NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical & Electronic Engineering

Radar In Military Services

Graduation Project
EE – 400

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To all of them, all my love.

INTRODUCTION

We had thought to do our work on the radar system, and then we search for the important part on this subject since the military radar system is one of the most common and important parts in the communication system.

In 1888 Heinrich Hertz showed that the invisible electromagnetic waves radiated by suitable electrical circuits travel with the speed of light, and that they are reflected in a similar way. From time to time in the succeeding decades it was suggested that these properties might be used to detect obstacles to navigation, but the first successful experiments that made use of them were in an entirely different context, namely, to determine the height of the reflecting layers in the upper atmosphere. One of these experiments, that of Tuve and Breit, made use of short repeated pulses of radiation, and this technique was employed in most of the developments of radar.

Electromagnetic radiation travels in empty space at a speed of 2.998 x 10^8 metes per second, and in air only slightly less rapidly; we can think of its speed as very nearly 300,000 kilometers per second. This speed is denoted by the letter *c*. Let us suppose that a very short pulse of radiation is directed towards an object at a distance *r*, and that a small fraction of this is reflected back to the starting point, so that it has traversed the distance 2r. This will take a time t = 2r/c. If we can measure this time we can determine an unknown distance to the target: r = 1/2ct. For useful terrestrial distances t is very small; an object 15 km away, for example, will return a signal in one ten-thousandth of a second.

In practice we need to know more about the target than its distance; we must also determine its direction. Arranging an antenna system to project a suitable radiation pattern that can be rotated in azimuth or elevation does this. As may be deduced from what follows, a very great deal of ingenuity and engineering skill has been devoted to the design of radar antennas.

The first successful radar installations in Great Britain in the years 1935 to 1939 used wavelengths in the 6 to 15 m band, and required very large antennas. Other equipment developed later used wavelengths of 3 m and 1.5 m; and in 1940 the invention of a new form of generator, the cavity magnetron, at once made it practicable to employ wavelengths of 10 cm and even less. Nearly all the radar development at the National Research Council in 1942 and later was done at centimeters wavelengths, universally referred to as microwaves.

In chapter one we are going to talk about the basic principles of the radar, the main components of it, the development. In this chapter we are going to talk also about the maximum unambiguous range. Frequencies and power used in radar, performance factor, factors influencing maximum range, effect of noise, and, target properties.

In chapter two present the Basic pulsed radar, receiver bandwidth requirements, factors governing pulse characteristics, Antennas and scanning, antenna scanning, Antenna tracking, Display methods, Pulsed radar system, Moving target indicator (MTI), and, Radar beacons.

Chapter three explains, shows other radar systems like CW Doppler radar, frequency-modulated CW radar, phased array radars, and, planar-array radar.

Chapter four is a bout the radar in military uses, from 1888 until now how there use it , how it was developed, and some examples of it.

CHAPTER ONE

BASIC PRINCIPLES

A typical radar system consists of the following components:

- A pulse generator that discharges timed pulses of UHF microwave/radio energy
- A transmitter
- A duplexer
- A directional antenna that shapes and focuses each pulse into a stream

Returned pulses that the receive antenna picks up and sends to a receiver that converts (and amplifies) them into video signals

- A recording device which stores them digitally for later processing and/or produces a real time analog display on a cathode ray tube (CRT) or drives a moving light spot to record on film.

Each pulse lasts only microseconds (typically there are about 1,500 pulses per second). Pulse length–an important factor along with bandwidth in setting the system resolution–is the distance traveled during the pulse generation. The duplexer separates the outgoing and returned pulses (i.e., eliminates their mutual interferences) by blocking reception during transmission and vice versa. The antenna on a ground system is generally a parabolic dish.

Radar antennas on aircraft are usually mounted on the underside of the platform so as to direct their beam to the side of the airplane in a direction normal to the flight path. For aircraft, this mode of operation is implied in the acronym SLAR, for Side Looking Airborne Radar. A real aperture SLAR system operates with a long (about 5.6 m) antenna, usually shaped as a section of a cylinder wall. This type produces a beam of no coherent pulses and uses its length to obtain the desired resolution (related to angular beam width) in the azimuthally (flight line) direction. At any instant the transmitted beam propagates outward within a fan-shaped plane, perpendicular to the flight line. A second type of system, Synthetic Aperture Radar (SAR), is exclusive to moving platforms. It uses an antenna of much smaller physical dimensions, which sends its pulses from different positions as the platform advances, simulating a real aperture by integrating the pulse echoes into a composite signal. It is possible through appropriate processing to simulate effective antenna lengths up to 100 m or more. This system depends on the Doppler effect (apparent frequency shift due to the target's or the radar-vehicle's velocity) to determine azimuthally resolution. As coherent pulses transmitted from the radar source reflect from the ground to the advancing platform (aircraft or spacecraft), the target acts as if it were in apparent (relative) motion. This motion results in changing frequencies, which give rise to variations in phase and amplitude in the returned pulses. The radar records these data for later processing by optical (using coherent laser light) or digital correlation methods. The system analyzes the moderated pulses and recombines them to synthesize signals equivalent to those from a narrow-beam, real-aperture system.

1.1 Basic Radar System

The operation of a radar system can be quite complex, but the basic principles are somewhat easy for the reader to comprehend. Covered here are some fundamentals, which will make the follow up material easier to digest. In figure (1.1) and timing diagram (figure1.2). A master timer controls the pulse repetition frequency (PRF). Theses pulses are transmitted by a highly directional parabolic antenna at the target, which can reflect (echo) some of the energy back to the same antenna. This antenna has been switched from a transmit mode to a receiver by a duplexer. The reflected energy is received, and time measurements are made, to determine the distance to the target. The pulse energy travels at 186,000 statute miles per second (162,000 nautical miles per second). For convenience, a radar mile (2000 yd or 6000 ft) is often used, with a little as 1 percent error being introduced by this measurement. The transmitted signal takes 6.16 μs to travel 1 radar mile; therefore the round trip for 1 mile is equal to 12.36 μs. With this information, the range can be calculated by applying equation (1.1).

$$\text{Range} = \frac{\Delta t}{12.36} \qquad (1.1)$$

t = time from transmitter to receiver in microsecond.

For higher accuracy and shorter range, equation (1.2) can be utilized.

$$\text{Range (yard)} = \frac{328\Delta t}{2} = 164\Delta t \tag{1.2}$$

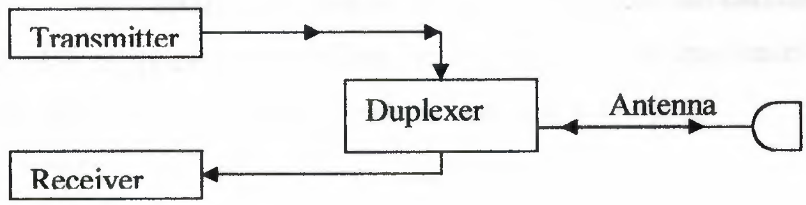
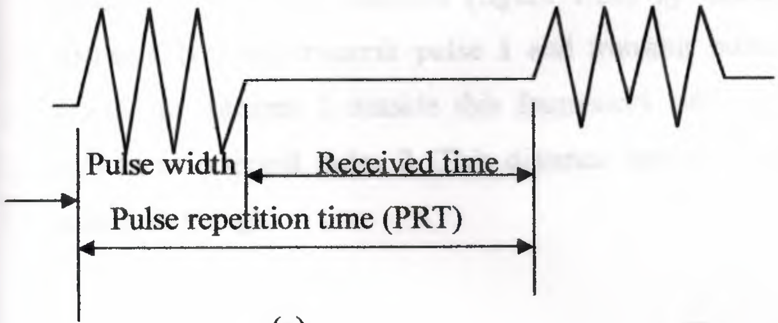
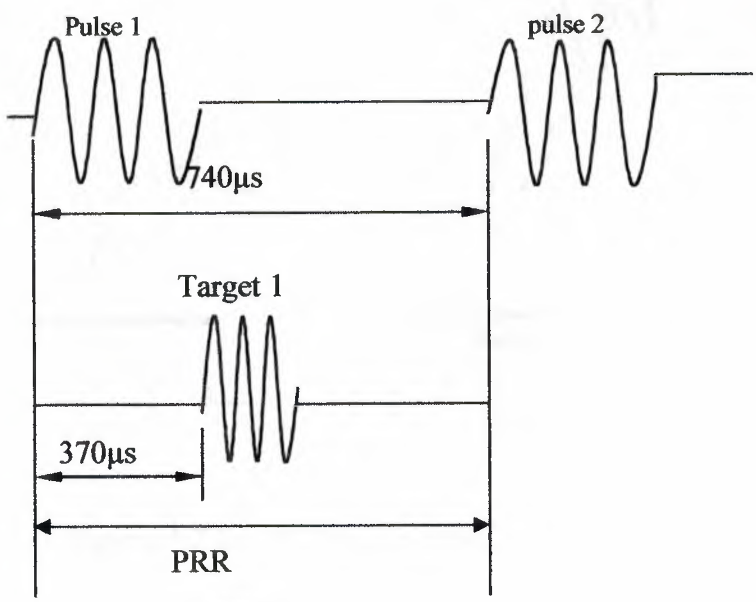


Figure 1.1 block diagram of elementary pulsed radar



(a)



(b)

Figure 1.2 timing diagram

After the radar pulse has been transmitted, a sufficient rest time (figure 1.2a) (receiver time) must be allowed for the echo to return so as not to interfere the next transmit pulse. This PRT, or pulse repetition time, determines the maximum distance to the target to be measured. Any signal arriving after the transmission of the second pulse is called second return echo and would give ambiguous indications. The range beyond which objects appear as second return echo is called the maximum unambiguous range (MUR) and can be calculated as shown in equation (1.3).

$$\text{mur} = \frac{PRT}{12.2} \tag{1.3}$$

Range in miles; PRT in μs

Refer to the timing diagram (figure 1.2a) by calculation, maximum unambiguous distance between transmit pulse 1 and transmit pulse 2 is 50 mi. Any return pulse related to transmit 1 outside this framework will appear as weak close-range pulse related to transmit pulse 2. This distance between pulse 1 and pulse 2 is called the maximum range.

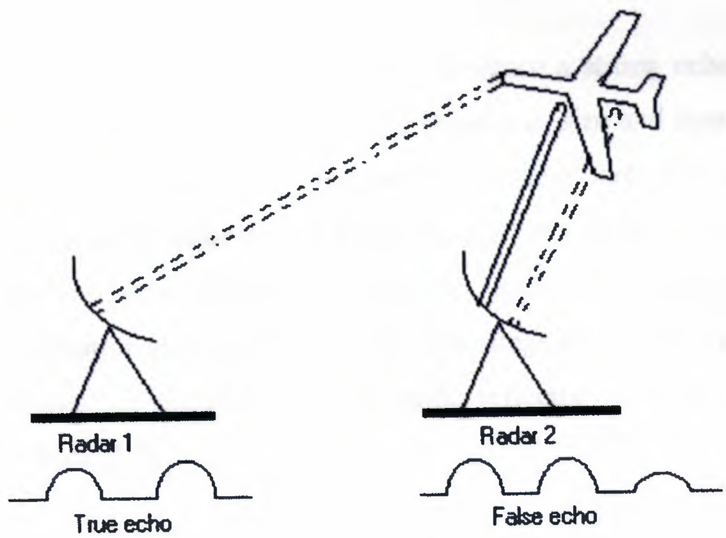


Figure 1.3 Double-range echoes

If a large reflected object is very close, the echo may return before the complete pulse can be transmitted. To eliminate ambiguity, the receiver is blocked, or returned off. Blocking of the receiver during the transmit cycle is common in must radar systems. A second problem arises with large objects at close range. The transmitted pulse may be reflected by the target for one complete round trip, figure (1.3). It may then, because of it's high energy level, be reflected by the transmitter antenna and bounced back to the target for a second round trip. This condition is called double range echoes. To overcome this form of ambiguity, Equation (1.4) is used to determine the minimum effective range.

Minimum range =164 PW

Range = yards

PW = μs

Other terms sometimes discussed in conjunction with the radar transmitter are duty cycle, peak power, and average power, to calculate the duty cycle the Equation (1.5) can be used.

$$\text{Duty cycle} = \frac{PW}{PRT} \qquad (1.5)$$

We can conclude that in order to produce a strong echo over a maximum range, high peak power is required. In some situations, size and heat are important factors (in radar in aircrafts) and low average power is requirement. We can see how low duty cycle is an important consideration. Commenting briefly on the other aspect of the radar set we find that the pulse-modulated magnetron, klystrons TWTs or CFAs are normally used as transmitter output tube, and the first stage of the receiver is often a diode mixer. The antenna generally uses a parabolic reflector of some form as will be mentioned in section (2.2).

1.1.1 Development of radar

From its inception, radar has used a system of sending powerful pulses of radio energy and then analyzing the returned echoes to determine the position, distance and possibly velocity of the target. However, the methods of doing so have evolved and become far more refined and sophisticated as time has by. The primary incentive was the imminence of war. Radar was made possible technology, which, at the time war broke out, was just beginning to show promise. This technology itself took great strides forward to meet the new challenges imposed by war.

The first radars worked at much lower frequencies than present systems as 60 MHz for the original British coastal air-warning radar because of sufficiently powerful transmitting tubes at higher frequencies. This was changed in 1940 with the appearance of the cavity magnetron, and the stage was then set for the development of modern radar. One of the prime requirements of a system is that it should have a fair degree of accuracy in its indication of target direction. This is possible only if the antennas used are narrow-beam ones, i.e., have dimensions of several wavelengths. That requirement cannot be fulfilled satisfactorily unless the wavelengths themselves are fairly short, corresponding to the upper UHF or microwave frequencies.

The advent of the magnetron also made possible the next steps in the evolution of radar, namely, airborne radar for the detection of surface vessels and then aircraft interception radar. In each of these, tight beams are necessary to prevent the receiver from being swamped by ground reflections, which would happen if insufficient discrimination between adjacent targets existed. Microwave radar for anti fire control was quickly developed, of which the most successful ground-based was the U.S. Army's SCR-584. It was capable of measuring the position of aircraft to within 0.10. And the distance, or range, to within 25 m. Such radars were eventually capable of tracking targets by locking onto them, with the aid of servomechanisms controlling the orientation of the antennas. Anti-surface vessel (ASV) radars became very common and quite accurate toward the end of the war. So did airborne radar for navigation, bombing or bomber protection; electronic navigation systems were also developed. Radar countermeasures were instituted, consisting mainly of jamming (transmission of confusing signals at enemy radar) or the somewhat more effective dropping of aluminum foil, in strips of about a half-wavelength, to cover approaching aircraft by producing false echoes. This ''chaff'' (American) or "window" (British) proved very effective, but its use in the war was considerably delayed. Each side thought that the other did not know about it and so it was kept secret; however, it eventually came to be used on a very large scale. One of the indications of the enormous growth in the importance of radar in World War II is the increase in the staff of the U.S. Army's Radiation Laboratory. It started with about 40 people in 1941, and numbers multiplied tenfold by 1945.

The subsequent developments of radar have also been numerous. They have included the use of wavelengths well into the millimeter range, at which atmospheric interference becomes noticeable, but for the presence of radar "windows." We have witnessed the use of greater powers at all wavelengths and the use of computers for a number of applications (especially fire control) to improve accuracy and reduce the time lag of manual operation. Long-range, fixed early-warning radars have been built, including the MEWS and BMEWS systems. These radars use huge antennas and enormous transmitting powers and are supplemented by radar-carrying high-flying aircraft, which have an extended radar horizon because of their height. Satellites carrying radar have been employed for military purposes, such as early detection of ballistic missiles, and civilian uses, notably in meteorology and mapping. Other important civilian uses of radar have included coastal navigation for shipping, position finding for shipping and aircraft, and air-traffic control at airports. This has extended the use of the landing facilities to weather conditions, which would have made them unusable without radar and its allied systems. Also, the use of radar by various police forces, for the control of traffic speed and the prosecution of offenders, is becoming commonplace.

Numerous scientific advances have been made with the aid of radar; for instance, as early as in 1945 an error of 900 m was found (by accident) in the map position of the island of Corsica. More recent scientific uses of radar on an interplanetary scale have yielded much useful information about the sun and the rest of the solar system, and especially about the distances and rotations of the various planetary bodies. For example, it is now known that the planet Mercury rotates with a speed not equal to its angular orbital velocity, so that it does not always present the same face to the sun.

1.1.2 Frequencies and powers used in radar

The frequencies employed by radar lie in the upper UHF and microwave ranges. As a result of wartime security, names grew up for the various frequency ranges, or bands, and these are still being used. One such term (the X hand), and the others will now be identified. Since there is not a worldwide agreement on radar band nomenclature, the names used in Table 1-1 are the common American designations.

BAND NAME	FREQUENCY RANGE GHz	MAXIMUM AVAILABLE PEAK POWER MW
UHF	0.3- 1.0	5.0
L	1.0-1.5	30.0
S	1.5-3.9	25.0
C	3.9-8.0	15.0
X	8.0-12.5	10.0
KU	12.5-18.0	2.0
K	18.0-26.5	0.6
Ka	26.5-40.0	0.25
V	40.0-80.0	0.12
N	80.0-170.0	0.01
A	Above 170	_

Table 1.1 radar bands

1.2 Radar Performance Factor

Quite apart from being limited by the curvature of the earth, the maximum range of radar set depends on a number of other factors. These can now be discussed, beginning with the classical radar range equation.

To determine the maximum range of radar set, it is necessary to determine the power of the received echoes, and to compare it with the minimum power that the receiver can handle and display satisfactorily. If the transmitted pulsed power is P_t (peak value) and the antenna is isotropic, then the power density at a distance r from the antenna will he as given by Equation (1.6), namely,

$$p = \frac{p_t}{4\pi r^2} \tag{1.6}$$

However, antennas used in radar are directional, rather than isotropic. If A_p the maximum power gain of the antenna used for transmission, so the power density at the target will be

$$p = \frac{A_p p_t}{4\pi r^2} \tag{1.7}$$

The power intercepted by the target depends on its radar cross-section, or effective area, will be discussed later on. If this area is S. the power impinging on the target will be

$$\text{p} = \text{pS} = \frac{A_p p_t S}{4\pi r^2} \tag{1.8}$$

the target is not an antenna. It is radiation may be thought of as being omni directional. The power density of its radiation at the receiving antenna will be

$$\text{p}' = \frac{P}{4\pi r^2} = \frac{A_p p_t S}{(4\pi r^2)^2} \tag{1.9}$$

Like the target, the receiving antenna intercepts a portion of the reradiated power, which is proportional to the cross-sectional area of the receiving antenna. However, it is the Capture area of the receiving antenna that is used here. Equation (1.10). The received power is

$$\text{P}' = P' A_0 = \frac{A_p P_t S A_0}{(4\pi r^2)^2} \tag{1.10}$$

Where A_0 =capture area of the receiving antenna.

If (as it is usual the case) the same antenna is used for both reception and transmission, we have equation (1.11) is for the maximum power gain,

$$A_p = \frac{4\pi A_0}{\lambda^2} \tag{1.11}$$

Substituting equation (1.11) into (1.10) gives

$$\text{P}' = \frac{4\pi A_0}{\lambda^2} \frac{P_t S A_0}{16\pi^2 r^4} = \frac{P_t A_0{}^2 S}{4\pi r^4 \lambda^2} \tag{1.12}$$

the maximum range r_{max} will be obtained when the received power is equal to the minimum receivable power of the receiver P_{min}. Substituting this into equation (1.12), and making r subject of the equation, we have

$$r_{\max} = \left(\frac{P_t A_0^2 S}{4\pi\lambda^2 P_{\min}} \right)^{1/4} \tag{1.13}$$

Alternatively, if Equation (1.11) is turned around so that $A_0 = A_p\lambda^2/4\pi$ is substituted into Equation (1.13), we have

$$r_{\max} = \left(\frac{P_t A_p^2 \lambda^2 S}{(4\pi)^3 P_{\min}} \right)^{1/4} \tag{1.13a}$$

Equations (1.13) and (l.13a) represent two convenient forms of the radar range equation., simplified to the extent that the minimum receivable power P_{min} has not yet been defined. It should also be pointed out that idealized conditions have been employed. Since neither the effects of the ground nor other absorption and interference have been taken into account, the maximum range in practice is often less than that indicated by the radar range equation.

1.2.1 Factors influencing maximum range

A number of very significant and interesting conclusions may be made if the radar range equation examined carefully. The first and most obvious is that the maximum range is proportional to the fourth root of the wok transmitted pulse power. The peak power must he increased sixteen fold, all else being constant; if a given maximum range is to he doubled. Eventually, such a power increase obviously becomes uneconomical in any particular radar system.

Equally obviously, a decrease in the minimum receivable power will have the same effect as raising the transmitting power and is thus a very attractive alternative to it. However, a number of other factors are involved here. Since P_{min} is governed by the sensitivity of the receiver (which in turn depends on the noise figure), the minimum receivable power may be reduced by a gain increase of the receiver, accompanied by a reduction in the noise at its input. Unfortunately, this may make the receiver more susceptible to jamming and interference, because it now relies more on its ability to amplify weak signals (which could include the interference), and less on the sheer power of the transmitted and received pulses. In practice, some optimum between transmitted power and minimum received power must always be reached.

The reason that the range is inversely proportional to the fourth power of the transmitted peak power is simply that the signals are subjected twice to the operation of the inverse square law, once on the outward journey and once on the return trip. By the same token, any property of the radar system that is used twice, i.e., for both reception and transmission, will show a double benefit if it is improved. Equation (1.13) shows that the maximum range is proportional to the square root of the capture area of the antenna, and is therefore directly proportional to its diameter if the wavelength remains constant. It is thus apparent that possibly the most effective means of doubling a given maximum radar system range is to double the effective diameter of the antenna. This is equivalent to doubling its real diameter if a parabolic reflector is used. Alternatively, a reduction in the wavelength used, i.e., an increase in the frequency, is almost as effective. There is a limit here also. The beam width of an antenna is proportional to the ratio of the wavelength to the diameter of the antenna. Consequently, any increase in the diameter-to-wavelength ratio will reduce the beam width. This is very useful in some radar applications, in which good discrimination between adjoining targets is required, hut it is a disadvantage in some search radars. It is their function to sweep a certain portion of the sky, which will naturally take longer as the beam width of the antenna is reduced.

Finally, Equation (1.13) shows that the maximum radar range depends on the target area, as might be expected. Also, ground interference will limit this range. The presence of a conducting ground, it will be recalled, has the effect of creating an interference pattern such that the lowest lobe of the antenna is some degrees above the horizontal. A distant target may thus be situated in one of the interference zones, and will therefore not be sighted until it is quite close to the radar set. This explains the development and emphasis of ‘‘ground-hopping” military aircraft, which are able to fly fast and close to the ground and thus remain undetectable for most of their journey.

1.2.2 Effect of noise

The previous section showed that noise affects the maximum radar range insofar as it determines the minimum power that the receiver can handle. The extent of this can now be calculated exactly. It is possible to calculate the equivalent noise power generated at the input of the receiver. N_r. This is the power required at the input of an ideal receiver having the same noise figure as the practical receiver. We then have

$$F = \frac{(S/N)_i}{(S/N)_0} = \frac{S_i N_0}{S_0 N_i} = \frac{S_i G(N_i + N_r)}{G S_i N_i} = 1 + \frac{N_r}{N_i} \qquad (1.14)$$

Where S_i = input signal power

N_i = input noise power

S_0 = output signal power

N_0 = output noise power

G = power gain of the receiver

We have

$$\frac{N_r}{N_i} = F - 1$$

$$N_r = (F-1)N_i = kT_0 \delta f (F-1) \qquad (1.15)$$

N_1

Nr (F — ON$_1$ kl$_0$ 8f(F — I) (16-15)

Where $kT_0\delta f$ = noise input power of receiver

k = Bolt Mann's constant 1.38 * 10^{-23} J/K

T_0 = standard ambient temperature I 7°C = 290 K

δf = bandwidth of receiver

It has been assumed that the antenna temperature is equal to the standard ambient temperature, which may or may not be true; but the actual antenna temperature is of importance only if a very low-noise amplifier is used. Reference may be made for the reasoning behind the substitution for N_i.

The minimum receivable signal for the receiver, under so-called threshold detection conditions, is equal to the equivalent noise power at the input of the receiver, as just obtained in Equation (1.15), This may seem a little harsh, especially since much higher ratios of signal to noise are used in continuous modulation systems. However, it must be realized that the echoes from the target are repetitive, whereas noise impulses are random. An integrating procedure thus takes place in the receiver, and meaningful echo pulses may be obtained although their amplitude is no greater than that of the noise impulses. This may be understood by considering briefly the display of the received pulses on the cathode-ray tube screen. The signal pulses will keep recurring at the same spot if the target is stationary, so that the brightness at this point of the screen is maintained (whereas the impulses due to noise are quite random and therefore not additive). If the target itself is in rapid motion, i.e., moves significantly between successive scans, a system of moving-target indication (coming in chapter three) may be used. Substituting these findings into Equation (1.13), we have

$$r_{\max} = \left[\frac{P_t A_0^2 S}{4\pi\lambda^2 k T_0 \delta f (F-1)} \right]^{1/4} \tag{1.16}$$

Equation (1-16) is reasonably accurate in predicting maximum range, provided that a number of factors are taken into account when it is used. Among these are system losses, antenna imperfection, receiver nonlinearties, anomalous propagation, proximity of other noise sources (including deliberate jamming) and operator errors, and/or fatigue (if there is an operator). It would be safe to call the result obtained with the aid of this equation the maximum theoretical range, and to realize that the maximum practical range varies between 10 and 100 percent of this value. However, range is sometimes capable of exceeding the theoretical maximum under unusual propagating conditions, such as super refraction.

It is possible to simplify Equation (1.16), which is rather cumbersome as it stands. Substituting for the capture area in terms of the antenna diameter ($A_0 = 0.65\pi D^2/4$) and for the various constants, and expressing the maximum range in kilometers, allows simplification to

$$r_{\max} = 48 \left[\frac{P_t D^2 S}{\lambda^2 \delta f (F-1)} \right]^{1/4} \tag{1.17}$$

Where r_{max} = maximum radar range, Km

P_t = peak pulse power, W

D = antenna diameter, m

S = effective cross-sectional area of target, m

δf = receiver bandwidth, Hz

λ = wavelength. M.

F = noise figure (expressed as ratio).

1.2.3 target properties

In connection with the derivation of the radar range equation, a quantity was used hut not defined. This was the radar cross-section, or effective area, the target. For targets whose dimensions are large compared to the wavelength, as aircraft microwave radar is used, the radar cross section may be defined as the objected area of a perfectly conducting sphere which would reflect the same power as e actual target reflects, if it were located at the same spot as the target. The practical nation is far from simple.

First of all, the radar cross section depends on the frequency used. If this is such at the target is small compared to a wavelength. Its cross-sectional area for radar appears much smaller than its real cross section. Such a situation is referred to as the Raleigh region. When the circumference of a spherical target is between 1 and 10 wavelengths, the radar cross section oscillates about the real one. This is the so-called resonance region. Finally. Fey shorter wavelengths (in the optical region) the radar and e cross sections are equal.

Quite apart from variations with frequency, the radar cross section of a target will depend on the polarization of the incident wave, the degree of surface roughness (If it is severe), the use of special coatings on the target and, most importantly of all. The aspect of the target. For instance, a large jet aircraft, measured at 425 MHz, has found to have a radar cross section varying between 0.2 and 300 m^2 for the fuselage, depending on the angle at which the radar pulses arrived on it. The situation is seen to be complex because of the large number of factors involved, so that a lot of work is empirical.

CHPTER TWO

PULSED SYSTEMS

Pulse systems can be descried in some details, starting with the block diagram of a typical pulse radar set and its description, followed by discussion of scanning and display method. Pulse radar can be divided broadly into search radars and tracking

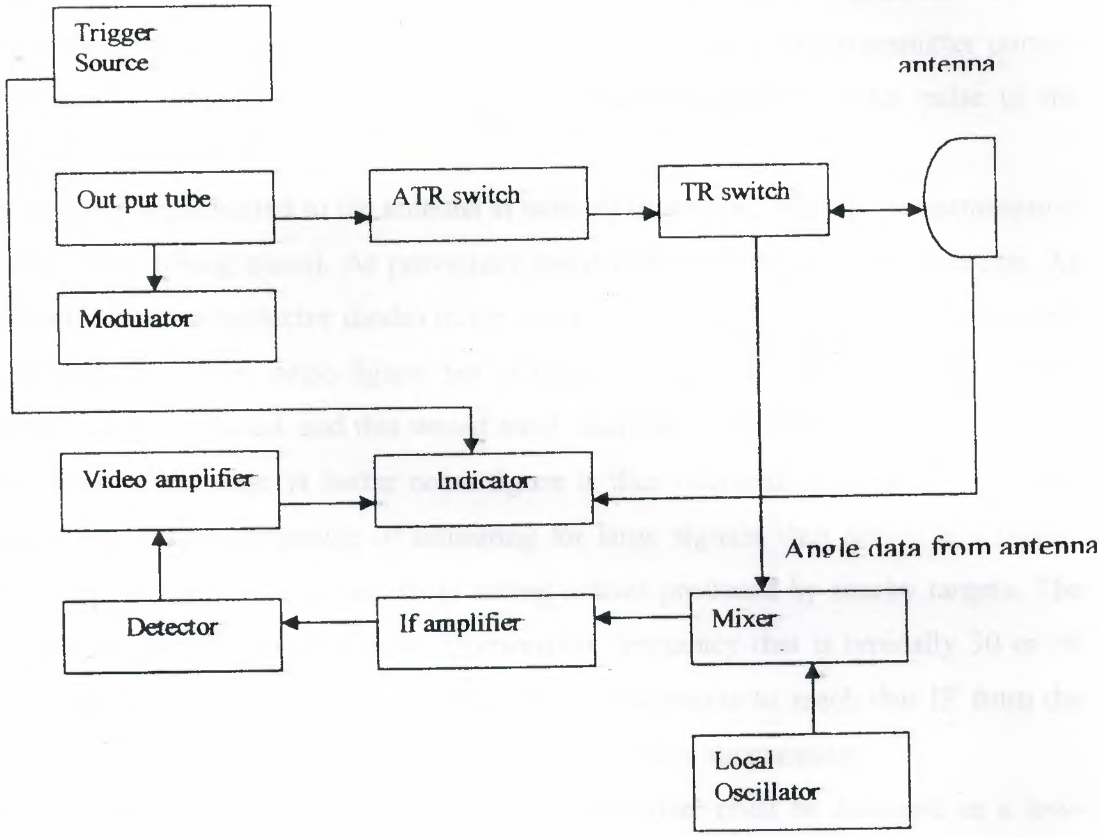


Figure 2.1 pulse radar block diagrams.

and some mention can be made of auxiliary systems such as beacon and transponders.

2.1 Basic Pulse Radar System

A very elementary block diagram of pulsed radar set was shown in figure (1.1) more detailed block diagram is given and it will be possible to talk a bout the pulsed system and the circuits used with those.

The block diagram of figure (2.1) shows the arrangement of atypical high-pulsed radar set. The trigger source provides pulses for the modulator. The modulator provides rectangular voltage pulses used as the supply voltage for the output tube, switching it on and off as required. This tube may be magnetron oscillator or an amplifier such as the Klystron, traveling wave tube or a crossed field amplifier, depending on specific requirements. If an amplifier is used, a source of microwave is required. While an amplifier may be modulated at a special grid, the magnetron cannot. If the radar is small powered one, it may use IMPATT or gun oscillator, or TRAPATT amplifiers. Bellow c band power transistor amplifier or oscillator may also be used. The transmitter portion of the radar is terminated with the duplexer, which passes the output pulse to the antenna for transmission.

The receiver is connected to the antenna at suitable times (i.e.. when no transmission is instantaneously taking place). As previously explained, the duplexer also does this. As shown here, a (semiconductor diode) mixer is the most likely first stage in the receiver, since it has a fairly low noise figure, but of course it shows a conversion loss. An RF amplifier can also be used, and this would most likely be a transistor or IC, or perhaps a tunnel diode or par amp. A better noise figure is thus obtained, and the RF amplifier may have the further advantage of saturating for large signals, thus acting as a limiter that prevents mixer diode burnout from strong echoes produced by nearby targets. The main receiver gain is provided at an intermediate frequency that is typically 30 or 60 MHz. However, it may take two or more down conversions to reach that IF from the initial microwave RF, to ensure adequate image frequency suppression.

If diode mixer is the first stage, the (first) IF amplifier must be designed as a low-noise stage to ensure that the overall noise figure of the receiver does not deteriorate. A noisy IF amplifier would play havoc with the overall receiver performance, especially when it is noted that the ''gain'' of a diode mixer is in fact a conversion loss typically 4 to 7 dB. A cascade connection is quite common for the transistor amplifiers used in the IF stage, because it removes the need for neutralization to avoid the Miller effect.

Another source of noise in the receiver of Figure (1.4) may be the local oscillator, especially for microwave radar receivers. One of the methods of reducing such noise is to use a vector or step-recovery diode multiplier. Another method involves the connection of a narrowband filter between the local oscillator and the mixer to reduce the noise bandwidth of the mixer. However, in receivers employing automatic frequency correction this may be unsatisfactory. The solution of the oscillator noise problem may then lie in using a balanced mixer and/or a cavity-stabilized oscillator. If used, AFC may simply consist of a phase discriminator which takes part of the output from the IF amplifier and produces a dc correcting voltage if the intermediate frequency drifts. The voltage may then be applied directly to a vector in a diode oscillator cavity.

The IF amplifier is broadband, to permit the use of fairly narrow pulses. This means that cascaded rather than single-stage amplifiers are used. These can be synchronous that is. All tuned to the same frequency and having identical band pass characteristics. If a really large bandwidth is needed, the individual IF amplifiers may be stagger-tuned the overall response is achieved by overlapping the responses of the individual amplifiers, which are tuned to nearby frequencies on either side of the center frequency. The detector is often a Schottky-barrier diode, whose, output is amplified by a video amplifier having the same bandwidth as the IF amplifier. Its output is then fed to a display unit, directly or via computer processing and enhancing.

Modulators In a radar transmitter, the modulator is a circuit or group of circuits whose function it is to switch the output tube ON and OFF as required. There are two main types in common use: lint -pulsing modulators and active-switch modulators. The latter are also known as driver-power-amplifier modulators and were called hard-tube modulators until the advent of semiconductor devices capable of handling some modulator duties.

Here the anode of the output tube (or its collector, depending on the tube used) is modulated directly by a system that generates and provides large pulses of supply voltage. Slowly charging and then rapidly discharging a transmission line achieve this. The charging is made slow to reduce the current requirements and is generally done through an inductance. The transmission line is able to store energy in its distributed inductance and capacitance. If the line is charged to a voltage V from a high-impedance source, this voltage will drop to 1/2V when a load is connected (the output tube) whose impedance is equal to the characteristic impedance of the line. However, at the instant of load connection the voltage across the line is 1/2V only at the input; it is still V everywhere else. The voltage drop now propagates along the line to the far end, from which it is reflected to the input terminals. It is thus seen that a voltage V will be maintained across the load for a time 2t, where t is the time taken by an electromagnetic wave to travel from one end of the line to the other.

If the pulse duration (2t) is to be 1µs, the line length must be 150 m. This is far too long for convenience, and consequently a pulse-farming network (PFN) is almost always substituted for the transmission line. As shown in Figure (2.2), which illustrates a very basic modulator, the PFN looks just like the equivalent circuit of a transmission line. It also behaves identically to the transmission line for frequencies below $f = 1/\pi$ square root of LC, where L and C are the inductance and capacitance, respectively, per section. In high-power radars, the device most likely for use as a switch is a hydrogen thyratron, because it is capable of switching very high powers and of rapid deionization. *Silicon-controlled rectifiers* (SCRs) may also be used to good advantage.

The advantages of the line modulator are that it is simple, compact, reliable and efficient. However, it has the disadvantage that the PEN must be changed if a different pulse length is required. Consequently, line modulators are not used at all in radars from which variable pulse widths are required, but they are often used otherwise. The pulses that are produced have adequately steep sides and flat tops.

The active-switch modulator is one that can also provide high-level modulation of the output tube, but this time the pulses are generated at a low power level and then amplified. The driver is often a blocking oscillator, triggered by a timing source and driving an amplifier. Depending on the power level, this may be a transistor amplifier or a powerful tube such as a shielded-grid triode. The amplifier then controls the Dc power supply for the output RF tube. This type of modulator is less efficient, more complex and bulkier than the line modulator, but it does have the advantage of easily variable pulse length, repetition rate or even shape. It is often used in practice.

Finally, low-level modulation is also sometimes possible. This may be done in UHF radar, which uses orthodox vacuum tubes, or at higher frequencies if a velocity-modulated amplifier is used. Also, in some low-power radars, it becomes possible to apply the output of the blocking oscillator directly to the output tube, simplifying the modulator circuitry.

Receiver bandwidth requirements Based on what we learned in Chapter 1. the bandwidth of the receiver correspond to the bandwidth of the transmitter and its pulse width. The narrower the pulses, the greater is the IF (and video) bandwidth required, whereas the RF bandwidth is normally greater than these, as in other receivers. With a given pulse duration *T*, the receiver bandwidth may still vary, depending on how many harmonics of the pulse repetition frequency are needed to provide a received pulse having a suitable shape. If vertical sides are required for the pulses in order to give a good resolution (as will he seen), a large bandwidth is required. It is seen that the bandwidth must be increased if more information about the target is required, but too large a bandwidth will reduce the maximum range by admitting more noise, as shown by Equation (1.16).

The IF bandwidth of a radar receiver is made n/T, where T is the pulse duration and n is a number whose value ranges from under 1 to over 10, depending on the circumstances. Values of n from I to about 1.4 are the most common. Because pulse widths normally range from 0.1 to 10 μs, it is seen that the radar receiver bandwidth may lie in the range from about 200 kHz to over 10 MHz. Bandwidths from I to 2 MHz are the most common.

2.1.2 Factors governing pulse characteristics

We may now consider why flat-Lopped rectangular pulses are preferred in radar and what it is that governs their amplitude, duration and repetition rate. These factors are of the greatest importance in specifying and determining the performance of a radar system.

There are several reasons why radar pulses ideally should have vertical sides and flat tops. The leading edge of the transmitted pulse must be vertical to ensure that the leading edge of the received pulse is also close to vertical. Otherwise, ambiguity will exist as to the precise instant at which the pulse has been returned, and therefore inaccuracies will creep into the exact measurement of the target range. This requirement is of special importance in fire-control radars. A flat top is required for the voltage pulse applied to the magnetron anode; otherwise its frequency will be altered .It also is needed because the efficiency of the magnetron, multicavity klystron or other amplifier drops significantly if the supply voltage is reduced. Finally, a steep trailing edge is needed for the transmitted pulse, so that the duplexer can switch the receiver over to the antenna as soon as the body of the pulse has passed. is will not happen if the pulse decays slowly, since there will be sufficient pulse power present to keep the TR switch ionized. We see that a pulse trailing edge, which is not steep, has the effect of lengthening the period of time, which the receiver is disconnected from the antenna. Therefore it limits the minimum range of the radar. This will be discussed in connection with pulse width.

The pulse repetition frequency, or PRF. is governed mainly by two conflicting factors. The first is the maximum range required, since it is necessary not only to be able to detect pulses returning from distant targets but also to allow them time to return before the next pulse is transmitted. If given radar is to have a range of 50 nmi (92.6 kin), at least 620 μs must be allowed between successive pulses; this period is called the pulse interval. Ambiguities will result if this is not done. If only 500 μs is used as the pulse interval, an echo received 120 μs after the transmission of a pulse could mean either that the target is 120/12.4 = 9.7 nmi (18 km) away or else that the pulse received is a reflection of the previously sent pulse, so that the target is (120 + 500)/12.4 = 50 nmi away. From this point of view, it is seen that the pulse interval should be as large as possible. The greater the number of pulses reflected from a target, the greater the probability of distinguishing this target from noise. An integrating effect takes place if echoes repeatedly come from the same target, whereas noise is random. Since the antenna moves at a significant speed in many types of radar, and yet it is necessary to receive several pulses from a given target, a lower limit on the pulse repetition frequency clearly exists. Values of PRF from 200 to 10,000/s are commonly used in practice, corresponding to pulse intervals of 5000 to 100 μs and therefore to maximum ranges from 400 to 8 nmi (740 to 15 km). When the targets are very distant (satellites and space probes, for example), lower PRFs may have to be used (as low as 30 pps).

If a short minimum range is required, then short pulses must be transmitted. This is really a continuation of the argument in favor of a vertical trailing edge for the transmitted pulse. Since the receiver is disconnected from the antenna for the duration of the pulse being transmitted (in all radars using duplexers), it follows that echoes returned during this period cannot be received. If the total pulse duration is 2 μs, then no pulses can be received during this period. No echoes can be received from targets closer than 300 m away, and this is the minimum range of the radar. Another argument in favor of short pulses is that they improve the range resolution, which is the ability to separate targets whose distance from the transmitter differs only slightly. Angular resolution, as the name implies, is dictated by the beam width of the antenna. If the beam width is 2°, then two separate targets that are less than 2° apart will appear as one target and will therefore not be resolved. If a pulse duration of 1 μs is used, this means that echoes returning from separate targets that are 1 μs apart in time, (i.e., about 300 m in distance) will merge into one returned pulse and will not be separated. It is seen that the range resolution in this case is no better than 300 m.

It is now necessary to consider some arguments in favor of long pulse durations. The main one is simply that the receiver bandwidths must be increased as pulses are made narrower, and Equation (1.16) shows that this tends to reduce the maximum range by admitting more noise into the system. Increasing the peak pulse power, but only at the expense of cost, size and power consumption may of course, counteract this. A careful look at the situation reveals that the maximum range depends on the pulse energy rather than on its peak power. Since one of the terms of Equation (1.16) is $P_t/\delta f$ and the bandwidth δf is Inversely proportional to the pulse duration, we are entitled to say that range depends on the product of PT, and T, and this product is equal to the pulse *energy*. We must keep in mind that increasing the pulse width while keeping a constant PRF has the effect of increasing the *duty cycle* of the output tube, and therefore its average power. As the name implies, the duty cycle is the fraction of time during which the output tube is *ON*. If PRF is 1200 and the pulse width is 1.5 μs, the period of time actually occupied by the transmission of pulses is 1200 x 1.5 =1800 μs/s. or 0.0018 (0.18 percent increasing the duty cycle thus increases the dissipation of the output tube. It may also have the effect of forcing a reduction in the peak power, because the peak and average powers are closely related for any type of tube. If large duty cycles are required, it is worth considering a traveling-wave tube or a crossed-field amplifier as the output tube, since both are capable of duty cycles in excess of 0.02.

2.2 Antennas and Scanning

The majority of radar antennas use dipole or horn-fed paraboloid reflectors, or at least reflectors of a basically paraboloid shape, (the cut paraboloid, parabolic cylinder or pillbox). In each of the latter, the beam width in the vertical direction (the angular resolution) will be much worse than in the horizontal direction, but this is immaterial in ground-to-ground or even air-to-ground radars. It has the advantages of allowing a significantly reduced antenna size arid weight, reduced wind loading and smaller drive motors.

2.2.1 Antenna scanning

Radar antennas are often made to scan a given area of the surrounding space, but the actual scanning pattern depends on the application. Figure 2.3 shows some typical scanning patterns. The first of these is the simplest but has the disadvantage of scanning in the horizontal plane only. However, there are many applications for this type of scan in searching the horizon, e.g., in ship-to-ship radar, The nodding scan of Figure 2.3b is an extension of this; the antenna is now rocked rapidly in elevation while it rotates more slowly in azimuth, and scanning in both planes is obtained. The system can be used to scan a limited sector or else it can be extended to cover the complete hemisphere. Another system capable of search over the complete hemisphere is the helical scanning system of Figure 2.3c, in which the elevation of the antenna is raised slowly while it

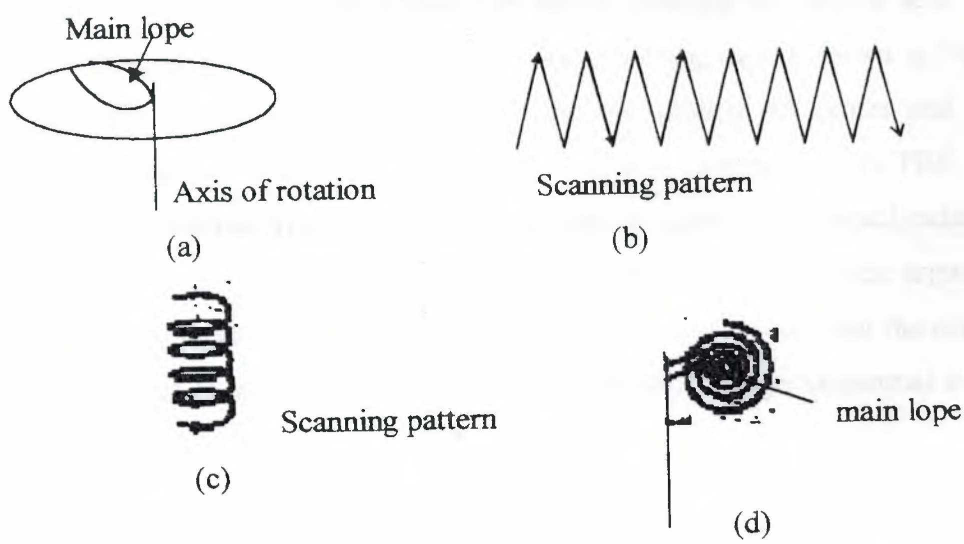


Figure 2.3 representative antenna-scanning patterns. (a) Horizontal; (b) nodding;(c) helical; (d) spiral.

Rotates more rapidly in azimuth. The antenna is returned to its starting point at the completion of the scanning cycle and typical speeds are a rotation of 6 rpm accompanied by a rise rate of 20^0/minute (World War II SCR-584 radar). Finally, if a limited area of more or less circular shape is to be covered, spiral scan may be used, as shown in Figure 2.3d.

2.2.2 Antenna tracking

Having acquired a target through a scanning method as just described, it may then be necessary to locate it very accurately, perhaps in order to bring weapons to bear upon it. Having an antenna with a narrow, pencil-shaped beam helps in this regard, but the accuracy of even this type of antenna is generally insufficient in itself. An error of only 1° seems slight, until one realizes that a weapon so aimed would miss a nearby target, only It 10 km away, by 175 m, (i.e., completely!). Auxiliary methods of tracking or precise location must be employed. The simplest of these is the lobe-switching technique illustrated in Figure 2.4a, which is also called sequential lobing. The direction of the antenna beam is rapidly switched between two positions in this system, as shown, so that the strength of the echo from the target will fluctuate at the switching rate, unless the target is exactly midway between the two directions. In this case, the echo strength will be the same for both antenna positions, and the target will have been tracked with much greater accuracy than would be achieved by merely pointing the antenna at it.

Conical scanning is a logical extension of lobe switching and is shown in Figure 2-4b. It is achieved by mounting the parabolic antenna slightly off center and then rotating it about the axis of the parabola, the rotation is slow compared to the PRF. The name conical scan is derived from the surface described in space by the pencil radiation pattern of the antenna, as the tip of the pattern moves in a circle. The same argument applies with regard to target positioning as for sequential lobing, except that the conical scanning system is just as accurate in elevation as in azimuth, whereas sequential lobing is accurate in one plane only.

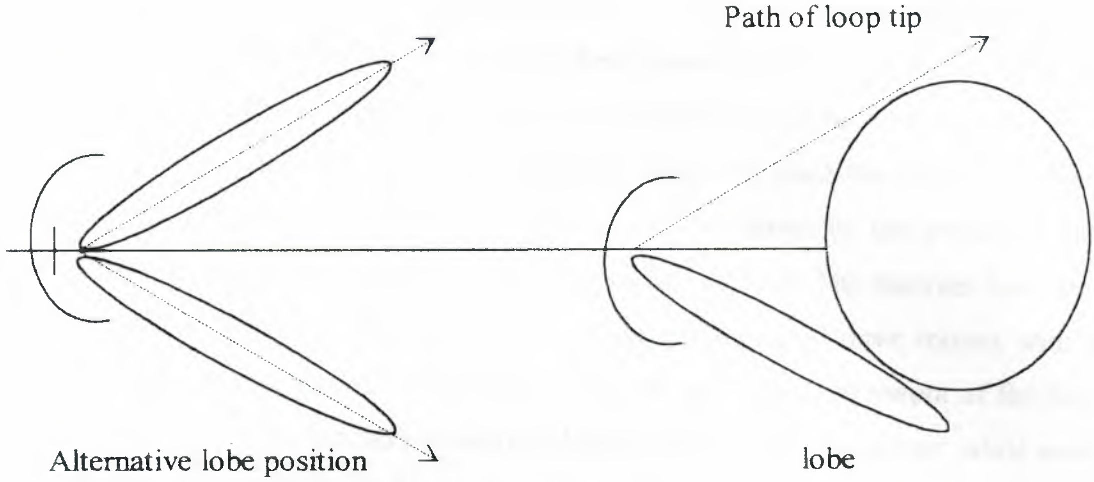


Figure 2.4 Antenna tracking. (a) Lobe switching; (b) conical scanning.

There are two disadvantages of the use of either sequential lobing or conical scanning. The first and most obvious is that the motion of the antenna is now more complex, and additional servomechanisms are required. The second drawback is due to the fact that more than one returned pulse to locate a target accurately (a minimum of four are required with conical scan, one for the extreme displacement of the antenna). The difficulty here is that if the target cross section is changing, because its change in attitude or for other reasons, the echo power will be changing also. Hence the effect conical scanning (or sequential lobing, for that matter) will be largely nullified. Form this point of view, the ideal system would be in which all the information obtained by conical scanning could be achieved with just one pulse. Such a system fortunately exists and is called monopulse.

In an amplitude-comparison monopulse system. Four feeds are used with the one-paraboloid reflector. The system using four horn antennas displaced about the central focus of the reflector is shown in figure 2.5. The transmitter feeds the horns simultaneously by a single horn. In reception, a duplexer using a rat race, is employed to provide the following three signals: the sum A+B+C+D, the vertical difference (A+C)-(B+D) and the horizontal difference (A+B)-(C+D).

Each of the four feeds produces a slightly different beam from the one reflector, so that in transmission four individual beam "stab out" in to space, being centered on a direction a beam would have had from single feed placed at the focus of the reflector. As in conical scanning and sequential lobing, no differences will be record if the target is precisely in the axial direction of the antenna. However, once the target has been acquired, any deviation from the central position will be shown by the presence of a vertical difference signal, a horizontal difference signal, or both. The receiver has three separate input channels (one four the three signals) consisting of three mixers with a common local oscillator, three IF amplifiers and three detectors. The output of the sum channel is used to provide the data generally obtained from a radar receiver, while each of the difference or error signals feeds a servo amplifier and motor, driving the antenna so as to keep it pointed exactly at the target, once this has been done, the output of the sum channel can be used for the automatic control of gunnery that is the function of the radar.

The advantage of monopulse, as previously mentioned, is that it obtains one pulse the information, which required several pulses in conical scanning. Pulse is not subject to errors due to the variation in target cross section. It requires extra receiving channels and a more complex duplexer and feeding arrangement will be bulkier and more expensive.

Some antennas arc required providing a certain amount of tracking themselves too bulky to move, e.g., the 120-by-50-m BMEWS antennas a Greenland. The feed is scanned on either side of the focus of the reflector. In simple systems, the feed horn may actually move, but in others a multiple-feed arrangement is used. This is rather similar to the monopulse feed but contains far more horns; signal is then applied to each horn in turn (also referred to as the "organ-pipe" scanner). An alternative to this system, which is rather similar to an interferometer, of using a number of fairly closely spaced fixed antennas and varying the dirt the scanning beam by changing the relative phase of the signals fed to the antennas. The name given to this is phased array. Note that no antenna movement required for scanning with either the phased array or the organ-pipe scanner. A description of various aspects of phased array radars is given in Section 3-3.

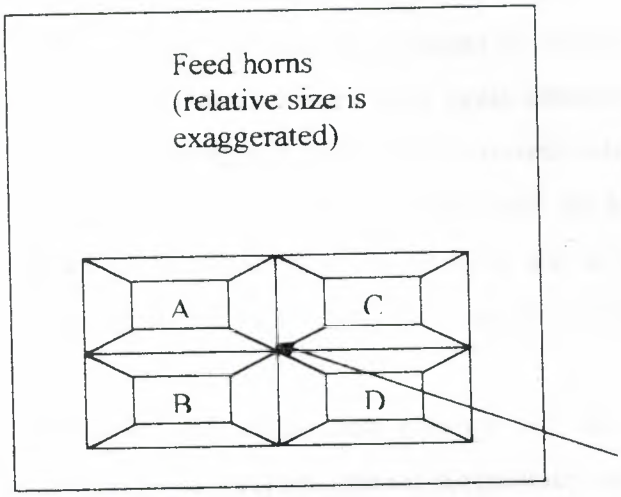


Figure 2.5 Feed arrangements for monopulse tracking

2.3 Display Methods

The output of a radar receiver may be displayed in any of a number of ways the following three being the most common: deflection modulation of a cathode-screen as in the A scope, intensity modulation of a CRT as in the plan-position indicator (PPI) or direct feeding to a computer. Additional information, such as height or velocity, may be shown on separate displays.

A scope as can be seen from Figure 2.6, the operation of this display system rather similar to that of an ordinary oscilloscope. A sweep waveform is applied horizontal deflection plates of the CRT and moves the beam slowly from left across the face of the tube, and then back to the starting point. The fly back period is rapid and occurs with the beam blanked out. In the absence of any received signal, the display is simply a horizontal straight line, as with oscilloscope. The demodulation receiver output is applied to the vertical deflection plates and causes the departures from the horizontal line, as seen in Figure 2.6. The horizontal deflection saw tooth waveform is synchronized with the transmitted pulses, so that the width of the CRT screen corresponds to the time interval between successive pulses. Displacement from the left-hand side of the CRT corresponds to the range of the target. The first 'blip" is due to the transmitted pulse, part of which is deliberately applied to the CRT for reference. Then come various strong blips due to reflections from the ground and nearby objects, followed by noise, which is here called ground clutter (the name is very descriptive, although the pips due to noise are not constant in amplitude or position). The various targets then show up as (ideally) large blips, again interspersed with grass. The height of each blip corresponds to the strength of the returned echo, while its distance from the reference blip is a measure of its range. This is why the blips on the right of the screen have been shown smaller than those nearer to the left. It would take a very large target indeed at a range of 40 km to produce the same size of echo as a normal target only 5 km away!

Of the various indications and controls for the A scope, perhaps the most important is the range calibration, shown horizontally across the tube. In some radars only one may be shown, corresponding to a fixed value of 1 km per cm of screen deflection, although in others several scales may be available, with suitable switching for more accurate range determination of closer targets. It is possible to expand any section of the scan to allow more accurate indication of that particular area (this is rather similar to band spread in communications receivers). It is also often possible to introduce pips derived from the transmitted pulse, which have been passed through a time-delay network. The delay is adjustable, so that the *marker* blip can be made to coincide with the target. The distance reading provided by the marker control is more accurate than could have been estimated from a direct reading of the CRT. A gain control for vertical deflection is provided, which allows the sensitivity to be increased for weak echoes or reduced for strong ones. In the case of strong signals, reducing the sensitivity will reduce the amplitude of the ground clutter.

By its very nature, the A scope presentation is more suitable for use with tracking than with search antennas, since the echoes returned from one direction only are displayed; the antenna direction is generally indicated elsewhere. Plan-position indicator, the PPI display shows a map of the target area. The CRT is now intensity-modulated, so that the signal from the receiver after demodulation is applied to the grid of the cathode-ray tube. The CRT is biased slightly beyond cutoff, and only blips corresponding to targets permit beam current and therefore screen brightness. The scanning waveform is now applied to a pair of coils on opposite sides of the neck of the tube, so that magnetic deflection is used, and a saw tooth current is required. The coils, situated in a yoke similar in appearance to that around the neck of a television picture tube, are rotated mechanically at the same angular velocity as the antenna. Hence the beam is not only deflected radically outward from the center and then back again rapidly but also rotates continuously around the tube. The brightness at any point on the screen indicates the presence of an object there, with its position corresponding to its actual physical position and its range being measured radically out from the center.

Long-persistence phosphors are normally used to ensure that the face of the PPI screen does not flicker. It must be remembered that the scanning speed is rather low compared to the 60 fields per second used with television, so that various portions of the screen could go dim between successive scans. The resolution on the screen tic-ponds on the beam width of the antenna, the pulse length, the transmitted frequency. And even on the diameter of the CRT beam. Circular screens are used with diameters ranging up to 40 cm, but 30 cm is most often used.

The PPI display lends itself to use with search radars and is particularly suitable when conical scanning is employed. Note should also be taken of the fact that distortion of true map positions will take place if PPI is used on an aircraft, and its antenna does not point straight down. The range then seen on the screen is called the slant range. If the antenna of a mapping radar points straight down from the aircraft body. But the aircraft is climbing; the terrain behind will appear shortened, while the area ahead is

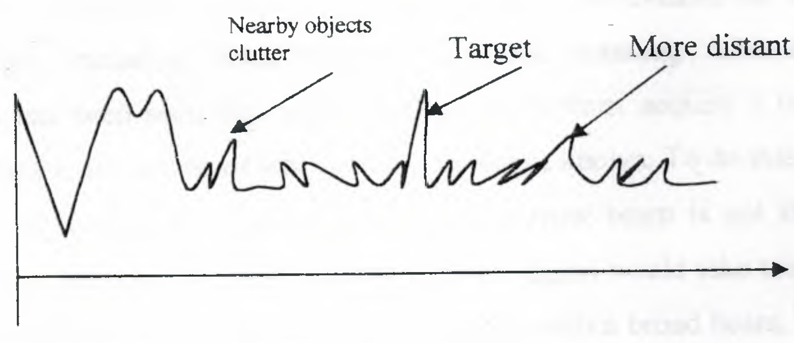


Figure 2.5 A scope display

distorted by being lengthened. If required, computer processing may be used to correct for radar attitude, therefore converting slant range into true range. It should be noted that the mechanics of generating the appropriate waveforms and scanning the radar CRT are similar to those functions in TV receivers. Discussion of those, including the need for saw tooth scanning waveforms, in conjunction with television receivers.

Automatic target detection the performance of radar operators may be erratic or inaccurate (people staring at screens for long hours do get tired); therefore the output of the radar receiver may be used in a number of ways that do not involve human operators. One such system may involve computer processing and simplification of the received data prior to display on the radar screen. Other systems use analog computers for the reception and interpretation of the received data, together with automatic tracking and gun laying (or missile pointing). Some of the more sophisticated radar systems are discussed later.

2.4 Pulsed radar system

A radar system is generally required to perform one of two tasks: It must either search for targets or else track them once they have been acquired. Sometimes the same radar performs both functions, whereas in other installations separate radars are used. Within each broad group, further subdivisions are possible, depending on the specific application. The most common of these will now be described.

2.4.1 search radar systems

The general discussion of radar so far in this chapter has revealed the basic features of search radars, including block diagrams, antenna scanning methods and display systems. It has been seen that such a radar system must acquire a target in a large volume of space, regardless of whether its presence is known. To do this, the radar must be capable of scanning its region rapidly. The narrow beam is not the best antenna pattern for this purpose, because scanning a given region would take too long. Once the approximate position of a target has been obtained with a broad beam, the information can be passed on to tracking radar, which quickly acquires and then follows the target. Another solution to the problem consists in using two fan-shaped beams (from a pair of connected cut paraboloids,), oriented so that one is directional in azimuth and the other in elevation. The two rotate together, using helical scan, so that while one searches in azimuth, the other antenna acts as a height finder, and a large area is covered rapidly. Perhaps the most common application of this type is the air-traffic-control radar used at both military and civilian airports.

If the area to be scanned is relatively small, a pencil beam and spiral scanning can be used to advantage, together with a PPI display unit. Weather avoidance and airborne navigation radars are two examples of this type. Marine navigation and ship-to-ship radars are of a similar type, except that here the scan is simply horizontal, with a fan-shaped beam. Early-warning and aircraft surveillance radars are also acquisition radars with a limited search region, but they differ from the other types in that they use UHF wavelengths to reduce atmospheric and rain interference. They thus are characterized not only by huge powers, but also by equally large antennas. The antennas are stationary, so that scanning is achieved by moving-feed or similar methods.

2.4.1 Tracking Radar Systems

Once a target has been acquired, it may then be tracked, as discussed in the section dealing with antennas and scanning. The most common tracking method used purely for tracking are the conical scan and monopulse systems described previously. A system that gives the angular position of a target accurately is said to be tracking in angle. If range information is also continuously obtained, tracking in range (as well as in angle) is said to be taking place, while a tracker that continuously monitors the relative target velocity by Doppler shift is said to be tracking in Doppler as well. If radar is used purely for tracking, then search radar must be present also. Because the two together are obviously rather bulky, they are often limited to ground or ship borne use and are employed for tracking hostile aircraft and missiles. They may also be used for fire control, in which case information is fed to a computer as well as being displayed. The computer directs the antiaircraft batteries or missiles, keeping them pointed not at the target, but at the position in space where the target will be intercepted by the dispatched salvo (if all goes well) some seconds later. Airborne tracking radars differ from those just described in that there is usually not enough space for two radars, so that the one system must perform both functions. One of the ways of doing this is to have a radar system, such as the World War II SCR-584 radar, capable of being used in the search mode and then switched over to the tracking mode, once a target has been acquired. The difficulty, however, is that the antenna beam must be a compromise, to ensure rapid search on the one hand and accurate tracking on the other. After the switchover to the tracking mode, no further targets can be acquired, and the radar is "Blind" in all directions except one.

Track-while-scan (TWS) radar is a partial solution to the problem, especially if the area to be searched is not too large, as often happens with airborne interception; Here a small region is searched by using spiral scanning and PPI display. A pencil beam can be used, since the targets arrive from a general direction that can be predicted. The operator can mark blips on the face of the CRT, and thus the path of the target can be reconstructed and even extrapolated, for use in fire control. The advantage of this method, apart from its use of only the one radar, is that it can acquire some targets while tracking others, thus providing a good deal of information simultaneously. If this becomes too much for an operator, automatic computer processing can be employed, as in the semiautomatic ground environment (SAGE) system used for air defense. The disadvantage of the system, as compared with the pure tracking radar, is hat although search is continuous, tracking is not, so that the accuracy is less than that obtained with monopulse or conical scan.

Tracking of extraterrestrial objects, such as satellites or spacecraft, is another specialized form of tracking. Because the position of the target is usually predictable, only the tracker is required. The difficulty lies in the small size and great distance of the targets. This does not necessarily apply to satellites in low orbits up to 600 km, but certainly is true of satellites in synchronous orbits 6,000 km up, and also of space vehicles. Huge transmitting powers, extremely sensitive receivers and enormous fully steer able antennas are required.

2.5 Moving target indicator (MTI)

It is possible to remove from the radar display the majority of clutter, that is, echoes corresponding to stationary targets, showing only the moving targets. This is often required, although of course not in such applications as radar used in mapping or navigational applications. One of the methods of eliminating clutter is the use of MTI, which employs the Doppler effect in its operation.

Doppler effect is the apparent frequency of electromagnetic or sound waves depends on the relative radial motion of the source and the observer. If source and observer are moving away from each other, the apparent frequency will decrease, while if they are moving toward each other, the apparent frequency will increase. This was postulated in 1842 by Christian Doppler and put on a firm mathematical basis by Armand Fizeau in1848. The Doppler effect is observable for light and is responsible for the so-called red shift of the spectral lines from stellar objects moving away from the solar system. It is equally noticeable for sound, being the cause of the change in the pitch of a whistle from a passing train. It can also be used to advantage in several forms of radar.

Consider an observer situated on a platform approaching a fixed source of radiation, with a relative velocity $+V_r$. A stationary observer would note f_t wave crests (or troughs) per second if the transmitting frequency were f_t. Because the observer is moving toward the source, that person of course encounters more than f_t crests per second. The number observed under these conditions is given by

$$f_t + f_t' = f_t\left(1 + \frac{v_r}{v_c}\right) \tag{2.1}$$

Consequently,

$$f_d' = \frac{f_t v_r}{v_c} \tag{2.2}$$

Where $f_t + f''_d$= anew observed frequency

f_d'' =Doppler frequency difference

Note that the foregoing holds if the relative velocity, v_r, is less than about 10 percent of the velocity of light. V_c, if the relative velocity is higher than that (most unlikely in practical eases), relativistic effects must be taken into account, and a some-what more complex formula must be applied. The principle still holds under those conditions, and it holds equally well if the observer is stationary and the source is in motion. Equation (2.2) was calculated for a positive radial velocity, but if, v_r is negative, f'' in Equation (2.2) merely acquires a negative sign. In radar involving a moving target, the signal undergoes the Doppler shift when impinging upon the target. This target becomes the "source' of the reflected waves, so that we now have a moving source and a stationary observer (the radar receiver). The two are still approaching each other, and so the Doppler effect is encountered a second time, and the overall effect is thus double. Hence the Doppler frequency for radar is

$$f_d = 2f_d' = \frac{2f_t v_r}{v_c} = \frac{2v_r}{\lambda} \tag{2.3}$$

Since $f_t/v_c = 1/\lambda$ where λ is the transmitted wavelength.

The same magnitude of Doppler shift is observed regardless of whether a target is moving toward the radar or away from it. With a given velocity. However, it will represent an increase in frequency in the former case and a reduction in the latter. Note also that the Doppler effect is observed only for radial motion, not for *tangential* motion. Thus no Doppler effect will be noticed if a target moves across the field of view of radar. However a Doppler shift will be apparent if the target is rotating, and the resolution of the radar is sufficient to distinguish its leading edge from its trailing edge. One example where this has been employed is the measurement of the rotation of the planet Venus (whose rotation cannot be observed by optical telescope because of the very dense cloud cover).

On the basis of this frequency change, it is possible to determine the relative velocity of the target, with either pulsed or CW radar, as will be shown. One can also distinguish between stationary and moving targets and eliminate the blips due to stationary targets. This may be done with pulsed radar by using moving-target indication.

2.5.2 Fundamentals Of MTI

Basically, the moving-target indicator system compares a set of received echoes with those received during the previous sweep. Those echoes whose phase has remained constant are then canceled out. This applies to echoes due to stationary objects, but those due to moving targets do show a phase change; they are thus not canceled, nor are noise, for obvious reasons. The fact that clutter due to stationary targets is removed makes it much easier to determine which targets are moving and reduces the time taken by an operator to "take in" the display. It also allows the detection of moving targets whose echoes are hundreds of times smaller than those of nearby stationary targets and which would otherwise have been completely masked. MTI can be used with a radar using a power oscillator (magnetron) output, but it is easier with one whose output tube is a power amplifier, only the latter will be considered here.

The transmitted frequency in the MTI system of Figure 2-7 is the sum of the outputs of two oscillators, produced in mixer 2. The first is the stalo, or stable local oscillator (note that a good case can be made for using a varactor chain here). The second is the coho, or coherent oscillator, operating at the same frequency as the intermediate frequency and providing the coherent signal, which is used as will be explained. Mixers 1 and 2 are identical, and both use the same local oscillator (the stab); thus phase relations

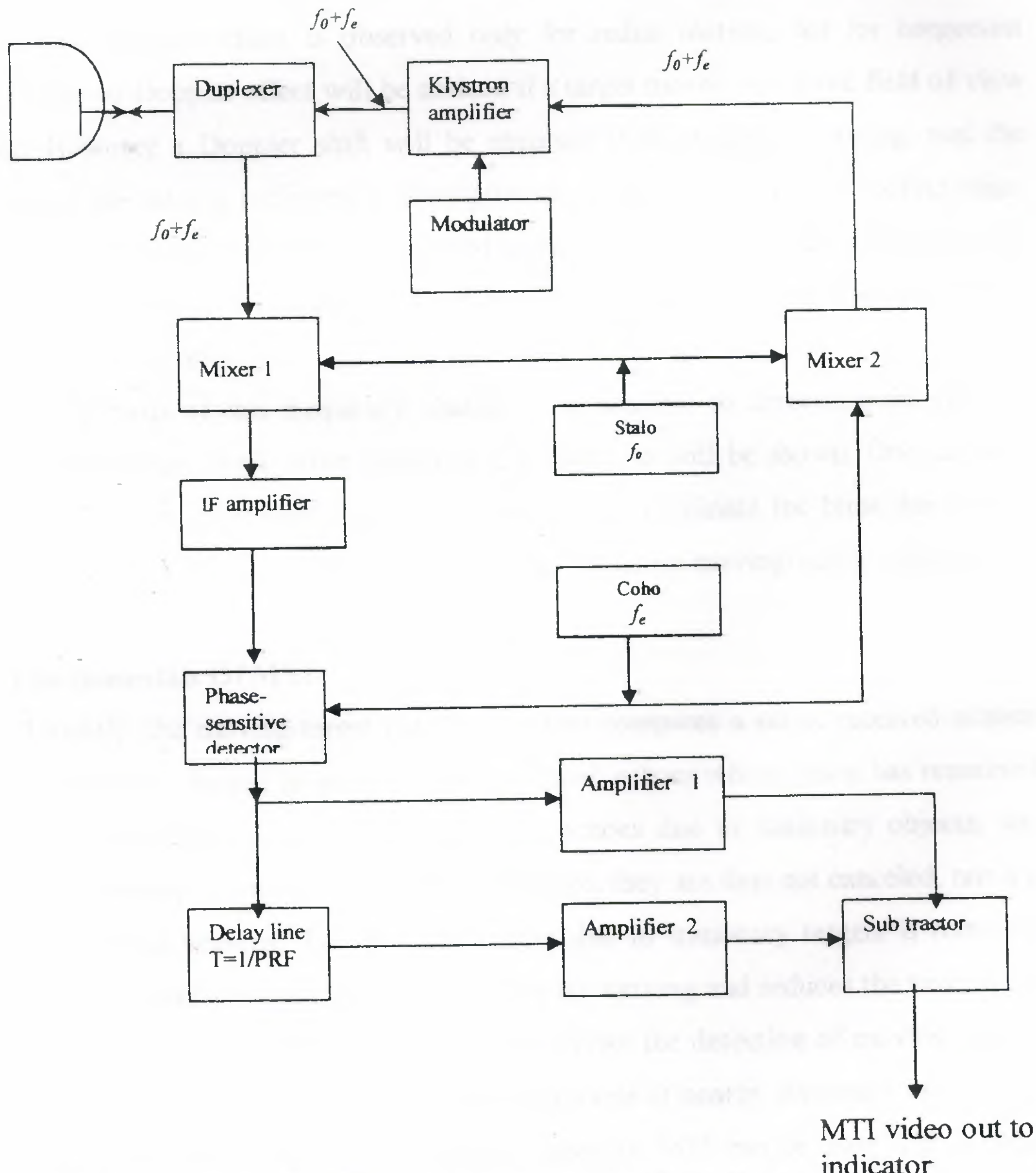


Figure 2.7 Block diagram of MTI radar using power amplifier output

existing in their inputs are preserved in their outputs. This makes It possible to use the Doppler shift at the IF, instead of the less convenient radio frequency f_0+f_e. The output of the IF amplifier and a reference signal from the echo are fed to the phase-sensitive detector, a circuit very similar to the phase discriminator.

The coho is used for the generation of the RF signal, as well as for reference in the phase detector. And the mixers do not introduce differing phase shifts. The transmitted and reference signals are locked in phase and are said to be coherent; hence the name of the coho. Since the output of this detector is phase sensitive, an output will be obtained for all fixed or moving targets. The phase difference between the transmitted and received signals will be constant for fixed targets, whereas it will vary for moving targets. This variation for moving targets is due to the Doppler frequency shift, which is naturally accompanied by a phase shift, but this shift is not constant if the target has a radial component of velocity. If the Doppler frequency is 2000 Hz and the return time for a pulse is 124 μs (10 nmi), the phase difference between the transmitted and received signals will be some value Φ (the same as for stationary target at that point) plus 2000/124 =16.12 complete cycles, or 16.12 *2π = 101.4 rad. When the next pulse is returned from the moving target, the latter will now be closer, perhaps only 123 μs away, giving a phase shift of 101.4 x 123/124 = 100.7 rad. The phase shift is definitely not constant for moving targets. The situation is illustrated graphically, for a number of successive pulses, Figure 2.8

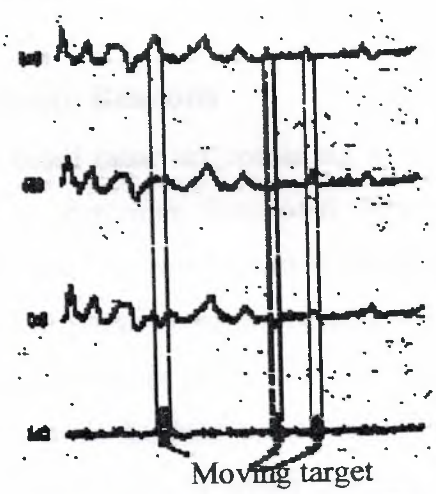


Figure .-8 operation of MTI radar ,(a),(b),(c) phase detector output for three successive pulses; (d) sub tractor output.

It is seen from Figure 2-8 that those returns of each pulse that correspond to stationary targets are identical with each pulse, but those portions corresponding to moving targets keep changing in phase. It is thus possible to subtract the output for each pulse from the preceding one, by delaying the earlier output by a time equal to the pulse interval, or 1/PRF. Since the delay line also attenuates heavily and since signals must be of the same amplitude if permanent echoes are to cancel, an amplifier follows the delay line. To ensure that this does not introduce a spurious phase shift, an amplifier is placed in the undelayed line, which has exactly the same response characteristics (but a much lower gain) than amplifier 1. The delayed and undelayed signals are compared in the sub tractor (adder with one input polarity reversed), whose output is shown in Figure 2-8d. This can now be rectified and displayed in the usual manner.

2.5.3 other analog MTI system

These include area MTI, which involves subtracting a complete scan from the previous one and displaying only the difference; it is done with storage CRTs. Another system is almost identical to the one described but uses a pulsed magnetron oscillator instead of an amplifier. A different technique must be employed here to achieve coherence, because each cycle of the magnetron oscillations begins with a phase quite unrelated to the previous pulsed cycle. Noncoherent MTI is also sometimes used, deriving the required phase variations by comparing the returns from stationary and radially moving targets. This method suffers from the disadvantage of requiring stationary targets in each scan in addition to the moving target. Note that all coherent systems require a fairly high pulse repetition frequency to ensure the return of several pulses from each target. This also describes airborne moving-target indicator (AMTI), in which compensation for the motion of the radar set is an added requirement.

2.5.4 delay lines

Delay lines Because of the delay times required, it would be unthinkable to use electromagnetic delay means in MTI. If the PRF is 1000, then the delay required is I ms, in which time an electromagnetic wave in an air-dielectric line travels 300 km! The method adopted to provide the requisite delay in practice is rather similar to that used with mechanical filters. The signal is converted into acoustic vibrations, passed through a mechanical resonant circuit and converted into an electrical signal at the output end, with a suitable transducer. The most commonly used material for the delay line is fused quartz, in which the velocity of *sound* is 5.44 m/ms.

Since this is still quite large (though manageable), the line can be folded. This consists in having a many-sided prism, in which the acoustic waves are reflected from the planesides. The signal then emerges 1 μs later if the total length of the folded path is 5.44 m. The attenuation in such a line is in excess of 40 dB, and this explains the amplifier accompanying the line on the block diagram of Figure 2.7.

2.5.5 Blind Speeds

When showing how phase shift varies if the target has relative motion, a fictitious situation, which gave a phase difference of 101.4 - 100.7 = 0.7 rad between successive pulses on the target was described in a previous section. If the target happens to have a velocity whose radial component results in a phase difference of exactly 2π rad between successive pulses, this is the same as having no phase shift at all. The target thus appears stationary, and echoes from it are canceled by the MTI action. A radial velocity corresponding to this situation is known as a blind speed, as are any integral multiples of it. It is readily seen that if a target moves a half-wavelength between successive pulses, the change in phase shill will be precisely 2π rad.

We may state that

$$v_b = PRF \frac{n\lambda}{2} \tag{2.3}$$

Where v_b=blind speed

λ= wavelength of transmitted signal

n= any integer (include 0)

The fact that blind speeds exist need not be a serious problem and does not normally persist beyond a small number of successive pulses. A target flying directly toward the radar set at a constant velocity could cause this, but it would be sheer coincidence, and a far-fetched one at that, for a target to do this accidentally. We do live in a world that produces sophisticated electronic countermeasures, and it is not beyond the realm of possibility that a target may be flying at a blind speed on purpose. A wideband receiver and microprocessor on board the target aircraft or missile could analyze the transmitted frequency and PRF and adjust radial velocity accordingly. The solution to that problem is to have a variable PRF. That presents no difficulty, but varying the delay in the MTI radar does. Having two delay lines and compensating amplifiers can do it. One of these can be a small delay line, having a delay that is 10 percent of the main delay, This second line will then be switched in and out on alternate pulses, changing the blind speed by 10 percent each time.

2.5.6 Digital MTI

Is possible to replace the delay line and amplifier arrangement of an analog MTI system with digital-to-analog conversion of the received signal. After the signal has been digitally coded, it can be stored in a computer memory. The echoes received from each pulse are now subtracted in the memory from those received from the previous pulse, whereupon the difference is converted to analog form and displayed as before. With digital MTI (or DMTI). No difficulties arise in varying the PRF. It may be varied almost randomly from one pulse to the next. Interestingly enough, the resolution limit in DMTI is governed, in part, by quantizing noise. Just like in pcm, analog signals must be quantized before their conversion to digital form.

2.6 Radar Beacons

Is a small radar set consisting of a receiver, a separate transmitter and an antenna which is often omni directional. When another radar transmits a coded set of pulses at the beacon, i.e., *interrogates* it, the beacon *responds* by sending back its specific pulse code. The pulses from the beacon, or *transponder* as it is often called, may be at the same frequency as those from the interrogating radar, in which case the main station together with its echo pulses receives them. They may alternatively be at a special beacon frequency, in which case the interrogating radar requires a separate receiver. Note that the beacon does not transmit pulses continuously in the same way as a search or tracking radar but only responds to the correct interrogation.

One of the functions of a beacon may be to identify itself. The beacon may be installed on a target, such as an aircraft, and will transmit a specific pulse code when interrogated. These pulses then appear on the PPI of the interrogating radar and inform it of the identity of the target. The system is in use in airport traffic control and also for military purposes, where it is called identification, friend or foe (IFF).

Another use of radar beacons is rather similar to that of lighthouses, except that radar beacons can operate over much larger distances. An aircraft or ship, having interrogated a number of beacons of whose exact locations it may be unaware (on account of being slightly lost), can calculate its position from the coded replies accurately and automatically.

The presence of a beacon on a target increases enormously the distance over which a target may be tracked. Such *active* tracking gives much greater range than the *passive* tracking so far described, because the power transmitted by the beacon (modest though it normally is) is far in excess of the power that this target would have reflected had it not carried a beacon. This is best demonstrated quantitatively, as in the next section.

Beacon range equation following the reasoning used to derive the general radar range equation;

$$P_B = \frac{A_{pT} P_{tT} A_{0B}}{4\pi r^2} \tag{2.4}$$

Where all symbols have their previously defined meanings, except that the subscript T is now used for quantities pertaining to the transmitter of the main radar, and B is used for the beacon functions. A_{0B} is the capture area of the beacon's antenna.

If $P_{min,B}$ is the minimum power receivable by the beacon, the maximum range for the interrogation link will be:

$$r_{max,I} = \sqrt{\frac{A_{pT} P_{tT} A_{0B}}{4\pi P_{min,B}}} \tag{2.5}$$

Substituting into Equation (2.4) for the power gain of the transmitter antenna from Equation (2.5), and for the minimum power receivable by the beacon from equation (2.6), and then canceling, we obtain the final form of the maximum range for the interrogation link that is

$$r_{\max,I} = \sqrt{\frac{A_{pT} P_{tT} A_{0B}}{\lambda^2 k T_0 \delta f (F_B - 1)}} \tag{2.6}$$

It has been assumed in equation (2.6) that the bandwidth and antenna temperature of the beacon are the same as those of the main radar. By an almost identical process of reasoning, the maximum range of the reply link is

$$r_{\max,R} = \sqrt{\frac{A_{pT} P_{tT} A_{0B}}{\lambda^2 k T_0 \delta f (F_T - 1)}} \tag{2.7}$$

Antenna is also tripled. A foldout, metallized umbrella spacecraft antenna with a 3-m (10-ft) diameter is certainly feasible. Again, the 13-dB noise figure for the beacon receiver is conservative, and reducing it to 10 dB (still fairly conservative) would further increase the range. A slower PRF and less insistence on pulses with steep sides would permit a tenfold bandwidth reduction and a similar pulse power increase from the beacon. A total range for the reply link could comfortably exceed 1000million Km, even allowing for the degradations mentioned above. That distance puts within all the planets up to and including Saturn.

CHAPTER THREE

OTHER RADAR SYSTEMS

A number of radar systems are sufficiently unlike those treated so far to be dealt separately. They include first of all CW radar which makes extensive use Doppler effect for target speed measurements. Another type of CW radar is modulated to provide range as well as velocity. Finally, phased array and planer array radars will be discussed in this "separate'' category. Here, the transmitted (and receiving) beam is steered not by moving an antenna but by changing the phase relationship in the feeds for a vast array of small individual antennas. These systems will described in turn.

3.1 CW Doppler radar

A simple Doppler radar, such as the one shown in figure 3.1, sends out continuous sine wave rather than pulses. It uses the Doppler effect to detect the frequency change caused by a moving target and displays this as a relative velocity.

Since transmission here is continuous, the circulator of figure 3-1 is used to provide insulation between the transmitter and the receiver. Since transmission is continuous, it would be pointless to use duplexer. The insulation of a typical circulator is

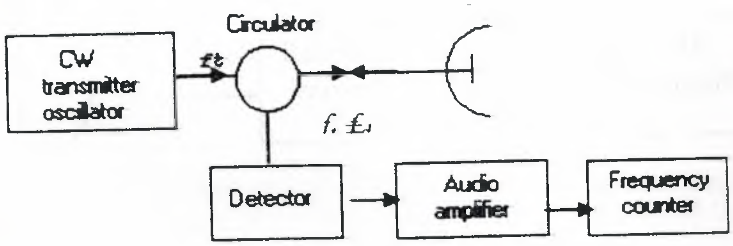


Figure 3.1 Simple Doppler CW Radar

of the order of 30 dB, so that some of the transmitted signal leaks into the receiver. The signal can be mixed in the detector with returns from the target, and the difference is the Doppler frequency. Being generally in the audio range in most Doppler applications, the detector output can be amplified with an audio amplifier before being applied to a frequency counter. The counter is a normal one, except that its output is shown as kilometers or miles per hour, rather than the actual frequency in hertz. The main disadvantage of a system as simple as this is its lack of sensitivity. The type of diode detector that is used to accommodate the high incoming frequency is not a very good device at the audio output frequency, because of the modulation noise which it exhibits at low frequencies The receiver whose block diagram is shown in Figure 3-2 is an improvement in that regard.

A small portion of the transmitter output is mixed with the output at a local oscillator, and the sum is fed to the receiver mixer. This also receives the Doppler - shifted signal from its antenna and produces an output difference frequency that is typically 30 MHz, plus or minus the Doppler frequency. The output of this mixer is

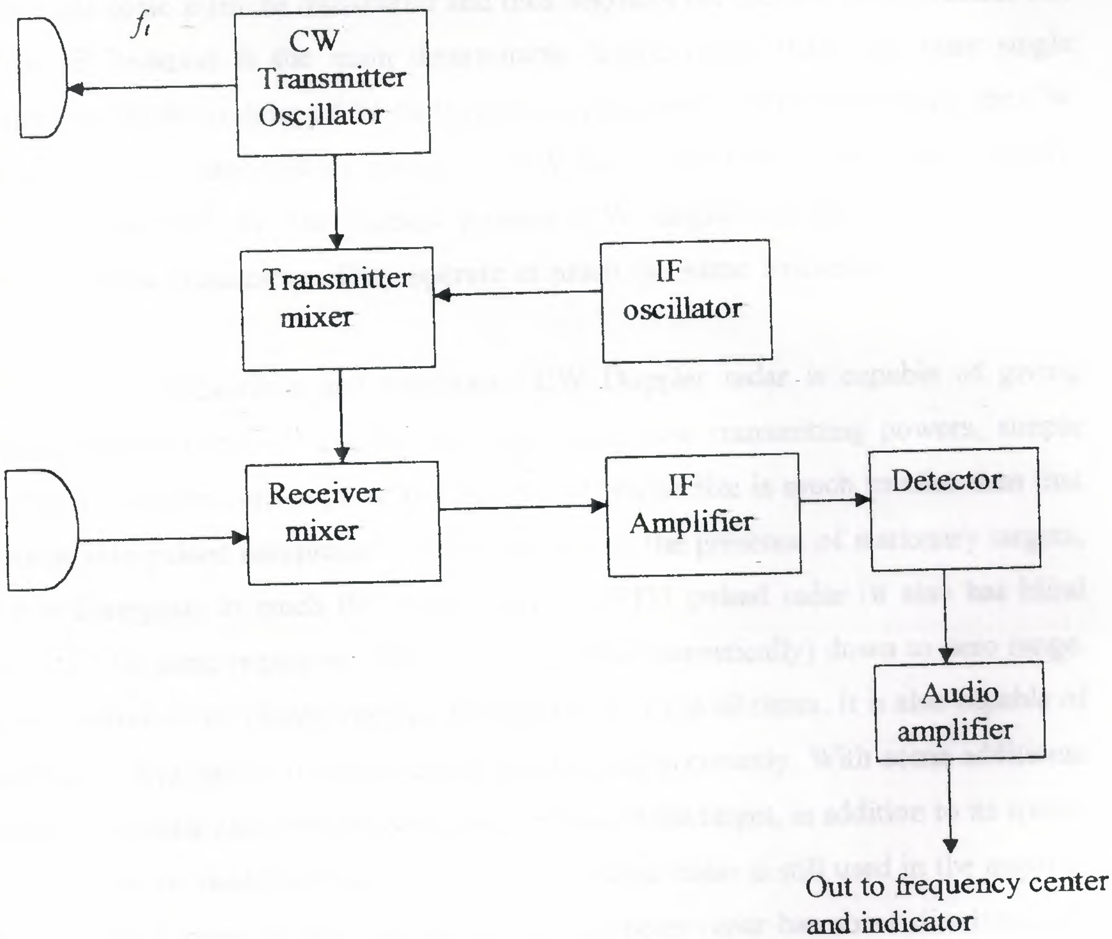


Figure 3.2 CW Doppler radar with IF amplification

amplified and demodulated again, and the signal from the second detector Is Just the Doppler frequency. Its sign is lost, so that it is not possible to tell whether the target is approaching or receding. The overall receiver system is rather similar to the super heterodyne. Extra sensitivity is provided by the lowered noise, because the output of the diode mixer is now in the vicinity of 30 MHz, at which FM noise has disappeared.

Separate receiving and transmitting antennas have been shown, although this arrangement is not compulsory. A circulator could he used, as in the simpler set of Figure 3-1. Separate antennas are used to increase the isolation between the transmitter and receiver sections of the radar, especially since there is no longer any need or a small portion of the transmitter output to leak into the receiver mixer, as there was in the simpler set. To the contrary, such leakage is highly undesirable, because it brings with it the hum and noise from the transmitter and thus degrades the receiver performance. The problem of isolation is the main determining factor, rather than any other single consideration in the limiting of the transmitter output power. As a consequence, the CW power from such radar seldom exceeds 100 W and is often very much less. Gunn or IMPATT diodes or, for the highest powers. CW magnetrons are used as power oscillators in the transmitter. They operate at much the same frequencies as in pulsed radar.

Advantages, applications and limitations CW Doppler radar is capable of giving accurate measurements of relative velocities, using low transmitting powers, simple circuitry, low power consumption and equipment whose size is much smaller than that of comparable pulsed equipment. It is unaffected by the presence of stationary targets, which it disregards in much the same manner as MTI pulsed radar (it also has blind speeds, for the same reason as MTI). It can operate (theoretically) down to zero range. Because, unlike in the pulsed system, the receiver is ON at all times. It is also capable of measuring a large range of target speeds quickly and accurately. With some additional circuitry. CW radar can even measure the direction of the target, in addition to its speed.

Before the reader begins to wonder why pulsed radar is still used in the majority of equipment, it must be pointed out that CW Doppler radar has some disadvantages also. In the first place, it is limited in the maximum power it transmits, and this naturally places a limit on its maximum range. Second, it is rather easily confused~ the presence of a large number of targets (although it is capable of dealing with than one if special filters are included). Finally (and this is its greatest drawback), Doppler radar is incapable of indicating the range of the target. It can only show its velocity, because the transmitted signal is unmodulated. The receiver cannot sense with a particular cycle of oscillations is being received at the moment, and therefore cannot tell how long ago this particular cycle was transmitted, so that range cannot be measured.

As a result of its characteristics and despite its limitations, the CW -radar system has quite a number of applications. One of these is in aircraft navigation for speed measurement, Another application is in a rate-of-climb meter for vertical takeoff planes., such as the ''Harrier,' which in 1969 became the first jet ever to on Manhattan Island. in New York City. Finally, perhaps its most commonly encountered application is in the radar speed meters used by police.

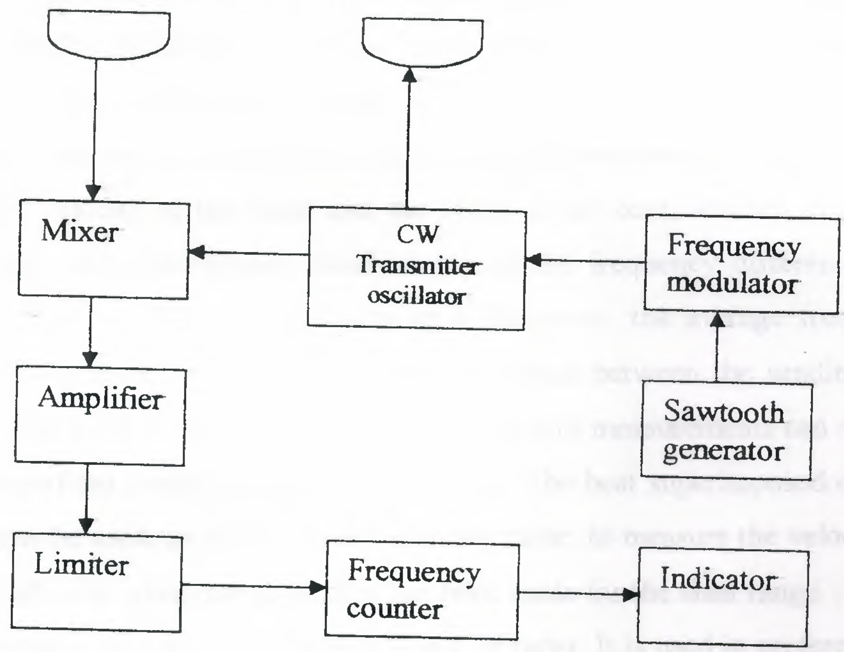


Figure 3.3 Block diagram of simple FM CW radar altimeter.

3.2 Frequency-modulated CW radar

The greatest limitation of Doppler radar, i.e., its inability to measure range, may be overcome if the transmitted carrier is frequency-modulated. If this is done, it should be possible to eliminate the main difficulty with CW radar in this respect, namely, its inability to distinguish one cycle from another. Using FM will require an increase in the bandwidth of the system, and once again it is seen that a bandwidth increase in a system is required if more information is to be conveyed (in this case, information with regard to range).

Figure (3.3) shows the block diagram of a common application of the FM CW radar system, the airborne altimeter. Sawtooth frequency modulation is used for simplicity, although in theory any modulating waveform might be adequate. If the target (in this case, the Earth) is stationary with respect to the plane, a frequency difference proportional to the height of the plane will exist between the received and the transmitted signals. It is due to the fact that the signal now being received was sent at a time when the instantaneous frequency was different. If the rate of change of frequency with time due to the FM process is known, the time difference between the sent and received signals may he readily calculated, as can the height of the aircraft. The output of the mixer in Figure (3.3), which produces the frequency difference, can be amplified, fed to a frequency counter and then to an indicator whose output is calibrated in meters or feet.

If the relative velocity of the radar and the target is not zero, another frequency difference, or beat, will superimpose itself on top of the frequency difference just discussed, because of the Doppler frequency shift. However, the average frequency difference will be constant and due to the time difference between the sending and return of a particular cycle of the signal. Thus correct height measurements can still be made on the basis of the average frequency difference. The beat superimposed on this difference can now be used, as with ordinary Doppler radar, to measure the velocity of (in this case) the aircraft, when due allowance has been made for the slant range.

The altimeter is a major application of FM CW radar. It is used in preference to pulsed radar because of the short ranges (i.e., heights) involved, since CW radar has no limit on the minimum range. Whereas pulsed radar does have such a limit. Fatly simple low-power equipment can be used, as with CW Doppler radar. Because of the size and proximity of the Earth. Small antennas can also be used, reducing the bulk of the equipment even further. A typical altimeter operates in the C band, uses a transmitter power typically from 1 to 2 W, easily obtained from an IMPATT or a Goon diode, and has it range of up to 10.000 m or more, with a corresponding accuracy of about 5 percent.

3.3 phased array radars

With some notable exceptions, the vast majority of radars have to cover an area in searching and/or tracking, rather than always being pointed in the same direction. This implies that the antenna will have to move, although it was seen that some limited beam movement can be produced by multiple feeds or by a moving feed antenna. As lone as antenna motion is involved in moving the beam, limitations caused by inertia will always exist, A limit on the maximum scanning speed will be imposed by antenna mechanics.

The problem encountered with a single antenna of fixed shape is that the shape of the beam it produces is also constant, unless some rather complex modifications are introduced. There is the difficulty caused by the fact that a single antenna can point in only one direction at a time. Therefore sending out only one beam at a time. This makes it rather difficult to track a large number of targets simultaneously and accurately. A similar difficulty is encountered when trying to track some targets while acquiring others. Such problems could be overcome, and a very significant improvement in versatility would result, if a stationary antenna could produce a moving beam. Although this cannot be done readily with a single antenna, it can be done with an any consisting of a large number of individual radiators. Beam steering can be achieved by the introduction of variable phase differences in the individual antenna feeders, and electronic variation of the phase shifts.

It will be recalled that the direction of the beam will be at right angles to the plane of the array if all the dipoles are fed in phase, whereas feeding them with a progressive phase difference results in a beam that is in the plane of the array, along the line joining the dipole centers. It will thus be appreciated that if the phase differences between the dipole feeds are varied between these two extremes, the direction of the beam will also change accordingly. Extending this principle one step farther, it can be appreciated that a plane dipole array. With variable phase shift to the feeders, will permit moving the direction of the radiated beam in a plane rather than a line. Nor do the individual radiators have to be dipoles. Slots in wave-guides and other, arrangements of small omni directional antennas will do as well. It is possible to arrange four such antenna arrays, obtaining a full hemispherical coverage.

Each plane array would, for hemispherical coverage, point 45° upward. The beam issuing from each face would have to move ±45° in elevation and ±45° in azimuth in order to cover its quadrant. In practical systems. Vast numbers of individual radiators are involved. One tactical radar has, in fact 4096 (2^{12}) radiating slats per face.

Types There are broadly two different types of phased arrays possible. In the first, one high-power tube feeds the whole array; the array is split into a small number of subarrays, and a separate tube feeds each of these. The feeding is done through high-level power dividers (hybrids) and high-power phase shifters. The phase shifters are often ferrite. Indeed, most of the advances in ferrite technology in the 1960s were spin-offs from phased array military contracts. It will be recalled that the phase shill introduced by a suitable piece of ferrite depends on the magnetic field to which the ferrite is subjected; this is by adjusting this magnetic field, a full 360° phase change is possible.

Digital phase shifters are also available, using PIN diodes in distributed circuits. A particular section will give a phase shift that has either of two values, depending on whether the diode is ON or OFF. A typical "4-bit" digital phase shifter may consist of four PIN phase shifters in series. The first will produce a shift of either 0 or 22½°, depending on the diode bias. The second offers the alternatives of 0 or 45°, the third 0 or 90° and the fourth 0 or 180°. By using various combinations, a phase shift anywhere between 0 and 360° (in 22½° steps) may be provided. The ferrite phase shifters have the advantages of continuous phase shift variation and the ability to handle higher powers. PIN diode phase shifters, although they cannot handle quite such high powers, are able to provide much faster variations in phase shill and therefore beam movement. As a good guide, the phase variations that take a few milliseconds with ferrite shifters (Figure 3-4) can be accomplished in the same number of microseconds with digital shifters.

A second broad type of phased array radar uses many RF generators, each of which drives a single radiating element or bank of radiating elements. Semiconductor diode generators are normally used, with phase relationships closely controlled by means of phase shifters, The use of YIG and microwave integrated circuit (MIC) phase shifters has enhanced several aspects of the phased array radar. The YIG phase shifter, when coupled with irises for matching purposes, results in a radiating element which is compact, easy to assemble and relatively inexpensive. The MIC phase shifter greatly reduces the size of arrays, since it is itself small and integrated into the radiating element.

These multi generator arrays provide wide-angle scanning over an appreciable frequency range. Scanning may be accomplished through a combination of mechanical and electronic means, or through electronic means alone. The array shown in Figure 3-6 employs RF generators to drive each horizontal bank of radiators. Elevation scanning can therefore be accomplished electronically, although horizontal scanning uses traditional mechanical techniques. The array shown in Figure 3-6 provides one generator for each radiating element, and this makes electronic scanning for both horizontal and vertical planes possible, although the cost for this type of away is of course significantly higher. The number of phases /generator elements increases from 70 for a typical array of the first type to 4900 for an array of the second type.

Arrays using multiple semiconductor diode generators have several advantages. The generators operate at much lower power levels and are therefore cheaper and more reliable, With so many independent RF generators, any failures that occur will be individual rather than total, arid their effect will thus be merely a gradual deterioration, not a catastrophic failure. The disadvantages of the second system include the high cost of so many Gunn or IMPATT or even TRAPATT oscillators. The lower available powers at higher frequencies are yet another problem; even 4096 oscillators producing 100-W pulses each give out only a little over 400 kW, much less than a medium-large tube. The power dissipation is more of a problem than with tubes, since efficiencies of diode RE generators are noticeably lower.

In a sense, phased array radars have been the "glamour " systems, in terms of development money spent and space devoted in learned journals. Certainly, there is no doubt that they can work and currently do so in quite a number of establishments. They can be astonishingly versatile. For example, the one array can rapidly locate targets by sending out two fan-shaped beams simultaneously. One is vertical and moves horizontally, while the other is horizontal and moves vertically. Once a target has been located, it can then be tracked with a narrow beam, while other wide beams meanwhile acquire more targets. The phased array radar utilizing electronic techniques benefits from inertia less scanning. Since the beam can be redirected and reconfigured in microseconds, one array can be programmed to direct pulses to various locations in rapid succession. The result is that the array can simultaneously undertake acquisition and tracking operations for multiple targets. The possibilities are almost endless. Because phased array radars have to perform complex tasks, they must themselves also be complex. This makes them atrociously expensive. One authority quotes it typical cost of $1 million for just the phase shifters and their drivers in one system. That still leaves the computer control, RF sources, power dividers and the arrays themselves, as well as the costs of testing and installation. A significant cost reduction could he achieved by mass production, if demand for phased array radars increases. It is to be hoped that this situation does not develop into a vicious circle.

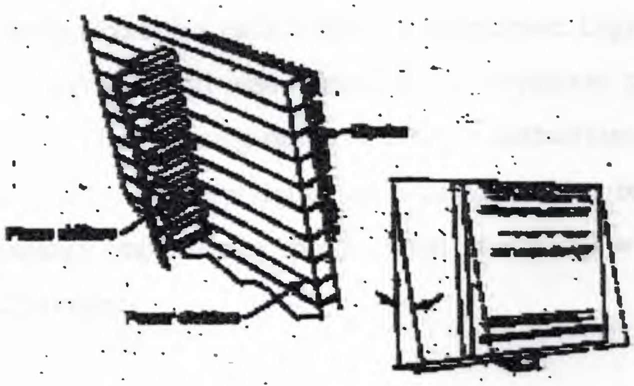


Figure 3.4 phased array antenna that provides for elevation scanning by feeding each horizontal row of elements with a separate phase shifter.

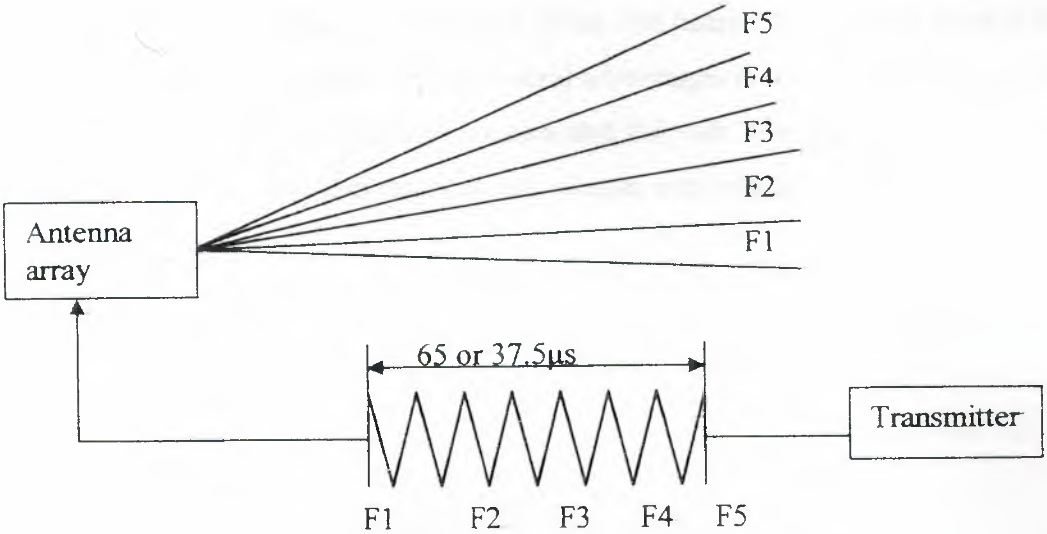
Related technology Signal processing is one aspect of radar technology, which has resulted in a significant improvement in radar capabilities. Signal processing systems currently in use with radar systems depend heavily on computer and microchip technology. These systems perform the functions of analyzing, evaluating and displaying radar data, as well as controlling the subsequent pulse emissions.

Signal processing used with radar systems includes filtering operations of the full bandwidth signal to separate signal waveforms from noise and interfering background signals. This accommodation to the electromagnetic environment in which the radar system operates is further enhanced by the ability to utilize computer algorithms to alter pulse frequency and other characteristics, in response to the transmissions of other systems. By varying the transmitted signals, it is possible for the system to attain significant immunity from interference (from other signals). Computer evaluation and control prevent interference to the system since the interfering signal cannot track the frequency changes and the sub pulses generated by the system at the direction of the signal-processing computer. Usable images can be obtained even in adverse or very active electromagnetic environments. This enhancement of the radar system capability is of particular value to military and other systems, which must operate, in close proximity to other radars. With sophisticated computer systems available to the radar, additional display manipulations and improvements can be achieved.

Radar systems benefit from large-scale integration in the same way as other electronic fields. As a "signal processor on a chip" becomes a reality, the cost, complexity and size of even a complex radar system will decrease. Digital simulation of analog filters and other devices will also contribute to reduction of system costs. Because real-time radar signal processing needs to execute instructions rates exceeding $2 * 10^7$ operations per second, the current digital switching speed has become a limiting factor. As digital technology improves in speed, signal processing will become even more important for radar systems.

3.3.1 Planar Array Radars

The planar array radar uses a high-gain planar array antenna. A fixed delay is established between horizontal arrays in the elevation plane. As the frequency is changed, the phase front across the aperture tends to tilt, with the result that the beam is moved in elevation.



Five subpulses each at different frequency

Figure 3.5 frequency scanning as used by planar array radar causes radars beam to be elevated slightly above one another.

Figure 3-5 shows a planar antenna array to which a burst of five sub pulses, each at a different frequency, is applied. The differing frequencies cause each successive beam to be elevated slightly more than the previous beam.

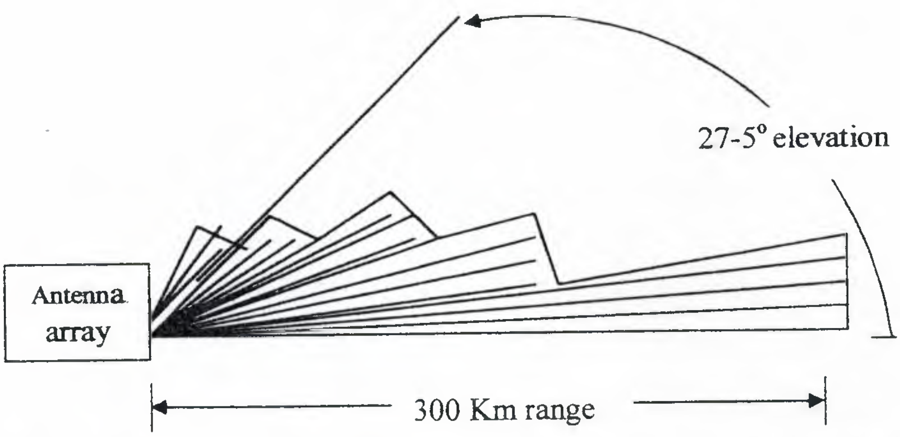


Figure 3.6 planer array radar showing five separate groups of fine beams, which permit scanning of 27.5° of elevation.

The radar illustrated in figure 3-6 with five of the five beams groups used scans a 27.5° elevation. The planner array system has several advantages in that each beam group has full-transmitted peak power, full antenna gain and full side lobe, performance. The use of frequency changes provides economical, simple and reliable inertia less elevation scanning.

CHAPTER FOUR

4.1 Air Defence

Historically, the military has played the leading role in the use and development of radar. The detection and interception of opposing military aircraft in air defence has been the predominant military use of radar. The military also uses airborne radar to scan largebattlefields for presence of enemy forces and equipment and to pick out precise targets for boms and missiles.

A typical surface-based air defance system relies upon several radar systems. First, a lower frequency radar with a high-powered transmitter and a large anntena searches the airspace for all aircraft, both friend and foe. A secondary radar system reads the transponder signals sent by each aircraft to distinguish between allies and enemies. After enemy aircraft are detected, operators track them more precisely by using high-frequency waves from special fire control radar systems. The air defence system may attempt to shoot down threatening aircraft with gunfire or missiles, and radar sometimes guides both gunfire and missiles. Longer-range air defence systems use missiles with internal guidance. These systems track a target using data from a radar system on the missiles. Such missile-borne radar system are called seekers. The seeker uses radar signals from the missile or radra signale from a transmitter on the ground to determine the position of the target relative to the missile, and then passes the information to the missiles guidance system. The military uses surface-to-air systems for defence against balistic missiles as well as aircraft. During the Cold War both the United States and the Union of Soviet Socialist Republics (USSR) did a great deal of research into defence against intercontinental ballistic missiles (ICBMs) and submarine-launched ballistic missiles. The United states and the USSR sigmed the Anti-Ballistic Missile (ABM) treaty in 1972. this treaty limited each of the superpower to a single, limited capability system. The U.S. system consisted of a low-frequency (UHF) phased-array radar around the perimeter of the country, another phased-array radar to track incoming missiles more accurately, and several very high-speed missiles to intercept the incoming ballistic missiles. The second radar guided

The interceptor missiles. Airborne air defence system incorporate the same functions as ground-based air defence, but special aircraft carry the large are search radar systems. This is necessary because it is difficult for high-performance fighter aircraft to carry both large radar system and weapons.

Modren warfare uses air-to-ground radar to detect targets on the ground and to monitor the movement of the troops. Advanced Doppler techniques and synthetic aperture radar have greatly increased the accuracy and usefulness of air-to-ground radar since their introduction in the 1960s and 1970s. Military forces around the world use air-to-ground radar for weapon aiming and for battelfield surveillance. The United States used the Joint Surveillance and Tracking Radar System (JSTARS) in the Persian Gulf War (1991), demonstarting modern radar's abilty to provide information about enemy troop concentrations and movements during the day or night, regardless of weather conditions.

The military uses several techniques to attempt to avoid detection by enemy radar. One common technique is jamming, that is, sending deceptive signals to the enemy's radar system. During World War II (1939-1945), flyers under attack jammed enemy radar by dropping a large clouds of chaff, small pieces of aluminum foil or some other material that reflects radar well. "False" returns from chaff hid the aircraft's exact location from enemy's air defense radar. Modern jamming uses sophisticated electronic system that analyze enemy radar, and then send out false radar echoes that mask the actual target echoes or deceive the radar about a target's location.

Stealth technology is a collection of methods that reduce the radar echoe sfrom aircraft and other radar targets. Special paint can absorb radar signals and sharp angles in the aircraft design can reflect radar signals in deceiving dirctions. İmprovements in jamming and stealth technology force the contiual development of high-power transmitters, antennas good at detecting weak signals, and very sensitive receivers, as well as techniques for improved clutter rejection.

4.1.1 Radar in World War II

None of the early demonstrations of radar generated much enthusiasm. The commercial and military value of radar did not become readily apparent until the mid-1930s. Befor World War II, the United States, France, and the United Kingdom were all carrying out radar reasearch. Begining in 1935, the British built a network of ground-based aircraft detection radar, called Chain Home, under the direction of Sir Robert Watson-Watt. Chain Home was fully operational from 1938 until the end of World War II in 1945 and was extremely instrumental in Britain's defence against Germen bombers. The British recognized the value of radar with frequency much higher than the radio waves used for most syetms. A breakthrough in radar technology came in 1939 when two British scientists, physicist Henry Boot and biophysicist John Randall, developed the resonant-cavity magnetron. This device generate high-frequency radio pulses with a large amount of power, and it made the development of microwive radar possible. Also in 1939, the Massachuestts Institute of technology (MIT) Radiation Laboratory was formed in Cambridge, Massachusetts, bring together U.S. and British radar research. İn March 1942 scientists demonstrated the detection of ships from air. This technology became the basis of anti ship and antisubmarine radar for the U.S.Navy

The U.S. Army operated air surveillance radar at the start of World War II. The army also used early forms of radar to direct antiaircraft guns. İnitially the radar systems were used to aim searchlight so soldier aiming the gun could see where to fire, but the system evolved into fire-control radar that aimed the guns automatically.

4.1.2 Radar during the Cold War

With the end of World War II, interest in radar development declind. Some expeiments continued, however; for instance, in 1946 the U.S. Army Signal Corps bounced radar signals off of the moon, unshering in the field of radar astronomy. The groeing hostility between the United States and the Union of Soviet Socialist Republics, the so-called Cold War-renewed military interest in radar improvments.

After the Soviets detnoted their first atomic bomb in 1949. interest in radar development, especially for iar defence, surged. Major programs included the installation of the Distant Early Warning (DEW) network of long-range radar across the northern reaches of North America to warn against bomber attacks. As the potential threat of attack by ICBMs increased, the United Kingdom, Greenland, and Alaska installed the Ballistic Missile Early Warning System (BMEWS).

4.2 Radar Systems Classification Methods

During World War II, each service used its own method to designate its electronic radar/tracking systems. For example, Army radars were classified under the initials SCR, which stood for "Signal Corps Radio." Different designations for similar systems confused manufacturers and complicated electronics procurement. In February 1943, a universal classification system was implemented for all services to follow, ending the confusion. To indicate that an electronic system designation followed the new universal classification, the letters "AN," for Army-Navy, were placed ahead of a three-letter code. The first letter of the three-letter code denoted the type of platform hosting the electronic device, for example: A-Aircraft; C-Air transportable (letter no longer used starting in the1950s); F-Fixed permanent land-based; G-General ground use; M-Ground mobile; S-Ship-mounted; T-Ground transportable. The second letter indicated the type of device, for example: P-Radar (pulsed); Q-Sonar; R--Radio. The third letter indicated the function of the radar system device, for example: G-Fire control; R-Receiving (passive detection); S-Search; T-Transmitting. Thus an AN/FPS-20 represented the twentieth design of an Army-Navy "Fixed, Radar, Search" electronic device.

4.2.1 World War II Radars

This section describes the World War II vintage radars that saw service during the Cold War. The systems are listed in numerical order, bypassing the three-letter code. During World War II, search and height-finder radars became components of America's electronic arsenal. The function of the search radar was to detect and obtain a line of bearing on an aircraft. Early models such as the SCR-270 and 271 looked like large bed-springs. Later designs, such as the AN/CPS-5 looked like a large oval dish. Search radars generally rotated full circle around a central axis. In contrast to the rotating search radar antenna, the horizontally mounted height-finder radar focused on the tracked aircraft's reported bearing. The radar antenna dish then scanned up and down to provide the operators with the estimated height of the aircraft.

4.2.1.1 AN/TPS-lB, 1C, 1D

Bell Telephone Laboratories developed this radar that subsequently was produced by the Western Electric Company. A crew of two could operate the radar. The 1B model could detect bombers at 10,000 feet at a distance of 120 nautical miles. The height detection and range on the 1C and 1D models exceeded those of the 1B. The transmitter sent its pulse at an L-band frequency between 1220 to 1280 megahertz (MHz). This long-range search radar was used in the temporary Lashup system beginning in 1948.

4.2.1.2 AN/CPS-4

Developed by MIT's Radiation Laboratory, this height-finding radar was nicknamed "Beaver Tail." The radar was designed to be used in conjunction with the SCR-270 and SCR-271 search sets. The CPS-4 required six operators. This S-band radar, operating in the 2700 to 2900 MHz range, could detect targets at a distance of ninety miles. The vertical antenna was twenty feet high and five feet wide. This radar was often paired with the AN/FPS-3 search radar during the early 1950s at permanent network radar sites.

4.2.1.3 AN/CPS-5

Bell Telephone Laboratories and General Electric developed this search radar. General Electric began producing sets in January 1945. Designated as a transportable medium-range search radar, the unit was ideal for use in the Lashup system in conjunction with the AN/TPS- 10 height-finder radar. It could be operated with a crew of ten. Some of these units remained to serve in the first permanent network. Designed to provide a solid search of up to 60 miles at 40,000 feet, the radar often had success tracking aircraft as far as 210 miles away.

4.2.1.4 AN/CPS-6, 6A, 6B

The AN/CPS-6 was developed during the later stages of World War II by the Radiation Laboratory at MIT. The first units were produced in mid-1945. General Electric developed and produced the A-model and subsequent B-model at a plant in Syracuse, New York. The unit consisted of two antennas. One of the antennas slanted at a forty-five degree angle to provide the height-finder capability. Initially, the radar was designed to detect fighter aircraft at 100 miles and16,000 feet. The radar used five transmitters that operated at S-band frequencies ranging from 2700 AN/CPS-6to 3019 MHz. It took twenty-five people to operate the radar. An AN/CPS-6 radar was installed as part of the Lashup system at Twin Lights, New Jersey, in 1949 and proved capable of detecting targets at ranges of eighty-four miles. The first units of the follow-on 6B radar set were ready for installation by mid-1950. Fourteen 6B units were used within the first permanent net-work. A component designed to improve the radar's range was added in 1954. Initial tests showed the 6B unit had a range of 165 miles with an altitude limit of 45,000 feet. One radar unit and its ancillary electronic equipment had to be transported in eighty-five freight cars. The Air Force phased out the 6B model between mid-1957 and mid-1959.

4.2.1.5 AN/TPS-10, 1OA /AN/FPS-4

MIT's Radiation Laboratory developed and produced the first version of this radar near the end of World War II. Zenith produced the A-model sets in the post-war period. The vertically mounted antenna was three feet wide and ten feet long. Two operators were needed to run the set. The initial model operated at a frequency of 9000 to 9160MHz and had a maximum reliable range for bombers of 60 miles at 10,000 feet. An updated version designated the AN/FPS-4 was produced by the Radio Corporation of America (RCA) beginning in 1948. Some 450 copies of this and the trailer-mountedAN/MPS-8 version were built between 1948 and 1955.

4.2.2 Early Cold War Search Radars

Early Cold War search radars essentially were advanced or improved versions of World War II era sets. In some cases, the performance of the new sets fell short of expectations.

4.2.2.1 AN/FPS-3, 3A

The AN/FPS-3 was a modified version of the AN/CPS-5 long-range search radar. The first units came off the Bendix production line and were ready for installation in late 1950. Forty-eight of these L-band units were used within the first permanent network. The AN/FPS-3B incorporated an AN/GPA-27, which increased the search altitude to65,000 feet. Installation of these modifications began in 1957.

4.2.2.2 AN/FPS-5

The AN/FPS-5 was a long-range search radar produced in the early 1950s by Hazeltine. Deployment was limited.

4.2.2.3 AN/FPS-8

The AN/FPS-8 was a medium-range search radar operating on the L-band at a frequency of 1280 to 1380 MHz. Developed in the 1950s by General Electric, over 200 units of this radar were produced between 1954 and 1958. Variants of this radar included theAN/GPS-3 and the AN/MPS-11.

4.2.2.4 AN/FPS-10

This unit was essentially a stripped down version of the AN/CPS-6B. Thirteen of these units served within the first permanent network.

SAGE System Compatible Search Radars

Various manufacturers began design work on compatible search radars for SAGE systems in the mid-1950s in conjunction with the development of the SAGE Command

and Control System. Because Project LAMPLIGHT indicated radar vulnerability to electronic countermeasures, the Air Force developed a series of radars that could shift frequency. These frequency-diversity (FD) radars included the AN/FPS-24, AN/FPS-27, andAN/FPS-35.

4.2.3 SAGE System Compatible Search Radar

4.2.3.1 AN/FPS-7, 7A, 7B, 7CI 7D

In the mid-1950s, General Electric developed a radar with a search altitude of 100,000 feet and a range of 270 miles. This radar was significant in that it was the first stacked-beam radar to enter into production in the United States. Designed to operate in the L-band at 1250 to 1350 MHz, the radar deployed in late 1959 and the early 1960s. The AN/FPS-7 was used for both air defense and air traffic control in New York, Kansas City, Houston, Spokane, San Antonio, and elsewhere. In the early 1960s, a modification called AN/ECP-91 was installed to improve its electronic countermeasure (ECM) capability. About thirty units were produced.

4.2.3.2 AN/FPS-20,20A, 20B

This Bendix-built radar was an AN/FPS-3 search radar with an AN/GPA-27 installed. Designed to operate in the L-band frequencies of 1250 to 1350 MHz, the radar had a range of over 200 miles. By the late 1950s this radar dominated the United States radar defense net. Deployment continued into the early 1960s. In June 1959, Bendix received a contract to provide private industry's MK-447 (the same as the military's AN/GPA-103) and MK-448 (AN/GPA-102) anti-jam packages to the radars. With the addition of these packages, the Air Force redesignated the radars. The AN/FPS-20A with the AN/GPA-102 became the AN/FPS-66 and the AN/FPS-20A with the AN/GPA-103 became the AN/FPS-67. Over 200 units were built.

4.2.3.3 AN/FPS-24

General Electric built an FD search radar designed to operate in the Very High Frequency (VHF) at 214 to 236 MHz. There were problems with this radar at the test site at Eufaula, Alabama, in 1960. These problems required many modifications. Additional problems occurred when deployment was attempted in 1961. When the radar finally deployed, bearing problems often occurred due to the eighty-five ton antenna weight. Twelve systems were built between 1958 and 1962.

4.2.3.4 AN/IFPS-27,27A

Westinghouse built an FD search radar designed to operate in the S-band at 2322 to2670 MHz. The radar was designed to have a maximum range of 220 nautical miles and search to an altitude of 150,000 feet. System problems required several modifications at the test platform located at Crystal Springs, Mississippi. Once these problems were solved, the first of twenty units in the continental United States became operational a Charleston, Maine, in 1963. The last unit was installed at Bellefontaine, Ohio, a year later. In the early 1970s, AN/FPS-27 radar stations that had not been shutdown received a modification (solid state circuitry replacing vacuum tubes) that improved reliability and saved on maintenance costs.

4.2.3.5 AN/FPS-28

Raytheon designed this search radar to operate at 410 to 690 MHz. A test unit was placed at Huoma Naval Air Station (NAS) in Louisiana.

4.2.3.6 AN/FPS-30

Bendix built this long-range search radar that operated in the L-band.

4.2.3.7 AN/FPS-31

Designed by Lincoln Laboratory, this huge radar was designed to be compatible with the SAGE system. A prototype was built at Jug Handle Hill in West Bath, Maine. The antenna was 120 feet wide and 16 feet high. Operations began in October 1955. After a period of unexpected clutter, it was determined that the radar received echoes from the aurora borealis (Northern Lights) and this hindered tracking. Although this model was never mass-produced for active use, lessons learned from this radar would continue supporting SAGE system research and development.

4.2.3.8 AN/FPS-35

This Sperry-built FD long-range search radar was designed to operate at 420 to 450MHz. It was first deployed in December 1960, but problems hampered the program. Four of these units were operational in 1962. The system suffered frequent bearing problems as the antenna weighed seventy tons.

4.2.3.9 AN/FPS-64, 65, 66, 67, 67A, 72

These radars were modified versions of the Bendix AN/FPS-20 search radar. See theAN/FPS-20 entry.

4.2.3.10 AN/FPS-87A

Bendix built this long-range L-band search radar that was based on the AN/FPS-20. See the AN/FPS-20 entry.

4.2.3.11 AN/IFPS-88

General Electric produced this updated version of the AN/FPS-8 radar in the late1960s. The AN/FPS-88 operated in the L-band at 1280 to 1380 MHz and featured some ECM capability.

4.2.3.12 AN/IFPS-91

This radar was another version of the AN/FPS-20 search radar produced by Bendix. See the AN/FPS-20 entry.

4.2.3.13 AN/IFPS-93

Raytheon modified the AN/FPS-20 radar to create this radar. See the AN/FPS-20entry.

4.2.3.14 AN/IFPS-100

This radar was another modernization of the Bendix AN/FPS-20 radar. See theAN/FPS-20 entry.

4.2.3.15 AN/FPS-107

This Westinghouse-built search radar operated in the L-band at 1250 to 1350 MHz. SAGE System Compatible Height-finder Radars.To complement the search radars, height-finding radars were developed to detect aircraft at increasing altitudes. The AN/FPS-6 would serve as the standard model for much of the Cold War.

4.2.3.16 AN/IFPS-6,6A, 6B

The AN/FPS-6 radar was introduced into service in the late 1950s and served as the principal height-finder radar for the United States for several decades there after. Built by General Electric, the S-band radar radiated at a frequency of 2700 to 2900 MHz. Between 1953 and 1960, 450 units of the AN/FPS-6 and the mobile AN/MPS- 14 version were produced.

4.2.3.17 AN/FPS-26

Avco Corporation built this height-finder radar that operated at a frequency of 5400 to 5900 MHz. This radar deployed in the1960s.

4.2.3.18 AN/FPS-89

General Electric produced this improved version of the AN/FPS-6 height-finder radar in the early

1970s. Operating in the S-band, this high-power radar was capable of detecting targets at a range of over 110 miles.

4.2.3.19 AN/FPS-90

Martin Marietta produced the high-powered version of the AN/FPS-6 height-finder radar. Seethe AN/FPS-6 entry.

4.2.3.20 AN/FPS-116

This radar was another modernized version of the ANAFPS-6 height-finder radar. Seethe AN/FPS-6 entry.

4.2.3.21 Gap-Filler Radars

Gap-filler radars were designed to cover areas where enemy aircraft could fly low enough to evade detection by distant long-range search radars. Between 1957 and 1962, some 200 AN/FPS-14 and AN/FPS-18 models were built.

4.2.3.22 AN/FPS-14

This medium-range search radar was designed and built by Bendix as a SAGE system gap-filler radar to provide low-altitude coverage. Operating in the S-band at a frequency between 2700 and 2900 MHz, the AN/FPS-14 could detect at a range of 65 miles. The system was deployed in the late 1950s and 1960s.

4.2.3.23 AN/FPS-18

This medium-range search radar was designed and built by Bendix as a SAGE system gap-filler to provide low-altitude coverage. The radar operated in the S-band at a frequency between 2700 and 2900 MHz. The system deployed in the late 1950s and 1960s.

4.2.3.24 AN/FPS-19

This Raytheon gap-filler radar was deployed on the Distant Early Warning (DEW)Line. It operated in the S-band.

4.2.4 North Warning System Radars

The North Warning System replaced the DEW Line system in the late 1970s. New equipment came with the change in system designation. A key component of the modernization was a long-range radar system formally known as Seek Igloo. The system is based around the AN/FPS-117.

4.2.4.1 AN/FPS-117

This 3-D long-range radar was built by GE Aerospace for use at Alaskan sites and on the Northern Warning System. The radar operated at 1215 to 1400 MHz and had a range of about 220 miles.

4.2.4.2 AN/FPS-124

This medium-range radar was built by Unisys to serve as an unmanned gap-filler radar on the North Warning System.

Ballistic Missile Early Warning System (BMEWS) Radars

With the advent of ballistic missiles, millions of dollars were spent to research, develop, test, and deploy BMEWS radars.

4.2.4.3 AN/FSS-7

This radar was a modified AN/FPS-26 height-finder radar produced by Avco Corporation to detect submarine-launched ballistic missiles. The system deployed at seven sites in the 1970s. Six sites were phased out during the early 1980s.The remaining unit continued in operation in the southeast for a few more years to provide coverage over Cuba.

4.2.4.4 AN/FPS-17

With the Soviet Union apparently making rapid progress in its rocket program, in1954 the United States began a program to develop a tracking radar. General Electric was the contractor and Lincoln Laboratory was the subcontractor. This tracking radar, the AN/FPS-1 7, was conceived, designed, built, and installed for operation in less than two years. Installed at Laredo AFB in Texas, the first AN/FPS-17 was used to track rockets launched from White Sands, New Mexico. The radar was unique; it featured a fixed-fence antenna that stood 175 feet high and 110 feet wide. The transmitter sent out ash pulse at a frequency between 180 to 220 MHz. Units were installed in the late1950s at Shemya Island in the Aleutians and in Turkey. The unit at Shemya subsequently was replaced by the Cobra Dane (AN/FPS-100) radar.

4.2.4.5 AN/FPS-49,49A

This large radar was built by RCA for use in the BMEWS program and the satellite-tracking program that deployed in the 1960s. The prototype unit operated at Moorestown, New Jersey. Two additional units were installed in Greenland and England. The radar frequency operated in the Ultra High Frequency (UHF) band and could track objects beyond 3,000 miles.

4.2.4.6 AN/FPS-50

This was a BMEWS program surveillance radar that used a large, fixed-antenna fence system. Two beams were projected from the antenna array. Objects passing through the lower-angled beam provided initial data and warning for the North American Air Defense Command (NORAD). Data produced when the object passed through the upper beam allowed computation of trajectories on launch and target points. The radar operated in the UHF range at 425 MHz. General Electric, Heavy Military Electronics Department, installed these systems at Clear, Alaska, and Thule, Greenland, during the early1960s.

4.2.4.7 AN/FPS-85

This UHF, 3-D, phased-array radar was designed by Bendix for satellite tracking. Built in the early 1960s at Eglin AFB in Florida, it was the first phased-array unit in the United States. A fire destroyed the first model in 1965. A rebuilt model became operational in 1969. The southward-sloped structure contained a square transmitter face placed alongside a larger octangular receiving face. The transmitter operated at a UHF frequency of 442 MHz. The AN/FPS-85 was also used to detect submarine-launched ballistic missiles.

4.2.3.8 AN/FPS-92

This improved version of the AN/FPS-49 tracking radar was used in the BMEWS Program. Built by RCA, this radar was installed at Clear, Alaska, in the late 1960s. The radar operated in the UHF band around 425 MHz and had a range of over 3,000 miles.

4.2.4.9 AN/FPS-108 (Cobra Dane)

Cobra Dane was a large single-faced, phased-array radar built by Raytheon in the 1970s on Shemya Island in the Aleutians. As the main component of the Cobra system, the radar had the primary role of providing intelligence on Soviet test missiles fired at the Kamchatka peninsula from locations in southwestern Russia. Other components of the Cobra system included the ship-based Cobra Judy phased-array radar and the aircraft-based Cobra Ball and Cobra Eye radars. In addition to determining Soviet missile capabilities, Cobra Dane had the dual secondary role of tracking space objects and providing ballistic missile early warning. The radar antenna face of the building measured about ninety feet in diameter and contained some 16,000 elements. The L-band radar had a range of 2,000 miles and could track space objects as far as 25,000 miles away.

4.2.4.10 AN/FPS-115

Raytheon built the PAVE PAWS phased-array, missile-warning radar deployed during the early 1980s. At the four continental United States sites, the ninety foot diameter circular panel radars were mounted on two walls of a triangular-shaped pyramid structure. The antenna operated at a frequency of 420 to 450 MHz. PAVE PAWS could detect targets at ranges approaching 3,000 miles.

4.2.4.11 AN/FPS-118 (OTH-B)

Designed and built by GE Aerospace, the OTH-B radar was deployed on the east and west coasts in the 1980s. The system reflected the radar beam off the ionosphere to detect objects from ranges of 500 to nearly 2,000 miles. The transmitter arrays operated at frequencies between 5 and 28 MHz. Fixed transmitter and receiving antenna arrays were separated by a distance of 80 to 120 miles.

4.2.4.12 PARCS

The acronym, PARCS, stands for Perimeter Acquisition Radar attack Characterization System. This huge structure was built as the main sensor for the Army's Safeguard missile system that deployed north of Grand Forks, North Dakota. Upon shut down of Safeguard in 1976, the Air Force took over the huge UHF phased-array radar for use in tracking ballistic missiles and objects in space.

4.3 Missile Detection and Defense

The Soviet ICBM threat dramatically changed U.S. priorities to building detection and defensive capabilities against ballistic missile attack. Although Sputnik shocked the national psyche, the potential threat of intercontinental ballistic missiles had long been anticipated. Since the German V-2 campaign against England towards the end of World War II, military planners had been working with scientists and engineers to develop an antiballistic missile strategy.

Before the advent of the SS-6 Sapwood and Sputnik, both the Army and the Air Force had been conducting research and development programs leading to an antiballistic missile. The Air Force program, called "Project Wizard," was conceptual in nature.

Project Wizard spent millions of dollars in various research labs to develop new technologies to counter the enemy threat. In contrast, the Army program, called "Nike Zeus," was more hardware oriented, building on technology of the earlier Nike Ajax and Nike Hercules antiaircraft missile programs.

In 1958, in the wake of Sputnik, President Eisenhower directed the cancellation of Project Wizard in favor of the Army Nike Zeus program. However, to defend against an attack, the United States needed the capability to detect an attack. Americans feared a nuclear Pearl Harbor, where without warning, nuclear bombs could drop from space, devastating American cities and crippling the military's ability to launch a counterattack. Without the means to defend against such an attack, Americans could only hope that the threat of massive retaliation would deter the Soviet Union from launching such a strike. Early warning would be critical to prepare the nation for the initial blow and allow SAC bombers to get off the ground.

Congress quickly approved funding to construct a Ballistic Missile Early Warning System (BMEWS). Radio Corporation of America (RCA) would develop and build theAN/FPS-49 tracking radars, GE and MIT would design and construct the AN/FPS-50 detection radars, and Western Electric would build the communication systems to connect the radars with command centers. Construction began immediately in the summer of 1958.

BMEWS required building installations at three locations to cover possible flight paths of missiles launched from the Soviet Union. Site I at Thule, Greenland, would host both AN/FPS-49 and AN/FPS-50 radars and receive top construction priority. Providing coverage for most missile approaches from the Eurasian landmass, the Thule site reached initial operating capability in October 1960. Clear, Alaska was selected for Site 11to provide warning against missiles launched from the far eastern Siberia region. Initially hosting only AN/FPS-50 detection radars, the Alaskan site began operating in late1961. Site III, at Fylingdale Moor, Yorkshire, England, was operational in September1963. At Fylingdale Moor, AN/FPS-49 tracking radars provided coverage of ICBMs launched at the United States from the far western Soviet Union and provided an alert for Europeans if the Soviets launched intermediate range missiles at targets in western Europe.

Construction at the ICBM detection station at Clear began in August 1958. Located eighty miles southwest of Fairbanks, the station consisted of dormitories, administrative buildings, storage warehouses, recreational facilities, radar buildings, transmitter and computer buildings, fuel facilities, and three huge fence antenna components of theAN/FPS-50.

Designed by GE and MIT's Lincoln Laboratory, the three fixed-in-place fence antennas stood 165 feet tall and 400 feet wide. These curved arrays sent two fan-shaped beams at differing angles beyond the earth's atmosphere. When an object passed through the lower-angled beam, the reflected radar pulses were picked up by supersensitive antennas and passed on to computers that determined the object's position and velocity. When objects passed through the higher -angled second beam, computers received additional information to determine trajectory, speed, impact point, impact time, and launch point. In 1966 a tracking radar was added to the site when Clear received an updated version of the AN/FPS-49. Designated as the AN/FPS-92, this tracking radar featured a movable antenna that locked onto objects identified by the detection radar. This provided additional data to NORAD headquarters.

NORAD received additional contributing sensors. In July 1973, Raytheon won a contract to build a system called "Cobra Dane" on Shemya Island in the Aleutian Islands off the Alaskan coast. Designated as the AN/FPS-108, Cobra Dane replaced AN/FPS- 17 andAN/FPS-80 radars placed at Shemya in the 1960s to track Soviet missile tests and to support the Air Force Space track System. Becoming operational in 1977, Cobra Dane also had a primary mission of monitoring Soviet tests of missiles launched from southwest Russia aimed at the Siberian Kamchatka peninsula. This large, single-faced, phased-array radar was the most powerful ever built.

In 1976, the Air Force began operating the Perimeter Acquisition Radar attack Characterization System (PARCS). The story of how the Air Force came to possess this huge, phased-array radar traces its roots back to the 1950s.

In February 1955, the Army contracted Bell Telephone Laboratories to develop an ABM system. This system would be built on the technologies obtained during Nike Ajax and Nike Hercules system development. However, the Nike Zeus system developed by Bell never deployed. Acting on advice that immediate deployment was not technically feasible at an acceptable cost, President Eisenhower decided in May 1959 to maintain Nike Zeus as a research and development program.

By January 1963, the research and development program had evolved into "Nike X" On September 18, 1967, Defense Secretary McNamara acknowledged that ABM defenses could still be overwhelmed by a massive Soviet ICBM attack. However, the emergence of a Chinese nuclear threat could be countered by deploying the Nike X system, renamed the Sentinel, around major metropolitan areas.

On March 14, 1969, the Nixon administration canceled the Sentinel deployment scheme. Instead ABM defense was deployed under the name "Safeguard" to protect America's strategic missile forces. Minuteman missile silos surrounding Grand Forks AFB, North Dakota, and Malmstrom AFB, Montana, would be the first to receive ABM defense.

As a result of the 1972 ABM agreement, the United States completed work only at the site north of Grand Forks. Declared operational in 1975, the Grand Forks ABM site, armed with 100 defending missiles, could provide only a limited defense against the hundreds of warheads that the Soviets could employ. Furthermore, nuclear war scenarios foresaw the radar complexes coming under immediate attack, rendering the intercepting missiles useles. Faced with this futile situation, the Army wanted to operate the system for at least a year and then incorporate the lessons learned for a follow-on system. However, Army plans were cut short on October 2, 1975, when Congress voted to deactivate the site within the following year. Eventually the Air Force assumed operations of Safeguard's Perimeter Acquisition Radar (PAR) and redesignated the site as Cavalier Air Force Station. From its North Dakota location, PARCS provided additional polar coverage to support BMEWS.

BMEWS, along with additional sensors, gave NORAD the capability to warn the National Command Authority of an attack launched from the Soviet Union. However, the Soviet Union could attempt to circumvent the warning system using different geographical approaches. The Cuban Missile Crisis of the fall of 1962 was one such attempt. The placement of intermediate range ballistic missiles in Cuba illustrated the vulnerability of the United States to an attack along its unprotected southern border. Only after a highs takes showdown between the two superpowers, were the missiles removed.

In the wake of the Cuban Missile Crisis, an AN/FPS-85 long-range phased-array radar was constructed at Eglin AFB in Florida. Designed by Bendix Corporation, the radar consisted of a large square transmitter array placed alongside an octangular receiving array mounted on a large structure facing the Gulf of Mexico. The structure hosting the radar burned in 1965, but was rebuilt and placed back in operation in 1969. This radar also served as the main sensor for the Air Force's Spacetrack System and watched the skies over Cuba and the Gulf.

The American triumph of keeping Soviet nuclear launch platforms out of Cuba and at a distance would be short-lived and American defense planners knew it. During the early 1960s, Soviet scientists and engineers worked feverishly to design and build Soviet ballistic missile submarines capable of launching missiles from relatively short distances off America's coastlines. Once again the United States needed the capability to detect incoming missiles to prevent the specter of an atomic sneak attack. In December 1961, the Air Force asked ADC for an evaluation of the capability of FD radars to detect Submarine-Launched Ballistic Missiles (SLBMs). Subsequently, AN/FPS-35 search radars located at Manassas, Virginia, and Benton, Pennsylvania, received modifications and began to be tested during the summer of 1962. During these tests, both radars attempted to track Polaris, Minuteman, Titan, and the Thor-Delta missile launched from Cape Canaveral, Florida. The tests revealed that the AN/FPS-35 had only marginal ability to detect missile launches. 73 However, using AN/FPS-35 or AN/FPS-24 FD radars to detect SLBMs continued to be considered a viable option given the fiscal constraints imposed on ADC.

Another option to detect SLBMs that was favored by ADC was to procure a series of An/FPS-49 radars. One of these units had been operating since 1961 at Moorestown, New Jersey, as the original sensor for the Air Force's Spacetrack System. To ADC's disappointment, a study by the Electronic Systems Division at Hanscom AFB, Massachusetts, revealed that using the Moorestown radar for dual use was infeasible. 74

The long-tem vision of ADC planners foresaw SLBM detection as a collateral mission of the OTB-B radar that was still under development. However, ADC could not wait for a system that still was in the research and development stage. In November 1964, desperate to field at least an interim system to warn the nation of a SLBM attack, ADC sought and received permission from the office of the Secretary of Defense to modify existing SAGE system radars.

In the ensuing months, makers of the various SAGE-compatible radar systems submitted proposals on the modifications that would enable their products to detect an object of at least two meters in size, at a range of 750 miles, within six seconds after launching. The radar then would continuously track this object within ten seconds of detection and notify NORAD Combat Operations Center within sixty seconds.

In July 1965, the Air Force selected Avco Corporation for an innovative proposal employing its AN/FPS-26 height-finder radar to detect SLBMs. The modified AN/FPS-26 radar system (redesignated as the AN/FSS-7) was slated for deployment at Point Arena. California; Mount Laguna California; Mount Hebo, Oregon; Charlestown, Maine; Fort Fisher, North Carolina; MacDill AFB, Florida; and Laredo Texas.

After years of testing and evaluation, the seven-site SLBM detection system became fully operational in 1971. A year later, twenty percent of the surveillance capability of the AN/FPS-85 located at Eglin AFB, Florida, also became dedicated to search for SLBMs.

During the 1970s, the Soviets developed SLBMs that could be launched from greater distances away from the American Coastline. For example, the Soviet Delta I class ballistic missile submarine carried the SS-N-8 missile that had a range of over 4,000 nautical miles. This was beyond the detection capability of either the AN/FSS-7 or the OTH-B radar system being developed. 78 Consequently, the Air Force had to turn to another solution.

The solution was a phased-array warning system to become known as "PAVE PAWS" (Perimeter Acquisition Vehicle Entry Phased-Array Warning System). Originally designed as a two-site system, PAVE PAWS sites were constructed in the late 1970s at Otis AFB, Massachusetts, and Beale AFB, California. From a distance, the PAVE PAWS structure looked like a three-sided pyramid with a flattened top. On the two seaward faces of the pyramid, Raytheon installed the AN/FPS-115 with its phased-array antenna. Thirty meters in diameter and consisting of 2,000 elements, each antenna could detect objects launched as far away as 3,000 miles. The Otis site became operational in 1979and the Beale site became operational a year later.

A contract for two more continental PAVE PAWS sites, was awarded in 1984. AnANfFPS-115 at Robins AFB, Georgia, became operational in 1986 and another unit at Eldorado AFS, Texas, was activated in 1987. Additional AN/FPS-115 PAVE, PAWS radars were installed in the 1990s at BMEWS sites at Thule, Greenland, and Fylingdale Moor, England, to assume the ICBM detection mission. As PAVE PAWS sites in the United States were activated, the older AN/FSS-7 radars were phased out, except for the MacDill AFB site that continued to provide additional coverage over Cuba .

Spacetracking and missile detection functions of the former Aerospace Defense Command were assumed by SAC in 1980. Control of these facilities became an Air Force Space Command responsibility with the activation of that command on September 1, 1982.

4.4 Ballistic Missile Early Warning System (BMEWS) Radars

With the advent of ballistic missiles, millions of dollars were spent to research, develop, test, and deploy BMEWS radars.

4.4.1 AN/FSS-7

This radar was a modified AN/FPS-26 height-finder radar produced by Avco Corporation to detect submarine-launched ballistic missiles. The system deployed at seven sites in the 1970s. Six sites were phased out during the early 1980s.The remaining unit continued in operation in the southeast for a few more years to provide coverage over Cuba.

4.4.2 AN/FPS-17

With the Soviet Union apparently making rapid progress in its rocket program, in1954 the United States began a program to develop a tracking radar. General Electric was the contractor and Lincoln Laboratory was the subcontractor. This tracking radar, the AN/FPS-1 7, was conceived, designed, built, and installed for operation in less than two years. Installed at Laredo AFB in Texas, the first AN/FPS-17 was used to track rockets launched from White Sands, New Mexico. The radar was unique; it featured a fixed-fence antenna that stood 175 feet high and 110 feet wide. The transmitter sent out ash pulse at a frequency between 180 to 220 MHz. Units were installed in the late1950s at Shemya Island in the Aleutians and in Turkey. The unit at Shemya subsequently was replaced by the Cobra Dane (AN/FPS-100) radar.

4.4.3 AN/FPS-49,49A

This large radar was built by RCA for use in the BMEWS program and the satellite-tracking program that deployed in the 1960s. The prototype unit operated at Moorestown, New Jersey. Two additional units were installed in Greenland and England. The radar frequency operated in the Ultra High Frequency (UHF) band and could track objects beyond 3,000 miles.

4.4.4 AN/FPS-50

This was a BMEWS program surveillance radar that used a large, fixed-antenna fence system. Two beams were projected from the antenna array. Objects passing through the lower-angled beam provided initial data and warning for the North American Air Defense Command (NORAD). Data produced when the object passed through the upper beam allowed computation of trajectories on launch and target points. The radar operated in the UHF range at 425 MHz. General Electric, Heavy Military Electronics Department, installed these systems at Clear, Alaska, and Thule, Greenland, during the early1960s.

4.4.5 AN/FPS-85

This UHF, 3-D, phased-array radar was designed by Bendix for satellite tracking. Built in the early 1960s at Eglin AFB in Florida, it was the first phased-array unit in the United States. A fire destroyed the first model in 1965. A rebuilt model became operational in 1969. The southward-sloped structure contained a square transmitter face placed alongside a larger octangular receiving face. The transmitter operated at a UHF frequency of 442 MHz. The AN/FPS-85 was also used to detect submarine-launched ballistic missiles.

4.4.6 AN/FPS-92

This improved version of the AN/FPS-49 tracking radar was used in the BMEWS Program. Built by RCA, this radar was installed at Clear, Alaska, in the late 1960s. The radar operated in the UHF band around 425 MHz and had a range of over 3,000 miles.

4.4.7 AN/FPS-108 (Cobra Dane)

Cobra Dane was a large single-faced, phased-array radar built by Raytheon in the 1970s on Shemya Island in the Aleutians. As the main component of the Cobra system, the radar had the primary role of providing intelligence on Soviet test missiles fired at the Kamchatka peninsula from locations in southwestern Russia. Other components of the Cobra system included the ship-based Cobra Judy phased-array radar and the aircraft-based Cobra Ball and Cobra Eye radars. In addition to determining Soviet missile capabilities, Cobra Dane had the dual secondary role of tracking space objects and providing ballistic missile early warning. The radar antenna face of the building measured about ninety feet in diameter and contained some 16,000 elements. The L-band radar had a range of 2,000 miles and could track space objects as far as 25,000 miles away.

4.4.8 AN/FPS-115

Raytheon built the PAVE PAWS phased-array, missile-warning radar deployed during the early 1980s. At the four continental United States sites, the ninety foot diameter circular panel radars were mounted on two walls of a triangular-shaped pyramid structure. The antenna operated at a frequency of 420 to 450 MHz. PAVE PAWS could detect targets at ranges approaching 3,000 miles.

4.4.9 AN/FPS-118 (OTH-B)

Designed and built by GE Aerospace, the OTH-B radar was deployed on the east and west coasts in the 1980s. The system reflected the radar beam off the ionosphere to detect objects from ranges of 500 to nearly 2,000 miles. The transmitter arrays operated at frequencies between 5 and 28 MHz. Fixed transmitter and receiving antenna arrays were separated by a distance of 80 to 120 miles.

4.4.10 PARCS

The acronym, PARCS, stands for Perimeter Acquisition Radar attack Characterization System. This huge structure was built as the main sensor for the Army's Safeguard missile system that deployed north of Grand Forks, North Dakota. Upon shut down of Safeguard in 1976, the Air Force took over the huge UHF phased-array radar for use in tracking ballistic missiles and objects in space.

4.5 Federal Aviation Administration (FAA) Radars

Beginning in the late 1950s, the Civil Air Administration (predecessor to the FAA) and the DoD began to cooperate to reduce duplication. By the late 1980s most radars performing air search for the military were operated by the FAA in the joint surveillance program. Because it is a civilian agency, the FAA uses a different radar designation system.

4.5.1 ARSR-1

This Raytheon-built Air Route Surveillance Radar (ARSR) was used by the FAA Authority Radar beginning in 1958. It operated on a L-band frequency of 1280 to 1350MHz with a maximum range of 200 miles.

4.5.2 ARSR-2

Developed by Raytheon in the 1960s as a replacement for the ARSR-1, this radar also operated in the L-band and had a similar maximum range to the ARSR-1.

4.5.3 ARSR-3,3D

This Westinghouse-built search radar was used by the FAA in the Joint Surveillance System (JSS). The radar operated in the L-band at 1250 to 1350 MHz and detected targets at a distance beyond 240 miles. The D model had height-finder capability.

4.5.4 ARSR-4

The FAA began installing this Westinghouse-built 3-D air surveillance radar in the1990s for the JSS system. By the late 1990s this radar will have replaced most of the 1960s-vintage AN/FPS-20 variant search radars.

4.6 COMMAND AND CONTROL SYSTEMS

Semi-Automatic Ground Environment (SAGE) System

The SAGE system was conceived by the Lincoln Laboratory at MIT in the early 1950s to receive various sensor inputs and to detect, identify, track, and provide interceptor direction against air-breathing threats to North America. The SAGE system removed Ground Control Intercept functions from several of the radar sites and reduced manpower requirements. The first SAGE control center became operational in 1958 and the system was completed in 1961. The number of SAGE centers was reduced from about two dozen in 1962 to six in 1969. These remaining six were retired in 1983. The SAGE system featured the IBMAN/FSQ-7 (Whirlwind II) large-scale, vacuum-tube, electronic, digital computer.

4.7.1 Backup Interceptor Control (BUIC) System

Because the SAGE system was vulnerable to attack from Soviet intercontinental ballistic missiles (ICBMs), the Air Force sought an alternative command and control system. In the early 1960s, some radar sites increased manning to pre-SAGE levels and manually assumed pre-SAGE Ground Control Intercept functions. The sites given this ability to perform command and control functions were called BUIC I sites. Starting in 1965, BUICII sites became operational. BUIC II sites featured the Burroughs AN/GSA-51 computer that allowed the automatic processing of data from various radar sites. BUIC III sites became operational in the late 1960s. These sites hosted the more capable Burroughs D825 digital computer and could support operations at eleven control consoles. During the early 1970s two BUIC sites were designated to serve as backup to each of the remaining six SAGE centers. Most BUIC sites were removed from service in the mid-1970s. The BUIC center at Tyndall AFB, Florida, remained in service until the early 1980s.

CONCLUSION

Much remains of the air and aerospace detection, command, and control systems built during the Cold War. Although only a fraction of the radar stations built during the1950s and 1960s remain in military hands, many are still operational under FAA control. However, the FAA is in the process of completing its modernization program to replace Air Force 1960s vintage FPS model radars. At former ADC sites, the radars have been removed and the facilities have been converted to perform new functions. Many sites, especially in remote locations, simply have been abandoned.

The blockhouses that once hosted SAGE centers remain intact at many locations, although the Whirlwind II computers and command consoles have long been removed. The four ROCCs built during the 1980s remain intact and operational. The intruding aircraft in the 1990s represent a different threat; attempting to smuggle illegal drugs into the country.

The BMEWS system will remain intact for the foreseeable future as long as more countries gain the capability to launch ballistic missiles. Cheyenne Mountain, Colorado, still serves as the nerve center for North America's missile tracking sensors.

Historians will long argue what brought about the demise of the Soviet Union and why World War III never was fought. While one school argues that the Soviet system collapsed under its own weight of inefficiency, another school vigorously contends that American military vigilance significantly contributed to the Soviet demise.

Nuclear deterrence, it is argued, eliminated direct military confrontation as an option for the Soviets. If such is the case, then the role of the thousands of men and women who operated the radar stations and command centers during the Cold War cannot be overlooked. They contributed to the deterrence in two ways. First, by being able to direct interceptor forces against intruding aircraft, the air defenders reduced the opponent's confidence level for mission success. Second, and more importantly, the warning provided by the air defense and later missile defense warning sensors gave America's nuclear forces the forewarning necessary to deliver a devastating retaliatory blow.

When viewing the hundreds of abandoned air defense structures dotting the American landscape, one should reflect on the roles of the thousands of men and women who operated the air defense systems. Part of their legacy is their contribution to the United States' triumph in the Cold War.

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