eBook

Fundamentals of Radar and RF Power Generation

February 2021

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Introduction

Fundamentals of Radar and RF Power Generation

This eBook covers the fundamentals of radar technology and RF power generation theory. These are very important topics as the military radar market is projected to grow from USD 14.0 billion in 2020 to USD 17.4 billion by 2025, at a CAGR of 4.4 percent during the forecast period according to ASD Reports. Increasing threats from high-speed missiles and aircraft have led to an increase in demand for surveillance and fire control radars. The increasing deployment of ballistic and stealth missiles has also led to a significant increase in the demand and performance level for military radars across the globe. Other applications of military radars include airborne fire control, surveillance activities, ground mapping and coastal surveillance.

The first article covers the military radar market and outlook through 2025 followed by an extensive article that takes a comprehensive look at the many aspects of radar technology including the basics of radar operation, how radar works and various types of radar systems. The key performance criteria are covered along with antenna design and future trends in the technology. The next two articles review the theory of operation for receiver protectors and magnetrons. The last article covers the underlying concepts of receiver protector life and how they apply to actual performance.

This is a very good guide to the basics of radar and the theory of operation of the key components that generate high power RF signals for radar systems. You will learn about all of these in this comprehensive guide. Thanks to CPI for sponsoring this eBook and providing the content so that we could bring it to you at no cost. We hope that you will learn about the many aspects of radar technology from reading it.

Pat Hindle, Microwave Journal *Editor*

Military Radars Market Worth $17.4 Billion by 2025

The military radars market is projected to grow from USD 14.0 billion in 2020 to USD 17.4 billion by 2025, at a CAGR of 4.4 percent during the forecast period. Increasing threats from high-speed missiles and aircraft have led to an increase in demand for surveillance and fire control radars.

Rise in the defense spending of emerging economies, growing regional tensions, and an increasing number of inter-country conflicts are major factors driving the military radars market. The increasing deployment of ballistic and stealth missiles in active war zones has also led to a significant increase in the demand for military radars across the globe. Other applications of military radars include airborne fire control, surveillance activities, ground mapping and coastal surveillance. The use of military radars in all these applications is fueling the growth of the military radars market, globally.

Based on the application, the air and missile defense segment is expected to lead the military radars market share during the forecast period.

Ongoing modernization programs in airspace monitoring in Asia Pacific region, activities such as sea-based military operations, drug trafficking, illegal migrations, demand for early warning threat detection systems, continuous demand for mine detection systems and equipment by U.S. military to tackle conflicts in the Middle East and Asia Pacific will drive the market for air and missile defense radars, globally.

Under Platform segment, Naval subsegment is estimated to be the largest and fastest-growing market.

The naval platform is estimated to be the largest and fastest-growing segment in the military radars market. The growth of this segment can be attributed to Increased efficiency and higher accuracy of ship-based naval radar systems drive this segment. The demand for effective weapon guidance systems for naval ships is boosting the growth of ship-based naval radars. Increasing investments by the Asian countries for the development of ship-based radar systems is further propelling the industry growth. More than half of the global shipbuilding activities are conducted in countries such as China, Japan and South Korea will drive the market for naval radars.

Based on the product type, the surveillance and early airborne warning radar segment is expected to lead the military radars market share during the forecast period.

The surveillance and early airborne warning radar segment is estimated to have the largest market share by value. Ongoing military modernization, replacement of obsolete radars and introduction of digital signal processing and solid-state modules are additional factors expected to drive the surveillance and early airborne warning radars market during the forecast period. The demand for technologically advanced early airborne warning radar systems is increasing as various major manufacturers from developed countries are developing carefully-shaped fighters which leads to a significant reduction in its detection range.

Raytheon Technologies Corporation (U.S.), Lockheed Martin Corporation (U.S.), Israel Aerospace Industries (Israel), Thales Group (France) and Leonardo S.P.A. (Italy) are some of the leading players operating in the military radars market.

Source: ASDReports - Market Research

How to Speak Radar

Basic Fundamentals and Applications of Radar

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Foreword

The following information is presented to give the reader a basic introduction to the subject of radar and to the application of radar equipment.

Historically, the basic principle of radar was demonstrated by Heinrich Hertz in 1888 and was later tested in Germany in the early 1900s. Nothing was really done to exploit the early demonstrations until the 1930s when a number of individuals, both in Europe and the United States, were concerned with the early detection of a bomber aircraft strike. Great Britain was first in deploying an operational radar system (the Chain Horne in 1937) using available components of radio technology. The Chain Home radar operated at the now unseemly frequency of about 25 MHz. Most of the allied radars in the late '30s operated at frequencies from about 75 to 200 MHz, since that was the limit of the vacuum tube technology at that time. Perhaps the most significant develop- ment to advance radar technology occurred at the end of the decade in 1939, when the microwave cavity resonator magnetron was invented in England. This device then provided the radar industry with a very high power transmitting tube enabling radars to operate at microwave frequencies. At about the same time, the Varian brothers invented the klystron, first developing the reflex klystron for receiver local oscillator application.

The existence of the magnetron and the reflex klystron then made it possible to produce very effective radar systems in the early World War II timeframe.

The evolution of the radar art has grown steadily to the present level that employs sophisticated computerized techniques and has stimulated the development of increasingly complex components. These components have been needed to continually advance the art of gathering and applying better information in order to achieve new objectives. Many different kinds of radar equipment are manufactured that perform a variety of functions but they all have one common purpose: the extraction of information from a reflected radio signal. A radar equipment can simply be defined as an information machine. The kind of information and the resolution or accuracy of that information is a measure of the radar system and can vary appreciably according to what a radar system is intended to accomplish.

The word **radar** is an acronym coined from the expression **"Radio Detection And Ranging."** As the following discussion will indicate, the original objectives of detection and ranging have grown to include radar imagery that approaches that of light photography.

HOW TO SPEAK RADAR

Uses of Radar

An equipment that uses the principles of radar is called a radar system. Such a system can be small enough to be installed in an automobile spotlight, such as a police speed-detection radar, or large enough to require one or more buildings to enclose a single radar system.

Some functions of radar systems are listed below together with an example of a typical radar system for each function.

Function	Example
1. Search	Early Warning Radar
2. Locate	Mortar Locator
3. Control	Air Traffic Control Radar
4. Navigate	Terrain Following Radar
5. Track	Target Tracking Radar
6. Map	Side-Looking Radar
7. Intercept	Attack Radar
8. Guide	Missile illuminator
9. Identify	Discrimination Radar
10. Measure	Velocimeter Radar
11. Warn	Threat Warning Radar
12. Dock	Capsule Docking Radar
13. Land	Microwave Landing System

Desired Information

In performing the above functions, the radar systems must obtain certain information from the radar signal. The kinds of radar information that can be extracted include:

1. Range
2. Range rate or velocity
3. Acceleration
4. Azimuth (angular) direction
5. Elevation angle
6. Target size
7. Target shape
8. Change in target shape
9. Particular target identification or "target signature" (such as spin rate)

Measurement Information

The extraction of information from the returned echoes of a radar transmitter is performed by analyzing the returned signals in terms of (1) the time of arrival of signals and (2) the detected the signal. In the first instance, measurements are made in the **time domain.** By knowing that the velocity of propagation of a radiated signal is equal to the velocity of light and by measuring the time elapsed between transmission and reception, the distance that the signal traveled can be determined and displayed. Thus, **range** measurement is made in the time domain. (Distance = Time x Velocity.) A radar signal will travel to a target one mile away and return in about 10 microseconds.

When a signal is reflected from a target

moving in a relative radial direction, an effective shift in frequency is experienced. This frequency shift is known to be caused by the Doppler Effect, and the magnitude of the frequency shift is measured by determining the frequency difference between the transmitted frequency and the frequency of the returned signal. This measurement is made in the **frequency domain** and is the means of determining the relative radial velocity of a moving target in relation to the position of the radar. In a very complex radar system, measurements may be made in both time and frequency domains in order to extract as much available information from the returned signal as can be obtained within the present art.

frequency changes or phase changes of

Resolution of Information

The degree of resolution of radar information is defined as how well a radar system can separate two signals that are close to each other either in terms of time measurement (range) or frequency measurement (velocity). Obtainable resolution depends upon (1) the amount of information transmitted (bandwidth and modulation), (2) the manner in which the transmitted signal is directed and received (antenna directiveness), and (3) the manner in which the returned signal is detected and processed.

Range resolution is obtained by using either (1) very short transmitted pulses so that targets that are close together can be detected at different times, (as a radar pulse may be long enough to dwell on two closely spaced targets simultanously), or by (2) employing modulation to the pulse to enable discrimination between two signals that are received simultaneously. This is described later in the section on Pulse compression.

Angular (azimuth or elevation) **resolution** depends upon the beamwidth of the antenna. Angular resolution decreases as the range increases, since the antenna beam becomes wider with increased range. The obvious way to improve angular resolution is to employ a very directional antenna beam that is as narrow as can be achieved. A second method is to apply advanced Doppler sensing techniques as is described later in the discussions on Synthetic Aperture Radar Systems and Doppler Beam Sharpening.

Velocity resolution depends upon the ability of the receiver and the detector to discriminate in frequency. Velocity measurements are achieved with a group of Doppler filters and the discrimination between adjacent Doppler frequencies is then determined by the frequency bandwidth and selectivity of each Doppler filter.

Generally, the factors that increase resolution can be summarized as follows:

Angular Resolution	Range Resolution	Velocity Resolution
1. Narrow Antenna Beamwidth	1. Short Pulsewidth	1. Narrow Doppler Frequency Filter Bandwidth
2. Doppler Sensing	2. Pulse Compression	2. Digital Doppler Processing

Ambiguous and Unambiguous Information

The words "ambiguous" and "unambiguous" are used frequently in radar system design considerations when speaking of extracting information when either (1) more than one signal is available for the correct information, making the correct value uncertain, or (2) there are conditions that do not allow the correct information to be extracted. If a measurement can be made in a continuous manner, the measurement is an unambiguous one. For example, if velocity is measured by measuring the Doppler frequency shift of a continuous wave (CW) transmission, the measurement is a continuous one and there is no extraneous velocity information that will confuse the mea-surement. However, if the CW transmission is interrupted at some periodic rate, the velocity information in terms of a frequency measurement relative to the carrier frequency becomes confused with the sidebands produced by the frequency of interruption. Further, the velocity information that corresponds to the frequency of interruption and its multiples cannot be measured. The capability to measure Doppler frequencies relative to pulse recurrence frequency is shown in **Figure 1**.

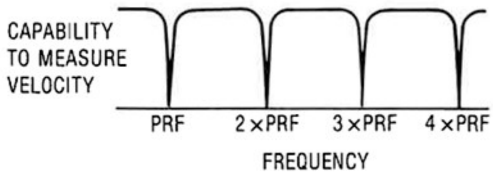


Figure 1. Velocity frequency measurement capability as a function of frequency of interruption (PRF).

In the case of range measurement, if only one pulse is transmitted, all ranges can be measured with no ambiguity. However, as soon as a second pulse is transmitted, unambiguous range measurements have the limit of the interpulse time before becoming ambiguous.

If a reflected signal appears at the same time as the next pulse is transmitted, the signal is not able to be detected and is said to be "eclipsed." If a reflected signal appears after the next pulse is transmitted, the signal is received as an ambig-uous signal and is referred to as a "second time around" target. **Figure 2** diagrams the time rela-tionship of various return signals in range measurements.

A comparison of measurements in both the time and frequency domains is illustrated in **Figure 3**. In advanced radars many modes of operation are required such as search, intercept, mapping, etc. Each mode has particular kinds of information that are desired and in order to obtain optimum information for a particular mode of operation, a change in the pulse recurrence frequency (PRF) is usually necessary. For example, in airborne radar, a low PRF operation will have the principal advantage of the ability to sort clutter from targets on the basis of range as clutter does not consume the entire unambiguous range interval. A low PRF system also is free of spurious signals called "ghosts" since the range is unambiguous and no range correlation is required. However, in the frequency domain the low PRF velocity information is ambiguous and can be blind at the velocities corresponding to each PRF line. Looking at the same parameters that correspond with the high

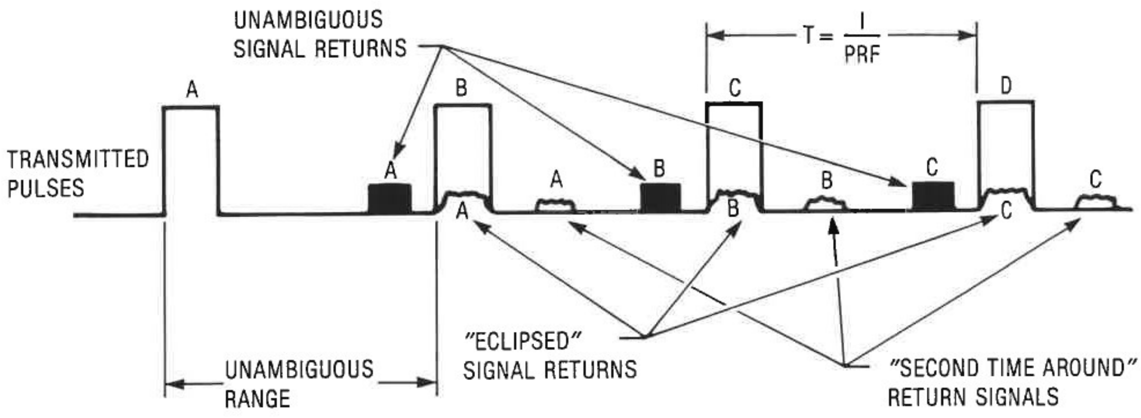


Figure 2. Signal returns in range measurements.

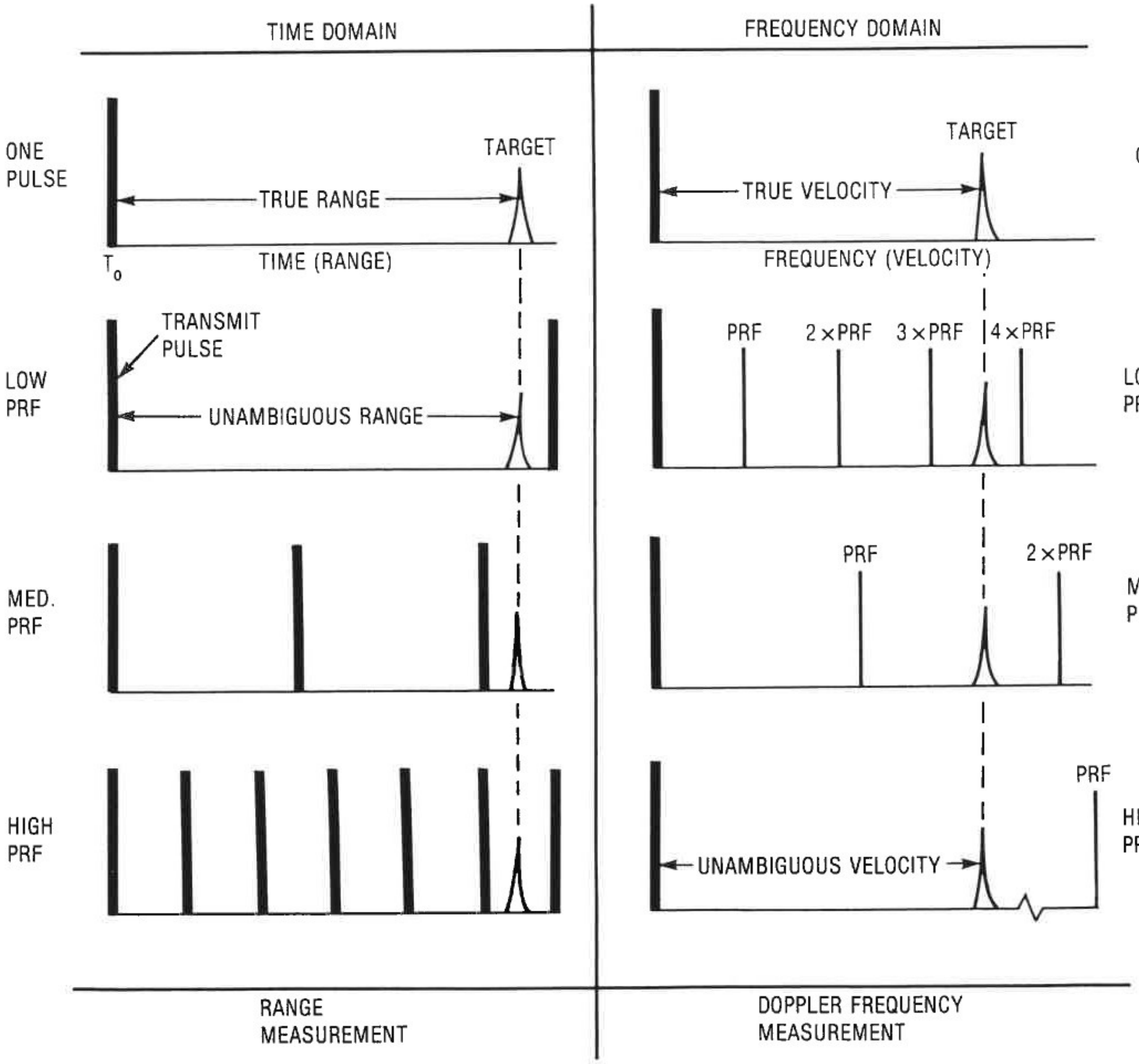


Figure 3. Information versus Pulse Recurrence Frequency.

PRF system, the measurement of frequency becomes unambiguous as there is significant Doppler frequency bandwidth between the PRF lines. For this reason, the PRF is commonly made more than the maximum expected Doppler frequency. The range measurement with a high PRF then becomes one of an ambiguous character and correlation techniques involving PRF switching are necessary to measure range. The above considerations and various compromises in each are taken into account in the design of the various waveforms that a radar system will use.

The Doppler Effect

The Doppler Effect is that effect which gives an apparent change in frequency if either the source of radiating energy or the reflecting target is in radial motion relative to the other. The Doppler frequency shift is a function of the relative radial velocity and the oscillating frequency and their relationship is shown in the formula:

$$F_d = \frac{2V_r}{\lambda} = \frac{2V_r F_o}{c}$$

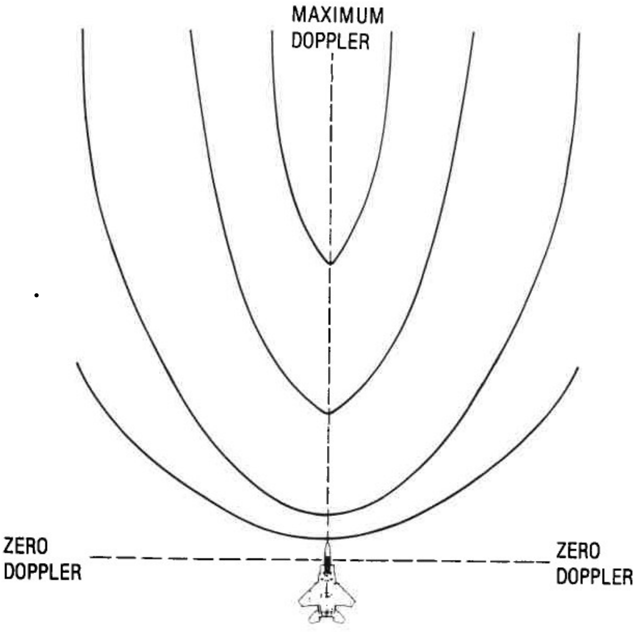


Figure 4. Curves of equal Doppler for an airborne radar.

where:

F_d = Doppler Frequency Shift
V_r = Relative Velocity
λ = Wavelength
F_0 = Transmitted Frequency
c = Velocity of Propagation

From the above equation, we learn that a radial velocity of one nautical mph provides a Doppler frequency shift of about 34 Hz at an operating frequency of 10 GHz.

Note that the **relative** radial velocity parameter is important in measuring Doppler frequency shift, since a vehicle moving at a high velocity in a circle about a fixed radiating source does not create a Doppler frequency shift, as the distance between the two objects does not change. Further, if the vehicle and the radar are moving in a straight line at the same velocity and in the same direction there is also a zero Doppler effect between the two as there is no change in range.

Figure 4 illustrates the Doppler shift of surface targets that an airplane would measure when looking forward at different angles from bore- sight. The plots of equal Doppler frequency shifts ("isodops") come about from the angle that the antenna beam scans off of boresight together with the angle relative to the ground plane.

The measurement of the Doppler Effect then becomes an important identifier of a target and can be used for measuring parameters such as target velocity, target acceleration and spin rate. As will be discussed in the discussions of synthetic aperture antenna and Doppler beam sharpening techniques, the measurement of Doppler frequencies is also used as a means of improving the azimuth resolution of a radar system.

Fourier Transforms

As mentioned, radar measurements are made in both time and frequency domains. A radar signal can be represented in either domain, and being able to translate the representation from one domain to the other is very useful in modern signal processing. The mathematical expression for transforming from the time domain to the frequency domain is called the **Fourier Transform**. For example, range signals in FM-CW radar are perceived in the frequency domain and may be transformed into time domain signals (Inverse Fourier Transform) for presentation on a display that shows signals in a time-based format. These transformations are now possible with modern digital devices and techniques. It is also done with optical processors as is the case with synthetic aperture radar data processing.

The Radar Equation

A radar system uses the phenomenon of a body reflecting (repropagating) high-frequency electromagnetic energy, to obtain an "echo" return to a high frequency transmission. The manner in which a wave of energy is transmitted (the waveform) and received is a choice that is always fitted to the intended use of a radar equipment. Generally, one particular measurement is desired most, such as range, so that other information (velocity, elevation, etc.) may be compromised, if necessary, as a less important objective.

The detection performance of any radar depends upon many factors that are related in what is traditionally known as the Radar Equation. There are a number of forms of this equation. One common form equates the ratio of the returned signal power, S, to the receiver noise power, N, as shown in the following:

$$\frac{S}{N} = \frac{PG^2\lambda^2\sigma}{(4\pi)^3R^4\overline{NF}\ kTB\ L}$$

Where:

P = Transmitted power
G = Antenna gain
A = Wavelength
Σ = Target cross section
R = Range of target
$\overline{NF}$ = Noise figure of receiver
k = Boltzman's Constant
T = Temperature
B = Bandwidth
L = Assorted losses

The radar equation is derived in the following steps:

1. The power **density** at a target of range R is equal to the peak power radiated from a transmitter divided by the area of a sphere of radius R.
$$P_d = \frac{P}{4\pi R^2}$$
2. If the signal is directed by an antenna with gain, G, then
$$P_d = \frac{PG}{4\pi R^2}$$
3. The reflected power density from the target will be a function of the target cross section, σ. The reflected power from the target is:
$$P_r = \frac{PG\sigma}{4\pi R^2}$$
4. The power **density** of the reflected signal at the radar is:
$$P_d = \frac{PG\sigma}{(4\pi R^2)^2}$$
5. The power of the reflected signal, S, at the radar is the product of the power density times the area of the antenna. (A = aperture)
$$S = \frac{PG\sigma A}{(4\pi R^2)^2}$$
6. Substituting the relationship of gain and aperture,
$$A = \frac{G\lambda^2}{4\pi}, \quad \text{then} \quad S = \frac{PG^2\lambda^2\sigma}{(4\pi)^3R^4}$$
7. When equating as S/N, the noise figure of the receiver, NF, and the thermal noise power, kTB, become part of the denominator.

$$\frac{S}{N} = \frac{PG^2\lambda^2\sigma}{(4\pi)^3R^4\overline{NF}\ kTB}$$

8. The term L, representing a number of losses in the radar system and propagation losses, is introduced accordingly, making the equation:

$$\frac{S}{N} = \frac{PG^2\lambda^2\sigma}{(4\pi)^3R^4\overline{NF}\ kTB\ L}$$

In a pulsed radar that operates with low pulse recurrence frequencies, typically less than 3 kHz, most of the returned energy will be utilized in detecting the received signal. If the frequency spectrum as shown in **Figure 17** is about 2 MHz wide, at the null points, a receiver with a band- width of a few megahertz will accept most of the energy in the returned signal. For this reason, when using the radar equation for low PRF pulsed radars, the peak value of transmitted output power times the duty cycle (PRF x pulsewidth) is used.

In pulsed radars that operate at high pulse recurrence frequencies from 10 kHz to 500 kHz (pulsed Doppler types), the usable returned energy is that of one spectral line, since the principal measurement of interest is a frequency domain measurement and the frequency (Doppler) information is common to each spectral line. Hence, only a portion of the returned energy is utilized and the power term in the radar equation becomes the peak transmitted power times the square of the duty cycle.

If R_0 is designated as the range that provides **unity** S/N, then the equation becomes:

$$R_0^4 = \frac{PG^2\lambda^2\sigma}{(4\pi)^3\overline{NF}\ kTB\ L}$$

When this range is known, then the S/N at other ranges can be calculated by using the relationship:

$$\frac{S}{N} = \left(\frac{R_0}{R}\right)^4$$

Significantly, the S/N is inversely proportional to the fourth power of range.

Knowing the above relationships, one can calculate the parameters for specified ranges that provide useful return signals.

Characteristics of Target Reflections

A particular target, an airplane for example, is made up of many surfaces and "point scatterers" that reflect the radar signal. The strength of the reflected signal is dependent upon the reflectivity and directivity of the target. Reflectivity is defined as the fraction of the intercepted signal power that is re-radiated. Directivity is defined as the ratio of power reflected to the radar compared to the power radiated from the target in all directions.

The combined return signal will be made up of reflections from different parts of the target and these reflections may either combine favorably or even cancel if the return path lengths are such that the differences in signal phase at the receiver are close to 180°. At 10 GHz the wavelength is only 3 cm so the possibility of fluctuations in signal strength is quite probable. This is referred to as target scintillation. There are a number of tech- niques to reduce target scintillation, including changing the frequency of the transmitted signal (frequency agility) and changing the polarization of the transmitted signal (polarization agility).

An important factor in the radar equation is that of Radar Cross Section (RCS). This describes the relative size of the target and is best visualized as the geometric cross-section of the target factored by the reflectivity and directivity of the target. To define radar performance the radar cross section is commonly specified in terms of a particular size of sphere, such as a sphere having 1 square meter of surface. An unfriendly target can reduce its radar cross section by geometric design that reduces directivity and by the use of absorptive materials that reduce reflectivity.

Targets with moving parts, such as turbine blades or tank treads, may reflect radar signals that can identify themselves to a certain degree. For example, a tank tread moves twice as *fast* as the tank it propels, so a radar that measures the Dop- pler frequencies in the target return from a tank will see two distinct frequencies, one twice the other.

Unfortunately, the radar cross section of a target varies considerably with the angle of reflection, making it difficult to use its "radar signature" as a reliable means of target identification. However, current advances in processing Doppler signals are improving the probabilities of target identification by increasing the capabilities of creating real time radar images.

Probability of Detection and False Alarms

A radar receiver has a means of setting the "threshold level"; a level a return signal must exceed to be seen on an indicator or to be used in some other manner. Unfortunately, noise signals are not at one constant level and can vary as illustrated in **Figure 5**. If a threshold level is set high enough to prevent any noise signals from appearing, the radar's sensitivity is reduced considerably. If the threshold is set too low, then too many false indications may be seen, and the noise signals will tend to complicate detection of the desired information. Therefore, a compromise level is selected by adjusting manually or automatically for specific operating conditions. The threshold level can then set the "false-alarm rate" of the radar, which is simply the number of false- alarm signals that appear in a given time period, such as one minute.

The probability of target detection depends on many variables, including propagation loss, the relationship between the signal-to-noise ratio, S/N, and the threshold setting in the detection circuitry. In the case of a moving antenna, it also is dependent upon such factors as antenna scan rate, antenna beamwidth, and the pulse recurrence frequency, all of which determine the "look time":

Obviously, the probability of target detection is increased with a more powerful transmitted signal, more antenna directivity, and longer transmission time on the target, together with a more sensitive receiver with a long "listen" time and an efficient detector. Unfortunately, all of these dependent factors cannot always be applied simultaneously, and performance compromises are often tolerated.

Clutter

Clutter, the bane of radar designers, is to radar what static is to radio. Although there are some specialized radars that are made to detect meteorological phenomena such as clouds, rainfall, wind shear, etc., most radars are designed to detect man-made objects such as tanks, ships, aircraft, etc. These man-made objects are detected to the exclusion of radar echoes from the ground, sea or weather phenomena. These unwanted echoes are usually spoken of together under the category of "clutter".

Clutter energy is proportional to the size of the radar cell. In the horizontal plane, the radar cell is the instantaneous area of illumination by a radar pulse of the target area, at a given range, as if the radar's antenna beam was stationary. (See **Figure 6**.)

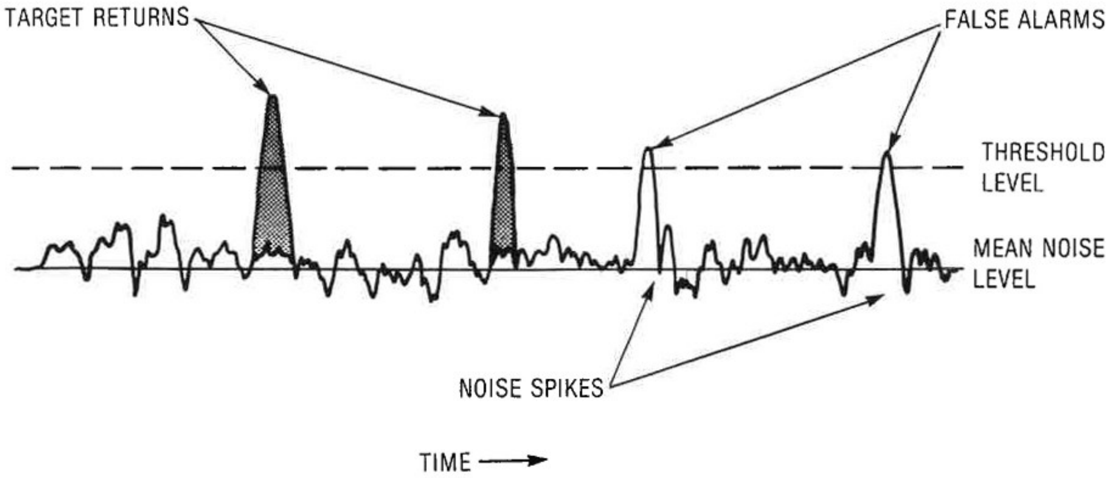
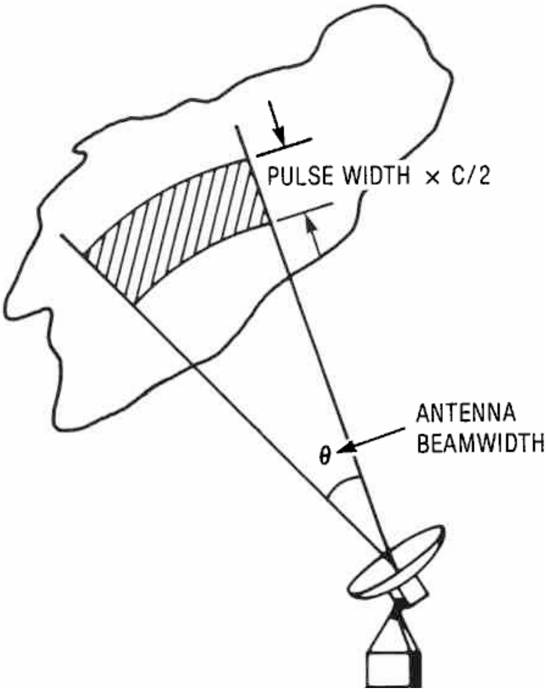


Figure 5. Comparative signal amplitudes and threshold level.



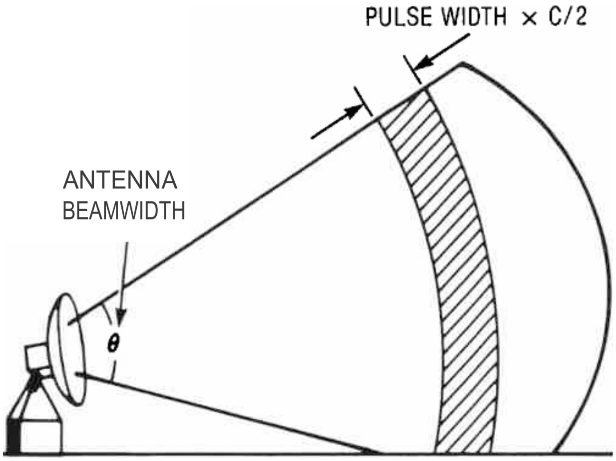


Figure 6. A radar cell.

The area of the cell is dimensioned by the antenna beamwidth, the pulse length and the angle of incidence. Reducing the antenna beamwidth or the pulse length will then reduce the size of the radar cell and the level of clutter. There are limits to doing that since the beamwidth of an antenna is a function of the antenna size while the pulse length affects the radiated pulse energy, an important parameter in target detection in terms of average power on the target. A third dimension in the radar cell is in the vertical plane and thus the vertical beamwidth is also a matter of concern. In this case, clutter is increased to the benefit of vertical radar coverage. Vertical coverage is sometimes improved by using a number of stacked beams (see **Figure 7**) in the vertical plane to increase the clutter performance as well as to add an altitude dimension to the radar. Fast vertically scanned narrow beams also are used to accomplish the same objective.

As radar measurements are obtained in time and frequency domains, methods for improving target-to-clutter performance are applied in both domains. The basic objective in designing clutter rejection in a radar is to be able to see the target in clutter and not merely to eliminate the clutter. If a radar can adjust the system's receiver gain so that the level of clutter is reduced to that of normal background noise, then any target larger than the clutter will be detectable. However, using this scheme only permits the detection of targets above the clutter level and the system will have no sub-clutter visibility, i.e., the capability of seeing tar- gets in clutter.

One means of improving clutter performance is to use an automatic receiver bias circuit called STC, Sensitivity Time Control. STC is a means of

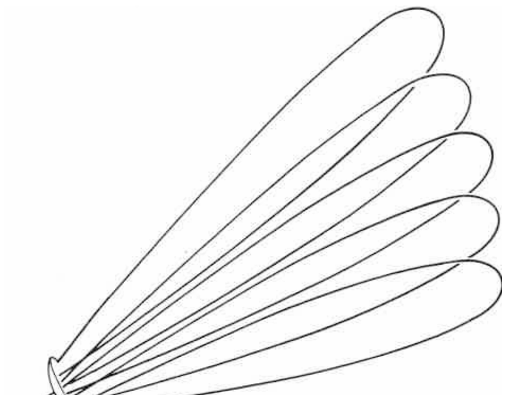


Figure 7. Stacked radar beams.

varying the bias (gain) on the radar receiver so the sensitivity is reduced at dose ranges and increases with longer ranges. (See **Figure 8**.) This is also effective in reducing false alarm targets that are caused by smaller targets such as birds, etc.

Another technique to reduce clutter by using time domain methods is to have a means of canceling out targets that are essentially fixed by storing them in some manner from pulse to pulse and canceling them against themselves, therefore making the radar essentially one that sees only moving targets. This is described later under the discussion of MTI radars.

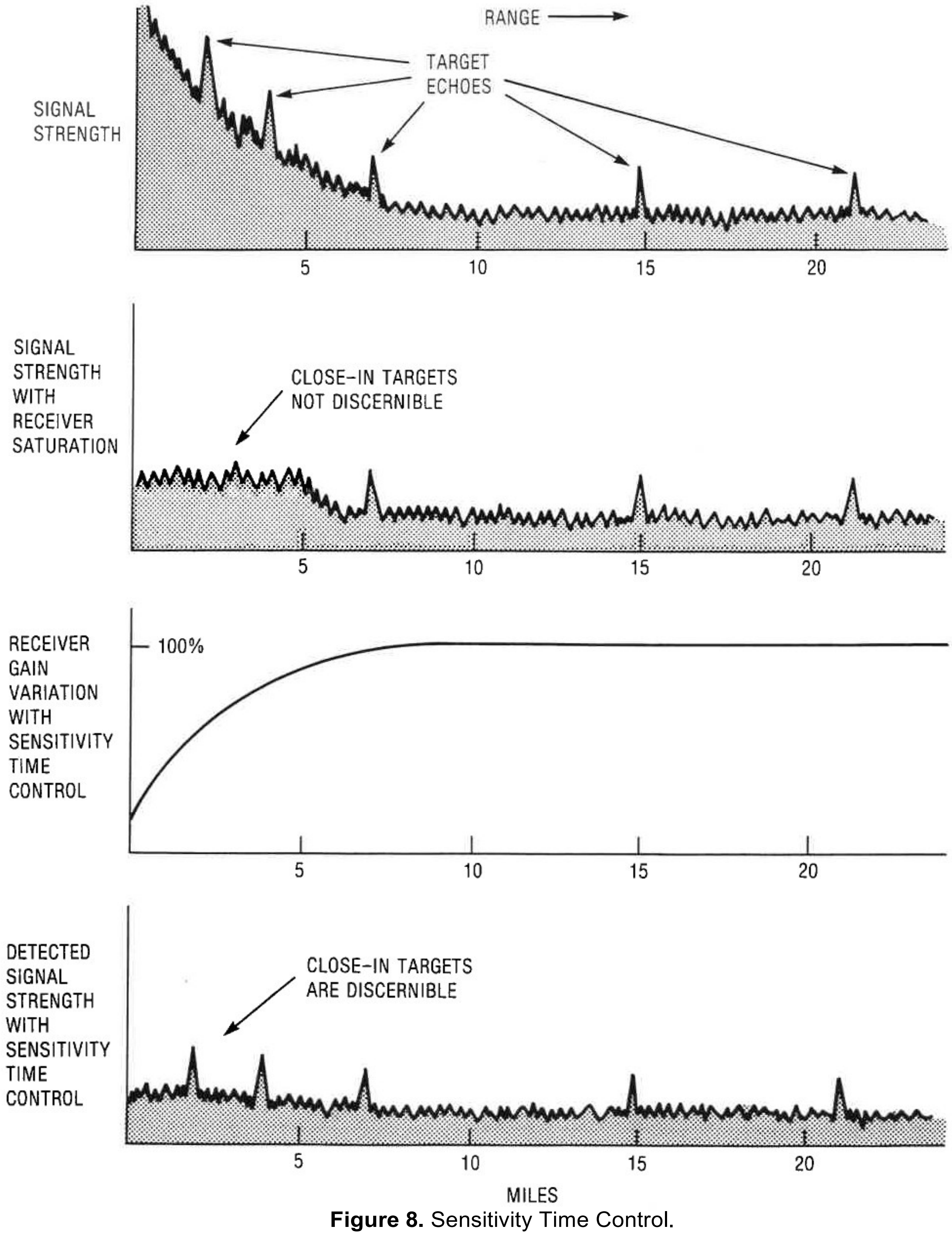


Figure 8. Sensitivity Time Control.

In order to detect Doppler frequency, the radar compares the target return with the phase of the transmitted pulse. Fixed targets will not cause a Doppler frequency shift and in a radar that is sensitive only to Doppler-shifted targets, the fixed targets are then essentially eliminated. Unfortunately, clutter in the frequency domain can occur due to moving leaves, trees, ocean waves, clouds, birds, etc. If the transmitter can be made to be very stable in phase, then real targets can be detected in a high clutter environment as clutter returns lack the periodicity of man-made targets returns, and with appropriate frequency filtering, the ability to see targets in clutter can be achieved.

If the radar itself is moving, such as an airborne radar, then the fixed targets on the ground also have Doppler shift to them (see **Figure 4**) which will give rise to clutter in the frequency domain not only from the reflections from the main beam of the antenna but also from the side lobes of the antenna.

Figure 9 illustrates how clutter in an airborne system is dependent on the velocity of the radar platform. To provide a clutter-free Doppler region for detection of high-speed targets, a high pulse recurrence frequency is used in order to spread the sidebands in the transmitted spectrum.

In any case, where one is trying to improve the target-to-clutter ratio it is very important to have the stability of the transmitter as good as is possible

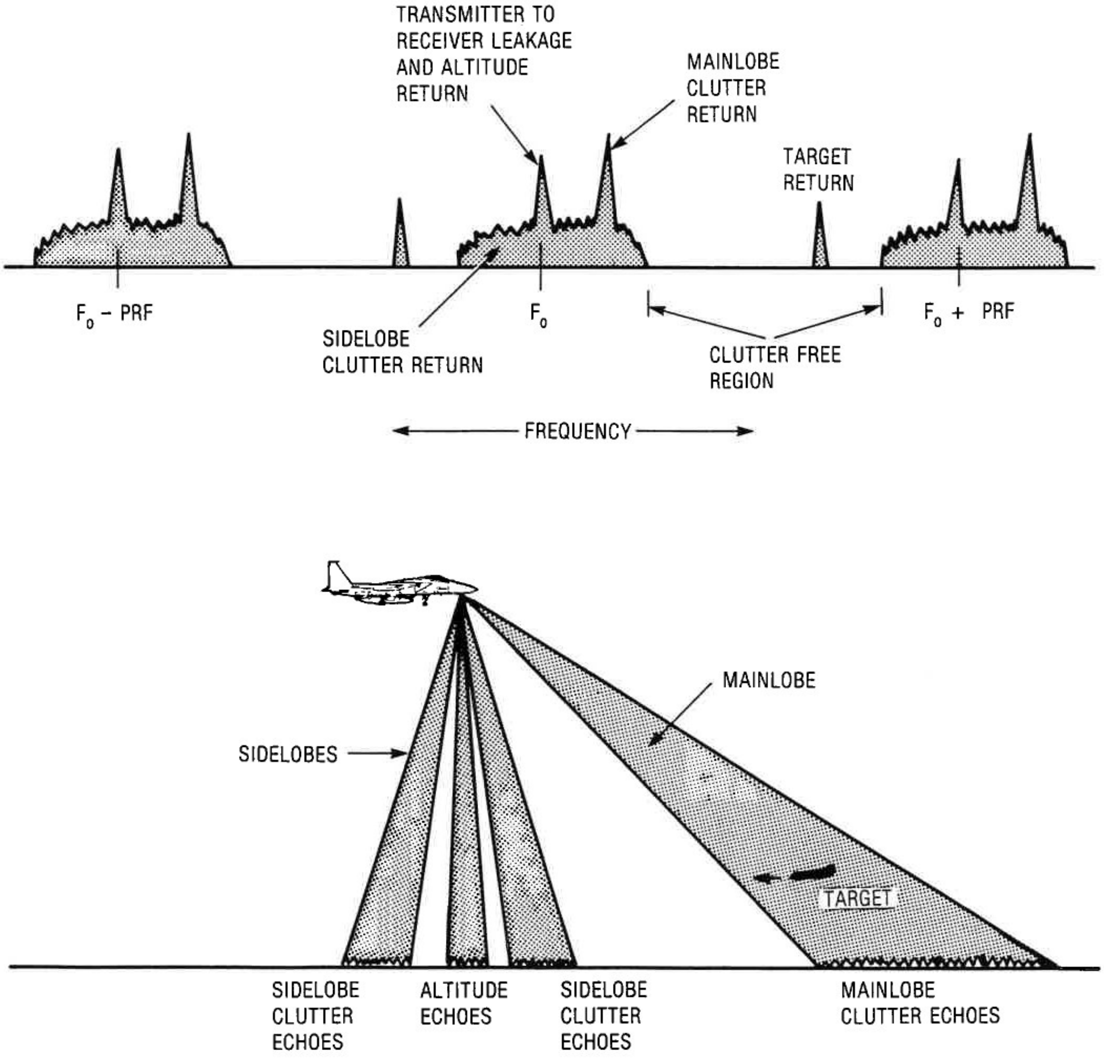


Figure 9. Airborne target/clutter Doppler returns.

as any particular variation in transmitter signal stability will adversely affect the target-to-clutter ratio. In addition, such other instabilities as time jitter, amplitude jitter, etc., will reduce the effectiveness of clutter reduction circuitry.

The sub-clutter visibility factor is defined as the ratio, at the input to the system, of the clutter energy to the signal energy of a target when it is just detectable at the output in the clutter residue. This is sometimes difficult to define and due to the fact that the sub-clutter visibility ratio does not take into account the overall performance at all target speeds, sometimes a preferred figure of merit is the target improvement factor. This is defined as the improvement in target-to-clutter ratio averaged over all target speeds.

There are various figures of merit for radars as far as clutter reduction is concerned. A typical number for a two-pulse canceller MTI (Moving Target Indication) radar is 30 dB where a three pulse canceller MTI radar can be as good as 40 dB. These figures can be compared with a pulse Doppler system where the sub-clutter visibility can be of the order of 50 to 60 dB. It should be noted that there are radar equipments, which can operate very acceptably with only 30 dB sub-clutter visibility, dependent upon the particular application and objectives.

Operating Frequency

The operating frequency of a radar is chosen to best achieve given objectives. Angular resolution can be improved by transmitting at high frequencies, since antenna beamwidth can be made smaller. Higher operating frequencies allow smaller antennas, more compact equipment pack- aging, etc., but compromise power handling capability and experience higher propagation attenuation losses. In some applications, where only short ranges are required, such as in an airport surveillance radar or a low-level tracking radar, higher operating frequencies are ideal for achieving optimum angular resolution. A radar frequency may be intentionally chosen at a frequency high in propagating attenuation for secure, short range operational reasons. Extremely long-range radars will use lower operating frequencies to take advantage of the various propagation phenomena such as refraction effects and lower propagation attenuation. **Figure 10** plots propagation attenuation loss due to water vapor as a function of operating frequency.

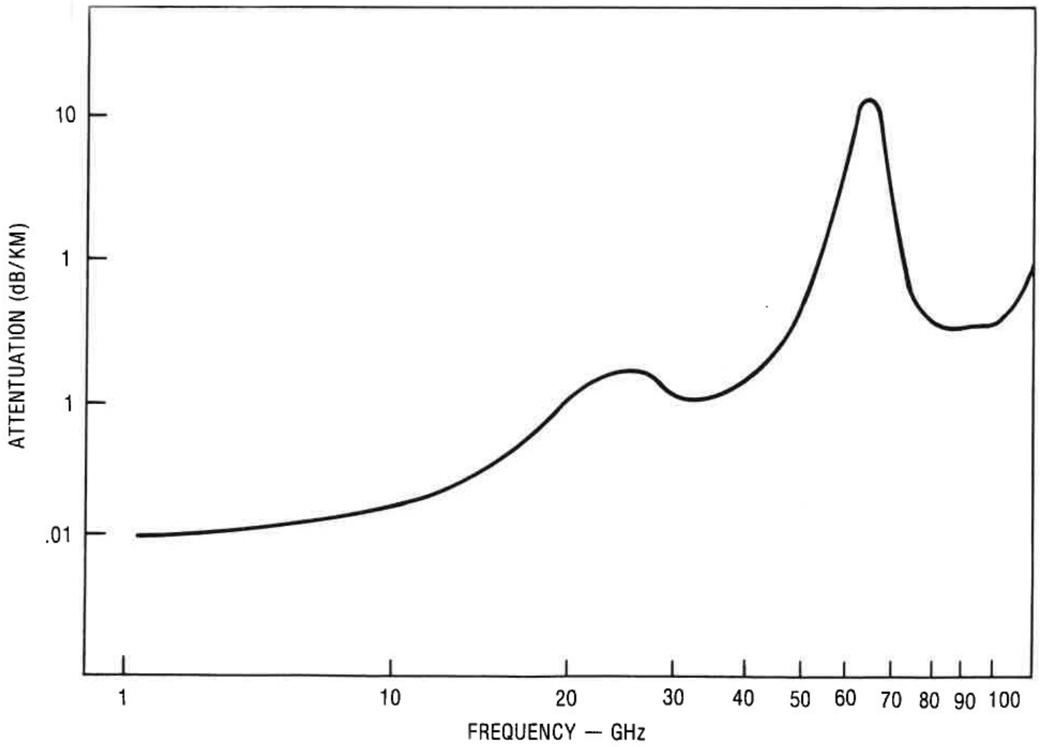


Figure 10. Atmospheric attenuation due to water vapor.

Types of Radars by Waveform

To obtain various kinds of information, different techniques must be used to optimize the kind of information that is desired. Thus, radar systems fall into the following categories according to the "waveform" or mode of operation that is employed in a radar system. The general categories are:

1. CW (Continuous Wave)
2. FM-CW (Frequency Modulated, Continuous Wave)
3. Pulsed
4. Pulsed Doppler

Radar Systems

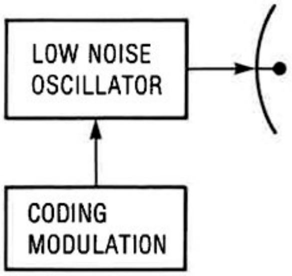
CW Systems

A CW radar utilizes the Doppler Effect for measurement and is used primarily where unambiguous velocity information is desired. CW radars are usually single target devices and are used principally for (1) CW missile guidance systems (the transmitters are called CW illuminators, since they illuminate the target with energy), (2) velocity measuring radars, including police radars and instrumentation radars, (3) personnel detection radars, and (4) rate-of-climb meters.

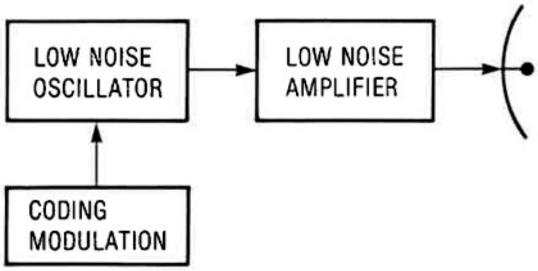
CW Illuminators

This kind of radar transmitter is characterized by its low noise requirements. In a CW guidance mode of operation, a missile is guided by information derived from the Doppler frequency shift in the reflected signal from the target, due to the relative velocities of the target and the missile. Since Doppler frequency shifts are usually less than 100 kHz, it is extremely important to transmit a "clean" Doppler signal spectrum, otherwise a spurious Doppler signal may look like a false target and can be confused with the true target Doppler signal.

A coded modulation capability is generally included in an illuminator to transmit information *to* the missile from the ground. Typical block dia- grams are shown in **Figure 11**.



(a) LOW POWER ILLUMINATOR



(b) HIGH POWER ILLUMINATOR

Figure 11. illuminator radar systems block diagrams.

Velocity Measuring Radars

A typical block diagram of a velocity-measuring radar is shown in **Figure 12**. In the case of a police radar or a "speed-gun"; the transmitting signal doubles as the local oscillator signal to provide a difference frequency that is dependent upon the velocity of the automobile. The difference frequency is simply measured and used *to* provide an indication on a meter.

Personnel detection CW radars perform much like police radars except that headphones can be

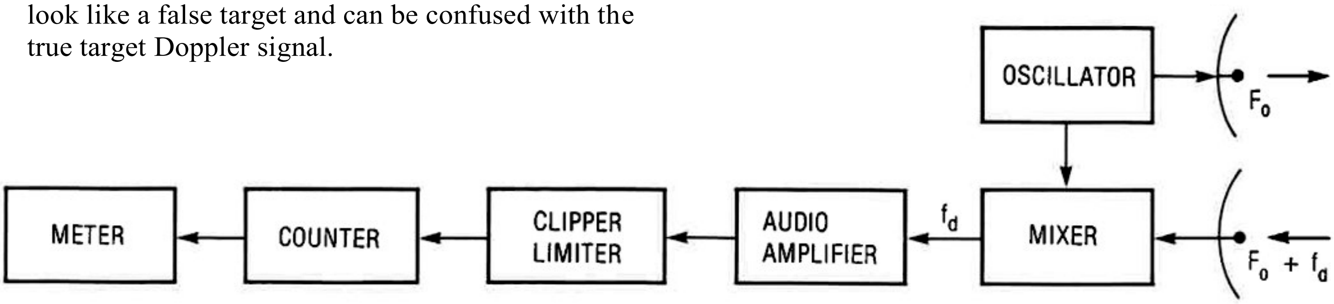


Figure 12. Velocity measuring radar block diagram.

used to detect the Doppler frequencies instead of a meter, as the Doppler frequencies will be audible.

Rate-of-climb radars operate similarly, except that they detect the phase relationship of a receding or approaching target by employing two receiver channels and local oscillator signals in quadrature. Transmitted power is generally less than one watt for police, personnel, and rate-of-climb types of radars.

CW radars are smaller than corresponding pulsed radars, although two antennas are required, and can operate against targets to almost zero range. CW systems can be somewhat power limited, since transmitter noise due to coupling between the antennas will affect receiver sensitivity.

FM-CW Systems

A CW radar to measure both range and velocity of a target is accomplished by broadening the transmitted frequency spectrum by frequency modulating the carrier frequency. Range, in terms of frequency, can be determined by measuring the difference between the received and transmitted frequencies as shown in **Figure 13**. The modulation can also be linear in one direction only, as in a "sawtooth" waveform.

When only range information is desired and the target is stationary, such as in an altimeter application, the modulation need not be linear, as shown in **Figure 13**, but can be sinusoidal or near sinusoidal, since only an average difference frequency measurement is required to yield an acceptable value of range. If the target is moving, the returned signal will include a Doppler shift in frequency. This information can be used to advantage in a Doppler Navigation Radar where both altitude (range) and velocity (Doppler shift) information are desired. When Doppler frequency shift information is desired, linear modulation is needed to provide an accurate measurement of Doppler frequency shift. **Figure 14** illustrates the frequency differences in an example where the returned signal frequency is affected by a positive Doppler frequency.

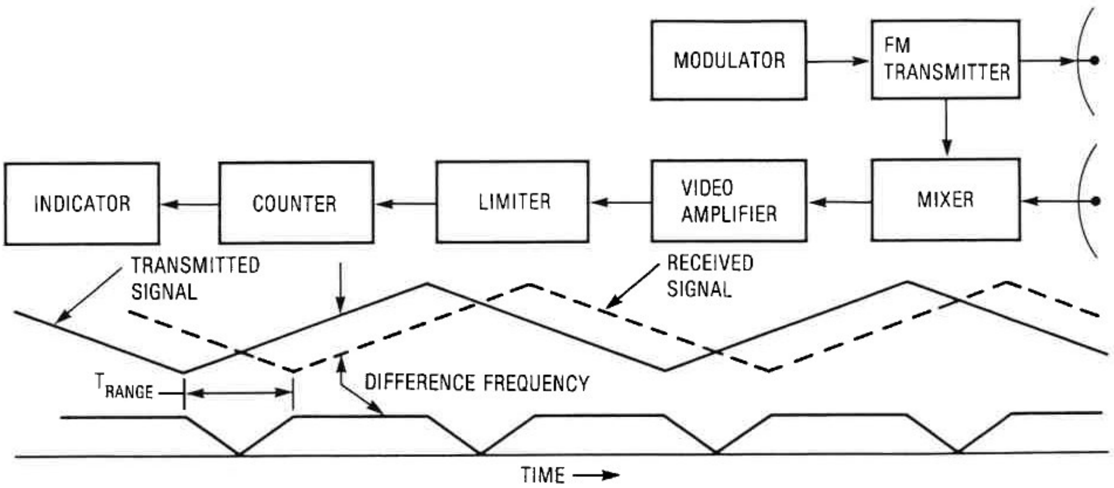


Figure 13. FM-CW range measuring radar block diagram.

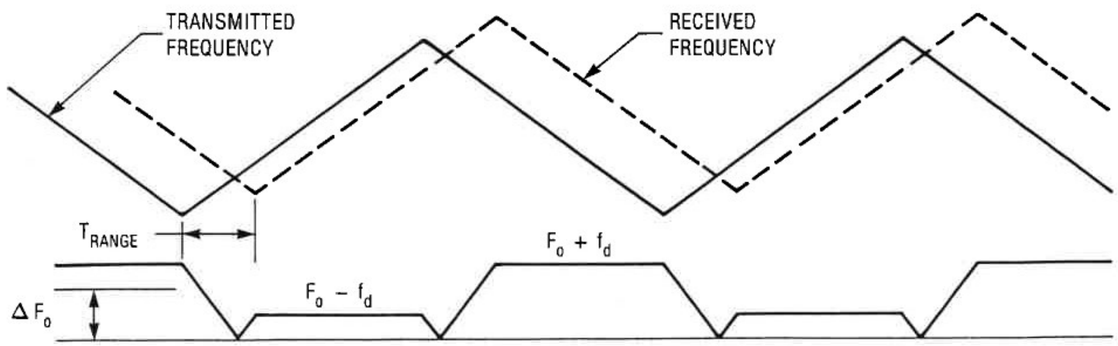


Figure 14. Doppler effect on the difference frequency in an FM-CW radar.

The positive Doppler frequency shift will have an effect on the received difference frequency, and a lesser total frequency shift will be observed if the frequency modulation is in an increasing frequency direction. When the modulation is in a decreasing frequency direction, the positive Doppler Effect will increase the total frequency shift. If a means is provided to measure each difference frequency, $F_0 + f_d$ and $F_0 - f_d$, then the difference between the two frequencies is twice the Doppler shift and can be used accordingly to measure velocity. **Figure 15** is a simplified block diagram of an FM-CW radar that can extract the average frequency difference (range) as well as the Doppler frequency shift (velocity).

FM-CW radar systems have long been used as single target systems as it has been difficult to separate targets on the basis of frequency discrimination and display them in a time referenced manner. Recent radar developments are taking advantage of the advancements in digital signal processing and FFT (Fast Fourier Transforms) technology to demonstrate a practical short-range navigation radar with acceptable range resolution. A real advantage in this type of radar is the ability to operate at very low power levels {a few watts), requiring a relatively simple transmitter. With low power output the LPI (Low Probability of Interception) of the radar can become attractive militarily.

A disadvantage of the FM-CW radar is in the need for two antennas, a transmitting and a receiving antenna, adding to system size and weight.

Another method of obtaining range information in a CW radar is by expanding the transmitted spectrum to more than one transmitted frequency. If two signals are transmitted, the phase relationship between the two signals will vary as a function of range, and radars can be designed to measure range by providing an accurate phase-measuring capability. The two-frequency type of radar is adaptable to surveying applications.

Pulsed Systems

Elements of Pulse Modulation

A pulsed radar can be considered an expansion of a CW radar with increased transmitted-spectrum bandwidth accomplished by pulse modulation. Pulse modulation is generally applied, as shown in **Figure 16**, at a periodic rate known as the Pulse Recurrence Frequency (PRF).

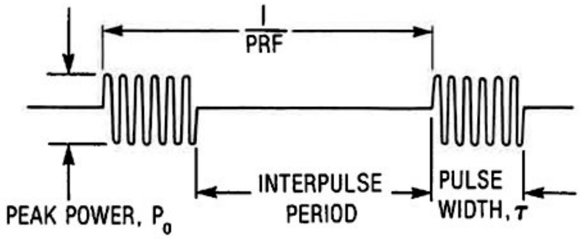


Figure 16. Pulse modulation terms.

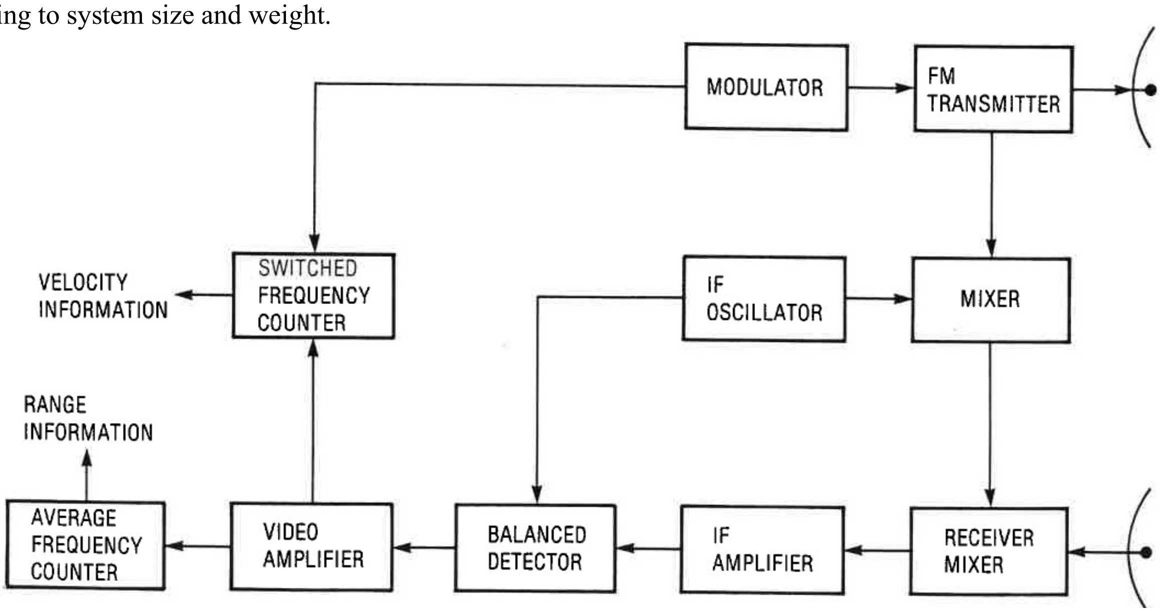


Figure 12. Velocity measuring radar block diagram.

Output power of a pulsed radar is related to both pulse width and PRF. Peak output power, P_0 in **Figure 16,** is related to the average output power by the formulas:

$$\text{Pulse Width} \times \text{PRF} = \text{Duty Cycle}$$

$$\begin{pmatrix}\text{Peak}\\ \text{Output Power}\end{pmatrix} \times \begin{pmatrix}\text{Duty}\\ \text{Cycle}\end{pmatrix} = \begin{pmatrix}\text{Average}\\ \text{Output Power}\end{pmatrix}$$

The transmitted spectrum, (**Figure 17**), shows the energy distribution in the PRF sidebands and the relationship of the pulse width, *T,* to the width of the transmitted spectrum.

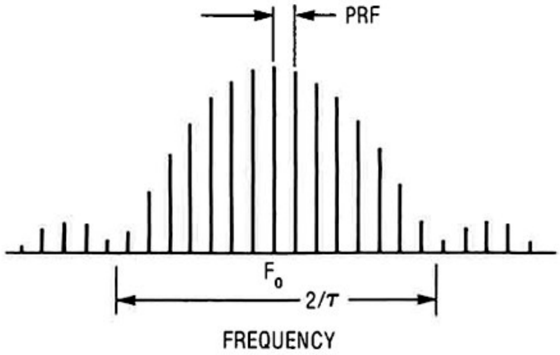


Figure 17. Pulsed radar frequency spectrum.

Example: Assume a radar has a peak output of 1 megawatt, a pulse width of 1 microsecond, and a PRF of 1000 hertz. By substituting these values into the above formulas, we can determine the average output power as follows:

$$\begin{aligned} PW(\text{sec}) \times PRF(\text{Hz}) &= (1 \times 10^{-6}) \times (1 \times 10^{3}) \\ &= 1 \times 10^{-3} \text{ Duty Cycle(Du)} \end{aligned}$$

$$\begin{aligned} P_o(W) \times Du &= (1 \times 10^{6}) \times (1 \times 10^{-3}) \\ &= 1 \times 10^{3} W(\text{average}) \end{aligned}$$

The basic advantage of a pulsed radar is that it provides a time interval during which the measurement of range can be accomplished by measuring the time it takes for a signal to propagate to the target and return. As mentioned previously, if a continuous transmission is interrupted, ambiguous information results. In this case, if only one pulse were transmitted, any measured range (in terms of time) would be unambiguous. However, as soon as a second pulse is transmitted, unambiguous range is limited to the time period of the interpulse period. For example, a radar with PRF of 1000 hertz and a pulse length of 1 microsecond has an interpulse period of 999 microseconds. Knowing that a radar signal propagates at a one nautical mile per 12.34 microsecond rate (round trip), 81 nautical miles (999/12. 34) can be measured before the next pulse is transmitted. This is the maximum unambiguous range of the radar. **Figure 18** shows a block diagram of a typical pulse radar system.

A radar produces a transmitted pulse by turning on a microwave power tube with a pulse voltage generated by a voltage modulator. The voltage modulator is timed by a continuously running timing oscillator that provides timing pulses to the voltage modulator and to the indicator at the pulse recurrence frequency. The transmitter produces pulses of RF energy to the antenna through the duplexer at the PRF rate. A return signal is routed through the duplexer to the superheterodyne receiver where it is detected as a pulse, amplified and applied to the indicator. The timing pulse starts a sweep on the cathode ray tube in the indicator and the target then modulates the sweep at a time corresponding to the range of the target. This simple radar then can provide range information and, knowing the direction of the antenna,

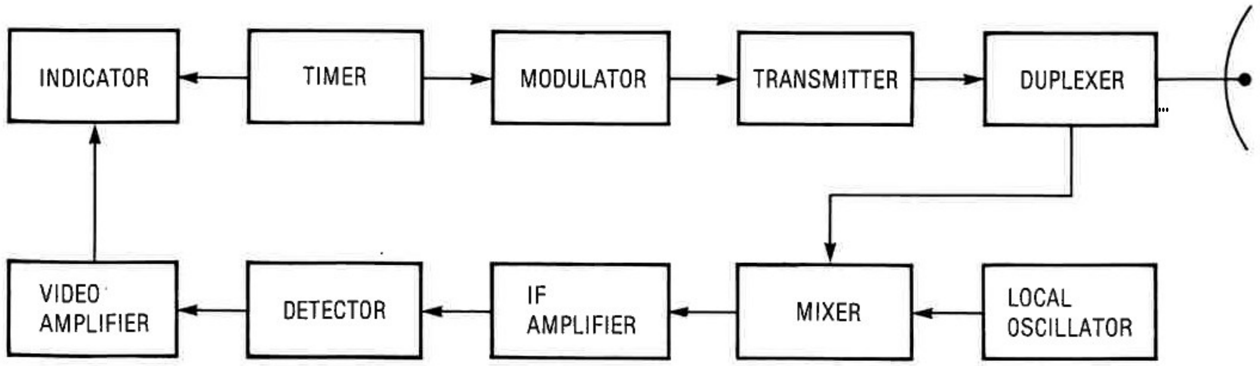


Figure 18. Pulsed radar system block diagram.

azimuth information. In the case of **Figure 18** the detector is an envelope detector, similar to AM radio, and phase information is lost in the detection process. This is referred to as a non-coherent radar.

Transmit-Receive Switching

A pulsed radar system can use one antenna, instead of two as required in CW systems, by using a duplexer, a device incorporating fast switches (gas tubes) to connect the transmitter to the antenna during the transmitted pulse, and then connecting the receiver to the antenna during the interpulse period. Gas tubes are called TR and ATR tubes and accomplish the switching action by the ionization and de-ionization of gases. The ionization and "recovery" times of these tubes play an important part in the achievable minimum range and receiver sensitivity characteristics of a radar system. Solid-state and ferrite devices are now being used frequently in radar systems to supplement or replace gas TR and ATR tubes.

Minimum Range Considerations

Some radar systems desire to "see" targets at very close ranges. When range measurement is made by using a pulsed waveform and by measuring the elapsed time between the transmitted pulse and the received signal, there are limitations to the minimum range that can be measured. The pulse width is one limitation, since the receiver cannot receive a signal until the transmitter pulse is turned off. Another limitation is the time required to turn the receiver on after the transmitter is turned off. The latter is referred to as the recovery time and is dependent upon the switching performance of the TR and ATR tubes (or whatever devices are used) in the duplexer.

The minimum range as a function of pulse width is simply $c\tau/2$ (c = velocity of light, τ = pulse width), as the signal propagates from the time of the leading edge of the transmitted pulse. Hence, a one-microsecond pulse limits the minimum range to 492 feet (984ft/s x ½). In other words, during a one-microsecond pulse, the pulse energy from the leading edge of the pulse has time to travel 492 feet and return while the transmitter is still on. If another microsecond is needed for switching, the minimum range increases to 984 feet. A radar system that must have short range capability must use a very short pulse width and have optimum receiver recovery time. To achieve shortest recovery time, a separate and isolated receiver antenna may be employed to eliminate the recovery time of switching devices.

Receiver Bandwidth

A radar receiver must be designed to extract the maximum information out of the return signal. The bandwidth of the receiver is related to the bandwidth of the transmitted signal, usually by a factor approximating the reciprocal of the pulse width. (A radar with a one-microsecond pulse width must have a receiver bandwidth of at least one MHz in order to best utilize the energy in the pulse signal.) Pulse width is a good indication of the use of a radar, since it provides some indication of the range resolution that is desired. As an example, if a short pulse width (100 nano seconds) is used for increased resolution; wider bandwidth receiver components are required.

Pulse Compression

The average transmitted power of a given radar may be increased (to increase detectability) by increasing the length of the transmitted pulse. However, a longer pulse width decreases the range resolution capability of the radar. In order to provide increased pulse width without compromising range resolution, a technique is used that provides for the transmission of a long pulse that can be compressed into a short pulse length in the receiver. This technique is called Pulse Compression.

Pulse Compression can be accomplished either by using a linear FM modulation or by phase coding the RF signal during the pulse.

Linear FM (sometimes called "chirp") pulse compression is accomplished by linearly modulating the RF signal during the pulse and then compressing the returned pulse by passing it through a delay line whose velocity of propagation is a function of frequency. In this way the RF signals "bunch up" to form a shorter pulse length.

A block diagram of a typical compression radar is shown in **Figure 19**. The waveforms involved in the pulse compression technique are shown in **Figure 20**. The effective pulse length is compressed to a pulse length of $1/\Delta F$ and the instantaneous peak power is increased by a factor of $\sqrt{\Delta F \tau}$.

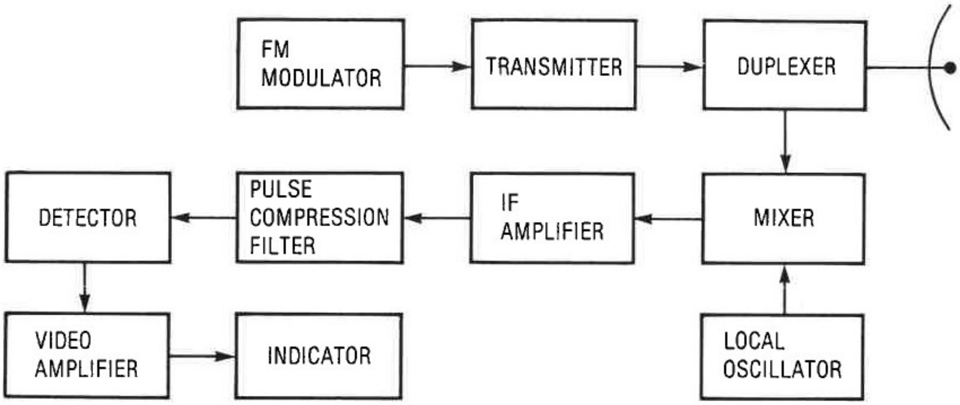


Figure 19. Pulse compression radar block diagram.

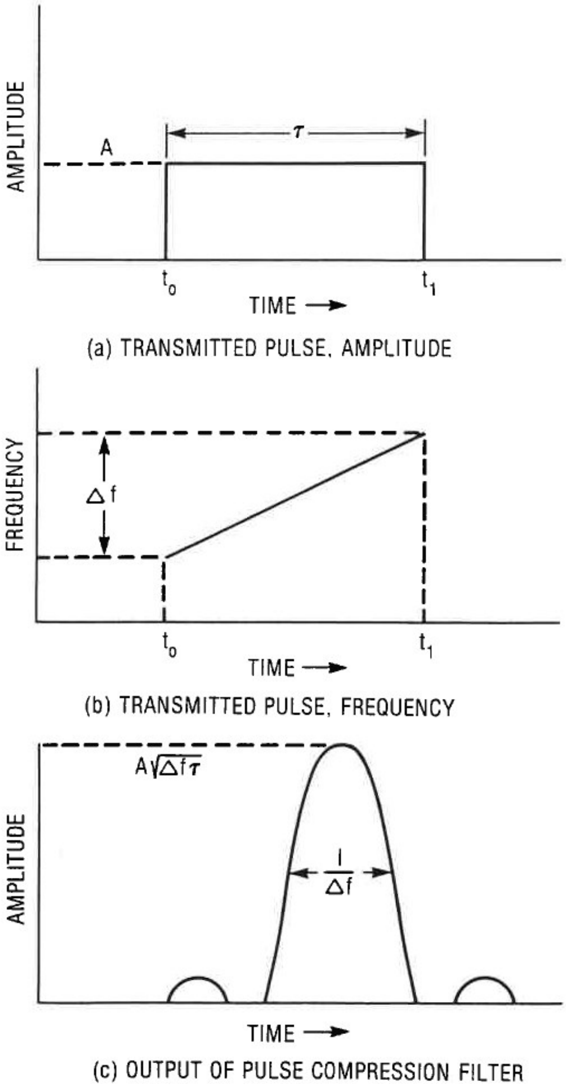


Figure 20. Pulse compression radar parameters.

Pulse compression circuitry adds some complexity to the radar system and makes the transmitter and receiver somewhat more expensive. Larger compression ratios require wider bandwidth components, such as transmitter tubes, and care must be taken to assure the waveform is accurately reproduced as it is amplified in the transmitter. A difference between the transmitted frequency-versus-time waveform and the frequency-versus-time characteristic of the delay line will result in the **time** side lobes of the compressed pulse to increase and present a problem in spurious target information.

Radars are in operation with as much as 1000 MHz of modulation in a linear FM pulse compression mode. This would equate to about 6 inches of range resolution. With that kind of range resolution, discrimination radars can then look at particular sections of a target in order to establish a radar *IJ* signature" of a target.

Pulse compression can also be accomplished using digital techniques in which a pulse length is divided into sections and each section is phase coded. **Figure 21** shows a BARKER 13 code, one commonly used binary code to achieve an improvement in range resolution.

More complex codes can be used such as a Frank code, which is a quadraphase code, wherein the pulses are coded in 90-degree variations. A binary code suffers in performance in time side-lobes with targets with high Doppler frequency shifts, as the Doppler return from the target shifts the phase coding so that in the extreme case, the phases at the end of the code are shifted 180 degrees. This amount of Doppler is referred to as the critical velocity at which the main lobe amplitude is seriously reduced while the time side lobes increase.

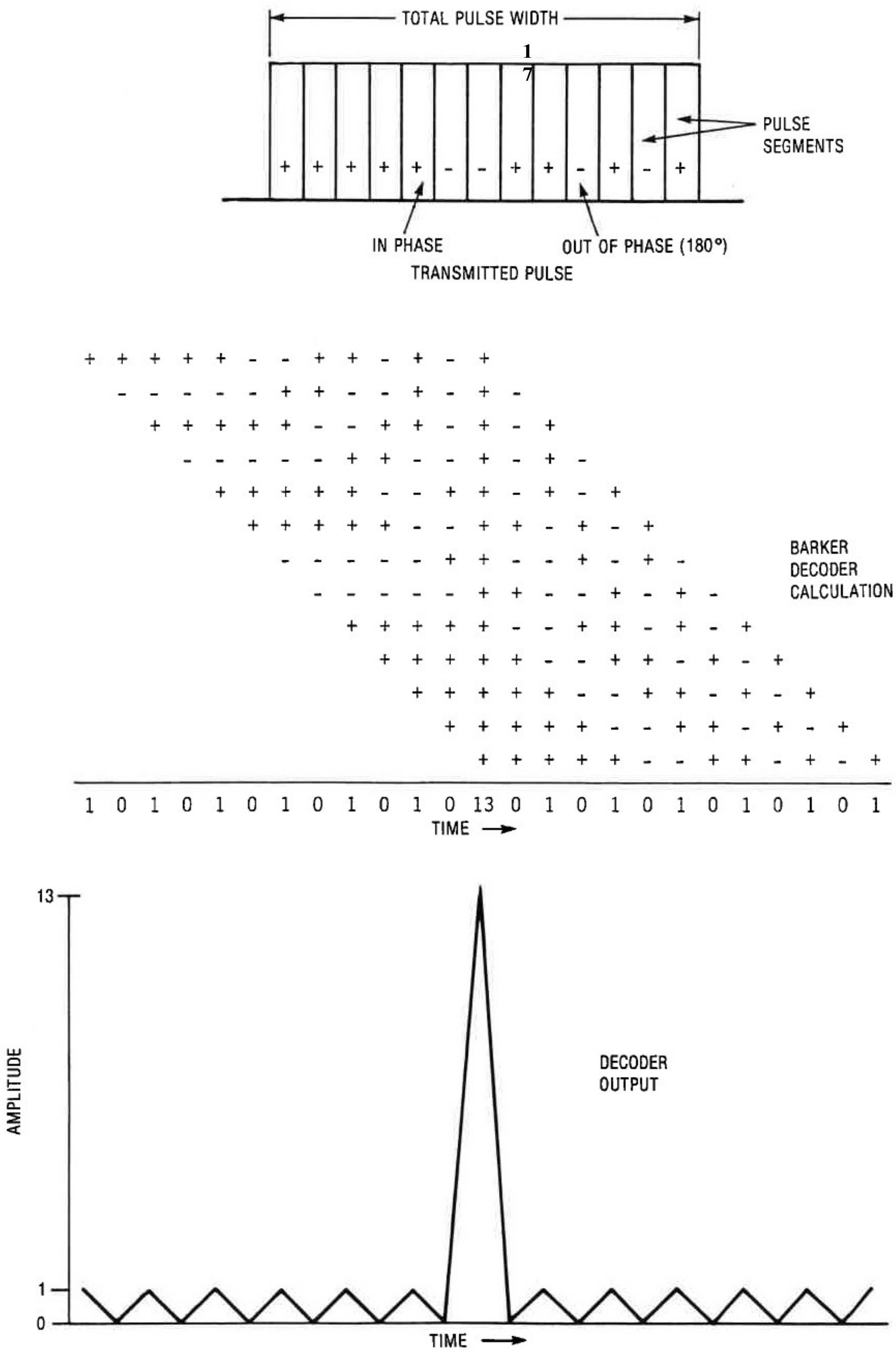


Figure 21. Digital pulse compression – Barker 13 Code.

Frequency Agility

A target can be considered to be a number of point scatterers wherein the amplitude of the wave of energy reflected from the target is dependent upon the phase relationships of the reflections from the many point scatterers. If enough independent "looks" can be taken of the target; i.e., independent radiations at different frequencies to provide different reflective phase combinations, then the summation of these independent "looks" will result in a better target return than if the same number of "looks" were taken at one frequency and added in the same manner. This is the basis for designing frequency agile systems for purposes of increasing the detection capabilities of a radar system. Systems are also made frequency agile for reasons of anti-jam capability and for that reason the wider the operating frequency band, the better the anti-jam capability can be.

To improve the detection capability, the frequency need only be changed a small amount, sometimes referred to as "dithering". If a target size is large compared to the resolution cell of the radar, the frequency dither required to achieve the detection improvement is approximately equal to the reciprocal of the pulse width. Thus, a system with a 0.5 microsecond pulse width would require only a 2 l\1Hz frequency dither for improved performance. If the target size is smaller than the resolution cell of the radar, the required frequency dither is a number approximating 150/D, where D is the target size. Thus, a 5-meter target would require 30 MHz of frequency dithering. The change of frequency need not be periodic or random but at least 20 pulses out of the total pulses occurring during an integration period should be displaced by the critical frequency separation. Improvements of 6 to 10 dB in detectability due to frequency agility has been reported. The generation of frequency agile transmissions is not difficult in a coherent amplifier type of transmitter, as shown in **Figure 23**. However, in a magnetron oscillator type of transmitter, the local oscillator must be made to follow the shifting transmitted frequency, a problem that requires somewhat complex circuitry and wideband local oscillators, depending upon the degree of frequency agility employed.

Agility in the radiated polarization of the transmitted signal is also of interest in achieving optimum detection performance and is receiving some attention in developmental systems although the improvement in performance due to polarization agility is reported to be less than 3 dB.

Phase Coherency

In detecting a target, a radar does not usually depend on just a single returned pulse to provide an indication but depends on the integration or the addition of a number of pulses that are reflected from a target. In a conventional pulsed radar, the received pulses are integrated by using a long-persistent-screen cathode ray tube and the human eye. In this case, the cathode ray tube acts as a storage device for the target information. In more advanced radar, information data is not always displayed on a CRT and another kind of storage device is used to integrate the information. Integration of signals can be performed either at the IF frequency (before the second detector) or at the video frequency (after the second detector). If the integration is performed at the IF frequency, it is called pre-detection integration or **coherent** integration; integration at the video frequencies is called post detection or **noncoherent** integration. See **Figure 22**.

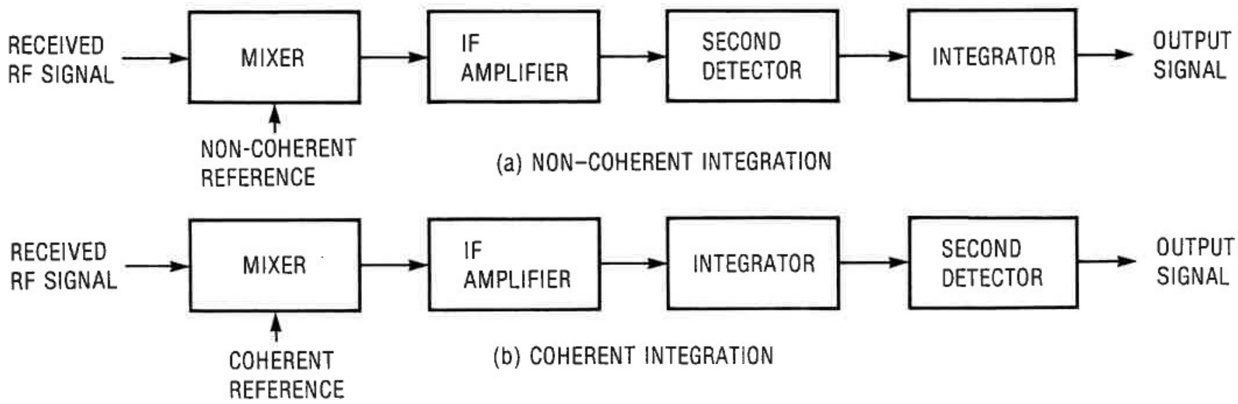


Figure 22. Coherent and non-coherent Integration.

Since the second detector's output is a rectified envelope of the pulse, phase information is lost, and integration can only be performed on the video pulse. In addition, the second detector can introduce some noise because of inherent non-linearities, reducing the integration efficiency. The coherent integrator preserves the phase information and does not suffer the second detector's loss in signal-to-noise ratio, making it a much better integrator. The coherent integrator requires preserving the phase of the received signal from pulse to pulse which in turn requires a coherent reference signal to maintain the phase relationship between the transmitted and received signals. All other things being equal, a coherent detection system can obtain longer detection ranges than a noncoherent detection system and also affords the measurement of Doppler frequencies, resulting in increased emphasis in the development of coherent systems. A typical coherent system is shown in **Figure 23**.

Systems may incorporate a coherent detection system on a single pulse basis to measure Doppler information.

A system using a magnetron transmitter (whose starting phase can be different on each transmitted pulse) can be adapted to provide Doppler information by phase locking a coherent reference signal with each transmitted pulse as shown in **Figure 24**.

MTI, AMTI, Delay Line Canceller

If an application, such as air traffic control radar, is interested only in moving targets, fixed targets can be effectively eliminated by a technique known as MTI, or Moving Target Indication. This technique takes advantage of the effect that the relative motion of a target has on the reflected radar signal. The fixed targets are reflected at the same frequency as the transmitted signal while the moving target reflections experience the Doppler frequency shift effect. The fixed targets can be regarded as DC signal components and the moving targets as AC signal components and if an interpulse period of information can be delayed a 1/PRF length in time and inverted in polarity, then the fixed-target components can be made to

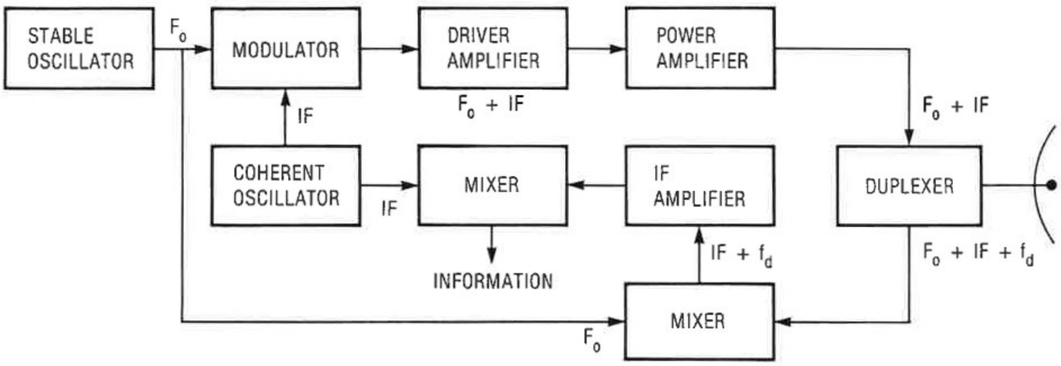


Figure 23. Coherent radar system block diagram.

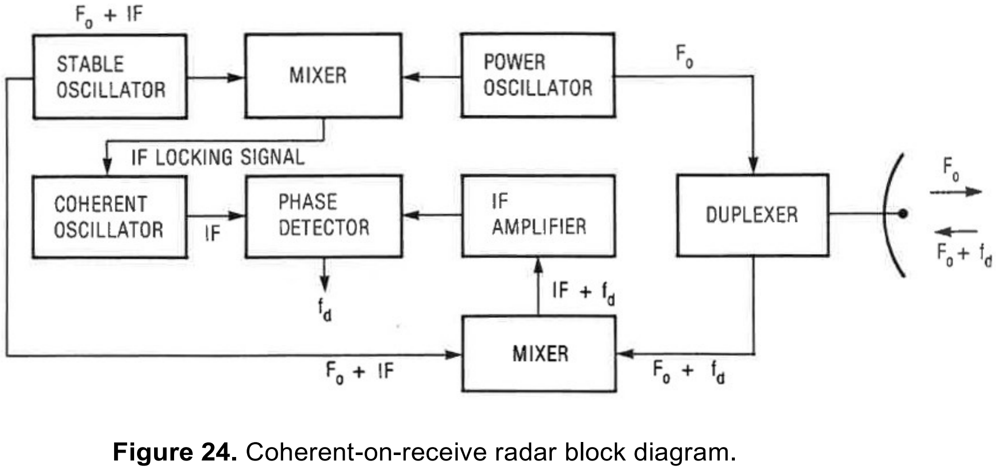


Figure 24. Coherent-on-receive radar block diagram.

cancel out, leaving the moving target components to subtract or add at their respective Doppler rates, depending on phase. **Figure 25** shows the process of extracting moving target information using a delay line cancellation technique.

In a radar employing an MTI detection system, the range information is unambiguous within the interpulse period. However, it can be seen that, in a pulsed radar, some velocity information becomes ambiguous, since any target velocities with Doppler frequencies corresponding to the pulse recurrence frequency and the multiples of the pulse recurrence frequency (see **Figure 1**) will not be "seen" by the receiver and are known as "blind *speeds"*. This may be better explained by saying that any Doppler shift *at* the PRF frequency or at multiples of the PRF frequency will not be discernible from the returned signals of the transmitted spectral PRF lines. The number of blind speeds of an MTI radar can be reduced by employing different or staggered P RF s on a time-sharing basis.

An MTI function in an airborne radar (AMTI) is somewhat more complex than in a fixed-location radar system, since in an airborne radar all targets have some Doppler frequency shift. Thus, a Doppler "bias" frequency must be applied to subtract out the vehicle's velocity component so cancellation can occur in the same manner as fixed targets and clutter are cancelled in ground-based radars. The problem gets more complex when the applied Doppler correction frequency must be changed when the antenna scans off the boresight position, since the Doppler frequency shift in the return signal varies with the direction the antenna points.

Range-Gated MTI

Radar equipment data processing methods take advantage of the digital data processing techniques that have been rapidly advanced by the computer industry. Because of the Doppler Effect, moving targets reflect a radar signal with a small frequency shift relating to the relative radial velocity of the target to the radar. Therefore, the existence of a Doppler frequency shift in a returned signal can be used as a digital difference between stationary and moving targets. The Doppler frequency shift is detected by standard frequency domain detection methods and is used to apply a video signal to an indicator. While the "moving target" signal is detected in the frequency domain, the time relationship to establish the range of the target is accomplished by sampling small segments

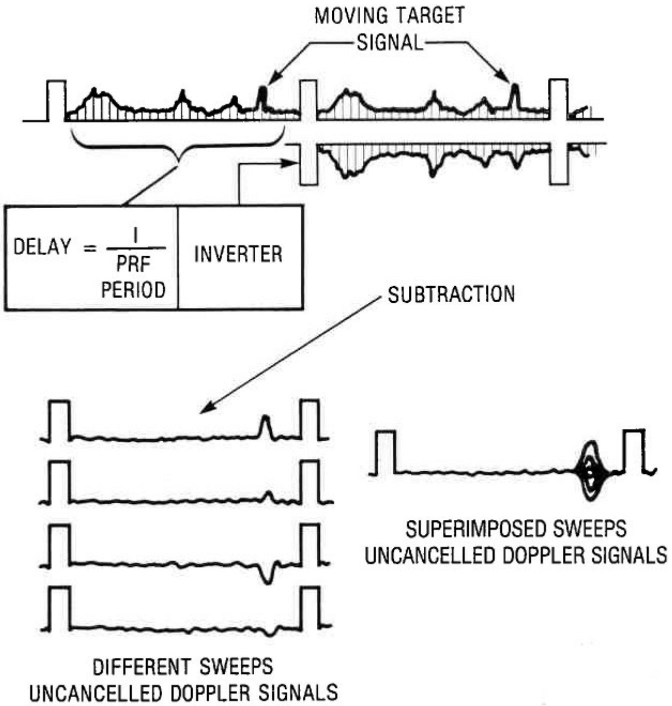


Figure 25. Delay line type of moving target indication.

of range by sequential time gating of the receiver. In this way, a signal that is detected with a Dopp1er frequency shift can be displayed on an indicator at a range position corresponding to the time of the “on” gate of the receiver during which the signal is received. All signals that are received from stationary targets can still be detected with standard amplitude detection methods and viewed on a separate indicator or processed as separate video signals. Most importantly, stationary target signals do not appear in the output of the frequency domain detector. Thus, the ratio between moving and stationary signals is improved substantially over a conventional delay line cancellation technique. The range-gated MTI system requires good frequency and phase stability during each PRF period to prevent the generation of false Doppler signals that would give rise to false moving targets or raise the level of the video threshold. Accordingly, range-gated MTI systems use very stable microwave amplifiers to achieve coherent operation with good continuous phase relationship during the PRF period.

Pulsed Doppler Radar Systems

A pulsed Doppler radar system and a pulsed radar system with MTI operation are quite similar, i.e., both systems are trying to obtain both range and velocity information. The real difference is that the pulsed Doppler radar extracts unambiguous **velocity** within finite limits at the cost ambiguous range information. The MTI radar has been described as extracting unambiguous **range** information within finite limits at the cost of ambiguous velocity information. In fact, many MTI radars do not measure the Doppler frequency if only objective is to separate moving and fixed targets. The pulsed Doppler radar is designed to extract Doppler information for purposes of finding and tracking a target in a high clutter environment and during high closing rate situations. An important feature of a pulsed Doppler system its capacity of detecting the presence of a frequency rather than detecting a signal above a determined amplitude level. This feature makes it an inherently automatic device that can detect signals at very low levels. Pulsed Doppler radars are characterized by high pulse recurrence frequencies usually in the 10 kHz to 300 kHz range and as in the case of MTI radar, use a technique of changing the PRF to minimize ambiguities, in this case, range. **Figure 26** shows a typical example of switching the PRF to measure the "second time around" signals and to identify them with the right transmitted pulse.

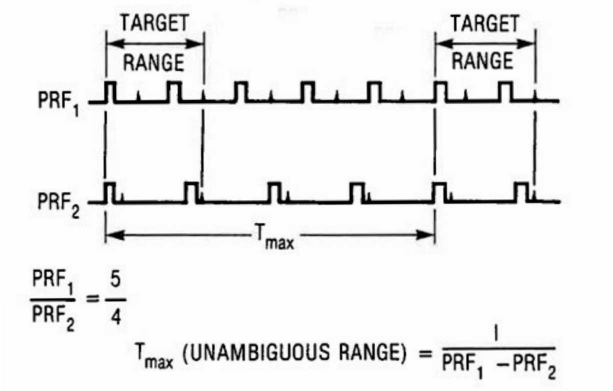


Figure 26. PRF switching tor measuring range.

The PRFs that are used have a numerical rela-tionship, such as 5 and 4 or 18 and 19, and will be dependent upon the unambiguous velocity limits to be handled (to avoid blind speeds) and the unambiguous range interval desired. **Figure 26** shows the relationship of two PRFs and the maximum unambiguous range interval. A typical block diagram of a pulsed Doppler system is shown in **Figure 27**.

Monopulse Radar Systems

In order to track a target, the radar must be able to discern the position, relative to the antenna boresight, of the radar return signal. Early radars mechanically scanned the target area from which an amplitude modulation of the returned signal was produced to sense the target's position. One popular antenna scan pattern was a conical pattern that resulted in a sinusoidal amplitude modulation of the returned signal whose phase and amplitude were dependent upon the target's position in the scan pattern. By servo control of the antenna's boresight position to minimize the modulation, the antenna could be made to point at or "track" the target. This technique is fairly easy to deceive with ECM equipment and has obvious mechanical drawbacks. A much better technique that now used that eliminates the mechanical scanning is called monopulse tracking. The monopulse tracking antenna technique is far more difficult to deceive in terms of its pointing capability.

A monopulse radar system is a tracking radar that derives all its tracking error information from a single pulse. In addition, new and independent

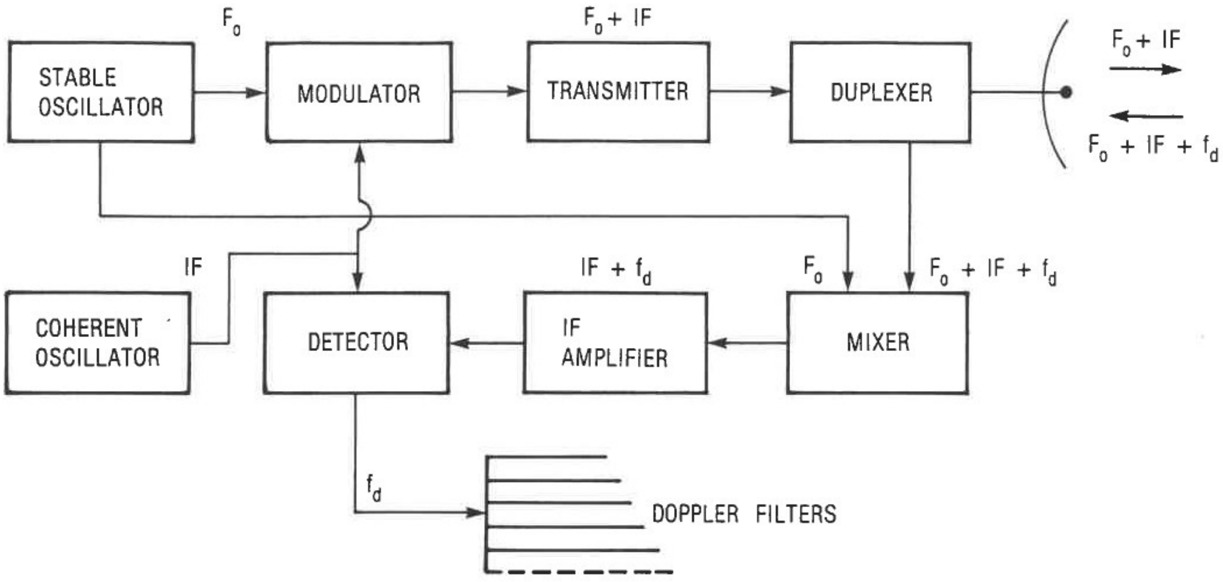


Figure 27. Pulsed doppler radar block diagram.

error information is generated with each new pulse. The basic principle of monopulse radar is that of combining the RF circuits of two antenna patterns to simultaneously obtain both sum and difference signals. The antenna patterns overlap as shown in Figure 28a. The sum of received signals of the two antenna patterns are shown in Figure 28b and the difference of the received signals in Figure 28c.

Physically, two antennas are not necessary since the "arithmetic" can be accomplished with a single parabolic reflector and two radiators, or "feeds," displaced from the focal point of the antenna.

The sum pattern is used for transmission of the pulse while both the sum and difference patterns are used to receive the pulse. Figure 29 shows a block diagram of a single-coordinate system.

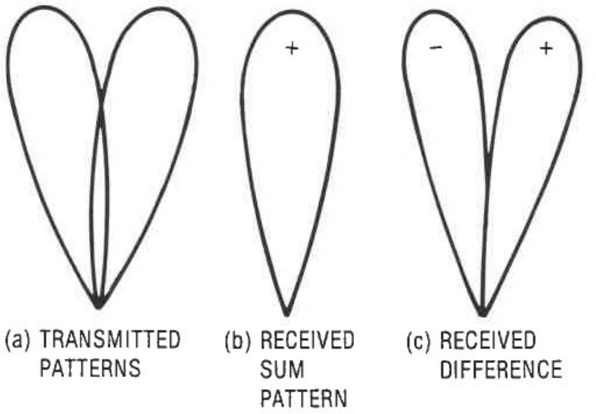


Figure 28. Monopulse radar antenna patterns.

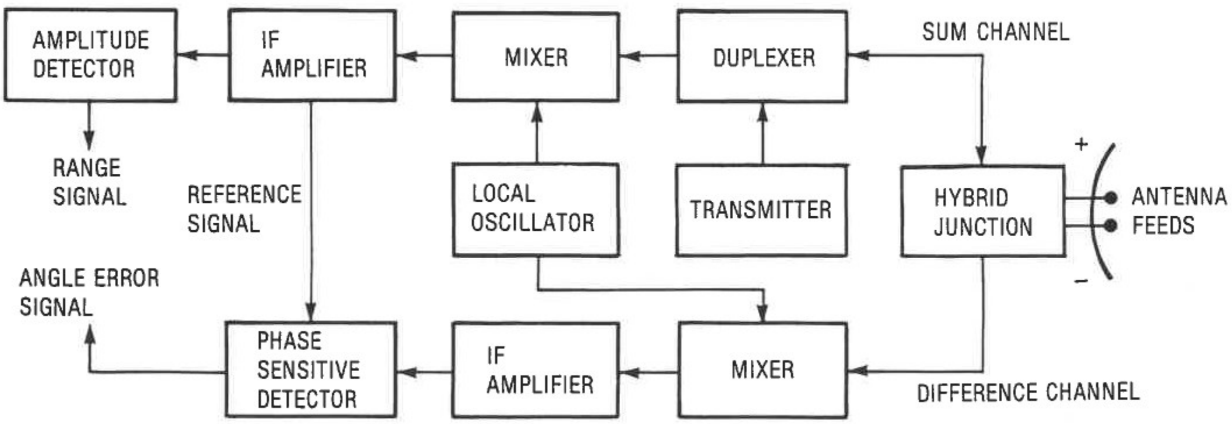


Figure 29. Amplitude-comparison monopulse radar block diagram.

The difference pattern signal provides the **magnitude** of the angle error while the sum pattern signal provides the reference needed to extract the **sign** of the error signal. The sum signal also provides a means of extracting the radar range measurement as in a conventional pulse radar. If two-coordinate information is desired (azimuth and elevation), then four (or even three) antenna feeds can be used to provide the sum and difference patterns in quadrature. Most current airborne tracking radars use some kind of monopulse method for tracking targets.

Synthetic Aperture Radar Systems

A synthetic aperture radar is one that employs a means of obtaining increased azimuth or angular resolution by using the technique of a synthetic aperture antenna. The main application of this radar technique is that of high-resolution radar mapping. The synthetic aperture antenna is the name given to a method of transmitting and receiving where the motion of the vehicle traveling in a straight line effectively creates a linear array of antenna elements as the vehicle moves through a specified time period (see **Figure 30**). The target information received in this time period is stored and later processed to achieve an increase in angular resolution.

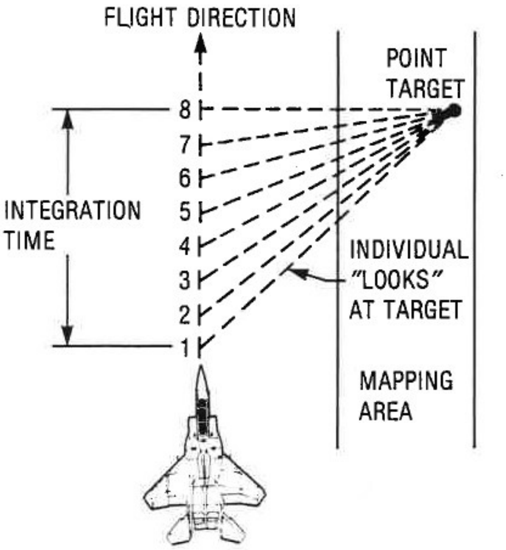


Figure 30. Synthetic aperture antenna.

The Doppler frequencies received from a point-target return signal will decrease as the vehicle approaches a perpendicular range position (**Figure 31**, Position 8) where the Doppler signal will be zero. The Doppler history of the point target as shown in **Figure 31** corresponds to the positions indicated in **Figure 30**.

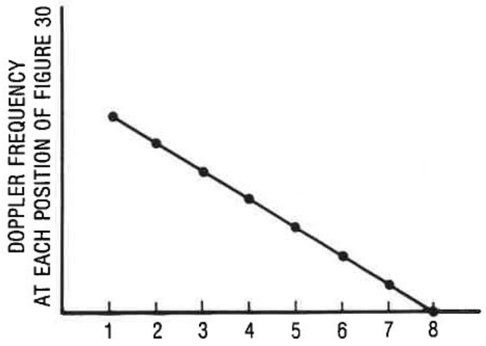


Figure 31. Doppler frequency history of a point target.

The Doppler histories of the target area are recorded on signal film by a photographic process as shown in **Figure 32**.

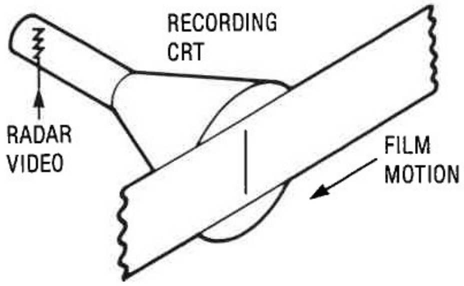


Figure 32. Recording of Doppler signal on raw data film.

A line is scanned on the film at the PRF rate. The vertical position then corresponds to range. The signal strength of the targets provides density modulation of the film (exposure). A simple drawing of the Doppler modulation and how it is recorded on film is shown in **Figure 33** corresponding to the Doppler history of **Figure 31**. The signal film then stores a Doppler history of each point target at its particular range as shown in **Figure 34**. The signal film is then processed in an optical processor to produce a radar image film, which in tum is used as a negative film to produce a photographic image, a radar map picture.

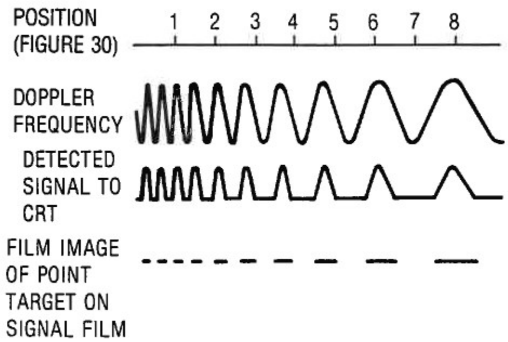


Figure 33. Doppler signal modulation of signal film.

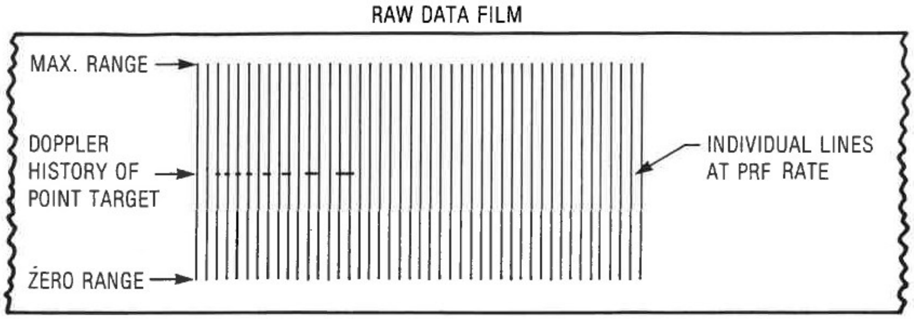


Figure 34. Synthetic aperture antenna radar signal film.

Each Doppler history performs as an individual Fresnel lens and when the signal film is illuminated by a coherent light source, such as a laser, each point target is focused on the image film as a point as illustrated in **Figure 35**. The entire radar map is made up of the integration of all the point targets and the angular resolution is then a function of the resolution capability of each point target. Of significance is the ability of the radar to maintain optimum resolution that is independent of range, referred to as having a "focused" antenna.

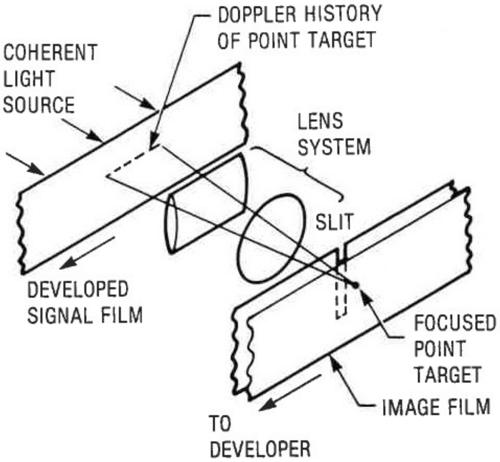


Figure 35. Fresnel lens effect on focusing point targets.

The range resolution of the synthetic aperture radar is achieved by pulse compression techniques. Thus the radar employs the ultimate in range and angular measurement techniques and provides the best radar resolution achievable in the present state of the art.

The disadvantage of the synthetic array radar of the 1970s, as described, was the time required to obtain the final radar image. It is not a "real-time" radar, or one where the radar image is instantly available as in standard radar systems.

In this case, the signal film is either physically returned to a processing facility or the radar data is transmitted to a processing facility which then produces an image film and radar map pictures.

The current technology of digitally processing radar data has been applied to synthetic aperture radars and together with the present capability of storing large amounts of data, a real-time display is now achievable. Some compromise in resolution, compared to optically processed data, may be tolerated to achieve a real-time display but present systems are achieving remarkable results. The use of the synthetic aperture principle to targeting air-to-ground weapons is another important application of a real-time high-resolution radar mapping system.

A further advantage of the synthetic aperture technique is that of being able to detect rotational Doppler information of a target that is also moving relative to the radar. This capability provides an image of the target that is more likely to provide a means of target identification than previous radar identification attempts. This technique is called Inverse Synthetic Aperture Radar (ISAR).

Doppler Beam Sharpening

Doppler beam sharpening is a radar technique that is used to improve the azimuth resolution of a radar. Where the usual azimuth resolution is dependent upon the beamwidth of the antenna, in the case of Doppler beam sharpening the beamwidth is divided up into segments by using many Doppler filters and by processing the receive signals using Fast Fourier Transform (FFT) techniques. The signal returns within an antenna beamwidth can be sorted because of the differences in the Doppler frequencies within the beamwidth (see **Figure 36**). That is, a target can be identified within the beamwidth by its particular Doppler frequency. This technique requires a very stable transmitter and coherent signal processing, as it is necessary to introduce a constant Doppler frequency offset so that the Doppler frequency

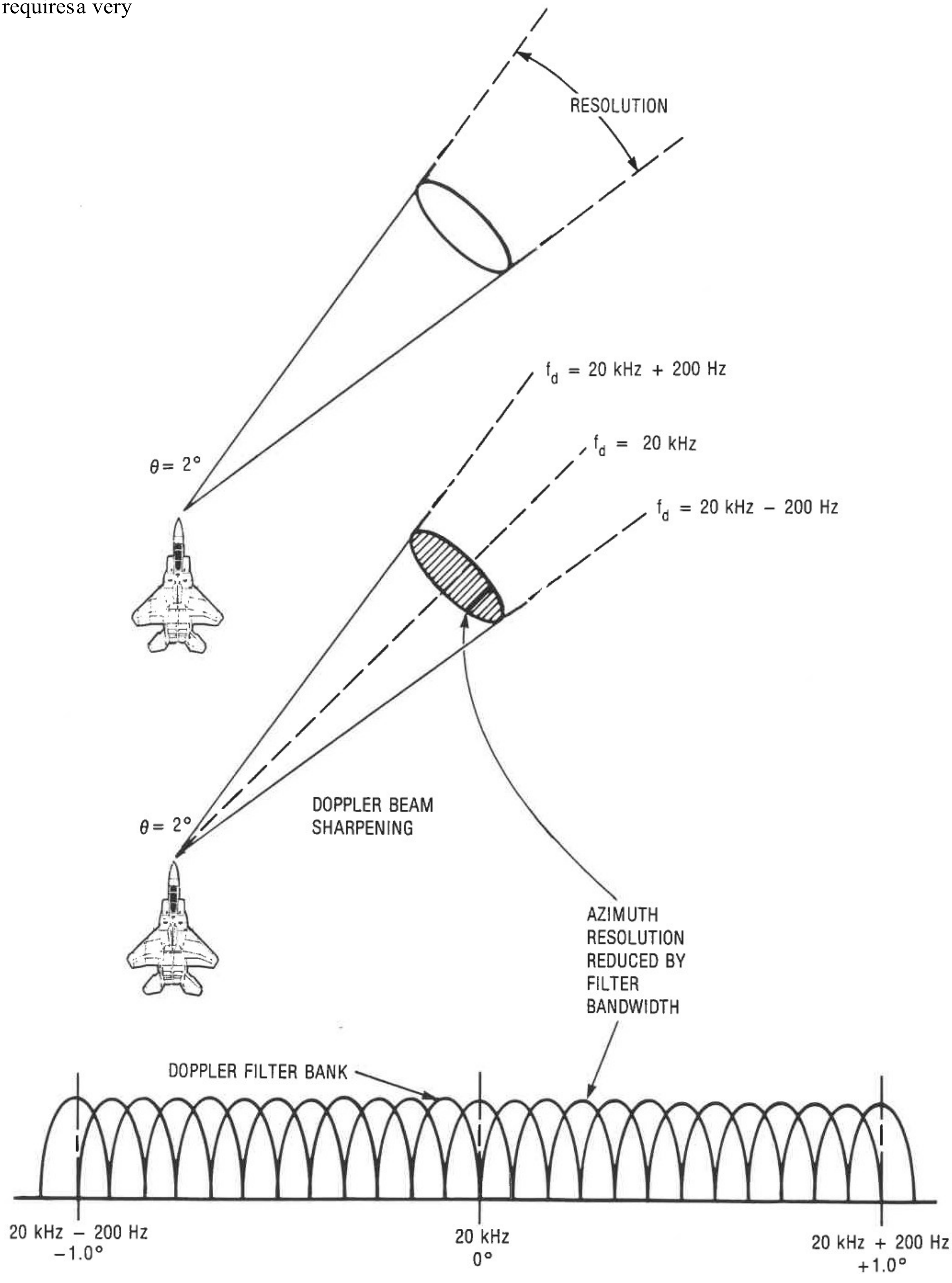


Figure 36. Doppler beam sharpening.

associated with the azimuth cursor is translated to zero frequency. The phase correction is derived from the aircraft velocity, the depression angle as well as the azimuth angle. Radar systems employing Doppler beam sharpening can use either fully coherent systems or, in the case of magnetron transmitter systems, they can be made to operate with a coherent-on-receive type of radar system.

Bistatic Radars

Bistatic radars by definition are radars that employ separate and widely spaced transmitting and receiving antennas rather than the normal single transmit/receive antenna used in **mono-static** radars.

Although a monostatic radar overshadows the bistatic radars in performance, the bistatic radar has special advantages that makes it quite attractive for particular applications.

The monostatic radar has the real disadvantage of being easily detected by its emission. Monostatic radars can be jammed or even targeted by antiradiation missiles that passively home on the radar's emission. The obvious advantage then of a bistatic radar is that its transmitter is located well away from the receiver and can be in some remote place where it is not adversely affected by jamming or by destruction from an ARM missile. If jamming is directed toward the radar transmitter, as is the normal case, then the receiver is effectively untouched by the jamming signal. However, a bistatic radar system would not be effective if the jamming is omnidirectional. The key technical issues having to do with the designs of bistatic radar involve the complexity of the geometry, the difficulty of controlling it, and the difficulty of implementing the synchronization, isolation and the platform locations. Part of the difficulty that arises in a bistatic system is that the illuminators and receivers are usually moving and are difficult to coordinate, especially in a hostile environment. In addition, the transmitter and the receiver and the target must all be visible to each other so that any obstacles of terrain and the horizon do not interfere with the required mutual visibility. The position of the illuminator with respect to the receiver is needed to solve the bistatic triangle (see **Figure 37**) between the illuminator, receiver and the target and it becomes very difficult when an illuminator is aboard an airplane, for example, as it is continually changing its position. For coherent operation it is usually necessary for the illuminator to be synchronized with the receiver thus the waveform radiated by the illuminating radar must be available or synthesized at the receiver in order to coherently process the bistatic signals reflected from the target. The constraints faced by bistatic systems at the present time, because of the particular geometries involved, will probably preclude their universal deployment in the near future.

Over-the-Horizon Radars

As microwave equipments are line of sight devices, a radar system is limited to that extent, with the exception of some diffraction and "ducting" effects. In order to detect targets over the horizon at significant ranges, 1000 nautical miles, for example, the radio waves must be "bounced" off the ionosphere as is done in long range radio communications. The radars that are designed to operate accordingly are called **OTH** radars (Over-The-Horizon).

As only lower frequency radio signals bounce off the ionosphere, the OTH radars make use of this propagation technique and operate at HF frequencies of the order of 15 to 20 MHz. The OTH radars employ a very large antenna that requires considerable real estate. The antenna must be high gain, cover a wide frequency range, be steerable in elevation and azimuth and be capable of handling high power. The coverage of the radar on the surface of the earth depends on the ionosphere. For proper coverage, a number of different frequencies may be required and programmable to the ionospheric conditions at a particular time.

The radar's waveform can be Pulse or FM-CW. In the pulse waveform, a long pulse length, such as a millisecond, is transmitted to achieve high average power on the target. The pulse repetition frequencies are low, such as 50 Hz, as the unambiguous range interval must accommodate ranges of several thousand miles.

Generally, a shaped RF pulse is used to reduce spectral energy away from the carrier to minimize interference with other users of the HF frequency band. In the FM-CW case, the transmitting and receiving antennas are located at separated sites at a considerable separation distance in hundreds of miles. This bistatic radar achieves high power output without the high peak power components required of a pulsed radar.

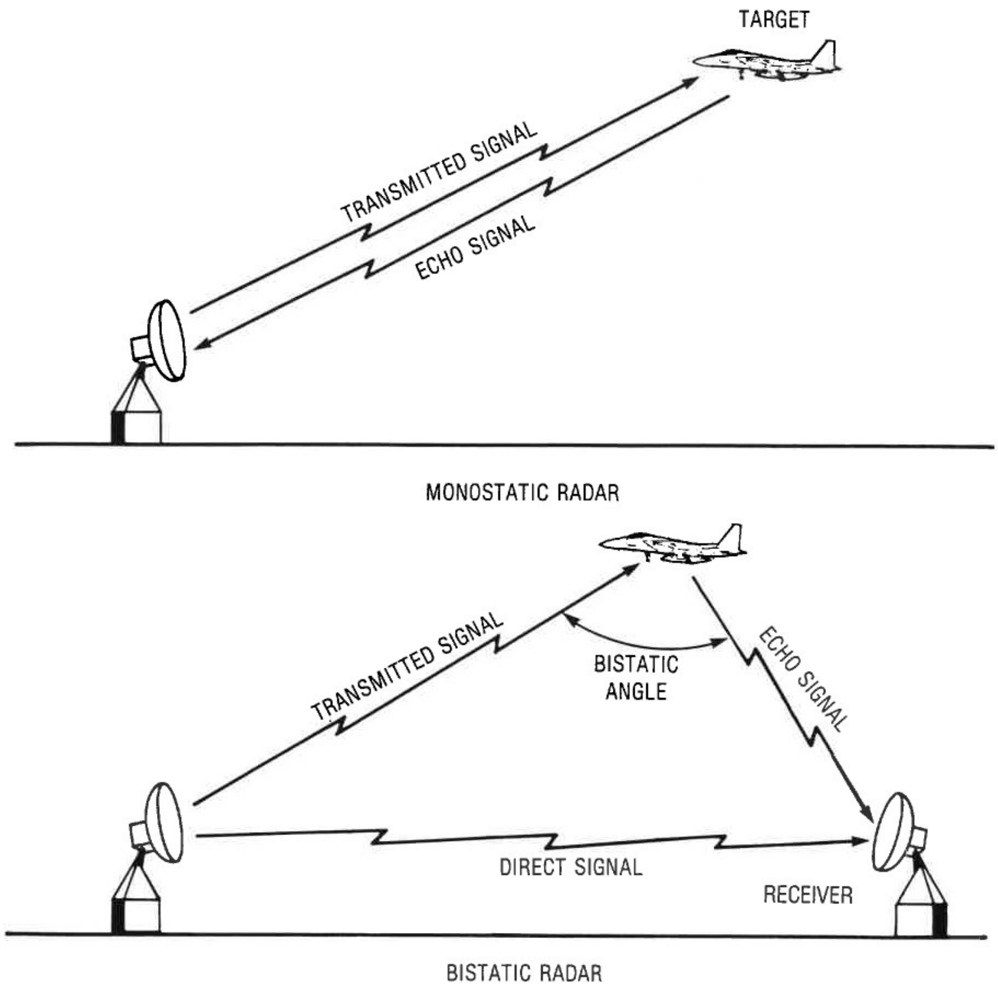


Figure 37. Bistatic radar.

OTH radars deal with problems of fading, multiplicity of paths from radar to target, ionospheric changes, auroral ionization and a large scattering area (clutter) that competes with desired target echoes. Given that the environment is sensed in real time and the radar's operating parameters can be adjusted to match the existing conditions, the OTH radar can be a very successful technique for the detection of long-range targets.

Missile RF Guidance Techniques

There are three types of RF guidance techniques commonly used in air defense guided missiles: (1) Beam Riding, (2) Command Guidance and (3) Homing Guidance.

The **Beam Riding** system is one where the missile does not perceive the target but detects its own position relative to the radar beam that is tracking the target. The missile keeps itself centered in the radar beam and attempts to hit the target which is also centered in the tracking radar beam. The missile must continuously maneuver to remain in the center of the beam even if the target is flying on a straight-line course. This can result in severe corrective maneuvers during the final intercept phase. Another drawback to the beam rider is that any angular tracking error at the radar becomes a larger error as the range is increased, as the antenna beamwidth increases with range, and therefore the accuracy of a beam rider system is inversely proportional to target range. For these reasons the beam riding technique is mostly used to guide missiles in the early portions of their flight and is used in conjunction with a homing type method.

In a **Command Guidance** system the target is tracked by a tracking radar and the missile does not perceive the target. Another radar will track the missile and the data from the missile tracking radar and the target tracking radar can be fed to a computer which will calculate the missile trajectory required for intercept. The trajectory information is continuously transmitted to the missile to "command" its best flight path. Thus, a more efficient trajectory can be used since the computer can plot the best flight path for the missile. As is the case with the beam rider, accuracy is also inversely proportional to range since a fixed angular error at the radar increases with range.

In the **Homing** type guidance the most widely used technique is that of **Semi-Active Radar Homing** in which an illuminating radar is needed to provide the transmitted energy so that the missile can passively guide on the reflected echo from the target. Thus, the semi-active radar method requires the radar illuminator to be pointed at the target until the missile has impacted.

In acquiring the target, the semi-active horning missile uses a narrow band frequency gate to search the spectrum and to lock on to the signal reflected from the target. The received signal is then coherently detected either against a signal received from the illuminator from a rear antenna in the missile or from a very stable oscillator reference on board the missile. The frequency spectrum of the illuminating radar must be free of any spurious outputs that might occur in the desired Doppler band relating to the velocity between the missile and the target. If the radar illuminator is transmitting a spurious output in the desired Doppler band then it can appear as a false target which could seriously affect missile performance. The noise specifications placed on an illuminator transmitter, especially a CW transmitter, are very severe and require special kinds of low noise klystrons or traveling wave amplifier tubes *to* meet the requirements.

A second homing method is that of the **Active Radar Homing** method in which the illuminating radar signal is on board the missile and the missile is completely autonomous, sometimes referred to as a "fire and forget" missile. The Homing type missile is considered to be the most intelligent of the three missiles, but it also can require the most complex equipment. Both the active and semi-active homing missile perceives the target with its own radar receiver and computes its own control signals. One advantage of the homing type missile technique is that as the missile gets closer to the target the quality of target information continually improves as range decreases.

The radar waveforms for illuminating a target can be either CW or pulsed Doppler. CW is the simplest and provides best lower altitude capability by discriminating against clutter on the basis of unambiguous Doppler frequency. A CW system will normally have a number of illumination radars which are directed by a separate tracking radar. Alternately, each can be made to be a self-tracking illuminating radar if two antennas are used. One advantage of a semi-active system is that it can provide much more power output in the illuminating signal when the transmitter is not restricted to the small confines of a missile. A pulsed Doppler waveform may also be used for either an active or semi-active illumination system for which the PRF is chosen high enough to yield unambiguous Doppler data. In a complex system where many targets must be tracked and illuminated, the illuminating signal can be essentially an interrupted CW signal in which the pulse may be of the order of milliseconds in length. In this case the missile would have to operate in a sampling data mode, extracting information during the time its target was illuminated and then holding the information until the next sample.

Although some semi-active missiles home during their entire flight, a homing type guidance system is usually only used during the last seconds of the intercept. Another guidance technique, either command or beam riding, is used during the mid-course of the flight in order to get the missile to an appropriate point where it can acquire the target and enter the terminal horning phase of its flight. This is considered more efficient from the standpoint of radar power in the missile trajectory as the total homing intercept range is reduced accordingly.

The trend in advanced air-to-air missile systems is in the direction of active homing guidance to eliminate the necessity for the aircraft to continually illuminate the target until the missile has impacted. Obviously, the "fire and forget" missile is the more popular choice for pilots. As missiles become more complex then so does the electronic countermeasures that are used to deceive the missiles and thus a number of different sensors and modes of operation are incorporated in advance missiles.

These include multi-modes where a missile can switch to a passive mode and home on the radiated signal ("Home-On-Jam") or can deploy another sensor, such as an IR sensor, to passively home on the target.

Active homing guidance does have the disadvantage of requiring a larger missile to carry the on-board transmitter, impacting on propellant, weight, missile maneuverability and not the least, the cost of the missile.

Semi-active guidance affords a smaller missile but is limited to the line of sight transmission of the illumination signal, requiring an airborne illuminator for intercepts of over-the-horizon targets.

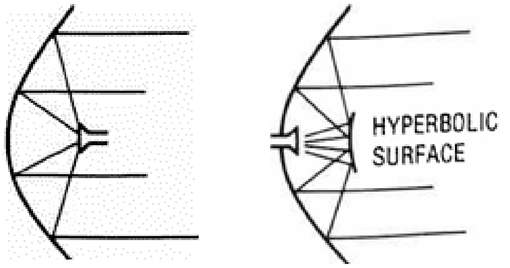
A variation of semi-active homing is called a "Track Via Missile" guidance system (TVM). In this system the missile receives the target's reflected illumination but, instead of processing the signal on board, the signal is retransmitted to the illuminating radar where the radar then computes the guidance information and retransmits a command guidance signal back to the missile. This system is used to handle a larger number of threats.

Antennas

From the radar equation, it can be seen that the detected radar range depends upon the antenna's gain, aperture and efficiency. Other system factors that enter into antenna design considerations are scanning rate, stabilization, power-handling capability, size, shape, etc.

Parabolic Reflectors

Most radars use a parabolic reflector of some kind, fed either at the focal point (**Figure 38a**) or at the su RF ace of the reflector in a Cassegrain Configuration (**Figure 38b**), to direct the beam in a focused manner.



(a) CONVENTIONAL FEED AT FOCAL POINT (b)CASSEGRAIN FEED

Figure 38. Parabolic antennas.

Parabolic reflector antenna surfaces are often modified to obtain wider field patterns for greater search areas, especially in airborne radar where ground illumination at all ranges is desired. One type of a modified parabolic reflector often used, is called a "cosecant squared" reflector. It provides a radiated field at both close and far ranges.

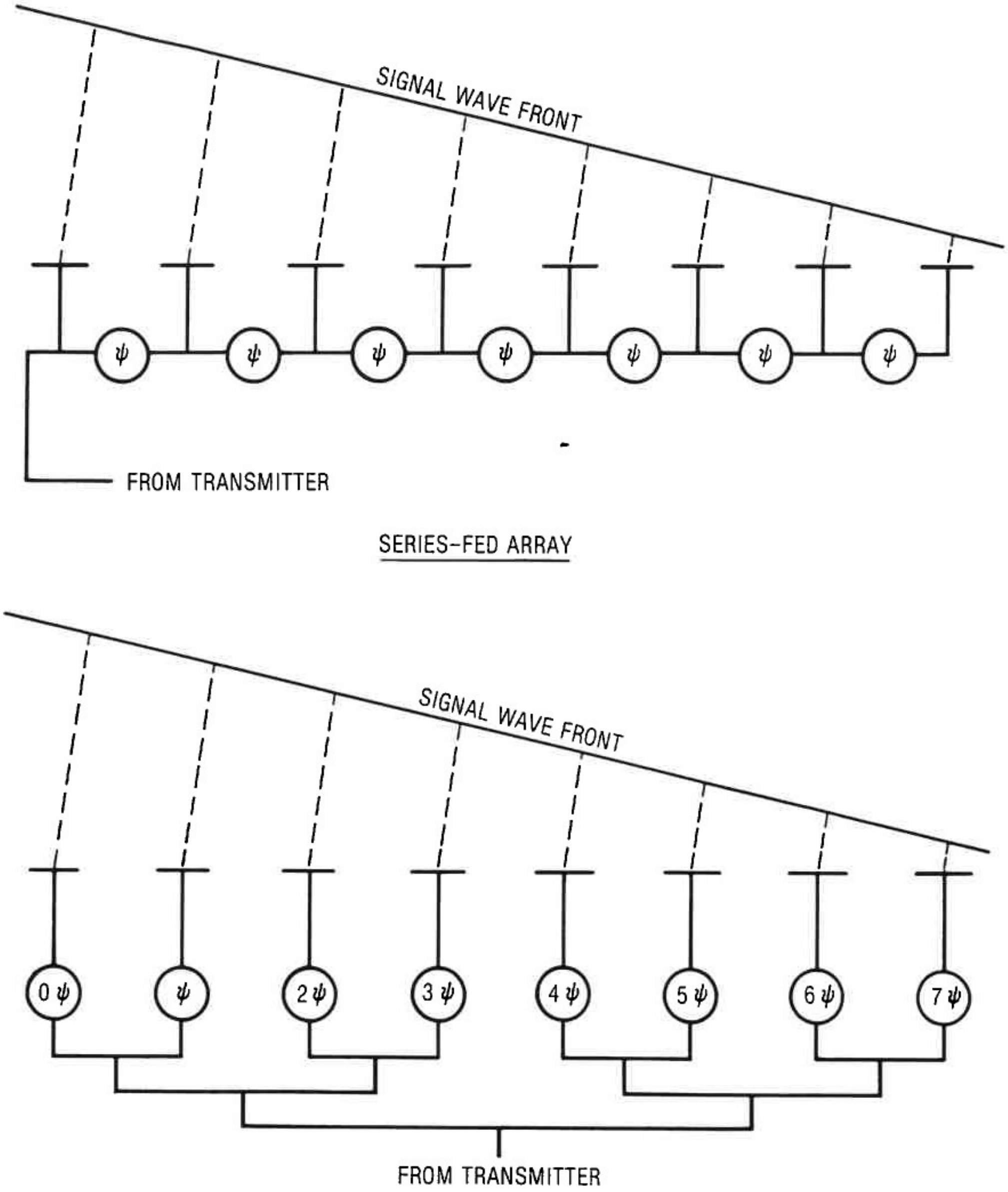
Phased Arrays

The phased array type of antenna is used to provide electronic scanning of the radar beam primarily for faster scanning requirements. Phased arrays can be fed by several methods, including the series and parallel methods shown in **Figure 39**. Another method is to uniformly radiate a lens type of array that is made up of a mosaic of phase shifters that are computer controlled to provide the desired beam.

The **phased array** antenna consists of many individual radiating elements that are suitably spaced with respect to one another. By controlling the phase and amplitude of the signals applied to each element, desired radiation patterns can be obtained from the combined action of all elements. If all elements are spaced in a straight line, it is called a **linear array.** If the elements are arranged in two dimensions in a plane, it is called a **planar array.** If each element has a separate transmitter device, it is called an **active array.**

The active phased array is used when many low power devices are desired to power each element of the array and the power output of each is then "space combined". This antenna configuration can use either low power helix type traveling wave tubes or soli-d state modules. Future low frequency search radars are being designed with solid state/active phased arrays when there is no concern for very large antenna dimensions, as solid-state devices are now available with adequate power output at lower frequencies. The phased array beams are steered by changing the phase or frequency on each radiating element, requiring control and duplicity of the phase/ frequency relationships of the power devices used.

Phased array antennas can produce many kinds of beam shapes, including fan and pencil beams. A single phased array may be used to scan elevation electronically, while scanning the azi
muth direction mechanically. Four fixed arrays can be made to scan electronically in all directions, i.e.,



PARALLEL-FED ARRAY

Figure 39. Phased array antenna feed alternatives.

a hemispherical scan. Hence, many combinations of electronic and mechanical scanning schemes are possible and are used accordingly to best fit the application.

Data Rate

The data rate is the rate at which the radar cell sees the target. Factors such as antenna beamwidth and antenna scan rate determine the number of echoes received from a target during a particular scan. A radar with a slow scanning antenna beam will have a longer dwell time on a particular target and will receive more pulses back during one scan. This can be important in determining the average power received from the target as well as the period of time in which a Doppler frequency can be measured. Where the number of pulses in a time measurement can be a factor in the detection of a target, the dwell time on the target must be long enough to measure the periodicity of a Doppler frequency. Electronically scanned antennas subsequently will have a limit in their scanning rate if the radar intends to process Doppler information.

Indicators

The radar indicator displays the radar signals in a format that provides the operator with the desired information. The displays can vary as can be seen in the examples in **Figure 40**. The indicator is commonly a particular type of cathode ray tube (CRT) to which a sweeping voltage signal is applied to cause a trace to appear on the face of the CRT. This trace corresponds to one interpulse period in time whose origin is the time when the RF pulse is transmitted from the radar antenna. When a target echo is received it is applied either to the deflecting plates of the CRT to create a picture as in the “A” display of **Figure 40** or to the grid of the CRT to amplitude modulate the light intensity of the moving trace that creates the "B”, "C" or "PPI" displays.

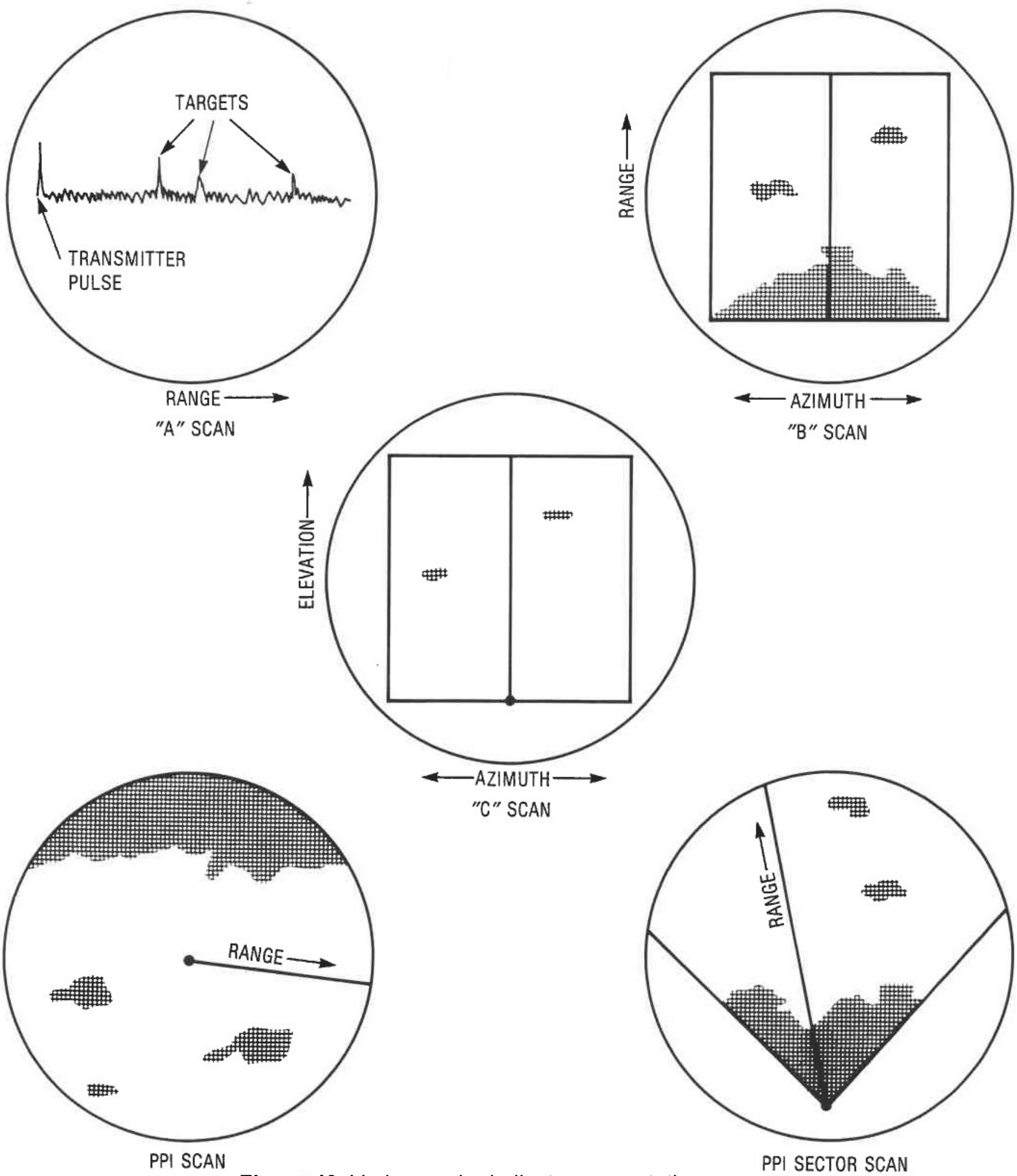


Figure 40. Various radar indicator presentations.

The simplest display is the "A" type whose stationary trace only displays the range and relative amplitude of the radar echoes. These were used in many early radars for ranging purposes but are no longer used in current radars as no azimuth information is presented.

The "B" display has a moving vertical trace that moves back and forth horizontally, effectively painting a picture of range versus azimuth information. The picture is distorted at the bottom so that it presents a distorted mapping image, but it is quite satisfactory for airborne radar where zero range distortion is of little concern. The "C" type which is also used in airborne applications is essentially the same as the "B" type except the vertical dimension is in elevation instead of range.

A very common display for search radars is the "PPI" (Plan Position Indicator) display which records radar data in polar format, ideal for 360° scanning antennas. The center of the screen is range zero. A variation is the Sector PPI display used for presenting ground mapping information that is not distorted as in the "B" type.

Most cathode ray tubes are made with long persistent phosphor screens so that the trace will remain until the next trace appears at that azimuthal position. Some advanced displays will also include CRTs that can display different colors to provide contrast in radar information.

In high performance aircraft, special displays are used to give the pilot direct alpha-numerical read outs, as time does not always allow radar display interpretation in a high-speed encounter. Such information as the radar mode, a visual horizon, relative altitude of target, target velocity, target acceleration, range, etc., are all provided for immediate information requirements.

Radar ECCM

In order to provide continued radar operation in an unfriendly environment, the radar must include additional equipment to provide an Electronic Counter Counter Measures (ECCM) technique capability. The unfriendly environment may include various jamming signals, both CW and pulse, at both narrow and wideband frequencies, as well as the numerous types of clutter, be it ground clutter, weather clutter or chaff (a cloud of tinfoil strips cut to desired wave lengths to give a large volume radar return).

In order to best challenge the jamming threat, a radar will have to be configured to use techniques in the time domain, frequency domain and the spatial domain to reduce the unwanted interference, either individually or in combination.

These techniques include frequency agility operation where the transmitter frequency is programmed to the frequency of least interference. Other techniques include coherent *side* lobe cancellation (CSLC) and side lobe blanking to reduce interference from stand-off jammers and deception jammers. Techniques earlier discussed in reducing clutter, STC, etc., are also used to reduce the effects of weather, clutter and chaff problems.

The military radar designer, who must be concerned with an unfriendly environment, will incorporate into the radar the techniques of frequency, amplitude, time, velocity and antenna pattern processing in order to obtain the intended performance from the radar system.

Low Probability of Intercept

One disadvantage of using a radar to detect a military target is that of transmitting a signal that can be detected by the enemy. The basic strategy is to radiate only when essential and then to radiate only enough power to achieve the desired range. As the range decreases, the radiated power is also decreased to minimize the probability of interception. This is called power management. Increasing the receiver sensitivity and the radar's ability to detect very weak targets will add to the LPI capability. Operating at higher frequencies where the propagation losses are high will also improve the LPI performance.

Microwave Tubes Used in **Radar Systems**

Early radar systems operated at low frequencies because electron tubes were not available for operation at higher frequencies. The density-modulated triodes and tetrodes used in commercial radio and communications transmitters were the only available high-power tubes until velocity modulated microwave tubes were invented and produced.

The **Magnetron** was the first practical high-power microwave oscillator produced in large quantities and it was the principal means of providing high power microwave pulses for radar systems until microwave amplifier tubes became available. The magnetron is a crossed-field oscillator (the magnetic focusing field is perpendicular to the electron beam) and is primarily used in non-coherent radar systems.

Magnetrons provide power at kilowatt and megawatt levels and are very efficient devices (the output power is high compared to the input power it needs to operate). They are used in many radar systems that (1) do not require coherent detection techniques, or (2) are designed for economy and limited performance. Commercial airborne weather radars, small boat radars, and terrain following radars are examples of magnetron type radars.

Magnetrons can be made to operate in coherent systems if a stable coherent signal, usually about 10 dB below the magnetron's power output, is used to "lock-up" the magnetron by injecting the signal into the magnetron. Other techniques to improve magnetron performance include priming the magnetron so that its starting time (jitter) is improved. A means of using a magnetron to provide a coherent-on-receive radar is shown in **Figure 24**.

The **Klystron** amplifier tube is probably the most reliable, stable and most economic microwave tube that can be used in a radar transmitter, if its bandwidth does not limit radar performance. The microwave tube industry is continuing to develop wider bandwidth klystrons and "smart" tuning klystrons in order to satisfy new system requirements. One advantage of a klystron is its shorter interaction length that allows permanent magnet focusing, providing the best electron optics for minimizing noise critical to systems that depend on Doppler frequency measurements. Additionally, higher average power output is achievable without having to use heavy, power consuming focusing solenoids. Even though the klystron suffers from wide bandwidth performance, its narrower bandwidth enhances the spectral purity of its output and that is sometimes a more desired radar feature than wide bandwidth performance.

To achieve wider operating bandwidth than a klystron can offer, the choice is either that of the **Traveling Wave Tube (TWT) or a Crossed Field Amplifier (CFA).**

There are several types of traveling wave tubes, made according to the power output and frequency bandwidth that is needed. The **helix traveling wave tube** can provide an octave or more of instantaneous frequency bandwidth at power levels up to several kilowatts. These TWTs are ideal for achieving wideband frequency agility for target enhancement and ECCM purposes and for providing wideband missile seeker performance. The helix TWT is also well suited for active phased array applications and for driver amplifier use when higher power TWTs are needed as final amplifiers. Higher power TWTs that provide more power output, but less bandwidth, are called **coupled cavity TWTs** and can provide power outputs in the 100s of kilowatts but at bandwidths usually less than 10 percent of the operating frequency.

As the trend in airborne radars has been toward combining many radar functions into one radar system, the transmitter becomes more complex in its requirements to change the radar waveform in order to suit the mode of operation. The total radar requirements call for wider operating frequency range, variable pulse recurrence frequency, variable pulse widths, coherency, pulse coding, power programming, etc. The modern airborne multi-mode radar systems generally use a gridded Coupled-Cavity Traveling Wave Tube (CCTWT) as the final amplifier in the transmitter, as it is the best device to provide the frequency bandwidth as well as the low noise attributes of a linear beam tube. The gridded electron beam feature allows modulating the tube at high pulse recurrence frequencies with low voltage modulating pulses, reducing considerably the modulator power while being able to achieve better pulse shaping of the signal.

Some search radars used hybrid tubes called **Twystrons,** a combination of klystron and traveling wave tube technology. These tubes are designed for power outputs in the megawatts and provide bandwidths of the order of 10 percent. A new type of high-power klystron amplifier, the **Extended Interaction Klystron (EIK),** is now being produced for replacement of Twystrons in new and existing systems. The EIK provides improved performance in bandwidth and promises to be a more reliable and less expensive power amplifier for wideband radar applications.

From the magnetron, a crossed field oscillator, the **Crossed Field Amplifier** (CFA) tubes evolved which are used in a number of radar systems. The CFA has the advantage of low operating voltage, good bandwidth and very good efficiency. It has suffered in gain (about 10-13 dB) compared to the

40-60 dB gain capability of the linear beam tubes but recent developments in CPA technology appear to increase CFA gain to the 20 to 25 dB range. The CFA also can be designed as a tube with little transmission loss when it is not turned on, so that it can be a power booster as desired for system power management.

Another family of microwave tubes is called **Gyrotrons**. These are tubes that provide much higher power than linear beam tubes at millimeter-wave frequencies. Most gyrotrons made to date have been designed for energy- producing machines. However, there is contin-uing interest in making gyrotron amplifiers if the radar community requires very high-power output levels at millimeter-wave frequencies, such as a megawatt at 100 GHz.

Radar System Bandwidth

The amount of operating bandwidth of a radar system is determined by one or more of the following performance requirements:

1. Narrow-band frequency agility to enhance detection and minimize target scintillation.
2. Narrow-to-wide band frequency bandwidth to allow modulation of the signal for pulse compression purposes.
3. Narrow-to-wide band frequency agility to handle multiple target tracking.
4. Wide band frequency agility to avoid hostile jamming signals.
5. Frequency control to avoid friendly interference.

It should be noted that when processing Doppler frequency information, the operating carrier frequency is not usually varied, as Doppler frequency shifts will vary linearly with the operating carrier frequency, thereby confusing the Doppler measurement.

The bandwidth of radar systems is determined by (1) what is actually needed to achieve the radar's objectives, (2) the ECM threat (real or anticipated), (3) frequency-limiting components of the system (such as a high velocity missile's radome frequency characteristics), and (4) the customer's desires. Generally, the wider the bandwidth of the system, the more expensive the system be- comes, as components become more complex and expensive.

Radar Techniques

Radar system manufacturers, in their attempt to make their products as salable as possible, try to incorporate as many of the state-of-the-art tech- niques as are economically feasible. Some of the more popular techniques now being used include:

1. Short pulse transmission
2. Digital data processing
3. Pulse compression
4. Pulse coding
5. Phase coherency (pulse-to-pulse phase relationship)
6. Coherency-on-receive (inter-pulse phase relationship)
7. MTI (Moving Target Indication), AMTI (airborne)
8. Monopulse tracking
9. Frequency agility
10. Polarization agility
11. Electronic scanning (phased arrays)
12. Synthetic aperture radars, ISAR (inverted SAR)
13. Doppler beam sharpening
14. PRF agility
15. ECCM
16. Low probability of intercept

The above items become some of the selling features of radar system manufacturers in their selling efforts to their customers. Again, the amount and quality of information that a radar system can extract from an operating environment is a measure of that system. Other factors include system acquisition cost, maintenance costs, efficiency of operation, and reliability.

Future Trends in Radar

New technologies will undoubtedly alter the capability of radar in the future to detect and process complex information faster and more efficiently. Radars will evolve into even more multimode systems than now exist. The digital signal processor art will improve significantly with VLSI (very large-scale integrated circuit technology) becoming a reality in practical system hardware. The improvements expected in data storage will further improve the real time capabilities in synthetic aperture radar and ISAR techniques. The latter, combined with VLSI capability will help to make on-board radar target discrimination more likely for future weapon deliveries.

The advances in solid state devices will push the solid-state transmitter art into the higher frequencies. One might expect a not-too-far off generation of advanced multi-mode airborne radars *to* be all solid state at X-band frequencies with active array antenna configurations. Antennas will become more conformal to the aircraft's geometry appearing not only in nose areas but in leading edges of wings and in various fuselage areas.

The continuing interest to develop more successful bistatic radars is likely to produce some deployable equipment in the future that will enhance military radar use. The advances in data processing should be of considerable assistance in solving the present complex problems now plaguing bistatic radar system designers.

The advancements in new microwave and millimeter-wave tube technologies will also provide the industry with devices to challenge new radar techniques and radar performance.

While radar technology has principally evolved from military requirements, new developments in detecting weather, wind shear, clear air turbulence, "microbursts", etc., will contribute significantly to the increased safety of the public, both on the ground and in the air.

Radar Relationships

1. Radar Equation

$$\frac{S}{N} = \frac{PG^2\lambda^2\sigma}{(4\pi)^3R^4\overline{NF}\ kTB\ L}$$

2. S/N at Range, R

$$\frac{S}{N} = \left(\frac{R_o}{R}\right)^4$$

R_o is the range at S/N = 1

3. Antenna Gain

$$G = \frac{4\pi A}{\lambda^2}$$

A = Aperture Area

4. Antenna Beamwidth, Half Power, Circular Linear Array

$$\Theta \cong \frac{57\lambda}{d}\ \text{degrees}$$

d = diameter

5. Duty Cycle of Pulsed Radar

$$Du = \text{Pulse Width} \times \text{PRF}$$

6. Average Power = Peak Power × Duty Cycle

7. Range

$$R = \frac{T_r c}{2}$$

T_r = time (round trip)

c = velocity of propagation

8. Unambiguous Range, Single PRF

$$R_u = \frac{c}{2\ \text{PRF}}$$

PRF = Pulse Recurrence Frequency

9. Unambiguous Range, Multiple PRF

$$R_u = \frac{c}{2(\text{PRF}_1 - \text{PRF}_2)}$$

10. Interpulse Period

$$T = \frac{1}{\text{PRF}} - \tau$$

τ = Pulse Width

11. Velocity of Propagation (velocity of light), c

$c = 2.997925 \times 10^8$ meters/second

c = 186,282 statute miles/second

c = 161,875 nautical miles/second

c = 984 feet/microsecond

Time to travel one (1) nautical mile, round trip,

$= 12.34 \times 10^{-6}$ seconds.

12. Doppler Frequency

$$F_d = \frac{2\ V_r F_o}{c}$$

V_r = Relative Velocity

F_o = Transmitted Frequency

13. Pulse Compression Ratio

Ratio = ΔF × Pulse Width

$$\text{Compressed Pulse Length} = \frac{1}{\Delta F}$$

$$\text{Compressed Pulse Amplitude} = A\sqrt{\Delta F \tau}$$

A is transmitted peak power of pulse.

14. Wavelength, Frequency

$$\lambda = \frac{c}{F}$$

$$F = \frac{30}{\lambda(\text{cm})}\text{ GHz}$$

$$\lambda = \frac{30}{F(\text{GHz})}\text{ CM}$$

c = Velocity of Propagation

F = Frequency

λ = wavelength

15. Receiver Bandwidth

(a) Low PRF Radars

$$BW = \frac{1}{\tau}$$

(b) High PRF Radars (Pulse Doppler)

$$BW\ (\text{each filter}) = \frac{B}{T_i^2}$$

B = Antenna Beamwidth,

T_i = Target Illumination Time

16. Noise Figure of an Amplifier

$$\overline{NF} = \frac{S/N\ \text{In}}{S/N\ \text{Out}}$$

17. Overall Noise Figure of a Series of Amplifiers, 1, 2, and 3.

$$\overline{NF} = \overline{NF}_1 + \frac{\overline{NF}_2 - 1}{G_1} + \frac{\overline{NF}_3 - 1}{G_1 G_2}$$

G = Amplifier Gain

18. Thermal Noise Level

kTB = −204 dBW/Hertz
= −114 dBm/MHz

19. Boltzman's constant

$$k = 1.38 \times 10^{-23}\text{ joule/degree}$$

Radar Bands*

BAND	FREQUENCIES
VHF	138–144 MHz 216–225 MHz
UHF	420–450 MHz 890–942 MHz
L	1215–1400 MHz
S	2300–2500 MHz 2700–3700 MHz
C	5250–5925 MHz
X	8500–10,680 MHz
Ku	13.4–14.0 GHz 15.7–17.7 GHz
K	24.05–24.25 GHz
Ka	33.4–36.0 GHz

*Bands assigned by International Telecommunications Union

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Receiver Protectors: Theory of Operation

Communications & Power Industries, Beverly, Mass.

Introduction

This article will give the reader a basic understanding of receiver protector technology. It discusses the various available types of receiver protector forms, their strengths and weaknesses, and how best to use them. It should be stated at the outset that choosing the best receiver protector configuration for any given application normally involves analyzing the needs of many conflicting operating requirements. Very often, apparent nuances in performance requirements can have a large effect on the final design approach. For those reasons, it is always advisable for the prospective user to consult with BMD's technical experts as early as possible in the design phase of a new application.

Receiver protectors are used in radar systems to protect the radar receiver from unwanted and potentially damaging high power signals. These signals may the reflected remnants of its own radar transmitter output or they may enter the system from outside sources. In any case, these signals are usually on the order of kilowatts to megawatts of peak power -- far too much for any receiver to survive.

In some configurations, the receiver protector may be a singular component which is located in the receive channel, just before the receiver. In other configurations, the receiver protector may also do "double duty" and actually perform the function of the radar duplexer as well. For that reason, this article will begin with a discussion of common duplexing techniques.

Radar Duplexers

Most radar systems (including missile seekers) use one antenna to perform the transmit and receive functions. Since most radars utilize very high power transmitters and very sensitive receivers, a radar using only one antenna requires a "front end" configuration which will alternately "connect" and "disconnect" the transmitter and receiver from the antenna on a pulse to pulse basis.

This is the function of the duplexer. A duplexer, in effect, acts as a very fast, self-actuating SPDT or transmit - receive switch.

The duplexer must be able to perform the following main functions:

- Connect the transmitter to the antenna (and disconnect the receiver) during the sending period.
- Connect the receiver to the antenna (and disconnect the transmitter) during the receive period.
- Provide for adequate isolation between the receiver and transmitter at all times.

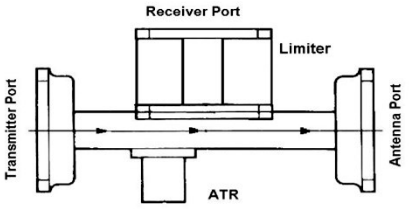
There are three main types of radar duplexers in common use. Each is discussed below.

Branched Duplexers

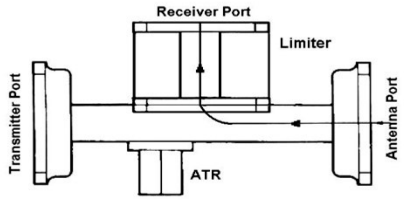
A typical branched duplexer is shown in Figure 1. This type of duplexer came into use during World War II and is still in use today in low cost radars, such as those found on small boats. The branched duplexer may employ one or more ATR (Anti-Transmit-Receive Tubes) and a receiver protector (RP).

During the transmit period, both the ATR and RP activate and present very low impedances at the waveguide walls which allows the transmitted energy to pass through to the antenna with low attenuation. Also, the RP provides additional receiver protection against that portion of the transmit pulse that leaks into the receive channel.

During the receive period, the receive signal passes through the inactivated RP (which is well matched to the transmission line impedance in this state) to the receiver. The ATR is also inactivated at this time. Its position is such that a high impedance is presented to the receive signal in the direction of the transmit channel, thus minimizing the loss of return signal energy in that direction.



Branched Duplexer shown in transmit condition



Branched Duplexer shown in receive condition

FIGURE 1

The main advantages to the branched duplexer are that it is simple, compact, and low cost. The main disadvantage is that it has a relatively limited operating bandwidth (approximately 5%) due to the fact that element spacings are critical.

Balanced Duplexers

Balanced duplexers make use of the features of two 3 dB short slot hybrid couplers, in combination with a switching element, to control the direction of power flow (Figure 2). A dual channel switching element is placed between two hybrids. The "switching element" could be any one of a number of receiver protector types (Pre-TR tube, TR tube, TRL, etc.) depending on the required performance parameters.

During the transmit period, the high power energy will enter at the transmit port and be split in half in each of the two channels. The switching element will activate presenting very low impedance at the dual channel plane of the input hybrid. The phase characteristics of the hybrid are such that the high power energy reflected at this plane will recombine in the antenna port, thus enabling the high power pulse to be directed from the transmitter out to the antenna with low loss. Because the switching element is, itself, a receiver protector, it will provide some amount of receiver protection against energy that would otherwise attempt to pass through to the receiver. Additional protection would be provided by the isolation characteristic of the output hybrid. If, due to the nature of the configuration, more receiver protection is required, a separate receiver protector component could be used in the receive channel just ahead of the receiver.

During the receive period, the receive signal enters at the antenna port, splits in the hybrid and passes through the switching element, which is inactive. This signal then passes through the output hybrid and, due to its phase characteristics, recombines in the receive channel.

Balanced duplexers may be designed in many different configurations, depending upon system requirements. For example, the dual switching element could be an entire TR Limiter. In this case, the switching element would also perform the full receiver protector function. An alternative approach might be to use only a Pre-TR tube as the switching element. In this case, a receiver protector would likely be required in the receive channel. It is also possible to employ ATR tubes as the switching element in a balanced duplexer. The choice of configuration depends on system requirements. BMD's Engineering Department should be consulted to determine the optimum configuration for your system.

The balanced duplexer provides advantages in the areas of power handling capability and operating bandwidth. The main disadvantage is physical size and, potentially, relative port locations. To some extent, this can be ameliorated by clever physical layout.

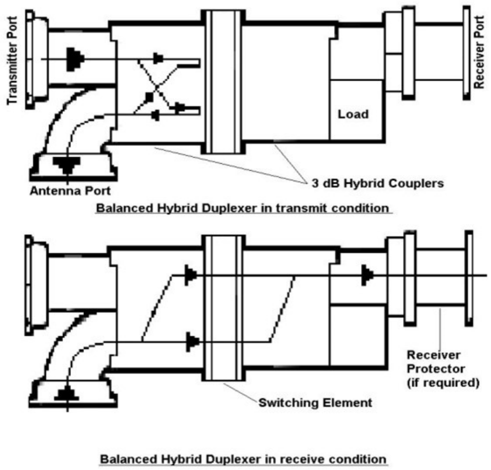
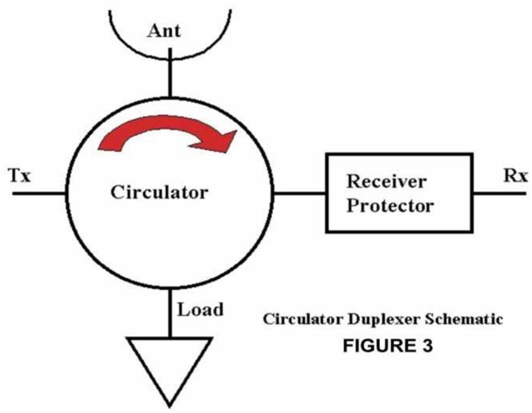


Figure 2

Ferrite Circulators

The ferrite circulator is, perhaps, the most common component employed to perform the duplexing function in most new system configurations. As its name implies, this component's ability to circulate power from port to port allows it to be employed as a duplexer, as shown in Figure 3. Strictly speaking, a duplexer is a three port device. And, therefore, it is theoretically possible to use a single junction, 3-port circulator as a duplexer. However, in most systems, this is not practical due to the fact that, in that case, much of the transmitter power would be reflected back into the transmitter, itself. Therefore, most duplexers are configured with 4-port circulators. This



Circulator Duplexer Schematic
FIGURE 3

may be done either by using two 3-port circulators or by using a differential phase shift circulator, which is an inherently four port device. Differential circulators are capable of much higher power handling than junction circulators. So, in practice, most duplexers are of this type.

In any case, the use of a ferrite circulator as duplexer will almost certainly require the use of a receiver protector in the receive channel. This is true because, depending upon bandwidth and design, the circulator will normally provide only 10 to 20 dB of isolation between the transmitter and receiver. This low amount of isolation is acceptable for only a small number of very low power systems. Therefore, a separate receiver protector is normally required.

Like balanced duplexers, ferrite circulators are relatively broadband components and they tend to be more compact (although this may not always be the case). Although there are exceptions, for most systems, ferrite circulators seem to provide the best balance between physical size, cost, and operating characteristics.

Receiver Protector Technical Terms and Considerations

Before delving into the discussion of the various types of receiver protectors and how they function, it is necessary to have a clear understanding of some technical terms as they relate to this particular product class.

Unlike most microwave components, receiver protectors must function successfully in three completely different operating states. The first two are usually called low power and high power states. In the low power state, the receiver protector is, effectively, inactivated. In this state, the desire is that the component be well matched to the transmission line so that the returning echo signal can pass through to the receiver with as low an insertion loss as possible. In the high power state, the device activates to protect the receiver from unwanted and potentially damaging high power signals. In the third state, the unit is in transition as it reverts back from the high power state to the low power state. This third state is normally referred to as recovery time.

In terms of receiver protector design considerations, the needs of these three states often conflict with one another, thus requiring many tradeoffs in design to achieve overall optimum performance. The next sections will discuss terms and considerations that are important for receiver protector characterization and design.

Low Power State

The low power state is sometimes referred to as the insertion loss state. This is the state that the receiver protector is in during the period of time that the radar system is quiescent and "listening" for target return echoes. In this state, the protector must be as well matched as possible and provide minimum insertion loss. To the system designer, the receiver protector's insertion loss means a dB for dB increase in noise figure. Therefore, in this state, design consideration is focused on achieving the desired instantaneous bandwidth with low VSWR and low absorptive losses. In some cases, such as for mono-pulse systems, the unit's insertion phase characteristic and/or its ability to phase track other units is also important.

One important consideration for receiver protector design in this state is the maximum input power level that the receive signal is expected to have. Receiver protector designs are done with the expectation that this level will not exceed –10 dBm (0.1 mW) peak. Above this power level, the standard receiver protector may be expected to begin to limit, thus compressing the input signal and/or causing unwanted signals such as harmonics or intermod products. For most systems, operation below –10dBm is more than adequate. However, depending upon other performance tradeoffs, it is often possible to design receiver protectors to hold off compression to higher power levels (such as 0 dBm or +10 dBm) when the need requires.

High Power State

The high power state refers to the unit's condition when it is activated and protecting the receiver from high power signals.

Inputs

The first step in high power design is to gain a complete understanding of the nature of all high power signals that could, potentially, be incident in the receive channel. These signals can come from a number of sources in a number of different ways:

- The system's own transmitter under normal operating conditions – This is the amount of power (referred to as "Normal Operating Power") that may be expected to be incident on the receiver protector when the system is operating normally. This is not the full transmitter power. Rather, it is a combination of the transmitter power that leaks through the duplexer to the receive channel plus the amount of power that is reflected into the receive channel as a result of the VSWR mismatch in the antenna channel (See Figure 4). In most systems the component reflected from the antenna port is far greater than that which leaks through the duplexer. If it is not otherwise known or specified the receiver protector will be designed with the idea that the Normal Operating Power is 10 dB below the transmitter power.

- Overload Power – This is the amount of power that would be incident in the receive channel in the event of an arc or catastrophic failure elsewhere in the system. In order to be safe, unless otherwise known, the Overload Power is assumed to be the full transmitter power.

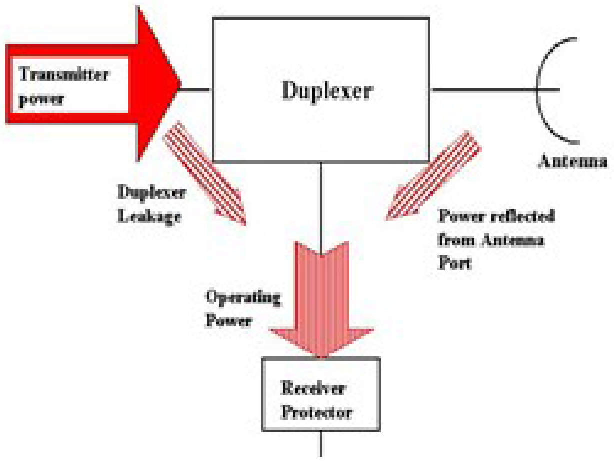


FIGURE 4

- In – band signals that enter the system through the antenna as a result of the emanations of other, nearby systems.

- Out of band signals – Again, these can be the received emanations of outside, nearby systems or they can be present as a result of transients, harmonics, and other out of band signals present on the system's own transmitter signal. This should be investigated very closely by the system designer. It has been the case in the past that such signals, which can be very difficult to detect, may cause the most problems. There are cases on record in which, after the fact, the receiver protectors in some radar systems have had to be replaced by upgraded designs because these out of band signals were not identified during the initial design process and were belatedly discovered to cause system operating problems.

Identification and characterization of all high power signals must be done in terms of their frequencies, peak power, pulsewidth, and duty cycle. Many modern systems operate with widely varying pulse and duty conditions. The receiver protector design engineer needs to know as much about these as possible. As a minimum, knowledge and specification of the maximum power levels and minimum and maximum pulsewidths and duty cycles are required.

Another important aspect of the input power characteristic is the pulse risetime. It takes a finite amount of time for any receiver protector to transition into its high power state. During this transition time, the leakage pulse will be somewhat higher than during the remaining portion of the pulse, when the unit has achieved its maximum protection characteristic. This transition period is referred to as the "spike." Its amplitude and width will depend, to some extent, on the risetime of the input pulse. In general, the spike amplitude will be higher for faster risetime.

Outputs

The output during the high power state is the form and the amount of energy that leaks through the unit as it performs its protection function. The performance characteristics that are relevant in this state are the Breakdown Power, Spike Leakage Power and Energy, and the Flat Power. With the exception of the Spike Energy, these parameters are amplitude parameters which are measured on the leakage pulse. Spike energy is a calculation which is based on the amplitude and width of the spike component of the leakage pulse.

Breakdown Power is, perhaps the most misunderstood of the leakage parameters. It can best be explained in the following way. In the Low Power State, a receiver protector is inactive. Therefore, at low power levels, the output pulse will approximately equal the amplitude and form of the input pulse. As the amplitude of the input pulse increases, the output pulse will, likewise, increase. At some point, depending upon the type of receiver protector, the unit will begin to activate and transition into its protection mode. This transition could be very abrupt (as in the case of a TR tube) or very gradual (as in the case of a diode limiter). In any case, there will come a point where the amplitude of the leakage pulse begins to decline for further increases of the input amplitude. This is the Breakdown Point. The Breakdown Power is, by definition and industry convention, the amplitude of the leakage pulse at the point where further increases of the input power result in a decline in the leakage power. **Therefore, in general, the Breakdown Power is the maximum full pulse leakage power that will be transmitted by the receiver protector for any value of input power within its rated operating power range.** For input power levels beyond the Breakdown Point, the leakage pulse will take the form of a spike and flat. As described in the section above, the spike is that portion of the leakage pulse which is at the leading edge and is the result of the finite amount of time it takes for the receiver protector to go into hard limiting. The flat is the main portion of the leakage pulse, which is exhibited after maximum limiting has been realized. Figure 5 shows these relationships in a general way.

Depending upon the type of receiver protector, pulse risetime, etc., the spike width will typically range between 2 and 20 nanoseconds. Spike energy is calculated as the area under the spike power - time curve. In practice, the convention is to treat the spike as a triangle and measure its width 3 dB below the peak amplitude. The spike energy is then calculated as:

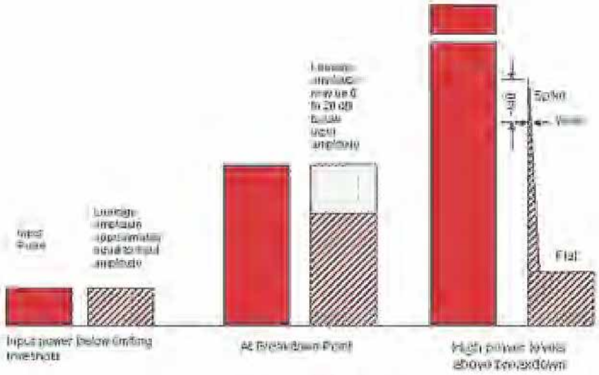
Spike Energy = (Spike Power - Specified Flat Power) multiplied by the spike width

This may be expressed either in ergs or nanojoules. In the past, spike energy was an important leakage parameter. However, for most modern systems, the spike amplitude requirement is so low that, in most cases, the energy is a non-issue as far as receiver protection is concerned. Very often, there is no point in even specifying it.

Clearly, a complete and accurate understanding of the power range over which the receiver protector will be expected to operate is very important for proper design and specification. If the unit is always expected to operate well above its breakdown point, then the Breakdown Power parameter may be of no practical concern. However, if the normal operating point of the receiver protector will be at, or close to, the breakdown point, then the Breakdown Power may the most important leakage parameter.

Recovery Time

In the Recovery Time state, the unit is in the process of transitioning back to the Low Power state from the High Power state. Recovery time measurement begins at the cessation of the transmitter pulse. This means the point on the trailing edge of the transmitter pulse where the power has dropped below the level at which limiting would be expected to occur. For all practical purposes, this means that the recovery time measurement begins at the point in time at which the input power has dropped to zero. See Figure 6.



Input – Output Characteristic Waveforms

FIGURE 5

The end point of the recovery time measurement may vary from product to product and is often based on the requirements of the system application. How ever, lacking any other specification, the standard industry definition is that recovery time is measured from the cessation of the transmitter pulse to the point at which the unit has returned to within -3dB of its quiescent insertion loss value.

The following key points regarding recovery time are relevant:

- Recovery time is a relative measurement. The end point of the measurement is made relative to the quiescent insertion loss value. For example, if the insertion loss of a particular unit is 0.5 dB, and the recovery measurement is specified to the 3 dB point, then the absolute insertion loss at the point of measurement will be 3.5 dB.

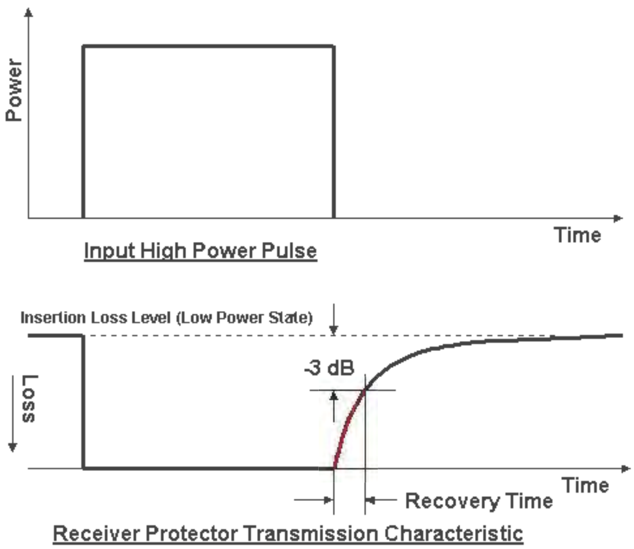
- Although amplitude recovery is, by far, the most common parameter specified, it is also possible to specify phase recovery when required.

- The need to meet a certain value of recovery time is fundamental in terms of choosing the best design approach for a particular application. Designing for a very fast recovery time can adversely affect other parameters. Therefore, it is very important to specify the recovery time as carefully as possible.

• As is discussed below, the various receiver protector technologies exhibit widely different recovery characteristics. In general, however, the recovery time for any given unit is a function of the incident power and pulsewidth. Higher power and wider pulsewidths mean longer recovery times.

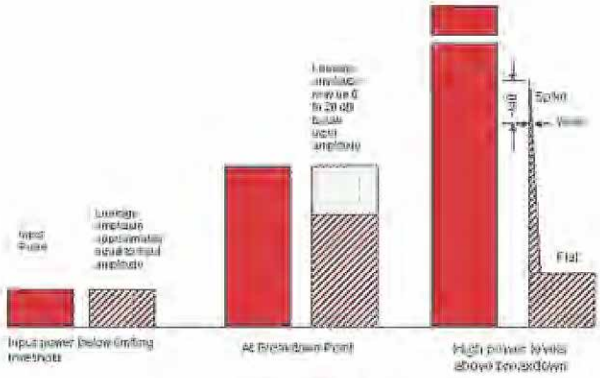
• Although a receiver protector should be designed to successfully handle and protect against all power levels up to its rated overload power, recovery time is usually specified only up to the maximum Normal Operating Power
.

• Clearly, from the discussion above, it can be seen that control of the trailing edge of the transmitter pulse is critical for fast recovery time requirements. A slow trailing edge can significantly delay the start of the recovery process.



Recovery Time

FIGURE 6



Input – Output Characteristic Waveforms

FIGURE 5

One final point: Although recovery time is a function of input power, this must be looked at on an element by element basis within the receiver protector. Each element within the receiver protector may have a different recovery characteristic and some elements may be protected by other elements. Therefore, the interaction between each of the elements in a receiver protector, as it relates to recovery time, is complex. For the end user, this may mean that, in some designs, the power level at which maximum recovery is observed may not be the maximum Normal Operating Power. In fact, in some designs, the maximum recovery time will be at power levels well below that point. This is another reason why a complete understanding of the expected operating power input characteristic is so important in order to optimize receiver protector performance.

Receiver Protector Design and Operation

This section will give a brief overview of the basic receiver protector technologies. It will begin with a discussion of active and passive receiver protectors, followed by a discussion of the various technologies used in receiver protector design and their operating characteristics.

Active vs. Passive

Simply stated, a passive receiver protector is one which is self-activated and requires no external control to perform its protection function. An active protector is, basically, a switch. Typically, SPST's or SPDT's are used to realize this type of design.

There are also hybrid designs, called "quasi-active", which employ a combination of passive and active elements.

All other things being equal, the passive approach is, by far, the preferred approach for any application. It will give more reliable protection over a much wider range of potential threats than is possible with an active protector. It is totally automatic and self-activating. It will perform its protection function against external signals (any for which it is designed) even if the radar is turned off.

Typically, the main reasons for using an active receiver protector are that, in some cases, it may be possible to achieve an all solid state design, faster recovery time, or in the case of an extremely low leakage requirement (less than +10 dBm).

However, normally, these benefits are more than adversely offset by the following risks, which are inherent in active receiver protector design:

- If the control signal fails, the receiver protector will fail. This is an additional factor which will reduce the inherent reliability of this approach.

- Active receiver protectors can only protect against signals which are synchronized with the transmitter pulse. Thus, there will be no protection for non-synchronous, external signals.

No protection is provided if the system is turned off. In some cases, it may be possible to design a receiver protector which, while providing basic receiver protection passively, may incorporate an active capability to enhance performance under normal operating conditions. This is also a reasonable alternative. However, active or quasi-active receiver protectors which require external control to perform the basic protection function are not recommended unless there is no other way to achieve desired overall performance and there is low or, preferably, no possibility of threats that may take advantage of the weaknesses inherent in this design approach.

Basic Receiver Protector Technologies

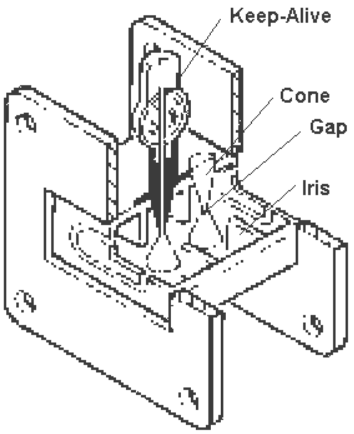
The best way to understand receiver protector technology is to realize that a receiver protector is usually not a singular component. In fact, it is normally an assembly of two or more elements, each of which employs different basic technologies. There are five basic technologies in common use today: TR tube, Pre-TR tube, ferrite limiter, diode limiter, and multipactor. Each technology has its own set of strengths and weaknesses. For any given design, the challenge for the engineer is to employ that combination of technologies which gives the best overall performance in light of the applicable requirements for that application. A discussion of each of the five technologies follows.

TR Tube

The TR tube is the most common receiver protector technology in use today. The construction of the TR tube includes one or more resonant filter sections in a piece of waveguide which is sealed at both ends with waveguide windows. Each filter section is a relatively high Q parallel L-C circuit. Truncated cones form the capacitive element and irises or posts the inductive element. These can be seen in Figure 7. The waveguide is then evacuated and back-filled with a gas, or combination of gasses, at below atmospheric pressure.

In the low power state, the TR tube is a bandpass filter whose characteristics are controlled by the dimensions and spacing of the filter elements and the windows. These dimensions are adjusted so as to realize minimum VSWR and insertion loss over the band of interest. The presence of a high power signal will cause an arc between the cone gaps. This will ionize the gas in the region of the cones, thus causing most of the power to be reflected from the device. If the power is high enough, the input window will fire as well, providing additional protection.

Gas discharges are inherently unstable. For that reason, some means of "priming" the gas is necessary in order to ensure stable firing on each and every pulse. The earliest TR tube designs employed



TR Tube with Keep-Alive
FIGURE 7

every pulse. The earliest TR tube designs employed a small electrode, called a "keep-alive", for this purpose. This is shown in Figure 7. The keep-alive was placed down the middle of one of the cones, which had been hollowed out for this purpose. The application of approximately -1000 VDC on the keep-alive would result in a constant trickle current between the electrode and the cone surface, thus providing free electrons for gas priming. This arrangement works well. However, in addition to the inconvenience of requiring a power supply, the keep-alive also limits useful tube life and is a source of a small amount of excess noise.

In order to overcome these problems, radioactive priming was developed. This method employs a very small radioactive source, which is enclosed within the TR tube body. The radioactive source is positioned so as to illuminate one of the cone gaps, thus providing a source of electrons for stable firing. Virtually all modern TR tubes use radioactive priming. It is a very safe technique which eliminates the need for the large power supply, makes the unit totally passive, and greatly increases tube life. It also eliminates the excess noise that the keep-alive had introduced. Please see the CPI/BMD website (www.cpii.com/bmd/rpfaq1.htm) for additional information.

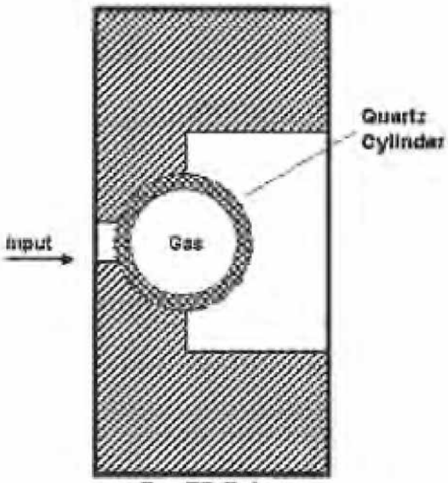
The salient characteristics of the TR tube are as follows:

- It provides a great deal of protection at a relatively low cost. For many applications it is unquestionably the best value.
- In addition to its performance within its fundamental operating frequency range, the TR tube also will provide a great deal of protection at out of band frequencies. This additional protection is realized as an inherent characteristic of the technology and comes at no extra cost.
- It is a moderate power handling device. Power handling is primarily limited by the temperature rise on the glass input window due to the gas discharge. This can be increased significantly by employing a ceramic window where necessary.
- The TR tube has a relatively long recovery time. Recovery time is directly related to input power and pulsewidth and inversely related to operating frequency.
- The TR tube has a limited operating life. Life is a function of the gas volume as well as other parameters such as power and duty cycle. A gas reservoir may be employed to extend operating life. For additional information, please see the CPI/BMD website (www.cpii.com/bmd/line3.htm).

• The TR tube has a very great dynamic operating power range and is very forgiving should its power handling rating be exceeded. The nature of the technology is such that its attenuation increases with increasing power. Thus, once activated, its flat leakage power remains quite constant for increasing input power levels.

Pre-TR Tube

The Pre-TR tube is also a gas plasma limiter and operates on the same principle as the TR tube



Pre-TR Tube

FIGURE 8

described above. The difference is that, in the Pre-TR tube, the gas is enclosed in a quartz tube (See Figure 8). This provides two advantages:

- Quartz has a much higher melting point than glass. Thus, a Pre-TR tube will handle much more power than a TR tube.
- Enclosing the gas entirely within a quartz cylinder allows for the use of gasses that cannot be used in a body-filled TR tube. These gasses have much faster recovery times.

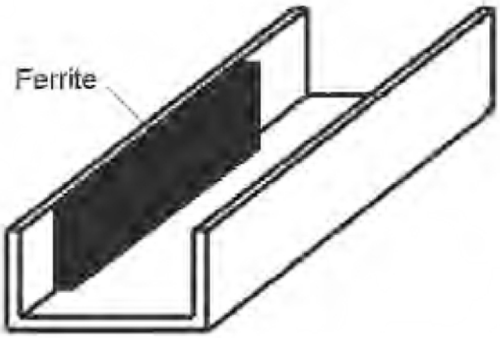
Also, this technology exhibits very low insertion loss (typically less than 0.1 dB).

The main disadvantage to the Pre-TR is that its low Q circuit will not provide as much protection, either in-band or out of band, as does the TR tube. Thus, the Pre-TR is employed as a low loss "pre-limiting" device at the input of a receiver protector assembly which allows the overall assembly to handle virtually any amount of power. The pre-TR must be followed by other receiver protector devices (Diode Limiter or TR Limiter) which will "clean up" the leakage to levels which are safe for the receiver.

Ferrite Limiter

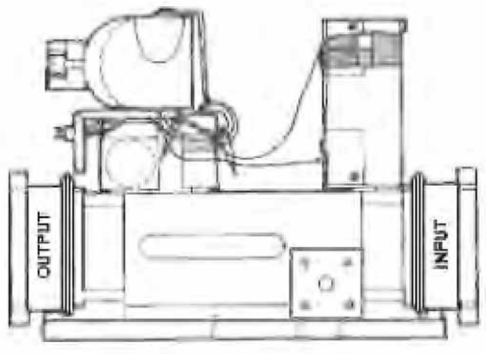
The ferrite limiter is an all solid state product. It employs ferrite material which is mounted along one or both waveguide walls (See Figure 9). The ferrite is magnetically biased with permanent magnets. The electrons in the ferrite will precess around the magnetic field lines. In the low power state, this device looks like a dielectrically loaded piece of waveguide. However, when the input power reaches a critical threshold, the RF energy will couple into the precession motion causing the ferrite to absorb power as the RF passes down the waveguide. The absorbed energy is converted to heat.

A ferrite limiter is a medium power handling device, suitable for use in applications where the average power is relatively low. Its main advantages are:
Its main disadvantages are that it exhibits relatively high insertion loss, can handle only a moderate amount of power and its performance is very sensitive to changes in ambient temperature. Also, its leakage is too high for a receiver to sustain. Thus, a ferrite limiter may be employed as a pre-limiting device in a receiver protector assembly where very fast recovery time is required. It is normally followed by a diode limiter.



Ferrite Limiter
(Cutaway View)

FIGURE 9



Multipactor
FIGURE 10

The main advantages to the multipactor are that it handles a large amount of average power and has virtually instantaneous recovery time (typically less than 10 nanoseconds). It is a limited life product and, as mentioned above, does require external DC bias. Like the other technologies discussed above, it must be followed by a diode limiter to clean up the leakage to levels which are safe for the receiver.

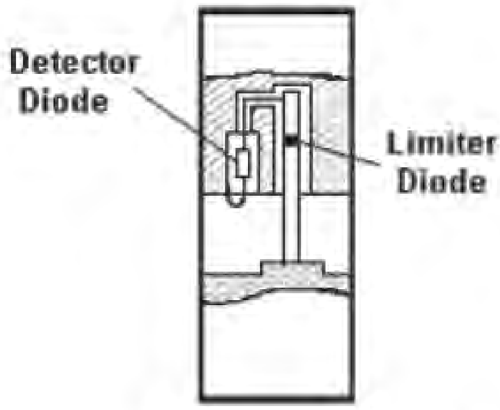
Diode Limiter

Since its inception in the late 1960's, the diode limiter has become fundamental building block of virtually every modern receiver protector design. To a large extent, this is because, other than an active (keep-alive primed) TR tube, it is the only receiver protector form that is capable of adequately protecting a modern receiver. All of the other devices described above are pre-limiting devices that must be followed by a diode limiter to achieve adequate protection.

The diode limiter's advantages are many:

- It is an all solid state product which has no operating life limit
- It does not require priming of any kind.
- It may be passive or active
- It may be designed as a multifunction component so that the benefits of additional functionality
- May be realized with a minimum size and insertion loss.
- May be realized in any type of transmission line

The main factor which restricts a diode limiter's usefulness is its power handling capability. In the early days, these devices were capable of handling only a few tens of watts of peak power. However, over the years, great strides have been made. Today, diode limiters are being designed as stand-alone receiver protectors into applications that once would have required the additional use of other pre-limiting technologies. Diode limiter power handling is, primarily, a function of operating frequency, peak power, and pulsewidth.



Diode Limiter
FIGURE 11

A typical single stage waveguide diode limiter is shown in Figure 11. The diode is mounted in a tunable choke section. In the low power state, the diode is not conducting. The choke section is tuned so as to provide the desired bandpass characteristic insertion loss and VSWR. In the high power state, the RF causes the diode to conduct. This detunes the circuit, thus causing a high reflection.

To complete the "DC" circuit, the diode, itself may be returned directly to ground or through a detector diode. Detector diodes may be used to provide a better current source for high power handling or to reduce leakage. depending upon bandwidth, a single diode stage may be expected to provide 15 - 20 dB of protection. Additional stages may be cascaded as necessary to achieve the desired amount of attenuation. Of course, insertion loss will increase as each stage is added.

The onset of limiting will occur at relatively low power levels, typically 0 to +10dBm. Thus, the leakage power will be low enough to adequately protect a modern receiver. Additionally, the diode limiter may be actively controlled to achieve greater power handling or lower leakage.

There are two main disadvantages with diode limiters. First, unlike the other technologies discussed above, they are not very forgiving. If subjected to even a slightly higher power level than their design rating, they may be degraded or destroyed. Second, they generally do not provide much out of band protection. Therefore, in order to avoid problems when considering the use of a diode limiter as a stand-alone receiver protector, it is incumbent upon the user to very carefully profile all of the expected in-band and out-of-band energy that may be incident upon the limiter.

The Receiver Protector Assembly

As noted above, most receiver protectors are not stand-alone components. They are actually assemblies which utilize two or more of the basic building block technologies discussed above.

Most receiver protectors will employ a diode limiter, as the basic element, to achieve the desired protection levels. Beyond that, depending upon the specific system requirements, one or more of the pre-limiting technologies may be employed. This is typically done either to achieve the desired overall power handling capability or recovery time.

Typical combinations are:

- TR Limiter -- Combination of TR tube and Diode Limiter
- Pre-TR, Limiter -- Combination of Pre-TR tube and Diode Limiter
- Pre-TR, TR Limiter -- Combination of Pre-TR tube, TR Tube, and Diode Limiter.
- Ferrite-Diode Limiter -- Combination of Ferrite Limiter and Diode Limiter

The many tradeoffs which must be considered when designing a receiver protector are too complex to describe in a brief article. Each application involves a different set of design criteria. Therefore, each application requires its own special receiver protector design. CPI's engineering staff should be consulted during the design phase of any new system or upgrade.

One final note. Although comprised of individual building blocks, the receiver protector assembly should always be treated as a singular component. In other words, the building blocks should never be separated physically in the system design. The receiver protectors with the best performance are, invariably, those in which the various building blocks are made to work together. Electrical spacing between elements is critical. And, some tuning is a normal part of receiver protector manufacture. The component parts should, in general, not be separated.

How to Specify a Receiver Protector

The following page contains a blank specification sheet which may be used to describe a new receiver protector requirement. We have tried to make the specification sheet as inclusive as possible. However, there may be other subtle issues which relate to a particular system application. Some of the information requested (such as phase tracking or STC) may not apply to a particular application. However, there is a minimum amount of information that is required for any application. These items are noted by an asterisk (*) on the specification sheet.

In general, and in order to be able to choose the best design configuration possible, the receiver protector design engineer should be given as complete an understanding as possible about the prospective environment in which the device will be expected to operate. This should be done as early as possible in the design phase of any new system.

Communications & Power Industries

Receiver Protector Description

	MIN	MAX	UNITS

Electrical

- Frequency
- Peak Power (Overload)
- Peak Power (Normal Operating)
- Pulsewidth(s)
- PRF(s)
- Leakage Power:
  Spike
  Flat
- Recovery Time
- Insertion Loss
- VSWR
- Phase Matching (if required)

Multifunction Capability (if desired)

Variable or Programmed Attenuation -- Specify amount, type, control method, available bias supplies, etc.

Excess Noise Generator -- Specify amount, control method, etc.

Mechanical

Overall Size
Connectors
Transmission Line

Environmental

Internal Waveguide Pressure
Operating Temperature
Altitude

With a history of producing high quality products, we can help you with your receiver protectors.
Contact us at BMDMarketing@cpii.com or call us at +1 978-922-6000.

Magnetron Theory of Operation

Communications & Power Industries, Beverly, Mass.

A magnetron is a high power microwave oscillator in which the potential energy of an electron cloud near the cathode is converted into r.f. energy in a series of cavity resonators similar to the one shown in Figure 1. As depicted by the low frequency analog, the rear wall of the structure may be considered the inductive portion, and the vane tip region the capacitor portion of the equivalent resonant circuit. The resonant frequency of a microwave cavity is thereby determined by the physical dimension of the resonator together with the reactive effect of any perturbations to the inductive or capacitive portion of the equivalent circuit. This is an important point and will be recalled later.

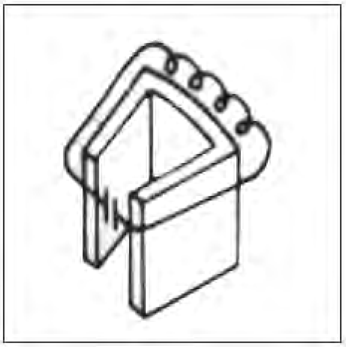


Figure 1 Magnetron Resonator

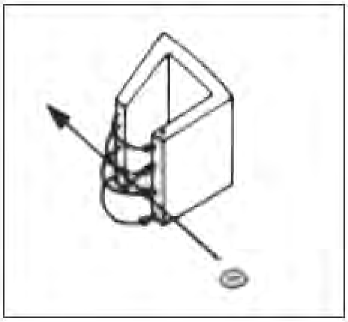


Figure 2 Energy Transfer Mechanism

In order to sustain oscillations in a resonant circuit, it is necessary to continuously input energy in the correct phase. Referring to Figure 2, if the instantaneous r.f. field, due to steady state oscillations in the resonator, is in the direction shown, and, an electron with velocity was to travel through the r.f. field such that the r.f. field retarded the electron velocity by an amount, the decrease in electron energy will be exactly offset by an increase in the r.f. field strength.
In a magnetron, the source of electrons is a heated cathode located on the axis of an anode structure containing a number of microwave resonators. See Figure 3.

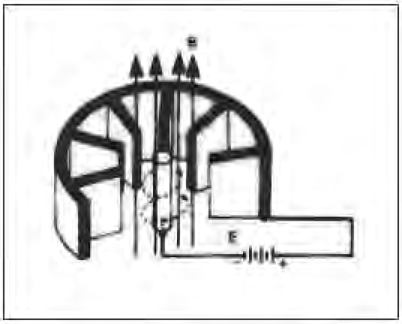


Figure 3 Anode/ Cathode Structure

Electrons leave the cathode and are accelerated toward the anode, due to the dc field established by the voltage source E. The presence of a strong magnetic field B in the region between cathode and anode produces a force on each electron which is mutually perpendicular to the dc field and the electron velocity vectors, thereby causing the electrons to spiral away from the cathode in paths of varying curvature, depending upon the initial electron velocity a the time it leaves the cathode.

As this cloud of electrons approaches the anode, it falls under the influence of the RF fields at the vane tips, and electrons will either be retarded in velocity, if they happen to face an opposing r.f. field, or accelerated if they are in the vicinity of an aiding r.f. field. Since the force on an electron due to the magnetic field B is proportional to the electron velocity through the field, the retarded velocity electrons will experience less "curling force" and will therefore drift toward the anode, while the accelerated velocity electrons will curl back away from the anode.
The result is an automatic collection of electron "spokes" as the cloud nears the anode (see Figure 4), with each spoke located at a resonator having an opposing RF field.On the next half cycle of r.f. oscillation, the RF field pattern will have reversed polarity and the spoke pattern will rotate to maintain its presence in an opposing field.

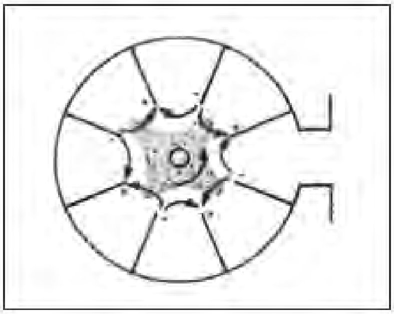


Figure 4 Electron spokes in a magnetron

The "automatic" synchronism between the electron spoke pattern and the RF field polarity in a crossed field device allows a magnetron to maintain relatively stable operation over a wide range of applied input parameters. For example, a magnetron designed for an output power of 200 kW peak will operate quite well at 100 kw peak output by simply reducing the modulator drive level.

You will note that the instantaneous RF field pattern, shown in Figure 4, has exactly 180° of phase change (radians) between every adjacent pair of resonator vanes and is therefore called the mode. Other oscillation patterns (modes) could be supported by the anode structure; however, the mode pattern will product the maximum number of electron spokes, and therefore the maximum transfer of energy to the RF field, i.e., highest efficiency mode. Assuring that the magnetron maintains mode oscillation, to the exclusion of all other modes, is one of the prime concerns of the magnetron designer.

The mode controlling techniques in a conventional magnetron, e.g., electrically connecting alternate vane tips together to assure identical potential, employing geometrical similarities between alternate resonators to favor mode oscillation, will adequately maintain mode control in conventional magnetron anodes. Due to mode separation parameters, the number of resonators in conventional magnetron anodes is limited and rarely exceeds 20 resonator vanes. Since the physical size of each resonator is fixed by the desired output frequency, the overall size of the anode is limited, thereby restricting cathode dimensions and heat dissipation capacity. The result is that at higher frequencies the conventional magnetron has reduced power output capability, lower reliability and a shorter operating lifetime than can be realized at the lower microwave frequencies.

The distinguishing feature of the coaxial magnetron is the presence of a high Q stabilizing cavity between the anode and the output waveguide.
The theory of operation presented for a conventional magnetron applies equally to the anode-cathode region of the coaxial structure. However, the coaxial stabilizing cavity affords very significant improvements in overall magnetron performance.

Superior mode control: Operating the cavity in the TE011 mode, and slot coupling alternate anode resonators to the cavity, produces anode control of such intensity as to permit the construction of coaxial magnetrons with many times the number of resonators that can be employed in a conventional type magnetron. This means lower cathode emission density, lower life and higher reliability.

Reduced RF fields in the anode: Whereas all stored energy in a conventional is confined to the vane resonators, in a coaxial magnetron approximately 85% of the total stored energy is contained in the stabilizing cavity. This means reduced RF field intensity at the vane tips, and less tendency to arcing.

Improved frequency stability: The redistribution of stored energy in the coaxial magnetron makes the high Q stabilizing cavity the prime determiner of magnetron output frequency. This means a lower pushing figure, a lower pulling figure, improved spectrum and reduced spurious emissions.

Improved tuning: In the conventional magnetron, tuning is accomplished by inserting inductive pins in the rear portion of each resonator, or by capacitive loading in the vane tip region.

Both techniques represent an adverse perturbation to the natural geometry of the resonators which often results in power output variation with tuning, starting instabilities, increased susceptibility to arcing and a generally reduced operating lifetime for the magnetron. In contrast the coaxial magnetron is tuned by moving a noncontacting plunger in the stabilizing cavity (see Figure 5). The result is a tuning characteristic with no discontinuities, broad tunable bandwidth, and none of the disadvantages resulting from perturbations in the anode-cathode region.

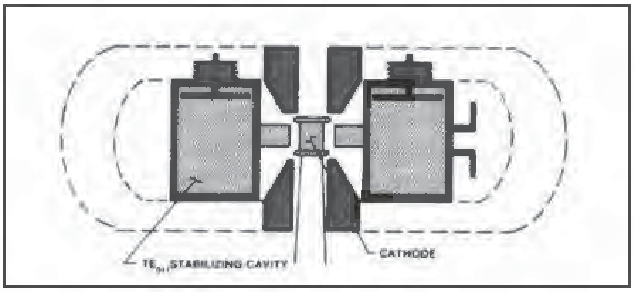


Figure 5: Coaxial Magnetron

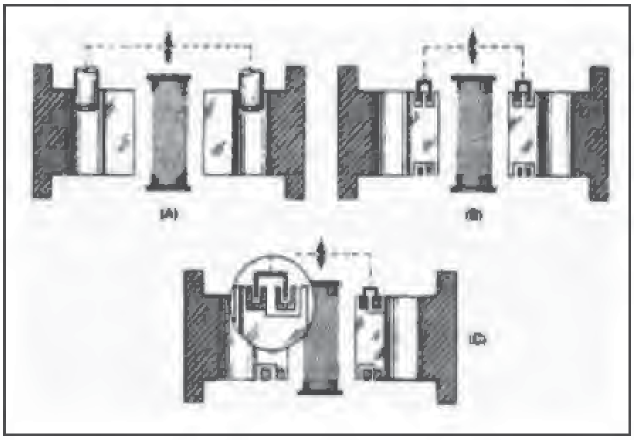


Figure 6: Three types of tuning schemes used in conventional magnetron resonator systems

Typical Magnetron Parameters

The following is a discussion and explanation of typical magnetron specification parameters.

Thermal Drift

At the time high voltage is first applied to a magnetrton, the thermal equilibrium of the device is suddenly altered. The anode vanes being to heat at the tips due to electron bombardment and the entire anode/cathode structure undergoes a transient change in thermal profile. During the time required for each part of the magnetron to stabilize at its normal operating temperature, the output frequency of the magnetron will "drift." The curve of output frequency vs. time during the period following initial turn on is called the "Thermal Drift" curve. Generally speaking, the maximum drift occurs during the first few minutes after turn on, and slowly approaches equilibrium over a period ranging from 10 to 30 minutes depending upon the structure mass, power output, type of cooling and basic magnetron design. Thermal drift curves across a variety of magnetron types operating at the same frequency and output power may differ radically from each other. Each type is usually designed for a particular purpose and subtle differences in the internal magnetron configuration can produce radical differences in the thermal drift curve.

It should be noted that a thermal drift effect will occur not only at initial turn-on, but whenever the peak or average input power to the magnetron is changed, e.g., a change of pulse duration, PRF or duty. Figure 7 shows typical thermal drift curves for a particular magnetron plotted as a function of duty. The dotted line indicates the effect of a change in duty from .001 to .0005 after thermal equilibrium has been initially achieved.

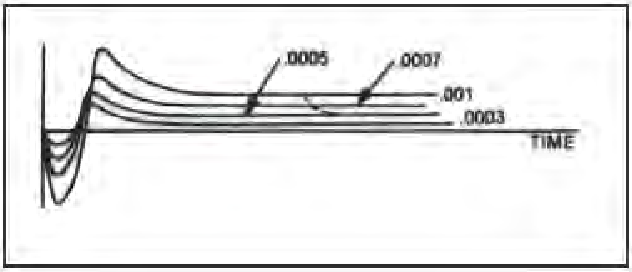


Figure 7: Typical thermal drift curves

Temperature Coefficient

After the thermal drift period has expired and a stable operating frequency has been achieved, changes to ambient conditions which cause a corresponding change in the magnetron temperature will produce a change in the output frequency. In this content ambient changes include cooling air temperature or pressure in air cooled magnetrons; mounting plate temperature in heat sink cooled magnetrons; and flow rate or temperature in liquid cooled magnetrons.

The change in magnetron output frequency for each degree change in body temperature, as measured at a specified point on the outside surface of the magnetron body, is defined as the Temperature Coefficient for the magnetron and is usually expressed in MHz/oC. For most magnetrons the temperature coefficient is a negative (frequency decreases as temperature increases) and is essentially constant over the operating range of the magnetron.

When estimating magnetron frequency change due to temperature coefficient, keep in mind that the temperature coefficient relates magnetron frequency to body temperature and there is not necessarily a 1:1 relation between body temperature and, for example, ambient air temperature. In addition, for airborne systems, the cooling effect of lower air temperature at altitude may offset by a corresponding reduction in air density.

Pushing Figure

The pushing figure of a magnetron is defined as the change in magnetron frequency due to a change in the peak cathode current. Referring back to the earlier theory discussion, we noted that the

the resonant frequency of a vane resonator is determined by its mechanical dimensions plus the reactive effect of any perturbation. The presence of electrons in the vicinity of the vane tips affects the equivalent capacitance of the resonator by an amount proportional to the density of the electrons and, since electron density is similarly related to peak pulse current, changes in pulse current level will produce changes in output frequency. The pushing figure expressed in MHz/Amp is represented by the slope of a frequency vs. peak current curve plotted for a particular magnetron type.

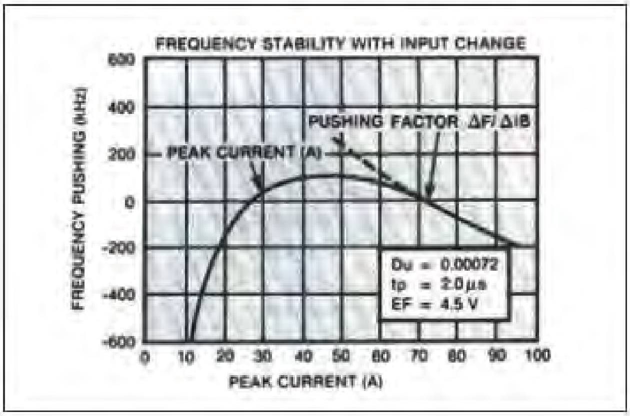


Figure 8: Typical thermal pushing curve

From the curve of Figure 8, it can be seen that the slope is not a constant over the full range of operating current. It is therefore meaningless to talk about a specific value for the pushing figure unless one also specifies the range of peak current over which it applies.

It should be noted that since power output is proportional to peak current in a magnetron, the pushing figure at peak current levels well below the normal operating point of the magnetron are usually unimportant because the power output at these current levels is low.

The primary importance of a low pushing figure near the magnetron operating point is that the pushing figure will determine intrapulse FM, and thereby will affect the spectral quality of the transmitting pulse.

The Pulling Figure is defined as the maximum change in output frequency that results when an external, fixed amplitude mismatch, located in the output waveguide, is moved through a distance of one half wavelength relative to the magnetron. Stated somewhat less formally, the pulling figure is a measure of a magnetron's ability to maintain a constant output frequency against changes in load mismatch.

During the design of a magnetron, the degree to which the output waveguide is electrically coupled to the internal resonator structure is selected to optimize certain performance parameters. Strong coupling increases output power and efficiency but also increases time jitter and sensitivity to changes to load mismatch. Generally, the coupling is chosen to obtain the best compromise between efficiency and stability.

Depending upon the phase relation between incident and reflected power at the output port of a magnetron, reflected power will appear as a reactance across the coupling transformer and effectively change the degree of coupling. Therefore, using a fixed mismatch and varying its distance from the magnetron output port will cause the magnetron frequency to shift and the output power to vary concurrently.

To standardize the measurement values, pulling figure is normally measured using a fixed 1.5:1 VSWR; however, in very high power magnetrons a 1.3:1 VSWR is often used. When referring to the pulling figure of a magnetron one should always indicate the VSWR value used in the measurement.

Frequency Agile Magnetrons

Frequency agility (FA) in regard to radar operations, is defined as the capability to tune the output frequency of the radar with sufficient speed to produce a pulse-to-pulse frequency change greater than the amount required to effectively obtain decorrelation of adjacent radar echoes.

It has been firmly established that FA, together with appropriate receiver integration circuits, affords reduced target scintillation/glint, improved ability to detect targets in a clutter environment, elimination of 2nd time around echoes, and improved resistance to electronic countermeasures, over that possible with a fixed frequency or tunable radar system. It is important to note that, with the exception of ECM resistance, increasing the pulse-to-pulse frequency spacing will increase the amount of system performance improvement that can be realized to a maximum occurring at the point where full pulse echo decorrelation is obtained (nominally 1/tp). Pulse-to-pulse frequency spacings greater than this critical value produce no further increase in system performance, and, in fact, may result in a performance decrease due to the large "IF" inaccuracies arising from the need for the AFC to correct larger pulse to pulse frequency errors.

On the other hand, as regards resistance to electronic jamming (ECCM), the greater the pulse-to-pulse frequency spacing, the more difficult it will be to center a jamming transmitter on the radarfrequency to effectively interfere with system operation.

Each radar system application must be considered separately to determine which FA parameters will best satisfy the particular need. Just as the FA requirements of each radar differ, so also do the mechanisms differ for optimally producing the required agility parameters. No single tuning scheme has been found which will universally satisfy the requirements of every FA application.

For this reason, CPI produces a broad range of FA tuning mechanisms for coaxial magnetrons; each mechanism offering the optimum combination of parameters for a particular application.

Frequency Agile Magnetron Classes

Frequency agile magnetrons fall into four classes:

- **Dither Magnetrons (D)** -- Output RF frequency varies periodically with a constant excursion, constant rate and a fixed-center frequency.

- **Tunable/Dither Magnetrons (T/D)** -- Output RF frequency varies periodically with a constant excursion and constant rate.The center frequency may be slowly tuned by hand or by external servomotor drive to any point within the tunable band.

- **Accutune(tm) Magnetrons (A)** -- Output RF frequency variations are determined by the waveshape of an externally generated, low level, voltage signal. With appropriate selection of a tuning waveshape, the Accutune magnetron combines the features of dither and tunable/dither magnetrons.

- **Accusweep(tm) Magnetrons (As)** -- Our best and most versatile tuning system. The output RF tuning rate and waveshape are infinitely variable within the design limits of each device. Customer inputs are typically any waveform from random to square wave and a + 5 volt command.

All CPI frequency-agile magnetrons provide a reference voltage output which is an accurate analog of the instantaneous RF output frequency. This signal greatly simplifies automatic frequency control of the system local oscillator frequency. The analog voltage is produced either by a self-generating, permanent magnet device requiring no external drive, or by a precision resolve or LVDT (Linear Voltage Displacement Transducer) acting in conjunction with one of CPI's solid-state frequency readout modules.

The Accutune and Accusweep magnetrons operate with a servo loop, feedback control, tuner drive and thereby utilize CPI's solid-state servo amplifier together with the frequency readout module.

Frequency Agile Magnetrons

permanent magnet device requiring no external drive, or by a precision resolve or LVDT (Linear Voltage Displacement Transducer) acting in conjunction with one of CPI's solid-state frequency readout modules.

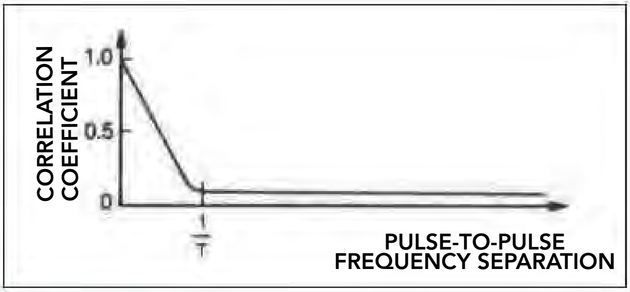
The Accutune and Accusweep magnetrons operate with a servo loop, feedback control, tuner drive and thereby utilize CPI's solid-state servo amplifier together with the frequency readout module.

Agile Magnetron Design Considerations

At first glance one might conclude that the largest frequency change at the highest rate will give the best radar performance. Unfortunately, this is not a true statement.

There have been many separate theoretical studies and comprehensive experiments performed to establish the relationship between radar performance improvement and pulse-to-pulse frequency difference. An understanding of the theoretical basis for the conclusions reached in these efforts is important. In order to preserve the continuity of our discussion, we will show only the results of these studies in this section.

Effective performance improvement is achieved when the frequency difference between radar pulses is large enough to eliminate any correlation between the return echoes. A plot of correlation coefficient versus pulse to pulse frequency difference is shown below.



Using this relationship, one finds that a radar operating at a 0.5 μs pulse duration will have efficient decorrelation between target echoes if pulses differ in frequency by at least 2 MHz. Note that the required frequency separation is a function only of the pulse duration.

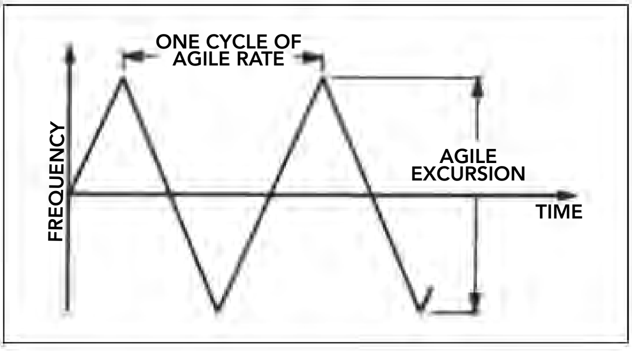
According to the plot of the figure, as frequency separation increases above the value 1/T, pulse decorrelation continues to improve, however, the amount of improvement is negligibly small for large increases in pulse frequency separation. In practical situations, the improvement in decorrelation obtained by increasing the frequency separation to values greater than 1/T is usually more than offset by other factors. For example, as pulse-to-pulse frequency difference increases, the receiver circuitry needed to assure stable LO (Local Oscillator) tracking also increases, in both complexity and physical size. The accuracy necessary for LO tracking relates directly to the IF bandwidth needed to pass the resultant video signal. Any increase in IF bandwidth, needed to offset inaccuracies in LO tracking, will reduce overall receiver sensitivity and tend to defeat the original purpose. Experience has shown that if one designs for pulse-to-pulse frequency separation as near as possible to, but not le ss than, 1 /T (where T is the shortest pulse duration used in the radar) optimum system performance will be achieved. Experimental studies have shown that performance improvement varies as N, where N is the number of independent (decorrelated) pulses integrated within the receiver circuitry, up to a maximum of 20 pulses.

It should be noted that the number of pulses, which can be effectively integrated, cannot be greater than the number of pulses placed on the target during one scan of the antenna and, therefore, the antenna beamwidth and scan rate become factors which must also be considered in determining the integration period of the radar.

Frequency Agile Magnetrons

Using the above, a design value for Agile Excursion can now be expressed in terms of radar operating parameters.

Agile Excursion = N/T



Agile Excursion: The total frequency variation of the transmitter during agile operation.

Agile Rate: The number of times per second that

the traansmitter frequency traverses the agile excursion and returns to its starting frequency.

NOTE: There are two excursions of the frequency band for each cycle of agile rate.

Where N is the number of pulses placed on the target during one radar scan, or 20 whichever is smaller, and T is the shortest pulse duration used in the system.

Determination of the required agile rate is now required. The object is to traverse the full agile excursion range in the time needed to transmit the number of pulses on the target during one antenna scan.

Example:

Assume one desires to add agility to a radar having the following operating parameters:

Pulse duration - 0.25, 0.5 & 1.0 µSec.
Duty Ratio - 0.001
Pulses on target - 16 per scan

Using the formulas derived above one obtains:

Agile excursion = N/T = 16/0.25 = 64 MHz
Pulse to pulse frequency separation = 1/T = 1/ 0.25 = 4 MHz
PRR = Duty / T = 0.001/ (0.25x10-6) = 4000 Hz
Time for 16 pulses = 16/ 4000 = 0.004 Sec
Agile Rate* = 1/(2x0.004) = 125 Hz

* The 2 in the denominator accounts for the fact that two excursions through the agile frequency range occur during each cycle of agile rate.

The agile parameters used above were derived using clutter reduction as the prime objective. Elimination of target scintillation requires the satisfaction of one additional constraint, namely that the agile excursion in MHz should be at least equal to 150/D, where D is the characteristic distance, in meters, between major reflecting points on the target cross section. For most practical situations, an excursion which satisfied the requirements of clutter reduction will usually be sufficient to satisfy the requirements of target scintillation also.

Further information and data on agile coaxial magnetrons can be obtained by requesting the Frequency Agile Magnetron Story booklet.

Beacon Magnetrons

Beacon magnetrons are small conventional magnetrons with peak power output less than 4 kW and average power output of less than 5 watts. Typically, they weigh 8 ounces.

The technical requirements for this class of magnetrons demand precise frequency control of the magnetron. The temperature stability factor is of great importance since it allows frequency control without additional electronics in the total radar transponder. The magnetron itself requires tunability but must have the properties of a fixed frequency magnetron after adjustment and locking. Thus, the techniques of temperature compensation must work over a band of frequencies. Also, frequency stability is essential over typical temperature ranges of -65°C to +100°C, and typical shock of 100 G, and vibration environments of 15 G (generally those of missile and aircraft electronic systems). Construction of beacon magnetrons can be simplified to contain five basic building blocks. They are the anode, tuner, cathode, output, and magnet. These may be arranged in block diagram fashion as shown in Figure 1.

The following sections will discuss each of the five parts of the magnetron.

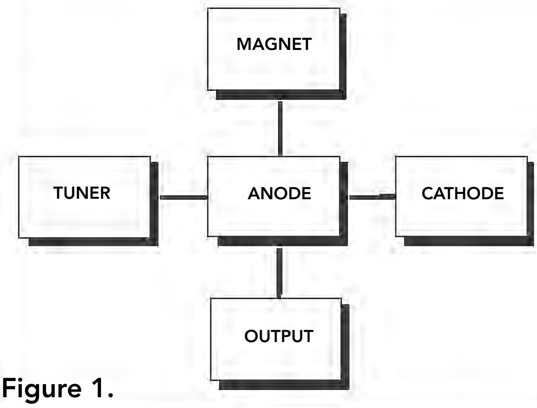


Figure 1.

Anode

The anode is the foundation of the magnetron circuit. It generally consists of an even number of microwave cavities arranged in radial fashion as shown. There are three possible anode configurations:

- **Hole and slot**
- **Vane tip**
- **Rising sun**

Figure 2.

Advantages and disadvantages of each type involve consideration of operating characteristics and construction techniques. The hole-and-slot and vane type normally have every other cavity strapped to each other by a conducting metal strip. The hole-and-slot type and the rising sun type are usually machined by hobbing methods out of solid copper stock. The vane type is generally made up of individual vanes assembled and brazed into a support ring. This requires assembly labor and brazing fixtures.

The anode provides the basic magnetron with its operating frequency. The central area provides C (capacitance) and the outer perimeter contributes L (inductance) to fulfill the relationship

$$F = 1/(2\pi \sqrt{LC})$$

Each anode is cold checked for "Q" - value and frequency. This involves general microwave impedance and resonance measurements techniques.

Beacon Magnetrons

Tuner

The tuner is the device which provides some magnetrons with the ability to vary from the basic frequency determined by the anode. Tuners fall into three basic categories:

- **Capacitive**
- **Inductive**
- **Combination of both**

A fundamental description of each is shown in Figure 3. The capacitive type is so named because in it a tuning member is introduced into the anode cavities affecting the E-field and hence the capacitance of the anode. This type can be constructed of either metal (copper) fingers which are inserted between adjacent anode vanes in the central portion of the anode or a dielectric or metallic ring which is inserted into the anode between its central vane straps.

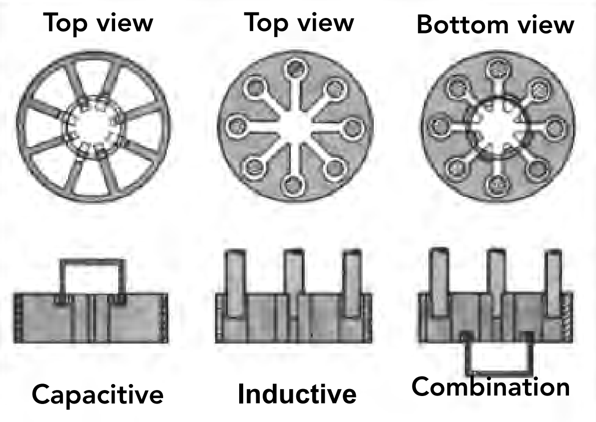


Figure 3.

The inductive type tuner is much the same as the capacitive but the tuning member enters the cavities in the back wall region where the H-field and Inductance are affected. The combination of the two is a complicated affair which affects both L and C and is used where extremely wide tunability is required. The attachment must necessarily involve a bellows or diaphragm arrangement in order to allow for mechanical movement and still contain the necessary vacuum envelope.

Figure 4 shows a simplified capacitive tuner-anode assembly. The magnetron tuner is generally composed of two parts, internal and external. The internal portion described above is that part which is enclosed by the vacuum envelope. The external portion is attached to the internal portion by some mechanical means and provides the drive mechanism to actually move the tuner the required distance to change L and C and therefore change frequency.

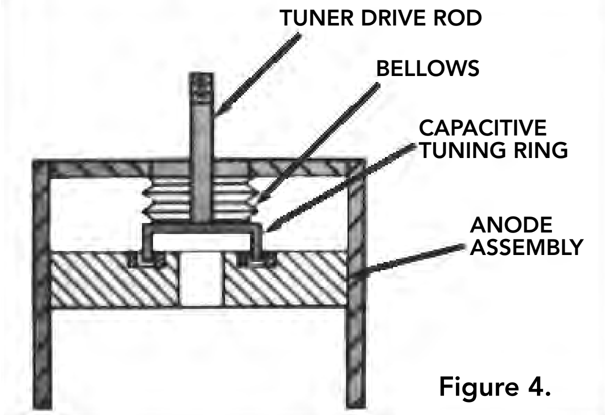


Figure 4.

Cathode

The cathode of a magnetron is the part which makes the magnetron an active device. This provides the electrons through which the mechanism of energy transfer is accomplished. The cathode is usually located in the center of the anode and is made up of a hollow cylinder of emissive material surrounding a heater.

Beacon Magnetrons

A cross- section of a simple magnetron cathode is shown in Figure 5. Many types of magnetron cathodes have been developed; each designed for a specific advantage. The fabrication of magnetron cathodes is carried out in very meticulous and precise environments. Each braze and weld must be inspected for completeness in order not to upset the designed heat flow characteristics. Magnetron cathodes are designed to operate at particular temperatures and owing to the phenomenon called "back bombardment" they cannot tolerate wide variations in construction and assembly techniques. As a further check on operating temperature of cathodes used in high reliability magnetrons, the cathode-heater assembly alone is evacuated and operated at a predetermined heater voltages and the cathode temperature checked with an optical pyrometer. This technique reveals any flaw or defect in construction prior to the time the cathode is actually assembled in a magnetron.

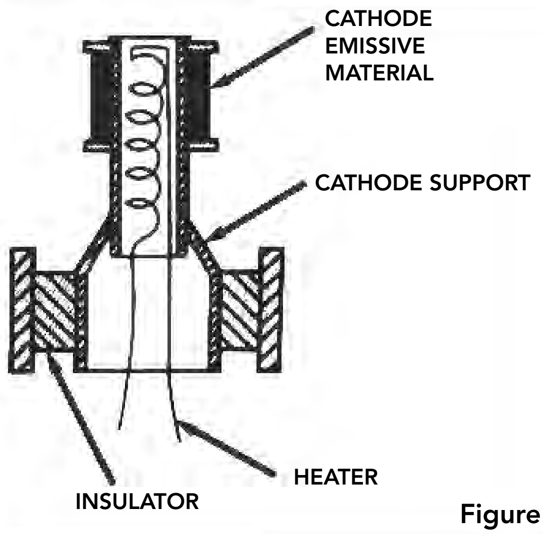


Figure 5.

The next step in the magnetron's construction is to attach the cathode to the tuner-anode assembly. This procedure also requires extreme care in the axial line-up and orientation of the cathode and anode. Any eccentricity between anode and cathode will produce variations in magnetron operation and can cause serious internal arcing or malfunction. Figure 6 shows a simplified cathode-tuner-anode assembly.

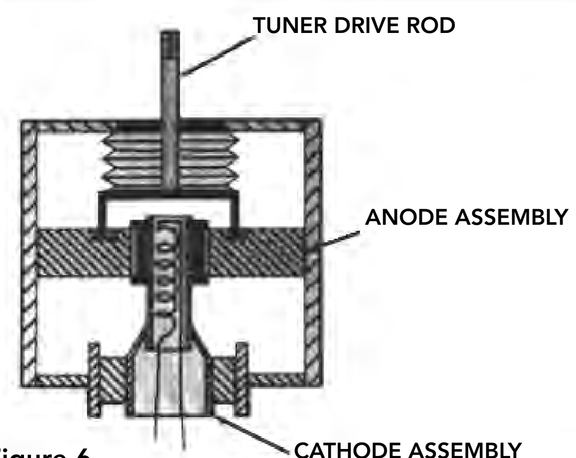


Figure 6.

Output

The output circuit in a magnetron is that portion of the device which provides the coupling to the external load. The RF energy produced in the cavities may be coupled by either a coaxial or waveguide type of output. Figure 7 shows both types. The coaxial design involves either a probe, a loop or a tapped vane coupling to the anode and concentric coaxial line through the vacuum envelope to the output connector. Suitable matching sections must be included along the line to provide for the correct impedance transformations and coupled load which appears at the anode. The center conduction of the coaxial line is insulated and supported along its length by either glass or ceramic beads.

Beacon Magnetrons

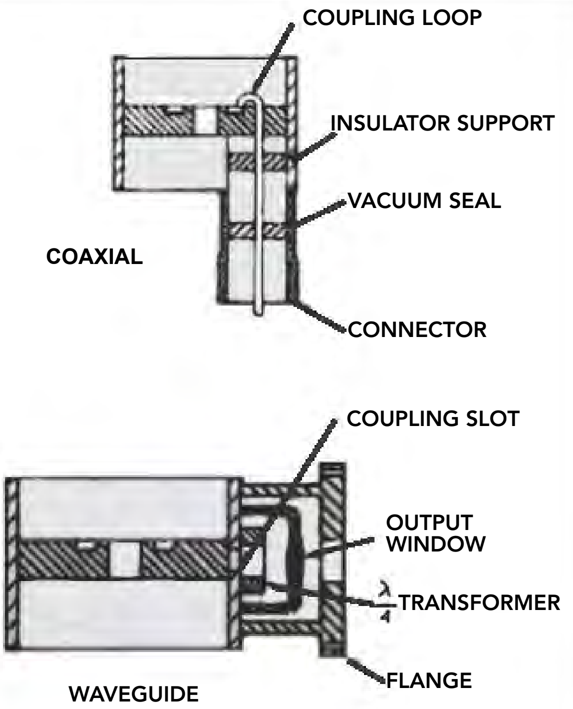


Figure 7.

The waveguide type of output is made up of a coupling slot in the back wall of a cavity, a 1/4 transformer, a vacuum seal window (either glass or ceramic) and a section of output waveguide. The sizes of the coupling slot and 1/4 transformer are determined by frequency, bandwidth and load coupling considerations. The type of vacuum seal window used is determined by the power output and pressurization requirements. Placement of the output window is extremely critical as far as position along the line is concerned, because any high VSWR which may be reflected back from the load that will cause a voltage maximum at the window will cause overheating and subsequent rupture of the vacuum seal.

Magnetic Circuit

The magnetic circuit associated with the magnetron is necessary to provide the crossed field type of operation which provides for the synchronization of the electron trajectories. The magnetic circuit shown here is composed of an external permanent magnet and associated internal pole pieces. The type and composition of the permanent magnet vary with particular requirements of field strength and stability. Size and weight are also important considerations. The transmission and focusing of the magnetic field from the external permanent magnet to the interaction gap between the anode and cathode is accomplished by the use of high permeability metal pole pieces shaped to focus the field lines as sharply as possible.

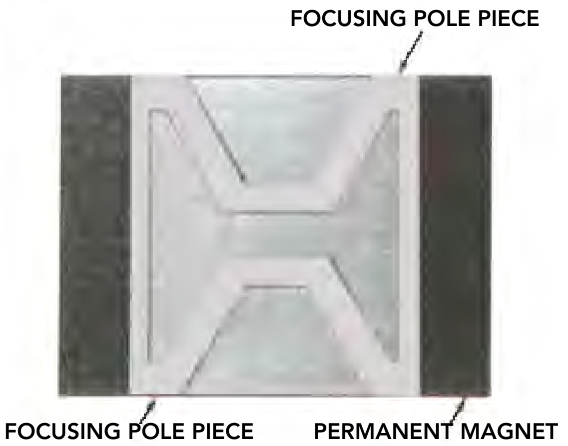


Figure 8.

With a history of producing high quality products, we can help you with magnetrons and many other radar products.

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That's Life: Considerations Relating to Receiver Protector Life

Dick Bilotta
Communications & Power Industries, Beverly, Mass.

Some types of microwave receiver protectors are limited life products. This is an area which is often not well understood by those who use them. Nevertheless, it is an important factor to take into consideration when choosing a receiver protector during system design. Failure to do so could result in needless extra operational and maintenance costs as well as the possible failure of a component at a critical moment. This article will give the reader a better understanding of the underlying concepts of receiver protector life and how they apply to actual performance.

To begin, not all types of receiver protectors have limited life. Only those products that contain some form of plasma limiter (TR tubes, TR Limiters, Pre-TR tubes, etc.) have a limited life. All-solid-state products (Diode limiters, switches, ferrite limiters, etc.) have no natural wear-out mechanism and are not part of this discussion.

TYPES OF LIFE

There are two types of life: operating life and storage life. Operating life is the number of hours that the unit can be expected to function in the system under its normal operating conditions before its performance degrades to the point where it no longer meets the specifications. The actual operating life of any tube depends on many different factors and environmental conditions. These are discussed below. Storage life refers to the period of time that a new, unused unit can be stored with no degradation in performance.

OPERATING LIFE

As a plasma limiter is operated in the system, certain internal changes take place. These changes cause the device's performance to slowly degrade over time. The changes are as follows:

- Gas cleanup - Gas molecules become absorbed in the waveguide walls, causing a drop in pressure. As the gas is used up, the high-power characteristics of the limiter will slowly degrade. Breakdown power, spike leakage power and recovery time will all increase slowly over time. Eventually, they will exceed their specification limits. Gas cleanup will occur in any plasma limiter – TR tube or pre-TR tube.
- Sputtering – TR tubes have an additional potential failure mechanism associated with the input window. As the window fires under high power conditions, microscopic particles of the metal frame are chipped off. Some of these particles fall onto the input window. This causes a buildup of metal on the input window glass over time. Eventually, this will degrade the unit's low power tuning characteristics. Insertion loss will increase.

Both of the above processes occur simultaneously any time the unit is subjected to high RF power conditions. The rate at which they progress depends upon a number of factors. These include operating power and duty cycle, the type and amount of gas with which the unit is filled, and the device's mechanical configuration.

A third life-limiting factor on older TR tubes is the high voltage keep-alive. This will degrade over time as well, as the TR tube is used. This degradation will adversely affect breakdown power and spike leakage. Often, the keep-alive is the element which will degrade at the fastest rate.

The above processes are very complex. Only a life test under actual operating conditions will give a meaningful indication of how long a particular design may be expected to last. Having said that, because of its long experience with this technology, CPI is able to make rough estimates of minimum operating life for various product types.

In most cases, for plasma limiters without a keep-alive, the gas cleanup occurs at a much faster rate than sputtering. Therefore, this factor is of most concern. One common way to offset the gas cleanup process is to incorporate a gas reservoir into the design. The gas that is depleted in the main body, is continually replaced with gas from the reservoir, thus extending overall operating life.

Also – in some applications, it is possible to set the incident power under normal operating conditions to a level which is below the firing threshold of the plasma limiter. In such applications, the plasma limiter fires only under overload conditions. This will greatly increase the useful operating life of a receiver protector, often by orders of magnitude.

STORAGE LIFE

The two factors that control storage life are the integrity of the gas vacuum seal (i.e. braze joints, microscopic leaks, etc) and the half life of the radioactive source. No long-term studies have ever been conducted which would provide sufficient data to accurately predict storage life. However, anecdotal evidence, based on actual tests, indicates that a properly manufactured hard brazed TR tube, with good seal integrity, can reasonably be expected to meet its specifications after at least 15 - 20 years on the shelf, unused.

Most plasma receiver protectors also use a small amount of radioactive material for priming. The radioactive half-life is well known. Most products contain enough radioactive material at manufacture such that they will last for many half-lives, thus making this particular design element the least likely to cause any storage life problems. Having said that, this could become an issue in those applications where the requirements are such that only a minimum amount of radioactive material may be used.

END OF LIFE INDICATIONS

In the course of normal use, a plasma limiter does not fail suddenly. Instead, its performance slowly degrades over time as it is used. This is good because it gives the system operator the ability to monitor the unit's condition and replace it before it degrades to the point where other parts of the system are affected. By definition, we say that a unit has reached its "end of life" when it fails to meet one or more of its specifications. Some specifications allow for a certain amount of degradation before the "end of life" is declared.

There are three typical end of life indications:

1. Long recovery time
2. High leakage power (Usually spike and breakdown power)
3. High insertion loss

Items 1 and 2 are caused by gas cleanup; item 3 is caused by sputtering on the input window.

Since, for most applications, gas cleanup usually proceeds at a faster rate than sputtering, long recovery time and high leakage are usually the first indications of end of life.

From the radar operator's point of view, the following system characteristics are some indications that may indicate that a plasma receiver protector is approaching, or has reached, its end of life:

- **Minimum** detectable range increases (Long recovery time, high leakage)
- Maximum detection range decreases (High insertion loss)
- High signal to noise ratio (High loss, high leakage)
- Radar fails to detect targets (High leakage may have destroyed the receiver protector and/ or following components)

REPLACEMENT AND LIFE CYCLE COST ISSUES

Having an understanding of the expected operating life of a plasma receiver protector is important because these devices naturally wear out and need to be replaced and/or refurbished from time to time. On the one hand the system operator would not want to replace the device any more often than is necessary. On the other, you don't want to wait until it fails completely as such failure could cause other system components, such as the receiver, to be destroyed. So, the system operator needs to balance these two concerns. There are ways to do that.

Receiver protectors tend to be one of the more expensive items in most microwave front ends. For obvious reasons, there is a natural tendency for the radar manufacturer to want to procure the least expensive design. But this is not always the best approach from a life-cycle cost point of view. It really depends on the nature of the radar system and what its operating situation is expected to be.

From the receiver protector point of view, during the design phase of any system, there may be opportunities to make design choices (both for the receiver protector as well as the system, itself) which could significantly affect the expected operating life of a plasma-based receiver protector. While it is true that designing an extended life receiver protector will likely increase its initial procurement cost, it is equally true that this increase in cost will be more than offset by the savings achieved in not having to replace it so often over the operating life of the radar system.

These are important design considerations that can and should be discussed with the receiver protector manufacturer during the design phase of any new system.

CONCLUSION

The purpose of this article has been to give the radar designer and user a brief primer on basic issues relating to the operating and storage life of plasma-based microwave receiver protectors. Every application is unique. Operating life is a very complex issue which is affected by many aspects of the product design as well as the operating environment to which it is subjected in actual system use. For those reasons, it is beyond the scope of this article to make any generalizations about how much actual operating life may be expected by plasma receiver protectors. Having said that, this is an important area of consideration that should take place during the design phase of any new system in order to achieve a receiver protector design which is optimized for use in that system.■

For more information on receiver protectors, contact CPI at ElectronDevices@cpii.com or call us at +1 (978) 922-6000.