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1.9 RADAR APPLICATIONS

Given that the fundamental radar functions are search/detect, track, and image, numerous remote sensing applications can be satisfied by the use of radar technology. The uses for radar are as diverse as ground-penetrating applications, for which the maximum range is a few meters, to long-range over-the-horizon search systems, for which targets are detected at thousands of kilometers range. Transmit peak power levels from a few milliwatts to several megawatts are seen. Antenna beamwidths from as narrow as less than a degree for precision tracking systems to as wide as nearly isotropic for intrusion detection systems are also seen. 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 U.S. 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 1-3 lists a subset of this “AN nomenclature” that is pertinent to radar. The n’s following the
TABLE 1-3  Subset of the AN Nomenclature System for U.S. Military Equipment Applicable to Radar Systems

<table>
<thead>
<tr>
<th>First Letter (Type of Installation)</th>
<th>Second Letter (Type of Equipment)</th>
<th>Third Letter (Purpose)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Piloted aircraft</td>
<td>L Countermeasures</td>
<td>D Direction finger, reconnaissance, or surveillance</td>
</tr>
<tr>
<td>F Fixed ground</td>
<td>P Radar</td>
<td>G Fire control or searchlight directing</td>
</tr>
<tr>
<td>M Ground, mobile (installed as operating unit in a vehicle which has no function other than transporting the equipment)</td>
<td>Y Signal/data processing</td>
<td>K Computing</td>
</tr>
<tr>
<td>P Pack or portable (animal or man)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S Water surface craft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T Ground, transportable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U Ground utility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V Ground, vehicular (installed in vehicle designed for functions other than carrying electronic equipment, etc., such as tanks)</td>
<td>Y Surveillance (search, detect, and multiple target tracking) and control (both fire control and air control)</td>
<td></td>
</tr>
</tbody>
</table>

designations are a numerical sequence. For example, the AN/TPQ-36 is a ground-based transportable special purpose radar, in this case for locating the source of incoming mortars. Another example is the AN/SPY-1, a shipboard surveillance and fire control radar (FCR) system.

1.9.1.1 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 ground-based or surface ship systems. Some applications prohibit the use of more than one radar or more than 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 and for many electronically scanned antenna systems.

Two-Dimensional Search  Some volume search systems employ a “fan”-shaped antenna pattern to perform the search, usually in the range and azimuth dimensions. 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 1-33 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 two-dimensional (2-D) system, providing position information in only two dimensions.
An example of a 2-D radar is the AN/SPS-49 shipboard radar, shown in Figure 1-34. The SPS-49 is a very long-range, two-dimensional air search radar that operates in the UHF band (850–942 MHz). Nominal maximum range of the radar is approximately 250 nmi. The AN/SPS-49 provides automatic detection and reporting of targets supporting the antiair warfare (AAW) mission in Navy surface ships. The AN/SPS-49 uses a large truncated parabolic mechanically stabilized antenna to provide acquisition of air targets in all sea states. Originally produced in 1975 by the Raytheon Company, the SPS-49 is a key part of the combat system on many surface combatants of several navies of the world. It has been extensively modified to provide better detection capabilities of both sea-skimming and high-diving antiship missiles.

The SPS-49 performs accurate centroiding of target range, azimuth, amplitude, ECM level background, and radial velocity with an associated confidence factor to produce accurate target data for the shipboard command and control system. Additionally, processed and raw target data are provided for display consoles.

The AN/SPS-49 has several operational features to optimize radar performance, including an automatic target detection capability with pulse-Doppler processing and clutter maps. This helps ensure reliable detection in both normal and severe clutter. A key feature of the most recent version of the radar, the SPS-49A (V)1, is single-scan radial velocity...
estimation of all targets, allowing faster promotion to firm track and improved maneuver detection.

The SPS-49 beamwidths are 3.3° in azimuth and 11° in elevation. The narrow azimuth beamwidth provides good resistance to jamming. The antenna rotates at either 6 or 12 rpm. The radar operates in a long-range or short-range mode. In the long-range mode, the radar antenna rotates at 6 rpm. The radar can detect small fighter aircraft at ranges in excess of 225 nautical miles. In the short-range mode, the antenna rotates at 12 rpm to maximize the probability of detection of hostile low-flying aircraft and missiles and “pop-up” targets. The MTI capability incorporated in the AN/SPS-49(V) radar enhances target detection of low-flying, high-speed targets through the cancellation of ground/sea return (clutter), weather, and similar stationary targets.

Three-Dimensional Search  Figure 1-35 depicts a pencil beam antenna that provides accurate range, azimuth, and elevation information. A system using this approach is termed a three-dimensional (3-D) search radar.

An example of 3-D search radar used by the U.S. Navy on surface ships, including large amphibious ships and aircraft carriers, is the AN/SPS-48 produced by ITT Gilfillan and shown in Figure 1-36. The antenna is the square planar array consisting of slotted
waveguide. The antenna is fed at the lower left into the serpentine structure attached to
the planar array. This serpentine provides frequency sensitivity for scanning in elevation.
The SPS-48 scans in the azimuth plane at 15 rpm by mechanical scanning and in the
elevation plane by electronic (frequency) scanning. The large rectangular antenna on top
of the main antenna is for the Identification, Friend, or Foe (IFF) system.
The SPS-48 operates in the S-band (2–4 GHz) at an average rated power of 35 kW.
The radar scans in elevation (by frequency shifting,) up to 65° from the horizontal. It can
detect and automatically track targets from the radar horizon to 100,000 ft. Maximum
instrumented range of the SPS-48 is 220 nmi.
The SPS-48 is typically controlled by the shipboard combat system. It provides track
data including range, azimuth, elevation, and speed to the combat system and to the display
system for action by the ships automated defense system and by the operators.

1.9.1.2 Air Defense Systems
The AN/TPS-75 air defense system used by the U.S. Air Force is shown in Figure 1-37.
It has functionality similar to a multifunction 3-D 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 IFF response. The IFF antenna angle is set back
somewhat in azimuth angle so that the IFF interrogation can occur shortly after target
detection as the antenna rotates in azimuth.
The AN/MPQ-64 Sentinel shown in Figure 1-38 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.

1.9.1.3 Over-the-Horizon 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. 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 ionospheric refraction has the effect of reflecting the EM signal. The frequency dependence of this effect is such that it is most effective in the HF band (3–30 MHz). Given the desire for a reasonably narrow beamwidth, the antenna must be very large at such low frequencies, typically thousands of feet long. Consequently, OTH antennas are often made up from separate transmit and receive arrays of elements located on the ground. Figure 1-39 shows an example of such a transmit array. Figure 1-40 depicts the operation of an over-the-horizon system, showing the ray paths for two targets.

### 1.9.1.4 Ballistic Missile Defense (BMD) Radars
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 it from 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 sea-based Cobra Judy system and X-Band (SBX) radar and the land-based Pave Paws and Theater High Altitude Air Defense (THAAD) AN/TPY-2 systems. Figure 1-41 shows the Pave Paws (AN/FPS-115) system, featuring its two extremely large pencil beam phased array antennas.

A newer system is the THAAD radar shown in Figure 1-42. 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.
1.9.1.5 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 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) that make infrared sensors ineffective.

Bistatic, *semiactive seekers* in the nose of a missile receive a reflected signal from a target that 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 NATO Seaparrow AAW missiles are examples of such a semiactive mode. The NATO Seaparrow requires a constant signal for homing. The Standard Missile does not. It requires illumination only during the last few seconds of flight. Figure 1-43 shows a Seaparrow being launched from a surface ship. Figure 1-44 shows a Navy Standard Missile 2 Block IIA launching from a guided missile destroyer.

**FIGURE 1-42**
Photograph of the Theater High Altitude Air Defense AN/TPY-2 radar.
(Courtesy of U.S. Missile Defense Agency.)

**FIGURE 1-43**
NATO Seaparrow semiactive homing AAW Missile.
(Courtesy of U.S. Navy.)
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The AIM-7 missile shown in Figure 1-45 is a semiactive 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.”

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 LOS. This mode is often referred to as the fire-and-forget mode. The helicopter-based Longbow FCR system shown in Figure 1-46 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.

1.9.1.6 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 1-47 is a photograph of an AN/MPQ-39 multiple-object tracking radar (MOTR), a C-band phased array instrumentation radar used at test ranges such as White Sands Missile Range.

Many indoor and outdoor target 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 1-48a 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 that serves as a platform for an instrumentation radar. Figure 1-48b shows a sample “quick look” ISAR image.

1.9.1.7 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 semiaactive mode as it approaches the target. Early 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 while continuing to perform the search function. Examples of such systems are the ship-based Aegis fire control radar (AN/SPY-1), the ground-based Patriot air defense radar, and certain airborne fire control radars commonly found in fighter-interceptor aircraft such as the MiG-29, F-15, F-16, F-18, the Sukhoi SU-27 series, and the F-22 aircraft.

An aircraft fire-control radar system may include, in addition to the radar, another RF or IR source to illuminate the target with RF energy or to locate the hostile aircraft by searching for its heat signature. For example, a semiaactive radar seeker in a missile can home on the target from the reflections of its own radar return signal or from the radar signal from the hostile aircraft radar system. Often, the more modern and sophisticated fire control systems include the capability to use the track data from other sources, such as land, sea, or airborne radar systems such as the Air Force E3A Sentry (AWACS) or Navy E2C AEW system. 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 may have its own short-range radar onboard for the final phase of the engagement.

Some radars perform both the search and track functions simultaneously. One example of this type of radar is the AN/SPQ-9A Surface Surveillance and Tracking Radar, developed by Northrop Grumman Norden Systems. The “Spook-9” is an X-band track-while-scan radar used with the Mk-86 Gunfire Control system on certain surface combatants. The latest model of the “Spook-9” is the AN/SPQ-9B, designed primarily as an antiship missile defense radar. It is designed to detect hostile missiles as they break the radar horizon even in heavy clutter while at the same time provide simultaneous detection and tracking of
1.9.1.8 Multifunction 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 independent 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 1-50

FIGURE 1-49
Photograph of an AN/SPQ-9B ship-based TWS radar slotted line antenna (a) and protective radome (b). (Courtesy of U.S. Navy.)

FIGURE 1-50
USS Ticonderoga CG-47 with the AN/SPY-1 radar installed. (Courtesy of U.S. Navy.)
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 that are required to provide full 360 degree coverage are visible in the figure.

1.9.1.9 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 1-51 shows an AN/TPQ-36.

1.9.1.10 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 (e.g., 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 (e.g., a particular class of aircraft). These techniques include high-resolution range profiles (Chapter 20), high-resolution cross-range imaging (Chapter 21), and high-resolution Doppler analysis (Chapter 17).

1.9.2 Commercial Applications
1.9.2.1 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) techniques to measure distance to the top of the fluid in a tank. Figure 1-52a is an example of a noncontact fluid level measuring radar that mounts through the top of a tank, as shown in part (b) of the figure.

1.9.2.2 Airport Surveillance Radars

Airport surveillance radars detect and track many commercial and general aviation planes simultaneously. They are typically 2-D 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 1-53 shows the antenna of the ASR-9 air surveillance radar, a common sight at most large U.S. commercial airports.

1.9.2.3 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 wind speeds (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.

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 Figure 1-54a. The contiguous 48 states are covered by a network of 159 systems. Figure 1-54b 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 related use of radar is in radio-acoustic sounding systems (RASS), which 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 compression of the air, which creates local variations in the dielectric properties of the atmosphere. A radar transmits pulses in the same vertical direction. The dielectric variations in the atmosphere result in radar backscatter from 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 1-55 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.

A very small equivalent radar cross section results from the acoustic disturbance. Normally, this small RCS would not be detectable, except for two special features of the combined system. Since the acoustic wave is spherical, and the radar wave is spherical, there is a focusing effect due to the fact that both the acoustic horns and the radar antenna are at the center of the sphere. Also, the acoustic wave is designed to produce on the order of 100 cycles at a particular wavelength. The radar frequency is chosen so that it has the
same wavelength. This condition creates a constructive interference condition providing a larger received signal.

1.9.2.4 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. 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.

1.9.2.5 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 (1 or 2 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 1-56 shows the display and control units of a common commercial radar, the Furuno FAR2817 X-band radars.

FIGURE 1-55
RASS system at Barrow, Alaska. (U.S. Government image.)

FIGURE 1-56
Control and display units of Furuno FAR2817 X-band marine radar for small ships. (Courtesy of Furuno. With Permission.)
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1.9.2.6 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.

An example of a satellite mapping radar is the Canadian RADARSAT 2 system, shown in an artist’s rendering in Figure 1-57. The satellite was launched in December 2007. Table 1-4 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.

1.9.2.7 Police Speed Measuring Radars
Police speed measuring radars are simple 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 equation (1.2) and is added to or subtracted from the speed

<table>
<thead>
<tr>
<th>Beam Mode</th>
<th>Nominal Swath Width</th>
<th>Approximate Resolution (Range)</th>
<th>Approximate Incidence Angle</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-Fine</td>
<td>20 km</td>
<td>3 m</td>
<td>30° – 40°</td>
<td>Selective Single Polarization</td>
</tr>
<tr>
<td>Multi-Look Fine</td>
<td>50 km</td>
<td>8 m</td>
<td>30° – 50°</td>
<td></td>
</tr>
<tr>
<td>Fine</td>
<td>25 km</td>
<td>12 m</td>
<td>20° – 41°</td>
<td>Quad-Polarization</td>
</tr>
<tr>
<td>Standard</td>
<td>25 km</td>
<td>25 m</td>
<td>20° – 41°</td>
<td></td>
</tr>
<tr>
<td>Standard Quad-Pol</td>
<td>100 km</td>
<td>25 m</td>
<td>20° – 49°</td>
<td></td>
</tr>
<tr>
<td>Wide</td>
<td>150 km</td>
<td>30 m</td>
<td>20° – 45°</td>
<td>Selective Polarization</td>
</tr>
<tr>
<td>ScanSAR Narrow</td>
<td>300 km</td>
<td>50 m</td>
<td>20° – 46°</td>
<td></td>
</tr>
<tr>
<td>ScanSAR Wide</td>
<td>500 km</td>
<td>100 m</td>
<td>20° – 49°</td>
<td></td>
</tr>
<tr>
<td>Extended High</td>
<td>75 km</td>
<td>18 m</td>
<td>49° – 60°</td>
<td>Single Polarization</td>
</tr>
<tr>
<td>Extended Low</td>
<td>170 km</td>
<td>40 m</td>
<td>10° – 23°</td>
<td></td>
</tr>
</tbody>
</table>
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 handheld, as shown in Figure 1-58.

1.9.2.8 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 (e.g., Ka-band or W-band) to provide a reasonably narrow azimuth beamwidth. There are challenges, however, in reducing the interpretations of nondangerous situations as dangerous, thus employing braking or steering commands unnecessarily.

1.9.2.9 Ground Penetration Radars
A ground-penetrating radar (GPR) has a low carrier RF (usually L-band and below) that 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 in 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 1-59 shows a vehicular-towed system designed to locate voids in concrete highways. The resulting plot, shown in Figure 1-60, shows the void as well as the reinforcing bars (rebar) used in the fabrication of the roadbed.

1.9.2.10 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 1-61 is a Freelflight Systems TPA3000 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%.
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FIGURE 1-59 =
A ground-penetrating system designed to locate voids in a concrete highway. (Courtesy of Geophysical Survey Systems, Inc. With permission.)

FIGURE 1-60 =
Plot showing highway void as well as the reinforcing bars (rebar) used in the fabrication of the roadbed. (Courtesy of Geophysical Survey Systems, Inc. With permission.)

FIGURE 1-61 =
Photograph of a radar altimeter. (Courtesy of Freeflight Systems Inc. With permission.)

1.10  |  ORGANIZATION OF THIS TEXT

This textbook is organized into four major parts. The first, consisting of Chapters 1–3, introduces the basic concepts and terminology of radar systems and operation, without many of the details. This part gives the reader an overview of the major issues in designing and evaluating radar systems. The remaining parts provide more detailed information about the elements of a radar system.
Part 2, consisting of Chapters 4–8, is concerned with the phenomenology of radar signals, including targets, clutter, Doppler shift, and atmospheric effects. This part provides the information needed to model realistic radar signals and thus to understand how to process them. Part 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, and signal processors.

Chapters 14–21 comprise the fourth part, on radar signal processing. Beginning with a review of digital signal processing principles, this part of the book 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.

FURTHER READING

There are a number of excellent introductory texts on radar systems and technology. The most classic 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 an introduction to a broad range of fundamental radar topics, with supporting mathematics at a straightforward level. Kingsley and Quegan’s book [5] is another good radar survey. All 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’s 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.

REFERENCES


CHAPTER 1  |  Introduction and Radar Overview

1.3 PROBLEMS

1. Find an expression for the range of a target in kilometers (km) for a reflected signal that returns to the radar $\Delta T \mu s$ after being transmitted.

2. Find the distance to a radar target (in meters) for the following round-trip delay times:
   a. 12 $\mu s$
   b. 120 $\mu s$
   c. 1.258 ms
   d. 650 $\mu s$

3. Find the delay times associated with the following target distances:
   a. 1 mile
   b. 1 km
   c. 100 km
   d. 250 miles
   e. 20 feet

4. Find the wavelength of the EM wave associated with the following carrier frequencies (in free space):
   a. 325 MHz
   b. 1.2 GHz
   c. 2.85 GHz
   d. 5.8 GHz
   e. 9.325 GHz
   f. 15.6 GHz
   g. 34.5 GHz
   h. 94 GHz

5. Find the carrier frequency associated with the following wavelengths for an EM wave in free space.
   a. 1 inch
   b. 0.35 cm
   c. 8.6 mm
   d. 90 cm
   e. 9.0 cm
   f. 1 foot

6. 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?

7. How far from an antenna must one be positioned such that the wavefront whose source is at your position is estimated to be planar at the antenna, for the following conditions, where $f$ is the carrier frequency, $\lambda$ is the wavelength in meters, and $D$ is the antenna dimension in meters:
# Problems

<table>
<thead>
<tr>
<th>$f$ (GHz)</th>
<th>$\lambda$ (meters)</th>
<th>$D$ (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. 10</td>
<td>–</td>
<td>1.0</td>
</tr>
<tr>
<td>b. –</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>c. 10</td>
<td>–</td>
<td>0.1</td>
</tr>
<tr>
<td>d. 3</td>
<td>–</td>
<td>1.0</td>
</tr>
<tr>
<td>e. 3</td>
<td>–</td>
<td>7.5</td>
</tr>
</tbody>
</table>

8. What is the approximate beamwidth in radians and in degrees for a circular aperture for each of the cases listed in problem 7?

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

10. The peak power of 200 kW radar is reduced by 3 dB. If its duty cycle is 1.0%, what is the resulting average power in dBW?

11. Find an expression for a radar’s maximum unambiguous range in kilometers if the radar’s PRF is $x$ kHz.

12. A high-PRF radar has a pulse width of 1.0 $\mu$s and a duty factor of 20%. What is this radar’s maximum unambiguous range?

13. Find the Doppler shift associated with the following target motions; where $v_t$ is the target speed, $\theta$ is the angle of velocity vector relative to LOS from the radar to the target, and $f$ is the radar carrier frequency:

<table>
<thead>
<tr>
<th>$v_t$</th>
<th>$\theta$</th>
<th>$f$ (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. 100 mph</td>
<td>$0^\circ$</td>
<td>10</td>
</tr>
<tr>
<td>b. 330 m/s</td>
<td>$0^\circ$</td>
<td>10</td>
</tr>
<tr>
<td>c. 15 m/s</td>
<td>$0^\circ$</td>
<td>10</td>
</tr>
<tr>
<td>d. 15 m/s</td>
<td>$45^\circ$</td>
<td>10</td>
</tr>
<tr>
<td>e. 15 m/s</td>
<td>$45^\circ$</td>
<td>3</td>
</tr>
<tr>
<td>f. 15 m/s</td>
<td>$60^\circ$</td>
<td>10</td>
</tr>
</tbody>
</table>

14. What is the maximum unambiguous Doppler shift that can be measured with a radar with a PRI of 0.25 milliseconds?

15. What is the range resolution of a radar system having the following characteristics?

<table>
<thead>
<tr>
<th>Pulse length</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. 1.0 $\mu$s</td>
<td>9.4 GHz</td>
</tr>
<tr>
<td>b. 1.0 $\mu$s</td>
<td>34.4 GHz</td>
</tr>
<tr>
<td>c. 0.1 $\mu$s</td>
<td>9.4 GHz</td>
</tr>
<tr>
<td>d. 0.01 $\mu$s</td>
<td>9.4 GHz</td>
</tr>
</tbody>
</table>

16. Consider a 2-D search radar having an antenna that is 6.5 meters wide. If it is rotating (in azimuth) at a constant rate of 0.8 radians per second, how long is a potential target in the 3 dB beam if the operating frequency is 2.8 GHz?

17. Consider a police speed timing radar with a circular antenna of 6 inch diameter.

a. What is the approximate beamwidth (in degrees) for an operating frequency of 9.35 GHz?

b. What is the approximate beamwidth (in degrees) for an operating frequency of 34.50 GHz?

c. What is the approximate diameter of the beam (in feet) at a distance of 0.25 miles for an operating frequency of 9.35 GHz?

d. What is the approximate diameter of the beam (in feet) at a distance of 0.25 miles for an operating frequency of 34.50 GHz?