Introduction to
RADAR SYSTEMS

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PREFACE

The subject matter of electrical engineering may be classified according to (1) components, (2) techniques, and (3) systems. *Components* are the basic building blocks that are combined, using the proper *techniques*, to yield a *system*. This book attempts to present a unified approach to the systems aspect of radar. Although the subject of radar systems is of particular interest to specialists in the radar field, it is also of interest to a much wider audience, especially the civilian and military users of radar, the electrical and mechanical components specialists whose devices make up a radar system, the operations analysts and systems engineers who must plan for employing radar as part of larger systems, as well as practicing engineers and scientists in related fields.

This book originated in the notes for a graduate course in radar systems engineering taught for several years in the Graduate Evening Division of Northeastern University (while the author was a staff member at MIT Lincoln Laboratory) and, later, as an off-campus course at the Martin Co. for the Drexel Institute of Technology. Since most electrical engineering courses are usually concerned with either components or techniques, a course dealing with electronic systems (in this instance, radar systems) broadens the engineering background of the student by giving him the opportunity to apply the material learned from his components and techniques courses, as well as introducing him to the techniques, tools, and analytical procedures of the systems engineer.

The book may be divided into four parts. Chapters 1 to 5 deal with subjects which are characteristic of radar per se and include a brief introduction and historical survey, the prediction of radar range performance, and discussions of the pulse, CW, FM-CW, MTI, pulse-doppler, conical-scan, and monopulse radars.

The second part, Chapters 6 to 8, is concerned with the subsystems and major components constituting a radar system, such as transmitters, modulators, duplexers, antennas, receivers, and indicators. The emphasis is on those aspects of components of interest to radar. Only brief consideration is given to the operating principles of components. Many books are available that can provide more detailed descriptions than is possible in the limited space allotted here.

The third part, Chapters 9 to 12, treats various topics of special importance to the radar systems engineer. These include the detection of signals in noise and the extraction of information from radar signals, both of which are based on modern communication theory and random-noise theory. This is followed by the environmental factors influencing radar design, for example, propagation, clutter, weather, and interference.

The last portion of the book deals with radar systems and their application. Several brief examples of radars are given in Chapter 13. The book concludes with a chapter on the application of radar to the detection of extraterrestrial objects such as planets, satellites, meteors, aurora, and the moon.

Although mathematics is a valuable tool of the systems engineer, no special mathematical background is assumed here. Where mathematics is necessary, it is reviewed briefly in the text.

To attempt to treat thoroughly all aspects of a radar system, its component parts, and its analysis is an almost impossible task within a single volume, since the subject of radar encompasses almost all electrical engineering. Extensive references to the published literature are included for those desiring more detail.

Radar has been used on the ground, on the sea, and in the air, and undoubtedly it will be used in space. The environment in which a specific radar operates will have an important influence on its design. Although an attempt is made to be as general as possible, when it is necessary to particularize the radar environment, a ground-based radar is assumed unless otherwise stated.

The function of the radar systems engineer is to utilize the available components and techniques to evolve a system that will operate in a particular environment and satisfy the objectives and requirements desired by the potential user. It is hoped that this book will serve to aid those involved in this process.

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THE NATURE OF RADAR

1.1. Introduction

Radar is an electronic device for the detection and location of objects. It operates by transmitting a particular type of waveform, a pulse-modulated sine wave for example, and detects the nature of the echo signal. Radar is used to extend the capability of man's senses for observing his environment, especially the sense of vision. The value of radar lies not in being a substitute for the eye, but in doing what the eye cannot do. Radar cannot resolve detail as well as the eye, nor is it yet capable of recognizing the "color" of objects to the degree of sophistication of which the eye is capable. However, radar can be designed to see through those conditions impervious to normal human vision, such as darkness, haze, fog, rain, and snow. In addition, radar has the advantage of being able to measure the distance or range to the object. This is probably its most important attribute.

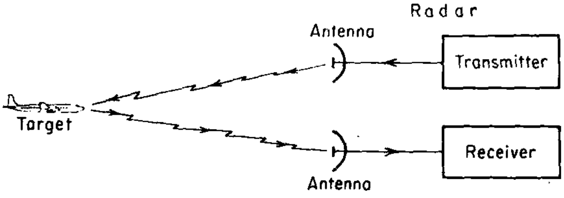

FIG. 1.1. Block diagram of an elementary form of radar.

An elementary form of radar, shown in Fig. 1.1, consists of a transmitting antenna emitting electromagnetic radiation generated by an oscillator of some sort, a receiving antenna, and an energy-detecting device, or receiver. A portion of the transmitted signal is intercepted by a reflecting object (target) and is reradiated in all directions. It is the energy reradiated in back direction that is of prime interest to the radar. The receiving antenna collects the returned energy and delivers it to a receiver, where it is processed to detect the presence of the target and to extract its location and relative velocity. The distance to the target is determined by measuring the time taken for the radar signal to travel to the target and back. The direction, or angular position, of the target may be determined from the direction of arrival of the reflected wavefront. The usual method of measuring the direction of arrival is with narrow antenna beams. If relative motion exists between target and radar, the shift in the carrier frequency of the reflected wave (doppler effect) is a measure of the target's relative (radial) velocity and may be used to distinguish moving targets from stationary objects. In radars which continuously track the movement of a target, a continuous indication of the rate of change of target position is also available.

The name *radar* reflects the emphasis placed by the early experimenters on a device to detect the presence of a target and measure its range. *Radar* is a contraction of the words *ra*dio *d*etection *a*nd *r*anging. It was first developed as a detection device to warn of the approach of hostile aircraft and for directing antiaircraft weapons. Although a well-designed modern radar can usually extract more information from the target signal than merely range, the measurement of range is still one of radar's most important functions. There seem to be no other competitive techniques which can measure range as well or as rapidly as can a radar.

Radar was the code word officially adopted by the United States Navy in November, 1940, as the designation for what had previously been called, among other things, *radio echo equipment*. The United States Army Signal Corps, which also did pioneer work in radar development, used the term *radio position finding* until it too adopted the name *radar* in 1942. The following year *radar* was substituted by the British for their own term *RDF*. The origin of the *R* is obscure, but *DF* is supposed to stand for *direction finding*, which was purposely chosen to hide the fact that a range-measuring device was under development. Shortly after the term was coined, however, means were devised for also determining the angular position, so that *RDF* almost immediately lost some of its usefulness as a code name. In France, radar was known as *DEM* (*détection électromagnétique*), and in Germany it was called *Funkmessgerat*. It is now almost universally called *radar*.

The most common radar waveform is a train of narrow pulses modulating a sine-wave carrier. Although the pulse is normally rectangular in shape, it need not be, and could be one of many possible shapes. The distance, or range,† to the target is determined by measuring the time taken by the pulse to travel to the target and return. Since electromagnetic energy travels at the speed of light, the range R is

$$R = \frac{c\,\Delta t}{2} \tag{1.1}$$

The velocity of light c is 3×10^8 m/sec, if R is measured in meters and Δt, the time duration for the wave to travel out and back, is measured in seconds. One microsecond of round-trip travel time corresponds to a distance of 0.081 nautical mile, 0.093 statute mile, 164 yd, or 492 ft. The accepted unit of distance is the nautical mile (n. mi.), which is equal to 6,076 ft, or 1,852 m. The radar range is also sometimes given in yards, especially for artillery or short-range missile fire control. In some instances, when measurement accuracy is secondary to convenience, the *radar mile* is used as a unit of range. A radar mile is defined as 2,000 yd. The difference between it and the nautical mile is less than 1 per cent.

Once the transmitted pulse is emitted by the radar, a sufficient length of time must elapse to allow any echo signals to return and be detected before the next pulse may be transmitted. Therefore the rate at which the pulses may be transmitted is determined by the longest range at which targets are expected. If the pulse repetition frequency were too high, echo signals from some targets might arrive before the transmission of the next pulse, and ambiguities in measuring range might result. Echoes that arrive after the transmission of the next pulse are called *second-time-around* (or multiple-time-around) echoes. Such an echo would appear to be at a much shorter range than the actual and could be misleading if it were not known to be a second-time-around echo. The range beyond which targets appear as second-time-around echoes is called the *maximum unambiguous range* and is

$$R_{\text{unamb}} = \frac{c}{2f_r} \tag{1.2}$$

where f_r = pulse repetition frequency, in cycles per second. A plot of the maximum unambiguous range as a function of pulse repetition frequency is shown in Fig. 1.2.

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† *Range* and *distance to the target* are used synonymously in radar parlance although, in artillery usage, range is the horizontal projection of the distance. For aircraft targets, *slant range* is sometimes used to represent the distance from radar to target, and *ground range* is used for the projection of the slant range on the ground.

Although most radars transmit a pulse-modulated waveform, there are a number of other suitable modulations that might be used to fulfill the functions of target detection and location. An example of a very important type of radar which does not use a pulsed carrier is the FM altimeter. Although the FM altimeter predates the application of radar and is not universally considered a radar, it nevertheless operates on the radar principle with the ground as the target. Even simple unmodulated CW transmissions have found application in radar. The most familiar is probably the radar speedometer, in widespread use by many highway police departments to enforce automobile speed limits. A radar employing an unmodulated CW transmission utilizes the doppler effect to detect the presence of moving targets. The doppler effect causes the signal reflected by a moving target to be shifted in frequency by an amount

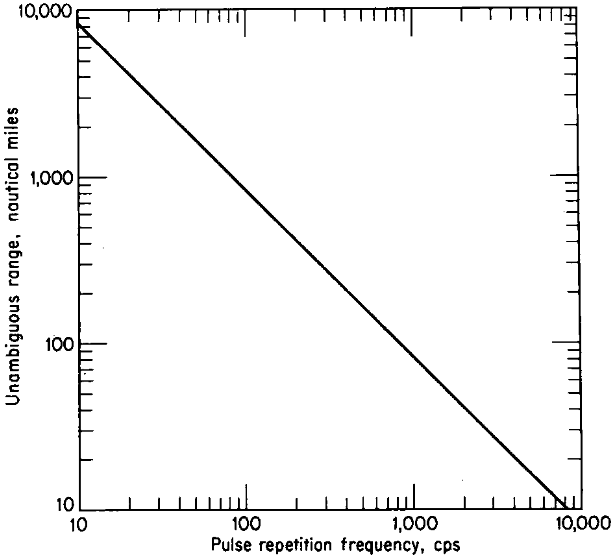

FIG. 1.2. Plot of maximum unambiguous range as a function of the pulse repetition frequency, based on Eq. (1.2).

$$f_d = \frac{2v_r}{\lambda} \tag{1.3}$$

where f_d = doppler frequency, cps
v_r = relative velocity between radar and target, m/sec
λ = wavelength of carrier frequency, m

1.2. The Radar Equation

If the power of the radar transmitter of Fig. 1.1 is denoted by P_t, and if an omnidirectional antenna is used, that is, one which radiates uniformly in all directions, the *power density* (power per unit area) at a distance R from the radar is equal to the transmitter power divided by the surface area $4\pi R^2$ of an imaginary sphere of radius R, or

$$\text{Power density from omnidirectional antenna} = \frac{P_t}{4\pi R^2} \tag{1.4}$$

Radars usually employ directive antennas, instead of omnidirectional antennas, to channel most of the radiated power P_t into some particular direction. The *gain* G_t of an antenna is a measure of the increased power radiated in the direction of the target as compared with the power that would have been radiated from an isotropic antenna. It may be defined [Eq. (7.6)] as the ratio of the maximum radiation intensity from the subject antenna to the radiation intensity from a lossless isotropic antenna with the same power input. The power density at the target from an antenna with a transmitting gain G_t is

$$\text{Power density from directive antenna} = \frac{P_t G_t}{4\pi R^2} \tag{1.5}$$

The target intercepts a portion of the radiated power and reradiates it in the direction of the radar [Eq. (1.6)].

$$\text{Power reradiated in radar direction} = \frac{P_t G_t \sigma}{4\pi R^2} \tag{1.6}$$

The parameter σ is the *radar cross section* of the target and has the dimensions of area. It is a characteristic of the target and is a measure of its size as seen by the radar. The power density in the echo signal at the radar receiving antenna is then

$$\text{Power density of echo signal at radar} = \frac{P_t G_t \sigma}{(4\pi R^2)^2} \tag{1.7}$$

The radar antenna captures a portion of the echo power. If the effective capture area of the receiving antenna is A_r, the echo power P_r received at the radar is

$$P_r = \frac{P_t G_t A_r \sigma}{(4\pi R^2)^2} \tag{1.8}$$

This is the fundamental form of the radar equation. Note that the important antenna parameters are the transmitting gain and the receiving area.

Antenna theory gives the relationship between antenna gain and effective area as

$$G_t = \frac{4\pi A_t}{\lambda^2} \qquad G_r = \frac{4\pi A_r}{\lambda^2} \tag{1.9}$$

where the subscripts *r* and *t* refer to the receiving and transmitting antennas, respectively. If a common antenna is used for both transmission and reception (as is usually the case), the reciprocity theorem of antenna theory states that $G_t = G_r = G$ and $A_t = A_r = A_e$. Using these relationships, Eq. (1.8) becomes

$$P_r = \frac{P_t A_e^2 \sigma}{4\pi \lambda^2 R^4} \tag{1.10a}$$

or

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4} \tag{1.10b}$$

The maximum radar range $R_{\max}$ is the distance beyond which the target can no longer be detected. It occurs when the received echo signal P_r just equals the minimum detectable signal $S_{\min}$. Therefore

$$R_{\max} = \left(\frac{P_t A_e^2 \sigma}{4\pi \lambda^2 S_{\min}} \right)^{\frac{1}{4}} \tag{1.11a}$$

or

$$R_{\max} = \left[\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 S_{\min}} \right]^{\frac{1}{4}} \tag{1.11b}$$

Equations (1.11*a*) and (1.11*b*) are two forms of the *radar equation* which describe range performance.

The above simplified versions of the radar equation do not adequately describe the performance of practical radars. Many important factors that affect range are not explicitly included. Because of the implicit nature of relationships between the parameters that appear in the radar equation, one must be careful about making generalizations concerning radar performance on the basis of these equations alone. For example, from Eq. (1.11*b*) it might be thought that the range of a radar varies as $\lambda^{\frac{1}{2}}$. On the other hand, Eq. (1.11*a*) would indicate a $\lambda^{-\frac{1}{2}}$ relationship, and Eq. (1.8) shows range independent of wavelength.

In practice, it is usually found that the observed maximum radar ranges are different from those predicted with the simple radar equation (1.11*a*) or (1.11*b*). Actual ranges are often much smaller than predicted. (There are some cases, however, where larger ranges might result, for instance, when anomalous propagation or subrefraction effects occur.) There are many reasons for the failure of the simple radar equation to correlate with actual performance, as discussed in Chap. 2.

1.3. Radar Block Diagram and Operation

The operation of a typical pulse radar using an oscillator such as the magnetron for the transmitter may be described with the aid of the block diagram shown in Fig. 1.3. Consider the box labeled "timer," in the upper right side of the figure. The timer, which is also called the trigger generator, or the synchronizer, generates a series of narrow timing, or trigger, pulses at the pulse repetition frequency. These timing pulses turn on the modulator which pulses the transmitter. Although the timer and the modulator both are switches, they are shown as separate boxes in the block diagram since different considerations enter into their design. The modulator must be capable of switching the high-power transmitter and might be a rather large device. On the other hand, the timer is of more modest proportions and only has to trigger the grid of a vacuum tube or thyratron.

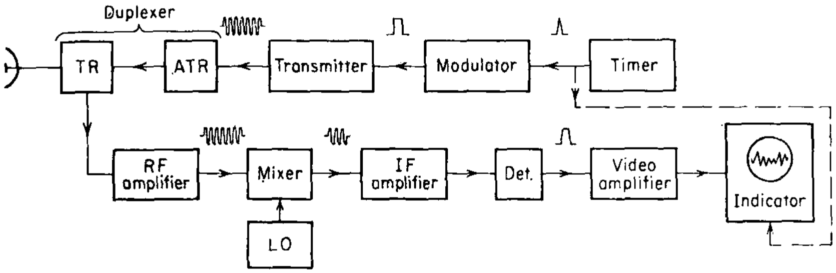

FIG. 1.3. Block diagram of a pulse radar.

A typical radar used for the detection of conventional aircraft at ranges of 100 or 200 miles might employ a peak power of the order of 1 to 10 Mw, a pulse width of several microseconds, and a pulse repetition frequency of several hundred pulses per second. The modulated RF pulse generated by the transmitter travels along the transmission line to the antenna, where it is radiated into space. A common antenna is usually used for both transmitting and receiving. A fast-acting switch called the *transmit-receive* (TR) switch disconnects the receiver during transmission. If the receiver were not disconnected and if the transmitter power were sufficiently large, the receiver might be damaged. After passage of the transmitted signal, the TR switch reconnects the receiver to the antenna.

A portion of the radiated power is reflected by the target back to the radar and enters the receiver via the same antenna as used for transmitting. The ATR (anti-transmit-receive) switch, which has no effect during the transmission portion of the cycle, acts on reception to channel the received signal power into the receiver. In the absence of the ATR, a portion of the received power would be dissipated in the transmitter rather than enter the receiver, where it belongs. The TR and the ATR are together called the *duplexer*. If separate antennas are employed for transmitting and receiving, a duplexer may not be necessary if the isolation between the two separated antennas can be made sufficiently large.

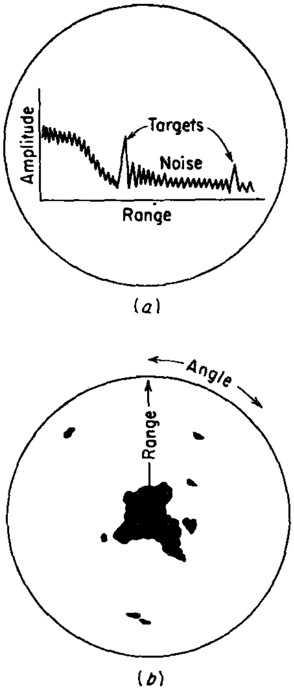

FIG. 1.4. (*a*) A-scope presentation displaying amplitude vs. range (deflection modulation); (*b*) PPI presentation displaying range vs. angle (intensity modulation).

The radar receiver is usually of the superheterodyne type. The RF amplifier shown as the first stage of the superheterodyne might be a low-noise parametric amplifier, a traveling-wave tube, or a maser. Many microwave radar receivers do not have an RF amplifier and use the mixer as the first stage, or front end. The mixer and local oscillator (LO) convert the RF signal to an intermediate frequency (IF) since it is easier to build high-gain narrowband amplifiers at the lower frequencies. A typical IF amplifier might have a center frequency of 30 or 60 Mc and a bandwidth of 1 or 2 Mc. A reflex klystron is commonly employed as the local oscillator. The RF pulse modulation is extracted by the detector and amplified by the video amplifier to a level where it can operate the indicator, usually a cathode-ray tube (CRT). Timing signals are also supplied to the indicator. Target positional information is obtained from the direction of the antenna and is used to properly display the coordinates of the target location. The two most common forms of indicators using cathode-ray tubes are the A-scope (Fig. 1.4*a*) and the plan position indicator, or PPI (Fig. 1.4*b*). The A-scope displays the target amplitude (*y* axis) vs. range (*x* axis), and no angle information is shown. The PPI maps the target in angle and range on a polar display. Target amplitude is used to modulate the electron-beam intensity (*z* axis) as the electron beam is made to sweep outward from the center with range. The beam rotates in angle in response to the antenna position.

The block diagram of Fig. 1.3 is only one version of a radar. Many variations are possible. Furthermore, the diagram is by no means complete since it does not include many devices normally found in most radars. Additional devices might include a means for automatically compensating the receiver for changes in radar frequency (AFC) or gain (AGC), receiver circuits for reducing interfering or unwanted signals, rotary joints in the transmission lines to allow movement of the antenna, circuitry for discriminating between moving targets and stationary objects (MTI), and means for allowing the antenna to automatically track a moving target.

Monitoring devices (not shown) are usually employed to ensure that the radar is operating properly. A simple but important monitoring device is a directional coupler inserted in the transmission line to sample a fraction of the transmitted power. The output from the directional coupler may be used as a measure of the transmitted power or to test the fidelity of the transmitted waveform.

A common form of radar antenna is a reflector with a parabolic shape fed from a point source. The parabolic reflector focuses the energy into a narrow beam just as does an optical searchlight or an automobile headlamp. The beam may be scanned in space by mechanically pointing the antenna.

1.4. Radar Frequencies

Conventional radars have been operated at frequencies extending from about 25 to 70,000 Mc, a spread of more than 11 octaves. These are not necessarily the limits since radars can be operated at frequencies outside either end of this range. The early radar developers were forced to design their equipments to operate at the lower frequencies, for the rather compelling reason that suitable components were not available at higher frequencies. The CH (Chain Home) radars employed by the British to provide early warning against air attack during World War II operated at a frequency in the vicinity of 25 Mc. This is a very low radar frequency by modern standards. Although higher transmitter powers are usually easier to achieve at the lower frequencies, the poor angular accuracy and poor resolution which result with antennas of reasonable size are not suitable for most applications. The antenna beamwidth is inversely proportional to the size of the antenna aperture (measured in wavelengths), and the lower the frequency, the broader will be the beamwidth for an aperture of a given size. For example, at 70,000 Mc, a 1° beamwidth can be obtained with a parabolic-reflector antenna approximately 1 ft in diameter. At 25 Mc, an antenna diameter of more than ½ mile would be necessary to achieve the same beamwidth. Considerations such as this stimulated the development of components and techniques at the higher radio frequencies, known as the microwave region.

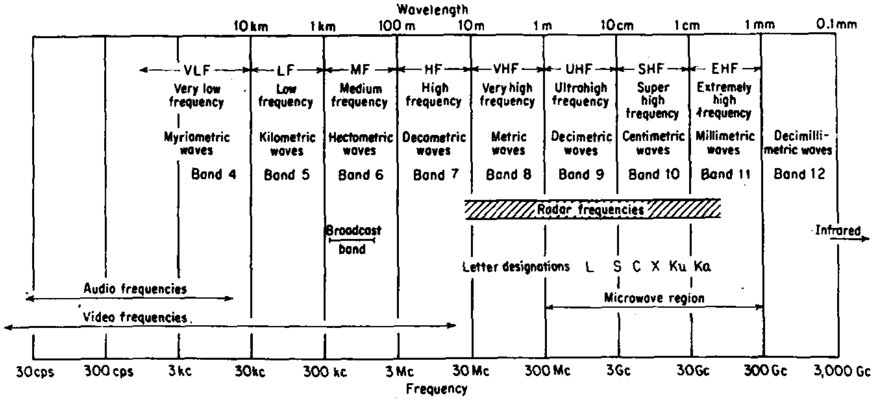

FIG. 1.5. Radar frequencies and the electromagnetic spectrum.

The place of radar frequencies in the electromagnetic spectrum is shown in Fig. 1.5. Some of the various nomenclature employed to designate the various frequency regions is also shown. The radar region is shown extending from about 25 to 70,000 Mc. Very few modern radars are found below 200 or above 35,000 Mc. An exception to this are radars that operate at high frequency (HF), about 2 to 20 Mc, and take advantage of ionospheric reflections. Radar frequencies are not found over the entire frequency region. They tend to group into separate bands for reasons of economy, both in terms of dollars and frequency allocations.

Early in the development of radar, a letter code such as *S*, *X*, *L*, etc., was employed to designate radar frequency bands. Although its original purpose was to guard military secrecy, the designations were carried over into peacetime use, probably out of habit and the need for some convenient short nomenclature. The more commonly used letter designations are indicated in Fig. 1.5 and in Table 1.1. Although these are a convenient form of nomenclature, they have no official status and there is not always general agreement as to the limits associated with each band.

Two other methods of naming frequency bands shown in Fig. 1.5 are based on frequency subdivisions and metric subdivisions. Their use is not very precise, and they define only general areas. For instance, the designation *ultrahigh frequency* (UHF) usually refers, in practice, to frequencies from about 300 to about 1,000 Mc. In radar parlance, L or S band would be used to designate the UHF frequencies above 1,000 Mc.

TABLE 1.1

Radar frequency band	*Frequency*
UHF	300–1,000 Mc
L	1,000–2,000 Mc
S	2,000–4,000 Mc
C	4,000–8,000 Mc
X	8,000–12,500 Mc
K_u	12.5–18 Gc
K	18–26.5 Gc
K_a	26.5–40 Gc
Millimeter	>40 Gc

The "band" method for designating frequency as adopted by the CCIR (Comité Consultatif International Radio) in 1953 is also shown in Fig. 1.5. The frequency "band N" extends from $3 \times 10^{N-1}$ to 3×10^{N} cps. The number of the exponent of 10 which expresses the upper frequency limit designates the band in question. For example, the UHF band extending from 3×10^8 to 3×10^9 is band 9.

The *microwave* region is that frequency region where distributed-constant, rather than lumped-constant, circuits are employed. Examples of distributed-constant devices are waveguides, cavity resonators, and highly directive antennas. The characteristic of the microwave region is that the size of the components is comparable with the wavelength. The transition between the microwave region and the lumped-constant region is not sharp. The lower limit of microwaves is shown as 300 Mc since waveguide components and power klystron amplifiers are commercially available at this frequency. The upper end of the microwave region is difficult to specify, but beyond the millimeter region, microwave techniques are more profitably replaced by optical techniques.

Also shown in Fig. 1.5 are the audio frequencies, which may be defined as the range of frequencies audible to the normal human ear. The video frequencies are also indicated. These are taken to be the range of frequencies that may be displayed on a cathode-ray tube. The video-frequency range is quite arbitrary. It extends from zero frequency to the order of several megacycles in most radar and television applications, although it can be considered to extend even higher since frequencies of several thousand megacycles or more may be displayed on cathode-ray tubes.

1.5. History of Radar Development†

Although the development of radar as a full-fledged technology did not occur until World War II, the basic principle of radar detection is almost as old as the subject of electromagnetism itself. Heinrich Hertz, in 1886, experimentally tested the theories of Maxwell and demonstrated the similarity between radio and light waves. Hertz showed that radio waves could be reflected by metallic and dielectric bodies. It is

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† Much of the material in this section concerning the early development of United States radar is based on an unpublished report by Guerlac.[1]

interesting to note that although Hertz's experiments were performed with relatively short wavelength radiation (66 cm), later work in radio engineering was almost entirely at longer wavelengths. The shorter wavelengths were not actively used to any great extent until the late thirties.

In 1903 a German engineer by the name of Hülsmeyer experimented with the detection of radio waves reflected from ships. He obtained a patent in 1904 in several countries for an obstacle detector and ship navigational device.[2] His methods were demonstrated before the German Navy, but generated little interest. The state of technology at that time was not sufficiently adequate to obtain ranges of more than about a mile, and his detection technique was dismissed on the grounds that it was little better than a visual observer.

Marconi recognized the potentialities of short waves for radio detection and strongly urged their use in 1922 for this application. In a speech delivered before the Institute of Radio Engineers, he said:[3]

> As was first shown by Hertz, electric waves can be completely reflected by conducting bodies. In some of my tests I have noticed the effects of reflection and detection of these waves by metallic objects miles away.
>
> It seems to me that it should be possible to design apparatus by means of which a ship could radiate or project a divergent beam of these rays in any desired direction, which rays, if coming across a metallic object, such as another steamer or ship, would be reflected back to a receiver screened from the local transmitter on the sending ship, and thereby, immediately reveal the presence and bearing of the other ship in fog or thick weather.

Although Marconi predicted and successfully demonstrated radio communication between continents, he was apparently not successful in gaining support for some of his other ideas involving very short waves. One was the radar detection mentioned above; the other was the suggestion that very short waves are capable of propagation well beyond the optical line of sight—a phenomenon now known as tropospheric scatter. He also suggested that radio waves be used for the transfer of power from one point to the other without the use of wire or other transmission lines.

Apparently Marconi's suggestion stimulated A. H. Taylor and L. C. Young of the Naval Research Laboratory to confirm experimentally the speculations concerning radio detection. In the autumn of 1922 they detected a wooden ship using a CW wave-interference radar with separated receiver and transmitter. The wavelength was 5 m. A proposal was submitted for further work but was not accepted.

The first application of the pulse technique to the measurement of distance was in the basic scientific investigation by Breit and Tuve in 1925 for measuring the height of the ionosphere.[4] However, more than a decade was to elapse before the detection of aircraft by pulse radar was demonstrated.

The first experimental radar systems operated with CW and depended for detection upon the interference produced between the direct signal received from the transmitter and the doppler-frequency-shifted signal reflected by a moving target. This effect is the same as the rhythmic flickering, or flutter, observed in an ordinary television receiver, especially on weak stations when an aircraft passes overhead. This type of radar originally was called *CW wave-interference radar*. Today, such a radar is called a *bistatic CW radar* (Sec. 13.6). The first experimental detections of aircraft used this radar principle rather than a monostatic (single-site) pulse radar because CW equipment was readily available. Successful pulse radar had to await the development of suitable components, especially high-peak-power tubes, and a better understanding of pulse receivers.

The first detection of aircraft using the wave-interference effect was made in June, 1930, by L. A. Hyland of the Naval Research Laboratory.[1] It was made accidentally while he was working with a direction-finding apparatus located in an aircraft on the ground. The transmitter at a frequency of 33 Mc was located 2 miles away, and the beam crossed an air lane from a nearby airfield. When aircraft passed through the beam, Hyland noted an increase in the received signal. This stimulated a more deliberate investigation by the NRL personnel, but the work continued at a slow pace, lacking official encouragement and funds from the government, although it was fully supported by the NRL administration. By 1932 the equipment was demonstrated to detect aircraft at distances as great as 50 miles from the transmitter. The NRL work on aircraft detection with CW wave interference was kept classified until 1933, when several Bell Telephone Laboratories engineers reported the detection of aircraft during the course of other experiments.[5] The NRL work was disclosed in a patent filed and granted to Taylor, Young, and Hyland[6] on a "System for Detecting Objects by Radio." The type of radar described in this patent was a CW wave-interference radar. Early in 1934, a 60-Mc CW wave-interference radar was demonstrated by NRL.

The early CW wave-interference radars were useful only for detecting the *presence* of the target. The problem of extracting target-position information from such radars was a difficult one and could not be readily solved with the techniques existing at that time. A proposal was made by NRL in 1933 to employ a chain of transmitting and receiving stations along a line to be guarded, for the purpose of obtaining some knowledge of distance and velocity. This was never carried out, however. The limited ability of CW wave-interference radar to be anything more than a trip wire undoubtedly tempered what little official enthusiasm existed for radar.

It was recognized that the limitations to obtaining adequate position information could be overcome with pulse transmission. Strange as it may now seem, in the early days pulse radar encountered much skepticism. Nevertheless, an effort was started at NRL in the spring of 1934 to develop a pulse radar. The work received low priority and was carried out principally by R. M. Page, but he was not allowed to devote his full time to the effort.

The first attempt with pulse radar at NRL was at a frequency of 60 Mc. According to Guerlac,[1] the first tests of the 60-Mc pulse radar were carried out in late December, 1934, and early January, 1935. These tests were "hopelessly unsuccessful and a grievous disappointment." No pulse echoes were observed on the cathode-ray tube. The chief reason for this failure was attributed to the receiver's being designed for CW communications rather than for pulse reception. The shortcomings were corrected, and the first radar echoes obtained at NRL using pulses occurred on Apr. 28, 1936, with a radar operating at a frequency of 28.3 Mc and a pulse width of 5 μsec. The range was only 2½ miles. By early June the range was 25 miles.

It was realized by the NRL experimenters that higher radar frequencies were desired, especially for shipboard application, where large antennas could not be tolerated. However, the necessary components did not exist. The success of the experiments at 28 Mc encouraged the NRL experimenters to develop a 200-Mc equipment. The first echoes at 200 Mc were received July 22, 1936, less than three months after the start of the project. This radar was also the first to employ a duplexing system with a common antenna for both transmitting and receiving. The range was only 10 to 12 miles. In the spring of 1937 it was installed and tested on the destroyer *Leary*. The range of the 200-Mc radar was limited by the transmitter. The development of higher-powered tubes by the Eitel-McCullough Corporation allowed an improved design of the 200-Mc radar known as XAF. This occurred in January, 1938. Although the power delivered to the antenna was only 6 kw, a range of 50 miles—the limit of the sweep—was obtained by February. The XAF was tested aboard the battleship *New York*, in maneuvers held during January and February of 1939, and met with considerable success. Ranges of 20 to 24 kiloyards were obtained on battleships and cruisers. By October, 1939, orders were placed for a manufactured version called the CXAM. Nineteen of these radars were installed on major ships of the fleet by 1941.

The United States Army Signal Corps also maintained an interest in radar during the early 1930s.[7] The beginning of serious Signal Corps work in pulse radar apparently resulted from a visit to NRL in January, 1936. By December of that year the Army tested its first pulse radar, obtaining a range of 7 miles. The first operational radar used for antiaircraft fire control was the SCR-268, available in 1938. The basic patent[8] describing the prototype of the SCR-268 was awarded to Colonel William R. Blair, a former director of the Signal Corps Laboratories. The claims contained in this patent apparently cover most of the basic ideas inherent in pulse-echo radio ranging and detection. Although Colonel Blair's patent may legally make him the originator of pulse radar, the spontaneous and independent development of pulse radar by several investigators in this country and abroad seems to make it difficult to assign sole credit to any one person for its origin.

The SCR-268 was used in conjunction with searchlights for radar fire control. This was necessary because of its poor angular accuracy. However, its range accuracy was superior to that obtained with optical methods. The SCR-268 remained the standard fire-control equipment until January, 1944, when it was replaced by the SCR-584 microwave radar. The SCR-584 could control an antiaircraft battery without the necessity for searchlights or optical angle tracking.

In 1939 the Army developed the SCR-270, a long-range radar for early warning. The attack on Pearl Harbor in December, 1941, was detected by an SCR-270, one of six in Hawaii at the time.[1] (There were also 16 SCR-268s assigned to units in Honolulu.) But unfortunately, the true significance of the blips on the scope was not realized until after the bombs had fallen. A modified SCR-270 was also the first radar to detect echoes from the moon in 1946.

The early developments of pulse radar were primarily concerned with military applications. Although it was not recognized as being a radar at the time, the frequency-modulated aircraft radio altimeter was probably the first commercial application of the radar principle. The first equipments were operated in aircraft as early as 1936 and utilized the same principle of operation as the FM-CW radar described in Sec. 3.3. In the case of the radio altimeter, the target is the ground.

In Britain the development of radar began later than in the United States.[9–12] But because they felt the nearness of war more acutely and were in a more vulnerable position with respect to air attack, the British expended a large amount of effort on radar development. By the time the United States entered the war, the British were well experienced in the military applications of radar. British interest in radar began in early 1935, when Sir Robert Watson-Watt was asked about the possibility of producing a death ray using radio waves. Watson-Watt concluded that this type of death ray required fantastically large amounts of power and could be regarded as not being practical at that time. Instead, he recommended that it would be more promising to investigate means for radio detection as opposed to radio destruction. (The only available means for locating aircraft prior to World War II were sound locators whose maximum detection range under favorable conditions was about 20 miles.) Watson-Watt was allowed to explore the possibilities of radio detection, and in February, 1935, he issued two memoranda outlining the conditions necessary for an effective radar system. In that same month the detection of an aircraft was carried out, using 6-Mc communication equipment, by observing the beats between the echo signal and the directly received signal (wave interference). The technique was similar to the first United States radar-detection experiments. The transmitter and receiver were separated by about 5.5 miles. When the aircraft receded from the receiver, it was possible to detect the beats to about an 8-mile range.