of interest) are detected in a background of interference. Inference comes in three different forms: (1) internal and external electronic *noise*, (2) backscatter (reflected EM waves) from objects *not* of interest, often called *clutter*, and (3) external EM waves created by other human-made sources, i.e., *electromagnetic interference* (*EMI*). Sorting target signals from noise is the primary function of the radar's detector. Sorting target signals from clutter returns is one of the primary function of the radar's signal processor. Detection and clutter suppression will be discussed further in this and subsequent chapters; they are a major concern of a significant portion of this textbook.

The third source of interference, EMI, can be unintentional, as in the case of signals from amateur radio or some cellular phone systems and noise from engine ignition or electric motor brushes, or intentional, as in the case of *jamming*. Jamming is the intentional transmission of interfering EM waves from another source towards a radar with the intention of denying the use of that radar to the radar operator. Jamming is a form of *electronic attack* (*EA*), one of the three

[1] The actual value of c in free space is 299,792,458 m/s, but $c = 3\text{x}10^8$ is an excellent approximation for almost all radar work.

principal disciplines in the area known as *electronic warfare (EW)*. The other two principal areas are *electronic protection* (*EP*) and *electronic support* (ES). An example of EP is *antenna sidelobe canceling*, a technique in which the antenna's sensitivity to EM waves in the direction of the jammer is greatly reduced. EP techniques are discussed further in Vol. II.

1.3 The Physics of EM Waves

Electromagnetic waves are oscillating electric and magnetic field waves. The behavior of EM waves is governed by the four laws, or equations, of electromagnetism known collectively as Maxwell's equations.

1.3.1 Maxwell's Equations

Before stating Maxwell's equations mathematically, it is useful to state their meaning in words. Maxwell's Equations simply stated in words are given in Table 1-1.

Table 1-1. Maxwell's Equations in Words

Gauss's Law for Electricity	"Electric charge produces electric fields."
Gauss's Law for Magnetism	"There is no magnetic charge."
Faraday's Law	"Time-varying magnetic fields produce electric fields."
Ampere-Maxwell Law	"Moving charge, i.e., current, (Ampere's Law) and time-varying electric fields (Maxwell's contribution) produce magnetic fields."

Maxwell's equations state that charged particles (e.g., electrons) produce electric fields (Gauss's Law for Electricity) and moving charged particles (currents) produce magnetic fields (Ampere's Law). Electric and magnetic fields can be visualized by the forces they exert on charged particles. A charged particle in the presence of an electric field will experience an *electric force*, while a moving charged particle in the presence of a magnetic field will experience a *magnetic force*. The sum of these two forces are given by the succinct equation [1]

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) \tag{1.2}$$

where $\vec{F}$ is the electromagnetic force vector, q is the charge of the charged particle, $\vec{E}$ and $\vec{B}$ are, respectively, the vector electric and magnetic fields in which the charged particle is moving, $\vec{v}$ is the velocity vector of the charged particle, and the symbol $\times$ denotes the vector cross-product.

Maxwell's Equations also state that electric fields are produced by time-varying magnetic fields (Faraday's Law) and vice versa, while magnetic fields are produced by time-varying electric fields (Maxwell's contribution of Ampere-Maxwell Law). This is what gives rise to a long-ranged electromagnetic wave. For example, consider a charge that is oscillating back and forth, e.g., an electron in an alternating current (AC) circuit. Since this charge has a time-varying velocity (acceleration), it produces both electric and magnetic fields that change in time in accordance with Gauss's and Ampere's Laws. It can be shown that if these two laws were the only laws of electromagnetism, then the amplitude of these electric and magnetic fields diminish as $1/R^2$, where R is the range from the charge, so that the fields would decay over a relatively short distance However, Faraday's Law states that the changing magnetic field also produces an electric field, while the Ampere-Maxwell Law states that the changing electric field produces a magnetic field. These changing electric and magnetic fields reinforce each other far out into the space from the oscillating charge. The result is that the amplitudes now decay more slowly, as $1/R$.

Mathematically, Maxwell's Equations can be expressed in either differential form or integral form. They are shown in integral form and described in words more precisely in Table 1-2.

Table 1-2. Maxwell's Equations.

Maxwell's Equations		
Name of Law	**Equation**	**Law in Words**
Gauss's Law for Electricity	$\oint_{surface} \vec{E} \cdot d\vec{A} = \dfrac{q}{\varepsilon_0}$	The flux of $\vec{E}$ through any closed surface equals the net charge inside that surface, q, divided by ε_0.
Gauss's Law for Magnetism	$\oint_{surface} \vec{B} \cdot d\vec{A} = 0$	The flux of $\vec{B}$ through any closed surface is zero.
Faraday's Law	$\oint_{loop} \vec{E} \cdot d\vec{s} = -\int_{area} \dfrac{\partial \vec{B}}{\partial t} \cdot d\vec{A}$	The circulation of $\vec{E}$ around any closed loop equals the negative time derivative of the flux of $\vec{B}$ through any area bounded by that loop.
Ampere-Maxwell Law	$\oint_{loop} \vec{B} \cdot d\vec{s} = \mu_0 i + \mu_0 \varepsilon_0 \int_{area} \dfrac{\partial \vec{E}}{\partial t} \cdot d\vec{A}$	The circulation of $\vec{B}$ around any closed loop equals μ_0 times the electric current, *i*, flowing through any area bounded by that loop plus $\mu_0\varepsilon_0$ times the time derivative of the flux of $\vec{E}$ through that area.

The constants ε_0, μ_0 are, respectively, the *permittivity* and *permeability* of free space. Their numerical values are such that

$$1/\sqrt{\mu_0 \varepsilon_0} = c \tag{1.3}$$

In free space (thus in the absence of charges and currents), Maxwell's equations can be reduced to the following vector differential equations:

$$\vec{\nabla}^2 \vec{E} = \mu_0 \varepsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2} \quad \text{and} \quad \vec{\nabla}^2 \vec{B} = \mu_0 \varepsilon_0 \frac{\partial^2 \vec{B}}{\partial t^2} \tag{1.4}$$

Equations (1.4) are the so-called *wave equations*, the solutions of which are respectively electric and magnetic field waves, i.e., electromagnetic waves, propagating at the speed $1/\sqrt{\mu_0 \varepsilon_0} = c$. A solution to the first wave equation above of particular interest to radar is a traveling sinusoidal electric field wave, with the amplitude of each directional component (*e.g.* horizontal and vertical) having the form

$$E = E_0 \cos\left(kz - \omega t + \phi\right) \tag{1.5}$$

where k is the *wavenumber*, ω is the radian frequency, and ϕ is the *phase* of the wave. These parameters and their significance are described in Section 1.4.3.2 below.

1.3.2 EM Wave Properties and Parameters

In free space, the oscillating electric, $\vec{E}$, and magnetic, $\vec{B}$ fields of the propagating EM wave are orthogonal and the direction of the propagating wave is orthogonal to both $\vec{E}$ and $\vec{B}$ (i.e., the EM wave is *transverse*). The direction of propagation is given by the direction of $\vec{S} = \vec{E} \times \vec{B}/\mu_0$ (the *Poynting vector*) and the intensity (power/area) of the wave is given by the magnitude of $\vec{S}$, i.e., $\left|\vec{S}\right|$. The ratio $\left|\vec{E}\right|/\left|\vec{B}\right|$ is *c*, the speed of the propagation of the EM wave (speed of light).[2] Therefore, if the direction of propagation and the properties of either vector field ($\vec{E}$ or $\vec{B}$) is known, then the properties of the other vector field can be determined. Consequently, the EM is typically described in terms of the electric field.

1.3.2.1 Polarization

The EM wave's polarization is the description of the motion and orientation of the electric field vector. Suppose the wave is traveling in the $+z$ direction in a Cartesian (x-y-z) coordinate system. Then the direction of the electric field $\vec{E}$ must lie in the x-y plane. An electric field oriented along some angle in the x-y plane thus has components in both the x and y directions, say E_x and E_y, as shown in Fig. 1-2. The amplitudes of these two components will each vary sinusoidally as in Eq. (1.5). The relative peak amplitudes and phases of E_x and E_y determine how the orientation of the resultant vector $\vec{E}$ varies with time, and thus the *polarization* of the EM wave. For example, if the y component of the electric field is zero, then $\vec{E}$ oscillates along the x axis and the EM wave is said to be *linearly polarized* in the x direction. If x represents a horizontally-oriented axis, the wave is *horizontally polarized.* Similarly, the wave would be vertically linearly polarized if the x component is zero but the y component is not. If E_x and E_y have the same magnitude and oscillate in phase with one another ($\phi_x = \phi_y$), the field will oscillate linearly along a 45º line in the x-y- plane. In general, the polarization will be linear if the x and y components differ in phase by any integer multiple of π radians; the angle of the polarization will depend on the relative magnitudes of E_x and E_y.

[2] $\vec{H} = \vec{B}/\mu_0$ is also referred to as the "magnetic field" and $\left|\vec{E}\right|/\left|\vec{B}\right| \equiv Z_0 = 377$ ohms is the impedance of free space. In this case, $\vec{B}$ is sometimes referred to as the "magnetic induction."

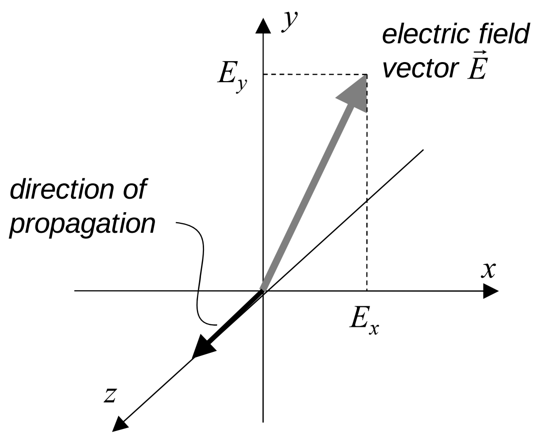


Figure 1-2. Polarization components of a transverse EM wave propagating in the +z direction.

If $E_x = E_y$ and the phases differ by an odd multiple of $\pi/2$, the tip of $\vec{E}$ traces out a circle as the wave propagates and the EM wave is said to be *circularly polarized*; one rotation sense is called “right-hand” or “right circular” polarization and the other, “left-hand” or “left circular” polarization. The most general polarization state is elliptical, in which the tip of $\vec{E}$ traces out an ellipse as the wave propagates.

1.3.2.2 Wavelength, Frequency, and Phase

As the EM wave propagates in space, the amplitude of $\vec{E}$ for a linearly polarized wave, measured at a single point in time, would trace out a sinusoid as shown in Fig. 1-3. This corresponds to holding t constant in Eq. (1.5) and letting z vary. The *wavelength* , λ, of the wave is the distance from any point on the sinusoid to the next corresponding point, e.g., peak to peak, null (descending) to null (descending), etc.

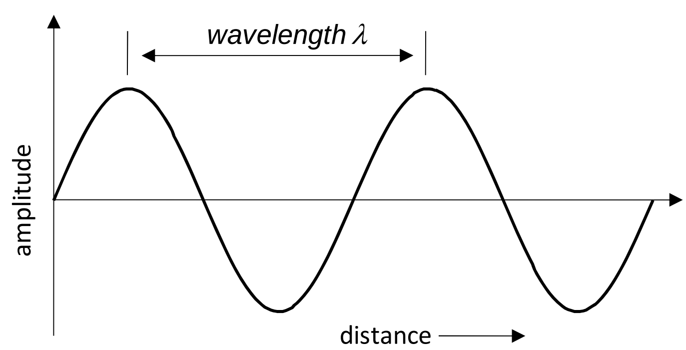


Figure 1-3. The wavelength of a sinusoidal electromagnetic wave.

If on the other hand a fixed location in space was chosen and the amplitude of $\vec{E}$ were observed as a function of time at that location, the result would be a sinusoid as a function of time as shown in Fig. 1-4. This corresponds to holding z constant in Eq. (1.5) and letting t vary. The *period* , T_p, of the wave is the time from any point on the sinusoid to the next corresponding part, e.g., peak to peak, null (descending) to null (descending), etc.. That is, the period is the time it takes the EM wave to go through one cycle. If the period is expressed in seconds, then the inverse of the period in the number of cycles the wave goes through in one second. This quantity is the wave's *frequency*, f,

$$f = \frac{1}{T_p} \tag{1.6}$$

Frequency is expressed in hertz (Hz); one Hz equals one cycle per second.

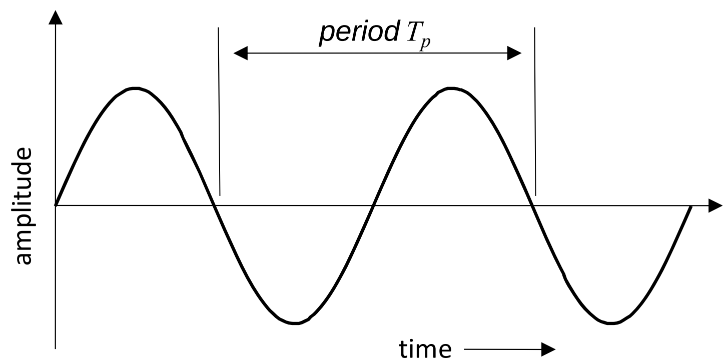


Figure 1-4. The period of a sinusoidal electromagnetic wave.

The wavelength and frequency of an EM wave are not independent; their product is the speed of the wave (c in free space),

$$\lambda f = c \tag{1.7}$$

Therefore, if either the frequency or wavelength is known, then the other is known as well. For example, an EM wave with a 3 cm wavelength has a frequency of

$$f = \frac{c}{\lambda} = \frac{3\times10^{8}\ \text{m/s}}{0.03\ \text{m}} = 10^{10}\ \text{Hz or 10 GHz} \tag{1.8}$$

where "G" stands for "giga" or 10^9.

Shown in Fig. 1-5 are the different types of EM waves as a function of frequency, from EM telegraphy to gamma rays. Although they are all EM waves, their characteristics are very different depending on their frequency. Radars typically operate in the range of 3 MHz to 300 GHz, though the large majority operate between about 1 GHz and 35 GHz. This range is divided into a number of radar "bands" [2] as shown in Table 1-3. Note that a given radar system will not operate over the entire range of frequencies within its design band, but rather over a limited range within that band. Authorization for use of frequencies as issued by the Federal Communication Commission in the United States limits the range of frequencies for a given system. Also, at frequencies above about 16 GHz, the specific frequencies are chosen to coincide with relative "nulls" in the atmospheric absorption characteristics, as will be discussed shortly.

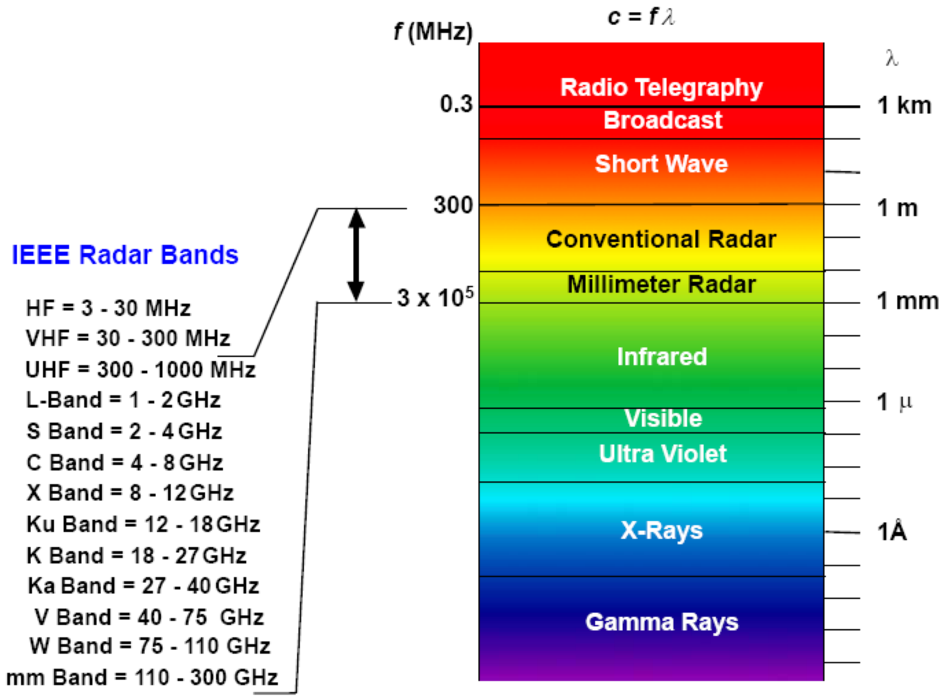


Figure 1-5. Electromagnetic wave spectrum.

Table 1-3. Radar bands.

Band	Frequency Range
High Frequency (HF)	3 – 30 MHz
Very High Frequency (VHF)	30 – 300 MHz
Ultra High Frequency (UHF)	300 MHz – 1 GHz
L	1 – 2 GHz
S	2 – 4 GHz
C	4 – 8 GHz
X	8 – 12 GHz
Ku ("under" K band)	12 – 18 GHz
K	18 – 27 GHz
Ka ("above" K band)	27 – 40 GHz
V	40 – 75 GHz
W	75 – 110 GHz
mm	100 – 300 GHz

As discussed above, the amplitude of the x or y component of the electric field of an electromagnetic wave propagating along the z axis can be represented mathematically as

$$E = E_0 \cos\left(kz - \omega t + \phi\right) \tag{1.9}$$

where E_0 is the peak amplitude and the *wave number, k,* and the *angular frequency,* ω*,* are given by

$$k = \frac{2\pi}{\lambda} \text{ radians/m}, \quad \omega = 2\pi f \text{ radians/sec} \tag{1.10}$$

Note that wave number is in units of radians per meter, and so is a kind of "spatial frequency". The factor ϕ is often called the *absolute*, *fixed,* or *initial phase*. It is arbitrary in that it depends on the electric field's initial conditions, i.e., the value of E for the arbitrarily chosen spatial and temporal positions corresponding to $z = 0$ and $t = 0$. For example, if $E = 0$ when $x = t = 0$, then $\phi = \pm\pi/2$ radians. The *phase* is the total argument of the cosine function, $kz - \omega t + \phi$, and depends on position, time, and initial conditions.

The *relative phase* is the phase difference between two waves. Two waves with a zero relative phase are said to be *in-phase* with one another. They can be made to have a non-zero phase difference, i.e., be *out-of-phase*, by changing the wave number (wavelength), frequency, and/or absolute phase of one (or both). Two waves originally in-phase can become out-of-phase if they travel different path lengths. Figure 1-6 illustrates two waves having the same frequency but out of phase by $\Delta\phi = 50°$. If the waves are viewed as a function of time at a fixed point in space, as in this figure, then one is offset from the other by $\Delta\phi/\omega$ seconds.

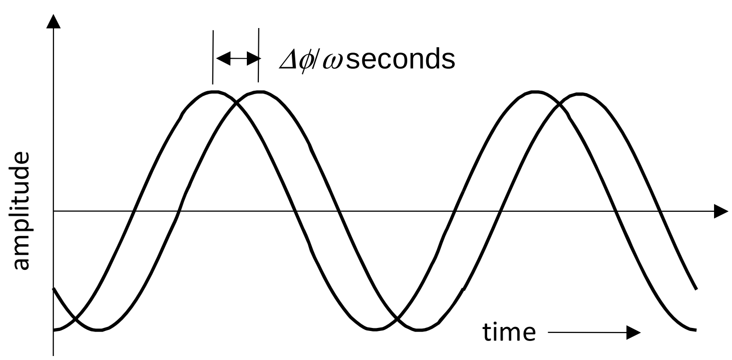


Figure 1-6. Two sinusoidal waves with the same frequency but a phase difference $\Delta\phi$*.*

The principle of superposition states that when two or more waves are present at the same place and the same time, the resultant wave is the sum, or superposition, of the waves. This sum depends on the amplitudes and phases of the waves. For example, two in-phase waves of the same frequency will produce a resultant wave that has an amplitude that is the sum of the two waves' respective amplitudes (*constructive interference*), while two out-of-phase waves will produce a resultant wave that has an amplitude that is less than this sum (*destructive* *interference*). Two waves of equal amplitude that are π radians (180 degrees) out-of-phase will produce a *null* result; i.e., no wave.

This interference behavior of waves gives rise to the phenomenon of *diffraction,* which is responsible for the formation of the antenna pattern and antenna beam (or *mainlobe* of the antenna pattern). Consider a circular (diameter *D*) planar antenna made up of many radiating elements, each of which is emitting EM waves of equal amplitudes in all directions. Assume that all the waves are in phase as they are emitted from the antenna elements. At a point along a line perpendicular (normal) to the plane and far away from the antenna (see Chapter 9 for a discussion of the antenna far field), all the waves will have essentially traveled the same path length and, therefore, will all still be in-phase with each other. Constructive interference will occur and the resultant wave will have an amplitude *N* times larger than the individual waves emitted from the elements. This represents the peak of the antenna beam. At any point off of this normal, the waves will have traveled different path lengths and, thus, destructive interference occurs and the resultant wave will have an amplitude less than *N* times larger. As the distance from the normal increases, this amplitude decreases, finally reaching a perfect null (complete destructive interference). The angular region between the first null to either side of the antenna normal defines the *mainbeam* or *mainlobe* of the antenna. Most of the radiated power is concentrated in this region. Twice the angular distance from the peak of the antenna mainbeam to the point where the EM wave power has dropped to half its peak value ($1/\sqrt{2}$ of the peak amplitude) is the half-power, or 3 dB, *beamwidth* , , θ_B and, for a circular aperture, is approximately given by

$$\theta_B = \frac{1.2\lambda}{D} \text{ radians} \tag{1.11}$$

At angles past the first null, the individual waves partially constructively interfere again so that the net amplitude starts to increase, rising to a peak, and then falls again to a second null. This pattern is repeated over and over again, forming an *antenna pattern* as shown in Fig. 1-7. This figure shows a one-dimensional planar "cut" through the two-dimensional pattern of an idealized two-dimensional antenna. The lobes outside the main lobe are called *antenna sidelobes.*

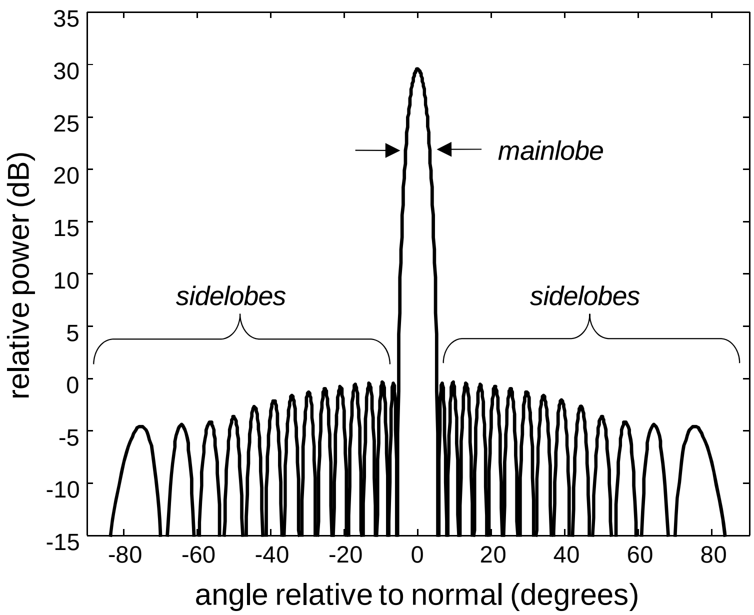


Figure 1-7. Idealized one-dimensional antenna pattern.

If the phases of the EM waves have different values when they are emitted from the elements, then they will no longer constructively interfere in the far field in the direction of the antenna normal. However, if these phase values are adjusted properly, the amplitude of the far-field resultant wave can be made to peak at some angle off of the normal. All the waves in this direction traveled different path lengths and, therefore, will have different path-length-induced phases. However, if the original phases upon emission are selected properly, they can be made to compensate for the path-length-induced phases and all the waves will be in-phase in that direction. Thus, by changing the phases of the emitted waves, the peak of the antenna beam will effectively scan from its normal position without the antenna physically moving. This is the basic concept behind a *phased array antenna* or *electronically scanned antenna* (ESA); it is discussed in more detail in Chapter 9.

1.3.2.3 Intensity

The *intensity, I,* of the EM wave is defined as the power (time-rate-of-change of energy) per unit area of the propagating wave. Thus, intensity is equivalent to *power density*. Consider a single antenna element emitting an EM wave of power *P* equally in all directions (*isotropic*) as shown in Fig. 1-8. The locus of all points having the peak amplitude at a given moment in time (*wavefront*) in this wave will be a sphere; the distance between adjacent concentric spheres will be the wavelength. Since the wave is isotropic, the power everywhere on the surface of a given spherical wavefront of radius *R* will be the same. Thus, the power density is the total radiated power, *P,* divided by the surface area of the sphere, or

$$I = \frac{P}{4\pi R^2} \tag{1.12}$$

Thus, the intensity of the EM wave falls off as $1/R^2$, where R is the distance from the isotropic source.

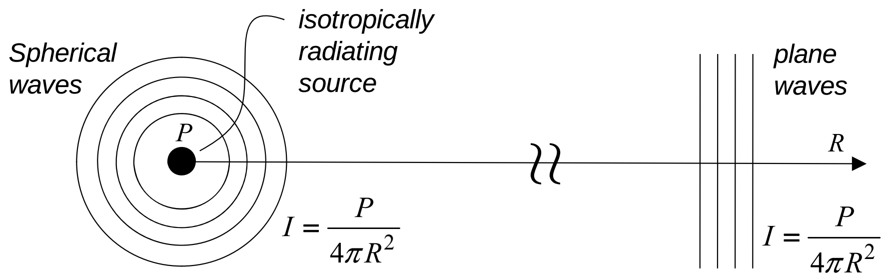


Figure 1-8. Intensity of Spherical Waves.

If the wave is sufficiently far from the source, and a limited spatial extent of the wave is considered, then the spherical wavefronts are approximately planar, as shown in the right-hand portion of Fig. 1-8.. This is call the *far field*, or plane wave, approximation. The far-field approximation is considered to hold for a collecting aperture of diameter D if it is at least $2D^2/\lambda$ meters from the source.

1.4 Interaction of EM Waves with Matter

A radar is a device that transmits and receives EM waves. These waves interact with matter, specifically, the radar's antenna, then the atmosphere, and then with the target. The relevant physical principles governing these interactions are reflection (target), attenuation & refraction (atmosphere), and diffraction (antenna).

1.4.1 Target Reflection

Reflection is the re-radiation of the EM wave from the surface matter of an object, such as terrain or a man-made target. Incident EM waves induce the electric charge in the matter to oscillate and thus to re-radiate the EM wave. This re-radiation is called *scattering* of the incident wave. If the matter is a conductor so that the electric charge is free to move in the matter, then essentially all the EM wave energy is re-radiated. If the matter is a dielectric material so that its electric charge is bound, some of the energy is re-radiated and some propagates through the matter and is absorbed.

The manner in which the EM wave is reflected from the surface depends on the roughness of the surface relative to the wavelength of the incident wave. Roughly speaking, roughness is the variation in surface height. It is usually quantified by the standard deviation of the surface height. If the surface is "smooth" (λ >> roughness), then the EM wave's angle of reflection θ_r equals its angle of incidence θ_i on the surface (see Fig. 1-9). This is called *specular* scattering. Most scattering from man-made objects in radar technology is specular.

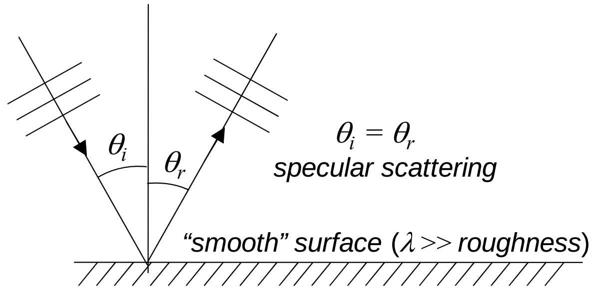


Figure 1-9. Specular scattering.

If, on the other hand, the surface is "rough" (λ << roughness), then the scattering is specular only over small local regions of the surface. Macroscopically, the incident energy appears to be reflected at all angles (see Fig. 1-10). This is called *diffuse* scattering. To accurately predict the scattering of EM waves from an object, both specular and diffuse scattering must be taken into consideration. Scattering from natural surfaces, especially at shorter wavelengths (higher frequencies), is often diffuse.

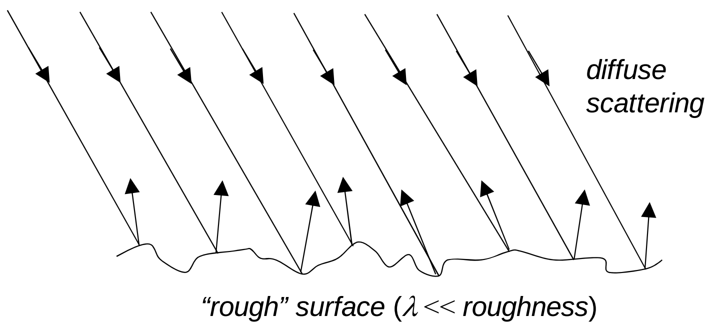
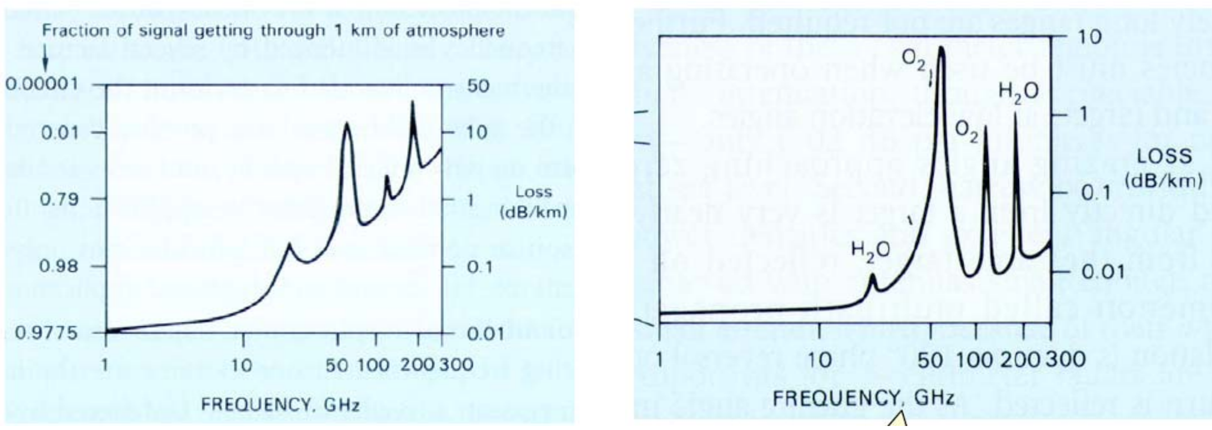


Figure 1-10. Diffuse scattering.

In radar technology, scattering phenomenology is quantified by the target parameter *radar cross section* (RCS)*, σ.* RCS has the units of area, e.g., m^2. The RCS of a target is not a single number, but a function of target viewing angle and of the frequency and polarization of the incident EM wave. RCS is a measure of not only how much of the incident EM wave is reflected from the target, but also how much of the wave in intercepted by the target and how much is directed back toward the radar's receiver. Thus, these three mechanisms, interception*,* reflection*,* and directivity all determine the RCS of a target. If a target is to be made "invisible" to a radar, i.e., be a *stealth* target, then its RCS must be made as low as possible. To do this, all three mechanisms must be addressed. That is, the amount of the EM wave energy that is intercepted by the target must be minimized, which is accomplished by minimizing the physical cross section of the target. The amount of energy reflected by the target must be minimized, which is accomplished by absorbing as much of the EM wave as possible through the use of *radar absorbing material* (RAM) on the surface of the target. Finally, the amount of the reflected energy that is directed towards the radar receiver must be minimized, which is accomplished by shaping the target. The RCS of terrain is discussed in more detail in Chapter 5, while that of targets, including stealth considerations, is discussed in Chapter 6.

1.4.2 Atmospheric Attenuation

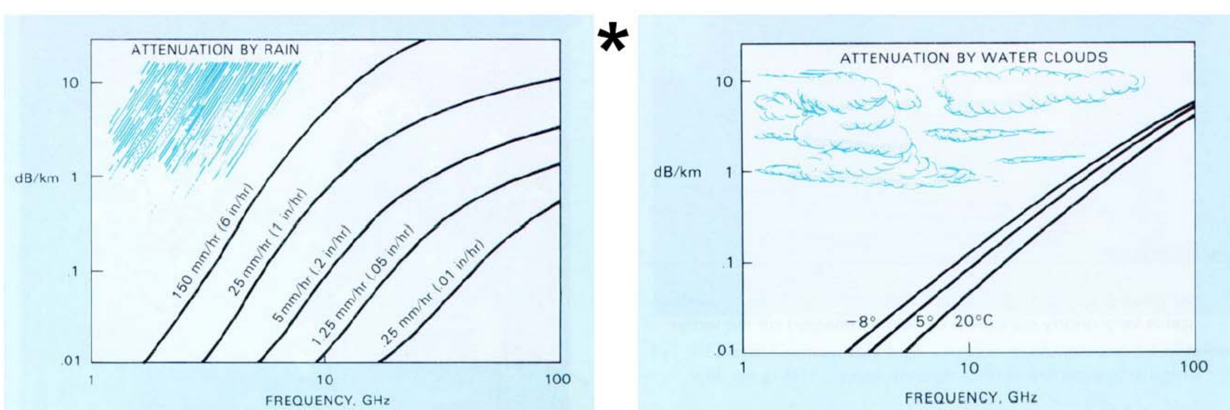
Figure 1-11 shows the atmospheric attenuation of EM waves in the atmosphere as a function of frequency. There is very little attenuation below a frequency of 1 GHz (L band). Above 1 GHz, the attenuation steadily increases and peaks are seen at 16 GHz (due to water absorption), 60 GHz (due to oxygen absorption), and at higher frequencies. Above 10 GHz (X band), there are troughs, or *windows*, in the absorption spectrum at 35 GHz (Ka band), 94 GHz (W band), and other higher frequencies. These windows are the frequencies of choice for radar systems in these higher frequency bands. For long-range radars, e.g., ballistic missile defense radars, frequencies at L band and below are generally required to minimize atmospheric attenuation.



(a) (b)

Figure 1-11. Atmospheric attenuation as a function of frequency. (a) At sea level. (b) At 30,000 feet above mean sea level.

Rain and clouds also attenuate EM waves as shown in Fig. 1-12. Rain attenuation increases with increasing rain rate and increasing frequency. At low frequencies, rain and cloud attenuation is small, giving radar systems their famous "all weather capability" not seen in electro-optical and infrared systems.



(a) (b)

Figure 1-12. Rain and cloud attenuation as a function of frequency. (a) Rain. (b) Clouds.

1.4.3 Atmospheric Refraction

Refraction is the bending of EM waves at the interface of two different dielectric materials. This occurs because the speed of the EM wave is a function of the material in which it is propagating; the more "optically dense" the material, the slower the speed. Consider a wave incident on the interface to two difference materials as shown in Fig. 1-13. Within the denser material (glass), the EM wave slows down due to a decrease in wavelength ($v = \lambda f$). The optical density of a material is quantified by the index of refraction, n, given by $n = c/v$ where v is the speed of the EM wave in the material. If this wave were incident on the interface at some angle as shown in Fig. 1-14, then given the reduction of wavelength in the material with a higher index of refraction, the only way the wavefronts can remain continuous across the interface is for them to bend at the interface. This bending is refraction.

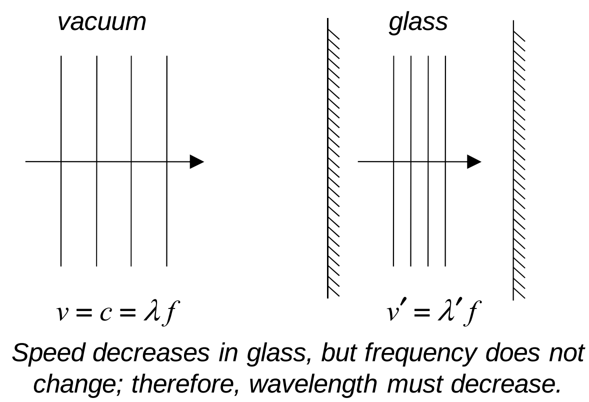


Figure 1-13. Difference in wavelength for wavefronts in two materials.

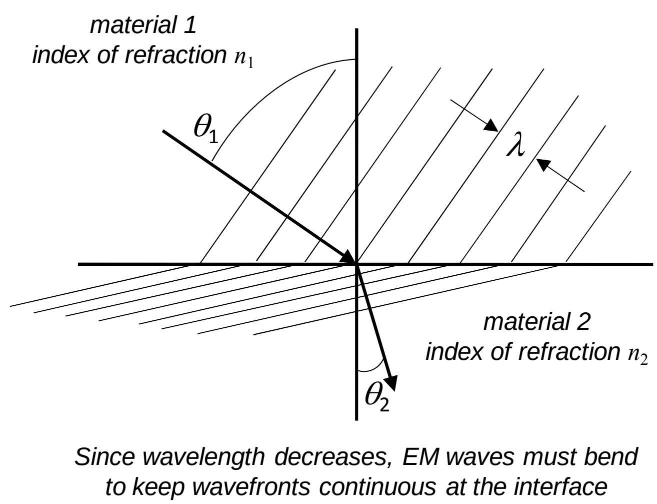


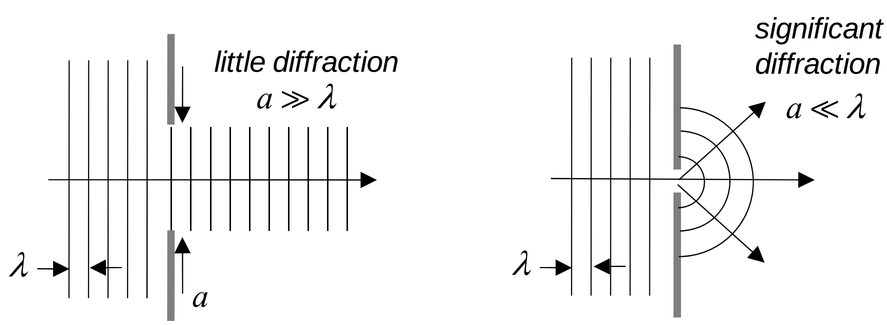
Figure 1-14. Bending of wavefronts incident at an angle on the interface of two materials.

In radar technology, refraction is encountered in radar systems directed up (or down) through the atmosphere at an angle relative to horizontal. The atmosphere thins with increasing altitude, causing the index of refraction to reduce. Therefore, the path of the transmitted EM wave will deviate from a straight line and bend back towards the earth. Deviations from straight-line propagation adversely affect target location and tracking accuracy unless refraction effects are accounted for.

Refraction can be beneficial for surface-to-surface radars (e.g. shipboard radars detecting other ships) since it can allow the EM wave to propagate over the visible horizon and detect ships not detectable optically. This effect is called ducting and radars that utilized this effect are called over-the-horizon (OTH) radars. (Other OTH radars use reflections off of the earth's ionosphere to achieve this OTH capability.)

1.4.4 Antenna Diffraction

Diffraction is the bending of the EM wave as they propagate through an aperture or around the edge of a object. Diffraction is an interference phenomenon as was discussed in Section 1.4.3.2 above. It gives rise to the antenna pattern, mainlobe and sidelobes. The amount of diffraction present depends of the size of the aperture (antenna), *a,* relative to the wavelength, λ, of the EM wave. Shown in Fig. 1-15 are two extreme cases.



Many paths of width λ through aperture, thus destructive interference in all directions except forward, preventing diffraction

Only one path of width λ through aperture, thus diffracts in all directions on other side, propagating isotropically

Figure 1-15. Extreme cases of diffraction.

The waves emitting from the aperture (idealized in Fig. 1-15 as an opening, or "slit," in a surface) can be thought of as being produced by many antenna elements, as in a phased array antenna, separated by a wavelength (or less) and all emitting waves isotropically. In physics, this is known as Huygen's Principle. If the aperture size is much greater than a wavelength, i.e., $a >> \lambda$, then there will many radiating elements present and there will be significant destructive interference in all but the forward direction. In this case, there is very little diffraction and the antenna beamwidth will be small. This can be seen from Eq. (1.11) (with *D* replaced with *a*):

$$\theta_B = \frac{1.2\lambda}{a} << 1 \text{ radian for } a >> \lambda \tag{1.13}$$

Conversely, if the aperture size is much smaller than a wavelength, then there is essentially only one radiation element present and no destructive interference takes place . In this case the EM waves propagate isotropically, producing significant diffraction effects and a large beamwidth.

Large antenna beamwidths have negative performance effects in many radar applications. For example, the ability to resolve targets in the cross-range dimension decreases with increasing beamwidth, while in air-to-ground radars, the amount of ground clutter (interfering echoes from terrain) detected increases with increasing antenna beamwidth. In addition, larger beamwidths result in reduced antenna gain, decreasing the signal-to-noise ratio.

Applications in which large antenna beamwidths are advantageous are: 1) in the search mode, and 2) in strip-map synthetic aperture radars. In the search mode, where high resolution is normally not required, a given volume can be searched faster with a wide beam. For a SAR, the larger the antenna beamwidth, the larger the (strip-map mode) can be and, thus, higher target resolution can be achieved (see Chapter 21).

1.5 Noise, SNR, and Detection

Maxwell's Equations state that all accelerating (oscillating) charges will give rise to EM waves. This is both good and bad for radars. It is good for radars in that it allows for the radar's transmitter to produce EM waves; electrons are excited (made to oscillate) at a specific frequency in a tuned circuit in the transmitter, thus producing EM waves of that frequency which are then sent to the radar's antenna. It is bad for radars in that due to random thermal motion of electrons, all objects in the universe with a temperature above absolute zero will be radiating EM waves at, collectively, almost all frequencies. These EM waves, called *noise*, will always be present at the radar's receiving antenna and will interfere with the reflected EM waves from the target. In addition, the radar's receiver, being an electrical device with oscillating electrons, will be generating its own internal noise that will also interfere with the received target signal.

Suppose the signal power, S, of the reflected EM wave from the target is much greater than the noise power, N, due to environmental and receiver noise. Equivalently, the mean signal-to-noise power ratio, SNR, is much greater than one (e.g., 100). If this is the case, a target echo signal can be discriminated from the noise by setting an *amplitude threshold* above the noise level but below the target level. Any received signals that are above this amplitude threshold are accepted and are assumed to be returns from targets, while signals below this threshold are assumed to be noise. This is the basic concept of threshold detection. In the example of Fig. 1-16. The signal is 200 samples of noise. A target was added with an SNR of 50 (14 dB) at sample 50. If the threshold is set at a value of 10 dB, the target+noise sample easily exceeds the threshold and so will be detected, while all but one of the noise-only samples does not cross the threshold. Thus, the target is separated from (almost all of) the noise.

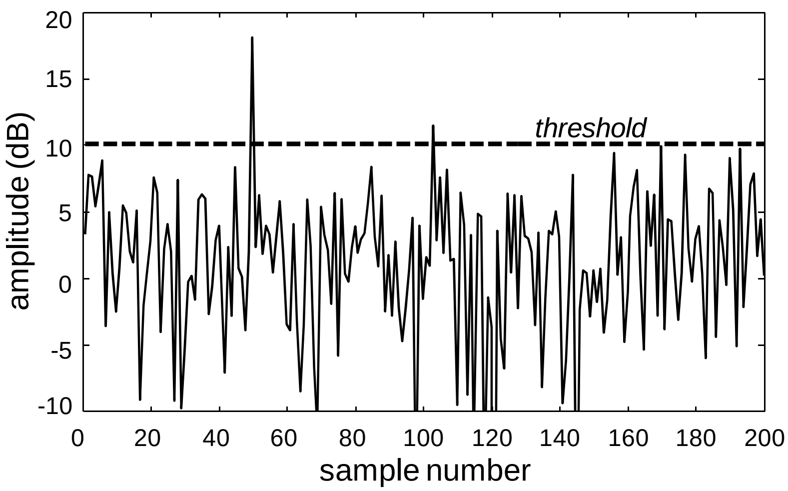


Figure 1-16. Threshold detection of a noisy signal.

Both the target signals and noise are random variables. Because of this, at any given time, the noise can "spike up" and cross the amplitude threshold giving rise to a *false alarm*. In Fig. 1-16, a single false alarm occurs at sample 103. In addition, the target signal at any given time can drop below the amplitude threshold, resulting in a *missed target detection*. Because of this random nature of target signals and noise, the detection performance of a radar must be given in terms of probabilities, usually the probability of detection, P_D, and the probability of false alarm, P_{FA}. P_D is the probability that a target signal will exceed the threshold and P_{FA} is the probability that the noise will momentarily spike above threshold. Perfect radar detection performance would correspond to $P_D = 1$ (or 100%) and $P_{FA} = 0$ (or 0%). Either P_D or P_{FA} can be arbitrarily set (but not both at the same time) by changing the amplitude threshold. When the threshold is raised, P_{FA} goes down, but unfortunately, so does the P_D. When the threshold is lowered, the P_D goes up, but, unfortunately, so does the P_{FA}. Thus, when the threshold is changed P_{FA} and P_D both rise or fall together. To increase the P_D while at the same time lowering the P_{FA}, the SNR must be increased. Chapter 2 develops a closed-form of the equation to predict the mean SNR called the *radar range equation* (RRE), while Chapters 3 and 15 discuss the methods for relating P_D and P_{FA} to SNR.

1.6 Basic Radar Measurements

Modern radars make target measurements in a multi-dimensional space:

Elevation angle, ϕ
Azimuthal angle, θ
Range, R
Doppler frequency, f_d
Polarization (up to five parameters)

Measurements in each of these dimensions are discussed in the following subsections.

1.6.1 Target Position

Target position must be specified in three-dimensional space. A radar naturally measures position in a spherical coordinate system (see Fig. 1-17 below). The target's angular position, here denoted by the azimuth and elevation angles θ and ϕ, is determined by the pointing angle of the antenna when the target detection occurs. This antenna-pointing angle can either be the actual physical pointing angle of a mechanically-scanned antenna or the electronic pointing angle of an electronically-scanned (phased array) antenna. (See Chapter 9 for more on antenna scanning mechanisms.) The target's range R, which is the third spherical coordinate, is determined by the round-trip time of the EM wave as discussed in Section 1.2 above.

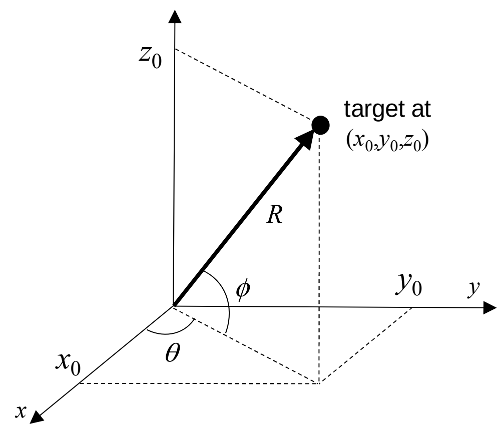


Figure 1-17. Spherical coordinate system depicting radar-target geometry.

1.6.2 Doppler Frequency Shift

If there is relative motion between the radar and the target, then the *frequency* of the EM wave reflected from the target and received by the radar will be different from the frequency of the wave transmitted from the radar. This is the well-known *Doppler effect*, common to all wave phenomenon and best known for sound waves. (Frequency is the number cycles the EM wave undergoes every second and is discussed in Section 1.4 below.) The Doppler frequency shift f_d, or "Doppler" for short, is the difference between the frequency of the received wave and that of the transmitted wave and is approximately given by

$$f_d \cong \frac{2v}{\lambda} \tag{1.14}$$

where v is the radial component[3] of the target's velocity vector relative to the radar and λ is the wavelength of the transmitted EM wave (wavelength is discussed in Section 1.4 below). This

[3] The radial component is the component of velocity along the range dimension (i.e., a straight line between the radar and the target),.

radial velocity component, *v*, is positive (and, thus, f_d is positive) for targets approaching the radar and negative (f_d negative) for targets receding from the radar.

Doppler is a very important quantity measured in modern radars. It is used to suppress returns from clutter, classify and identify moving targets and targets with moving components, e.g., aircraft, helicopters, trucks, tanks, etc., and in a *synthetic aperture radar* (*SAR*), Doppler is used to improve the *resolution* of the radar. For example, consider a stationary radar designed to detect moving targets on the ground. The EM wave return from a moving target will have a non-zero Doppler shift, whereas the return from stationary clutter (trees, rocks, buildings, etc.) will essentially have a zero Doppler shift. Thus, Doppler can be used to sort (discriminate) returns from targets and clutter by employing a high-pass filter in the radar's signal processor. This is the essence of *moving target indication* (*MTI*) radars discussed in Chapter 17.

With knowledge of the few Doppler facts given above, one can easily understand how Doppler can be used to improve the resolution in a SAR. Consider an aircraft with a radar on board pointing out of the side of the aircraft down to the ground, i.e., a *sidelooking* radar. If the radar's antenna has a one degree *beamwidth* and the ground is 1000 meters from the radar, then the antenna beam will be approximately 21 meters wide in the cross-range dimension (the direction of aircraft motion, which is also perpendicular to the range dimension) on the ground. This means that two objects on the ground at the same range and closer than 21 meters in the cross-range dimension essentially appear as one object to the radar, i.e., they are not resolved. However, Doppler can be used to resolve objects within the antenna's beam. As shown in Fig. 1-18, objects in the front, middle, and back of the beam will have a positive, zero, and negative Doppler, respectively. In fact, each object in the beam with a different cross-range spatial location will have a different Doppler. Therefore, if the radar's signal processor is capable of sorting (filtering) the EM wave returns according to Doppler, this is tantamount to sorting the objects in the cross-range dimension, thus resolving objects at different positions. Doppler processing is discussed further is Chapters 8 and 17, and synthetic aperture radar in Chapter 21

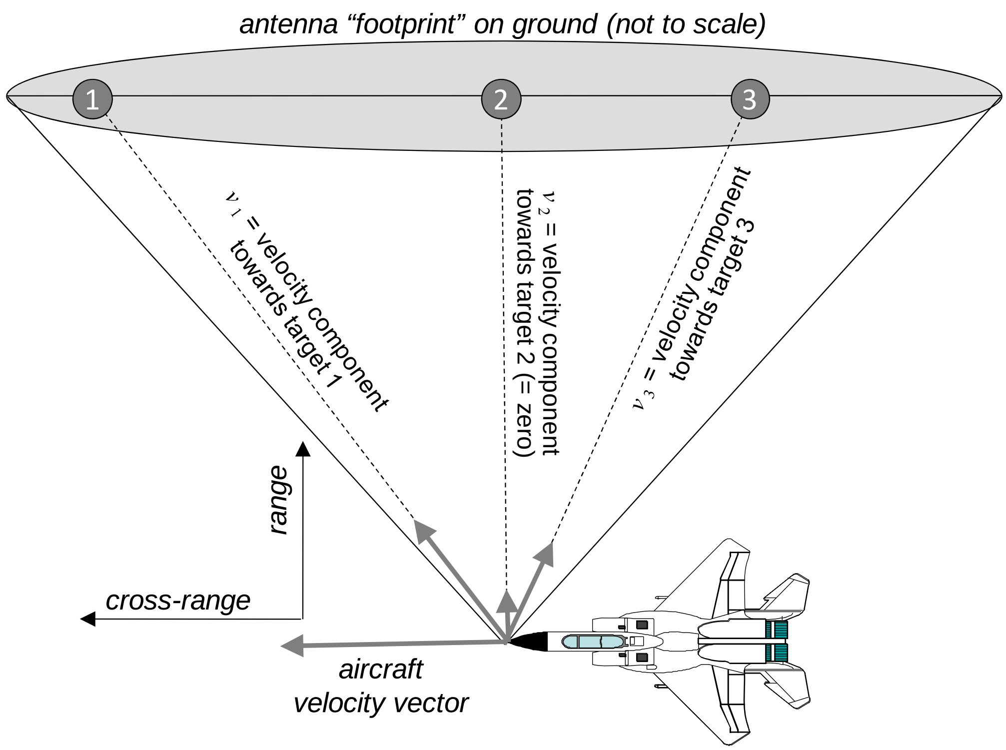


Figure 1-18. Synthetic aperture radar geometry.

1.6.3 Polarization

Polarization refers to the vector nature of the EM wave transmitted and received by the radar antenna. The EM wave's polarization is sensitive to the geometry of the object from which it reflects; different objects will change the polarization of the incident EM wave differently. Therefore, the change in polarization of the EM wave when if reflects from an object carries some information regarding the geometrical shape of that object. This information can be used to discriminate unwanted reflected waves (e.g., returns from rain) from those reflected from targets. Thus, polarization can be used to discriminate targets from clutter and even to facilitate in identifying different targets of interest.

Maximum polarization information is obtained when the *polarization scattering matrix* (*PSM*) of a target is measured. This requires the radar to be polarization-agile on transmit and to have a dual-polarized receiver. A EM wave of a given polarization (e.g., horizontal polarization) is transmitted and the polarization of the resulting reflecting wave is measured in the dual-polarized receiver. This measurement requires, at a minimum, the measurement of the *amplitude* of the wave in two orthogonal polarization receiver channels (e.g., horizontal and vertical polarizations) and the *relative phase* between the waves in these two channels. The transmit polarization is then changed to an orthogonal state (e.g., vertical polarization) and the polarization of the resulting reflecting wave is measured again. This results in five measured data, three amplitudes and two relative phases. For a *monostatic* radar (co-located transmitter and receiver), this reduces to five unique measured data since the two cross-polarization amplitudes will have the same numerical value. These data constitute the elements of the PSM.

Ideally, the two transmit polarizations should be transmitted simultaneously, but in practice they are transmitted at different, but closely spaced times (typically on successive pulses). This time lag creates some uncertainty in the integrity of the PSM, however, if the two transmit times are closely spaced, the uncertainty is minor. Polarization processing is discussed further in Vol. II.

1.7 Basic Radar Configurations and Waveforms

There are two basic configurations of radar systems, monostatic and bistatic, as shown in Fig. 1-19. In the bistatic configuration, there are separate antennas for the transmit and receive radar functions. In the monostatic configuration, one antenna serves both the transmitter and receiver.

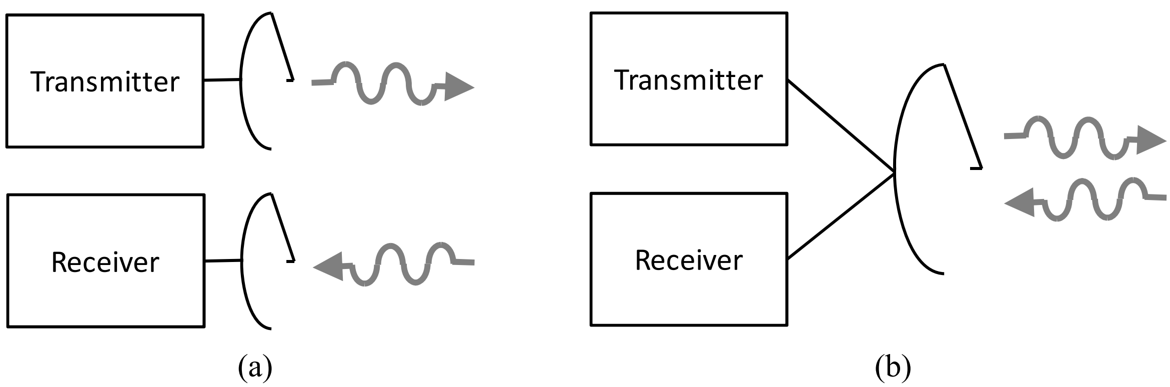


Figure 1-19. Basic radar configurations: (a) Bistatic. (b) Monostatic.

1.7.1 Bistatic Radar Configuration and CW Waveform

The transmitter is often a high power device that can transmit EM waves with power levels in the range hundreds of kilowatts (10^3 watts), or even megawatts (10^6 watts). The receiver, on the other hand, is a power sensitive device which can respond to EM waves in the range of milliwatts to microwatts (10^{-3} to 10^{-6} watts) or less. High power EM waves from the transmitter, if introduced directly into the receiver, would prevent the detection of targets (self jamming) and could severely damage the receiver's sensitive components. Therefore, the receiver must be *isolated* from the transmitter to protect it from the transmitter's high power EM waves. The bistatic radar configuration can provide this isolation by physically separating the transmitter and receiver. *Continuous wave* (CW) radars, which transmit EM waves without interruption (continuously) within some long time interval, often employ the bistatic configuration to effect transmitter/receiver isolation.

Since a CW radar is continuously transmitting, determination of the transmitted EM wave's round-trip time and, thus, target range, must be accomplished by changing the characteristics of the wave; for example, changing the wave's *frequency* or the wave's *phase*. These frequency modulation (FM) and phase modulation (PM) techniques effectively put a timing mark on the EM wave thus allowing for target range determination. CW radars tend to be simple radars and are used for such applications as police radars, altimeters, and proximity fuses. CW radars are discussed in Vol. II.

The bistatic radar configuration obviates the necessity for the transmitter and receiver to be collocated and, thus, can also be employed to enhance the radar's capability of detecting *stealth* targets. How well a radar can detect a target will depend on the RCS of that target in the direction of the radar. Recall that a target's RCS is a measure of the strength of the EM waves that are reflected from the target back towards the radar. Stealth targets are designed to have a very low RCS in the supposed direction of the radar's receiver. The assumption is usually made that the radar's transmitter and receiver are collocated and so the stealth target will be designed to have a very low *monostatic* RCS in the direction of the radar's transmitter/receiver. For example, a stealth aircraft will typically have a low RCS in the forward direction, the supposed direction of the threat's radar transmitter/receiver. However, if the threat radar's receiver is located elsewhere, then it is the aircraft's *bistatic* RCS, the RCS in the direction of the receiver for a given transmitter direction, that will determine the aircraft's delectability. This bistatic RCS is usually much greater than the forward direction monostatic RCS. Thus, the target is no longer "stealthy" to the bistatic radar.

1.7.2 Monostatic Radar Configuration and Pulsed Waveform

Most modern radars are monostatic, a more efficient design since only one antenna is required. These radars tend to be *pulsed* radars as opposed to CW radars. The pulsed radar waveform is shown in Fig. 1-20.

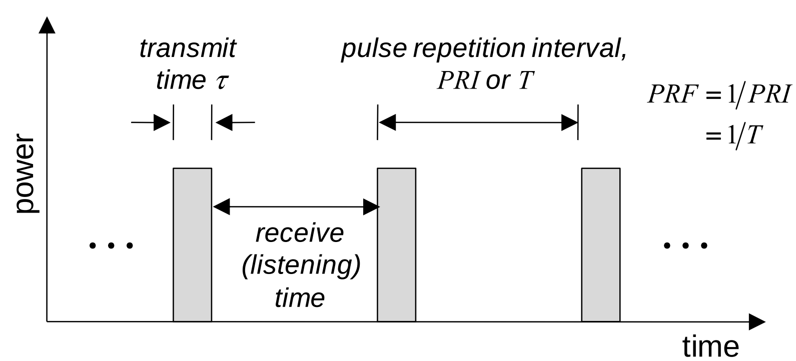


Figure 1-20. Pulsed radar waveform.

Pulsed radars transmit EM waves during a very short time period, or *pulsewidth* τ, typically 0.1 to 10 microseconds (μs), but sometimes as little as a few nanoseconds (10^{-9} seconds). During this time, the receiver is turned off, or *blanked*, thus protecting its sensitive components from the transmitter's high power EM waves. This blanking is usually accomplished with a transmit/receive (TR) switch as discussed in Chapter 11. During the time between pulses when the transmitter is not transmitting, typically one microsecond to tens of milliseconds, the receiver is turned on to receive any EM waves (echoes) that may have been reflected from targets. This "listening" time plus the pulsewidth represents one pulsed radar cycle time, normally called the *interpulse period* (IPP) or *pulse repetition interval* (PRI), denoted as *PRI* or *T*. The number of transmit/receive cycles the radar completes per second is called the *pulse repetition frequency* (PRF), *PRF*. The PRF is measured in pulses per second (PPS), but is often expressed in hertz (one cycle per second). Obviously, the PRF is also the number of pulses transmitted per second. The PRF and PRI are related according to

$$PRF = \frac{1}{PRI} = \frac{1}{T} \tag{1.15}$$

The fraction of time the transmitter is transmitting during one radar cycle is called the *duty factor* (or *duty cycle*), d_t, and from Fig. 1-17 is given by

$$d_t = \frac{\tau}{T} = \tau \cdot PRF \tag{1.16}$$

The average power, P_{avg}, of the transmitted EM wave is given by the product of the peak transmitted power, P, EM and the duty factor:

$$P_{avg} = P \cdot d_t = P \cdot \tau \cdot PRF \tag{1.17}$$

Recall that target range is inferred by measuring the delay time from transmission of a pulse to reception of the reflected signal. Problems can occur in a pulsed radar in determining the range to distant targets. If the pulse round-trip travel time, ΔT, between the radar and the distant target is greater that the interpulse period T, then the EM wave in a given pulse will not return to the radar's receiver before the next pulse is transmitted. Now there is a *range ambiguity*; the received pulse could be a reflection of the pulse that was just transmitted and, thus, a reflection from a close-in target, or it could be a reflection of a previously transmitted pulse and, thus, a reflection from a distant target.

This situation is illustrated in Fig. 1-21.The tall rectangles represent transmitted pulses; the shorter rectangles represent the received echoes from two targets. The shading of the target echoes matches the shading of the pulse from which they originated. The time delay to target A and back is less than the PRI T, so the echo from target A from a given pulse is received before the next pulse is transmitted. The time delay ΔT to target B, however, is greater than T; specifically, suppose $\Delta T = T + \Delta t$. Then the reflection from target B due to pulse #1 occurs Δt seconds after pulse #2, as shown in the figure. Consequently, it is unclear if this echo is from a short range target Δt seconds away or a longer range target ΔT seconds away.

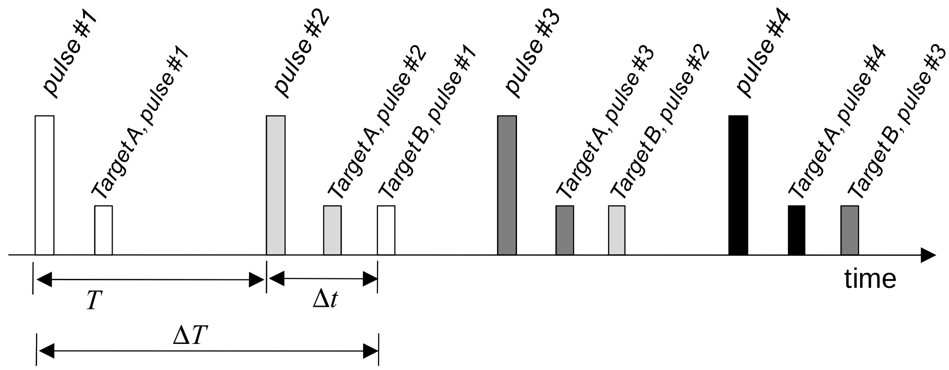


Figure 1-21. Pulsed radar range ambiguity.

Range ambiguities can be avoided by ensuring that the interpulse period T is high enough or, equivalently, the pulse repetition frequency PRF is low enough, such that all echoes of interest from a given pulse return to the radar receiver before the next pulse is transmitted. The round trip time for the radar wave from Eq. (1.1) is given by

$$\Delta t = \frac{2R}{c} \tag{1.18}$$

Thus, to prevent range ambiguities, the following condition must be satisfied:

$$PRF \geq \Delta t = \frac{2R_{\max}}{c} \quad \text{or} \quad R_{\max} \leq \frac{c \cdot PRI}{2} = \frac{c}{2PRF} \tag{1.19}$$

where R_{max} is the maximum target range of interest. Conversely, the *unambiguous range* is the maximum range at which a target can be located and still be measured unambiguously by the radar. It is given by

$$R_{ua} = \frac{c}{2PRF} \tag{1.20}$$

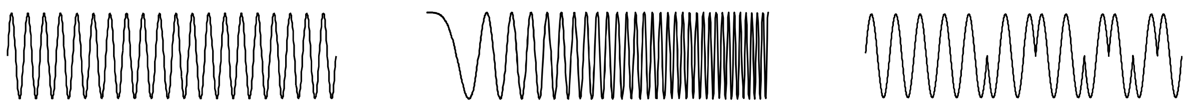
Clearly from Eq. (1.20), lowering the PRF of the radar will increase the radar's unambiguous range. However, lowering the radar's PRF has a negative consequence. Most modern radars measure the Doppler frequency shift of the received EM wave. However, a pulsed radar samples the Doppler frequency shift at the pulse repetition frequency. This can lead to *aliasing* errors if the sampling rate (PRF) is not high enough, as discussed in Chapter 13.

One statement of the Nyquist sampling criterion or theorem is that "the maximum frequency that can be unambiguously measured is half the sampling rate ." A similar statement holds for measuring negative frequencies. In a radar, Doppler frequency is being sampled at the radar's PRF, thus, the range of Doppler frequencies that can be unambiguously measured is

$$f_d = \pm PRF/2 \tag{1.21}$$

Maximizing unambiguous range leads to lower PRFs, while maximizing unambiguous Doppler shift leads to higher PRFs. In many systems, there is no single PRF that can meet these opposing requirements. Fortunately, as discussed in Chapter 14, there are signal processing techniques such as staggered PRFs that allow radars to unambiguously measure range and Doppler at almost any PRF.

Figure 1-20 showed the timing of a pulsed radar waveform. There are a number of choices available for the actual shape of the waveform comprising each pulse. Figure 1-22 illustrates three of the most common. Part (a) of the figure is a simple pulse, oscillating at the radar's RF frequency. This is the most basic radar waveform. Also very common is the *linear FM* or *chirp* pulse of Fig. 1-22(b). This waveform sweeps the oscillations across a range of frequencies during the pulse transmission time. For example, a chirp pulse might sweep from 8.9 to 9.1 GHz within a single pulse, a swept bandwidth of 200 MHz. Part (c) of the figure illustrates a *phase coded* pulse. This pulse has a constant frequency, but changes its relative phase between one of two values, either zero or π radians, at several points within the pulse. These phase changes cause an abrupt change between a sine function and a negative sine function. Because there are only two values of the relative phase used, this example is a *biphase coded* pulse. More general versions exist that use many possible phase values.



(a) (b) (c)

Figure 1-22. Three common choices for a single pulse in a pulsed radar waveform. (a) Simple pulse. (b) Linear FM or chirp pulse. (c) Biphase coded pulse.

The choice of pulse waveform affects a number of tradeoffs between signal to noise ratio, resolution in range, resolution in Doppler, sidelobe behavior, ambiguities in range and Doppler, and other aspects of radar performance. These waveforms and their design implications are discussed in Chapter 20.

1.8 Basic Radar Functions

While there are hundreds of different types of radars in use, the large majority have three basic functions: (1) search/detect, (2) track, and (3) image. These functions are briefly discussed now, followed by a discussion of some of the many types of radar systems and how they apply these functions.

1.8.1 Search/Detect

Almost all radars have to search a given volume and detect targets without *a priori* information regarding the targets' presence or position. A radar searches a given volume by pointing its antenna in a succession of beam positions that collectively cover the volume of interest. A mechanically scanned antenna moves through the volume continuously. Rotating antennas are an example of this approach. An electronically-scanned antenna (ESA) is pointed to a series of discrete beam positions, as suggested in Fig. 1-23.

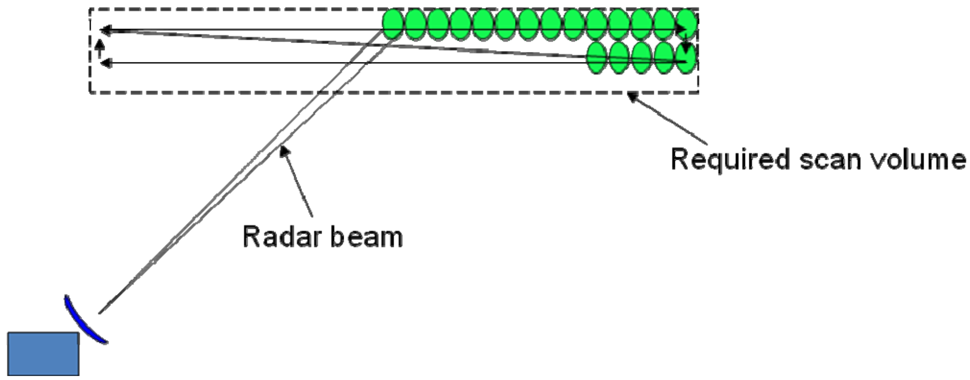


Figure 1-23. Coverage of a search volume using a series of discrete beam positions.

At each position, one or more pulses are transmitted, and the received data is examined to detect any targets present using the threshold techniques described earlier. For example, 10 pulses might be transmitted in one beam position of an ESA. The detected data from each pulse might then be noncoherently integrated (summed) in each range bin to improve the SNR. This integrated data would then be compared to an appropriately-set threshold to make a detection decision for each range bin. The antenna is then steered to the next beam position, and the process repeated. This procedure is continued until the entire search volume has been tested, at which point the cycle is repeated.

A major issue in search is the amount of time required to search the desired volume once. The search time is a function of the total search volume, the antenna beamwidths, and the *dwell time* spent at each beam position. The latter in turn depends on the number of pulses to be integrated and the desired range coverage (which affects the PRF). Optimization of the search process involves detailed tradeoffs between antenna size (which affects beamwidths and thus number of beam positions needed), dwell time (which affects number of pulses available for integration), and overall radar timeline. The search and detection process and these tradeoffs are discussed in more detail in Chapter 3.

1.8.2 Track

Once a target is detected in a given search volume, a measurement is made of the target *state*, that is, its position in range, azimuth angle, and elevation angle and, often, its velocity. Tracking radars measure target states as a function of time. Individual position measurements are then combined and smoothed to estimate a target *track.*

Tracking implies measuring the position or velocity of a target to an accuracy better than the radar's resolution. A variety of techniques are used to do this. For instance, the azimuth position can be estimated to a fraction of the antenna azimuth beamwidth in a mechanically scanned radar by measuring the detected target strength on several successive pulses as the antenna scans, and then computing the centroid of the resulting measurements. This concept is illustrated in Fig. 1-23. Similar concepts can be applied in range and Doppler. These and other measurement techniques are described in Chapter 18.Individual measurements are invariably contaminated by measurement noise and other error sources. An improved estimate of the target position over time is obtained by *track filtering*, which combines multiple measurements with a model of the target dynamics to smooth the measurements. For example, the dotted line in Fig.

1-24 shows the actual position of a target that is initially moving away from the radar in some coordinate at constant velocity, and then at time step 30 stops moving (constant position). The small triangles represent individual noisy measurements of the position, and the solid line shows the estimated position using a particular *alpha-beta filter*. More advanced systems use various forms of the Kalman filter and other techniques. Track filtering is discussed in Chapter 19.

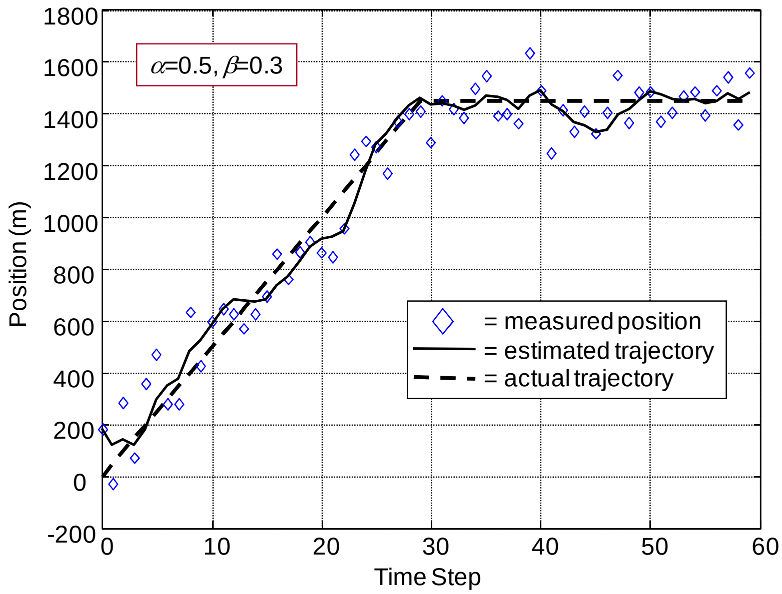


Figure 1-24. Example of track filtering for smoothing a series of individual position measurements.

The optimum radar configurations for tracking and searching are different. Consequently, these search and track functions are sometimes performed by two different radars. This is common in situations where radar weight and volume are not severely limited, i.e., land-based and ship-based operations. When radar weight and volume are limited, as in airborne operations, the search and track functions must be performed by one radar which must then compromise between optimizing search and track functions. For example, a wide antenna beamwidth is desirable for the search mode and a narrow antenna beamwidth is desirable for the track mode, resulting in a medium antenna beamwidth compromise solution.

1.8.3 Imaging

In radar, "imaging" is a general term that refers to several methods for obtaining detailed information on discrete targets or broad-area scenes. Synthetic aperture radars (SARs) form two-dimensional images of an area at resolutions ranging from 100 m or more, to well under 1 m. The first case would typically be used in wide-area imaging from a satellite, while the latter would be used in detailed imagery from an airborne (aircraft or *unmanned autonomous vehicle* (UAV) platform. Figure 1-25 is an example of an 1 m resolution airborne SAR image of the Washington, DC mall area. Two-dimensional SAR imagery is used for a variety of earth resources and defense applications, including surveillance, terrain following, mapping, resource monitoring, and so forth. It is discussed in more detail in Chapter 21 of this volume, and in vol.

II. In recent years, *interferometric SAR* (IFSAR or InSAR) techniques have been developed for generating three-dimensional SAR imagery. An introduction to IFSAR is given in vol. II.

Figure 1-25. 1 m resolution SAR image of the Washington, D.C. mall area. (Courtesy of Sandia National Laboratories. Used with permission.)

To accomplish their mission, many radars must not only detect, but also identify the target before further action (e.g., defensive, offensive, traffic control, etc.) is initiated. One common way to attempt identification is for the radar to measure a one-dimensional high-range-resolution "image" (often called a *high range resolution (HRR) profile*) or two-dimensional range/cross-range image of the target, a high-resolution Doppler spectrum, or to determine target polarization characteristics. The radar will employ specific waveforms and processing techniques, such as pulse compression SAR processing, or polarization scattering matrix estimates, to measure these properties. These techniques are discussed, respectively, in Chapter 20 and Chapter 21, and in greater depth in Vol. II. *Automatic target recognition* (ATR) techniques are then used to analyze the resulting "imagery" and make identification decisions.

1.9 Radar Applications

Given that the fundamental radar functions are search/detect, track, and image, there are numerous remote sensing applications that can be satisfied by the use of radar technology. Some examples are now given. The grouping into "military" and "commercial" applications is somewhat arbitrary; in many cases the same basic functions are used in both arenas. The radar applications represented here are some of the most common, but there are many more.

1.9.1 Military Applications

In about 1945, the US military developed a system of identifying designations for military equipment. The designations are of the form AN/xxx-nn. The x's are replaced with a sequence of three letters, the first of which indicates the installation, or platform (*e.g.* A for airborne), the second of which designates the type of equipment (*e.g.* P for radar), and the third of which designates the specific application (*e.g.* G for fire control). Table 1-4 lists a subset of this "AN nomenclature" that is pertinent to radar. The *n*'s following the designation are a numerical sequence. For example, the AN/TPQ-36 is a ground-based mobile special purpose radar, in this case for locating the source of incoming artillery. Another example is the AN/SPY-1, a shipboard surveillance and fire control radar system.

Table 1-4. Subset of the AN Nomenclature System for U.S. Military Equipment Applicable to Radar Systems.

1st Letter (Type of Installation)		**2nd Letter (Type of Equipment)**		**3rd Letter (Purpose)**	
A	Piloted Aircraft	L	Countermeasures	D	Direction finger, reconnaissance, and/or surveillance
F	Fixed Ground	P	Radar	G	Fire control or searchlight directing
M	Ground, mobile (installed as operating unit in a vehicle which has no function other than transporting the equipment			N	Navigational aids (including altimeter, beacons, compasses, racons, depth sounding, approach, and landing)
P	Pack or portable (animal or man)			Q	Special, or combination of purposes
S	Water surface craft			R	Receiving, passive detecting
T	Ground, transportable			S	Detecting and/or range and bearing, search
V	Ground, vehicular (installed in vehicle designed for functions other than carrying electronic equipment, etc., such as tanks			Y	Surveillance (search, detect, and multiple target tracking) and control (both fire control and air control)

Search radars

Often, the primary functions associated with the search and track requirements are performed by two independent radar systems. One system performs the search function, and another performs the track function. This is common, though not always the case, for a ground-based or surface ship system. Some applications prohibit the use of more than one radar or one aperture. For example, platforms that have limited prime power or space for electronics force the search and track requirements to be performed by one system. This is common in an airborne application.

Some volume search systems employ a "fan" shaped antenna pattern to perform the search. Usually the antenna aperture will be quite wide (horizontally) and somewhat narrower vertically. This leads to a narrow azimuth beamwidth and a wide elevation beamwidth. The elevation extent of the search volume is covered by the wide elevation beamwidth, while the azimuth extent is covered by mechanically scanning the antenna in azimuth. Figure 1-26 depicts a fan beam pattern searching a volume. This configuration is common in air traffic control or airport surveillance systems. A system with this beam pattern can provide accurate range and azimuth position, but provides poor elevation or height information due to the wide elevation beamwidth. Consequently, it is termed a 2D system, providing position information in only 2 dimensions.

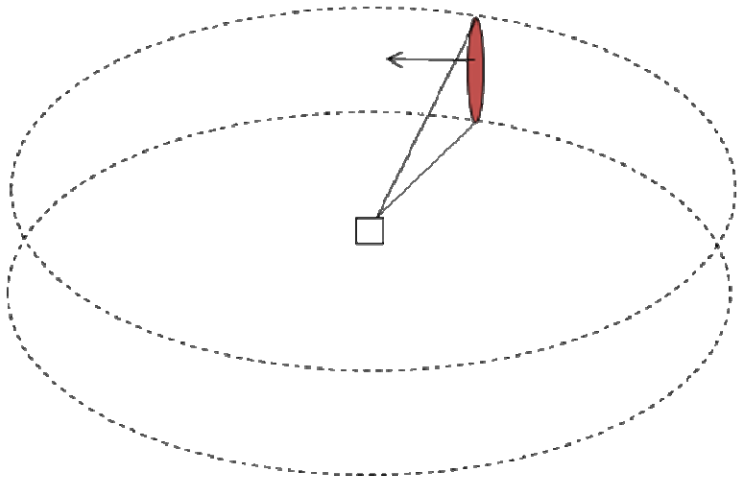


Figure 1-26. Fan beam searching a volume providing 2-D target position.

The AN/SPS-49 radar is a ship-based search radar that operates at S-band. Figure 1-27 is the photograph of the AN/SPS-49 2D search radar antenna; notice that it is much wider than it is tall. It is therefore a 2D radar, providing good range and azimuth information, but, because of the wide elevation beamwidth, no elevation information. A tracking system that tracks a target initially detected by this system must perform a limited vertical (elevation) search to locate the target.

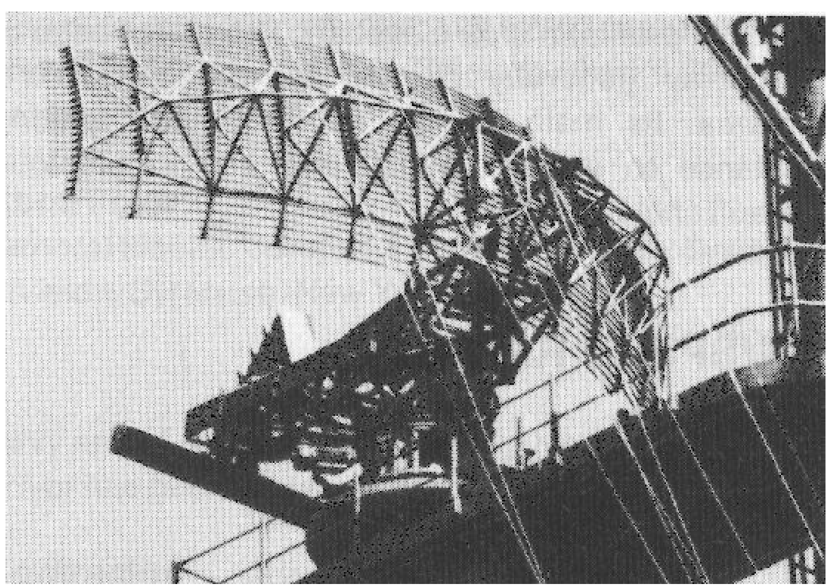


Figure 1-27. AN/SPS-49 Surface-based 2-D air search radar.
(Courtesy of XXX XXX XXX, Inc. Used with permission.)

Figure 1-28 depicts a pencil beam antenna which provides accurate range, azimuth, and elevation information. A system using this approach is termed a 3D search radar. An example of a 3D search radar used by the U.S. Navy on surface ships, including destroyers, cruisers, and aircraft carriers, is the AN/SPS-48 produced by ITT Gilfillan and shown in Fig. 1-29. The antenna is the square planar array. It scans in the azimuth plane by mechanical scanning, and in the elevation plane by frequency scanning.

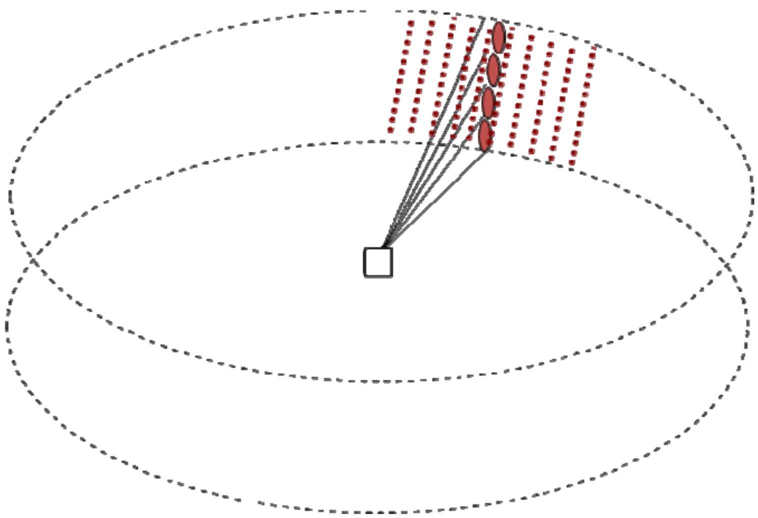


Figure 1-28. Pencil beam searching a volume providing 3-D target position.

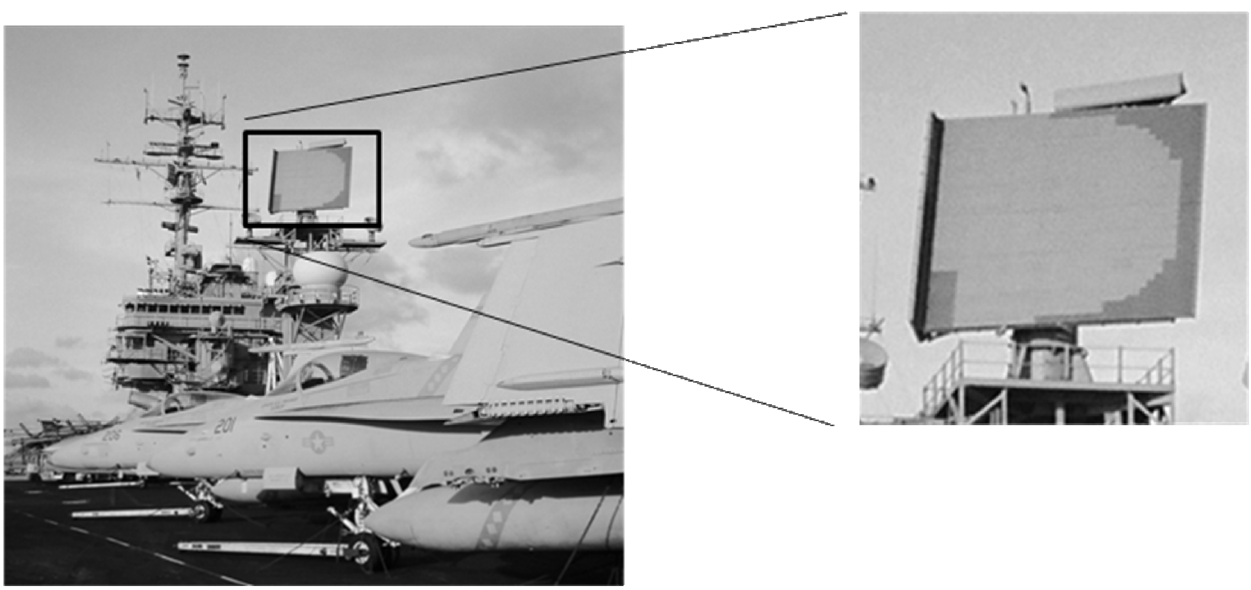


Figure 1-29. AN/SPS-48 ship-based 3-D air search radar.
(Courtesy of U. S. Navy. Used with permission.)

<u>Air defense systems</u>

The AN/TPS-75 air defense system used by the U.S. Air Force is shown in Fig. 1-30. It has functionality similar to multi-function 3D search radar. It scans mechanically in the azimuth direction, and electronically in the elevation dimension by means of frequency scanning. The long, narrow antenna shown at the top of the square array is an antenna that interrogates the detected targets for an identification-friend-or-foe (IFF) response. The IFF antenna angle is set back somewhat in angle so that the IFF interrogation can occur shortly after target detection as the antenna rotates in azimuth.

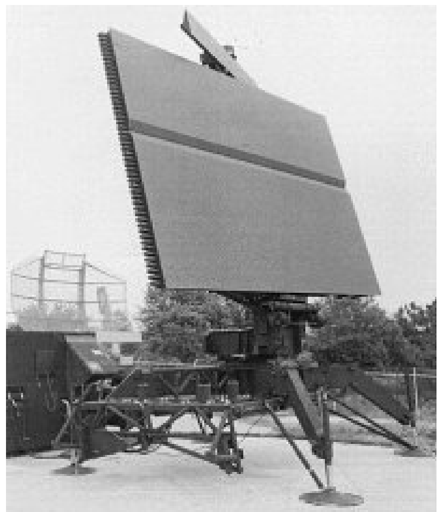


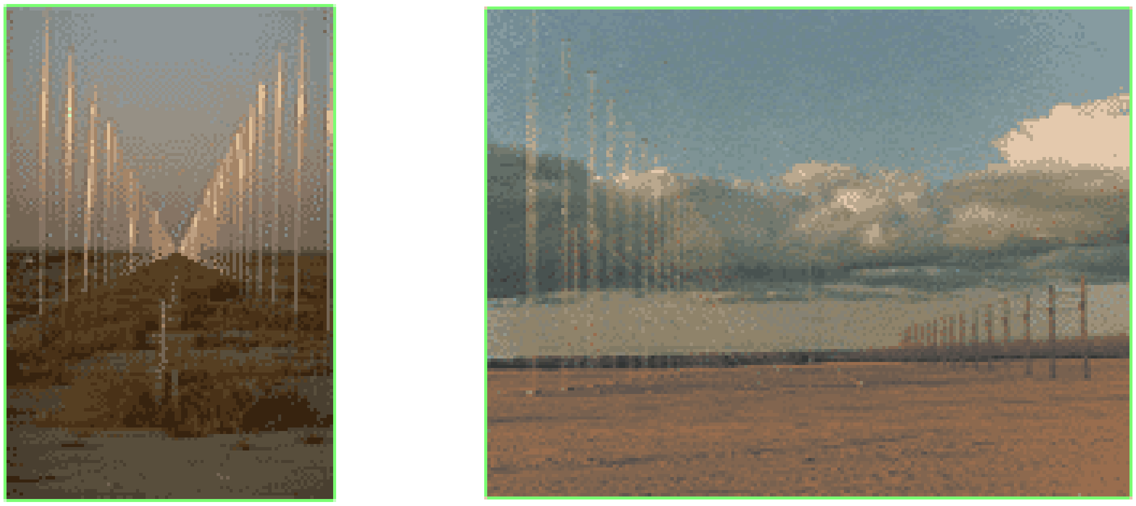
Figure 1-30. AN/TPS-75 air defense radar.
(Courtesy of XXX XXX XXX, Inc. Used with permission.)

The AN/MPQ-64 Sentinel shown in Fig. 1-31 is an air defense radar used by the U.S. Army and U.S. Marine Corps with similar functionality. This is an X-band coherent (pulse Doppler) system, using phase scanning in one plane, and frequency scanning in the other plane. The system detects, tracks and identifies airborne threats.

Figure 1-31. photo of an AN/MPQ-64 Sentinel air defense radar. (Courtesy of XXX XXX XXX, Inc. Used with permission.)

Over-the-horizon (OTH) Search Radars

During the cold war, the United States wanted to detect ballistic missile activity at very long ranges. Whereas many radar applications are limited to “line-of-sight” performance, ranges of several thousand miles were desired. Over-the-horizon (OTH) radars were developed for this application. These radars take advantage of the refractive effect in the ionosphere to detect targets at extremely long ranges, sometimes thousands of miles, around the earth. The refraction has the effect of reflecting the EM signal. The frequency dependence of this effect is such that it is most effective at HF frequencies (3-30 MHz). Given the desire for a reasonably narrow beam width, the antenna must be very large, at such low frequencies, typically thousands of feet long. Consequently, OTH antennas are often made up from an array of elements located on the ground. Figures 1-32 (a) and (b) show an example of such a transmit and receive array respectively. Figure 1-33 depicts the operation of an over-the-horizon system, showing the ray paths for two targets.



(a) (b)

Figure 1-32. Over-the-horizon radar system. (a) transmit array, (b) receive array. (Courtesy of XXX XXX XXX, Inc. Used with permission.)

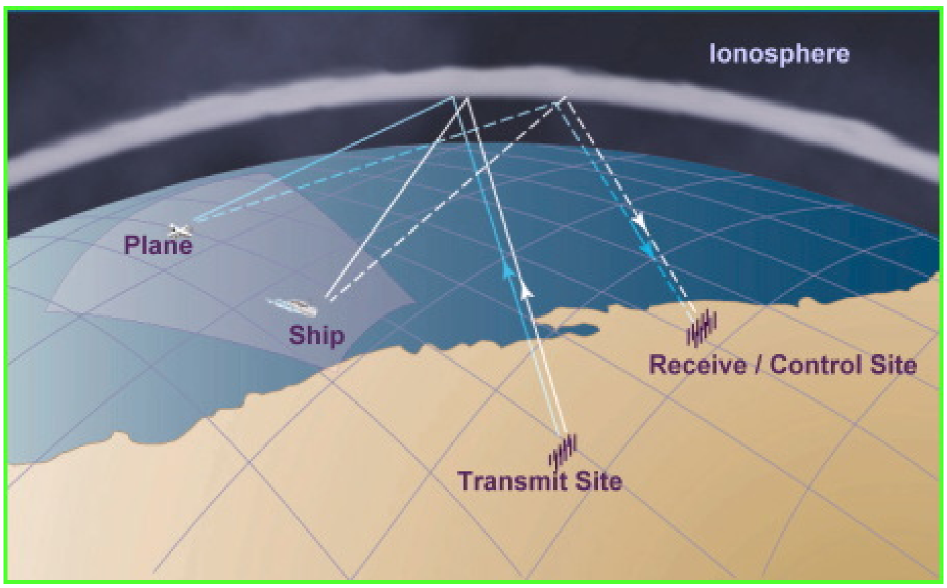


Figure 1-33. Over-the-horizon radar concept.
(Courtesy of XXX XXX XXX, Inc. Used with permission.)

<u>Ballistic Missile Defense (BMD) Radars</u>

Radar systems can detect the presence of incoming intercontinental ballistic missiles (ICBMs) thousands of kilometers away. These systems must search a large angular volume (approaching a hemisphere) and detect and track very low-RCS, fast-moving targets. Once detected, the incoming missile must be monitored to discriminate any debris and decoys from the warhead. This is accomplished with high range resolution and Doppler processing techniques that are well-suited to radar. Examples of BMD radar systems are the theater high altitude air defense (THAAD) system, the sea-based Cobra Judy system, the land-based Pave Paws system, and the sea-based X-band (SBX) radar. Figure 1-34 is a photograph of the Pave Paws (AN/FPS-115) system, showing its two extremely large pencil beam phased array antennas. BMD radars are discussed in Chapter 14 of Vol. II.

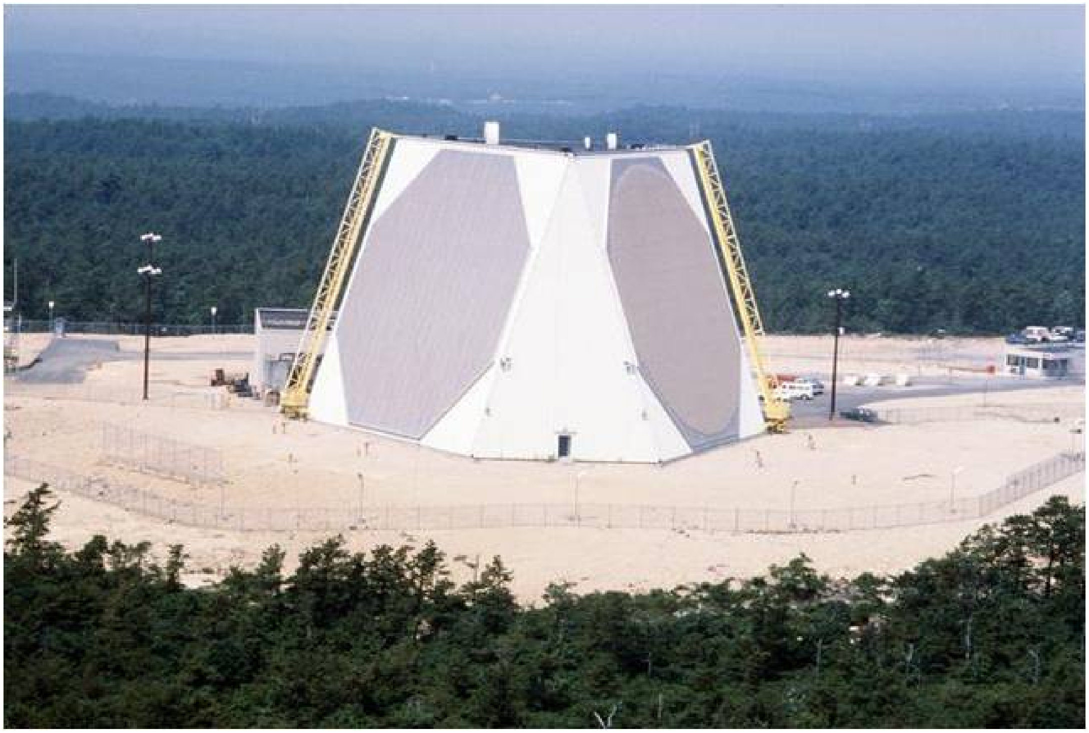


Figure 1-34. Pave Paws (AN/FPS-115) ballistic missile defense radar. (Courtesy of XXX XXX XXX, Inc. Used with permission.)

A newer system is the Theater High Altitude Air Defense (THAAD) radar shown in Fig. 1-35. It is an X-band coherent active phased array system, with over 25,000 active array elements. As opposed to fixed-location systems such as the AN/FPS-115, it is transportable so that it can be redeployed as needed.

Figure 1-35. Photograph of the Theater High Altitude Air Defense (THAAD) radar.

Radar Seekers and Fire Control Radars

While many air-to-air and air-to-ground missile systems designed to attack threat targets employ infrared sensors to detect the thermal (heat) signatures of these targets, there are also many missile systems that employ radars to detect and track the targets of interest. Radar systems can operate at longer ranges and in atmospheric conditions (*e.g.*, fog and rain) which make infrared sensors ineffective.

Bistatic, *semi-active seekers* in the nose of a missile receive a reflected signal from a target which is being “illuminated” with an RF signal transmitted from a fire control radar on a stand-off platform (e.g., aircraft, ship). Such systems require that the platform maintain line-of-sight (LOS) to the target until it is engaged by the missile. Ship-based Standard Missile (SM) and Standard Missile 2 (SM2) are examples of such a semi-active mode. Figure 1-36 shows a Standard Missile 2 being launched from a surface ship.

Figure 1-36. Standard missile 2 being launched from a surface ship.

The AIM-7 missile shown in Fig. 1-37 is a semi-active air-to-air missile used in variety of airborne interceptors, including the U.S. Navy F-14, U.S. Air Force F-15 and F-16, and the U.S. Marine Corps F/A-18 aircraft. The radar in the aircraft illuminates the target as the missile is launched so that the seeker has a signal to which it can “home”.

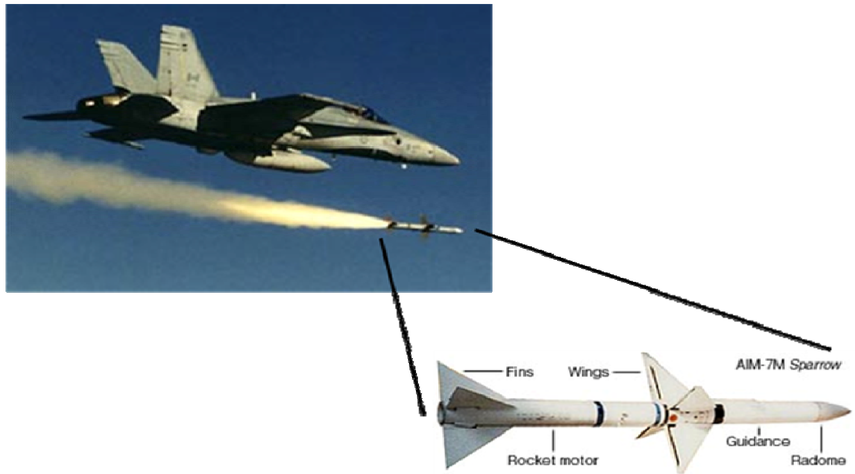


Figure 1-37. AIM-7 Sparrow semi-active air-to-air missile.

An active radar seeker in the nose of a missile can perform a limited search function and track the target of interest in an autonomous mode, eliminating the requirement of the platform to maintain line-of-sight. This mode is often referred to as the *fire-and-forget* mode. The helicopter-based Longbow fire control radar (FCR) system shown in Fig. 1-38 is an example of such a system. The Longbow radar is mounted on an Apache helicopter above the main rotor. The missile has its own internal radar *seeker*. The target is acquired, located, and identified by the FCR and target location information is sent to the missile. Once the missile is launched, the helicopter can descend into a protected posture while the missile autonomously acquires and engages the target with its onboard radar seeker. Seekers are discussed in Chapter 8 of Vol. II and fire control radars are discussed in Chapter 10 of Vol. II.

Figure 1-38. Apache Longbow fire control radar and active hellfire missile.

Instrumentation/Tracking Test Range Radars

Many defense department test ranges use instrumentation radars to aid in testing events. For example, missile testing at the White Sands Missile Range in New Mexico and at the U.S. Army Missile Command in Huntsville, Alabama require that the target drones and missiles be tracked by precision tracking radars to aid in analyzing tests results and to provide for range safety. Large antennas provide a narrow beamwidth to achieve accurate track data. Long dwell times associated with these radars result in very high Doppler resolution measurements yielding target motion resolution (TMR) data for event timing analysis and phase-derived range (PDR) data for exact relative range measurements. Figure 1-39 is a photograph of an AN/MPQ-39, a C-band phased array instrumentation radar used at test ranges such as White Sands Missile Range.

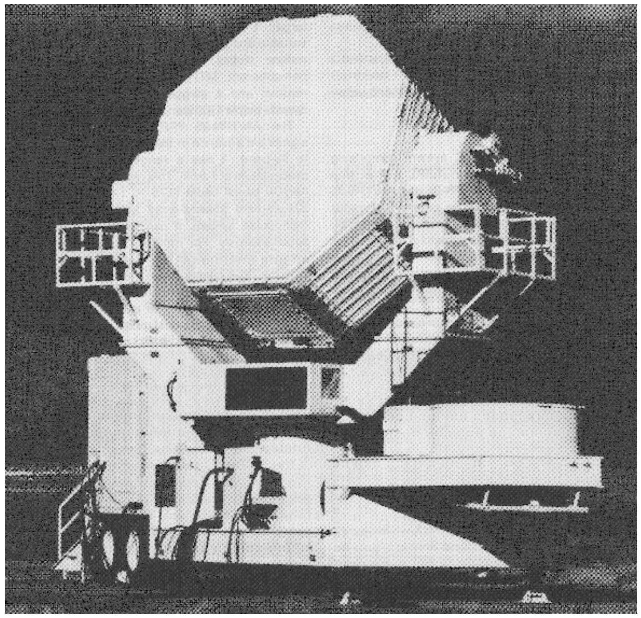
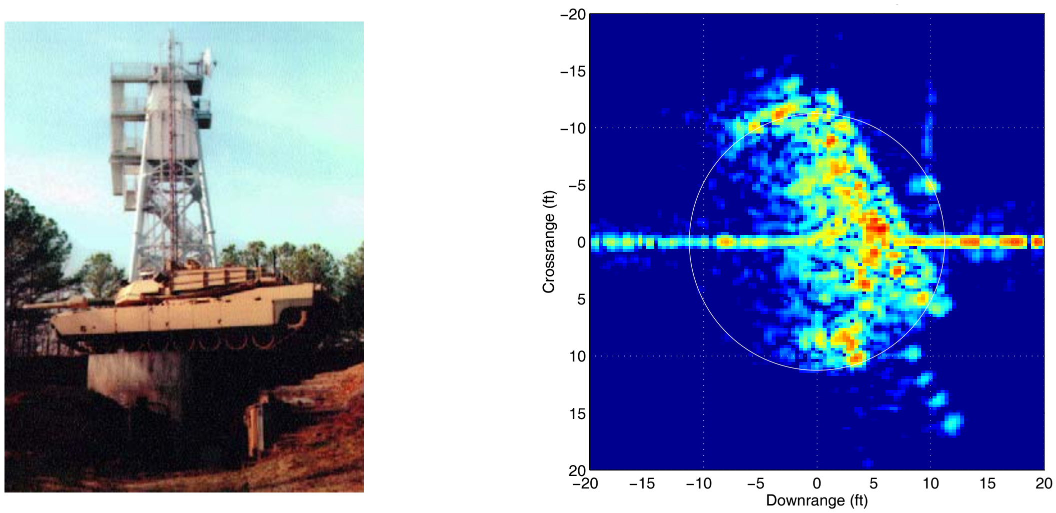


Figure 1-39. AN/MPQ-39 C-band phased array instrumentation radar.

Many indoor and outdoor target radar cross section (RCS) measurement ranges are designed to measure the RCS of threat targets and provide inverse synthetic aperture radar (ISAR) images of such targets to train pattern-recognition-based target identification systems. Indoor RCS ranges measure small targets, such as missiles and artillery rounds, as well as scale models of threat vehicles and aircraft. Outdoor ranges measure the RCS characteristics of full-sized targets such as tanks and aircraft. Figure 1-40(a) is an example of an outdoor ISAR range located at the Georgia Tech Research Institute (GTRI). The tank is on a large turntable that is flush with the ground; access to the turntable machinery is from behind the turntable. In the distance is a tower which serves as a platform for an instrumentation radar. Figure 1-40(b) shows a sample "quick look" ISAR image



(a) (b)

Figure 1-40. (a) Turntable ISAR range. View is from behind the target, looking past the turntable to the radar tower in the background. (b) Quick-look image of a tank. (Photos courtesy of the Georgia Tech Research Institute. Used with permission.)

Tracking, fire control and missile support radars

Ground-based, ship-based, and airborne tracking radars support fire control missions by providing target position and velocity estimates so that an interceptor can position itself to detect and track the target, either autonomously or in a semi-active mode as it approaches the target. Historically, tracking radar systems could track only one target at a time. Tracking of multiple targets simultaneously required multiple radars. Modern radar tracking systems can track multiple targets using electronically scanning antennas. Examples of such systems are the ship-based Aegis fire control radar, the ground-based Patriot air defense radar, and airborne fire control radars in airborne interceptors such as the F-15, F-16, F-14, F-18 and F-22 aircraft.

A fire-control radar system may include, in addition to the radar, another RF source to illuminate the target with RF energy. For example, a semi-active radar seeker in a missile can home on the target from the reflections of the radio waves from an RF source on an aircraft. Tracking and up-linking data to an airborne interceptor in flight is another mission of a fire control radar. The airborne interceptor may be guided solely by the tracking radar or it may have its own short-range radar onboard for the final phase of the engagement.

The AN/SPQ-9, shown in Fig. 1-41, is a single-target tracking radar used on surface ships. Since it can track only one target at a time, multiple radars are required if it is necessary to track multiple targets. Often, four AN/SPQ-9 systems will be assembled on the ship's superstructure.

(a) (b)

Figure 1-41. Photograph of an AN/SPQ-9 ship-based tracking radar.
(Courtesy of XXX XXX XXX, Inc. Used with permission.)

Multi-function radars

The advent of electronically scanned antennas using phased array antenna technology (described in Chapter 9) enables radar systems to interleave multiple functions. In particular, search and track modes can be implemented using one radar. The AN/SPY-1 is an example of a phased array multifunction radar used on surface ships. Figure 1-42 shows the AN/SPY-1 mounted on the USS Ticonderoga, the first ship to have the Aegis fire control system installed. The AN/SPY-1 is a major component of the Aegis system. Two of the four antenna faces required to provide full 360 degree coverage are visible in the photo.

Figure 1-42. USS Ticonderoga CG-47 with the AN/SPY-1 radar installed.
(Courtesy of U.S. Navy, used with permission.)

Artillery Locating Radars

Another application of the multifunction radar is the artillery locating radar function. Artillery Locating Radars are designed to search a volume just above the horizon to detect artillery (*e.g.*, mortar) rounds and track them. Based on a round's calculated ballistic trajectory, the system can then determine the location of the origin of the rounds. The U.S. Army Firefinder radar systems (AN/TPQ-36 and AN/TPQ-37) are examples of such radars. These are phased array systems employing electronically scanned antennas to perform the search and track functions simultaneously for multiple targets. Figure 1-43 is the photograph of an AN/TPQ-36.

Figure 1-43. AN/TPQ-36 Firefinder radar system used for weapons location.

Target Identification Radars

Early radar systems could detect a target and determine its position if the signal-to-noise ratio was sufficient. The result of a target detection was a “blip” on the display screen. Little information regarding the nature of the target was available. Modern radar systems have the ability to produce more information about a given target than just its presence and location. Several techniques are available to aid in discriminating the target from clutter, classifying it as a particular target type (for example, a wheeled vehicle such as a truck, vs. a tracked vehicle such as a tank), and even with some degree of success identifying the target (for example, a particular class of aircraft). These techniques include high resolution range profiles, described in Chapter 20, high resolution cross-range “imaging” described in Chapter 21, high resolution Doppler analysis described in Chapter 17, and polarimetric techniques, which measure geometric and physical characteristics of the target (see Chapter 15 of Vol. II).

1.9.2. Commercial Applications

Process Control Radars

Very short range radars can be used to measure the fluid levels in enclosed tanks very accurately or determine the “dryness” of a product in a manufacturing process to provide feedback to the process controller. A typical system uses a fairly high frequency such as 10 GHz and uses frequency-modulated continuous wave (FMCW, discussed in Vol. II) techniques to measure distance to the top of the fluid in a tank. Figure 1-44(a) is an example of a non-contact fluid level measuring radar that mounts through the top of a tank, as shown in part (b) of the figure.

(a) (b)

Figure 1-44. Non-contact radar fluid level sensor.
(Courtesy of Rosemount, Inc. Used with permission.)

Airport Surveillance Radars

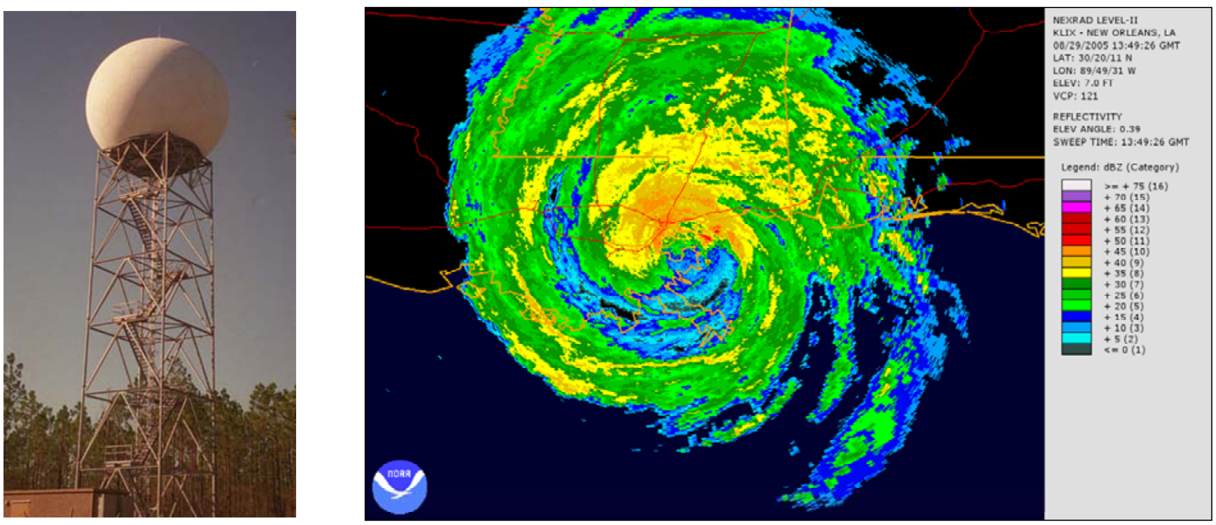
Airport surveillance radars detect and track many commercial and general aviation planes simultaneously. They are typically 2D systems as described previously, rotating mechanically in azimuth while using a wide elevation beamwidth to provide vertical coverage. As the radar's antenna beam makes its 360-degree scan and detects an aircraft target, the target track file is updated and displayed to the operator. Often a beacon transponder on the aircraft reports the flight number and altitude back to the surveillance radar. Figure 1-45 shows the antenna of the ASR-9 air surveillance radar, a common sight at most large U.S. commercial airports.

Figure 1-45. Antenna of the ASR-9 airport surveillance radar.
(Courtesy of Northrop-Grumman Corporation. Used with permission.)

Weather Radars

Government and news organizations keep track of weather activities using radar in conjunction with other weather station instruments. Modern Doppler weather radars measure not only the reflectivity of precipitation throughout the radar's field of view (FOV), but also the windspeeds (using Doppler techniques) and a measure of turbulence called the *spectral width*. Indeed, Doppler weather radar images are ubiquitous on television, and their basic features are widely understood by the general population. Some modern weather radars can also discriminate between rain and hail using polarization characteristics of the precipitation echo, while others can detect wind shear and rotating atmospheric (tornado) events using Doppler techniques. Weather radar is discussed in Chapter 16 of Vol. II.

In the United States, the primary operational network of weather radars used by the National Weather Service is the WSR-88D ("NEXRAD"). The antenna tower for a typical installation is shown in Fig. 1-45(a). The contiguous 48 states are covered by a network of 159 systems. Figure 1-45(b) shows the reflectivity image of Hurricane Katrina from the WSR-88D in New Orleans, Louisiana on August 29, 2005, a few minutes before the radar shut down.



(a) (b)

Figure 1-45. (a) Antenna tower for the WSR-88D (NEXRAD) radar. (b) Reflectivity image of Hurricane Katrina. (U. S. Government images.)

A related use of radar is in Radio-acoustic Sounding Systems (RASS) can measure the temperature profile above the ground for several kilometers of altitude without invading the atmosphere with anything more than an acoustic wave and a radar RF signal. An acoustic wave is transmitted vertically. The acoustic wave causes local variations in the dielectric properties of the atmosphere. A radar sends pulses in the same vertical direction. The dielectric variations result in radar backscatter form which the Doppler shift, and thus the speed of the acoustic wave can be recorded. Since the speed of sound is related to air temperature, the temperature profile can then be inferred. Figure 1-46 shows a RASS system located at the Alaska North Slope site at Barrow, Alaska. The large central square horn is the radar profiler antenna. The four surrounding circular sensors are the acoustic sources.

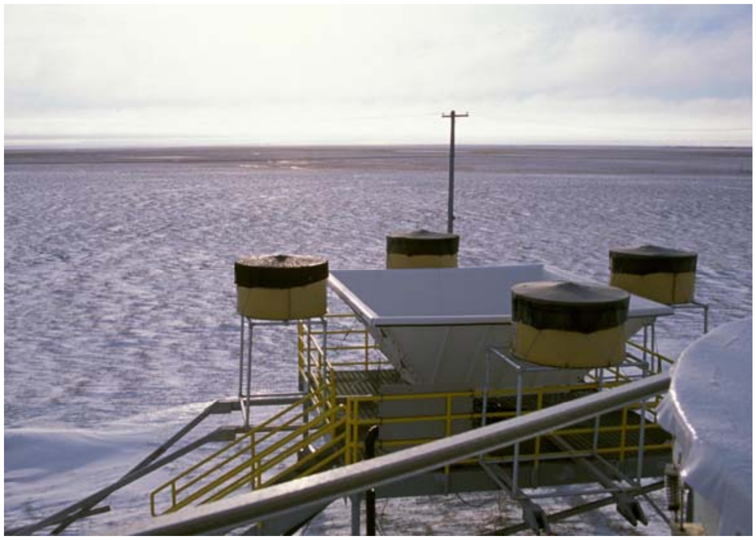


Figure 1-46. RASS system at Barrow, Alaska.

Wake Vortex Detection Radars

Large aircraft in flight produce a significant wake vortex, or turbulence, behind them in what might be otherwise laminar or still air. This vortex can persist for some time, depending on the local atmospheric conditions, and can present a dangerous flight control situation for light aircraft landing or taking off immediately behind large aircraft. Normally a separation of a minute or so is sufficient for this wake turbulence to dissipate. However, in some conditions, the wake turbulence persists for longer periods. Radars placed at the end of a runway can sense this wake turbulence and warn an approaching aircraft about such conditions.

Marine Navigation Radars

Radar systems can provide navigation information to a ship's captain. Shorelines, channel buoys, marine hazards (above the water surface) and other marine traffic can easily be detected at distances in excess of that required for safe passage of a ship, even in foul weather. Such systems often employ a narrow antenna azimuth beamwidth (one or two degrees) and a relatively wide elevation beamwidth (10 degrees or more). The Canadian LN-66 and U.S. AN/SPS-64 radars are examples of navigation radars for military ships. Figure 1-47 shows the display and control units of a common commercial radar, the Furuno FAR2817 X band radars.

Figure 1-47. Control and display units of Furuno FAR2817 X-band marine radar for small ships.

Satellite Mapping Radars

Space-based radar systems have the advantage of an unobstructed overhead view of the earth and objects on the earth's surface. These systems typically operate from satellites in low earth orbit, which is on the order of 770 km altitude. Pulse compression waveforms and synthetic aperture radar (SAR) techniques (described in Chapters 20 and 21) are used to obtain good range and cross-range resolution. Space-based radars are discussed in Chapter 13 of Vol. II.

An example of a satellite mapping radar is the Canadian RADARSAT 2 system, shown in an artists's rendering in Fig. 1-48. The satellite was launched in December 2007. Table 1-5 lists the resolution modes available in RADARSAT 2. Obtainable resolutions range from 100 m for wide area imaging, down to 3 m for high-resolution imaging of limited areas. Another series of space-based mapping radars are the Shuttle Imaging Radars (SIR) A, B, and C, which operate at altitudes of about 250 km.

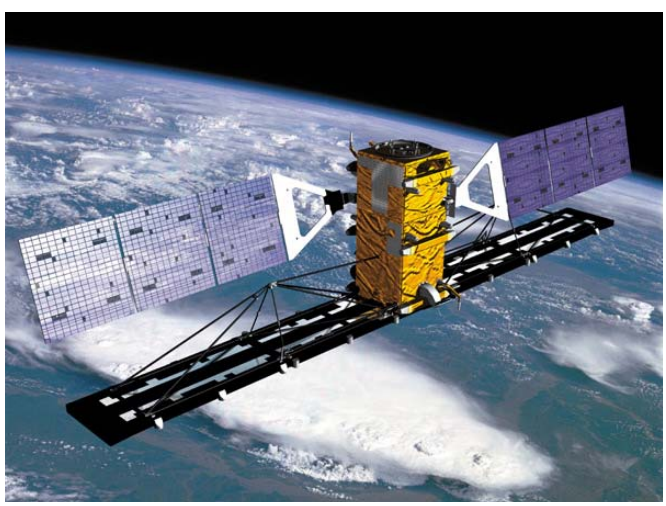


Fig. 1-48. Artist's rendering of the RADARSAT 2 satellite mapping radar.

Table 1-5. RADARSAT 2 resolution modes.

Beam Mode	Nominal Swath Width	Approximate Resolution (Range)	Approximate Resolution (Azimuth)	Approximate Incidence Angle	Polarization
Ultra-Fine	20 km	3 m	3 m	30° - 40°	Selective Single Polarization
Multi-Look Fine	50 km	8 m	8 m	30° - 50°	
Fine Quad-Pol	25 km	12 m	8 m	20° - 41°	Quad-Polarization
Standard Quad-Pol	25 km	25 m	8 m	20° - 41°	
Fine	50 km	8 m	8 m	30° - 50°	Selective Polarization
Standard	100 km	25 m	26 m	20° - 49°	
Wide	150 km	30 m	26 m	20° - 45°	
ScanSAR Narrow	300 km	50 m	50 m	20° - 46°	
ScanSAR Wide	500 km	100 m	100 m	20° - 49°	
Extended High	75 km	18 m	26 m	49° - 60°	Single Polarization
Extended Low	170 km	40 m	26 m	10° - 23°	

Police Speed Measuring Radars

Police speed measuring radars are simple continuous wave (CW) radars that can measure the Doppler frequency shift for a target (vehicle) in the antenna beam. When the relative speed is derived from the Doppler shift (using Eq. 1.2) and added to, or subtracted from, the speed of the police cruiser, the absolute speed of the vehicle can be determined. The radars use very low transmit power, and simple signal detection and processing techniques, such that they can be hand-held, as shown in Figure 1-49.

Figure 1-49. Photograph of a hand-held, single-antenna police speed-timing radar. (Courtesy of XXX XXX XXX, Inc. Used with permission.)

Automotive Collision Avoidance Radars

Collision avoidance radars installed in automobiles are currently under development and have been deployed in some models. These short-range systems usually employ an inexpensive antenna which may be electronically scanned and a millimeter-wave radar (Ka-band or W-band, for example) to provide a reasonably narrow azimuth beamwidth. There are challenges, however, in reducing the interpretations of non-dangerous situations as dangerous thus employing braking or steering commands unnecessarily.

Ground Penetration Radars

A ground penetrating radar (GPR) has a very low RF carrier frequency (usually L-band and below) which can penetrate the ground (as well as other surfaces) and detect dielectric anomalies several feet deep. Almost any object that is buried will create a dielectric discontinuity with the surrounding ground resulting is a reflection of the transmitted wave. Extremely high range resolution (on the order of 2-3 cm or less) is important in such applications. The range resolution is achieved by using very wide bandwidth. The challenge for these systems is designing an antenna system that has a high percentage bandwidth, and efficiently couples the EM wave into the ground, or other material. Common uses for GPR include buried pipe detection, gas leak location, buried land mine detection, tunnel detection, and concrete evaluation and void detection in pavements.

Figure 1-50 is a photograph of a vehicular-towed system designed to locate voids in concrete highways. The resulting plot, shown in Figure 1-51, shows the void as well as the reinforcing bars (rebar) used in the fabrication of the roadbed.

Figure 1-50. Photograph of a system designed to locate voids in a concrete highway. (Courtesy of Geophysical Survey Systems, Inc. Used with permission.)

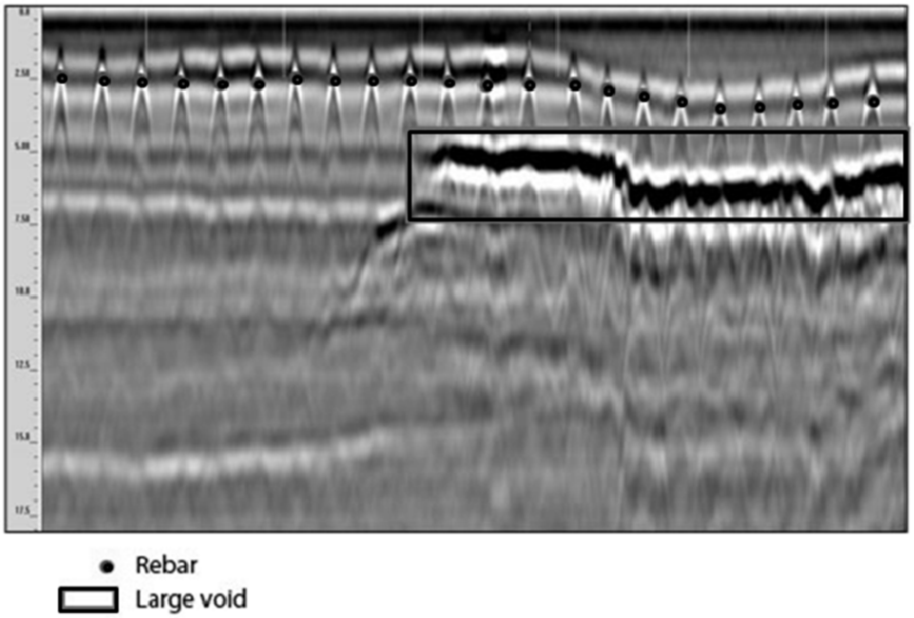


Figure 1-51. Plot showing highway void as well as the reinforcing bars (rebar) used in the fabrication of the roadbed. (Courtesy of Geophysical Survey Systems, Inc. Used with permission.)

Radar Altimeters

Relatively simple FMCW radars are used to determine the height of an aircraft above ground level (AGL), from nearly 0 feet to several thousand feet altitude. A strong ground reflection will be received from the surface when the radar is pointed directly downward and the range of the ground will be the altitude of the radar/aircraft. Radar altimeters are used in commercial as well as military aircraft. Figure 1-52 is the photograph of a Freeflight Systems TRA-3000 radar altimeter, showing the flush-mounted antenna and the display unit. This is an FMCW radar with about 100 MHz bandwidth, operating in the 4.2 to 4.4 GHz region. It provides altitude accuracy of about 5 to 7%.

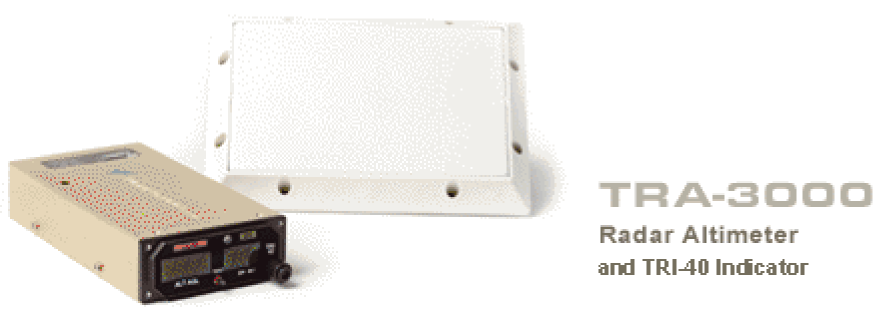


Figure 1-52. Photograph of a radar altimeter.

1.9 The Ubiquitous dB

The decibel (dB) is widely used in radar technology. Many radar parameters are expressed in units of dB due to the large dynamic range of these parameters. RCS is a good example. RCS values can range from 10^{-3} m^2 (insects) to over 10^6 m^2 (aircraft carriers). This represents nine orders of magnitude, a range of a billion to one (10^9). In dB units, these RCS values become –30 dB and 60 dB, respectively, a range of only ninety. Thus, in dB, the scale becomes significantly compressed and easier to deal with mathematically.

The value of a quantity in dB is always computed relative to some reference value. The first step in converting a value to dB is therefore to divide it by the reference value. For example, consider power, P. Before taking the logarithm of P, it is divided by a reference power P_0, say, $P_0 = 1$ watt. Now the logarithm is taken

$$\log_{10}\left(\frac{P}{P_0}\right) \tag{1.22}$$

This is the power in "bels." Multiplying this by 10 yields the power in decibels,

$$P \text{ in dB} = 10\log_{10}\left(\frac{P}{P_0}\right) \tag{1.23}$$

To convert from dB space to linear space, the inverse operation is performed:

$$x_{linear} = 10^{x_{dB}/10} \tag{1.24}$$

Shown in Fig. 1-26 is a scale comparing values of some parameter (*e.g.* power) in linear space and dB space.

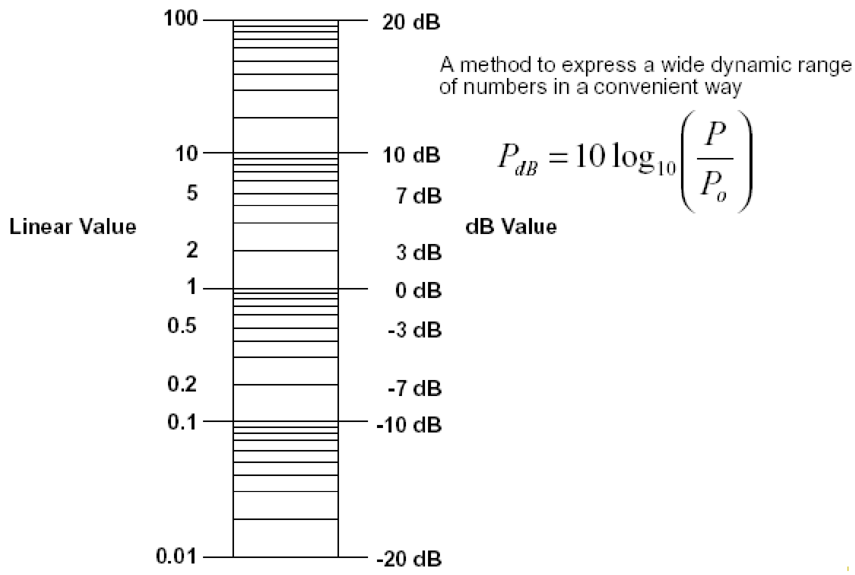


Figure 1-26. Linear and dB spaces.

There is only one problem. This may be a convenient way for a transmitter engineer to express power, but a receiver engineer would have probably chosen the reference power to be $P_0 = 10^{-3}$ watt = 1 milliwatt. Somehow the choice of the reference parameter must be conveyed to the user. This is done by modifying the way the unit "dB" is written. In the case of power, for example, the unit is expressed as "dBW"(dB relative to 1 watt) if $P_0 = 1$ watt and "dBm" (dB relative to 1 milliwatt) if $P_0 = 1$ milliwatt.

Some features of the dB to note are (1) values in dB can only be determined for positive parameters (the dB of a negative parameter is not allowed) and, (2) a negative dB value means that the linear value of the parameter is less than the reference value, *e.g.* the ratio P/P_0 is less than one.

Manipulating parameters in dB space makes linear-space arithmetic operations simpler; multiplication becomes addition and division becomes subtraction. This is due to the mathematical properties of the logarithm. For example, the liner equation $x = yz$ becomes $x = y + z$ if *x, y* and *z* are expressed in dB. Similarly, $x = y/z$ becomes $x = y - z$ if *x, y* and *z* are expressed in dB. Also, the equation $x = y^a$ becomes $x = ay$ if *x* and *y* are expressed in dB (*a* is not in dB). This was of great utility before the age of hand-held scientific calculators and high-speed computers, but is of little use today. The one exception is in the determination the linear value of a parameter given in dB when a calculator is not available. Table 1-5 lists several "dBs to remember."

Table 1-6. dBs to remember

dB	**Linear**
0	1
1	1-1/4
3	2
10	10
$10x$	10^x
$-10x$	10^{-x}

With this table and the arithmetic properties of dBs, one can determine the approximate linear value of any parameter given in dB without resorting to a scientific calculator. For example, the linear equivalent of 7 dB can be determine by noting

$$7 \text{ dB} = 3 \text{ dB} + 3 \text{ dB} + 1 \text{ dB} \tag{1.25}$$

and, from the table, that 3 dB corresponds to a linear value of 2 while 1 dB corresponds to a linear value of 1-1/4. From this and the arithmetic properties of dB, Eq. (1.25) becomes

$$7 \text{ dB} = 2 \times 2 \times 1\tfrac{1}{4} = 5 \tag{1.26}$$

An alternative way to reach the same conclusion is to note that

$$7 \text{ dB} = 10 \text{ dB} - 3 \text{ dB}. \tag{1.27}$$

From the table, 10 dB = 10 and 3 dB = 2. Thus Eq. (1.27) becomes

$$7 \text{ dB} = 10 \div 2 = 5 \tag{1.28}$$

Some radar parameters commonly expressed in dB are shown in Table 1-7.

Table 1-7. Radar parameters commonly expressed in dB.

Radar Parameter	**dB expression**
Antenna Gain	dBi (gain relative to isotropic)
Power Gain	dB (power out / power in)
Power Loss	dB (power in / power out)
Power	dBW (power relative to 1 watt) dBm (power relative to 1 milliwatt)
RCS	dBsm (RCS relative to 1 square meter)

1.10 Organization of This Text

This textbook is organized into four major sections. The first, consisting of Chapters 1 – 3, introduce the basic concepts and terminology of radar systems and operation, without many of the details. This section gives the reader an overview of the major issues in designing and evaluating radar systems. The remaining sections then provide more detailed information about the elements of a radar system.

Section 2, consisting of Chapters 4 – 8, is concerned with the phenomenology of radar signals, including targets, clutter, Doppler shift, and atmospheric effects. This section provides the information needed to model realistic radar signals and thus to understand how to process them. Section 3 comprises Chapters 9 – 13 and represents the “hardware” section of the radar system. These chapters describe the types and characteristics of typical modern radar transmitters, receivers, antennas, receivers, and signal processors.

Chapters 14 – 21 comprise the fourth section, on radar signal processing. Beginning with a review of digital signal processing principles, this section describes a wide variety of radar signal analysis and processing methods, ranging from basic threshold detection through Doppler processing, tracking, and an introduction to imaging.

Vol. II of *Principles of Modern Radar* addresses advanced concepts and technqiue3s as well as radar applications. It provides much greater depth in a variety of imaging, clutter suppression, and tracking techniques, as well as detailed discussions of a wide range of radar applications.

1.11 Further Reading

There are a number of excellent introductory texts on radar systems and technology. The most classis is Skolnik’s text [3], now in its third edition, which provides a primarily qualitative overview of a wide range of radar systems, technologies, and issues. Toomay and Hannen [4] provide a thorough introduction to a broad range of fundamental radar topics, with supporting mathematics at a relatively simple level. Kingsley and Quegan’s book [5] is another good radar survey. All four of the preceding textbooks, like this one, provide sample problems to aid in understanding and applying the concepts. Stimson’s text [6] focuses on airborne radars, but is perhaps the best-illustrated book on radar. It provides an excellent intuitive and visual discussion of many radar topics.

More advanced introductions are provided by Mahafza [7] and Peebles [8] Mahafza provides a number of MATLAB scripts to support the textbook topics. Peebles’ text is the most advanced of those discussed here, providing very thorough coverage at an advanced undergraduate or beginning graduate student level. Finally, Richards [9] provides a senior or graduate-level text that concentrates on the signal processing aspects of radar such as Doppler processing, integration, detection, waveforms, and imaging. His text provides a good basis for study of more advanced radar signal processing sources.

1.12 References

[1] K. E. Lonngren, S. V. Savov, and R. J. Jost, *Fundamentals of Electromagnetics with MATLAB*, 2nd Ed. (SciTech Publishing, Raleigh, NC, 2007)

[2] IEEE Standard 521-2002.

[3] M. I. Skolnik, *Introduction to Radar Systems, 3rd Ed.*. (McGraw-Hill, New York 2003)

[4] J. C. Toomay and P. J. Hannen, *Radar Principles for the Non-Specialists, 3rd Ed.* (SciTech Publishing, Rayleigh, NC, 2004.)

[5] S. Kingsley, S. Quegan, *Understanding Radar Systems,* (SciTech Publishing, Rayleigh, NC, 1999)

[6] G. W. Stimson, *Introduction to Airborne Radar* 2nd Ed. (SciTech Publishing, Rayleigh, NC, 1998)

[7] B. R. Mahafza, *Radar Systems Analysis and Design Using MATLAB*. (Chapman and Hall/CRC. Boca Raton, FL, 2000).

[8] P. Z. Peebles, Jr., *Radar Principles*. (Wiley, New York, 1998)

[9] M. A. Richards, *Fundamentals of Radar Signal Processing*. (McGraw-Hill, 2005).

1.13 Problems

1. Find an expression for the range of a target in kilometers (km) for a reflected signal that returns to the radar x μs after being transmitted? [0.15x km]

2. Find the wavelength of a 2 GHz EM wave. [15 cm]

3. Find the Doppler shift of a target approaching an X-band (10 GHz) radar at a 60^o angle off of the range dimension moving at a speed of 50 mph. [745 Hz]

4. If the intensity of a transmitted EM wave at a range of 500 m from the radar is 0.04 W/m^2, what is the intensity at 2 km? [0.0025 W/m^2]

5. Consider a very simple 1-D phased array antenna consisting of two isotropic, in-phase, radiating elements separated by a distance d (where d is much greater than λ, the wavelength of the transmitted EM wave). Show that the first null off of boresight in the far-field antenna pattern occurs at angle $\theta \cong \lambda/d$ radians.

6. Find an expression for a radar's maximum unambiguous range in kilometers if the radar's PRF is x kHz. [150/x km]

7. A high-PRF radar has a pulse width of 2.5 μs and a duty factor of ½. What is this radar's maximum unambiguous range? [750 m]

8. What is the maximum unambiguous Doppler shift that can be measured with a radar with a PRI of 0.25 milliseconds. [2 kHz]

9. The peak power of 200 kW radar is reduced by 3 dB. If it's duty cycle is 1.0%, what is it resulting average power in dBW? [30 dBW]

10. Using the "dBs to Remember" table and without using a calculator, determine the RCS in square meters of a 14 dBsm target. [25 m^2]