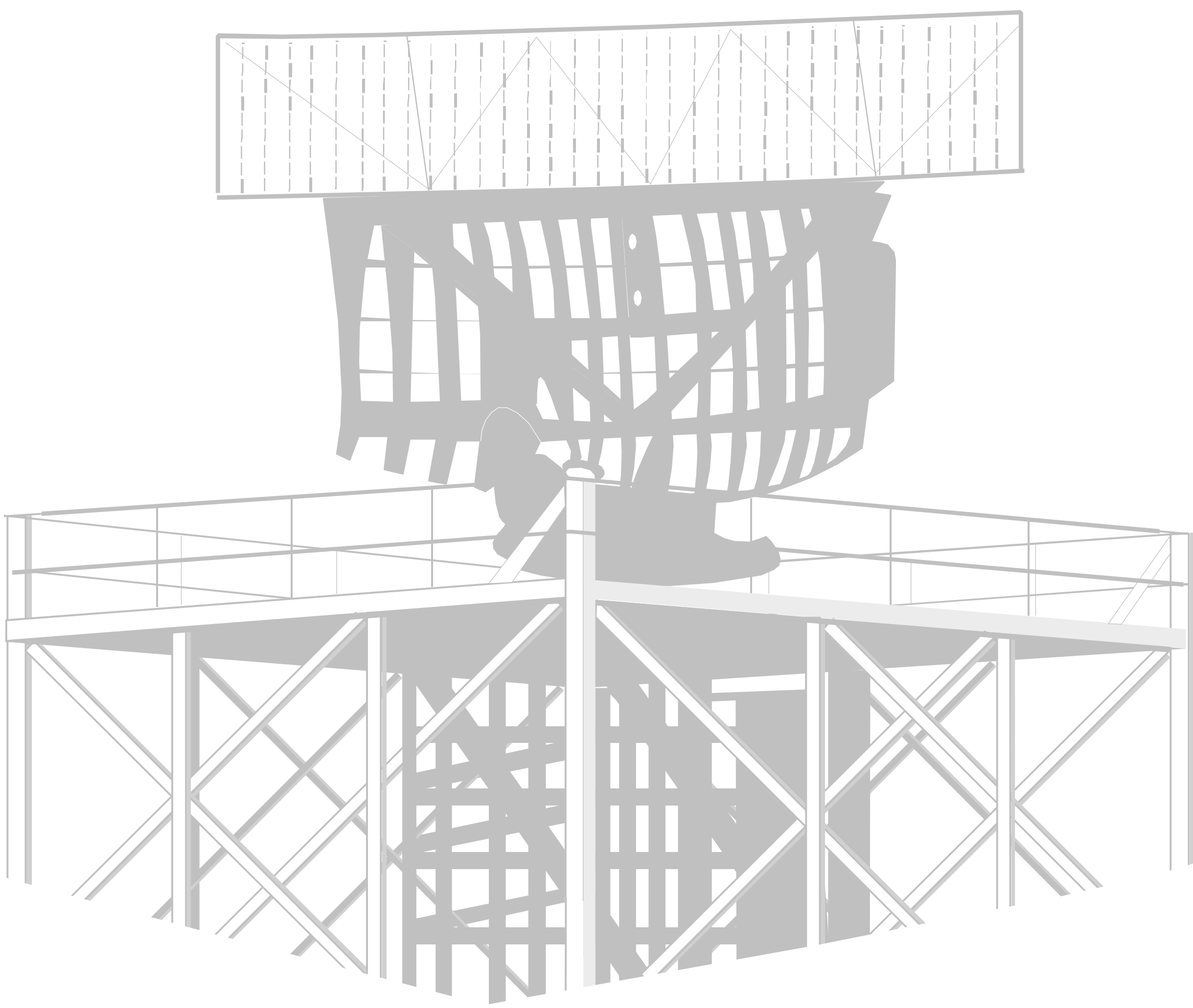
Federal Radar Spectrum Requirements



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Federal Radar Spectrum Requirements

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EXECUTIVE SUMMARY

The availability of the radio spectrum in the United States is critical to over 40 radio services that provide functions ranging from air traffic control to amateur radio operations. Although the radio frequency spectrum is not a consumable resource, the use of a frequency at a given location usually prevents that frequency from being used by others in the same geographic area. This need for exclusive geographic use to preclude harmful interference has led to current spectrum regulations that establish spectrum use rules, such as granting licenses for spectrum use, and partitioning the spectrum for shared use between radio services.

The National Telecommunications and Information Administration (NTIA), under a mandate from Congress to develop long-range spectrum plans, initiated the Strategic Spectrum Planning Program. As part of this long-term planning effort, NTIA released its *NTIA Requirements Study* (U.S. National Spectrum Requirements: Projections and Trends) in March 1995 addressing all radio services, and found that eight of these services needed access to additional spectrum in order to satisfy user requirements to the year 2004.

While all radio services are important to the nation, one of the very important uses of spectrum is for radars. Radars, by means of the propagation properties of radio waves, can determine an object's position, velocity and/or other characteristics. Radars come in a variety of sizes and power, from ultra-wideband milliwatt systems to very high-power systems used primarily for long-range search and surveillance. This report limits its investigation to mainly radars used for military radiolocation, radionavigation, meteorological, and Earth observations.

Although the NTIA Requirements Study indicated spectrum allocated for the radionavigation, radiolocation, and meteorological radars was considered to be adequate to the year 2004, this report revisits Federal radar spectrum requirements needed to support continued and evolving radar requirements in the United States based on information gathered from spectrum management data, agency inputs, available literature, and the life cycle projections of the platforms employing radar. This report describes the present and projected spectrum requirements for many Federal radar users.

For the purposes of spectrum planning, the following table lists frequency bands that have been identified as necessary to support radar spectrum requirements for various Federal agencies. The information in the table below should be considered as long-range planning information for Federal radar systems. Because Federal agency missions are unlikely to change, and radar platforms are likely to be updated or replaced, the actual time frame for the radar spectrum requirement is likely to be extended beyond the 20–year time frames shown below.

20–Year Federal Spectrum Requirement Forecast for Radar Bands

Frequency Bands	Federal Government Use
92–100 GHz	Airborne fire-control, beacons, atmospheric research, cloud detection, and synthetic vision radars
31.8–36 GHz	Airborne navigational, mapping, weather, beacon, terrain following & avoidance; aircraft carrier PAR, test range, atmospheric & oceanic research, altimeter, scatterometer, and synthetic vision radars
24.05–24.65 GHz	Doppler radiolocation, vehicle speed detection, scatterometer, and precipitation radars
15.4–17.3 GHz	Airborne and shipborne multimode search, battlefield, aircraft carrier PAR, fire-control, test range, ASDE, scatterometer, precipitation, atmospheric research, and spaceborne radars
13.25–14.2 GHz	Airborne and shipborne search and acquisition Doppler, airborne weather, altimeters, scatterometer, precipitation, environmental research, and spaceborne radars
8.5–10.55 GHz	Airborne and shipborne surveillance and navigation, fire-control, battlefield, maritime, weather, test range, airborne radionavigation, ATC, SAR's, altimeters, ASDE, scatterometer, vehicle speed detection, and spaceborne radars
5250–5925 MHz	NOAA weather radars, FAA TDWR, surveillance and air defense (airborne, shipborne, land-based), fire-control, maritime, test range, SAR's, altimeters, scatterometer, airborne, and spaceborne radars
4200–4400 MHz	Aircraft radar altimeters
3100–3650 MHz	DOD surveillance and air defense (airborne, shipborne, land-based), ATC, SAR's, altimeters, test range, and spaceborne radars
2700–3100 MHz	ATC, maritime, and weather radars; DOD shipborne, airborne, ground air surveillance radars; range control, and spaceborne radars
2310–2385 MHz	Planetary and lunar radar
1215–1390 MHz	ATC, SAR's, and DOD early warning air defense, battlefield, shipborne long-range surveillance, and spaceborne radars
890–942 MHz	Navy shipborne long-range surveillance, test range, NASA research, and wind profiler radars
420–450 MHz	DOD early warning and long-range surveillance radars; and wind profiler radars
216–220 MHz	DOD space surveillance radar
3–30 MHz	DOD OTH and surface wave radar

FOREWORD

The Battle of Britain (June - September 1940) pitted the air forces of England and Germany in a aerial duel of proportions unknown until that time. The Royal Air Force (RAF), although largely outnumbered, had two advantages. One advantage was that they were fighting on home territory, and the other was the use by the English of a newly-developed electronic device termed RADAR to detect incoming waves of aircraft in time to launch and vector RAF fighters to intercept them. Prime Minister Churchill later proclaimed, about the RAF, "Never in the field of human conflict was so much owed by so many to so few."

The use of radar during that battle was critical to the outcome. Radar was used to leverage the air resources and skills of the RAF pilots to defeat a superior enemy. Today we call this type of leverage a "force multiplier" where a small number of warfighters can defeat larger numbers by use of these systems. Radar and other electronic systems are important today as force multipliers much as the old "Chain Home" radar system was critical during World War II.

Although the military forces are the primary users of radar systems, other Federal agencies such as the Federal Aviation Administration (FAA), National Aeronautical and Space Administration (NASA), and National Oceanic and Atmospheric Administration (NOAA) have critical applications for these systems. The use of radar by the Federal agencies assists in the preservation of life and property, enhances weather forecasting, environmental and resource monitoring, and allows safe and efficient transportation by air and sea.

The National Telecommunications and Information Administration (NTIA) released a report in 1995 entitled U.S. National Spectrum Requirements: Projections and Trends (hereinafter *NTIA Requirements Study*) where it addressed 18 radio services and developed a spectrum forecast for a 10–year period. The study concluded that eight of these services needed access to additional spectrum in order to satisfy user requirements to the year 2004. The study also concluded that the spectrum allocated for radar use, such as the radionavigation, radiolocation, and meteorological aids radio services, was adequate for the foreseeable future.

However, as a result of spectrum transfers mandated by the Omnibus Budget Reconciliation Act of 1993 (OBRA–93)[1], the Balanced Budget Act of 1997 (BBA–97)[2], and the constant pressure on Federal spectrum by potential commercial users, NTIA was requested to undertake a follow-on study to document current and future Federal radar spectrum requirements.

NTIA's approach to this study was to document current Federal radar uses, review radars currently in the systems review cycle, examine the projected life cycles of radar platforms that radars are expected to operate on and support, and investigate research and development efforts that may lead to future radar spectrum requirements.

NTIA believes that the preservation of adequate radar spectrum is imperative, not only for national defense, but for other Federally-mandated services, and should be a high priority for national spectrum managers.

Endnotes: Foreword

1. Omnibus Budget and Reconciliation Act, Title VI, § 6001(a)(3), Pub. L. No. 103–66, 107 Stat. 379, (Aug. 10, 1993) (codified at 47 U.S.C. § 921 et seq.) [hereinafter OBRA–93].

2. Balanced Budget Act of 1997, Pub. L. No. 111, Stat. 251 (1997), § 9233(a) (4) [hereinafter BBA–97].

Chapter 1

RADARS AND FEDERAL GOVERNMENT APPLICATIONS

INTRODUCTION

In today's life style, many U.S. citizens are assisted in their personal life by information garnered from land-based, airborne, shipborne, and spaceborne radars. We hear daily weather broadcasts from television and radio stations where the weather radar is mentioned, providing significant detailed information of the weather situation. Air travelers are generally aware that air traffic control radars help with the safe and efficient movement of commercial and military aircraft, although the radars are not always visible to the traveler. Many automobile drivers know of radar speed guns and their use by law enforcement units to help curb speeding drivers. Many ocean-going boats and ships employ maritime surveillance and weather radars to help in piloting during adverse weather conditions.

Historically, the military is primarily credited with developing the radar. The term RADAR is derived from the description of its first primary role as a RAdio Detection And Ranging system. Originally, it was developed as a means of detecting approaching aircraft at long ranges to enable military defenses to react in sufficient time to counter incoming threats. Most natural and man-made objects reflect radio frequency waves and, depending on the radar's purpose, information can be obtained from objects such as aircraft, ships, ground vehicles, terrain features, weather phenomenon, and even insects. The determination of the object's position, velocity and other characteristics, or the obtaining of information relating to these parameters by the transmission of radio waves and reception of their return is sometimes referred to as radiodetermination.[1]

RADAR FUNDAMENTALS

In most cases, a basic radar operates by generating pulses of radio frequency energy and transmitting these pulses via a directional antenna. When a pulse impinges on a object[2] in its path, a small portion of the energy is reflected back to the antenna. The radar is in the receive mode in between the transmitted pulses, and receives the reflected pulse if it is strong enough. The radar indicates the range to the object as a function of the elapsed time of the pulse traveling to the object and returning. The radar indicates the direction of the object by the direction of the antenna at the time the reflected pulse was received.

The "radar equation" mathematically describes the process and may be used to determine maximum range as a function of the pulse width (PW) and the pulse repetition rate (PRR). In most cases, narrow pulses with a high PRR are used for short-range, high-resolution systems, while wide PW's with a low PRR may be used for long-range search.

In general, a higher gain (larger aperture) antenna will give better angular resolution, and a narrower pulse width will give better range resolution. Changing the parameters of radars to satisfy a particular mission requires radar designers to have a variety of frequencies to choose from so that the system can be optimized for the mission and the radar platform.

RADAR DEVELOPMENTS

Radar as a means of detection has been around for over 60 years, and although technology has become immensely more sophisticated than it was in the 1930's, the basic requirement remains the same—to measure the range, bearing, and other attributes of a target. Regardless of whether the system is land-based, shipborne, airborne, or spaceborne, this remains true since whatever the target may be, aircraft, ship, land vehicles, pedestrians, land masses, precipitation, oceans—all provide returns of the transmitted radar energy. What has changed dramatically is the system design, the method and speed of processing the return radar signals, the amount of information which can be obtained, and the way that the information is displayed to the operator. The key to modern radar systems is the digital computer and its data processing capability which can extract a vast amount of information from the raw radar signals and present this information in a variety of graphic and alphanumeric ways on displays as well as feeding it direct to weapon systems. It also enables the systems to carry out many more tasks such as target tracking and identification. In addition, modern signal processors provide adaptive operation by matching the waveform to the environment in which the radar is operating.

Much of the development effort over the past 50 years has been aimed at a number of operational requirements: improvements in the extraction of return signals from the background of noise, provision of more information to the operator, improvement of displays, and increased automation. Other developments have responded to the increasing operational requirements for radars to operate in a hostile electromagnetic environment. It is no longer enough to provide only bearing and range information; to this must be added altitude information, the ability to track a large number of moving targets, including airborne targets at supersonic and hypersonic speeds and to carry out normal surveillance at the same time. The latest shipborne surveillance and tracking radars, and some land-based systems, are designed to allocate the threat priority to incoming targets and guide weapons against them on this basis. Many radars are specifically designed for fire-control of missiles and guns, and also for use in missile guidance and homing systems, which entails packing the system into a very small space. In the airborne role, systems have to be packaged into a relatively small space with units sometimes scattered around the airborne vehicle.

Radars have seen significant use in the Earth exploration-satellite service (EESS) especially with the deployment of airborne and spaceborne synthetic aperture radars (SAR's). Significant contributions in the areas of Earth observations, assisting in natural resource monitoring, hazard monitoring, and other global benefits can be attributed in part to the use of radars. The general categories of the active spaceborne sensors used in the EESS include SAR's, altimeters, scatterometers, precipitation, and cloud profile radars.

RADAR PROPAGATION LIMITATIONS

There are numerous radio frequency bands allocated to support radar operations in the United States. TABLE 1 below presents the broad categories of the radio frequency spectrum and why geophysical and mechanical limitations make one region of the spectrum more attractive for a particular radar application. These limitations are some of the reasons why operational compromises are necessary for today's multi-role, multi-function radars.

GENERAL APPLICATIONS–FEDERAL GOVERNMENT RADARS

Over the years, radar has been used for many and varied military and non-military purposes. Most Federal Government radars are functionally classified as either surveillance or tracking radars, or some combination of the two. A surveillance radar is designed to continuously search for and detect new targets. The basic surveillance radar function has a 2–dimensional (2–D) plot showing the target object position in degrees from North (azimuth) and range (distance) from the radar. Radars that can determine azimuth, distance, and elevation are called 3–dimensional (3–D) radars. A tracking radar calculates a path for individual targets by using radar return echoes from one scan to the next, and are usually 3–D radars. Radars that perform both surveillance and tracking are loosely called multi-mode radars. A sampling of some of the more significant Federal Government radar applications are described as follows:

Air Traffic Control

Radar is an important tool in the safe and efficient management of the U.S. national airspace system (NAS) which is the largest, busiest, most complex, and technologically advanced aviation operation in the world. Safe and efficient air travel involves radars for short-range surveillance of air traffic and weather in the vicinity of airports, the long-range surveillance and tracking of aircraft and weather on routes between airports, and the surveillance of aircraft and ground vehicles on the airport surface and runways.

Aeronautical Radionavigation

Radar is employed by many of today's pilots to assist in aircraft navigation. For instance, the aircraft height above ground is determined by radar altimeters that assist in safe and efficient flight. Airborne Doppler navigation radars measure the vector velocity of the aircraft and determines the distance traveled. Weather avoidance radars identify dangerous weather phenomena and assist the pilot to avoid them. Some military pilots, who train at low altitudes, use terrain-following and terrain-avoidance radars that allow the pilot to closely fly over the ground and fly over or around other obstacles in its path.

TABLE 1
Frequency Bands and Radar Operational«Propagation Limitations

LF 30–300 kHz	Allocations are provided in the frequency range but no radar usage or applications have been identified.
MF 300–3000 kHz	Used by continuous wave (CW) radar systems for accurate position location. Very high noise levels are characteristic of this band.
HF 3–30 MHz	Refractive properties of the ionosphere make frequencies in this band attractive for long-range radar observations of areas such as over oceans at ranges of approximately 500–2000 nautical miles. Only a few radar applications occur in this frequency range because its limitations frequently outweigh its advantages: very large system antennas are needed, available bandwidths are narrow, the spectrum is extremely congested with other users, and the external noise (both natural noise and noise due to other transmitters) is high.
VHF 30–300 MHz	For reasons similar to those cited above, this frequency band is not too popular for radar. However, long-range surveillance radars for either aircraft or satellite detection can be built in the VHF band more economically than at higher frequencies. Radar operations at such frequencies are not affected by rain clutter, but auroras and meteors produce large echoes that can interfere with target detection. There have not been many applications of radar in this frequency range because its limitations frequently outweigh its advantages.
UHF 300–3000 MHz	Larger antennas are required at the lower end than at the upper end of the UHF band. As compared to the above bands, obtaining larger bandwidths is less difficult, and external natural noise and weather effects are much less of a problem. At the lower end, long-range surveillance of aircraft, spacecraft, and ballistic missiles is particularly useful. The middle range of this band is used by airborne and spaceborne SAR's. The higher UHF end is well suited for short to medium-range surveillance radars.
SHF 3 GHz–30 GHz	Smaller antennas are generally used in this band than in the above bands. Because of the effects of atmospheric absorption, the lower SHF band is better for medium-range surveillance than the upper portions. This frequency band is better suited than the lower bands for recognition of individual targets and their attributes. In this band, Earth observation efforts employ radars such as SAR's, altimeters, scatterometers, and precipitation radars .
EHF 30–300 GHz	It is difficult to generate high power in this band. Rain clutter and atmospheric attenuation are the main factors in not using this frequency band. However, Earth observation efforts are made in this band employing radars such as altimeters, scatterometers, and cloud profile radars.

Ship Safety

U.S. Navy and U.S. Coast Guard (USCG) ships employ maritime navigation radars to assist in avoiding collisions, assisting in making landfall, and piloting in restricted waters. Radars are also used on shore for harbor surveillance supporting the vessel traffic system (VTS).

Space

NASA astronauts first used and continue to use spaceborne radars to assist in the rendezvous of their spacecraft with other spacecraft or space objects, as well as with the docking and landing of spacecraft. Spaceborne radars have also been used for altimetry, ocean observation, remote sensing, mapping, navigation, and weather forecasting.

Law Enforcement

The familiar police speed-gun radars are a well-known application of radar for law enforcement. Radars are also used by many Federal agencies for intrusion detection systems in various protected areas. Lately, land-based, airborne, and shipborne radars are being employed in Federal law enforcement efforts.

Environmental Monitoring

Radar is an important application for several Federal agencies involved in making weather observations, conducting geological surveys, and making Earth observations. In the meteorological aids service, radars are employed to detect precipitation, wind speeds, wind shear at airports, forming tornadoes, and hurricanes. Radars have been used in space to assist in weather forecasting (hurricanes, tropical storms, etc.), measure ocean characteristics and mineral resources on Earth. Finally, scientists are employing radars to help monitor bird migrations as well as insect migrations and their flight characteristics.

Instrumentation

Radar is used extensively by various Federal agencies on test ranges to track aircraft, unmanned aircraft, spacecraft, and missiles to measure and determining quantitatively the actions that take place during test flights. Federal geologists and surveyors use radar devices for precise position measurements associated with geological and water/shoreline boundary surveys.

National Defense

Radar originally was developed to meet the needs of the military services, and it continues to have critical applications for national defense purposes. For instance, radars are used to detect aircraft, missiles, artillery and mortar projectiles, ships, land vehicles, and satellites. In addition, radar controls and guides weapons; allows one class of target to be distinguished from another; aids in the navigation of aircraft and ships; and assists in reconnaissance and damage assessment.

Military radar systems can be divided into three main classes based on platform: land-based, shipborne, and airborne. Within these broad classes, there are several other categories based mainly on the operational use of the radar system. For the purposes of this report, the categories of military radars will be as described below, although there are some "gray" areas where some systems tend to cover more than one category. There is also a trend to develop multimode radar systems. In these cases, the radar category is based on the primary use of the radar.

Land-Based Air Defense Radars. These radars cover all fixed, mobile, and transportable 2–D and 3–D systems used in the air defense mission.

Battlefield, Missile Control, and Ground Surveillance Radars. These radars also include battlefield surveillance, tracking, fire-control, and weapons-locating radar systems, whether fixed, mobile, transportable, or man-portable.

Naval and Coastal Surveillance, and Navigation Radars. These radars consist of shipborne surface search and air search radars (2–D and 3–D) as well as land-based coastal surveillance radars.

Naval Fire-Control Radars. These are shipborne radars that are part of a radar-based fire-control and weapons guidance systems.

Airborne Surveillance Radars. These radar systems are designed for early warning, land and maritime surveillance, whether for fixed-wing aircraft, helicopters, or remotely piloted vehicles (RPV's).

Airborne Fire-Control Radars. Includes those airborne radar systems for weapons fire-control (missiles or guns) and weapons aiming.

Spaceborne Radar Systems. Considerable effort has been applied to spaceborne radar (SBR) research for intelligence, surveillance, and reconnaissance missions over the last 30 years. The Department of Defense (DOD) seems to be expressing new interest in SBR.

Military Air Traffic Control (ATC), Instrumentation and Ranging Radars. These include both land-based and shipborne ATC radar systems used for assisting aircraft landing, and supporting test and evaluation activities on test ranges. See Appendix B for descriptions of shipborne ATC radars.

TYPES OF RADARS

Some of the more prominent types of radars used by Federal agencies are described below. These descriptions are not precise, for each of these radar types usually employ a characteristic waveform and signal processing that differentiate it from other radars.

Simple Pulse Radar: This type is the most typical radar with a waveform consisting of repetitive short-duration pulses. Typical examples are long-range air and maritime surveillance radars, test range radars, and weather radars. There are two types of pulse radars that uses the Doppler frequency shift of the received signal to detect moving targets, such as aircraft, and to reject the large unwanted echoes from stationary clutter that do not have a Doppler shift. One is called moving-target indication (MTI) radar and the other is called pulse Doppler radar. Users of pulse radars include the Army, Navy, Air Force, FAA, USCG, NASA, Department of Commerce (DOC), Department of Energy (DOE), U.S. Department of Agriculture (USDA), Department of the Interior (DOI), National Science Foundation (NSF), and Department of Treasury.

Moving-Target Indication (MTI) Radar: By sensing Doppler frequencies, an MTI radar can differentiate echoes of a moving target from stationary objects and clutter, and reject the clutter. Its waveform is a train of pulses with a low PRR to avoid range ambiguities. What this means is that range measurement at the low PRR is good while speed measurement is less accurate than at a high PRR's. Almost all ground-based aircraft search and surveillance radar systems use some form of MTI. The Army, Navy, Air Force, FAA, USCG, NASA, and DOC are large users of MTI radars.

Airborne Moving-Target Indication (AMTI) Radar: An MTI radar in an aircraft encounters problems not found in a ground-based system of the same kind because the large undesired clutter echoes from the ground and the sea have a Doppler frequency shift introduced by the motion of the aircraft carrying the radar. The AMTI radar, however, compensates for the Doppler frequency shift of the clutter, making it possible to detect moving targets even though the radar unit itself is in motion. AMTI radars are primarily used by the Army, Navy, Air Force, and the USCG.

Pulse Doppler Radar: As with the MTI system, the pulse Doppler radar is a type of pulse radar that utilizes the Doppler frequency shift of the echo signal to reject clutter and detect moving aircraft. However, it operates with a much higher PRR than the MTI radar. (A high-PRR pulse Doppler radar, for example, might have a PRR of 100 kHz, as compared to an MTI radar with PRR of perhaps 300 Hz) The difference of PRR's gives rise to distinctly different behavior. The MTI radar uses a low PRR in order to obtain an unambiguous range measurement. This causes the measurement of the target's radial velocity (as derived from the Doppler frequency shift) to be highly ambiguous and can result in missing some target detections. On the other hand, the pulse Doppler radar operates with a high PRR so as to have no ambiguities in the measurement of radial velocity. A high PRR, however, causes a highly ambiguous range measurement. The true range is resolved by transmitting multiple waveforms with different PRR's.[3] Pulse Doppler radars are used by the Army, Navy, Air Force, FAA, USCG, NASA, and DOC.

High-Range Resolution Radar: This is a pulse-type radar that uses very short pulses to obtain range resolution of a target the size ranging from less than a meter to several meters across. It is used to detect a fixed or stationary target in the clutter and for recognizing one type of target from another and works best at short ranges. The Army, Navy, Air Force, NASA, and DOE are users of high-range resolution radars.

Pulse-Compression Radar: This radar is similar to a high-range resolution radar but overcomes peak power and long-range limitations by obtaining the resolution of a short pulse but with the energy of a long pulse. It does this by modulating either the frequency or the phase of a long, high-energy pulse. The frequency or phase modulation allows the long pulse to be compressed in the receiver by an amount equal to the reciprocal of the signal bandwidth. The Army, Navy, Air Force, NASA, and DOE are users of pulse-compression radars.

Synthetic Aperture Radar (SAR): This radar is employed on an aircraft or satellite and generally its antenna beam is oriented perpendicular to its direction of travel. The SAR achieves high resolution in angle (cross range) by storing the sequentially received signals in memory over a period of time and then adding them as if they were from a large array antenna. The output is a high-resolution image of a scene. The Army, Navy, Air Force, NASA, and NOAA are primary users of SAR radars.

Inverse Synthetic Aperture Radar (ISAR): In many respects, an ISAR is similar to SAR, except that it obtains cross-range resolution by using Doppler frequency shift that results from target movements relative to the radar. It is usually used to obtain an image of a target. ISAR radars are used primarily by the Army, Navy, Air Force, and NASA.

Side-Looking Airborne Radar (SLAR): This variety of airborne radar employs a large side-looking antenna (i.e., one whose beam is perpendicular to the aircraft's line of flight) and is capable of high-range resolution. (The resolution in cross range is not as good as can be obtained with SAR, but it is simpler than the latter and is acceptable for some applications.) SLAR generates map-like images of the ground and permits detection of ground targets. This radar is used primarily by the Army, Navy, Air Force, NASA, and the USCG.

Imaging Radar: Synthetic aperture, inverse synthetic aperture, and side-looking airborne radar techniques are sometimes referred to as imaging radars. The Army, Navy, Air Force, and NASA are the primary users of imaging radars.

Tracking Radar: This kind of radar continuously follows a single target in angle (azimuth and elevation) and range to determine its path or trajectory, and to predict its future position. The single-target tracking radar provides target location almost continuously. A typical tracking radar might measure the target location at a rate of 10 times per second. Range instrumentation radars are typical tracking radars. Military tracking radars employ sophisticated signal processing to estimate target size or identify specific characteristics before a weapon system is activated against them. These radars are sometimes referred to as fire-control radars. Tracking radars are primarily used by the Army, Navy, Air Force, NASA, and DOE.

Track-While-Scan (TWS) Radar: There are two different TWS radars. One is more or less the conventional air surveillance radar with a mechanically rotating antenna. Target tracking is done from observations made from one rotation to another. The other TWS radar is a radar whose antenna rapidly scans a small angular sector to extract the angular location of a target. The Army, Navy, Air Force, NASA, and FAA are primary user of TWS radars.

3–D Radar: Conventional air surveillance radar measures the location of a target in two dimensions–range and azimuth. The elevation angle, from which target height can be derived, also can be determined. The so-called 3–D radar is an air surveillance radar that measures range in a conventional manner but that has an antenna which is mechanically or electronically rotated about a vertical axis to obtain the azimuth angle of a target and which has either fixed multiple beams in elevation or a scanned pencil beam to measure its elevation angle. There are other types of radar (such as electronically scanned phased arrays and tracking radars) that measure the target location in three dimensions, but a radar that is properly called 3–D is an air surveillance system that measures the azimuth and elevation angles as just described. The use of 3–D radars is primarily by the Army, Navy, Air Force, NASA, FAA, USCG, and DOE.

Electronically Scanned Phased-Array Radar: An electronically scanned phased-array antenna can position its beam rapidly from one direction to another without mechanical movement of large antenna structures. Agile, rapid beam switching permits the radar to track many targets simultaneously and to perform other functions as required. The Army, Navy, and Air Force are the primary users of electronically scanned phased-array radars.

Continuous-Wave (CW) Radar: Since a CW radar transmits and receives at the same time, it must depend on the Doppler frequency shift produced by a moving target to separate the weak echo signal from the strong transmitted signal. A simple CW radar can detect targets, measure their radial velocity (from the Doppler frequency shift), and determine the direction of arrival of the received signal. However, a more complicated waveform is required for finding the range of the target. Almost all Federal agencies used some type of CW radar for applications ranging from target tracking to weapons fire-control to vehicle-speed detection.

Frequency-modulated Continuous-wave (FM-CW) Radar: If the frequency of a CW radar is continually changed with time, the frequency of the echo signal will differ from that transmitted and the difference will be proportional to the range of the target. Accordingly, measuring the difference between the transmitted and received frequencies gives the range to the target. In such a frequency-modulated continuous-wave radar, the frequency is generally changed in a linear fashion, so that there is an up-and-down alternation in frequency. The most common form of FM-CW radar is the radar altimeter used on aircraft or a satellite to determine their height above the surface of the Earth. Phase modulation, rather than frequency modulation, of the CW signal has also been used to obtain range measurement. The primary users of these radars are the Army, Navy, Air Force, NASA, and USCG.

High Frequency Over-the-Horizon (HF OTH) Radar: This radar operates in the high frequency (HF) portion of the electromagnetic spectrum (3–30 MHz) to take advantage of the refraction of radio waves by the ionosphere that allows OTH ranges of up to approximately 2,000 nautical miles. HF OTH can detect aircraft, ballistic missiles, ships, and ocean-wave effects. The Navy and Air Force use HF OTH radars.

Scatterometer: This radar is employed on an aircraft or satellite and generally its antenna beam is oriented at various aspects to the sides of its track vertically beneath it. The scatterometer uses the measurement of the return echo power variation with aspect angle to determine the wind direction and speed of the Earth's ocean surfaces.

Precipitation Radar: This radar is employed on an aircraft or satellite and generally its antenna beam is scanning at an angle optimum to its flight path to measure radar returns from rainfall to determine rainfall rate.

Cloud Profile Radar: Usually employed aboard an aircraft or satellite. The radar beam is oriented at nadir measuring the radar returns from clouds to determine the cloud reflectivity profile over the Earth's surface.

Enhanced«Synthetic Vision Radars. These radars are under development for aviation use and will provide computer-generated visual scenes during approaches and landings. Radars operating at 34.7–35.2 and 92–100 GHz ranges will be used to provide the pilot with high-resolution video displays of the terrain and environment during low visibility conditions. The NASA, FAA, and DOD are involved in these efforts.

Endnotes: Chapter 1

1. In spectrum management, the term *radiodetermination* is defined as: “The determination of the position, velocity and/or other characteristics of an object, or the obtaining of information relating to these parameters, by means of the propagation properties of radio waves.” Later in this report, the two sub-categories of radiodetermination, radiolocation and radionavigation, are discussed.

2. In the case of a radar in the meteorological aids service, the “object” may be rain, inhomogeneities in the atmosphere, etc.

3. A modified form of pulse Doppler radar that operates at a lower PRR (10 kHz, for example) than the above-mentioned high-PRR pulse Doppler system has both range and Doppler shift ambiguities. It is, however, better for detecting aircraft with low closing speeds than high-PRR pulse Doppler radar (which is better for detecting aircraft with high closing speeds). An airborne medium-PRR pulse Doppler radar might have to use seven or eight different PRR’s in order to extract the target information without ambiguities.

Chapter 2

RADARS AND SPECTRUM MANAGEMENT

INTRODUCTION

Spectrum management is a combination of administrative and technical procedures which are necessary to ensure the efficient operation of radio communications, taking into account legal, economic, engineering, and scientific aspects for the use of the radio frequency spectrum. Current spectrum management policies are under increasing strain as the public's demand for wireless services grows, and new spectrum-related technologies and applications emerge. In the United States, NTIA is responsible for managing the Federal Government's use of the radio spectrum. Management of the spectrum for the private sector, including State and local governments, is the responsibility of the Federal Communications Commission (FCC).

SPECTRUM CERTIFICATION OF FEDERAL RADAR SYSTEMS

NTIA's authority in spectrum management is extensive. The National Telecommunications and Information Administration Act [1] and the Office of Management and Budget (OMB) Circular No. A-11 provide NTIA with the authority to assign frequencies and approve the spectrum use of new systems. Federal users must obtain frequency assignments before they can operate transmitters. OMB Circular No. A–11 requires that Federal users obtain certification of spectrum support from NTIA (certification that new radiocommunication systems are expected to be able to operate compatibly with existing and planned stations) before developing and procuring major systems. Spectrum certification is especially important for radar systems because of their long lead times and large system costs.

In the Federal Government, the identification of spectrum requirements, including radar systems, occurs primarily through two ongoing, but separate, processes at NTIA—the systems review and frequency assignment processes. Two standing subcommittees of the Interdepartment Radio Advisory Committee (IRAC), the Spectrum Planning Subcommittee (SPS) and the Frequency Assignment Subcommittee (FAS), support this effort. Systems review and frequency assignment information is supplemented through NTIA spectrum resource assessments, spectrum occupancy measurements, and preparations for international radio conferences. The collective information available from these sources portray short- and mid-term Federal spectrum requirements.

The systems review process exists to satisfy the spectrum certification requirements of OMB Circular No. A–11.[2] The systems reviewed are "major" systems (including all space radiocommunications systems). A system is considered "major" if it will have a significant impact on existing or potential future use of the portion of the spectrum in which it is intended to operate. The systems review identifies the level of conformity of the system to the spectrum standards and to the U.S. National Table of Frequency Allocations. Systems that do not conform, but are otherwise compatible with existing uses, are generally approved on a secondary or noninterference basis to other systems, current or future, that do conform. Systems that have potential for interference, but are essential for national defense, are reviewed with regard to the coordination and conditions required to allow operation in the United States.

Approximately 36 radar systems are currently under systems review within the SPS. Of the 36 radar systems, the Departments of the Army, Navy, and Air Force have 14, 11, and 8, respectively. The National Aeronautics and Space Administration, Department of Commerce, and Department of Energy each have one. While there has been a trend for radar systems to move into higher frequency bands, it is interesting to note that there are a few radar systems operating in or through the HF and very high frequency (VHF) bands.

FREQUENCY ALLOCATION OVERVIEW

Under current regulations, before spectrum can be used, it must first be *allocated* for a particular use. These regulations are either the FCC's regulations contained in Title 47 of the Code of Federal Regulations, or the regulations governing Federal use of the spectrum contained in the Manual of Regulations and Procedures for Federal Radio Frequency Management (*NTIA Manual*).[3] At the present time, the radio frequency spectrum in the United States from 9 kHz to 300 GHz is completely allocated to one or more radio services.

As a basic plan for usage, the radio spectrum is allocated to various radio services in blocks of frequencies. The concept of the block allocation system provides for a band of contiguous frequencies dedicated to one or more radio services, depending on the technical and operational characteristics of the service(s). A block so dedicated is said to be allocated to the radio service(s) associated with that block. Further, within a block, the radio services may have a hierarchical structure that grants rights or imposes limitations on the services relative to other services in the same block.[4] Footnotes to the allocation table draw attention to the use of a specific band by providing for an additional allocation, alternative allocation, or a different category of service. Within the United States, the compilation of these spectrum blocks, along with associated footnotes, is called the *U.S. National Table of Frequency Allocations*,[5] and is used for general spectrum planning. The table also further separates those allocation blocks that are managed by NTIA from those managed by the FCC.[6] For the allocation of frequencies internationally, the world has been divided into three regions as contained in the *International Telecommunication Union (ITU) Table of Frequency Allocations* of Article 8 of the ITU Radio Regulations. The United States is within Region 2 as shown in the figure below.

There is, however, considerable flexibility in the block allocation system. Footnotes to the allocation blocks may permit operation of additional radio services in the spectrum block, restrict the operation of services allocated in the block, specify or clarify the relative status of services in a block, or stipulate other requirements for operation. Other footnotes may permit multi-mode operation, where the transmitted signal is used for more than one purpose, and would otherwise be separate radio services.

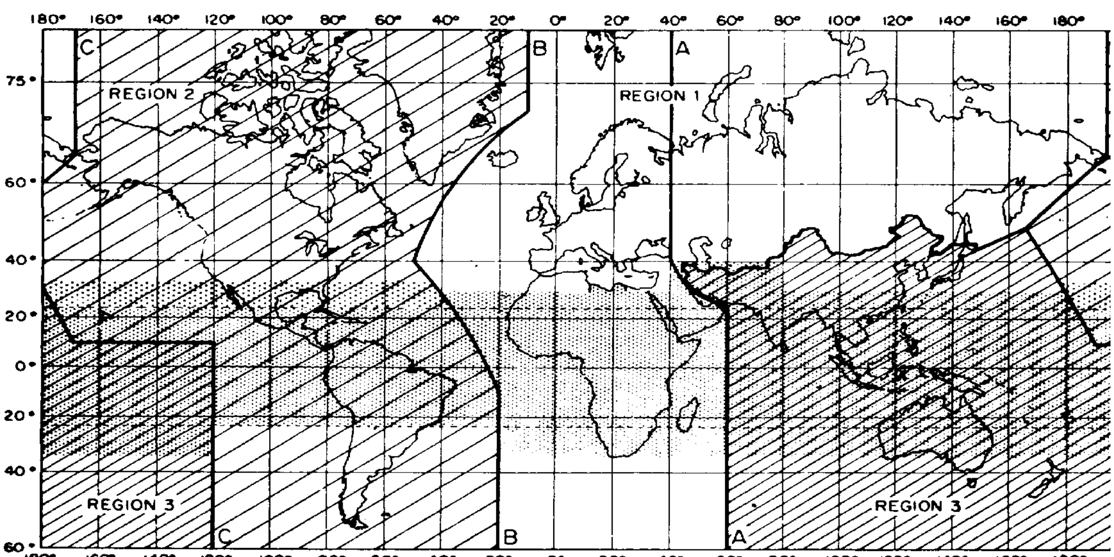

Figure 2–1. Chart of ITU Regions.

RADIO SERVICES SUPPORTING RADARS

Radars typically operate in radio frequency bands of the electromagnetic spectrum that are allocated for the radiodetermination, Earth exploration-satellite, and the meteorological aids radio services. Since radars became operational over 60 years ago, the need for management of spectrum for their use became apparent and scores of frequency bands have been allocated for their use. These allocations are contained in the U.S. National Table of Frequency Allocations.

In spectrum management, the term *radiodetermination* is defined as: "The determination of the position, velocity and/or other characteristics of an object, or the obtaining of information relating to these parameters, by means of the propagation properties of radio waves." In the U.S. National Table of Frequency Allocations, no allocation is listed for the radiodetermination service *per se* because, in practice, radiodetermination operations are allocated either as the radionavigation service or the radiolocation service, with the radionavigation service also subdivided as aeronautical radionavigation service and maritime radionavigation service.

These radio services are just part of the 34 radio services defined in the NTIA Manual.[7] These six radio services are defined below and are treated as distinct radio services in subsequent sections of this report when considering radar.

a. The radionavigation service is defined as "radiodetermination used for the purpose of navigation, including obstruction warning."[8] The radionavigation service is unique in that it is referred to as a safety service—any radiocommunication service that is used permanently or temporarily in the safeguarding of human life and property.[9]

(1) A subset of the radionavigation service intended for the benefit and for the safe operation of aircraft is defined as the aeronautical radionavigation service[10] and is considered a safety service.

(2) The maritime radionavigation service is a subset of the radionavigation service intended for the benefit and for the safe operation of ships[11] and is also considered a safety service.

b. The radiolocation service is defined as "a radiodetermination service used for the purposes other than those of radionavigation."[12]

c. The meteorological aids service is a radiocommunication service used for meteorological, including hydrological, observations and exploration.[13]

d. The Earth exploration-satellite service is a radiocommunications service between earth stations and one or more space stations, which may include one or more space stations, in which:

(1) Similar information is collected from airborne or earth-based platforms;

(2) Such information may be distributed to earth stations within the system concerned;

(3) Platform interrogation may be included.

This service may also include feeder links necessary for its operation.[14]

Radar Trends: Frequency and Power

Since radars were first developed, it appears that the frequency and power requirements of many radars have been increasing. This may have been the result of users' radar search requirements as well as advancing technology to support greater surveillance distances, placing radars on shipborne and airborne platforms, and accommodating the shrinking available platform space. The following chart shows that radar frequency usage had already expanded by 1960 to the full spectrum available for practical use.[15]

The trends in radar power are similar to those of frequency. By 1960, both peak and average power had reached levels about as high as those used in today's high-power radars.

Frequency Bands Supporting Radar Allocations

Frequency bands that provide the greatest protection for radars are those that have a primary allocation and where radars in that radio service share with no other primary users. Next in the level of protection are the bands that are allocated on a primary basis but share this status with one or more radio services. Less protection is afforded where bands are allocated to the radiolocation, radionavigation, Earth exploration-satellite , or meteorological aids radio services on a secondary basis to other radio services. The frequency bands that support radar operations in the radiolocation, radionavigation aeronautical radionavigation, maritime radionavigation, Earth exploration-satellite, and meteorological aids radio services shown in the U.S. National Table of Frequency Allocations are listed in TABLE 2 below.

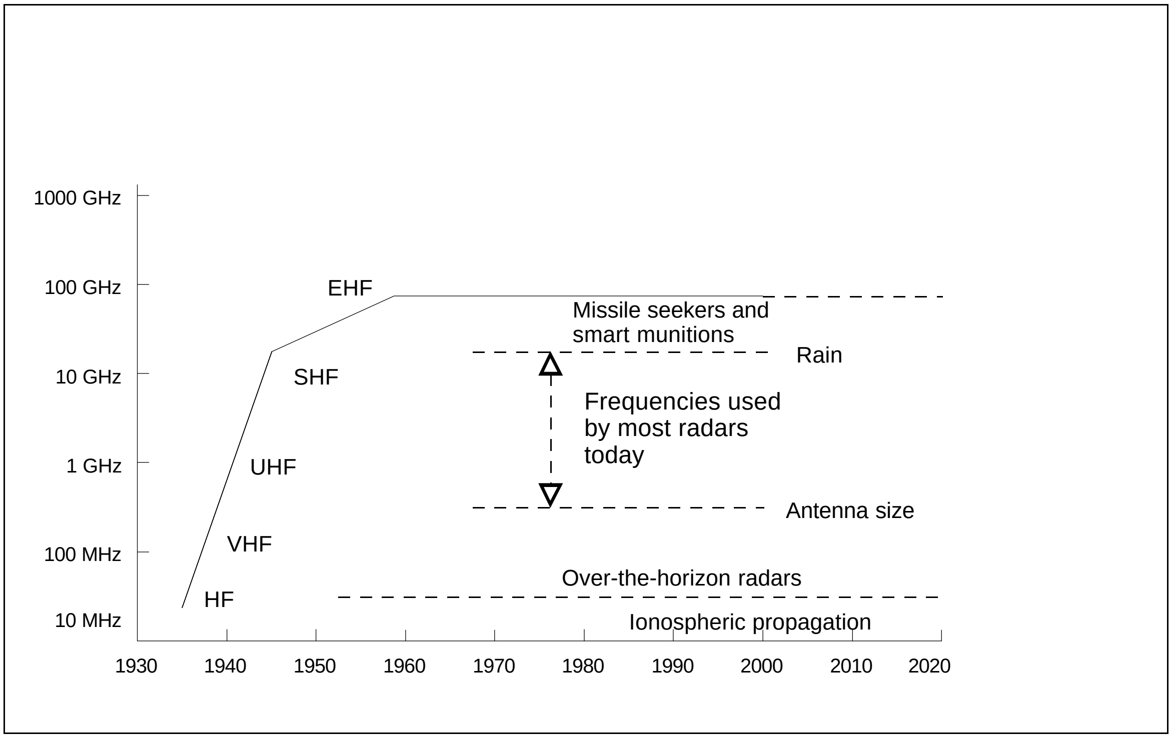

Figure 2-2. Radar Frequency Usage

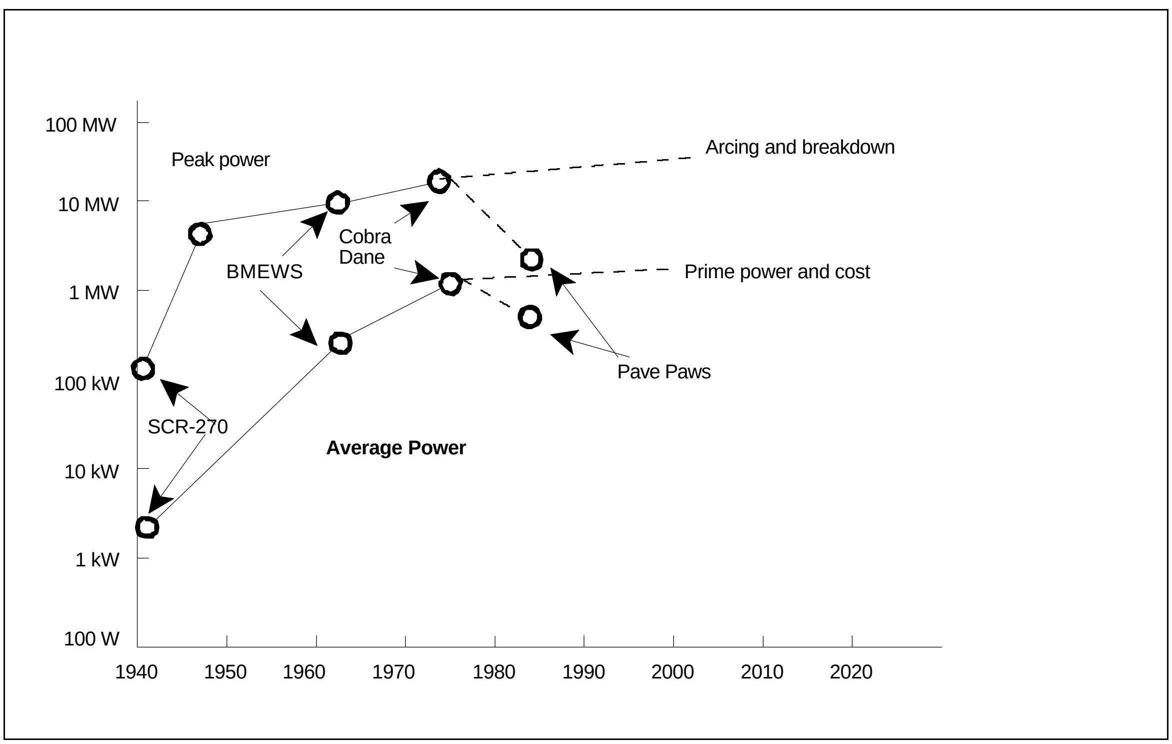

Figure 2-3. Radar Transmitter Power.

TABLE 2
U.S. Radar Operating Bands, Radio Services, and Allocation Status

Frequency Band (MHz)	Radiolocation		Radionavigation		Aeronautical Radionavigation		Maritime Radionavigation		Meteorological Aids		Earth Exploration-Satellite	
216–225 [1]	Sec											
420–450	Pri											
890–902	NIB											
902–928	Pri											
928–942	NIB											
1215–1240 [2]	Pri										Pri	Pri
1240–1300 [2]	Pri				Pri	Pri					Pri	Pri
1300–1350	Sec											
1350–1370	Pri				Pri	Pri						
1370–1390	Pri											
2310–2320	Sec	Pri										
2320–2345	Pri	Pri										
2345–2360	Sec	Pri										
2360–2390 [3]	Pri											
2390–2417	NIB											
2417–2450	Sec											
2450–2483.5	Sec	Sec										
2483.5–2500	Sec											
2700–2900	Sec				Pri	Pri			Pri			
2900–3000	Sec						Pri	Pri	Pri			
3000–3100	Sec						Pri	Pri				
3100–3300 [2]	Pri	Sec									Sec	Sec
3300–3500	Pri	Sec										
3500–3650 [4]	Pri	Sec			Pri							
4200–4400					Pri	Pri						
5250–5350 [2]	Pri	Sec									Pri	Pri
5350–5460 [2]	Pri	Sec			Pri	Pri					Pri	Pri
5460–5470	Sec	Sec	Pri	Pri								
5470–5600	Sec	Sec					Pri	Pri				
5600–5650	Sec	Sec					Pri	Pri	Pri	Pri		
5650–5925	Pri											
8500–8550	Pri	Sec										
8550–8650 [2]	Pri	Sec									Pri	Pri
8650–8750	Pri	Sec										
8750–8850	Pri	Sec			Sec	Sec						
8850–9000	Pri	Sec										
9000–9200	Sec	Sec			Pri	Pri						

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Frequency Band (MHz)	Radiolocation		Radionavigation		Aeronautical Radionavigation		Maritime Radionavigation		Meteorological Aids		Earth Exploration-Satellite	
9200–9300	Sec	Sec					Pri	Pri				
9300–9500	Sec	Sec	Pri	Pri					Sec	Sec		
9500–9800 [2]	Pri	Sec									Pri	Pri
9800–9975	Pri	Sec										
9975–10025	Pri	Sec									Sec	Sec
10025–10500	Pri	Sec										
10500–10550	Pri	Pri										
13250–13400 [2]					Pri	Pri					Pri	Pri
13400–13750 [2]	Pri	Sec									Pri	Pri
13750–14000	Pri	Sec										
14000–14200			Pri	Pri								
15400–15700					Pri	Pri						
15700–17200	Pri	Sec										
17200–17300 [2]	Pri	Sec									Pri	Pri
17300–17700	Sec											
24050–24250	Pri	Sec									Sec	Sec
24250–24450				Pri								
24450–24650			Pri	Pri								
24750–25050			Pri	Pri								
25050–25250				Pri								
31800–33400			Pri	Pri								
33400–35500	Pri	Sec										
35500–36000 [2]	Pri	Sec									Pri	Pri
59000–64000	Pri	Pri										
66000–71000			Pri	Pri								
76000–77000	Pri	Pri										
77000–78000	Pri	Pri										
78000–79000	Pri	Pri									Pri	Pri
79000–81000	Pri	Pri										
92000–94000	Pri	Pri										
94000–94100 [2]	Pri	Pri									Pri	Pri
94100–95000	Pri	Pri										
95000–100000	Sec		Pri	Pri								
126000–134000	Pri	Pri										
134000–142000	Sec	Sec	Pri	Pri								
144000–149000	Pri	Pri										
190000–200000			Pri	Pri								

TABLE 2
U.S. Radar Operating Bands, Radio Services, and Allocation Status

Frequency Band (MHz)	Radiolocation		Radionavigation		Aeronautical Radionavigation		Maritime Radionavigation		Meteorological Aids		Earth Exploration-Satellite	
231000–235000	Sec	Sec										
238000–241000	Sec	Sec										
241000–248000	Pri	Pri										
252000–265000			Pri	Pri								

Notes:
1. This band is used for a DOD space surveillance radar system. Under BBA–97, this band was identified for reallocation on January 2002. The space surveillance radar located at three transmitter sites and six receiver sites will be protected indefinitely. *See* National Telecommunications and Information Administration, U.S. Department of Commerce, Special Report 98-36, Spectrum Reallocation Report, Response to Title III of the Balanced Budget Act of 1997, (Feb. 97) at iv-v.
2. Allocation for EESS is pending implementation of World Radio Conference 97 changes.
3. The 2385–2390 MHz portion of this band is identified for reallocation on January 2005.
4. Prior to OBRA–93, 3100–3700 MHz was allocated to the radiolocation service on a primary basis. The 3650–3700 MHz portion was identified for reallocation on Jan 1999. Three essential military radar operations will be continued at three sites. See National Telecommunications and Information Administration, U.S. Department of Commerce, NTIA Special Publication 95-23, Spectrum Reallocation Final report (Feb. 1995), at 4-16 to 4-4-21.

EROSION OF RADIOLOCATION SPECTRUM AVAILABILITY

Spectrum is allocated internationally as a result of international radio conferences held under the auspices of the International Telecommunication Union (ITU). The World Radiocommunication Conferences (WRC's) determine the spectrum allocation to radio services for the three ITU Regions.[16] Many administrations use the international Table of Frequency Allocations as a template for their national frequency allocation tables. For this reason, decisions made at international conferences have a profound effect on worldwide use of specific frequency bands. Many administrations do not have the heavy operational use of radiolocation as the United States, and the potential for commercial use of radiolocation bands creates a pressure to reallocate radiolocation bands to other services. Although the United States has not always followed the ITU allocations when establishing domestic allocations to allow for operation of high-priority systems, a lack of worldwide allocations make it difficult to operate some military systems globally without individual coordination with host countries.

International Changes

Changes to approximately 3.64 GHz of internationally allocated spectrum supporting radar operations in Region 2 have been effected at three WRC's and are described below:

WARC–79

The World Administrative Radio Conference held in 1979 (WARC–79) revised the international Table of Frequency Allocations and Radio Regulations that affected radar operation status in frequency bands from 200 MHz to 20 GHz. Although the United States may not have implemented all of the changes affecting radiolocation, the following summarizes allocation changes totaling 856 MHz in the Region 2:[17]

a. In the 216–225 MHz band, the primary status of the radiolocation service ceased after January 1, 1990 and after this date, no new radiolocation stations could be authorized, and any existing radiolocation devices were afforded secondary status.[18]

b. In the 420–450 MHz band, radiolocation was downgraded from primary to secondary status in 20 MHz. The 20 MHz includes the 420–430 MHz and 440–450 MHz bands.[19]

c. In the 890–942 MHz, 3400–3700 MHz, 5850–5925 MHz, and 17.3–17.7 GHz bands, radiolocation was downgraded from primary to secondary status.[20]

WARC–92

Reallocations at WARC–92 affected the radiolocation service in two bands: 13.75–14.0 GHz and 17.3–17.8

GHz. Taking into account WARC–79 changes, an additional 350 MHz of spectrum allocation changes affecting radiolocation was made at this WARC. Prior to WARC-92, the radiolocation service enjoyed exclusive primary status in the 13.75–14.0 GHz band. The reallocation at WARC-92 added the fixed-satellite service as co-primary with the radiolocation service. In the 17.3–17.8 GHz band, where the radiolocation service had worldwide secondary status to the fixed satellite service (Earth-to-space), the broadcast satellite service (BSS) allocation was added with a primary status. The BSS allocation is scheduled to be in effect on April 1, 2007.[21]

WRC–97

The WRC–97 affected the radiolocation and radionavigation services in 2,435 MHz of spectrum allocations. In the United States, the radiolocation service was affected by upgrading the secondary allocation of radio services in some of its bands to primary. Either by direct table listing or by footnote, the EESS and space research (SR) services were upgraded in the following bands: 1215–1300 MHz, 3100–3300 MHz (secondary status), 5250–5460 MHz, 8550–8650 MHz, 9500–9800 MHz, 13.4–13.75 GHz, 17.2–17.3 GHz, 35.5–36 GHz, and 94–94.1 GHz. The radionavigation service allocations at 31.8–33.4 GHz were affected with the addition of the fixed service as a co-primary service.

National Changes

Even within the United States, radiolocation bands have been reduced to make room for emerging commercial services. As a result of the OBRA–93 and BBA–97, changes affecting the radiolocation and the aeronautical radionavigation services in the national table of allocations will be made in the very near future. In approximately 139 MHz of the 255 MHz of spectrum identified for reallocation, future private-sector users may be affected by adjacent-band interference from radars. The bands affected are:

a. 216–220 MHz. Prior to the BBA–97, this band was allocated to the radiolocation service on a secondary basis. This band was identified by NTIA, under the BBA–97, to be reallocated on a mixed-used basis with a scheduled availability date of January 1, 2002. The military space surveillance radar system sites will be protected indefinitely.[22]

b. 1390–1400 MHz. Prior to OBRA–93, the entire 1350–1400 MHz band was allocated to the radiolocation service on a primary basis. Under the OBRA–93, NTIA identified the 1390–1400 MHz for reallocation to the private sector on January 1, 1999.

c. 2300–2310 MHz. This band was identified by NTIA for reallocation, effective August 10, 1995, for exclusive private-sector use under OBRA–93. Any existing Federal Government operations in this band are on a non-interference basis to private-sector operations.

d. 2385–2450 MHz. Under the BBA–97, the 2385–2390 MHz radiolocation band was identified for reallocation for private-sector use effective January 2005. Under OBRA–93, the 2390–2400 MHz and 2402–2417 MHz portions of this band were identified for immediate reallocation, effective August 10, 1994, for exclusive private-sector use. The same was applied to the 2400–2402 MHz band but became effective August 10, 1995. The 2417–2450 MHz was identified for reallocation, effective August 10, 1995, for mixed government and non-government use under OBRA–93

e. 3650–3700 MHz. Prior to reallocation, the entire 3500–3700 MHz band supported radar operations to include radiolocation and aeronautical radionavigation. The 3650–3700 MHz band was identified by NTIA for reallocation, effective 1 January 1999, for mixed government and non-government use under OBRA–93.[23]

Summary of Allocation Changes Affecting Radar Operations

Since 1979, spectrum allocated for radar operations in the United States has seen some erosion of allocations whether it be from changes of its status from primary to secondary, the sharing with non-radar primary radio services, spectrum allocation transfers, or lost allocations. The total amount of spectrum affected is about 3.78 GHz and is depicted in the following table:

TABLE 3
Summary of Allocation Changes

Amount of Spectrum Affected	Action	Arena
847 MHz	Primary to Secondary Status	WARC–79 (Region 2)
9 MHz	Lost Allocation	WARC–79 (Region 2)
750 MHz	Share with New Primary Service	WARC–92 (Region 2)
2,435 MHz	Share with New Primary Service	WRC–97
139 MHz	Allocations Transferred to FCC	OBRA–93, BBA–97

Note: In WARC–92, 400 MHz of the 750 MHz indicated above was also changed at WARC–79.

SUMMARY OF RADAR OPERATIONS

3–30 MHz Band. This band, normally referred to as the high frequency (HF) band, has only a small portion allocated to the radiolocation service and with only a secondary status. Radars operate in various portions in the HF band on a non-interference basis. Typical radars in this band are referred to as over-the-horizon radars or skywave radars.

216–225 MHz Band. This band is allocated on a secondary basis to the radiolocation service and government radiolocation operation is limited to the military services. In this band, the United States operates the Navy space surveillance (SPASUR) radar as part of the North American Air Defense (NORAD) system for space detection and tracking. The SPASUR system detects and tracks satellites as they passes through its fan-shaped radar beams extending from San Diego on the west coast to Fort Stewart, Georgia on the east coast.[24]

420–450 MHz Band. In the United States, this band is allocated on a primary basis to Federal Government radiolocation service operations. Military radar support includes national air defense radar systems for surveillance of spacecraft and ballistic missiles; service-unique ground and airborne early warning radars; battlefield radar systems for search/surveillance, position location; shipborne long and medium-range air search and surveillance radars; and maritime radionavigation. Non-military radars operations support law enforcement, wind profiling, nuclear safety programs, and environmental monitoring.

890–902 MHz Band. In the United States, this band is allocated exclusively to the non-Government for fixed, mobile, land mobile, and aeronautical mobile services. However, Federal Government off-shore radiolocation operation is permitted on a non-interference basis limited to the military services. Radiolocation operation is primarily by the Navy for their shipborne radars.

902–928 MHz Band. In the United States, this band is allocated on a primary basis to Federal Government radiolocation service operations. Federal Government usage include Navy shipborne long-range air surveillance radars, vehicle tracking radars, and mobile range control radars supporting research, development, test, and evaluation (RDT&E) activities.[25]

928–942 MHz Band. In the United States, this band is allocated to the radiolocation service for Government ship stations (off-shore areas) on a non-interference basis to non-Government land mobile stations. Radiolocation operation is primarily by the Navy for their shipborne radars.

1215–1390 MHz Band. In various portions of this band, the radiolocation and aeronautical radionavigation radio services share co-primary status. Primary status for the radiolocation service is in two portions of the band, 1215–1300 MHz and 1350–1390 MHz, and is secondary in the 1300–1350 MHz portion. From 1240–1370 MHz, the aeronautical radionavigation service has primary status. The band 1390–1400 MHz was once allocated to the radiolocation service on a primary status but was identified for reallocation under OBRA–93 (1390–1400 MHz) to the private sector on January 1, 1999. The military services operate many radars in this band that perform such functions as air defense surveillance; military and national test range instrumentation radars; battlefield early warning, surveillance and tracking, man-portable search and target acquisition;

shipborne long-range air surveillance; and minimally attended radars. Non-military radars provide air route surveillance; test range safety surveillance radars; and spectral imaging radars. This band has been identified by the FAA as needed for aeronautical surveillance in the modernized air traffic control system.[26] Pending implementation of WRC–97 allocation changes, the EESS shares primary status in the 1215–1300 MHz band. NASA performs Earth observations in this band and operates spaceborne active sensors primarily SAR imaging radars.

2310–2385 MHz Band. The radiolocation service has primary status in this band except for 2320–2345 MHz, in which it is secondary. NASA operates a tri-static planetary and lunar radar in this band supporting space exploration. The National Science Foundation operates a high-power radar in its research and studies of objects beyond the moon.

2417–2500 MHz Band. The radiolocation service has secondary status in the 2417–2450 MHz portion of this band and government radiolocation operation is limited to the military services. Government radiolocation services is permitted in the remainder of the band (2450–2500 MHz) on the condition that harmful interference is not caused to non-Government services.

2700–2900 MHz Band. The aeronautical radionavigation and meteorological aids radio services share co-primary status in this band; however, the radiolocation service is secondary for government radiolocation services. The FAA and military services operate airport surveillance radars for the safe and efficient management of aircraft during approach and departures to/from airports or military airfields. Many Federal agencies operate weather radars in support of the national meteorological operations with the Next Generation Weather Radar (NEXRAD) being the most recently commissioned system. There are approximately 150 NEXRAD commissioned sites belonging to the DOC (National Weather Service), DOD (Air Force), and Department of Transportation (FAA).[27] NASA also operates a range safety surveillance radar to detect aircraft and ships during airborne test operations as well as during space launches.

2900–3100 MHz Band. The maritime radionavigation service has primary status throughout this band; however, it shares co-primary status with the meteorological aids radio service in the 2900–3000 MHz portion of the band. The meteorological aids allocation is limited to government NEXRAD systems where accommodation in the 2700–2900 MHz band is not technically practical.[28] Radiolocation services are secondary in this band. The USCG and the Navy operate numerous shipborne maritime radionavigation and search radars as well as positioning aids to radionavigation. Several NEXRAD radars are supported in this band. This band supports various military radiolocation services such as air base and tactical airfield ATC surveillance radars; medium and long-range battlefield air defense radars; and shipborne long-range air surveillance radars. Non-military radiolocation radars support such functions as atmospheric weather research and studies; marine fisheries; range safety search and surveillance; NASA ships; and law enforcement. This band has been identified by the FAA as needed for aeronautical surveillance as well as for critical aviation support services in the modernized air traffic control system.[29]

3100–3650 MHz Band. The radiolocation service has primary allocation status throughout this band for Government operations and is secondary for non-Government operations. Primary status is shared in the 3500–3650 MHz with aeronautical radionavigation service where it is primary only for Government operations. The military services have radiolocation operations throughout the band in support of air base and tactical airfield ATC search and surveillance; aircrew bombscoring; airborne search and surveillance; battlefield weapons-locating, Doppler radar; shipborne fleet air defense radar systems (search and surveillance, tracking, fire-control, etc.); aircraft carrier precision approach control; and point area defense for small surface ships and patrol craft. Other radiolocation radars support non-military functions at the many national and agency test ranges for search radars for range safety to detect unauthorized transiting aircraft and ships. Pending implementation of WRC–97 allocation changes, the EESS has secondary status in this band. NASA performs Earth observations in this band and operates spaceborne active sensors primarily SAR imaging radars

4200–4400 MHz Band. This band is allocated on a primary basis for aeronautical radionavigation where its only use in this band is for aircraft radar altimeters.

5250–5925 MHz Band. This band contains five radio service allocations supporting radars with many sharing sub-bands. The radiolocation service is primary in the sub-bands 5250–5460 MHz and 5650–5925 MHz. In the 5350–5460 MHz band, the aeronautical radionavigation service is co-primary with the radiolocation service. The radionavigation service is primary in the 5460–5470 MHz band. In the 5470–5650 MHz band, the maritime radionavigation service has primary status and is co-primary with the meteorological aids service in the 5600–5650 MHz portion. Finally, the radiolocation service is primary in the 5650–5925 MHz band and is secondary in the 5460–5650 MHz band. The military services operate numerous radars in the 5250–5925 MHz band in support of national and military test range surveillance and instrumentation operations; airborne radar transponders; battlefield missile surveillance and tracking; weather radar observations; shipborne fire-control of surface-to-air missiles; shipborne surface search radars; shipborne missile and gunfire-control radar; and navigational aids to assist in precise positioning of ships. Non-military government radar operations include support for airborne weather and navigation; missile and rocket target instrumentation radars at test sites and ranges; range safety surveillance radars; radar transponders aboard unmanned airborne vehicles; airborne radionavigation radars; nuclear incidents situations; weather phenomena research and studies; geological and water/shoreline surveys; and airport terminal Doppler weather radars. Pending implementation of WRC–97 allocation changes, the EESS shares primary status in the 5250–5460 MHz band. NASA performs Earth observations in this band and operates spaceborne active sensors such as SAR imaging radars, altimeters, and scatterometers.

8500–9000 MHz Band. The radiolocation service has primary status throughout this band for Government radiolocation services and is secondary for non-Government operations. In the sub-band 8750–8850 MHz, the aeronautical radionavigation service has secondary status. The military services operate numerous radars for such operations as airborne multimode weapons fire-control; airborne search and interception radars; mobile and portable battlefield radars for air search and surveillance; artillery, rockets, and mortar locating radars; airborne anti-submarine warfare radar; shipborne weapons fire-control radars; submarine surface navigation and search radars; and airborne maritime Doppler surveillance radars. Non-military radars are supported in this band for such search and tracking of airborne test/experimental manned and unmanned vehicles; tracking radars supporting nuclear reactor test activities and limited nuclear test band treaty; mobile meteorological radars; and land-based planetary radars. With implementation of WRC–97, the EESS will share the 8550–8650 MHz band on co-primary basis where NASA operates spaceborne active sensors consisting primarily of SAR imaging radars, altimeters, and scatterometers.

9000–9200 MHz Band. The primary radio service in this band is aeronautical radionavigation and the radiolocation service is secondary for Government operations. The users of this band are the military services in support of fixed and mobile base and airfield ATC precision approach radars (PAR); airborne search and rescue radar and law enforcement radars; airborne maritime Doppler navigation and surveillance radars. This band has been identified by the FAA to support a new, low-cost version of an airport surface detection equipment (ASDE) in the modernized air traffic control system.[30]

9200–10550 MHz Band. From 9200–9500 MHz, the maritime radionavigation service is primary from 9200–9300 MHz, radionavigation service is primary from 9300–9500 MHz, radiolocation is secondary from 9200–9500 MHz, and the meteorological aids is secondary from 9300–9500 MHz. Pending implementation of WRC–97 allocation changes, the EESS shares primary status in the 9500–9800 MHz band. NASA performs Earth observations in this band and operates spaceborne active sensors such as SAR imaging radars and plans to operate altimeters and scatterometers. NASA also operates spaceborne active sensors in the 9975–10025 MHz band and plans to operate mainly spaceborne weather radars in this band. The radiolocation service has primary status in the remainder of the band, 9500–10550 MHz. The military services are the primary Federal users of this band with operations such as bomb scoring radars; intrusion detection radars; airborne search and rescue radars; airborne multi-mode weapons fire-control radars; airborne search and interception radars; airborne weather and navigation; airborne beacon rendezvous radar; airborne terrain following and terrain avoidance radars; airborne anti-submarine warfare radars; airborne maritime surveillance radars; mapping and imaging radars; airborne side-looking surveillance radar; airborne reconnaissance and surveillance radars; mobile and portable battlefield radars for air search and surveillance; artillery-, rocket-, and mortar-locating radars; battlefield ATC ground approach control radars; microwave landing system radars; battlefield air defense weapons fire-control radar; base security and area perimeter surveillance radars; weather radars; various shipborne navigation and surveillance radars for ships/boats, aircraft, and submarine periscopes; guided missile fire-control radars; land-based harbor search radars; military and national test range instrumentation radars; and vehicle speed detection radars. Non-military use support airborne weather radars; maritime search and navigation radars; natural resource pulse radar used in the study of fire properties (wind, flame, particle velocities, etc.); entomological radar to study aerial population and flight characteristics of insects and their migration patterns; ground and airborne meteorological research radars; marine sanctuary monitoring radars; land-based radionavigation radar; range safety search, surveillance, and instrumentation radars; airborne radar beacons; cadastral and geological survey radars; atmospheric studies and wind research radars; space shuttle support ships; maritime mobile radars; and vehicle speed detection radars.

13250–14200 MHz Band. The aeronautical radionavigation service is primary in the 13250–13400 MHz portion of this band, the radiolocation service is primary in the 13400–14000 MHz portion, while the radionavigation service is primary in the remainder, 14000–14200 MHz.[31] The predominant users in this band are the military services for airborne and shipborne radars. Airborne radar applications support multimode Doppler navigation and search radars; and navigation and sea search radars. Shipborne radar applications in 13400–14400 MHz band include pulse Doppler search and acquisition radars as well as pulse Doppler weapons system control radars. Non-military applications include airborne ocean wave spectrometer radars that measure ocean surface characteristics. Pending implementation of WRC–97 allocation changes, the EESS shares primary status in the 13250–13750 MHz band. NASA performs Earth observations in this band and operates spaceborne active sensors such as altimeters, scatterometers, and precipitation radars.

15400–17700 MHz Band. The aeronautical radionavigation service is primary in the 15400–15700 MHz portion of this band while the radiolocation service has primary and secondary allocations in the 15700–17300 MHz and 17300–17700 MHz bands, respectively. Pending implementation of WRC–97 allocation changes, the EESS secondary status in the 17200–17300 MHz band will be upgraded to primary. NASA performs Earth observations in this band and operates spaceborne active sensors such as scatterometers and precipitation radars. The military services are the largest users of this band with airborne multi-mode weapons fire-control radars; airborne search and interception radars; airborne weather and navigation radars; airborne terrain following and terrain avoidance radars; battlefield weapons-locating radars; battlefield aircraft approach landing system radars; battlefield mobile and portable ground surveillance radars weapons guidance/control radars; aircraft carrier precision approach and landing system radars; shipborne weapons fire-control radars; shipborne navigational radars; and various national and military test range target tracking and instrumentation radars. Non-military radar applications in this band include microwave landing systems supporting the space shuttle; search radars supporting atmospheric research studies; airport surface detection equipment radars for the control of aircraft and ground vehicles on airport surfaces.

24050–24650 MHz Band. In this band, the sub-band 24050–24250 MHz has primary and secondary status for Government and non-government operations, respectively. In the 24050–24250 MHz band, the EESS operate spaceborne active sensors on a secondary basis. The EESS intends to operate mainly scatterometers and precipitation radars in this band. From 24250–24650 MHz, this sub-band is allocated to the non-government for radionavigation on a primary basis; however, the Government shares co-primary status at 24450–24650 MHz. The predominant Government operations in this band is for the use of vehicle speed detection radars in 24050–24250 MHz. The 24250–24450 MHz band was reallocated on May 1997 (FCC 97-95) by the FCC to the fixed service to support the Digital Electronic Message Service (DEMS) service.

24750–25250 MHz Band. The radionavigation service has primary status in this band and the Government has primary allocation status in only the 24750–25050 MHz band. NTIA could not identify any operational radar usage in this band. The band 25050–25250 MHz was reallocated on May 1997 (FCC 97-95) by the FCC to the fixed service to support the DEMS service.

31800–36000 MHz Band. In this band, the radionavigation service is primary in the 31800–33400 MHz portion and the radiolocation service is primary in 33400–36000 MHz. The military services have radars in this band for airborne navigational and mapping radars; weather avoidance; aircraft radar beacon rendezvous; airborne terrain following and avoidance radars; airborne long-range mapping radars; aircraft carrier precision approach and landing system radars; cloud measurement radars; military and national test range instrumentation radars; and vehicle speed detection radars. NASA, FAA, and the DOD are involved in synthetic vision radar research at around 35 GHz. Non-government radar operations support millimeter wave radar research of atmospheric radiation measurements; multi-mode airborne radar altimeters for profiling topographic features of land and ocean surfaces; and radar measurements of aircraft wake vortices during approach and departures. With implementation of WRC–97, the EESS will share the 35500–36000 MHz band on co-primary basis where NASA plans to operate spaceborne active sensors such as scatterometers and wideband altimeters.

92000–95000 MHz Band. This band is allocated to the radiolocation service on a primary basis. The military operates airborne pulse Doppler fire-control radars and airborne radiometer beacons. NASA, FAA, and the DOD are involved in synthetic vision radar research at around 94 GHz. Additionally, numerous RDT&E is conducted in this band for various radar systems. Non-military operations consist of ground-based CW pulse radars in the high-resolution profiling of clouds and for airborne test and evaluations of cloud detection radars. With implementation of WRC–97, the EESS will share the 94000–94100 MHz band on co-primary basis. NASA performs Earth observations in this band and is planning to operate cloud profile radars.

95000–100000 MHz Band. This band is allocated to the radionavigation service on a primary basis and to the radiolocation service on a secondary basis.

Endnotes: Chapter 2

1. The National Telecommunications and Information Administration Organization Act, Pub. L. No. 102–538, 106 Stat. 3533 (1992) (codified at 47 U.S.C. § 901 *et seq.*).

2. NTIA Manual, *infra* note 3, § 8.2.5 at 8–4. OMB Circular A–11, Section 12.4(e) requires that "estimates for the development and procurement of major communications-electronics systems (including all systems employing satellite (space) techniques) will be submitted only after certification by the NTIA that the radio frequency required for such systems is available."

3. National Telecommunications and Information Administration, Manual of Regulations and Procedures for Federal Radio Frequency Management § 1.1, at 1–1 (Sep1995, Jan and May 1997 revisions) [hereinafter NTIA Manual].

4. Radio regulations provide two levels of protection: primary and secondary. Radio services allocated on a primary basis have equal rights within the same band. Secondary services are on a non-interference basis to the primary services.

5. The *U.S. National Table of Frequency Allocations* is comprised of the U.S. Government Table of Frequency Allocations and the FCC Table of Frequency Allocations. The National Table indicates the normal national frequency allocation planning and the degree of conformity with the ITU Table of Frequency Allocations.

6. Copies of the NTIA spectrum wall chart, the *NTIA Manual*, the *Extract of the NTIA Manual* (containing the *U.S. National Table of Frequency Allocations*) and the FCC Rules (Parts 1 to 19) containing the *U.S. National Table of Frequency Allocations* are available from the Government Printing Office (GPO) or from the NTIA homepage: www.ntia.doc.gov. For ordering information and GPO address, contact Norbert Schroeder, Vice–Chairman, Interdepartment Radio Advisory Committee (ph: 202–482–3999, fax: 202–501–6198, or email: nschroeder@ntia.doc.gov).

7. *See* NTIA Manual, *supra* note 3, §, 6.1.1, at 6–1 to 6–16.

8. *Id.*, §, 6.1.1, at 6–12 .

9. *Id.*, §, 6.1.1, at 6–13.

10. *Id.*, §, 6.1.1, at 6–2.

11. *Id.*, §, 6.1.1, at 6–8.

12. *Id.*, §, 6.1.1, at 6–11.

13. *Id.*, §, 6.1.1, at 6–9.

14. *Id.*, §, 6.1.1, at 6–4. The EESS is where SAR imaging, altimetry, scatterometry, precipitation monitoring, and cloud profile monitoring is done.

15. David K. Barton (ANRO Engineering, Inc.), Keynote Address at the 1999 Tri–Service Radar Symposium (June 22, 1999).

16. Previous conferences were known as World Administrative Radio Conferences (WARC’s).

17. Similar changes were made in ITU Regions 1 and 3 for the bands discussed.

18. In this band, the DOD operates a national space detection and tracking radar system.

19. The DOD operates in this band a national air defense radar system for surveillance of spacecraft and ballistic missiles as well as other types of airborne shipborne, and battlefield radar systems. These DOD radars are radiolocation systems and the secondary allocation status applies not only in Region 2 but also in Regions 1 and 3.

20. The DOD operates numerous radiolocation radar systems in these bands on a secondary allocation status and, at times, must operate them worldwide.

21. S5.517. NTIA believes that the use of the 17.3–17.7 GHz band by radiolocation may be impractical after 2007.

22. *See* Balanced Budget Act of 1997, Pub. L. No. 111, Stat. 251 (1997), § 9233(a) (4); *see* also TABLE 3-2 and Figure 3-2 at 3-18 and 3-19, respectively.

23. Three essential military radar operations will be continued at three sites. *See* National Telecommunications and Information Administration, U.S. Department of Commerce, NTIA Special Publication 95-23, Spectrum Reallocation Final Report (Feb. 1995), at 4-16 to 4-21.

24. Jane's Information Group Limited, *National and International Air Defense Systems*, Jane's Radar and Electronic Warfare Systems, 1995–96, at 35 (Bernard Blake ed, 7th ed, 1995).

25. Department of Transportation, Federal Aviation Administration, Radio Spectrum Requirements for a Modernized Air Traffic Control System, July 1997, at 31 [hereinafter FAA Spectrum Requirements]. This FAA report was in response to a recommendation by the White House Commission on Aviation Safety and Security report that the FAA should identify and justify the frequency spectrum necessary for the transition to a modernized air traffic control system.

26. *Id.*

27. U.S. Department of Commerce, National Oceanic and Atmospheric Administration/OFCM, The Federal Plan for Meteorological Services and Supporting Research, FCM P1–1998, June 1998, at ix.

28. *See* U.S. Footnote US316, NTIA Manual, *supra* note 3, § 4.1.3, at 4–113.

29. *See* FAA Spectrum Requirements, *supra* note 25, at 31 and 42.

30. *Id.*

31. At 13250–13400 MHz, primary status of radiolocation applies to Government operations and is secondary for non-government operations.

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Chapter 3

RADARS AND THE ELECTROMAGNETIC SPECTRUM

INTRODUCTION

The range of all electromagnetic waves is called the electromagnetic spectrum. In the electromagnetic spectrum, long wavelengths correspond to the radio frequency spectrum, intermediate wavelengths to millimeter and infrared radiation, short wavelengths to visible and ultraviolet light, and extremely short wavelengths to x–rays and gamma rays. Figure 3–1 is a graphical depiction of the electromagnetic spectrum.

In the electromagnetic spectrum, there is generally no basic bounds on radar frequencies. Any electromagnetic device that detects and locates a target by radiating electromagnetic energy and uses the echos scattered from a target can be classified as a radar, regardless of its frequency. Radars have operated at frequencies from a few megahertz to the ultraviolet region of the electromagnetic spectrum. The fundamental principles of radars are the same at any frequency; however, the technical implementation is widely different. Most radars, in practice, operate between 400 MHz to 36 GHz; however, there are some notable exceptions.

The optical and radio portions of the electromagnetic spectrum occupy positions coincidental with two important transparent bands in the Earth's atmosphere and ionosphere. These transparent bands are commonly referred to as the optical and radio windows, and are depicted in Figure 3. The optical and radio windows are important because they allow these electromagnetic waves to pass through the atmosphere and be received on the Earth's surface.[1]

Radars operate in radio frequency bands normally designated for radar operations to ensure compatible operations with other radar systems. These frequency bands are sometimes identified by a letter band and are used by many radar engineers and others involved with radar matters. These letters generally refer to older military designations of the different frequency bands in which these radars operate. They relate back to the early development of radar in World War II when the letter designators were used for purposes of secrecy and after the requirement for secrecy was no longer needed, these letter band designators remained.

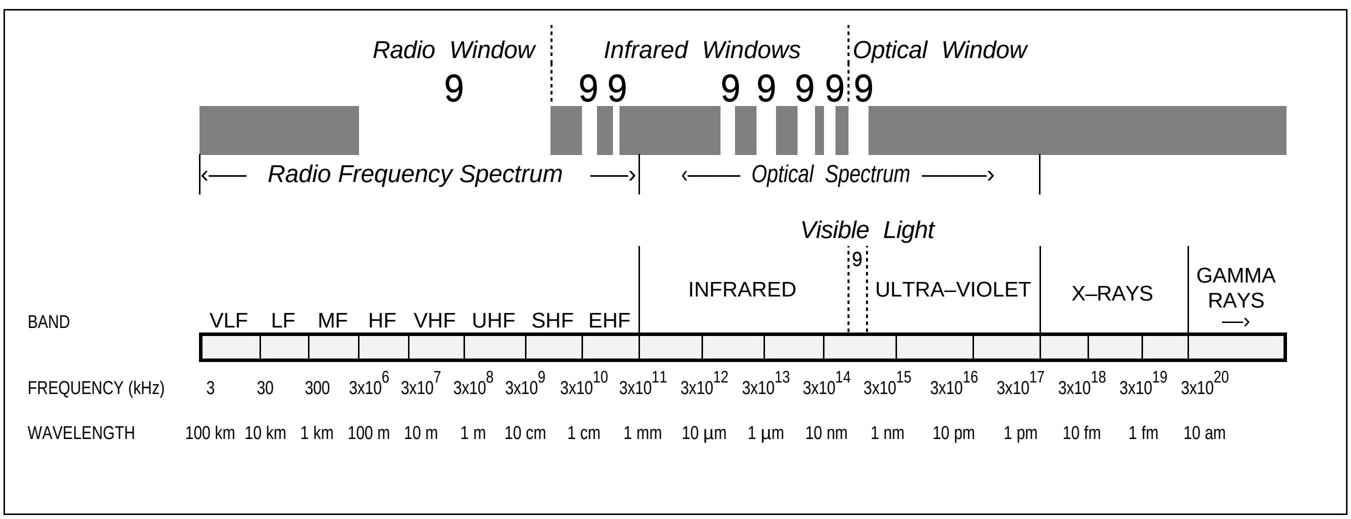

Figure 3–1. The Electromagnetic Spectrum.

RADAR FREQUENCY SELECTION

The best frequency to use for a radar depends upon its application. Like most other radio design decisions, the choice of frequency usually involves tradeoffs among several factors such as physical size, transmitted power, antenna beamwidth, and atmospheric attenuation.

Physical Size. The dimensions of the hardware used to generate and transmit radio frequency power are, in general, proportional to wavelength. At lower frequencies where wavelengths are longer, the hardware is usually large and heavy. At the higher frequencies where the wavelengths are shorter, radars can be housed in smaller packages and operate in more limited spaces with correspondingly less weight.

Transmitted Power. The choice of frequency (wavelength) indirectly influences the ability of radar to transmit large amounts of power because of its impact on hardware size. The levels of power that can be reasonably handled by a radar transmitter are largely limited by voltage gradients and heat dissipation requirements—the larger, heavier radars operating at wavelengths on the order of meters can transmit megawatts of average power, whereas millimeter-wave radars may be limited to only a few hundred watts of average power.

Beamwidth. The narrower the beam, the greater the transmitted power that is concentrated in a particular direction at any one time, and the finer the angular resolution. The width of the radar's antenna beam is directly proportional to the ratio of the wavelength to the width of the antenna. At low frequencies, large antennas must generally be used to achieve acceptably narrow beams. At higher frequencies, small antennas will suffice.

Atmospheric Attenuation. In passing through the atmosphere, radio waves may be attenuated by two basic mechanisms: absorption and scattering. The absorption is mainly due to oxygen and water vapor. The scattering is due almost entirely to liquid hydrometeors. Both absorption and scattering increase with frequency. Below about 100 MHz, atmospheric attenuation is negligible. Above about 10 GHz, it becomes increasingly important.

Figure 3–2 below is intended to show how, at about 10 GHz, absorption, scattering and refraction by atmospheric gases and liquid hydrometeors (rain, fog, sleet, and snow) become important limiting factors for electromagnetic wave propagation.

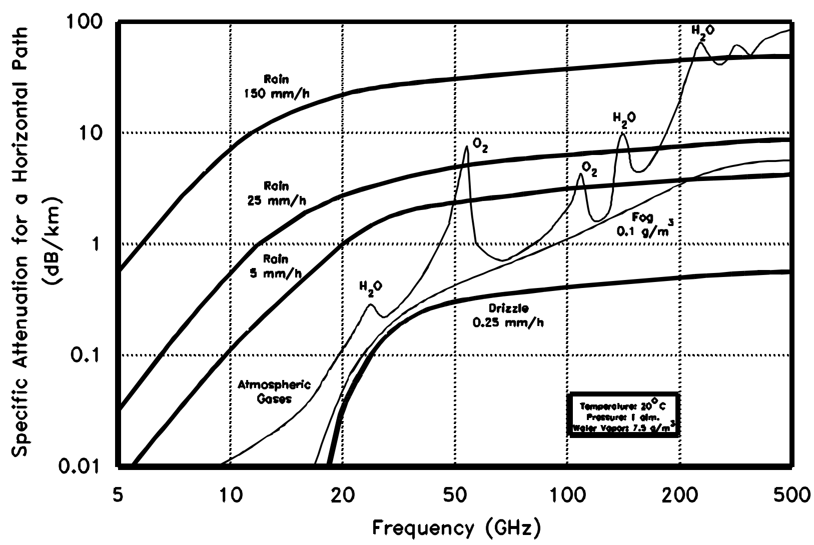

Figure 3–2. Attenuation Due to Atmospheric Gases and Liquid Hydrometeors.

RADAR DESIGN CONSIDERATIONS

From the preceding discussion, it is apparent that the selection of the operating radio frequency band is influenced by several factors such as the radar's intended function, its operational environment, the physical constraints of the radar's operating platform, and cost. To illustrate this, the following table depicts the relationship among the radar design requirements and spectrum issues.

TABLE 4
Spectrum Issues Versus Radar Design Requirements

Radar Design Requirements	Impact on Spectrum Characteristics		
	Frequency	**Bandwidth**	**Power**
Mission: surveillance, tracking, etc.	Primary	Primary	Secondary
Target Recognition: aircraft, ship, clouds, etc.	Primary	Primary	Secondary
Antenna: shape, size	Primary	Primary	Secondary
Mobility: size, weight, etc.	Primary	Secondary	Secondary
Environment: land, sea, air, etc.	Primary	Secondary	Secondary
Mutual Interference	Primary	Primary	Secondary
Spectrum Regulations	Secondary	Secondary	Secondary

Note: In varying degrees, the above radar design requirements will influence frequency selection, bandwidth, and power. However, some factors have more influence than others on the spectrum elements. The primary and secondary designations are relative indications of this influence on the radar design. Physical constraints are shown to outweigh regulations since they are less amenable to modification (i.e., the mission and the laws of nature can not be change).

The characteristics of the specific electromagnetic spectrum band selected for radar development have a significant impact on the information provided to the user. Radar systems in low bands provide the ability to detect targets at long distances and track space assets. On the other hand, high-band systems have only limited ability for search functions, but can track objects with very high precision, potentially forming an actual image of the object to assist in classification and discrimination. For example, the 8–12 GHz missile defense radar requires cuing by low-band radar systems to focus on a specific search area. Because of the relationships between frequency bands and capabilities, DOD and the Navy specifically, will continue to retain radar systems that operate throughout the spectrum.[2]

Ground-Based Applications. Ground-based radars operate in most allocated frequency bands. At one end are the long-range multi-megawatt surveillance radars. Unconstrained by size limitations, they can be constructed large enough to provide acceptable high angular resolution while operating at relatively low frequencies. Over-the-horizon radars can operate in the HF band (3–30 MHz) where the ionosphere is ideally reflective. Space surveillance and early warning radars operate in the very high frequency (VHF) and ultrahigh frequency (UHF) bands where atmospheric attenuation and natural noise are nearly negligible. These bands, however, are crowded with communications signals, so their use by radars is restricted to special applications and geographic areas. Where such long ranges are not required and some atmospheric attenuation and noise is tolerable, ground-based radars may be reduced in size by moving up to higher frequencies.

Shipborne Applications. Physical size becomes a limiting factor aboard ships for many applications including radar systems. While at the same time, the ship's requirement to operate in various types of weather conditions puts a constraint on the upper portions of the radio frequency spectrum that may be used. This limit is eased somewhat where extremely long ranges are not required. Higher frequencies are usually employed when operating against surface targets and targets at low elevation angles, such as sea-skimming missiles.

The radar return received directly from targets at very low elevation angles are very nearly canceled by the return from the same target reflected off the water (multipath propagation). This cancellation is due to a 180E phase reversal occurring when the return is reflected. As the elevation angle increases, this multipath propagation problem decreases.

This multipath problem decreases at higher frequencies. For this reason, the short wavelengths of the 2.7–10.5 GHz band are widely used for surface search, detection of low flying targets, and piloting of ships.[3]

Airborne Applications. In an aircraft, the housing limitations of radars are more severe than on ships. Frequencies in the 400–1000 MHz and 2000–4000 GHz bands are the lowest frequency bands where aircraft radars operate. These bands provide the long detection ranges required by military airborne early warning aircraft and their antennas are very large to provide the desired angular resolution. Above these bands, the next application are radar altimeters using the 4200–4400 MHz band.[4]

Airborne weather radars, which require greater directivity, operate in 5.2–5.9 GHz and 8.5–11 GHz bands. The choice of these two bands for airborne weather radars indicates a dual trade-off of functional requirements: one is between storm penetration/scattering and the other is storm penetration/equipment size. If there is too much scattering, the radar will not penetrate deeply enough into the storm to see its full extent. However, if too little energy is scattered back to the radar, the storm will not be visible on the radar scope. The larger aircraft use 5.2–5.9 GHz band weather radars, even though they are larger and heavier, because of the better storm penetration capabilities and longer range performance. The majority of smaller aircraft employ lighter weight 8.5–11 GHz band weather radars that provide adequate performance.

The majority of military fighter aircraft have attack and reconnaissance radars operating in the 8.5–11 GHz and 13–18 GHz bands with a large number operating in the upper portions in the 8.5–11 GHz band. This upper portion of the 8.5–11 GHz band is very attractive because of its relatively low atmospheric attenuation and availability of narrow beamwidths.

Frequencies above the 8.5–11 GHz and 13–18 GHz bands are used where limited range is not a problem and angular resolution and small size are desirable. Aircraft radars operating in the 31–36 GHz band are used for ground search functions and for terrain following and terrain avoidance.

Spaceborne Applications. In a space platform, the power and space limitations for radar systems are most severe. Considering the limited power available on space platforms and the availability of small radar components make radars operating in the UHF and above frequency ranges a better choice. For spaceborne surveillance radars, the frequencies from 1–18 GHz would be good choices. Frequencies from 1–11 GHz are frequency bands where SAR imaging radars operate. Spaceborne altimeters generally use frequencies in the 2–18 GHz band while scatterometers generally use frequencies between 5–36 GHz. Frequencies around the 13–18 GHz band is where precipitation radars generally operate.

Endnotes: Chapter 3

1. Source for these transparent bands came from John D. Kraus. *See* John D. Kraus, Radio Astronomy, 2nd ed., 1986, at 1–4. These transparent bands are the result of the resistance (opacity) of Earth's gases to certain electromagnetic radiation. The opacity of air to visible light is very small; hence, we have no difficulty seeing each other. The water vapor contained in the air is opaque to various wavelengths in the infrared frequency ranges.

2. Department of Navy email comments from Mr Bruce Swearingen, Director, Naval Electromagnetic Spectrum Center, at 2. (*See* email from swearinb@navemscen.navy.mil, March 24, 2000 on file at NTIA).

3. For a discussion of ground echoes, *see* Richard K. Moore, *Ground Echo*, Radar Handbook, at 12.3 (Merrill I. Skolnik, 2nd ed. 1990).

4. Radar altimeter use of the 4200–4400 MHz band allows for conveniently small equipment packages because the band permits good cloud penetration, require modest amounts of power, and do not require highly directional antennas for satisfy altimeter requirements.

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Chapter 4

INVENTORY OF FEDERAL RADAR USE

This chapter will briefly survey the principal uses of radar by various Federal Government agencies. So that the reader can relate the material presented in previous chapters to the applications describe here, the kinds of radars generally employed in the applications will be categorized as land-based, shipborne, airborne, or spaceborne.

Federal Aviation Administration: Air Traffic Control

The national air traffic control system operated by the FAA has as its purpose the safe and efficient operation of aircraft flying in the vicinity of airports, aircraft flying enroute from one airport to another, and aircraft and vehicles on the ground at airports. Commercial aviation and general aviation, as well as military aircraft, are all included within the purview of an air traffic control system.

Several different radars are employed for the control of air traffic. The airport surveillance radar (ASR) provides information on the location and movement of all aircraft flying within the vicinity of airports. It is sometimes referred to as a terminal radar. The air route surveillance radar (ARSR) has as its purpose the detection and tracking of aircraft that are enroute from one airport to another with a radar range of about 200 nautical miles. For this reason, it is sometimes called an enroute radar. The airport surface detection equipment (ASDE) is a radar that maps the airport surface to provide information to the controller concerning aircraft on the ground as well as certain vehicular traffic within the airport. The ASR and ARSR radars also provide the air traffic controller with the location of hazardous weather. The location of dangerous weather phenomena such as "downbursts" and windshear can be pinpointed with a specially configured terminal Doppler weather radar (TDWR) located near airports. On board FAA aircraft, there are radar altimeters as well as radionavigation and weather radars. Further, for vehicle speed detection on one of its facilities, the FAA operate a Doppler speed detection radar. The following table depicts the range of radars operated by the FAA and their operating frequency bands.

Radar Category	Radar Function	Frequency Band (MHz)
Land Based	Air Route Surveillance	1240–1370
	Airport Surveillance	2700–2900
	Weather Radars	2700–3000 5600–5650
	Airport Surface Detection Equipment	15700–16600
	Vehicle Speed Detection	10450–10550
Airborne	Aircraft Altimeter	4200–4400
	Radionavigation & Weather	8750–8850
Shipborne	Radionavigation & Weather	9300–9500

The military departments also provide air traffic control primarily at and around their air bases, naval air stations, and airfields. Their primary ATC radar operates in the 2700–2900 MHz band and the military departments also use the 1030/1090 MHz interrogator-responder systems.

U.S. Coast Guard: Coastal and Waterway Security

The USCG has four main roles: maritime law enforcement, maritime safety, national defense, and marine environmental protection. In accomplishing these responsibilities, the USCG employs various radars: shipborne maritime radionavigation and search radars; shipborne air search and surveillance radars; radar beacons; radar altimeters; airborne maritime Doppler navigation and surveillance radars; airborne search and rescue radars; land-based and shipborne harbor surveillance radars; and radar speed detection devices. An inventory of the USCG radars is described in the following table:

Radar Category	Radar Function	Frequency Band (MHz)
Land Based	Harbor Surveillance	9300–9500
	Radionavigational Aids	2900–3100 9300–10000
	Vehicle Speed Detection	10450–10525

Shipborne	Search & Surveillance	420–450 9200–10000
	Radionavigation & Search	2900–3100
Airborne	Surveillance Radars	420–450
	Radar Altimeters	4200–4400
	Navigation & Surveillance	8500–9000 9000–9200 9200–9600
	Search & Rescue	9000–9200 9200–9600 13250–13400

Department of the Navy: National Defense

The primary mission of the Department of the Navy is to protect the United States by the effective prosecution of war at sea including, with its Marine Corps component, the seizure or defense of advanced naval bases; to support, as required, the forces of all military departments of the United States; and to maintain freedom of the seas. Naval and marine forces depend heavily on radar systems and many of their radars can be categorized as: land-based national air defense radars; naval surveillance and navigation radars; naval fire-control radars; airborne surveillance and navigation radars; airborne fire-control radars; battlefield, missile control and ground surveillance radars; land-based air defense; air traffic control for land-based Naval Air Stations and carrier-based flight operations; and range safety, surveillance, and instrumentation radars. The following table depicts the inventory of naval and marine forces radars. The frequency bands indicated are the bands where the radars are authorized to operate and may not reflect the complete tuning range for some of the radar systems.[1]

Radar Category	Radar Function	Frequency Band (MHz)
Shipborne	Search & Surveillance	420–450
	Navigation & Search	420–450
	Search & Surveillance	902–928
	Long-Range Surveillance	1215–1390
	Long-Range Surveillance	2900–3100
	Fleet Air Defense System	3100–3500
	Missile & Gunfire-control	3400–3650
	Long-Range Surveillance	3500–3650
	Long-Range Surveillance	3550–3650
	Aircraft Carrier ATC–PAR	3550–3650
	Missile & Gunfire-control	5250–5800
	Surface-to-Air Missile Control	5400–5900
	Sea Surface Search	5400–5900
	Ship Positioning NAVAID	5400–5550
	Missile & Gunfire-control	8500–9600
	Submarine Surface Nav/Search	8500–9000
	Fire-control & Surveillance	8500–9600
	Navigation & Surveillance	9300–10000
	Guided Missile Fire-control	10000–10550
	Combat Surveillance	10000–10550
	Missile & Gunfire-control	10200–10500
	Missile & Gunfire-control	13400–14400
	Aircraft Carrier ATC–PAR	15300–15900
	Gunfire-control	16000–17000
	Navigational	16000–17000
	Aircraft Carrier ATC–PAR	31800–33400
	Fire-control	92000–100000
Airborne	Early Warning	420–450
	Radar Altimeters	4200–4400
	Radar Transponders	5500–5900
	ASW Search & Detection	8500–9600
	Weapons Fire-control/Targeting	9200–9800
	Maritime Surveillance	9200–9800
	Helicopter Search	9200–9800
	ASW Search & Detection	9600–10000
	Radar Transponders	9200–10000
	Helicopter Nav/Search	13250–13400
Land Based	Over-the-Horizon	3–30
	Space Surveillance	216–220
	Tactical Air Defense	1215–1390
	Base ATC Search	2700–2900
	Weather	2700–2900
	Tactical Long-Range Surveillance	2900–3100
	Weather	5600–5650
	Airfield Precision Approach	9000–9200
	Battlefield Weapons Locating	9300–10000
	Battlefield NAVAID	9300–10000
	Perimeter Surveillance	10200–10500
	Vehicle Speed Detection	10450–10550
	Battlefield Weapons Locating	15840–16160

	Battlefield Precision Approach	15300–15900
	Vehicle Speed Detection	24050–24250
	Range Safety, Surveillance, Target Tracking & Instrumentation	5400–5900 9200–9600 9600–10000 10000–10550 15700–17300

Department of the Army: National Defense

As part of our national military team, the Army focuses on land operations. Its soldiers are trained with modern arms and equipment and are ready to respond quickly. In the battlefield environment, the Army relies on radars for success. The Army spectrum of radars that it operates and trains on can be categorized as: land-based air defense radars; battlefield, missile control and ground surveillance radars; airborne surveillance and navigation radars; military ATC radars; and range safety, surveillance, and instrumentation (telemetry) radars. The table below depicts the various Army radar functions and operating frequency bands:

Radar Category	Radar Function	Frequency Band (MHz)
Land Based	Battlefield Ground Surveillance	420–450
	Position Location	420–450
	Battlefield Early Warning	1215–1390
	Man-portable Early Warning	1215–1390
	Air Defense	1215–1390
	Airfield ATC Search	2700–2900
	Battlefield ATC Search	2700–2900
	Weather Radars	2700–2900
	Air Defense	2900–3100
	Battlefield Weapons Locating	3100–3400
	Doppler Radar Sensors	3100–3400
	Battlefield Missile Surveillance	5250–5925
	Battlefield Missile Tracking	5250–5925
	Weather Radars	5600–5650
	Battlefield Search & Surveillance	8500–9600
	Battlefield Weapons Locating	8500–9600
	Airfield Precision Approach	9000–9200
	Battlefield GCA	9000–9600
	Battlefield Air Defense	9200–10000
	Battlefield Weapons Locating	9200–10000
	Anti-aircraft Gun Fire-control	9200–9500
	Weather Radars	9200–9500
	Battlefield Surveillance	10000–10550
	Perimeter Intrusion Detection	10000–10550
	Vehicle Speed Detection	10450–10550
	Battlefield Microwave Landing System	15300–15900
	Portable Ground Surveillance	15700–17300
	Battlefield Weapons Locating	15700–17300
	Battlefield Surveillance & Tracking	15700–17300
	Battlefield Weapons Fire-control	15700–17300
	Vehicle Speed Detection	24050–24250
	Doppler Radars	>30000
	Range Safety, Surveillance, Target Tracking, & Instrumentation Radars	902–928 1215–1390 5250–5925 9200–10000 33400–36000
Airborne	Radar Altimeters	4200–4400
	Radar Beacons	5250–5925
	Side Looking Airborne Radar	9200–9500
	Navigation, Weather, & Mapping	9200–10000

Department of the Air Force: National Defense

The Department of the Air Force is responsible for defending the United States through control and exploitation of air and space. Radars are heavily employed by the Air Force and many can be categorized as: land-based national air defense radars; ground surveillance radars; airborne surveillance and navigation radars; airborne fire-control radars; spaceborne radars; military ATC radars; and range safety, surveillance, and instrumentation radars. The following table describes the Air Force's inventory of radars:

Radar Category	Radar Function	Frequency Band (MHz)
Land Based	Intrusion Detection	VHF
	Long Range Surveillance	420–450
	Air Defense	1215–1390
	Search Radars	1215–1390
	Base Search Radars	2700–2900
	Airfield Search Radars	2700–2900
	Weather Radars	2700–3000
	Airfield Surveillance Radars	2900–3100
	Airfield ATC Radars	3100–3650
	Bomb Scoring Radars	3100–3650
	Weather Radars	5600–5650
	Target Bomb Scoring	8500–9000
	Airfield PAR	9000–9200
	Base PAR	9000–9200
	Bomb Scoring Radars	9200–10000
	Intrusion Detection	9200–10000
	Intrusion Detection	10000–10550
	Perimeter Surveillance	10000–10550
	Vehicle Speed Detection	10450–10550
	Missile Guidance/Control	15700–16600
	Missile Guidance/Control	16600–17300
	Vehicle Speed Detection	24050–24250
	Cloud Height Detection	33400–36000
	Vehicle Speed Detection	33400–36000
	Range Safety, Surveillance, & Instrumentation Radars	902–928 1215–1390 2700–2900 5400–5925 15700–16600 33400–36000
Airborne	Airborne Surveillance	3100–3650
	Search & Surveillance	3350–3600
	Radar Altimeters	4200–4400
	Fire-control & Intercept	8500–9000
	Multi-mode Fire-control	9200–10000
	Intercept Radars	9200–10000
	Navigation & Mapping	9200–10000
	Navigation & Weather	9200–10000
	Beacon Rendezvous	9200–10000
	Terrain Following/Avoidance	9200–10000
	Maritime Surveillance	9200–10000
	Search & Rescue Radars	9200–10000
	Fire-control Radars	9200–10000
	Multi-mode Doppler Navigation	13250–13400
	All Weather Target Attack	15700–16600
	Multi-mode Fire-control	15700–16600
	Intercept Radars	15700–16600
	Terrain Mapping & Avoidance	15700–16600
	Multi-mode Doppler Navigation	16600–17300
	Intercept Radars	16600–17300
	Terrain Mapping & Avoidance	16600–17300
	Navigation & Weather	31800–33400
	Beacon Rendezvous Radars	31800–33400
	Terrain Following & Avoidance	31800–33400
	Long Range Mapping	31800–33400

National Aeronautics and Space Administration: Space Research

NASA conducts flight research for the solution of problems of flight within and outside the Earth's atmosphere and develops, constructs, tests, and operates aeronautical and space vehicles. It also conducts Earth exploration experiments and operations for Earth observation and aids in resource monitoring, hazard monitoring, and other benefits to the global community. Finally, NASA conducts activities required for the exploration of space with manned and unmanned vehicles and arranges for the most effective utilization of the scientific and engineering resources of the United States with other nations engaged in aeronautical and space activities for peaceful purposes.

Radars are one of its chief tools supporting NASA's mission described above. Its radars almost cover the entire spectrum of frequency bands for radar operations and can generally be grouped as: range safety, surveillance, and instrumentation (telemetry) radars; airborne transponders; airborne search and navigation radars; airborne and ground weather radars; radar altimeters; maritime search and surveillance radars; space transportation system (STS, space shuttle) navigational radars; planetary radars; STS landing system radars; airborne surveying radar altimeters; cloud detection and profiling radars; aircraft radiometer beacons; ocean wave, wind, and vortex research radars; spaceborne SAR's, altimeters, scatterometers, precipitation and cloud profile radars. The table below describes NASA's inventory of radars:

Radar Category	Radar Function	Frequency Band (MHz)
Shipborne	Search & Surveillance	2900–3100
	Navigational & Search	9300–9500
Land Based	Range Safety, Surveillance, & Instrumentation Radars	2700–2900 3000–3500 5250–5925 9200–9500
	Search & Surveillance	420–450
	Wind Measurement Radars	902–928
	Planetary Radars	2310–2345
	Weather Radars	5600–5650
	Planetary Radars	8500–9000
	Vortex Research Radars	9200–9500
	Ground Weather Radars	9300–9500
	Wind Shear Measurement	9300–9500
	Vehicle Speed Detection	10450–10550
	STS Landing System	15460–15616
	Vehicle Speed Detection	24050–2250
	Vehicle Speed Detection	34400–36000
	Vortex Research Radars	34900–35800
Airborne	Search & Navigation	5250–5925
	Airborne Transponders	5400–5900
	Precision Tracking Radars	9000–9200
	Search & Navigation	9200–9500
	Airborne Weather Radars	9300–9500
	Airborne Transponders	9300–9500
	Radar Altimeters	4200–4400
	Ocean Wave Spectrometer	13250–13400
	Ground/Ocean Mapping	33400–36000
	Aircraft Radiometer Beacons	85000
	Aircraft Radiometer Beacons	92000–95000
	Cloud Detection & Profiling Radars	92000–95000
Spaceborne	SAR Imaging Radars	1215–1300
	SAR Imaging Radars	3100–3300
	SAR's, Altimeters, and Scatterometers	5250–5460
	SAR's, Altimeters, and Scatterometers	8550–8650
	SAR's, Altimeters, and Scatterometers	9500–9800
	Weather Radars	9975–10025
	Altimeters, Scatterometers, Precipitation Radars	13250–13750
	Scatterometers, & Precipitation Radars	17200–17300
	Scatterometers, & Precipitation Radars	24050–24250
	Altimeters & Precipitation Radars	35500–36000
	Altimeters & Precipitation Radars	78000–79000
	Cloud Profile Radars	94000–94100

Department of Commerce: Environmental Monitoring

The DOC has many different bureaus that encourage, serve, and promote the nation's international trade, economic growth, and technological advancement. The NOAA works to improve our understanding and benefits of the Earth's physical environment and oceanic resources. NOAA is the largest user of radars in the DOC and its radars support the National Marine Fisheries Service, National Ocean Service, Office of Oceanic and Atmospheric Research, National Weather Service, and National Environmental Satellite, Data, and Information Service. NOAA's radars can be categorized as: land-based search and surveillance radars; land-based radionavigational radars; weather radars; shipborne surveillance and navigational radars; airborne surveillance and navigational radars; aircraft weather radars; radar altimeters; coastal and marine sanctuaries surveillance radars; and radar speed gun. The following table depicts the variety of radars employed by the DOC:

Radar Category	Radar Function	Frequency Band (MHz)
Land Based	Wind Profilers	404
	Wind Profilers	449
	Weather Radars	2700–3000
	Weather Radars	5600–5650
	Balloon Tracking Radars	8500–9000
	Atmospheric Research	9200–10000
	Marine Sanctuary Surveillance Radars	9200–10000
	Radionavigation Radars	9300–9500
	Vehicle Speed Detection	10450–10550
Shipborne	Radionavigation & Search	2900–3100
Airborne	Radar Altimeters	4200–4400
	Weather Research & Nav	5370–5480
	Radionavigation & Weather	9300–9500

Department of Energy: Science and Technology Research

The DOE is a leading science and technology agency whose research supports our nation's energy security, national security, environmental quality, and contributes to a better quality of life for all Americans. Quite an array of radiocommunications is used to facilitate many of the DOE's programs in its laboratories or at its many test ranges. Many radars are employed by DOE to support its mission at its many test ranges, sites, and facilities. Radars are used for perimeter monitoring; motion sensing; weather research and environmental monitoring; security surveillance; terrain mapping and air sampling; weapon system testing and flight test tracking; joint programs with other agencies; and a variety of research and development programs. Radars can be generally categorized as intrusion detection radars; fixed and mobile search and surveillance radars; range safety, surveillance, and instrumentation radars; aircraft radionavigation and weather radars; mobile meteorological radars; speed gun radars; wind profiler radars; airborne radar transponders; atmospheric and cloud research radars. The table below provides an inventory of the various radars employed by DOE:

Radar Category	Radar Function	Frequency Band (MHz)
Land Based	Intrusion Detection Radars	30–100
	Wind Profiler Radars	404 449
	Mobile Search Radars	420–450
	Wind Profiler Radars	915
	Surveillance Radars	8500–9000
	Mobile Weather Radars	8500–9000
	Vehicle Speed Detection	10450–10550
	Atmospheric Research	15700–16600
	Vehicle Speed Detection	24050–24250
	Atmospheric Research	33400–36000
	Range Safety, Surveillance, Target & Missile Tracking, & Instrumentation Radars	1215–1390 2900–3100 3100–3650 5400–5900 8500–9000 9200–9600
Airborne	Radar Transponders	5250–5925
	Radionavigation Radars	5350–5460
	Weather Radars	9300–9500

U.S. Department of Agriculture: Supporting Production of Agriculture

The USDA, in addition to developing and expanding the markets of agricultural products, works to enhance the environment and to maintain production capacity by helping landowners protect the soil, water, forests, and other natural resources. The Departments's research findings benefit all Americans. Radar devices are used by the Department to support its mission areas of research and the management of natural resources and the environment. Its inventory of radars includes airborne weather radars, maritime surveillance radars, entomological radars, and pulse radars and are described in the following table:

Radar Category	Radar Function	Frequency Band (MHz)
Land Based	Entomological Radar (Insect Research)	9300–9500
	Natural Resource Management	9300–9500
	Vehicle Speed Detection	10450–10550
Shipborne	Maritime Search Radar	9200–9500
Airborne	Airborne Weather Radar	9300–9500

Department of the Interior: Land and Resources Management

The DOI manages the nation's public lands and mineral resources, national parks, national wildlife refuges, and western water resources. Radars aid the DOI in its land and resource management by providing position location determination in support of geological survey activities: coastal waterway, lake, and river mapping and other related survey activities. Additionally, radar speed detection devices assist park managers with maintaining vehicle speed detection at various national parks. The following table describes the various radars and their operating frequency bands:

Radar Category	Radar Function	Frequency Band (MHz)
Land Based	Mobile Geological Survey Radars	5470–5600 9350–9450 10000–10550
	Vehicle Speed Detection	10450–10550 24050–24250

Department of Justice: Law Enforcement

The Department of Justice (DOJ) plays a significant role in protecting American citizens through it efforts for effective law enforcement, crime prevention, and crime detection. In doing so, the Department employs a variety of radiocommunications equipment including radar devices. Radars are employed by the various DOJ agencies for radar altimeters, vehicle tracking, and crime scene investigations. The following table describes the functions and frequency bands employed the DOJ.

Radar Category	Radar Function	Frequency Band (MHz)
Land Based	Vehicle Tracking	UHF
	Crime Scene Investigations	UHF
Airborne	Radar Altimeters	4200–4400

National Science Foundation: Research and Testing

The NSF promotes the progress of science and engineering through the support of research and education programs. The NSF employs radars for wind and atmospheric testing, radar altimeter aboard the National Center for Atmospheric Research aircraft, range safety (search radars), and for the study of objects beyond the Moon. An inventory of the types of radars employed by the NSF is described in the table below:

Radar Category	Radar Function	Frequency Band (MHz)
Land Based	Atmospheric Research–Wind Profiler Radar	908–928
	Radar Astronomy	2380
	Weather Radars	2700–2900
	Weather Radars	9200–9400
	Search Radar	9200–9500
Airborne	Radar Altimeters	4200–4400

Department of Treasury: Law Enforcement

One of the basic functions of the Department of Treasury is law enforcement. Land-based, airborne, and shipborne surveillance and acquisition radars are used by various Treasury agencies to execute their mission. Also, radars are used for automatic vehicle identification. The table below lists some of the radar bands employed by radars of the Treasury Department.

Radar Category	Radar Function	Frequency Band (MHz)
Land Based	Surveillance Radars	420–450 2900–3100 9200–9500
Shipborne	Maritime Mobile Radar	9400–9500
Airborne	Balloon-borne Surveillance Radars	1215–1390

Veterans Administration, US Postal Service, Health and Human Services, General Services Administration:

These agencies employ radars for vehicle speed detection on their various facilities.

Radar Category	Radar Function	Frequency Band (MHz)
Land Based	Vehicle Speed Detection	10450–10550 24050–24250

Endnotes: Chapter 4

1. Department of Navy email comments from Mr Bruce Swearingen, Director, Naval Electromagnetic Spectrum Center, at 2. (*See* email from swearinb@navemscen.navy.mil, March 24, 2000 on file at NTIA).

Chapter 5

RADAR SPECTRUM REQUIREMENTS

INTRODUCTION

The NTIA Requirements Study addressed 18 radio services, and developed a 10–year forecast of national spectrum needs. In that study, it noted that spectrum allocated for radiolocation, radionavigation, and meteorological aids was adequate. This study revisits Federal radar spectrum requirements at the request of several Federal agencies. Additionally, radar spectrum requirements of the EESS (active) are also discussed herein.

As discussed earlier, radar developers and the eventual radar users need assurance that spectrum will be available for their use not only to amortize their investments but also to accomplish the agencies' mission. In the NTIA Requirements Study, NTIA cited radar experts who concluded that radars employing new technologies have an approximate 15–20 year development time between concept to deployment.[1] A classic example was the NEXRAD radar (Weather Surveillance Radar–1988 Doppler, WSR–88). The program began in FY81, had its first limited production WSR–88 radar installed at Oklahoma City, Oklahoma in 1990, and was commissioned in 1994.[2] So when radars systems are in the conceptual, design, and developmental stage, the manufacturer and end user need some assurance that the radar band will be available when the radar is commissioned and for some time in the future for the user to amortized its investment. The FAA, which operates some of the WSR–88's, has planned enhancements to this system that will extend the radar's service life to 2040.[3]

Historically, the development and acquisition of aeronautical radionavigation and maritime radionavigation systems usually considered the requirements of diverse international groups, including the North Atlantic Treaty Organization (NATO) and other allies, International Civil Aviation Organization (ICAO), and the International Maritime Organization (IMO). Radar requirements such as performance, standardization, and cost not only influence the search for an international consensus on a selection of radionavigation radar systems but also on their operating frequency bands.

The FAA and USCG are Federal users of spectrum as providers and operators of radionavigation services. The FAA use of spectrum is primarily in support of aeronautical safety services used within the National Airspace System. This exclusively allocated spectrum must be free from interference due to the safety of life aspects of FAA services. The USCG also uses spectrum as a provider of critical maritime radionavigation services and whose maritime radionavigation systems must also be interference free.

While DOD access to current radar spectrum bands will continue, the overall trend is toward a greater demand for spectrum especially in bands that support surveillance, fire control and imaging radar. The largest increase in spectrum use by radar systems will occur in the upper frequency bands, above 6 GHz, with an overall 70 percent growth in DOD spectrum use projected over the next decade.[4]

PROJECTED REQUIREMENTS: RADARS UNDER SYSTEMS REVIEW

As mentioned earlier, various Federal agencies currently have a total of 36 radar systems under systems review. For most of these radar systems, the table below depicts the agencies, radar system description, and operating frequency range. A short description of the radars under systems review is provided for selected radar systems.

The Army has 14 systems under systems review, the Navy has 11 systems, and the Air Force has 8 systems. Information on most of these radar systems are not yet releaseable.

The NASA system is an airborne VHF radar for the measurement of terrestrial vegetative biomass. The BioSAR will enable the investigation of 82 percent of the Earth's biomass which is beyond the capabilities of currently available SAR systems, which benefit NASA's mission to Planet Earth. NASA has five EESS active sensor types: SAR's, altimeters, scatterometers, precipitation radars, and cloud profile radars. Examples of planned NASA radar systems usage include for the SAR: the shuttle radar topography mission (SRTM) to be flown on the Shuttle in 2000; for the altimeter: the ocean topography experiment (TOPEX) follow-on; for the scatterometer: the SEAWINDS; for the precipitation radar: the tropical rain measuring mission (TRMM) follow-on; and for the cloud profile radar (the cloud satellite, CLOUDSAT).

TABLE 5
Radars Under SPS Review

Agency	System Description	Operating Frequency Range (MHz)
DOE	Ground Penetrating Radar	.009–600
Commerce	Alaska MF Radar	2.409–2.451
Navy	HF OTH Radar	5–30
Navy	HF Frequency Surface Wave Radar	15–25
Army	DARPA Foliage Penetration SAR	25–93 150–597
Army	ARL Ultrawide Band Radar	40–1800
NASA	NASA Biomass SAR (BioSAR)	80–120
Navy	ERIM Concealed Target Detection Radar	187–913
Navy	Wideband Impulse Transmitter Radar	210–1690
Army	Geographic SAR (GeoSAR)	9630–9790
Navy	AN/TPS–59 (V) 1 Radar	1215–1400
Air Force	Next Generation Target Control System	1370–1385
Air Force	Linear Array Intrusion Detection System	1678–2678
Air Force	AN/GPN–XX Digital ASR (ASR–11)	2700–2900
Navy	Naval Space Command Bi-Static Radar	3100–3600
Navy	Signature Managed ATC Approach & Landing System	3195–3690
Air Force	Hughes XR640–3500A SAR	8400–9000
Army	ATNAVICS PAR	9000–9200
Army	Multimode Survivable Radar	9200–10500
Army	Interferometeric SAR	9456.5–9749.5
Navy	AN/SPQ–9B Radar	9467.5–9972.5
Army	Crusader Projectile Tracking System	15700–16200
Air Force	SAR (Tier III UAV)	15970–16970
Army	Tactical Endurance SAR	15970–16970
Army	Small Tactical SAR	16472–17128
Air Force	Haystack Millimeter Wave Radar	33400–36000 92000–100000
Army	Millimeter Wave Ground Radar	34000–35986

The DOE system is a micro-power pulse radar using ultra-wideband technology that is being developed for applications including bridge-deck inspection, ground penetration, mine detection and precision distance resolution. The system is expected to be activated in 1999 with the technology expanded to many other applications over the next several decades.

INCREASED MILITARY RADAR DEVELOPMENT

Planning for the increased access to the electromagnetic spectrum required by future radar systems is essential to maintaining information superiority. The military systems using radar provide the United States with the capability to conduct effective campaigns and to maintain security in peace. The guidance and fire control radar systems for precision munitions used in the Gulf War and in Bosnia allow military missions to be conducted against high-value targets in populated areas with minimal risk to civilians. The new Theater High Altitude Area Defense System (THAAD) radar system will afford warfighters protection against conventional and nuclear, biological, or chemical theater missiles, while the National Missile Defense (NMD) radar will protect civilian populations. The Discoverer II space-based radar is designed to aid in detecting moving targets and delivering precision guided munitions accurately.[5]

The growth in electromagnetic spectrum use is due primarily to the fielding of follow-on systems with enhanced features that require increased spectrum access for functionality. The use of surveillance, fire control and imaging radars will increase significantly during the projected period. New systems such as the AN/SPY-2, AN/TPS-59 (v)1 and new generations of missile defense radars are due to be fielded during this period, as well as a new constellation of space-based synthetic aperture radars for increased imaging capabilities in support of contingency operations. These new radars generally process a much wider bandwidth signal than current generation systems, to provide enhanced target recognition capabilities. The wider processing band of newer systems relative to current systems is reflected in the projected 70 percent increase in overall spectrum use.[6]

Radar systems above 6 GHz currently planned for deployment include THAAD and NMD ground-based radar systems that take advantage of the characteristics of high frequencies, as do the Discoverer II space-based radar and the F-22 radar system. All radar systems are expected to receive future upgrades which will include features such as multi-function and dual band modes and systems designed for intrusion detection and improved space surveillance.[7]

New developments are centering on the upper bands, but these developments are generally intended to enhance capabilities rather than supplant the existing systems in the lower bands. Additionally, the trend in radar is towards wider bandwidths to better discriminate target objects and to provide additional signal processing for anti-jam techniques. While DOD access to current radar spectrum bands will continue, the overall trend is toward a greater demand for spectrum especially in bands that support surveillance, fire control and imaging radar. The largest increase in spectrum use by radar systems will occur in the upper frequency bands, above 6 GHz, with an overall 70 percent growth in spectrum use projected over the next decade.[8]

PROJECTED REQUIREMENTS: CURRENT RADAR SYSTEMS

The following sections describe the projected usage time frame for various Federal agencies' radar systems. Some requirements were extracted from reports, derived as a function of the radar platform's life cycle, or a forecast based on the agency's continuing mission requirements.

FAA Spectrum Requirements for a Modernized Air Traffic Control System

Historically, the requirements for specific frequency bands for different aeronautical radionavigation applications necessitated that segments of spectrum be reserved for specific applications. In many cases, allocations for aeronautical use was exclusive in order to meet the stringent requirements of aviation safety. As the FAA transitions to a more modernized air traffic control system, it has identified and justified the spectrum necessary to support its mission. Included in its list of spectrum requirements, was spectrum for the operations of FAA radars. The following is a summary of those requirements. NTIA believes the FAA spectrum requirements will remain unchanged in the foreseeable future.

1215–1390 MHz. Air route surveillance radars will be needed and remain essential for the foreseeable future to both satisfy civil aviation's need for long-range surveillance, and to provide weather data to air traffic controllers.[9]

2700–2900 MHz. Airport surveillance radars operating in this band will remain essential to providing safe and reliable air traffic control near airports. Replacements for ASR's deployed in the early 1970's are being jointly developed by the FAA and DOD. Further, plans for a new "multipurpose" terminal radar have been outlined that would combine the terminal surveillance and weather radars of some of today's operating radars about the year 2020. If deployed, this new radar would likely use the same spectrum as the two systems its replaces (2700–2900 and 5600–5650 MHz, and part of 5150–5250 MHz).[10]

2700–3000 MHz. The NEXRAD operates in this frequency band and is the primary system for collecting wide-area weather information for flight planning purposes. The FAA believes that planned enhancements to the NEXRAD should extend its service life to the year 2040.[11]

4200–4400 MHz. According to the FAA and ICAO, radar altimeters will remain an essential element of the modernized air traffic control system. The spectrum used by these systems will be needed indefinitely, and must be available for exclusive use. Also, because of the critical safety aspects of its use, this band must be protected from out-of-band interference due to adjacent-channel or harmonics encroachment.[12]

5150–5250 and 5600–5650 MHz. Terminal Doppler weather radars will continue to provide weather surveillance in the air traffic control terminal areas. These two frequency bands will be needed to support the modernized air traffic control system.[13]

5350–5470 MHz, 9300–9500 MHz, and 13250–13400 MHz. The FAA believes that airborne weather radars operating in these bands will continue to be important to commercial aviation, especially in those areas with limited or no air traffic control service.[14]

9000–9200 MHz. A low cost ASDE system is being developed in this band to support ground surveillance at smaller airports. Designed to complement the more complex, expensive ASDE–3 system that is installed at larger airports, this system will assist controllers at reducing the number of runway incursions, a top priority in improving the safety of the flying public.[15]

15700–16200 MHz. The FAA is currently using this band for ASDE–3 radars and sees continued use of this band in the foreseeable future. Additionally, to satisfy the need for ASDE systems at smaller airports, this band is being considered along with the 9000–9200 MHz for the development of a low-cost ASDE.[16]

24250–24650 MHz. The ASDE operating in these bands have been decommissioned and the FAA has identified no further requirements for this band.[17]

Navy Radar Spectrum Requirements

As the Navy looks to the 21st century, it is redefining sea power as well as its ability to project and sustain power ashore. The Navy's use of radars aboard its various platforms (ship, aircraft, and shore vehicles) play a significant role in its platform's mission accomplishment. NTIA envisions the Navy radar usage requirements to increase, particularly above 6 GHz, but to be accommodated within the current frequency allocations.

Shipborne Radars. Shipborne radars support the ship's mission support operations during the ship's operational life cycle. Naval ships are normally projected to be in operation for 20–30 years while aircraft carriers are projected for a 40–50 year life cycle.[18] Thus, the various U.S. Navy shipborne radars will continue to operate on their supporting platforms for at least the next 20 years. For example, the AN/SPN-43 radar has been in use for over 30 years. As required, these systems are removed from decommissioned ships and re-installed into new ship construction. Thus, the Navy's active fleet of air-capable ships are always equipped with the AN/SPN-43 radar. These bands are:

420–450 MHz

902–928 MHz
1215–1390 MHz
2900–3100 MHz
3100–3650 MHz
5250–5900 MHz
8500–10550 MHz
13400–14000 MHz
15300–15900 MHz
16000–17000 MHz
31800–33400 MHz
92000–100000 MHz

Airborne Radars. The range and depth of naval aviation supports a broad force structure representing diverse missions such as air-to-air, air-to-ground, fleet early warning, troop transport, and search and rescue functions. The main sizing elements in current Navy planning includes:

- An aircraft carrier fleet comprising 11 active and one reserve carrier.[19]

- By the turn of the century, 10 active and one reserve air wing will support the carriers. Each air wing will comprise 50 high performance F-18 and F-14 multiple mission capable strike fighter aircraft, EA-6B's, E-2C's, S-3B's and ES-3A's. [20]

- Marine aircraft wings will consist of three active and one reserve squadrons.[21]

- Maritime patrol aircraft at the turn of the century will consist of 12 active and 8 reserve squadrons flying P-3C aircraft supporting increasing multi-mission anti-surface warfare requirements.[22]

The Navy expects its aviation effectiveness to remain unchanged in the foreseeable future and its present aircraft and replacements to be in operation to at least the year 2020. Therefore, the radar frequency bands supporting airborne radars will be required to at least the year 2020 in the following bands:

420–450 MHz
4200–4400 MHz
5500–5900 MHz
8500–10000 MHz
13250–13400 MHz

Land-Based Radars. The Navy operates many various land-based radars ashore. Many are integral systems supporting the USMC, air traffic control at its naval air stations, and many others for its various tests ranges. NTIA believes Navy ground-based radar spectrum requirements will remain the same in the foreseeable future. These bands are:

3–30 MHz
216–220 MHz
1215–1390 MHz
2700–2900 MHz
2900–3000 MHz
5400–5900 MHz
9000–10550 MHz
15300–17300 MHz
24050–24250 MHz

Air Force Radar Spectrum Requirements

Airborne and Land-based Radars. The Air Force employs thousands of aircraft and aviation systems in mission areas such as aerospace control, theater battle management, combat delivery, strategic air defense, surveillance and reconnaissance, airlift and rescue, and special operations. Both airborne and land--based radars are integral parts supporting the various Air Force mission areas. By the year 2020, the Air Force aircraft force structure for fighter, bomber, and attack aircraft will number approximately 2,800; airlift and rescue aircraft approximately 675; special operations aircraft approximately 175; airlift and refueling aircraft approximately 775; and other aircraft approximately 160.[23] NTIA believes the airborne and land-based radars operating in the following bands will be required to at least the year 2020 to support the various Air Force mission areas:

420–450 MHz
902–928 MHz
1215–1390 MHz
2700–2900 MHz
2900–3100 MHz
3100–3650 MHz
4200–4400 MHz
5400–5925 MHz
8500–10550 MHz
13250–13400 MHz
15700–17300 MHz
31800–33400 MHz

33400–36000 MHz

Army Radar Spectrum Requirements

Airborne Radars. Army aviation provides versatile, rapidly deployable, responsive forces that overcome the limitations of ground systems by easily negotiating terrain obstacles; expanding the battle space; massing the effects of fire without missing forces; and delivering precise, lethal fires. Airborne radar systems are an integral part of the resources employed by Army aviation to ensure successful airborne missions. As a result of its downsizing, the Army has reduced rotary-wing aircraft to approximately 4,805. This is also the projected number of rotary-wing aircraft it plans to have in the year 2020.[24] NTIA envisions no change to the Army airborne radar spectrum requirements in the foreseeable future. The following radar bands will be needed to support the Army airborne radar systems to at least the year 2020:

4200–4400 MHz
5250–5925 MHz
9200–10000 MHz

Land-Based Radars. Army forces are primarily ground forces that, when deployed, rely heavily on radars for air and battlefield defense. While in-garrison, radars are used for land-based air defense, training in the proper use of battlefield, missile control and ground surveillance radars. Additionally, the Army uses many radars on its various test and operational ranges for range safety, surveillance, and instrumentation (telemetry). NTIA believes Army ground based radar spectrum requirements will remain the same in the foreseeable future. These bands are:

420–450 MHz
902–928 MHz
1215–1390 MHz
2700–2900 MHz
2900–3400 MHz
5250–5925 MHz
8500–10550 MHz
15300–17300 MHz
24050–24250 MHz
33400–36000 MHz

U.S. Coast Guard Radar Spectrum Requirements

Airborne Radars. The USCG presently operates throughout the United States and its Possessions approximately 202 aircraft from its 26 Air Stations.[25] These aircraft are primarily of four different types: the HH-65 Dauphin helicopter for short-range recovery missions; the HH–60 Jayhawk helicopters for medium-range recovery missions; the HU–25 Guardian fixed-wing aircraft for medium-range surveillance; and the HC–130V Hercules fixed-wing for its long-range surveillance missions.[26] Each aircraft is equipped with radar systems that are integral assets that help the USCG accomplish its various roles. Aircraft in the USCG inventory have a planned service life of 20 years. Presently, all but the HH-60 helicopter are undergoing mission analysis for replacement, fleet rehabilitation, or future acquisition decisions. The planned service life for the USCG aircraft is around the year 2010. All the radar bands that the USCG uses aboard its aircraft will be needed to at least the year 2010.

420–450 MHz
4200–4400 MHz
8500–9600 MHz
13250–13400 MHz

Shipborne Radars. With U.S. maritime trade possibly tripling by 2020, the number of oceangoing vessels transiting U.S. waters will increase.[27] Coupled with USCG's increased role in maritime law enforcement against illicit maritime activities, the USCG will place heavy reliance on its ships and its various surveillance systems. Shipborne radars will be one of the tools expected to be employed in support of the USCG mission. USCG ships, like Navy ships, are normally projected to an operational life cycle for 20–30 years. Therefore, the various USCG shipborne radars will continue to operate on their supporting platforms for at least the next 20 years. NTIA believes USCG shipborne radar spectrum requirements will remain the same in the foreseeable future. These bands are:

420–450 MHz
2900–3100 MHz

9200–10000 MHz

Land-Based Radars. Land-based radars are employed by the USCG as aids to navigation, search and rescue services, port safety and security, as well as for automobile vehicle speed detection. NTIA envisions no reduction in this USCG mission requirement and foresees continued USCG radar usage in the following bands.

2900–3100 MHz
9300–10000 MHz
10450–10550 MHz

NASA Radar Spectrum Requirements

Radar is a very important tool that NASA employs as it conducts flight research within and outside the Earth's atmosphere and the testing and operation of aeronautical and space vehicles. Additionally, NASA makes good use of radars in the exploration of space with manned and unmanned vehicles and in its Earth exploration programs. NTIA foresees long continued use of radars by NASA for land-based, airborne, shipborne, and spaceborne missions and operations well beyond 2020.

420–450 MHz
902–928 MHz
1215–1300 MHz
2310–2345 MHz
2700–2900 MHz
2900–3500 MHz
4200–4400 MHz
5250–5925 MHz
8500–9800 MHz
9975–10025 MHz
10450–10550 MHz
13250–13750 MHz
15460–15616 MHz
17200–17300 MHz
24050–24250 MHz
33400 MHz
35500–36000 MHz
78000–79000 MHz
85000 MHz
92000–95000 MHz
130000–195000 MHz
>300000 MHz

Department of Commerce Radar Spectrum Requirements

With the nation's increased reliance on accurate weather forecasts, weather-related information, and desire for better management of our natural resources, the dependence on radars to assist in these efforts is also increased. NTIA sees a radar spectrum requirement by NOAA (primarily NWS and NFS) for the foreseeable future in the following bands:

404 MHz
449 MHz
2700–3100 MHz
4200–4400 MHz
5370–5480 MHz
5600–5650 MHz
8500–9000 MHz
9200–10000 MHz
10450–10550 MHz

Department of the Interior Radar Spectrum Requirements

As the Department of the Interior moves into the 21st century, its mission to continue land and resource management will more than likely continue. Its reliance on radars to support its geological survey and park management activities will also be required and NTIA sees their radar spectrum requirement continuing for the foreseeable future in the following bands:

5470–5600 MHz
9350–9450 MHz
10450–10550 MHz
24050–24250 MHz

Department of Agriculture Radar Spectrum Requirements

The Department of Agriculture envisions the continued need for its radars in the research and management of natural resources and the environment. NTIA sees their radar spectrum requirement continuing for the foreseeable future in the 9300–9500 MHz and 10450–10550 MHz frequency bands.

Department of Justice Radar Spectrum Requirements

The Department of Justice expects to continue employing a variety of radio communications equipment including radar devices in its law enforcement, crime prevention, and crime detection efforts. NTIA sees their radar spectrum requirements continuing for the foreseeable future in the 300–3000 MHz and 4200–4400 MHz bands.

National Science Foundation Radar Spectrum Requirements

In its promotion of scientific and engineering research programs, the NSF employs radars for a variety of purposes ranging from atmospheric research, radar astronomy, and range safety. NTIA envisions the NSF's need for radars to supports its research programs well into the future. The following frequencies and frequency bands are anticipated to be required by the NSF in the foreseeable future:

908–928 MHz
2380 MHz
2700–2900 MHz
9200–9500 MHz

Department of Treasury Radar Spectrum Requirements

In its law enforcement function, the Department of Treasury will continue to employ land-based, airborne, and shipborne radars well into the future. NTIA expects their radar spectrum requirements to continue for the foreseeable future in the following bands:

420–450 MHz
1215–1390 MHz
2900–3100 MHz
9200–9500 MHz

Department of Energy Radar Spectrum Requirements

Radars are an important tool that DOE employs in its research that supports our nation's energy security, national security, and environmental quality. The Department envisions its use of radars well into the future. NTIA sees their radar spectrum requirements continuing for the foreseeable future in the following bands:

30–100 MHz
404 MHz
420–450 MHz
915 MHz
1215–1390 MHz
2900–3650 MHz
5250–5925 MHz
8500–9000 MHz
9200–9600 MHz
10450–10550 MHz
15700–16600 MHz
24050–24250 MHz
33400–36000 MHz

The Department of Energy laboratories are performing research in new radar techniques with possible uses ranging from ground penetrating technologies with 3-D displays to support law enforcement, materials composition, construction safety, medical research and national security.

Veterans Administration, US Postal Service, Health and Human Services, and the General Services Administration:

These departments employ radars for vehicle speed detection on their various facilities. NTIA expects 10450–10550 MHz and 24050–24250 MHz will continue to be used well into the future for vehicle speed detection.

Expected Radar Systems for Systems Certification

Considerable effort has been applied to spaceborne radar research for the Northern American continental defense and for Earth observations over the last 30 years. The DOD and NASA have led the U.S. efforts in SBR research.

With two new SBR systems being investigated, the DOD seems to have expressed new interest in launching SBR systems. One SBR system is the Discoverer II program that will develop and demonstrate an affordable SBR with high-range resolution ground moving target indication, synthetic aperture radar imaging capabilities, and digital terrain mapping elevation data collection. The other is the Tactical Satellite Radar (TACSRAD) envisioned as a spaceborne, multi-mission active and passive system. The envisioned TACSRAD constellation will be medium Earth orbit, consisting of 10 satellites in an equatorial orbit, and providing essentially continuous coverage from the Equator to approximately 60 degrees north and south latitudes. Each of these SBR systems are expected to operate in at least one of the radar bands between 1–20 GHz.

Pending WRC–97 implementation of new frequency allocations for EESS, NASA has plans to use these bands for SAR imaging, altimeter, scatterometers, cloud profiling, and precipitation radars. These spaceborne radars are planned in the 8550–8650, 9500–9800, 17200–17300 MHz, 35500–36000 MHz, and 94000–94100 MHz bands.

NTIA expects these spaceborne radar systems will be submitted for systems certification. Should development lead to procurement, NTIA expects the DOD and NASA to seek worldwide notification as well as protection. It is expected the DOD spaceborne radar systems will seek authorization to operate in at least one of the radar bands between 1–20 GHz. and the planned NASA spaceborne radars in the spectrum indicated. Spectrum for these spaceborne radar systems will probably be required beyond 2025.

Increased Military Radar Usage

For military radar systems, the increased demand for information of all types has resulted in the increased use of radar in the battlespace and procurement of radar systems with improved target detection range and target definition. Consequently, the density of radar emitters in military operating areas is projected to increase which directly translates into increased use and demand for electromagnetic spectrum. Given this increase in density, high-power radar system spectrum requirements must also reflect consideration of the guard bands necessary to protect the radar functionality and avoid interference to adjacent spectrum users in the battlespace. These guard bands vary as a function of design-specific characteristics including but not limited to peak radiated power, the level of noise outside the radar fundamental emission , and their relationship to one another. Further, widely varying radar system mission requirements dictate operations in a wide range of frequency bands, with large and varying bandwidths, from 300 MHz through 12 GHz and beyond.[28]

Total Federal Radar Spectrum Requirements

For the purposes of spectrum planning, the following table lists frequency bands that have been identified as necessary to support radar spectrum requirements for various Federal agencies. The information in the table below should be considered as long-range planning information for Federal radar systems. Because Federal agency missions are unlikely to change, and radar platforms are likely to be updated or replaced, the actual time frame for the radar spectrum requirement is likely to be extended beyond the 20–year time frames shown below.

20–Year Federal Spectrum Requirement Forecast for Radar Bands

Frequency Bands	Federal Government Use
92–100 GHz	Airborne fire-control, beacons, atmospheric research, cloud detection, and synthetic vision radars
31.8–36 GHz	Airborne navigational, mapping, weather, beacon, terrain following & avoidance; aircraft carrier PAR, test range, atmospheric & oceanic research, altimeter, scatterometer, and synthetic vision radars
24.05–24.65 GHz	Doppler radiolocation, vehicle speed detection, scatterometer, and precipitation radars
15.4–17.3 GHz	Airborne and shipborne multimode search, battlefield, aircraft carrier PAR, fire-control, test range, ASDE, scatterometer, precipitation, atmospheric research, and spaceborne radars
13.25–14.2 GHz	Airborne and shipborne search and acquisition Doppler, airborne weather, altimeters, scatterometer, precipitation, environmental research, and spaceborne radars
8.5–10.55 GHz	Airborne and shipborne surveillance and navigation, fire-control, battlefield, maritime, weather, test range, airborne radionavigation, ATC, SAR's, altimeters, ASDE, scatterometer, vehicle speed detection, and spaceborne radars
5250–5925 MHz	NOAA weather radars, FAA TDWR, surveillance and air defense (airborne, shipborne, land-based), fire-control, maritime, test range, SAR's, altimeters, scatterometer, airborne, and spaceborne radars
4200–4400 MHz	Aircraft radar altimeters
3100–3650 MHz	DOD surveillance and air defense (airborne, shipborne, land-based), ATC, SAR's, altimeters, test range, and spaceborne radars
2700–3100 MHz	ATC, maritime, and weather radars; DOD shipborne, airborne, ground air surveillance radars; range control, and spaceborne radars
2310–2385 MHz	Planetary and lunar radar
1215–1390 MHz	ATC, SAR's, and DOD early warning air defense, battlefield, shipborne long-range surveillance, and spaceborne radars
890–942 MHz	Navy shipborne long-range surveillance, test range, NASA research, and wind profiler radars
420–450 MHz	DOD early warning and long-range surveillance radars; and wind profiler radars
216–220 MHz	DOD space surveillance radar
3–30 MHz	DOD OTH and surface wave radars

Endnotes: Chapter 5

1. National Telecommunications and Information Administration, U.S. Department of Commerce, NTIA Special Publication 94–31, U.S. National Spectrum Requirements: Projections and Trends (1995), at 141.

2. U.S. Department of Commerce/NOAA, Office of the Federal Coordinator for Meteorology, The Federal Plan for Meteorological Services and Supporting Research, Fiscal Year 1999, FCM P1–1998, June 1998, at vii–ix.

3. Department of Transportation, Federal Aviation Administration, Radio Spectrum Requirements for a Modernized Air Traffic Control System, July 1997, at 30 [hereinafter FAA Spectrum Requirements].

4. Department of Navy email comments from Mr Bruce Swearingen, Director, Naval Electromagnetic Spectrum Center, at 2. (*See* email from swearinb@navemscen.navy.mil, March 24, 2000 on file at NTIA).

5. *Id.* at 3.

6. *Id.*

7. *Id.*

8. *Id.* at 2.

9. *See* FAA Spectrum Requirements, *supra* note 3, at 29 and 31.

10. *Id.*

11. *Id.* at 37.

12. *Id.* at 22–23.

13. *Id*. at 31.

14. *Id.* at 30.

15. Email comments from Mr Tim Pawlowitz (*See* email from Theresa.Simon@FAA.gov, Dec 10, 1999, on file at NTIA).

16. *See* FAA Spectrum Requirements, *supra* note 3, at 30.

17. *Id.*

18. Interview with Mr Anthony Nickens, Division Director, Corporate Research & Development, Naval Sea Systems Command, U.S. Department of the Navy, April 21, 1999.

19. *See* Department of Defense, Joint Aeronautical Commander Group Aviation Science & Technology Plan, Volume 1: Aviation Vision, March 1999, at 29–20 [hereinafter DOD Aviation Vision].

20. *Id.*

21. *Id.* Each air wing will consist of high performance F-18 and AV-8B aircraft for close air support and EA-6B aircraft for electronic warfare.

22. *Id.*

23. *Id.*

24. *Id.*

25. The USCG Auxiliary (a civilian volunteer group) operates approximately 206 aircraft to assist with USCG missions.

26. *See* DOD Aviation Vision, *supra* note 19, at 29–20.

27. U.S. Department of Transportation, U.S. Coast Guard, Coast Guard 2020, at 9.

28. *See* Swearingen, *supra* note 4, at 2.

LIST OF ACRONYMS AND ABBREVIATIONS

AEW	Airborne Early Warning
am	Attometer (10^{-18} meter)
AMTI	Airborne Moving-Target Indication
ARSR	Air Route Surveillance Radar
ASDE	Airport Surface Detection Equipment
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
BBA–97	Balanced Budget Act of 1997
BSS	Broadcast Satellite Service
CLOUDSAT	Cloud Satellite
cm	Centimeter (10^{-2} meter)
CW	Continuous Wave
DEMS	Digital Electronic Message Service
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOJ	Department of Justice
EESS	Earth Exploration-Satellite Service
EHF	Extra High Frequency
FAA	Federal Aviation Administration
FAS	Frequency Assignment Subcommittee
FCC	Federal Communications Commission
fm	Femtometer (10^{-15} meter)
FM	Frequency Modulation
FM-CW	Frequency-Modulated Continuous-wave
GHz	Gigahertz (10^{9} Hertz)
HF	High Frequency
HF OTH	High Frequency Over-the-Horizon
ICAO	International Civil Aviation Organization
IFF	Identification, Friend or Foe
IMO	International Maritime Organization
IRAC	Interdepartment Radio Advisory Committee
ISAR	Inverse synthetic aperture radar
ITU	International Telecommunication Union
kHz	Kilohertz (10^{3} Hertz)
MHz	Megahertz (10^{6} Hertz)
mm	Millimeter (10^{-3} meter)
MTI	Moving-Target Indication
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NEXRAD	Next Generation Weather Radar
nm	Nanometer (10^{-9} meter)
NMD	National Missile Defense
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Air Defense
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
OBRA–93	Omnibus Budget Reconciliation Act of 1993
OMB	Office of Management and Budget
PAR	Precision Approach Radars
pm	Picometer (10^{-12} meter)
PRR	Pulse Repetition Rate
PW	Pulse Width
RAF	Royal Air Force
RDT&E	Research, Development, Test, and Evaluation
RPV	Remotely Piloted Vehicle
SAR	Synthetic Aperture Radar
SBR	Spaceborne Radar
SHF	Super High Frequency
SLAR	Side-looking Airborne Radar
SPASUR	Space Surveillance
SPS	Spectrum Planning Subcommittee
SR	Space Research
SRTM	Shuttle Radar Topography Mission
TDWR	Terminal Doppler Weather Radar
THAAD	Theater High Altitude Area Defense System
THZ	Terahertz (10^{12} Hertz)
TOPEX	Ocean Topography Experiment
TRMM	Tropical Rain Measuring Mission
TWS	Track-While-Scan
UHF	Ultra High Frequency
USDA	U.S. Department of Agriculture
VHF	Very High Frequency
VTS	Vessel Traffic System
WARC	World Administrative Radio Conference
WRC	World Radiocommunication Conference (formerly WARC)
µm	Micrometer (10^{-6} meter)
2–D	2–Dimensional
3–D	3–Dimensional