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TEST

RADAR SYSTEM
TEST AND EVALUATION

By

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Textbook for use in teaching test and evaluation of radar systems, including theory of operation, operating characteristics, and test methodology. Topics include basic radar theory, radar parameters, radar cross section, pulse radar, doppler radar, tracking radar, doppler beam sharpening, radar hardware and test equipment, and test methods.

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RADAR SYSTEM TEST AND EVALUATION

1.0 Introduction

The word "radar", first adopted in 1940, is an acronym for the words "radio detection and ranging." Those words adequately expressed the purpose of the "radar" devices of that time. In order to understand the nature of modern radar, however, a broader definition must be devised.

In the broad sense, a radar is a device which generates an electromagnetic field with properties designed to "exercise the system" in a manner which makes "observable" quantities of interest to the observer. Quantities of possible interest are the presence, position, velocity, size, shape, motion, and reflectivity of an object in the field. Note that the "object" can be a target structure or vehicle, the surface of the earth, atmospheric disturbances, an electronic transponder, or even the vehicle carrying the radar itself. Typical radar applications are target sensing (detection, location, tracking, viewing, and identification), relative velocity measurement, navigation, weather avoidance, ground mapping, terrain avoidance/following, and weapon delivery. The factors which determine the "system" are the characteristics of the radar, the quantities to be observed (application), the environment, and the physical laws governing the propagation of electromagnetic waves. The environment includes terrestrial and atmospheric features, background noise, and possibly intentional jamming. The physical laws governing electromagnetic wave propagation

1.1

are those which give rise to the phenomena of reflection, refraction, absorption, diffraction, and wave interference.

Viewed in the context of a system parameter identification problem, it is evident that an ideally designed radar will not merely pulse its carrier, but will employ variations in every possible field parameter in an effort to "exercise the system" in a manner which will make most visible those quantities of interest. Tne variable parameters of the transmitted electromagnetic wave are its amplitude, its frequency or phase, its polarization, and its direction of propagation. Ideally, all of these parameters should be continuously varied in an optimal fashion. The resulting transmitted signal might be described as a sort of wailing, stuttering scream.

The parameter-varying techniques and devices available to the radar designer are waveform modulation (AM, FM, PPM, PWM, PCM, spread spectrum, etc.), autocorrelation (timing), cross-correlation (signal recognition), antenna design (directivity and polarization), multiple antennas, and multiple antenna sites. The limitations on the use of these techniques are those of hardware (size, weight, power, cost, etc.), wave propagation (physical laws), and strategy (operational contraints, security, etc.). It is the task of the radar designer to perform the necessary tradeoffs to reconcile requirements with limitations. It is the task of the radar evaluator to determine the extent to which the design tradeoffs compromise performance and whether or not the design requirements were met.

The term "radar" is usually taken to imply radio frequency electromagnetic waves. Optical phenomena (visible, ultraviolet, and infrared radiation), however, are also electromagnetic waves, and, for that reason most of what we say about radio-frequency "radar" also applies to such devices as the laser ranger. The differences that do exist are a result of the fact that different physical phenomena predominate in different portions of the electromagnetic frequency spectrum.

In the following material, the reader will be provided with the necessary information to allow him to design experiments (tests) which will reveal the significant characteristics of the radar unit being evaluated. Sufficient theoretic background will be provided to allow him to understand the design of the radar and thereby anticipate its likely performance characteristics (strengths and weaknesses). Only in this manner can an adequate test plan be devised. The difficulties in designing an adequate test are, in large part, due to the ever-present funding and time limitations. The tester virtually never has enough time or funding to perform exhaustive testing. For that reason, he must be able to concentrate on those tests which will reveal the likely performance weaknesses of the subject radar. Only by understanding the radar design and its implications can he identify the appropriate areas of concentration for a given mission.

The first section will present the necessary background theory. The second section will discuss the pertinent characteristics of various types of radars. The third section will present the radar system per-

formance characteristics to be experimentally determined and the methods
for their measurement. A separate section will present the non-performance
(environmental, electromagnetic compatibility, hardware viability, main-
tainability, reliability, and crew safety) characteristics to be deter-
mined, the general methods for their determination, and the applicable
specifications and references.

1.4

2.0 Radar Theory

2.1 Basic Radar Theory

A radar system functions by radiating electromagnetic waves into "space" and determining the nature of the echoes reflected from objects in the resulting field. The echo returned to the radar by a reflecting object will be a facsimile of the transmitted signal, delayed in time by the two-way propagation time of the wave, shifted in frequency by the doppler shift due to relative radial motion of the target, and altered in amplitude and direction of propagation by the reflectivity of the target and the characteristics of the intervening medium.

By "time-coloring", (modulating), the outgoing waveform, the system can recognize corresponding portions of that waveform in the returning waveform and thereby determine range to the target by measuring elapsed time. By utilizing directional transmitting and/or receiving antennas, the bearing (azimuth and elevation) to the target may be determined by observing the direction from which the returning signal is greatest. An alternate, and more precise, method of determining bearing utilizes two receiving antennas. By measuring the difference in phase between the signals observed at the two antennas, the system can determine the bearing to the target. This type of angle determination is sometimes called interferometry because interference between the two signals is the basis of measurement. A radar using this technique is sometimes called a monopulse radar since theoretically it can determine target bearing from a

single pulse. By measuring the difference between the transmitted and received frequencies (the doppler shift), the system can determine the relative, radial component of velocity of the target. These three quantities: range, bearing, and velocity constitute the basic measureable characteristics of the target. Other characteristics, such as size, shape, and aspect angle, can be derived from refinements of the basic measurements.

An alternate view point concerning the extraction of target information from radar returns is based upon determination of the rates of change of return signal amplitude (A) and phase (ϕ) with respect to time (t), position of observation (x), and transmission frequency (f). That is:

(1) $\left(\frac{\partial \phi}{\partial f}\right)_{t,x}$ = Range

(4) $\left(\frac{\partial A}{\partial f}\right)_{t,f}$ = Size

(2) $\left(\frac{\partial \phi}{\partial x}\right)_{t,f}$ = Angle

(5) $\left(\frac{\partial A}{\partial x}\right)_{t,f}$ = Shape   [2.1.1]

(3) $\left(\frac{\partial \phi}{\partial t}\right)_{x,f}$ = Velocity

(6) $\left(\frac{\partial A}{\partial t}\right)_{x,f}$ = Rotation

These partial derivatives can be re-stated in the following terms. (1) When frequency is changed, the phase of the return signal will change by an amount proportional to target range. (2) As the position of observation is changed, the direction of maximum rate of change of phase will be in the direction of the target. (3) When the phase of the return with respect to that of the transmitted signal is observed as a function of time, the time rate of change of phase (doppler frequency shift) will be

2.2

proportional to the relative, radial velocity of the target. (4) When frequency is changed, the amplitude of the return (radar cross section of the target) will change as a known function of the ratio of the dimension of the target to the wavelength, thus allowing determination of the size of the target. (5) When the target is observed simultaneously from several positions of observation, the variation in return amplitude with position yields information about the shape of the target. And (6), when the return amplitude is observed as a function of time, information is obtained about target rotation. This rather unusual viewpoint concerning extraction of information from radar returns is highly useful in that it yields an insight into the fundamental measurements required of a radar. For example, when it is realized that the determination of target bearing involves measuring the rate of change of phase with respect to change of position of observation, it is immediately clear why a large antenna (large position span) has high angular resolution.

2.3

2.2 Pulsed Radar

The simplest type of ranging radar is that which alternately transmits and receives. Not only does the pulsing time-color the outgoing waveform, thereby providing for determination of range, but the alternate transmit and receive periods avoid the problem of interference between outgoing and incoming signals (target returns). A simplified block diagram of such a radar is shown in Figure 2.2.1. The oscillator produces a radio frequency sinusoidal signal. This signal is amplitude modulated (pulsed) by the modulator when triggered by a signal from the timer. The resulting pulse train (periodic bursts of sinusoidal radio frequency waves) is then amplified by the transmitter, (a power amplifier), and routed by the transmit/receive switch to the antenna, where it is radiated into space. The returning signal (echo) is intercepted by the antenna and routed by the transmit/receive switch to the receiver, where it is differentiated from other (unwanted) signals, on the basis of frequency, and amplified. The detector demodulates the incoming waveform, thereby recovering the envelope of the pulsed waveform. The envelope of the pulses is then used by the timer to determine elapsed time between transmit and receive, and thus range to the target.

A slightly expanded block diagram for a radar receiver/detector is shown in figure 2.2.2. In this diagram, a new element has been introduced: the signal mixer. A mixer is essentially a device that multiplies two signals together, in this case the incoming RF signal and the output of the local oscillator. The result of the mixing process is to convert the

2.4

Pulse Radar, Block Diagram

Figure 2.2.1

2.4a
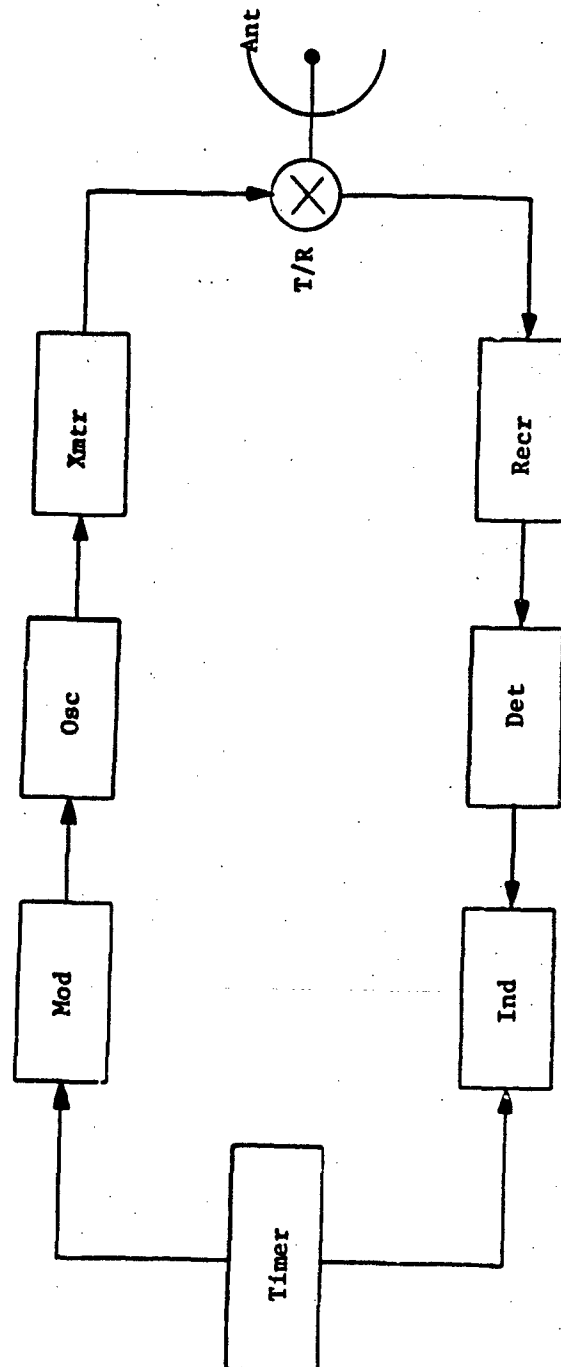
Superheterodyne Receiver

Figure 2.2.2

Ant ω_0

Tuner

ω_0

RF Amp

ω_0

Osc

$\omega_0 + \omega_{if}$

Mixer

ω_{if}

IF Amp

ω_{if}

Det

video

Video Amp

Video Output

2.4b
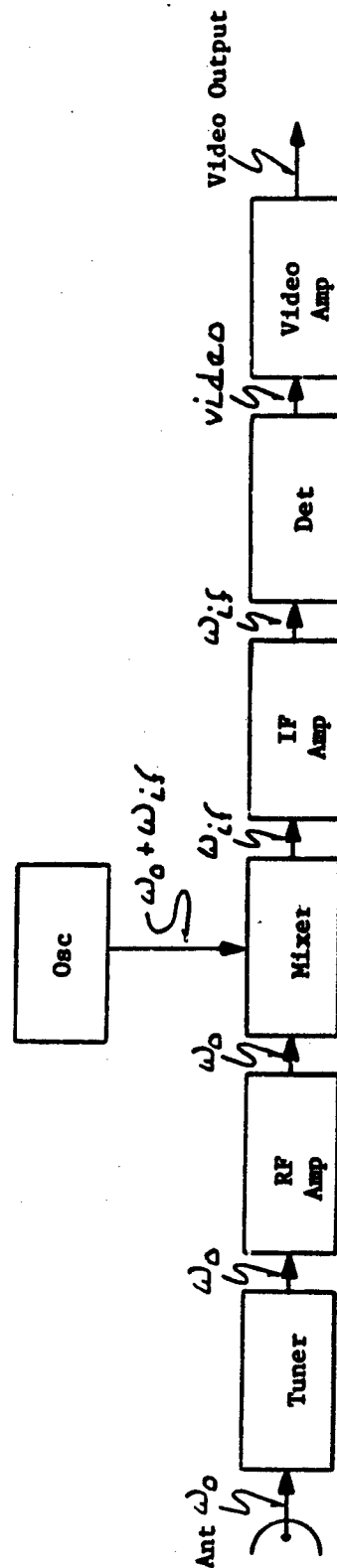
incoming signal carrier frequency from the outgoing radio frequency (RF) to a much lower intermediate frequency (IF). This conversion is performed entirely for convenience in signal processing to follow.

The circuit of Figure 2.2.2 operates in the following manner. The radar return signal is intercepted by the antenna and passed through a tuned circuit which discriminates against all signals not of the proper carrier frequency. The selected RF return is then amplified by an RF amplifier. In the mixer, the RF return is "mixed with" (multiplied by) a signal generated by the local oscillator. Since the oscillator signal frequency is offset from the return RF frequency by an amount equal to the intermediate frequency, the output of the mixer has the same information as did the original RF signal, but with an intermediate frequency carrier. This IF signal is then amplified and passed through an envelope detector. The output of the detector is a signal identical to the envelope of the original IF signal, with no carrier. This video signal can then be amplified and processed as required.

A pulse train waveform is shown in Figure 2.2.3. In that figure are defined the basic parameters associated with a pulsed waveform. In Figure 2.2.4 is shown a less-idealized pulse envelope waveform. In this figure, the finite rise and fall times are evident as is the non-flat top of a typical pulse. Note that the value for the pulse peak power (P_{pk}) does not coincide with the peak of the power curve. In this field, the pulse peak power (P_{pk}) is defined as that value which, when multiplied by the pulse width (τ_p) yields a product equal to the energy in the pulse

Pulse Train Parameters

time →

$PRF = \dfrac{1}{PRI}$

$f_0 = \dfrac{1}{T_0}$
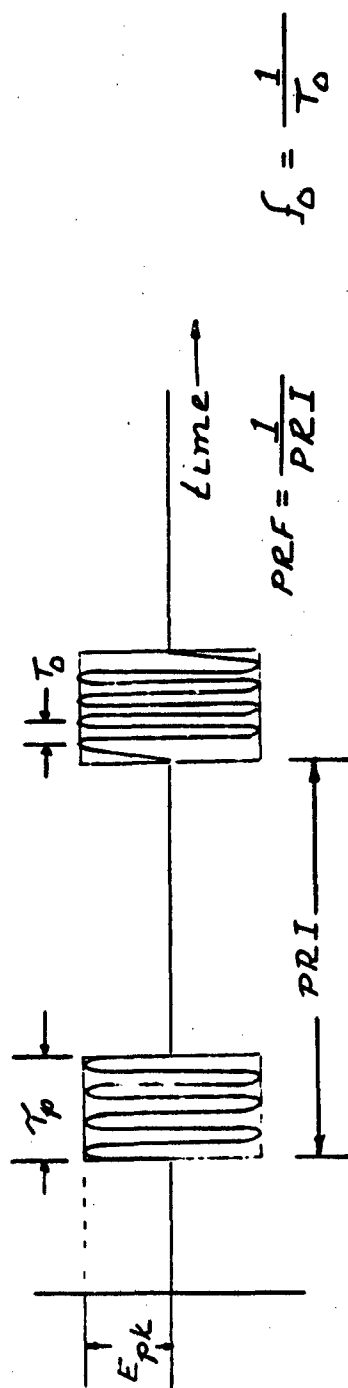
E_{pk} = Pulse Amplitude (Volts)

PRI = Pulse Repetition Internal (Secs)

PRF = Pulse Repetition Frequency (PPS)

τ_p = Pulse Width (Secs)

T_0 = Carrier Period

f_0 = Carrier Frequency

Figure 2.2.3

Pulse Envelope Parameters

$P(t) =$ Power (Watts)

$P_{pk} =$ Pulse Peak Power (Watts) $= \dfrac{1}{\tau_p} \displaystyle\int_{0}^{PRI} P(t)\, dt$

$\tau_p =$ Pulse Width (Secs)

$\tau_r =$ Pulse Rise Time (Secs)

$\tau_f =$ Pulse Fall Time (Secs)

Figure 2.2.4

2.5b
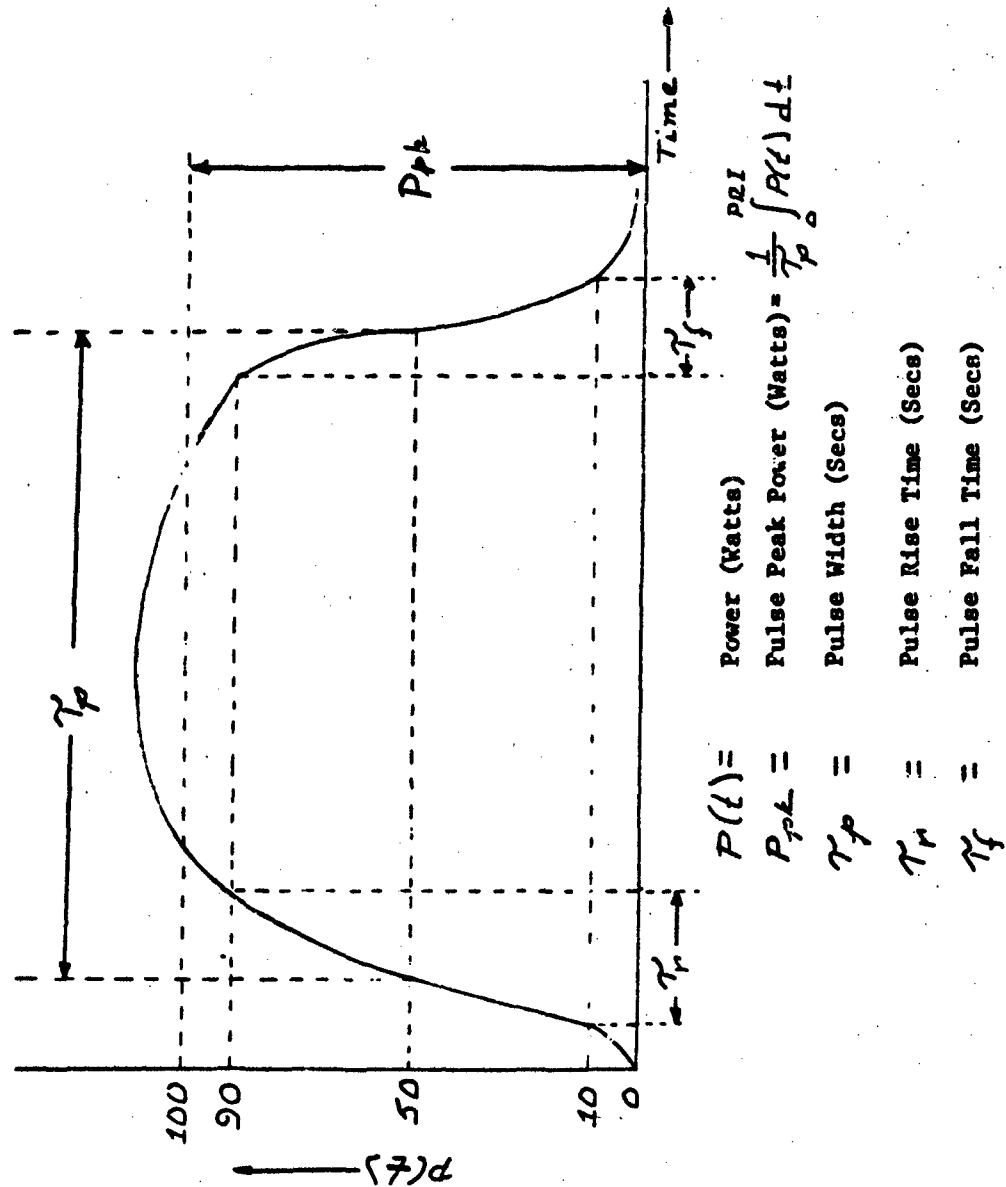
(area under the envelope). This convention acknowledges the fact that, for most considerations, the important parameter with respect to pulse "size" is the total energy in the pulse and not the peak of the power curve. The concepts of average power and duty cycle are introduced in Figure 2.2.5. Note that the average power, Pav, is defined as the pulse power time-averaged over one complete pulse repetition interval.

The principal disadvantages of a pulsed radar, in comparison with a continuous-wave radar, are those due to sampled-data effects. That is, effects due to the fact that target return data are not continuously available. The most direct sampled-data effect is the existence of blind ranges. If the target return arrives at the radar receiver during the time interval when another pulse is being transmitted, the return will be lost. Since the time of target return arrival is a function of range, targets at certain ranges will be invisible. Those ranges are termed "blind ranges". The zero-order blind range is zero range and is evidenced by the minimum range problem in a pulsed radar.

Blind ranges, other that zero, can be avoided, when possible, by selecting a pulse repetition interval large enough that all returns from targets of interest will arrive before the next transmitted pulse. The first non-zero blind range can be increased by staggering the pulse repetition interval; that is, by alternating long and short intervals.
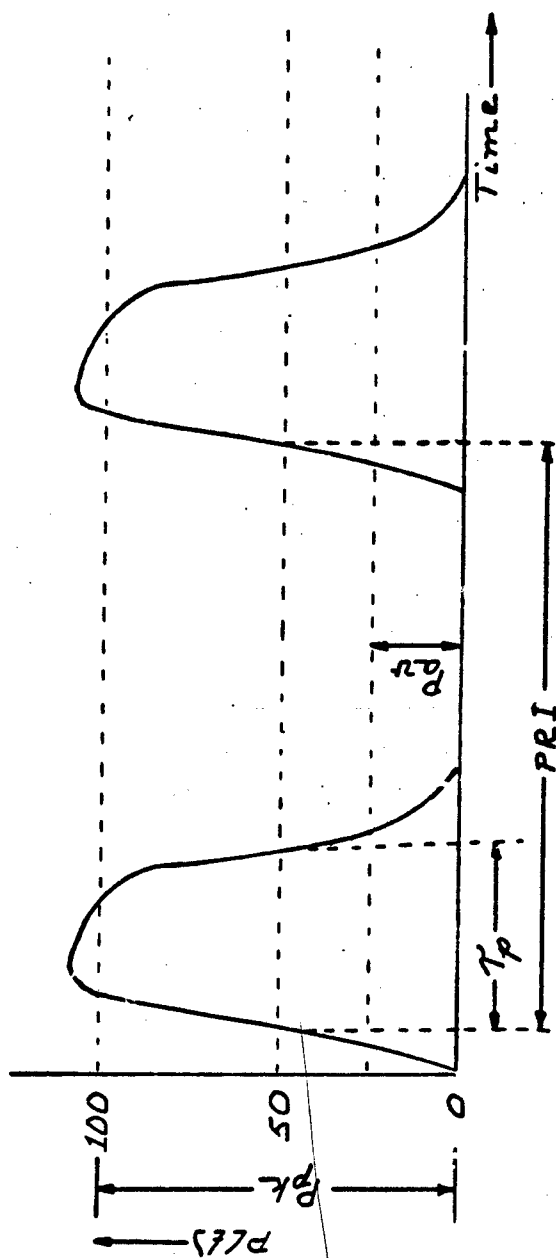
Figure 2.2.5

2.6a

2.3 Pulse Radar Parameters

2.3.1 Range Measurement -- As indicated in Figure 2.3.1, the determination of range to the target involves measuring the "time of flight" of a pulse to the target and back. This time interval is then divided by two, to get one-way travel, and multiplied by the speed of propagation. It should be noted that the speed of propagation depends upon the properties of the medium. A number convenient for purposes of estimating time intervals is the "radar mile". This time interval, 12.36 microseconds, is the approximate time it takes for a pulse to propagate to a target one nautical mile away, and return.

2.3.2 Minimum Range -- The minimum range measureable by a pulse radar is a function of its pulse width. The radar alternately transmits a pulse and listens for a return. If the return arrives back at the radar before the radar is switched to the receive mode, the return pulse will be lost. Thus, the minimum total time of flight of the pulse must be greater than the pulse duration (τp), assuming that the radar is switched to receive immediately upon completing the transmitted pulse. The pertinent relationships are shown in Figure 2.3.2.

2.3.3 Range Resolution -- Range resolution is defined as the minimum separation in range of two targets that can be distinguished by the radar. In determining the minimum separation, it is assumed that the radar can resolve the two targets if their returns are just separated in space.

2.7

Range Measurement
(Simple Pulse Radar)

Stg. Ampl.

Trans. Pulse

Target Return

Δt

time
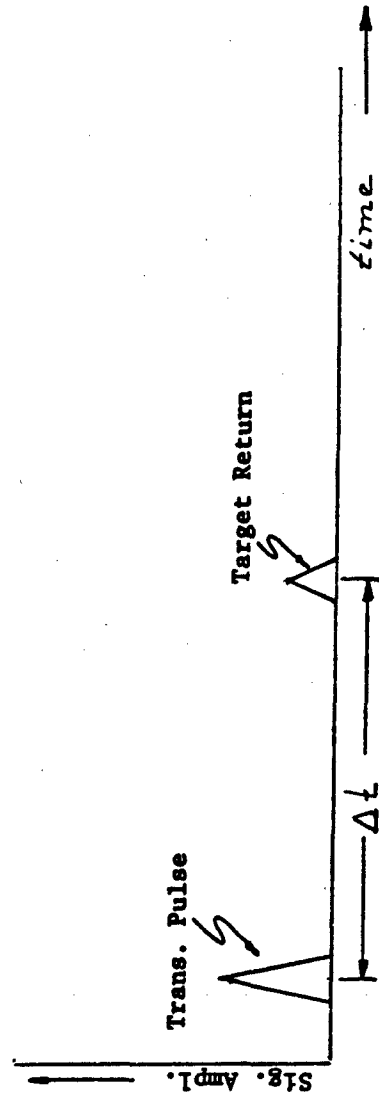
$$R = \frac{c \Delta t}{2}$$

C = Vel. of Propagation

Figure 2.3.1

2.7a

Minimum Range
(Simple Pulse Radar)

Transmitted Pulse

τ_p

$\Delta \ell$
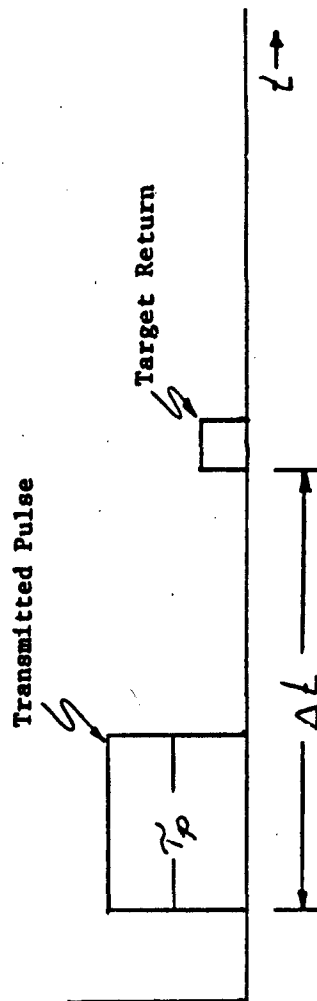
Target Return

$\ell \rightarrow$

- Require $\Delta t > \tau_p$

- $\Delta t = \dfrac{2R}{c}$

- $R_{min.} = \dfrac{c \, \tau_p}{2}$

- c = Velocity of Propagation

Figure 2.3.2

2.7b

Refer to Figure 2.3.3. This requirement imposes a minimum target spacing (or maximum pulse width) as shown in that figure.

2.3.4 Range Ambiguity -- Range ambiguity is caused by the reception of a target return after another pulse has been transmitted. Such a return is called a second-time-around-echo (STAE). (Note that third-time-around-echoes, etc. are also possible). An STAE creates uncertainty as to whether the return is from a distant target, in response to the first pulse, or from a nearby target, in response to the second pulse. If the radar range timer resets coincidentally with the beginning of each transmitted pulse, as in most radars, the second, incorrect indication will be produced. In order to avoid this situation, the pulse repetition interval must be long enough so that all significant returns are in before the next pulse is transmitted. Figure 2.3.4 depicts a second-time-around-echo and develops the minimum pulse repetition interval, (or maximum unambiguous range), required to avoid the STAE. The STAE range ambiguity problem also can be resolved by "coloring" alternate pulses so that their returns can be matched to their corresponding transmitted pulses. One way of coloring a pulse is to shift carrier frequency. Another, more common, way is to alternate long and short pulse repetition intervals.

2.3.5 Directional Measurement -- The simplest method of determining the bearing of a target is to employ a narrow-beamwidth transmitting and/or receiving antenna as shown in Figure 2.3.5.1. When target returns are obtained, the target is known to be in the antenna beam, the direction

2.8

Range Resolution
(Simple Pulse Radar)

Transmitted Pulse

τ_p

Return from Target at R1

Return from Target at R2

τ_p

τ_p

Δt_R

- Require $\Delta t_R > \tau_p$
- $\Delta t_R = \dfrac{2\Delta R}{c}$
- $\Delta R_{min} = \dfrac{c\,\tau_p}{2}$ or $\tau_p\,max. = \dfrac{2\Delta R}{c}$

Figure 2.3.3

2.8a

Range Resolution

(Simple Pulse Radar)

Transmitted Pulse

Return from Target at R1

Return from Target at R2

τ_p

τ_p

τ_p

Δt_R
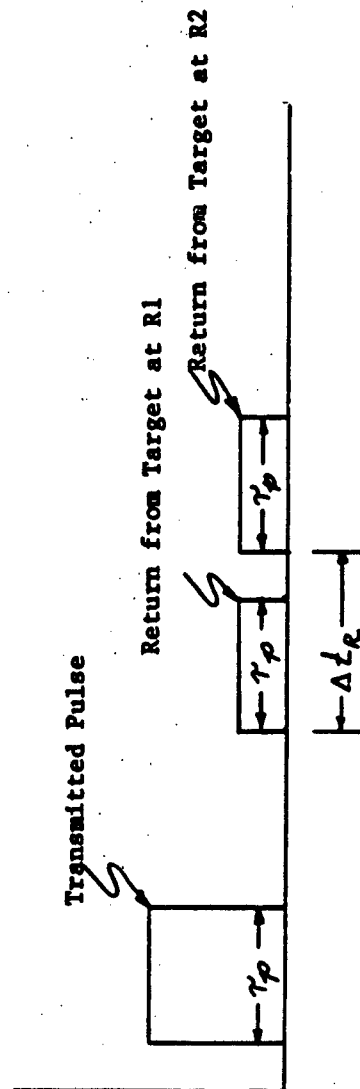
- Require $\Delta t_R > \tau_p$

- $\Delta t_R = \dfrac{2 \Delta R}{c}$
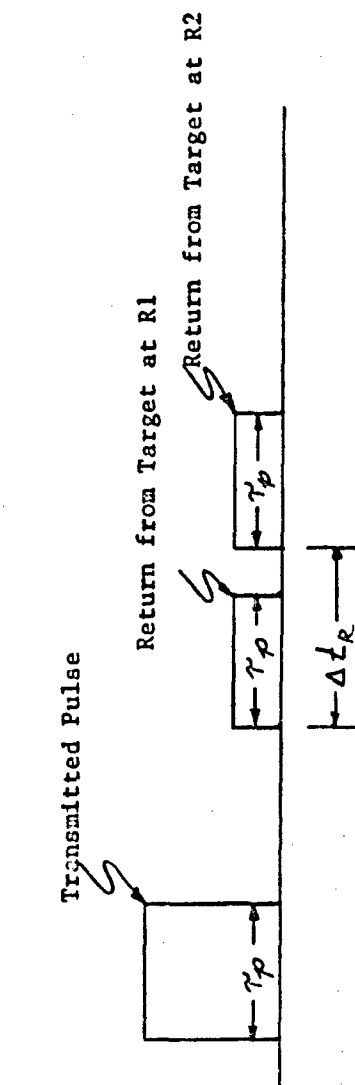
- $\Delta R_{min.} = \dfrac{c \, \tau_p}{2}$ or $\tau_{p \, max.} = \dfrac{2 \Delta R}{c}$

Figure 2.3.3

Range Ambiguity
(Simple Pulse Radar)

Transmitted Pulse No. 1

Transmitted Pulse No. 2

Target Return (STAE)*

time →

*Second-Time-Around Echo
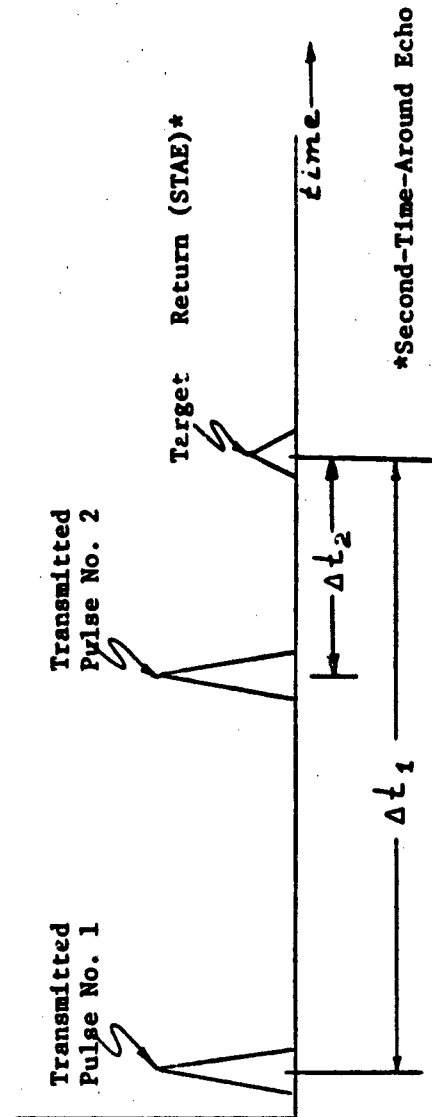
- Actual Range = $\frac{c(\Delta t_1)}{2}$

- Apparent Range = $\frac{c(\Delta t_2)}{2}$

- Require $PRI > \Delta t_1 = \frac{2R}{c}$

- $R_{max} = \frac{c \, PRI}{2}$ or $PRI_{min} = \frac{2 R_{max}}{c}$

- Can be Resolved by Pulse Coloring (AM, FM, PPM, PWM, Etc.)

Figure 2.3.4

2.8b

Directional Measurement
(Non-Interferometric Radar)
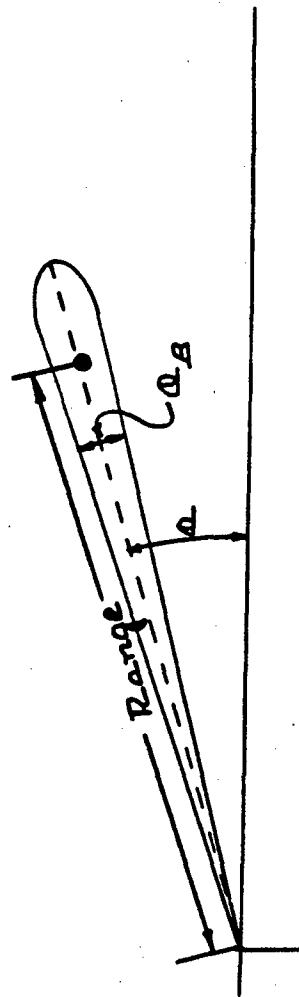
• Bearing (Δ) determined by antenna orientation for maximum return.

Figure 2.3.5.1

of which is known. This method of angle determination is dependent upon the antenna beam characteristics and is less precise than the determination of range, which is independent of antenna characteristics. A more precise, and generally superior, method of angle determination is that known as interferometry. This method utilizes two antennas. Target bearing is determined by measuring the difference in phase between the target returns received at the two antenna positions. The geometry is shown in Figure 2.3.5.2. Target angle (θ) is determined by measuring phase difference ($\Delta\phi$). With this method, the measurement of angle is dependent only upon the ability of the radar signal processor to measure relative phase, a requirement similar to the timing function utilized for range determination. A weakness of interferometry is the fact that angle determination ambiguities exist for relatively large angles off boresight. These ambiguities, analogous to antenna sidelobes, can be resolved by redundant measurements.

2.3.6 Angular Resolution -- For a simple, non-interferometric radar, angular resolution depends upon antenna beamwidth as depicted in Figure 2.3.6. The usual definition of angular resolution requires that, in order to be resolvable on the basis of bearing, two targets must be sufficiently separated that they cannot simultaneously fall within the "beamwidth" of the antenna. Note, however, that the beamwidth of an antenna is defined by the half-power points. Thus, the two targets may be outside the "beamwidth" and still simultaneously fall within the actual antenna beam, thereby producing coalesced returns. For this reason,

Directional Measurement
(Interferometer Radar)

Target

α

Antenna Boresight

λ_o

Antennas

$\Delta\phi$

d

e_o
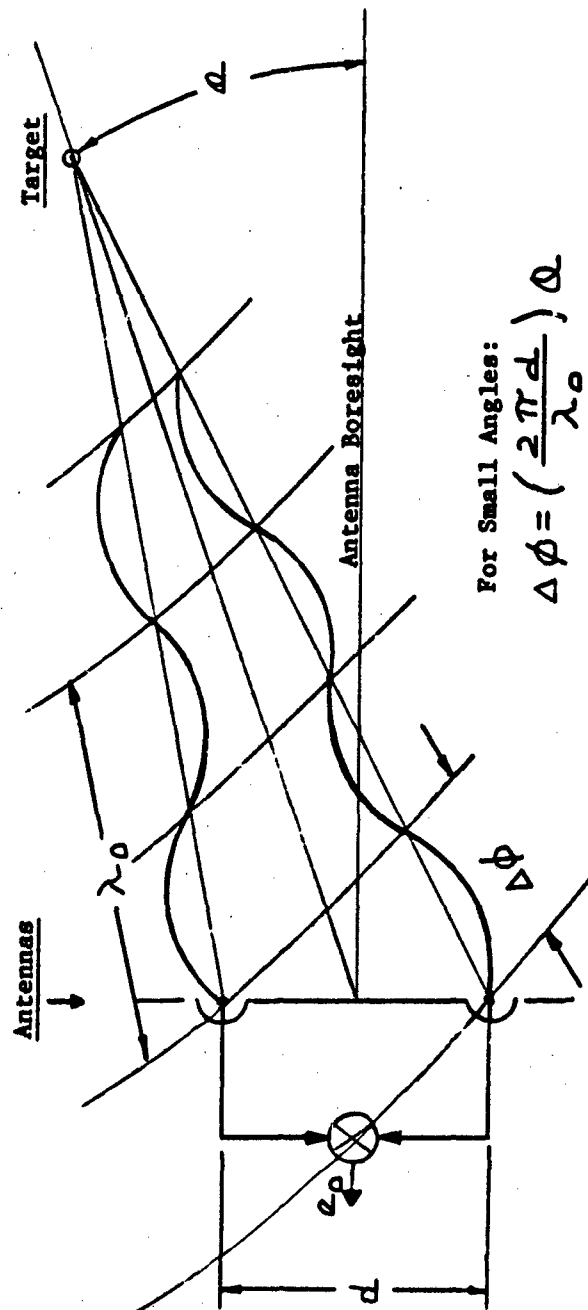
For Small Angles:

$$\Delta\phi = \left(\frac{2\pi d}{\lambda_o}\right)\alpha$$

Target Bearing Determined by Measuring Phase difference $\Delta\phi$.

d = Linear Separation of Antennas
e_o = Interferometer Output
α = Target Relative Bearing
λ_o = Radar Wavelength
$\Delta\phi$ = Signal Phase Difference at Antennas

Figure 2.3.5.2

2.9a

Angular Resolution
(Non-Interferometric Radar)
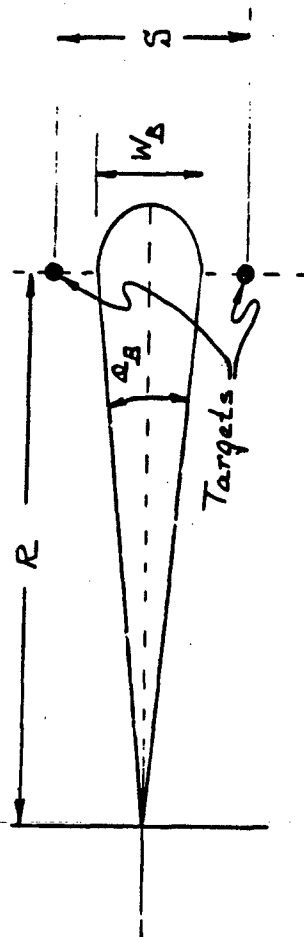
- $\Theta_B =$ Angular Beam Width (Radians)
- $W_B =$ Linear Beam Width (Meters)
- $R =$ Target Range (M)
- $S =$ Target Lateral Separation (M)

- Require $W_B < S$
- $S_{min.} = R\,\Theta_B$ or $\Theta_{B(max.)} = \dfrac{S}{R}$

Figure 2.3.6

the angular resolution will be a function of the signal processor target
threshold level, the level above which a return is considered a target
return. It should be noted that two targets unresolvable on the basis
of bearing may be resolvable on the basis of range or velocity. For an
interferometric radar, angular resolution depends upon the ability of
the signal processor to distinguish between two signals on the basis of
phase. A number of circuits are employed for this purpose, including
phase sensitive detectors, zero-crossing detectors, and phase-locked
loops.

As indicated above, the range resolution of a simple, non-interferometric
radar is generally much better than its bearing (azimuth or elevation)
resolution. Two very powerful techniques are available for improving
the angular resolution of a radar. These techniques are the synthetic
array, also called the synthetic aperture, and doppler beam sharpening.
Doppler beam sharpening "sharpens the beam" by resolving targets on the
basis of velocity; that is, on the basis of their (different) doppler
frequency shifts. The synthetic array is an "array" created by a single
antenna assuming multiple positions in space. Ground mapping from a
moving aircraft is an excellent candidate for either doppler beam
sharpening or synthetic aperture signal processing. Doppler beam sharpen-
ing is discussed in Section 2.18 of this text. Synthetic aperture antennas
are discussed in the text on communications systems.

2.3.7 Angle Ambiguity -- Ambiguity in azimuth or elevation is caused by
the presence of antenna side lobes. As indicated in Figure 2.3.7, a target
actually being picked up in a side lobe will be assigned a

2.10

Angle Ambiguity
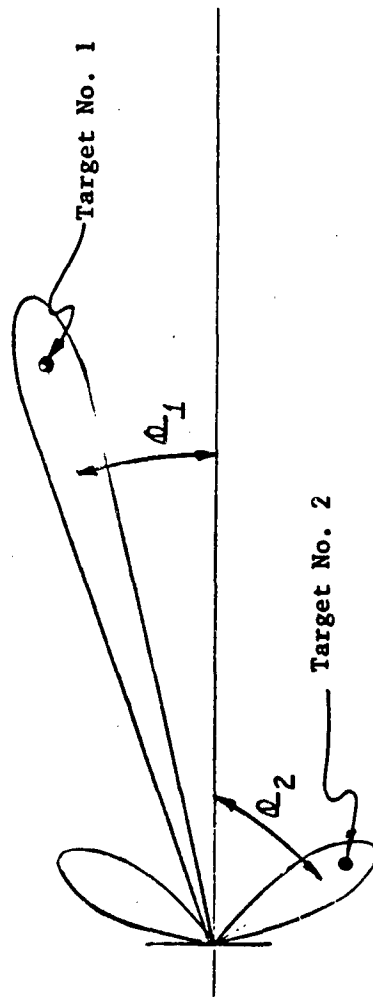
Due to Illumination by the Side Lobe, Target No. 2 will be indicated at the same angular position as Target No. 1.

Figure 2.3.7

2.10a

bearing concident with that of the main lobe (antenna boresight).

Minimization of antenna sidelobes is the most direct method of eliminat-

ing angle ambiguity. An alternate method of resolving the ambiguity

involves the use of signal processing logic which anticipates the

existence of ambiguous returns from known sidelobes. Another method

utilizes an omnidirectional "guard channel" receiver to identify

ambiguities.

2.3.8 Blind Ranges (Eclipsing)--When the target is at a range such that

the target return arrives at the radar receiver during the interval

when a pulse is being transmitted and the receiver is turned off, the

return pulse will be lost. When the timing is such that only a portion

of the pulse is lost, it is said to be "eclipsed" by the transmission

period. Since all succeeding transmissions will eclipse target returns,

there are, theoretically, an infinite number of "blind" ranges. Figure

2.3.8 shows the effective reduction in signal strength due to eclipsing

and specifies the relationship between pulse repetition interval and

the blind ranges.

Eclipsing—Blind Ranges
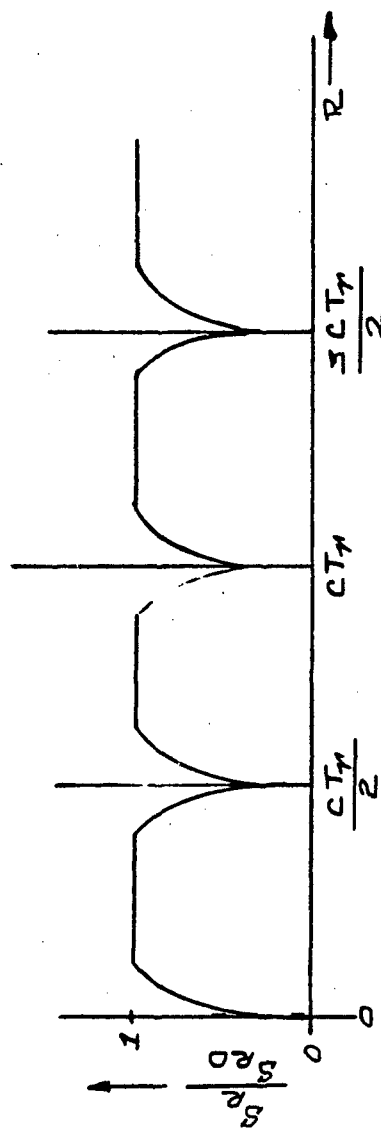
C = Velocity of Propagation

R_{Blind} = Blind Range = $n\left(\dfrac{cT_r}{2}\right)$, $n = 0, 1, 2, \cdots$

S_R = Signal Strength at Range R with Eclipsing

S_{Ro} = Signal Strength at Range R without Eclipsing

T_r = Pulse Repetition Internal

Figure 2.3.8

2.11a

2.4 The Radar Range Equation

One of the most important characteristics of a radar system is the maximum range at which it can perform a given function. This maximum range, not to be confused with maximum unambiguous range, is dependent upon the transmitter power, the transmitting and receiving antenna directivities, the reflectivity (radar cross section) of the target, the wave geometric spreading (free-space attenuation), atmospheric absorption and scattering, system internal losses, internal and external noise, and, finally, the minimum signal-to-noise ratio at the receiver required to perform the specific function in question.

A brief derivation of the radar range equation follows. Given a transmitted power, P, at the transmitter, the power density of the wave incident upon a target located at range R is given by:

$$P_T = \frac{P}{4\pi R^2} \qquad \text{(Watts/Square Meter)} \qquad [2.4.1]$$

This relationship, the result of spherical spreading of the waves, describes the phenomenon known as "free-space attenuation" and is independent of atmospheric absorption or scattering. It is also independent of antenna directivity. If the antenna is directive, the expression in equation [2.4.1] is multiplied by the directive gain of the transmitting antenna, G. Thus:

$$P_T = \frac{PG}{4\pi R^2} \qquad \text{(Watts/Square Meter)} \qquad [2.4.2]$$

2.12

The power intercepted and reflected by the target is then:

$$P_T = p_T \sigma = \frac{P G \sigma}{4 \pi R^2} \quad \text{(Watts)} \qquad [2.4.3]$$

where σ is the radar cross section of the target. Note that radar cross section is the effective reflecting area of the target and involves target physical area, reflectivity, and directivity. The power density at the radar receiver, p_R will again be reduced by free space attenuation over a range R. Thus:

$$p_R = \frac{P G \sigma}{(4 \pi R^2)^2} \quad \text{(Watts/Square Meter)} \qquad [2.4.4]$$

The power actually captured by the receiving antenna is:

$$P_R = p_R A = \frac{P G \sigma A}{(4 \pi R^2)^2} \quad \text{(Watts)} \qquad [2.4.5]$$

where A is the effective (capture) area of the receiving antenna. If the transmitting and receiving antennas are identical, the transmitting antenna gain, G, and the receiving antenna capture area, A, are related by the equation:

$$A = \frac{\lambda^2 G}{4 \pi} \quad \text{(Square Meters)} \qquad [2.4.6]$$

where λ is the signal wavelength. The cumulative effects of other, non-specific losses in the radar are included in the range equation by inserting a loss factor, L, equal to or greater than unity, in the denominator. Thus the equation for power delivered to the receiver becomes:

$$P_R = \frac{P G \sigma A}{(4 \pi)^2 L R^4} \quad \text{(Watts)} \qquad [2.4.7]$$

2.13

Equation [2.4.7] can be solved for the maximum radar range attainable, R_{max}, for a given required minimum power at the receiver input, P_{min}. Thus:

$$R_{Max} = \left[\frac{P G \sigma A}{(4\pi)^2 L P_{Min}} \right]^{1/4} \quad \text{(Meters)} \qquad [2.4.8]$$

In a typical radar receiver, the maximum range actually depends more upon the signal-to-noise ratio, (S/N), than upon the signal power alone. P_{min} can be expressed in terms of $(S/N)_{min}$ by the relationship:

$$P_{Min} = (S/N)_{Min} N \quad \text{(Watts)} \qquad [2.4.9]$$

where N is the noise in the system, referred to the input. In turn, the system noise, N, can be expressed in terms of the minimum attainable noise, that is, thermal noise, No, and a noise figure, Fn, for the radar. Thus:

$$N = F_n N_o \quad \text{(Watts)} \qquad [2.4.10]$$

Thermal noise is a function of the absolute temperature of the system, T, the noise bandwidth of the system, Bn, and Boltzmann's Constant, k. Thus:

$$N_o = k T B_n \quad \text{(Watts)} \qquad [2.4.11]$$

combining equations [2.4.9] through [2.4.11]:

$$P_{Min} = k T B_n F_n (S/N)_{Min} \quad \text{(Watts)} \qquad [2.4.12]$$

This expression can be substituted for P_{min} in equation [2.4.8], giving:

$$R_{Max} = \left[\frac{P G \sigma A}{(4\pi)^2 L k T B_n F_n (S/N)_{Min}} \right]^{1/4} \qquad \begin{array}{c} [2.4.13] \\ \text{(Meters)} \end{array}$$

Equation [2.4.13] is the radar range equation in a form reasonably suitable for application. Its application, however, must be approached with caution. The principal problem resides in the factor $(S/N)_{min}$.

The minimum required signal-to-noise ratio depends upon many factors, including not only such complex factors as the required probability of detection and the acceptable probability of false alarm, but also such poorly defined factors as the experience and proficiency of the operator. As a result of these limitations, the radar range equation is useful only for obtaining a rough estimate of the maximum range to be expected, or for determining the relative effect of various parameters on performance. Notice, for example, the one-quarter exponent on the right side of the equation. That exponent means that doubling the maximum range requires that the transmitter power be increased by a factor of sixteen, if all other factors remain constant.

2.5 Radar Target Cross Section

The radar cross section of a target is that area which, when multiplied by the radar signal power density incident upon the target, yields a reflected power that, if radiated isotropically by the target, would result in a return back at the radar equal to that of the actual target. This definition, while cumbersome, is the simplest formulation that adequately reflects the complex nature of radar cross section. Rarely is the radar cross section of a physical target equal to its actual profile area, often being very much smaller or very much larger than that area. Radar cross section depends upon the physical dimensions of the target relative to the wavelength of the radiation, the modulation and polarization of the transmitted wave, and the reflectivity, absorptance, shape, orientation, and range of the target. Wave interference between reflections from various portions of a target plays an especially complex and important role in determining its radar cross section.

When the dimensions of the target are much less than the wavelength, the radar cross section will tend to be much smaller than the profile area of the target. This phenomenon is called Rayleigh scattering. When the dimensions of the target are much greater than the wavelength, the radar cross section will tend to be equal to the profile area of the target. This is referred to as optical scattering. When the dimensions of the target are approximately equal to the wavelength,

2.16

the radar cross section can be much larger than the profile area of the target. This condition is known as resonance.

An excellent example of the phenomena described above is the case of a simple conductive sphere. Figure 2.5.1 shows a plot of the normalized radar cross section of a sphere as a function of the ratio of the sphere radius to the radiation wavelength. In the Rayleigh region, the cross section is approximately proportional to $1/\lambda^4$ where λ is the wavelength of the radiation. In the optical region, the cross section is approximately equal to πa^2, the profile area of the sphere. In the resonance region, the cross section magnitude oscillates about πa^2, reaching an absolute maximum when $a = \frac{\lambda}{2\pi}$. Note that this example assumes a perfectly reflecting, non-absorbing sphere. The strong dependence of cross section on radius of the sphere is due to diffraction effects.

In Figure 2.5.2 are shown normalized polar plots of the radar cross section of two spheres as a function of aspect angle. In Figure 2.5.2a the two spheres are separated by one wavelength. In Figure 2.5.2b, they are two wavelengths apart. Note the strong angular dependence of cross section due to wave interference effects. As a final example of the complexity of the dependence of radar cross section on aspect angle, Figure 2.5.3 shows a polar plot of the radar cross section of a B-26 aircraft. At some aspect angles, the target virtually disappears. Fortunately, in actual practice, the relative motion of the radar and the target tends to produce an "average" cross section, which scintillates but doesn't disappear for long periods of time.

2.17
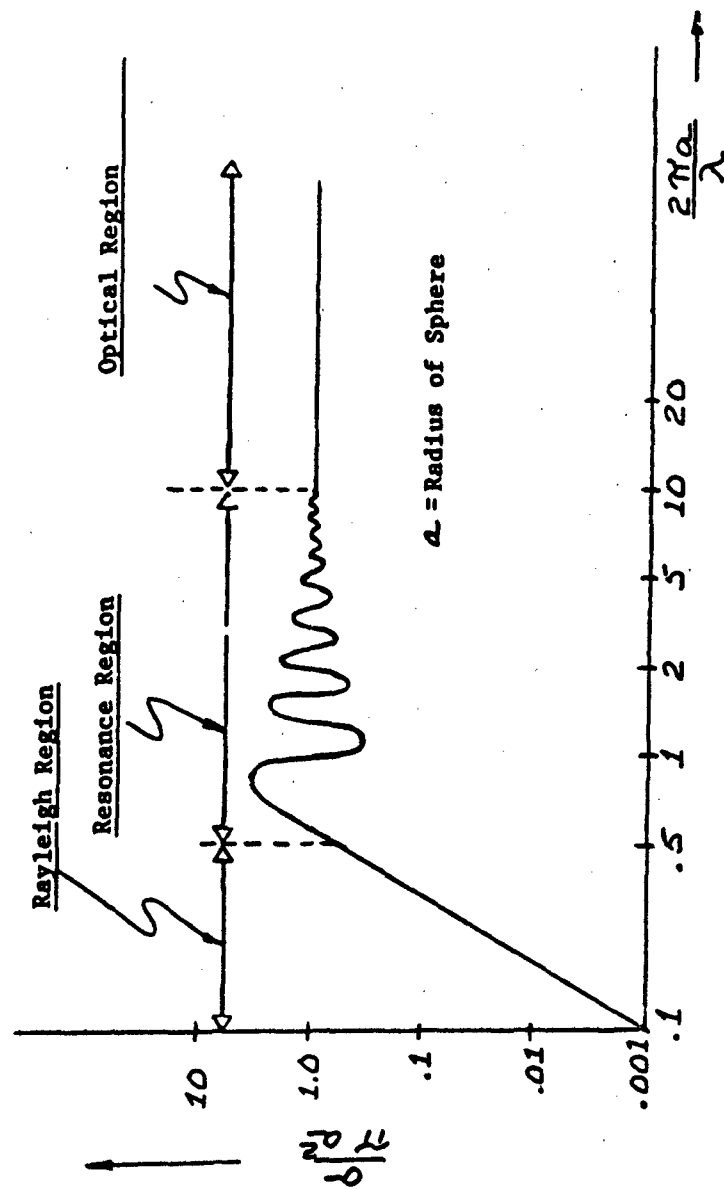
Radar Cross Section of a Sphere

Figure 2.5.1

Radar Cross Section of Two Spheres

(a)

(b)

Figure 2.5.2

2.17b
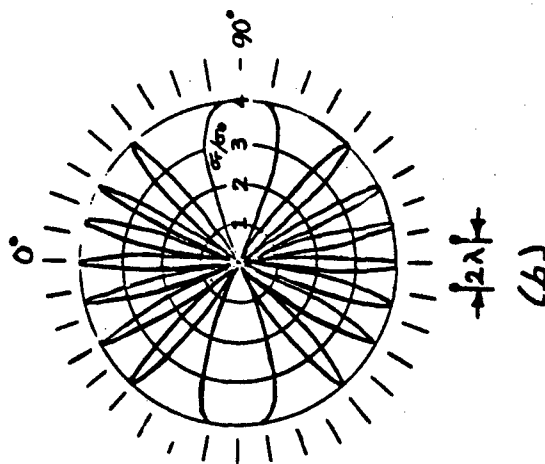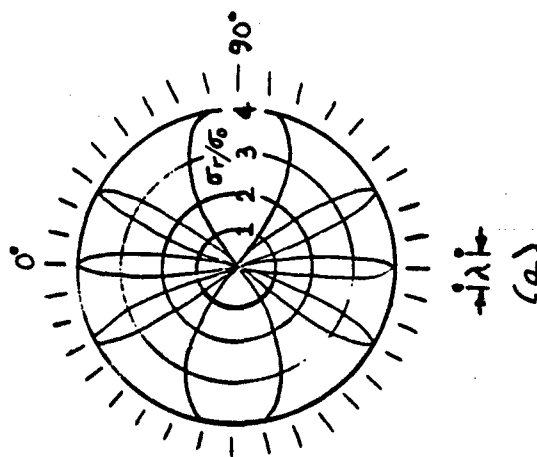
Radar Cross Section of a B-26
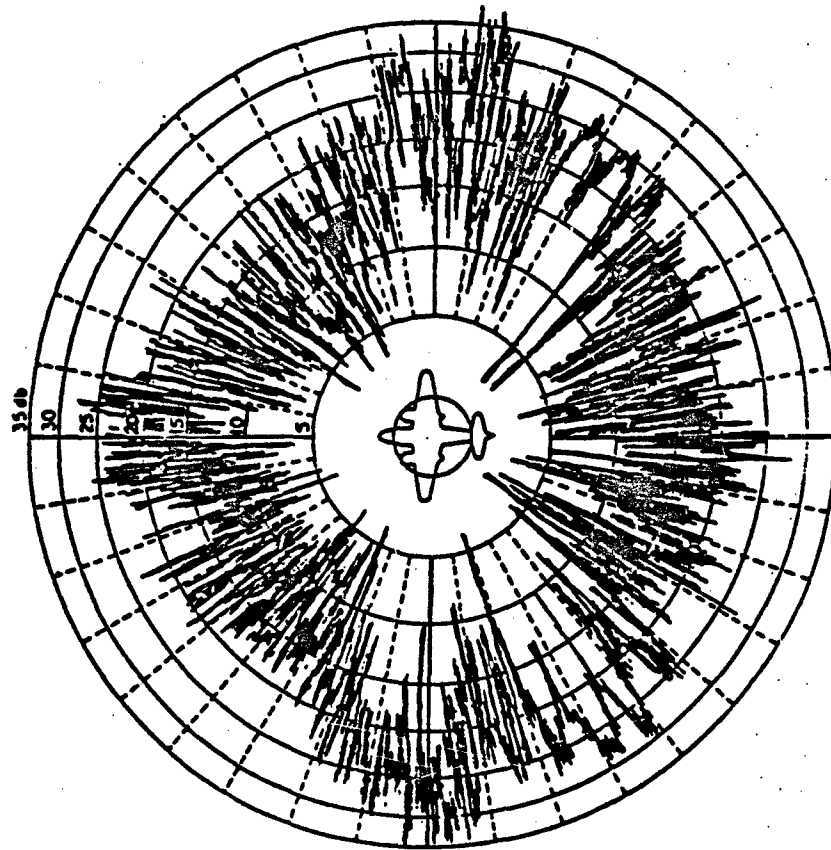
Figure 2.5.3

2.6 Probabilities of Detection and False Alarm

Due to the presence of noise, random and otherwise, the performance of
a radar ultimately must be measured in terms of the probability of de-
tection and the probability of false alarm. The probability of detection
is defined as the probability that a target will be indicated when there
is, in fact, a target to be detected. The probability of false alarm is
defined as the probability that a target will be indicated when there is,
in fact, no target to be detected. Clearly, these two quantities are
correlated by the presence of noise. If the detection threshold of a
radar receiver is lowered, the probability of detection is increased,
but the probability of false alarm is also increased. It is possible,
(see, for example, Radar Detection and Tracking Systems by S. A.
Hovanessian), to calculate the single-look probability of detection,
P_d, as a function of the signal-to-noise power ratio and the probability
of false alarm, P_{fa} , assuming Gaussian noise. This relationship is
shown in Figure [2.6.1] for a non-scintillating target. Note that the
curves are not explicitly dependent on the detector threshold level
and the noise amplitude. Figure [2.6.1] is presented here to give the reader
a measure of the sensitivity of the required signal-to-noise ratio to
probability of detection and probability of false alarm.

2.7 Pulse Integration

Figure [2.6.1] presented the single-look probabilities of detection
and false alarm for a typical radar. Rarely do modern-day radars work

2.18

P_{f_a} = Probability of False Alarm
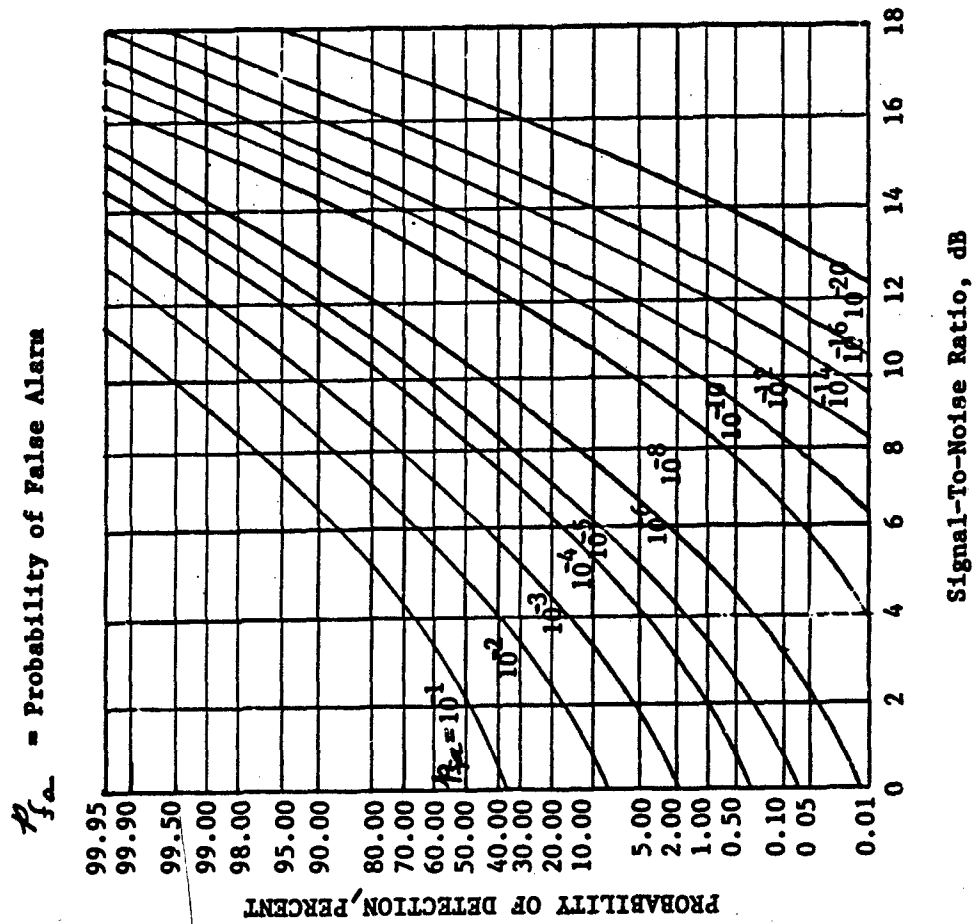
Figure 2.6.1 Probability of Detection vs Signal-to-Noise Ratio

2.18a

with single-look data. The returns from a number of pulses or even scans are usually combined. This technique, called pulse integration, is an extremely simple and effective method of simultaneously increasing the probability of detection while decreasing the probability of false alarm. The fundamental reason for the efficacy of pulse integration is the fact that random noise, when integrated (summed) over a period of time, tends to average out to zero while the target return, being deterministic, tends to add in a cumulative manner.

There are two methods of pulse integration, pre-detection and post-detection. The term detection refers here to the process by which the carrier is deleted from the radar signal. When the carrier is eliminated, useful information, (carrier phase), is lost. For that reason, pre-detection pulse integration, (of coherent returns), yields a greater increase in probability of detection than does post-detection integration. For pre-detection pulse integration, the required signal-to-noise ratio for n pulses is related to the required signal-to-noise ratio for one pulse by the relationship:

$$(S/N)_{Req\ (n\ pulses)} = \frac{1}{n}(S/N)_{Req\ (1\ pulse)} \qquad [2.7.1]$$

For post-detection pulse integration the relationship in equation [2.7.1] is degraded by an integration efficiency factor, E_i, equal to or less than unity. Thus, for post-detection pulse integrations:

$$(S/N)_{Req\ (n\ pulses)} = \frac{1}{n E_i}(S/N)_{Req\ (1\ pulse)} \qquad [2.7.2]$$

2.19

Figure 2.7.1 presents a comparison of pre-detection and post-detection
efficiency as a function of the number of pulses integrated.

As previously indicated, the maximum range of a pulse radar, for a
given function, is dependent upon the total energy in the pulse rather
than the peak power attained during the pulse. In this light, pulse
integration can be considered a method of combining the energy of
many pulses. Pulse integration also tends to average out random noise,
thereby further increasing maximum range.

Integration Improvement Factor

Pre-Detection Integration

Post-Detection Integration
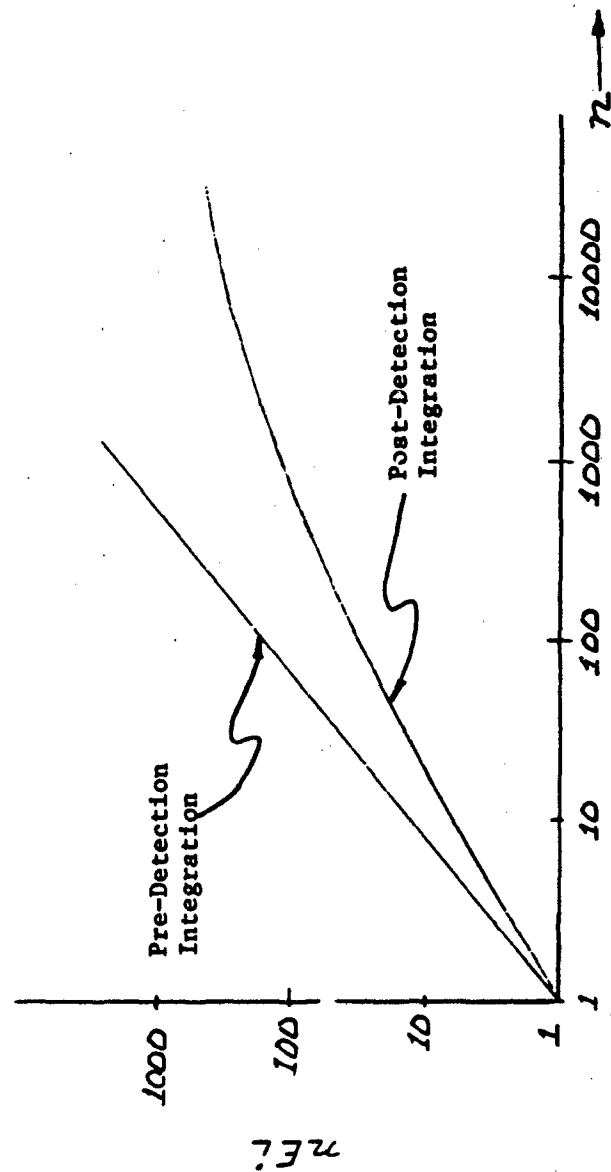
n = Number of Pulses Integrated

E_i = Integration Efficiency Factor

Figure 2.7.1

2.20a

2.8 Correlation Detectors

An ideally designed radar would utilize all available information in
its efforts to detect the presence of an incoming target return. That
is, it would carefully shape the outgoing signal and would then look
for that "shape" in the received signals. The process of comparing
two signals in this manner is termed cross-correlation. While exten-
sive use of signal correlation detectors is fairly new, even the
earliest "radars" employed a form of signal correlation. The tuned
circuit used in those radars to select a return on the basis of carrier
frequency actually constituted a matched filter, a type of signal
correlation device.

Mathematically, the correlation coefficient for two signals, $R_{xy}(\tau)$,
is defined by the equation:

$$R_{xy}(\tau) = \int_{-\infty}^{+\infty} x(t)\, y(t-\tau)\, dt$$

[2.8.1]

In practical application, the infinite correlation time is, of course,
impossible. Therefore, the following approximation is employed.

$$R_{xy}(\tau) = \frac{1}{T} \int_{-T/2}^{+T/2} x(t)\, y(t-\tau)\, dt$$

[2.8.2]

As indicated by equations [2.8.1] and [2.8.2], the correlation co-
efficient is a function of the relative delay time parameter, τ. Thus,

2.21

if x(t) is a radar target return and y(t-τ) is the transmitted wave-
form, the correlation coefficient generated by equation [2.8.2] will
be a maximum when τ is equal to the time required for the transmitted
signal to travel to the target and back. A modern correlation detector
radar employs this principle to determine range to the target.

If, in equation [2.8.2], y(t-τ) = x(t-τ), the autocorrelation co-
efficient of x(t) is obtained. Autocorrelation also can be employed
to improve radar target signal detection by recognizing the periodicity
of the radar target returns.

A practical implementation of a cross-correlation detector is shown in
Figure 2.8.1. In this arrangement, a long-time-constant low-pass
filter is used to approximate the integration function. In Figure 2.8.2
is shown the signal-to-noise ratio at the output of a orrelation de-
tector versus the input signal-to-noise ratio, for both cross-correlation
and autocorrelation detectors. The tremendous potential of correlation
techniques is evident in the vast improvement in signal-to-noise ratio
indicated for this simple case. When highly complex signal shaping is
employed the improvement can be even greater.

2.9 The Matched Filter

Equation 2.8.1, (in Section 2.8), defined the cross-correlation coefficient
for two signals. It has been shown, (see Introduction to Radar Systems
by M. I. Skolnik), that the integration of the product indicated by

2.22

Correlation Detection

● Block Diagram, Typical Correlation Detector

$x(t)$

$x(t) \, y(t-\tau)$

| Mixer (Multiplier) |
| Low-Pass Filter (Integrator) |

$R_{x,y}(\tau)$

$y(t)$

| Delay (τ) |

$y(t-\tau)$

Figure 2.8.1

2.22a
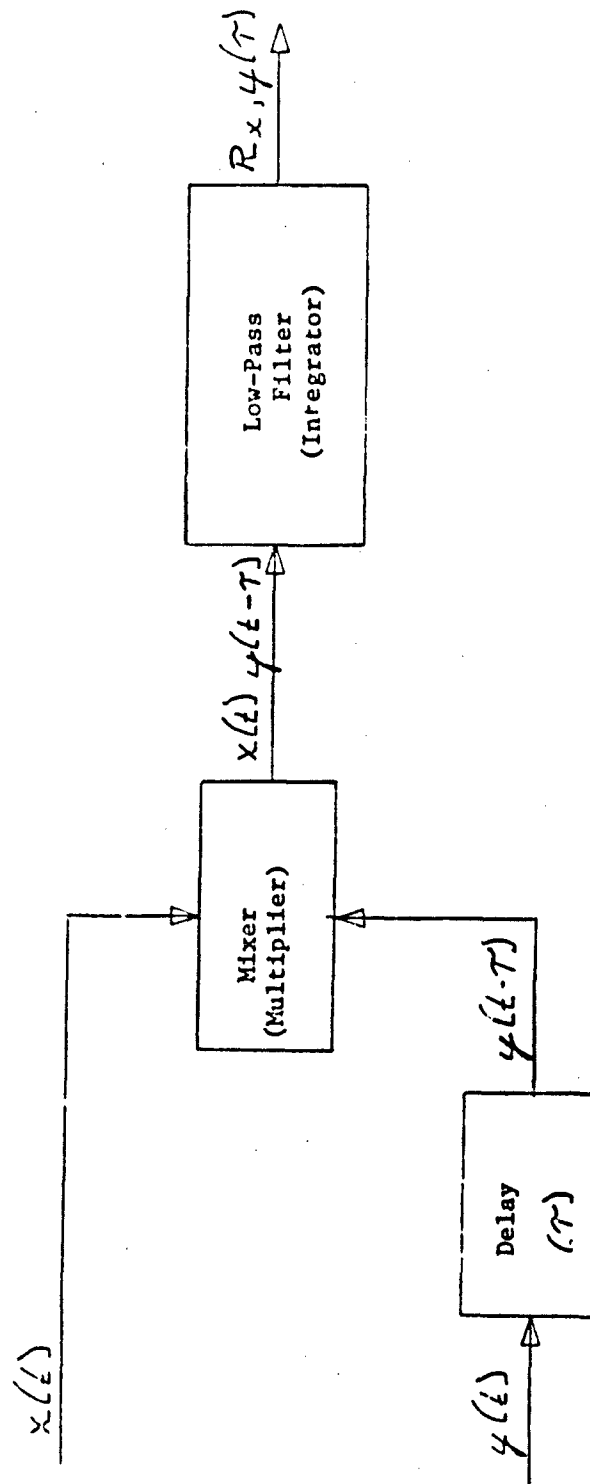
Correlation Detection

- Plots of Signal-to-Noise Ratio at Output of Digital Correlation Detector Versus Input Signal-to-Noise Ratio. (Signal is Sinusoid in Presence of Random Noise. Number of Samples Processed = 60,000)
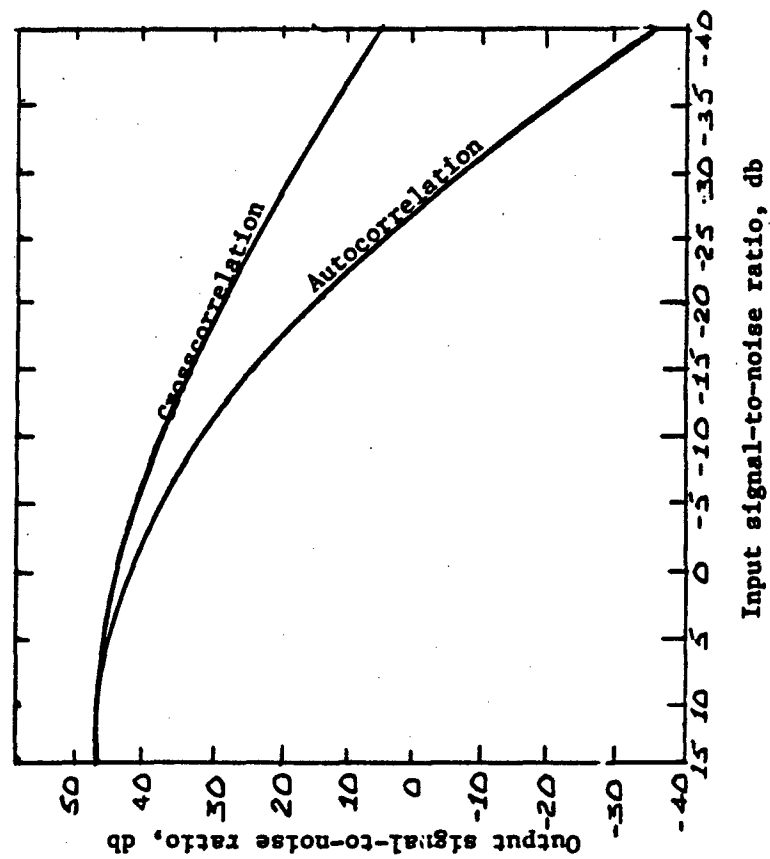
Figure 2.8.2

equation 2.8.1 can be accomplished by passing one of the signals

through an electronic device whose impulse response has a waveform

identical to the waveform of the second signal, but reversed in time.

Such a device is called a "matched filter". If the signal to be

recognized is a pure sinusoid, the matched filter will have an impulse

response which "rings" at the carrier frequency. A device with this

characteristic would be a resonant circuit tuned to that frequency.

2.10 Pulse Compression

The maximum range of a pulse radar is improved by an increase in pulse
width (pulse energy). On the other hand, range resolution is deteoriated
by an increase in pulse width. Pulse compression is a technique that
allows the transmission of long, high energy pulses while retaining the
range resolution advantages of short pulses. This effect is achieved
by compressing the return pulses in the receiver before extracting the
range information.

In order to allow compression of the pulses they are time-colored by
frequency modulating the carrier; that is, the carrier frequency is
increased linearly with time as shown in Figure 2.10.1. This technique
is known as chirp. The pulse compressor shown in Figure 2.10.1 is
simply an ordinary passive delay line. The characteristics of a delay
line are such that the velocity of propagation of a signal through the
line is proportional to the frequency of the signal. Thus, the early,
low-frequency portion of each pulse travels through the line more slowly
that the later, high-frequency portion, thereby compressing the pulse
in time. A disadvantage of pulse compression is the broadening effect
of the delay line on the spectrum (frequency content) of the signal.
This broadening of the spectrum decreases the accuracy with which doppler
processing can recover target velocity.

Pulse Compression

• Block Diagram, Typical Pulse Compression Radar
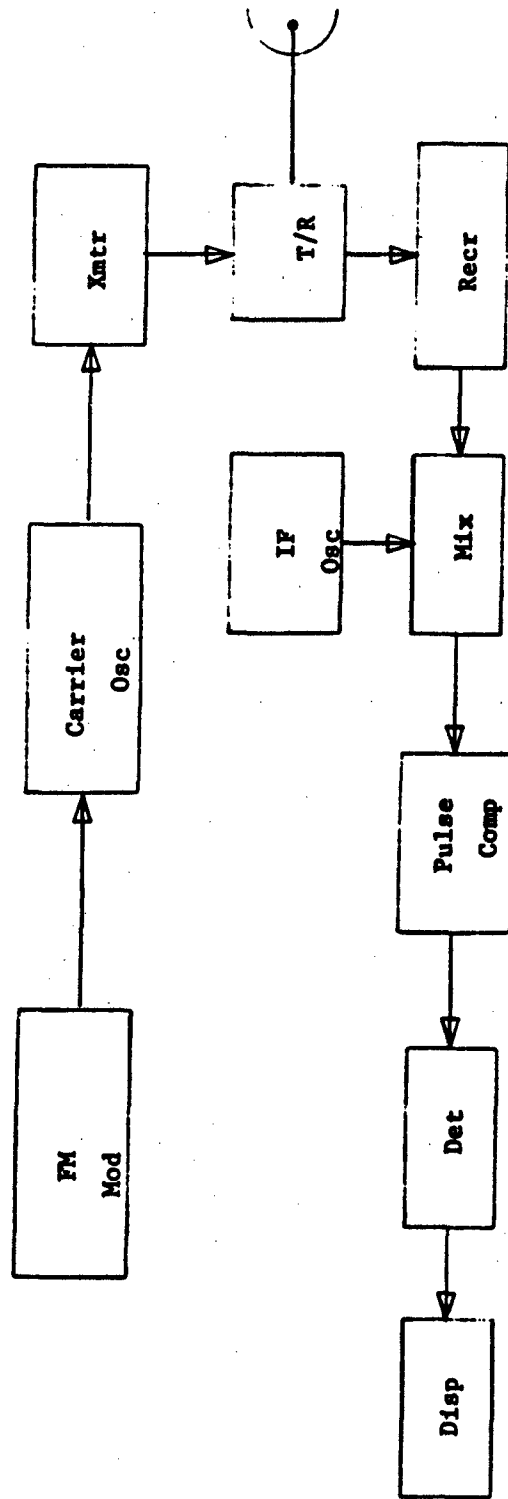
• Transmitted Pulse Frequency and Waveform

Figure 2.10.1

2.24a
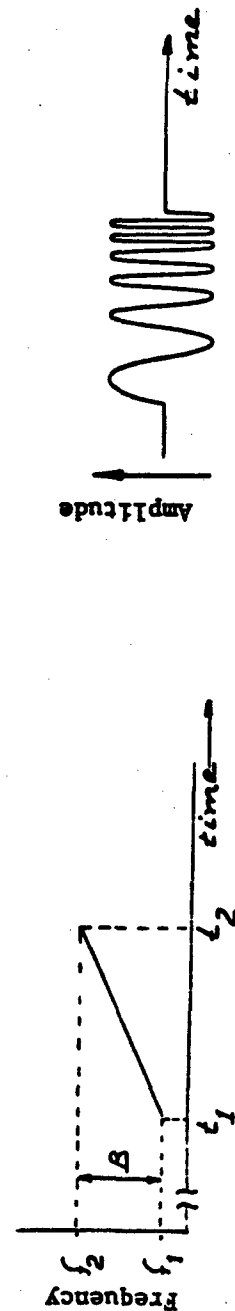
2.11 Continuous-Wave Doppler Radar

2.11.1 Continuous Wave Radar

In section 2.2, pulsed radars were described. The principal advantages of pulsed radar were seen to be the ease of separating the transmitted signal from the received signal (on the basis of time), and the capability of determining target range. The principal disadvantages of pulsed radar were seen to be sampled-data effects; principally blind ranges, including minimum range.

A non-pulsed, or continuous-wave, radar has relative advantages and disadvantages which are, or course, reciprocal to those of the pulsed radar. Its primary advantages are the absence of sampled-data effects (no blind ranges or minimum range problem), its simplicity (no pulsing required and, hence, smaller required bandwidth), and its higher average power for a given peak power. Its primary disadvantages are the necessity to distinguish between simultaneous transmitted and received signals and the inability to range employing a pure, unmodulated CW signal. As it happens, both of these disadvantages can be overcome by time coloring the outgoing signal via frequency modulation. If doppler processing is provided, thereby giving the radar the ability to distinguish returns on the basis of small frequency shifts, the transmitted and returned signals can be separated on the basis of the doppler shift produced by a moving target. A target with zero relative velocity, however, will be invisible to such a radar. This characteristic is a serious weakness of some moving

target indicators. In a later section of this text, it will be seen that a pulsed-doppler radar exhibits "blind speeds" in addition to the one for zero relative velocity.

In Figure 2.11.1.1 is presented the block diagram of a simple, unmodulated continuous wave doppler radar. The unmodulated carrier from the oscillator is amplified by the transmitter and routed to the antenna by a duplexing device such as a circulator. The received signal is simultaneously routed by the duplexer to the receiver, along with some leakage from the transmitter. The return signal is then separated from the leakage on the basis of frequency (doppler shift), and processed as required. In the frequency-discriminating function, the leakage can actually serve an essential function by acting as the reference frequency signal.

2.11.2 The Doppler Shift

The transmitted and received waveforms for a pure continuous wave doppler radar are shown in Figure 2.11.2.1. The transmitted waveform is, ideally, of constant frequency and constant amplitude. The received waveform has an amplitude modulation caused only by target scintillation and other inadvertent effects. (Any variation in amplitude is, in fact, removed before the signal is processed to determine frequency shift). The frequency of the received signal is constant for a constant target relative velocity (doppler shift).

Continuous-Wave Doppler Radar

A = Antenna

Recr = Receiver

Ind = Indicator

Osc = Oscillator

Xmtr = Transmitter

DX = Duplexer

Freq Disc. = Frequency Discriminator

Figure 2.11.1.1

2.26a

Waveforms

ω_T = Trans. Frequency
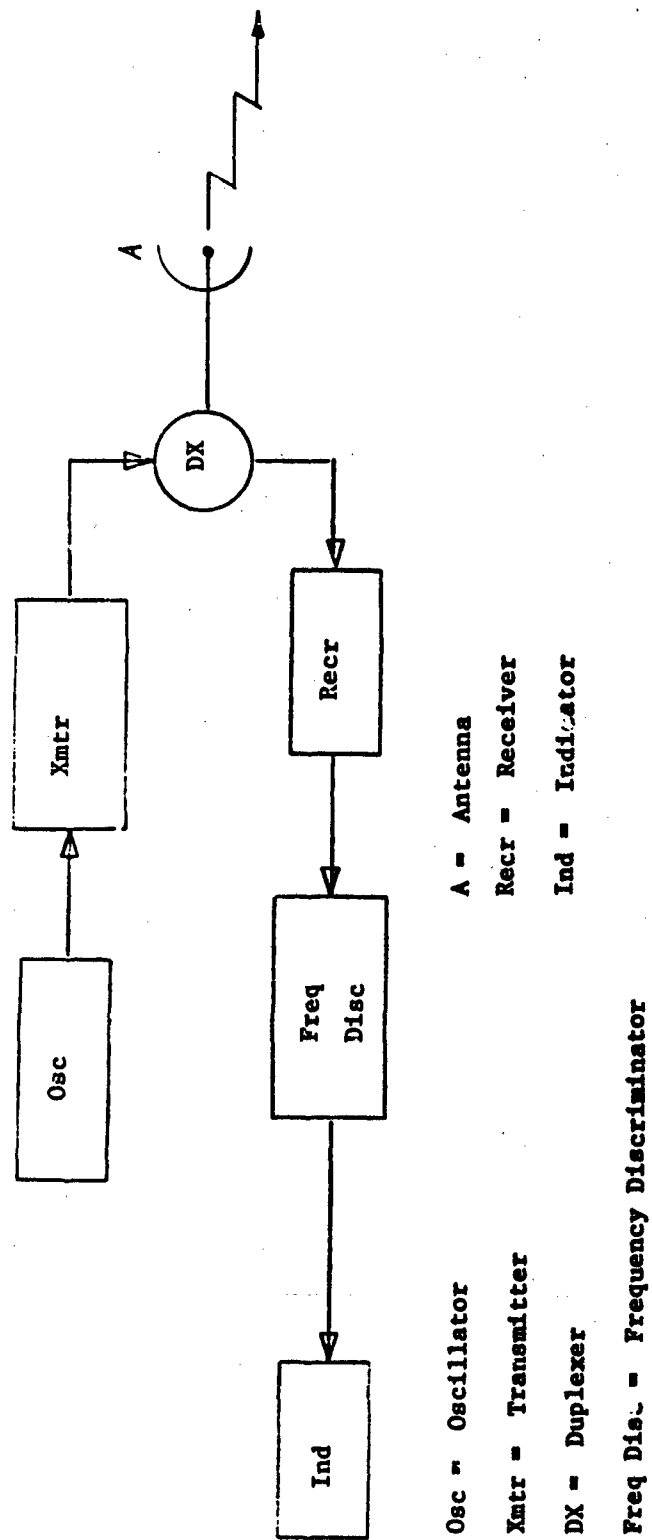
ω_R = Received Frequency

(Frequency Shift Exaggerated)

• Transmitted Waveform
 - Continuous Wave
 - No Pulsing
 - No Modulation

• Received Waveform
 - Continuous Wave
 - FM Modulated by Target Velocity
 - AM Modulated by Target Cross Section

Figure 2.11.2.1

2.26b

In order to illustrate the origins of the doppler frequency shift, the following discussion examines the apparent frequency of a short burst of sinusoidal carrier as it is transmitted, reflected, and received by stationary and moving vehicles. The first case of interest is that depicted in Figure 2.11.2.2. For this case, the transmitter is stationary and the receiver is closing with a velocity v_R as indicated in the figure, the doppler shift (Δf) due to receiver velocity is given by:

$$\Delta f = \frac{f_T v_R}{c}$$

[2.11.2.1]

where the symbols are defined in the figure. The second case of interest is that depicted in Figure 2.11.2.3. For this case, the receiver is stationary and the transmitter is closing with velocity v_T. As indicated in the figure, the doppler shift (Δf) due to transmitter velocity is given by:

$$\Delta f = \frac{f_T v_T}{c}$$

[2.11.2.2]

It can be seen that, except for second-order terms in v/C, equation [2.11.2.1] and equation [2.11.2.2] indicate that motion of the transmitter and motion of the receiver are equivalent. The third case of interest is that for which both the transmitter and the receiver are in motion as shown in Figure 2.11 2.4. As indicated in the figure, the doppler shift (Δf) is given by:

$$\Delta f = \frac{f_T (v_T + v_R)}{c}$$

[2.11.2.3]

2.27

$v_T = 0$

T

$nC_T = f_T \Delta T_T$

$v_P = C$

L_P

$L_P = C \Delta T_T$

v_R

R

$NC_R = NC_T = f_T \Delta T_T$

$\Delta T_R = \frac{L_P}{C + v_R} = \frac{C \Delta T_T}{C + v_R}$

$f_R = \frac{NC_R}{\Delta T_R} = f_T \left(1 + \frac{v_R}{C}\right)$

$\Delta f = f_R - f_T = \frac{f_T v_R}{C}$

Figure 2.11.2.2

2.27a
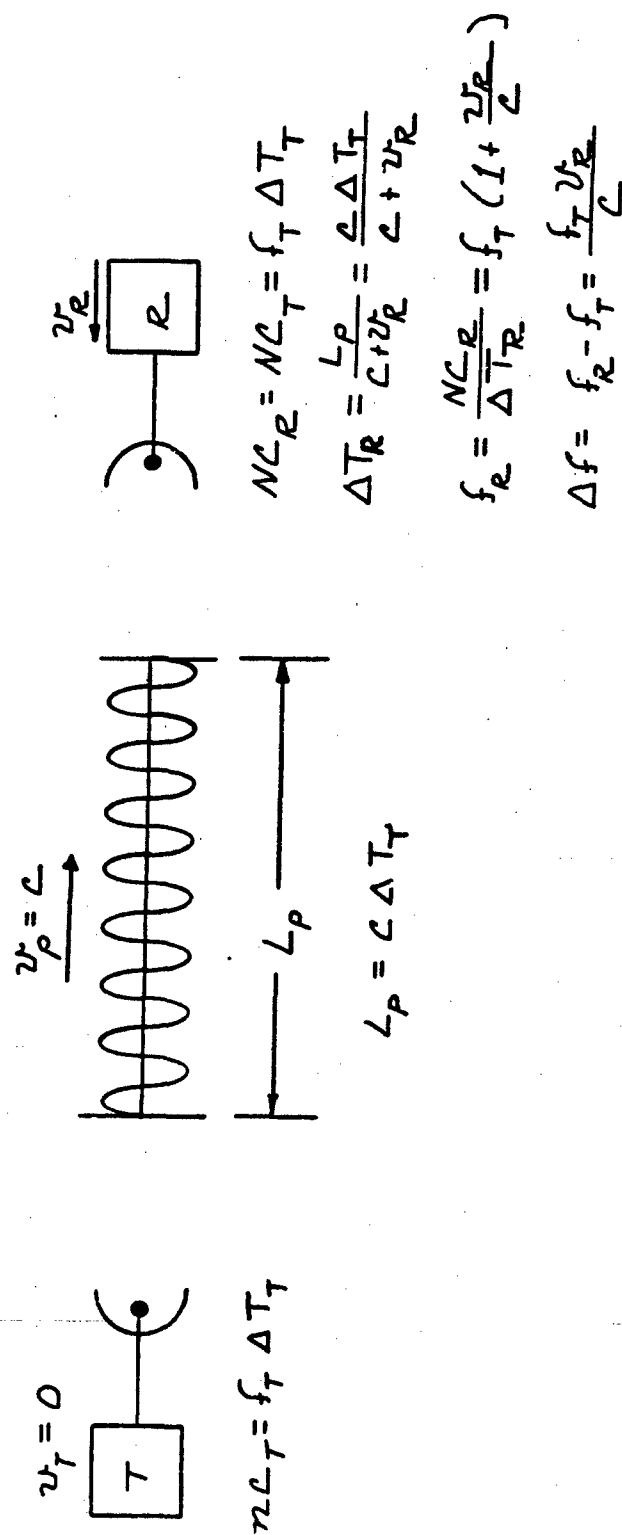
Doppler Shift
Due to Motion of Transmitter

$v_R = 0$

v_T

$v_P = C$

L_P

$L_P = (C - v_T)\,\Delta T_T$

$\frac{C}{2} \cdot \Delta t_T$

$C \cdot \Delta t_T$

$NC_T = f_T\,\Delta T_T$

$NC_R = NC_T = f_T\,\Delta T_T$

$\Delta T_R = \frac{L_P}{C} = \frac{(C - v_T)\,\Delta T_T}{C}$

$f_R = \frac{NC_R}{\Delta T_R} = \frac{f_T}{1 - v_T/C}$

$f_R = f_T\left(1 + \frac{v_T}{C}\right)$

$\Delta f = f_R - f_T \cong f_T\frac{v_T}{C}$
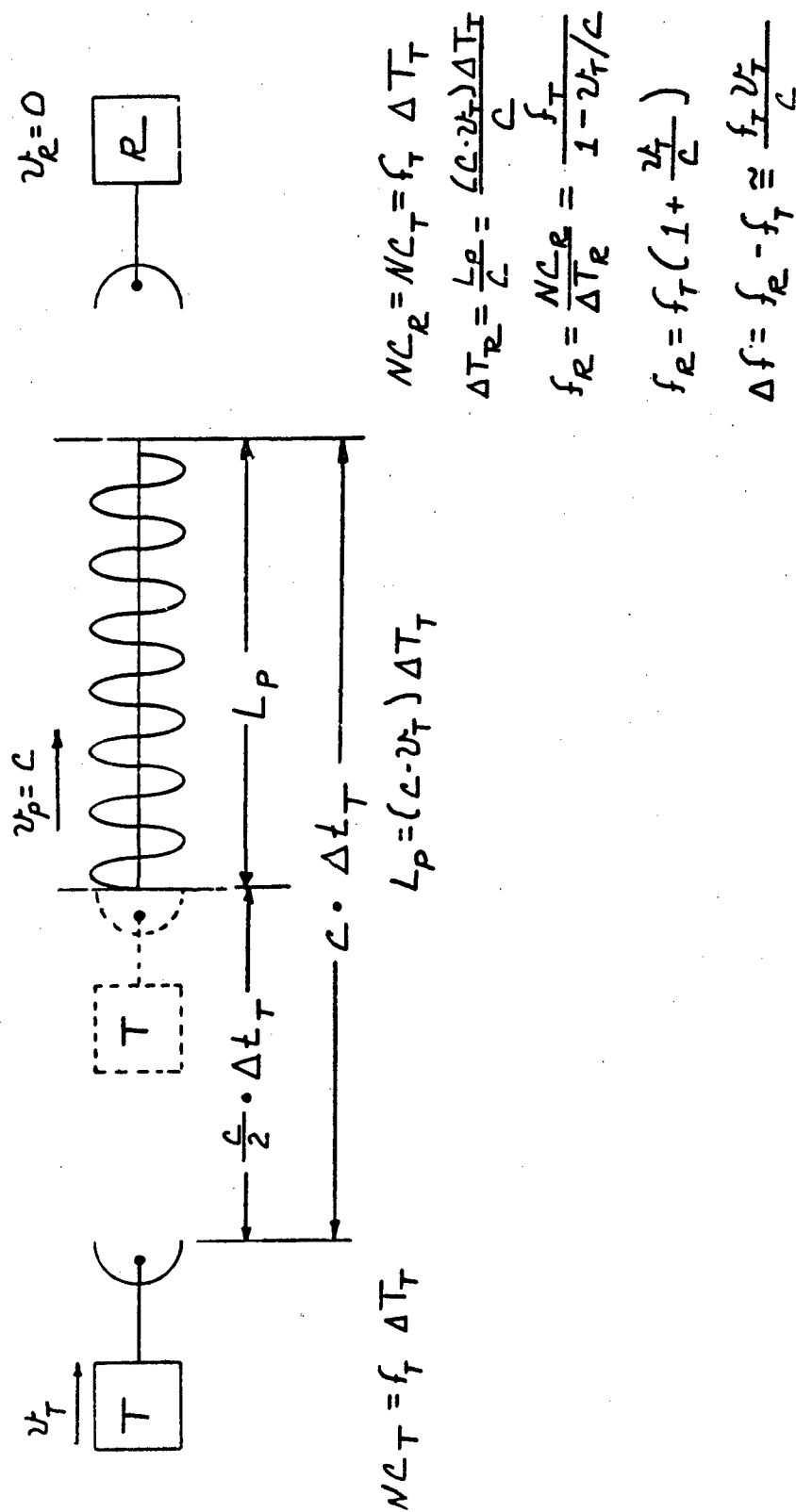
Figure 2.11.2.3

2.27b

Doppler Shift
Due to Motion of Both Transmitter & Receiver

$$NC_T = f_T \, \Delta T_T$$

$$v_p = c$$
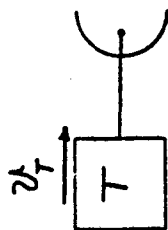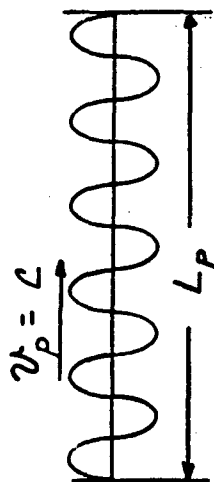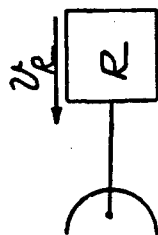
$$L_P = (c - v_T) \, \Delta T_T$$

$$NC_R = NC_T = f_T \, \Delta T_T$$

$$\Delta T_R = \frac{L_P}{c + v_R} = \frac{(c - v_T)\Delta T_T}{c + v_R}$$

$$f_R = \frac{NC_R}{\Delta T_R} = f_T \left(\frac{c + v_R}{c - v_T} \right)$$

$$f_R = f_T \left(1 + \frac{v_T + v_R}{c} \right)$$

$$\Delta f = f_R - f_T = \left(\frac{v_T + v_R}{c} \right) f_T = f_T \frac{v_T + v_R}{c}$$

Figure 2.11.2.4

2.27c

Equation [2.11 2.3] indicates, again, that it is the total velocity between transmitter and receiver that produces the doppler shift. The final case of interest is the case of co-located (monostatic) transmitter and receiver as shown in Figure 2.11.2.5. For this case, the transmitter/receiver is moving to the right with velocity v_{TR} and the target is moving to the left with velocity v_T. The transmission and reception of the radar pulse are the same as described in the previous cases. The reflection of the pulse by the target can be considered a second, simultaneous, reception and re-transmission of the signal. As indicated in the figure, the doppler shift for each transmit/receive operation is given by:

$$\Delta f = \frac{f_T v}{c} \qquad\qquad [2.11.2.4]$$

Thus, for the entire transmit/reflect/receive operation, the doppler shift is given by:

$$\Delta f = \frac{2 f_T v_r}{c} \qquad\qquad [2.11.2.5]$$

where v_r is the relative, radial component of velocity between the transmitter/receiver and the target.

Equation [2.11.2.5] can be solved for the relative target velocity, v_r, giving:

$$v_r = \frac{c \, \Delta f}{2 f_T} \qquad\qquad [2.11.2.6]$$

2.28

Doppler Shift

Due to Relative Motion of Target
With Respect to Transmitter/Receiver

$\mathcal{V}_{T/R}$

T/R

$\mathcal{V}_{TP} = c$

$\mathcal{V}_{RP} = c$

$\mathcal{V}_T$

Target

- $\dfrac{\Delta f}{f_o} = \dfrac{2\mathcal{V}_r}{c}$

- $\Delta f = \dfrac{2\mathcal{V}_r}{\lambda_o} \quad \left(\lambda_o = \dfrac{c}{f_o}\right)$

- $\mathcal{V}_r$ = Relative Radial Velocity of Transmitter/Receiver & Target

Figure 2.11.2.5

2.28a

From equation [2.11.2.6], it can be seen that the ability of a pure CW radar to determine target velocity depends upon its knowledge of the velocity of wave propagation, its ability to measure frequency differences, and the accuracy and stability of the frequency of the transmitted signal. The minimum detectable target velocity depends upon the monochromaticity and frequency stability of the transmitted signal. The primary application of an unmodulated CW radar is, of course, moving target detection. When the ground clutter return, (rather than the transmitted signal), is employed as the frequency-reference, target velocity relative to the ground can be measured. This type of velocity detection has found wide application in both the airborne moving target indicator (AMTI) and the moving-base speed detector employed by police.

2.11.3 Frequency Modulated CW Radar

As previously indicated, the CW radar can be given a ranging capability by time coloring the transmitted signal. One method of time coloring the signal is by frequency modulation. The block diagram of a frequency modulated CW radar is shown in Figure 2.11.3.1. The only change from the unmodulated system shown in Figure 2.11.1.1 is the addition of the frequency modulator. Otherwise the operation is the same as that described earlier. Any time-dependent-frequency modulation scheme can be employed. Operational systems have used both sinusoidal and linear frequency variations with time.

2.29

FM CW Radar

Osc = Oscillator   DX = Duplexer

Freq Mod = Frequency Modulator   A = Antenna

Xmtr = Transmitter   Recr = Receiver

Freq Disc = Frequency Discriminator Ind = Indicator

Figure 2.11.3.1

2.29a
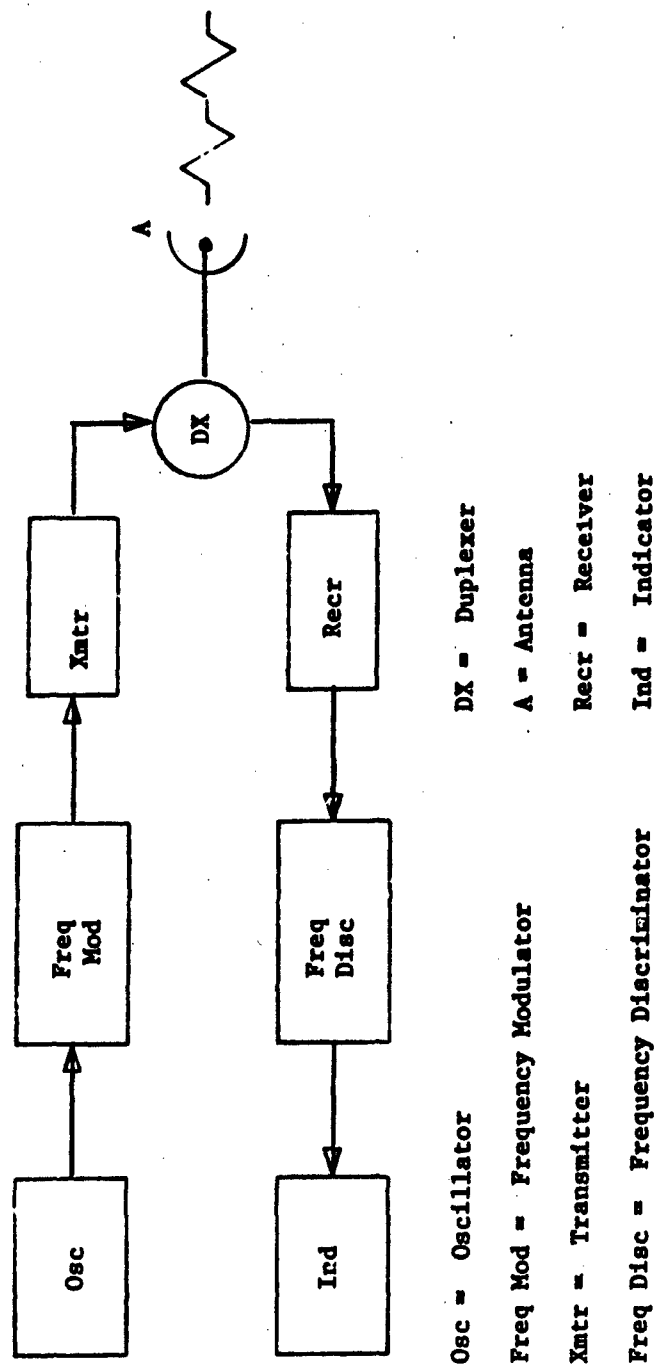
For purposes of illustrating FM ranging with a CW radar, a linear time variation of frequency will be assumed in the following development. Assume that the system shown in Figure 2.11.3.1 produces a CW transmitted signal of constant amplitude and with a frequency ramped up and down linearly with time as shown in Figure 2.11.3.2. At any point in time, the frequency of the return from a moving target, arriving back at the radar, will differ from the frequency of the transmitted signal. The frequency differential will be the result of two separate effects. As indicated in Figure 2.11.2.2, part of the differential will be due to doppler shift and part will be due to the change in the transmitted frequency during the time of flight of the radar pulses. The doppler shift is, of course, a measure of the target relative velocity, and shifts the return signal frequency curve vertically as shown in Figure 2.11.3.3. The time of flight of the pulses is a measure of target range, and shifts the curve horizontally as shown in Figure 2.11.3.4. Employing the notation presented on the figures, the total frequency differential, Δf_t, is equal to the sum of that due to relative velocity, Δfv, and that due to range, Δf_r.
That is:

$$\Delta f_T = \Delta f_v + \Delta f_r \qquad\qquad [2.11.3.1]$$

During the period of transmitted rise, then:

$$\Delta f_{Tr} = \Delta f_{vr} + \Delta f_{rr} \qquad [2.11.3.2]$$

And, during the period of transmitted frequency fall:

$$\Delta f_{Tf} = \Delta f_{vf} + \Delta f_{rf}$$

$$[2.11.3.3]$$

2.30

Frequency Modulation
(Saw Tooth)
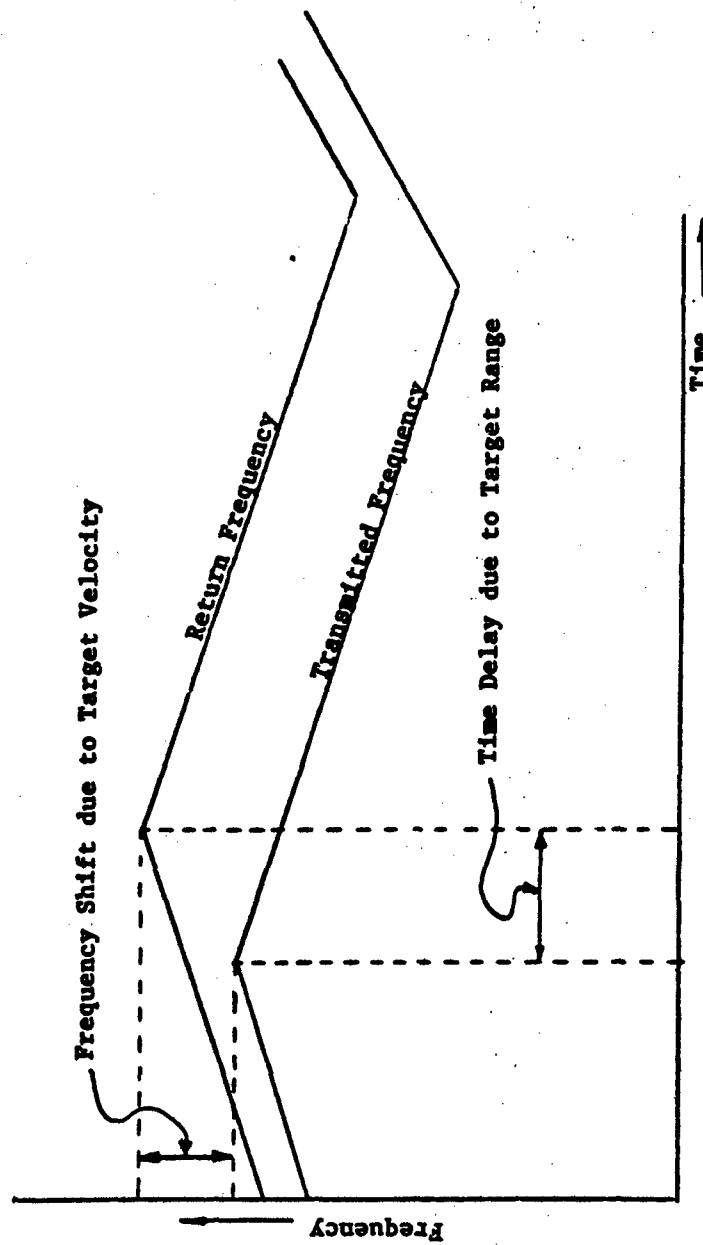
Figure 2.11.3.2

2.30a

Frequency Shift Due to Target Velocity

(At Zero Range)

Δf_{ν} = Doppler shift due to closing velocity

$$\Delta f_{\nu r} = \Delta f_{\nu f} = \Delta f_{\nu} = \frac{2Vf_T}{c}$$

Figure 2.11.3.3

2.30b
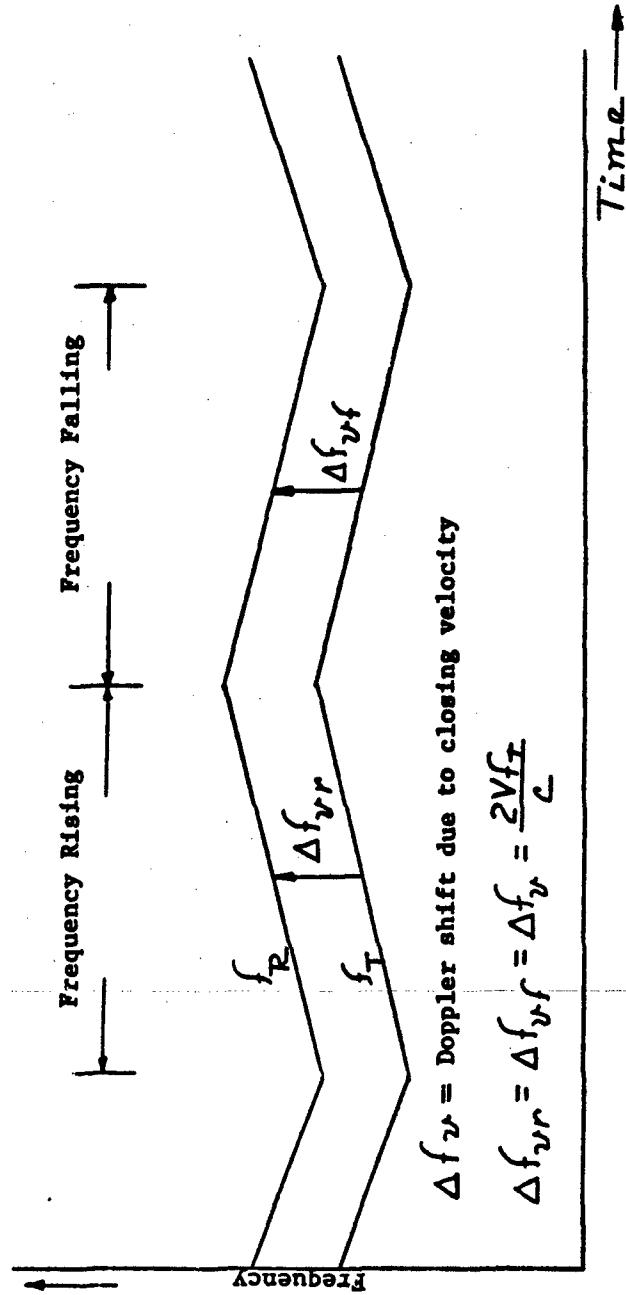
Frequency Shift Due to Target Range

(At Zero Relative Velocity)

Δt_r = Time Delay Due to Target Range

Δf_{rr} = Frequency Shift Due to Time Delay

$\Delta f_{rf} = -\Delta f_{rr} = \Delta f_r$

Figure 2.11.3.4

2.30c
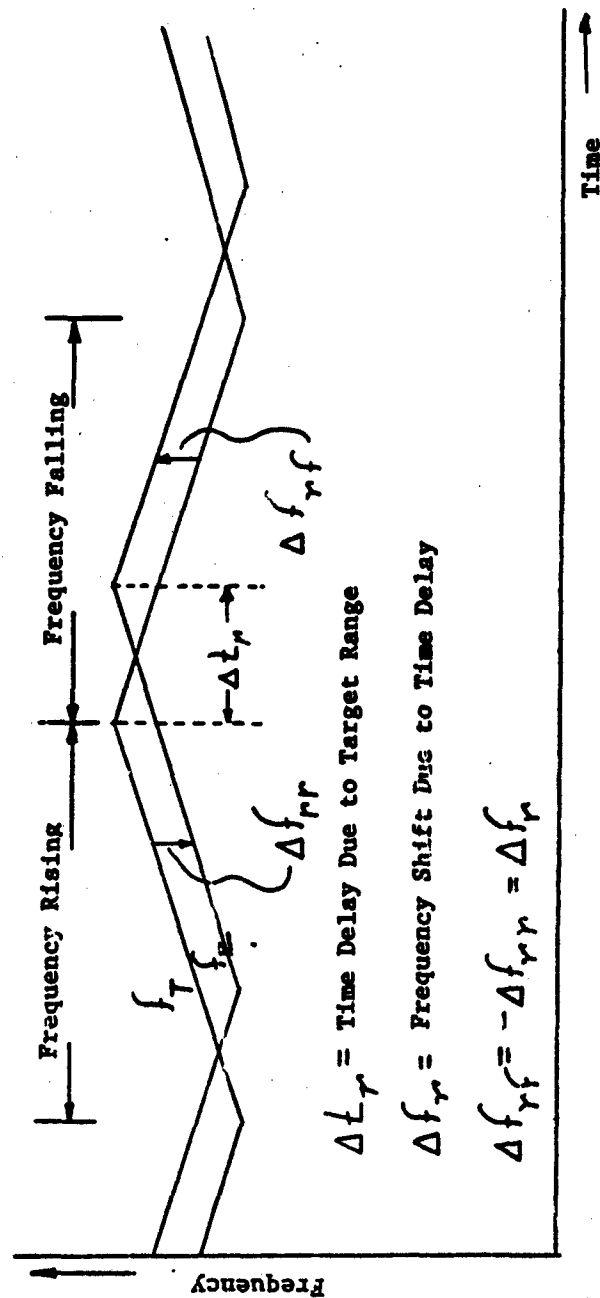
As previously indicated, the doppler shifts involved are:

$$\Delta f_{v_r} = \Delta f_{v_f} = \frac{2 f_T v_r}{c} \qquad [2.11.3.4]$$

where v_r is the radar/target relative, radial component of velocity. The frequency differentials due to range, Δf_r, are equal to the products of the time rates of change of transmitted frequency, $\pm \dot{f}$, and the pulse time of flight, $\frac{2R}{c}$, that is:

$$\Delta f_{r_r} = -\Delta f_{r_f} = -\frac{2 \dot{f}_T R}{c} \qquad [2.11.3.5]$$

where R is the radar/target range. Combining equations [2.11.3.2] to [2.11.3.4]:

$$\Delta f_{T_r} = \frac{2 f_T v_r}{c} - \frac{2 \dot{f}_T R}{c}$$

$$\Delta f_{T_f} = \frac{2 f_T v_r}{c} + \frac{2 \dot{f}_T R}{c} \qquad [2.11.3.6]$$

Equations [2.11.3.6] can be solved for target range and velocity, giving:

$$R = \left(\frac{c}{4 \dot{f}_T}\right)\left(\Delta f_{T_f} - \Delta f_{T_r}\right)$$

$$V = \left(\frac{c}{4 f_T}\right)\left(\Delta f_{T_f} + \Delta f_{T_r}\right) \qquad [2.11.3.7]$$

Thus, employing frequency modulation, both target range and velocity can be determined simply by taking the sum and difference of the frequency differentials during frequency rise and frequency fall. From equations [2.11.3.7] it can be seen that the ability of an FM – CW doppler radar to determine range and velocity depends upon the same factors previously discussed in this section for an unmodulated doppler radar.

2.31

2.11.4 Frequency Modulated Continuous-Wave Radar Parameters

2.11.4.1 Range Measurement -- The fundamental problem of range deter-
mination with and FM - CW radar is the same as that for a pulsed radar.
The only significant difference is that the quality of the measurement
depends on the ability of the radar to discriminate frequencies rather
than times of arrival.

2.11.4.2 Minimum Range -- Since target returns are received continuously
in an FM - CW radar, there are no minimum range or blind range problems.

2.11.4.3 Range Resolution -- For the reasons indicated in section 2.11.4.1
the range resolution of an FM - CW radar is a function of the radar's
ability to discriminate frequencies rather than times of arrival.

2.11.4.4 Range Ambiguity -- The range ambiguity in any radar is a result
of the periodicity of the time-coloring of the transmitted signal. For
that reason, the FM - CW radar exhibits a range ambiguity for ranges
greater than the maximum unambiguous range, R_{MU}, given by:

$$R_{MU} = \frac{c T_r}{2} \qquad \qquad [2.11.4.1]$$

where Tr is the modulation repetition interval.

2.11.4.5 Directional Measurement -- Whether accomplished by a narrow-beam
antenna or by interferometer techniques, the directional measurement with

2.32

an FM - CW radar is identical to that for a pulse radar as described in sections 2.3.5 to 2.3.7.

2.11.4.6 Maximum Range -- The radar range equation for an FM - CW radar is the same as that for a pulse radar, as described in section 2.4 It should be noted, however, that for a CW radar, average power and peak power are equal.

2.12   Pulse-Doppler Radar

2.12.1   The Effects of Pulsing a Doppler Radar

A pulse doppler radar is essentially a pulse radar to which has been added the ability to discriminate between return signals on the basis of frequency. The block diagram for a basic pulse doppler radar is presented in Figure 2.12.1.1. In that figure, the frequency-discriminating (velocity-determining) and time-measuring (range-determining) circuits are shown in parallel. In most existing systems, the two operations are performed in tandem and are not so well separated. The principal advantage of pulsing a doppler radar is, of course, the elimination of the problem of isolating the receiver from the signal due to leakage from the transmitter and from unwanted returns reflected from nearby objects such as the radome.   (Note that ranging could be performed without pulsing by, for example, frequency modulating the carrier as previously discussed.)

The concept of pulsing a doppler radar seems, at first glance, quite simple. There is, however, a major complication: frequency folding or aliasing. In any sampled-data system, the sampling process creates new frequencies, replicating the original signal spectrum, in the frequency domain, at intervals equal to the sampling rate. Thus, the process of pulsing a pure sinusoidal carrier, as indicated in Figure 2.12.1.2(a), creates the spectrum shown in Figure 2.12.1.2(b).

2.34

Basic Pulse Doppler Radar

Figure 2.12.1.1

2.34a
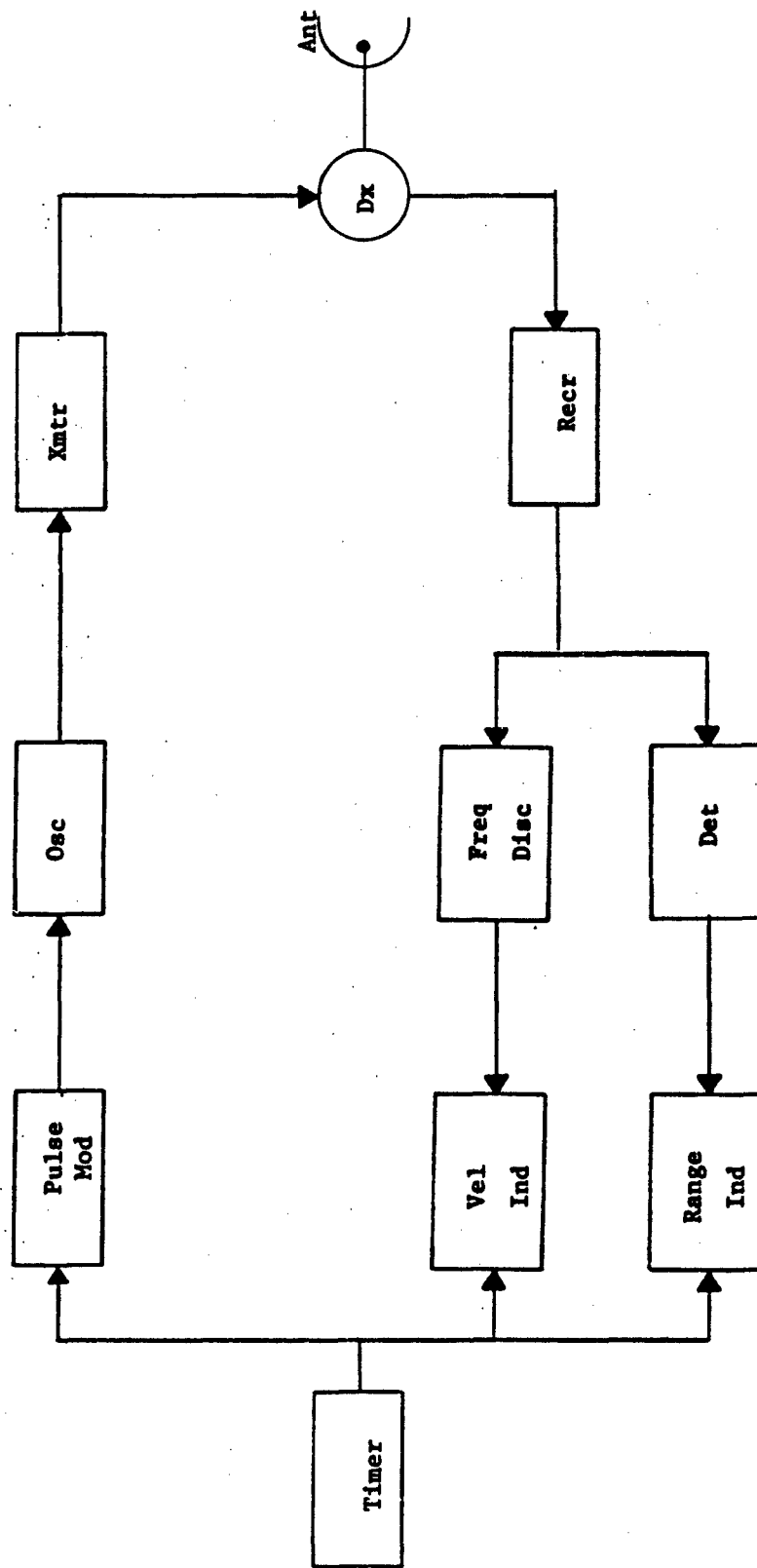
Coherent Pulse Waveform

(a) TIME DOMAIN

$P(t)$

$\sin \omega_0 t$

$P(T) \sin \omega_0 t$

(b) FREQUENCY DOMAIN

$$\sum \left(\frac{\tau}{T} \cdot \frac{\sin n\pi \frac{\tau}{T}}{n\pi \frac{\tau}{T}} \right)^2 \quad \text{ENVELOPE}$$

NOTE: SPECTRAL LINES VANISH FOR NO PHASE COHERENCE
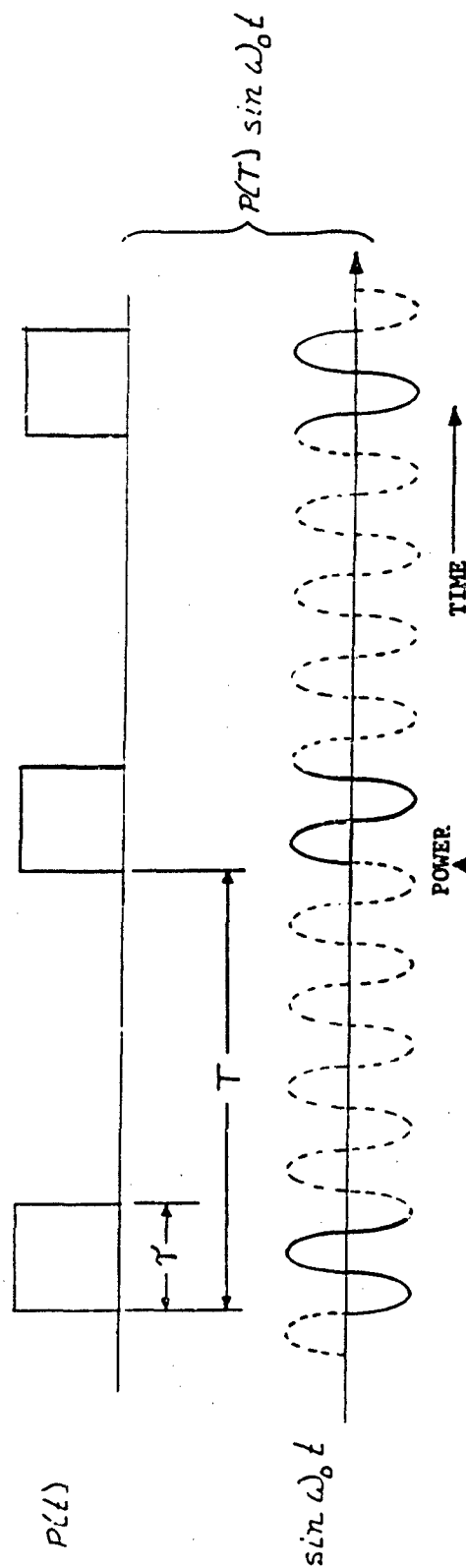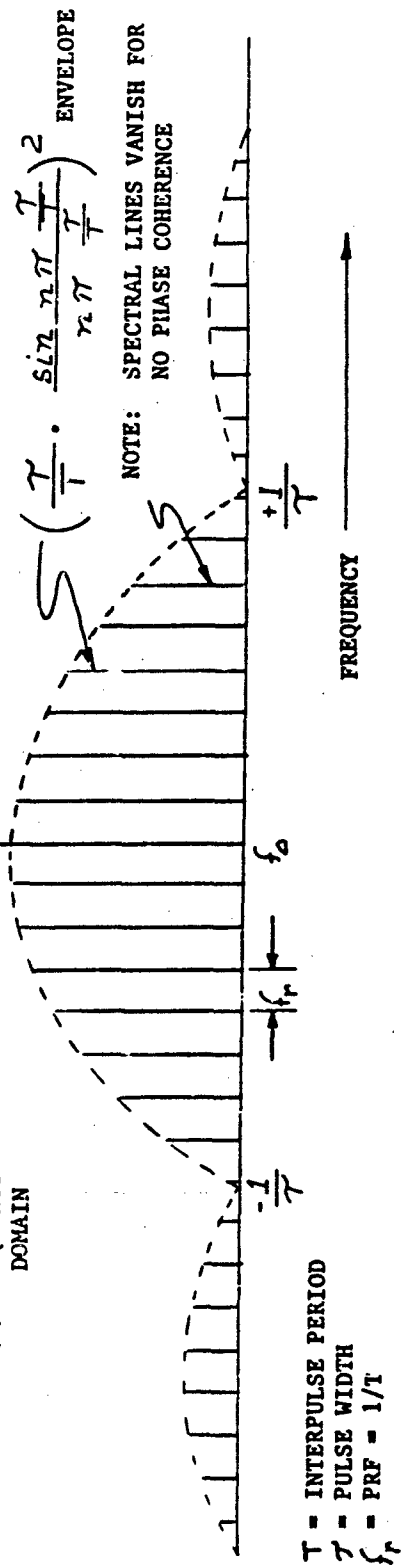
T = INTERPULSE PERIOD
τ = PULSE WIDTH
f_r = PRF = 1/T

2.34b

Figure 2.12.1.2

The most difficult operation in a doppler radar is that of measuring the frequency shift of the return. The creation of a multitude of new signal frequencies is, therefore, a serious matter. For every new frequency in the transmitted signal, there will be a corresponding frequency, somewhat shifted by the doppler effect, in the return signal. It is the task of the doppler processor to match these signals by pairs and determine the doppler shift. Unless the pulse repetition frequency is extremely high, creating a very large spacing between the replicated signals, the situation will be as shown in Figure 2.12.1.3 where the doppler shift is several times the spacing between the replicated frequencies in the transmitted signal. Under such circumstances, the doppler processor is unable to identify the relevant frequency pairs and, therefore, gives an ambiguous indication of target velocity. In Figure 2.12.1.4 are presented typical pulse repetition frequencies, a typical doppler shift, and the relative spacings in the frequency domain.

2.12.2 Airborne Pulse Doppler Radar Returns

The antenna radiation pattern for a typical airborne pulse doppler radar is shown in Figure 2.12.2.1. In addition to the main lobe, intended to illuminate the targets of interest, there are side lobes which illuminate the ground both before and behind the antenna. The spectrum (frequency content) of the radar returns will be similar to that shown in Figure 2.12.2.2. The frequency of any given return will be determined by two factors: the transmitted frequency and the relative, radial component of

2.35

Frequency Domain

Transmitted
Spectrum

f_o

Frequency

Doppler
Shift

Received
Spectrum
(Point Target)

f_o

Frequency

Figure 2.12.1.3

Doppler Shift = $\dfrac{-2V_R}{\lambda}$

For X Band, $\lambda \cong 0.1\,FT.$

$\therefore$ D.S. $\cong \dfrac{20\ Hz}{Ft/Sec}$

$\cong \dfrac{33\ Hz}{Knot}$

$\cong \dfrac{19\ KHz}{Mach}$

2.35a
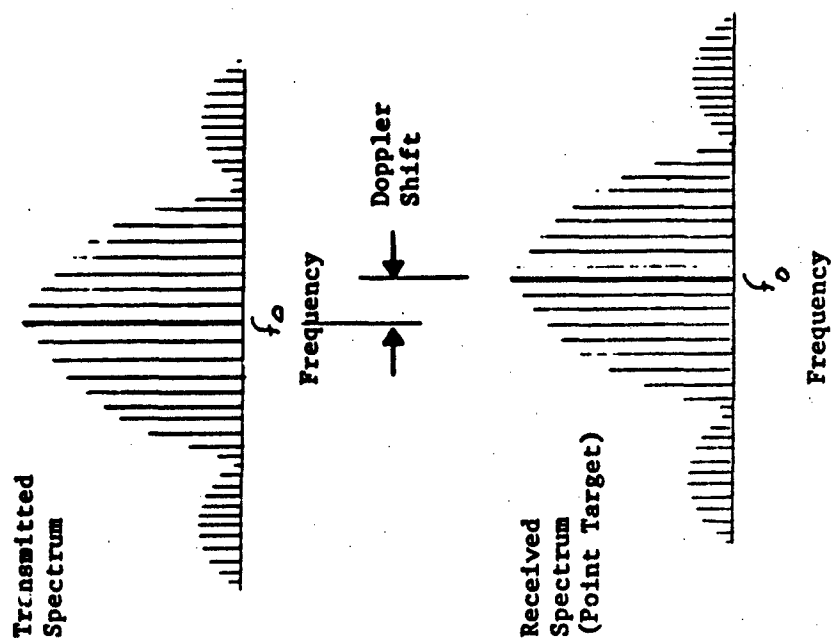
Effect of PRF on Spectrum

Time Domain
(1 MSEC ≈ 80 Miles)

Frequency Domain
(18.5 KHz ≈ Mach 1)

CW

High PRF

Medium PRF

Low PRF

300 KHz

20 KHz

1 KHz

$3.3 \mu s$

$50 \mu s$

$1000 \mu s$

300 KHz

20 KHz

1 KHz
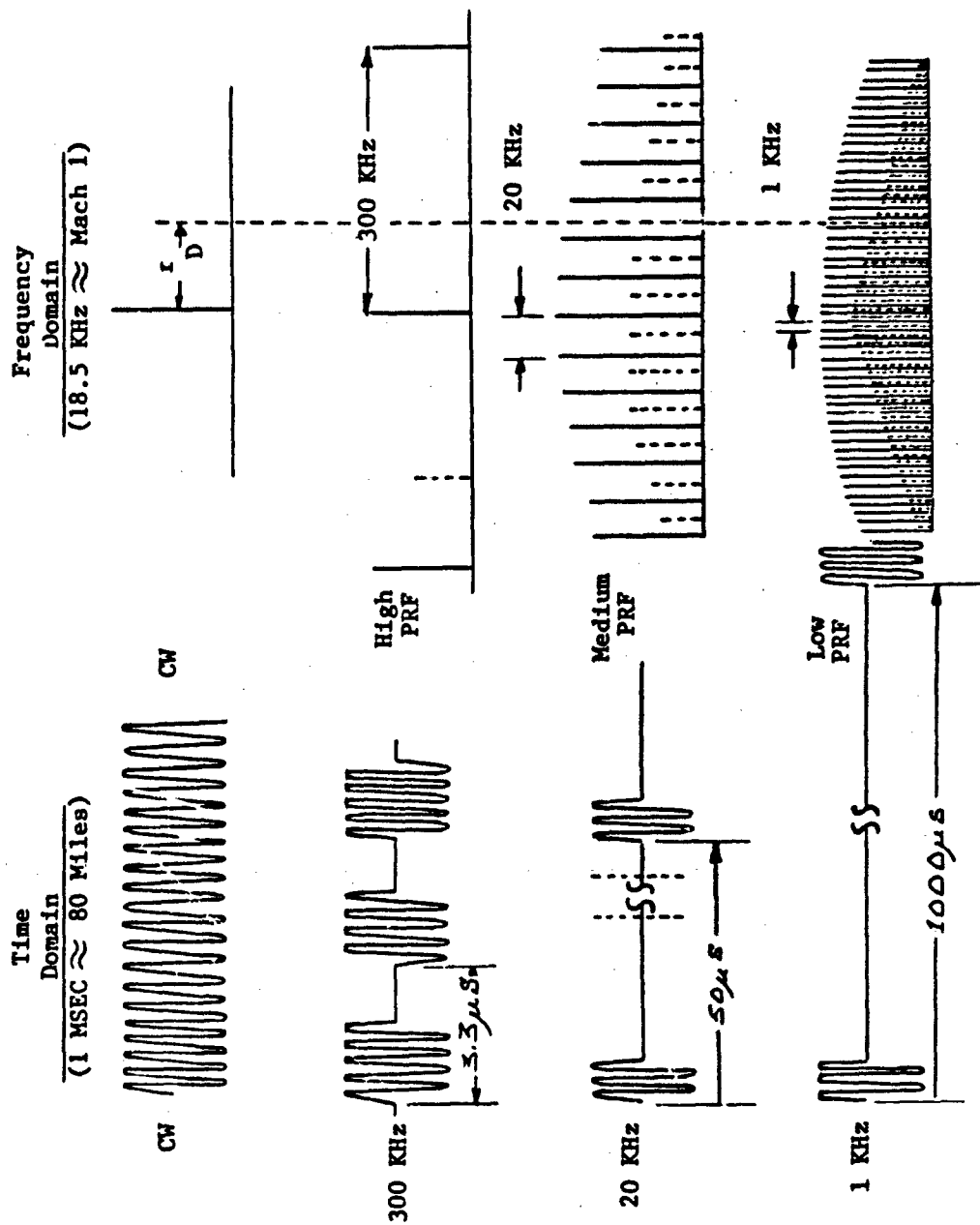
Figure 2.12.1.4

2.35b

Antenna Energy Radiation Pattern

Main Lobe

Portion of Main Lobe Strikes Ground at Long Range

$$f = \frac{2V}{\lambda}$$

Velocity Return

Ground Moving Target

Sidelobe Return

Altitude Return

Figure 2.12.2.1

2.35c
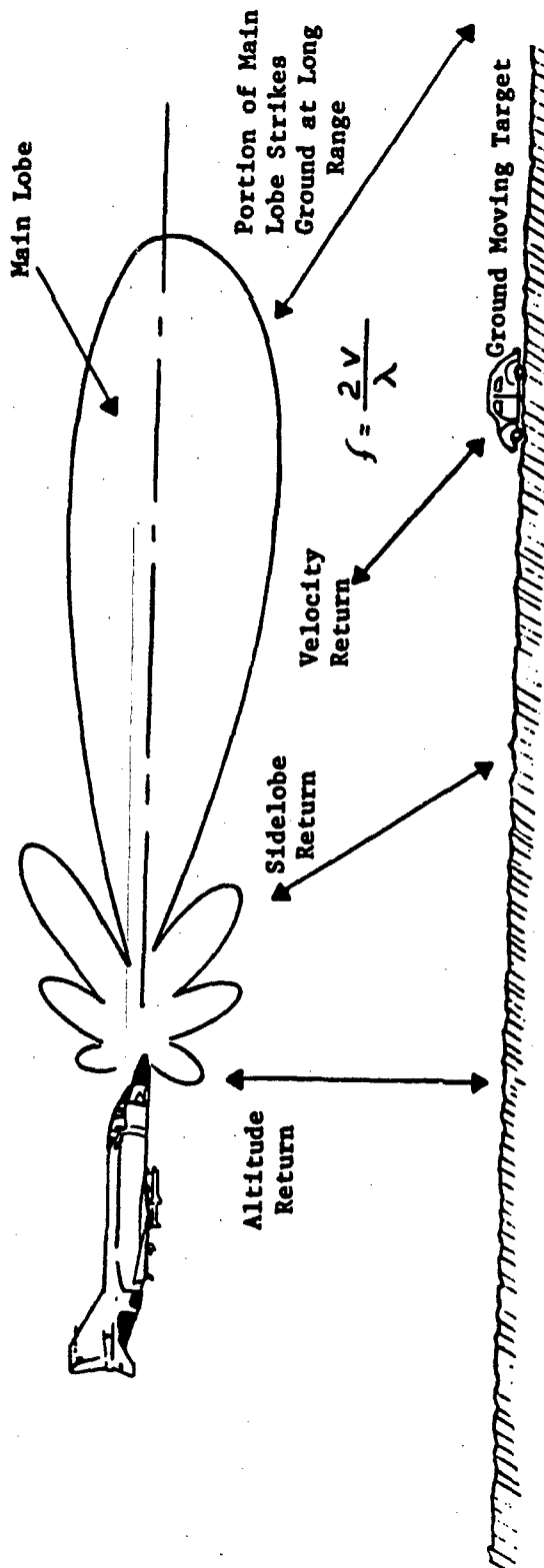
Airborne Doppler Return Spectrum

(Primary Spectrum Only)

Altitude Return

Main Lobe Clutter

Closing Target Return

Sidelobe Clutter

Noise

Power

$f_o - \dfrac{2Va/c}{\lambda_o}$

f_o

$f_o + f_{gr}$

$f_o + f_{dt}$

$f_o + \dfrac{2Va/c}{\lambda_o}$

f
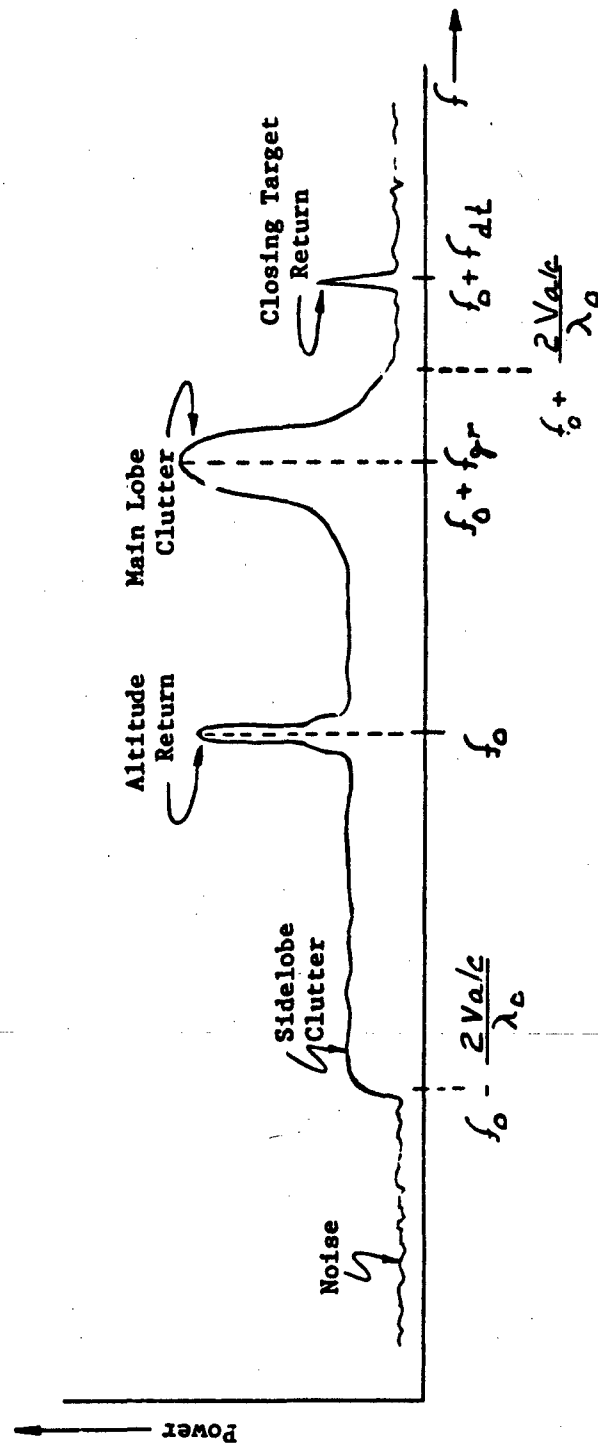
$f_o, \lambda_o =$ Transmitted Carrier Frequency, Wave Length

$f_{gr} =$ Doppler Shift of Ground Return Due to Va/c

$f_{dt} =$ Doppler Shift of Target Return Due to V_{tr}

$Va/c =$ Relative Radial Velocity of Aircraft with respect to Illuminated Ground Area

$V_{tr} =$ Relative Radial Velocity of Target with respect to Aircraft

Figure 2.12.2.2

2.35d

velocity between the reflecting object and the radar. The frequency of

the main lobe clutter (large return from the area where the main lobe

hits the ground), fo+fgr, is due to the radial component of the ground

speed of the radar-carrying aircraft. Note that the radial component

of ground speed with respect to a given spot on the earth will depend

on three variables: the aircraft velocity vector, the antenna depression

angle, and the antenna scan angle off the nose of the aircraft. There-

fore, the frequency of the main lobe clutter continuously changes as

the aircraft changes velocity and altitude, as the antenna scans, and as

the topography of the terrain changes. The frequency of the altitude

return is fo. (The rate of closure of the aircraft with the ground

directly under the aircraft is assumed to be zero). The entire clutter

pedestal, due to antenna main and side lobes hitting the ground, extends

from a minimum frequency of $\left(f_0 - \dfrac{2V_{a/c}}{\lambda_0}\right)$ to a maximum frequency

of $\left(f_0 + \dfrac{2V_{a/c}}{\lambda_0}\right)$. The value $2V_{a/c}/\lambda_0$ is the doppler shift

that would result from the radar aircraft flying directly toward a fixed

object on the ground (a mountain, perhaps). The target return shown in

the figure is assumed to be from a target closing on the radar aircraft

at a rate somewhat in excess of that of the ground itself. There is, of

course, a certain amount of noise signal present at all frequencies.

Only the primary (non-folded) spectrum of the radar returns is shown in

Figure 2.12.2.2. Due to the pulsing, this spectrum is replicated, up

and down the frequency scale, at intervals of the pulse repetition fre-

quency, fr. This effect is illustrated in Figure 2.12.2.3. In that

2.36

Airborne Doppler Return Spectrum
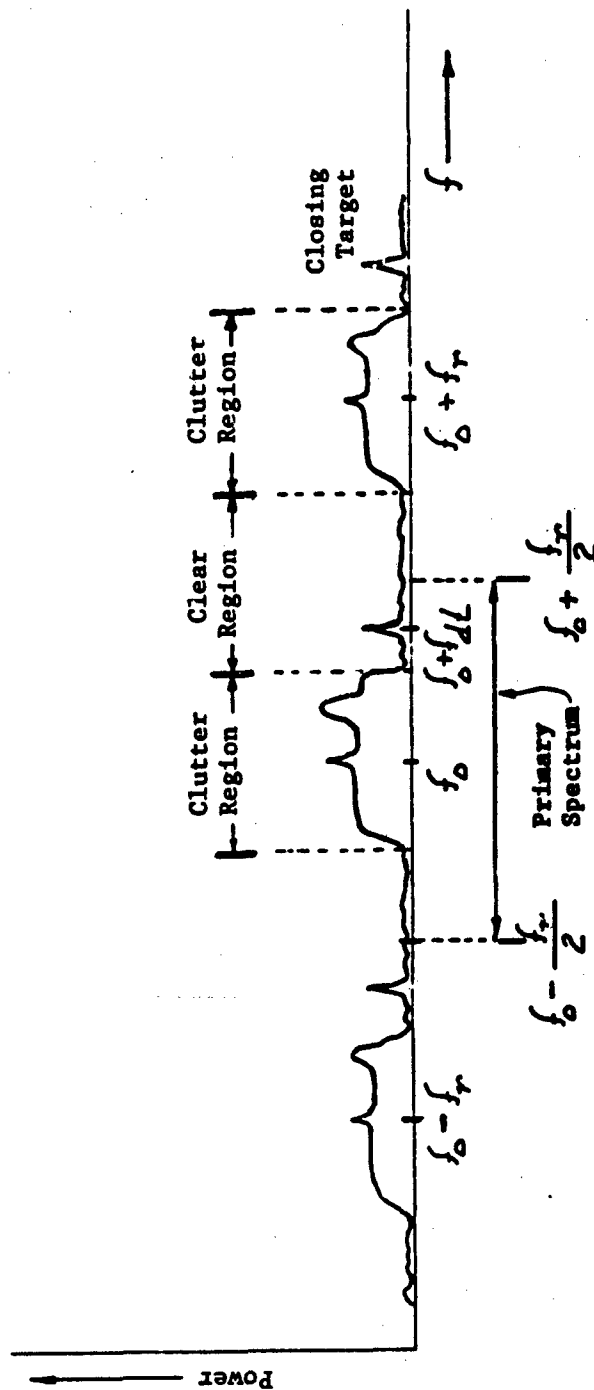
f_o = Transmitted Carrier Frequency

f_r = Pulse Repetition Frequency

f_{dt} = Doppler Shift Due to Target Velocity

Figure 2.12.2.3

figure are defined the primary spectrum, the clutter regions, and the clear regions. It is important to note that the phenomenon of frequency folding is such that every signal appearing in any portion of the spectrum must also appear, somewhat attenuated, in every other corresponding (folded) portion of the spectrum. Thus, a target actually appearing in the primary spectrum will be aliased to all folded spectra as shown. On the other hand, a target actually appearing in one of the folded spectra will be aliased into every other folded spectrum as well as the primary spectrum. For example, a rapidly opening target will also appear as a slowly closing target.

It is, of course, desirable to detect a target in the clear region, where the ratio of the signal strength of the target return to that of the noise and clutter signals is greatest. Some radars filter out all returns not in the clear region, thus presumably obtaining a less-cluttered presentation. Other radars allow the operator to look into the clutter pedestal, on the basis that it is sometimes possible to detect a target through the clutter.

2.13 Pulse Doppler Radar Parameters

2.13.1 Range Measurement -- If pulse ranging is employed, the character-
istics of range measurement for a pulse doppler radar are identical to
those described in Sections 2.3.1 to 2.3.4 and 2.3.8 for pulse radars in
general. If frequency modulation ranging and a very high PRF are employed,
the range measurement characteristics are identical to those described in
Section 2.11 for FM - CW ranging. Note that the very high pulse repetition
frequency prevents velocity anomalies due to frequency folding.

2.13.2 Directional (Angle) Measurement -- If directional measurement is
accomplished using a narrow beam antenna as described in Section 2.3.5,
the characteristics of directional measurement (accuracy, resolution,
ambiguity, etc.) for a pulse doppler radar are identical to those described
in Sections 2.3.5 to 2.3.7 for pulse radars in general.

If directional measurement is accomplished by interferometry as described
in Section 2.3.5, the angular accuracy is independent of antenna beam pattern
and depends upon the ability of the radar to measure relative phase. If
the phase-measuring accuracy of the radar is $\delta\phi$, the angular determina-
tion accuracy, $\Delta\theta$, is given by:

$$\Delta\theta = \left(\frac{\lambda_o}{2\pi d}\right)\delta\phi$$

[2.13.1]

where d is the linear separation of the two antennas and λ_o is the signal
wavelength. Equation [2.13.1] also applies to angular resolution for an

2.38

interferometer radar. That is, if the phase-measuring resolution of the radar is $\delta\phi$, the angular resolution, $\Delta\theta$, is given by equation [2.13.1].

The angle ambiguities of an interferometer radar are independent of the beam patterns of the individual antennas. The maximum unambiguous target angle off boresight is due to phase angle ambiguity and is given by:

$$\theta_{MU} = \frac{180\,\lambda_o}{\pi\,d}$$

[2.13.2]

where the parameters are defined as for equation [2.13.1].

2.13.3 Velocity Measurement -- The ability of the pulse doppler radar to determine target velocity is a function of its ability to measure frequency shift. If the frequency shift-measuring accuracy of the radar is δf , the velocity determination accuracy is given by:

$$\Delta v_r = \left(\frac{\lambda_o}{2}\right)\delta f$$

[2.13.3]

Similarly, if the frequency resolution is δf , the velocity resolution, Δv_r, is then given by equation [2.13.3].

2.13.4 Clear Region Velocities

In order for a target return to fall within the first upper clear region as shown in Figure 2.12.2.3, the target's radial velocity with respect to the radar aircraft, Vtr, must satisfy the following inequality with

2.39

respect to the radar aircraft's ground velocity, Va/c:

$$\left(f_0 + \frac{2 V_{a/c}}{\lambda_0}\right) \leq \left(f_0 + \frac{2 V_{tr}}{\lambda_0}\right) \leq \left(f_0 + f_r - \frac{2 V_{a/c}}{\lambda_0}\right) \quad [2.13.4]$$

Thus, the target velocity, Vtr, must satisfy the inequalities:

$$V_{tr} \leq \left(\frac{\lambda_0 f_r}{2} - V_{a/c}\right)$$

$$[2.13.5]$$

$$V_{tr} \geq V_{a/c}$$

Thus, in order for the target return not to fall within the first upper folded clutter pedestal, the pulse repetition frequency, fr, must satisfy the inequality:

$$f_r \geq \frac{2}{\lambda_0}\left(V_{a/c\,(Max)} + V_{tr\,(Max)}\right) \quad [2.13.6]$$

where Va/c (Max) and Vtr (Max) are the maximum expected values for the respective aircraft relative velocities and λ_0 is the radar signal wavelength.

2.13.5 Target Velocity Ambiguity

The radar return primary spectrum is defined as that range of frequencies that falls between the mid-point of the first lower clear region and the mid-point of the first upper clear region as shown in Figure 2.12.2.3. In order to avoid target velocity ambiguity, (mistaking a slowly closing target for a rapidly opening target for instance), the target return

2.40

must fall within the primary spectrum region as shown in that figure. This constraint requires that the radial velocity of the target relative to the radar satisfy the inequality:

$$|V_{tr}| \lesssim \frac{\lambda_0 f_r}{4}$$

[2.13.7]

or that the radar pulse repetition rate satisfy the inequality:

$$f_r \gtrsim \frac{4 \, V_{tr}(Max)}{\lambda_0}$$

[2.13.8]

where Vtr (Max) is the maximum expected radial velocity of the target relative to the radar.

2.13.6 Target Blind Speeds

When the doppler shift (relative velocity) of the target places its return in one of the frequency ranges occupied by the clutter pedestals, it is said to be at a "blind speed". The blind speeds are, therefore, defined as those relative, radial target velocities for which:

$$f_{dt} = n \, f_r$$

[2.13.9]

where n is an integer, zero or greater. The blind speeds are then:

$$V_{tr} = \frac{n \, \lambda_0 \, f_r}{2}$$

[2.13.10]

2.41

2.13.7 Velocity and Range Ambiguity Tradeoff

As indicated in Section 2.13.4 and 2.13.5, a high pulse repetition fre-
quency is required to avoid velocity ambiguities and blind speeds. In
Sections 2.3.4 and 2.3.8, however, it was demonstrated that, for a pulse
ranging radar, a low pulse repetition frequency is required to avoid
range ambiguities and blind ranges. These conflicting requirements
create a dilemma for the radar designer because, for typical airborne
radar applications, these requirements cannot simultaneously be satisfied
by a judicious choice of pulse repetition frequency. In Figure 2.13.7.1
is shown a tradeoff chart relating pulse repetition frequency and carrier
frequency to maximum unambiguous range and maximum unambiguous target
velocity, for a pulse doppler radar. From this chart, it can be seen
that the conflicting velocity and range requirements create a serious
problem for the radar designer. That is, for typical airborne radar
applications, no single pulse repetition frequency satisfies both require-
ments. Some operational systems switch pulse repetition frequency to
achieve satisfactory operation for a given situation. Another approach
is that of employing a high pulse repetition frequency to avoid velocity
ambiguity and employing a superimposed frequency modulation for ranging,
thus avoiding the range ambiguities that would be produced by the high
pulse rate. The radar evaluator should be aware of the design tradeoffs
and should plan his test program to examine their anticipated impact on
performance.

2.42

RANGE/VELOCITY AMBIGUITY TRADEOFF

Figure 2.13.7.1

2.42a
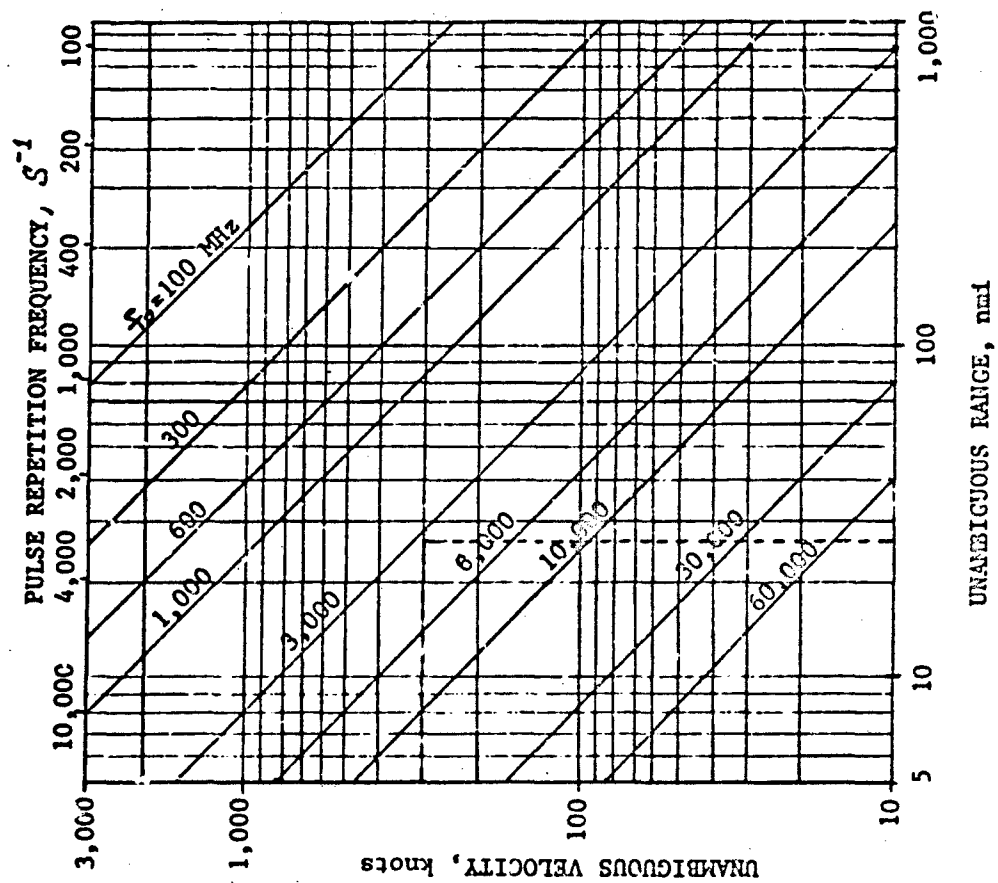
2.13.8 Jet Engine Modulation

As previously indicated, the most difficult task for a doppler radar is the determination of the small frequency shifts due to the doppler effect. This task is complicated by an effect known as jet engine modulation (JEM). This effect is caused by the reflection of the radar beam from the moving blades in an aircraft turbine engine, as shown in Figure 2.13.8.1. The doppler shift caused by the velocity of the turbine blades alters the spectrum of the overall radar return, thereby causing false indications of aircraft velocity. The magnitude of the spurious signals can be surprisingly large and can cause a velocity tracker to break lock.

The JEM signature of a particular aircraft/engine depends upon the turbine RPM, the number of turbine blades, the geometry of the surrounding structure, and the radar look angle. JEM signature can be used as a means for identifying a target beyond visual range.

2.43

Jet Engine Modulation (JEM)

Rotating Turbine Blades Produce Modulation of Doppler Radar Return
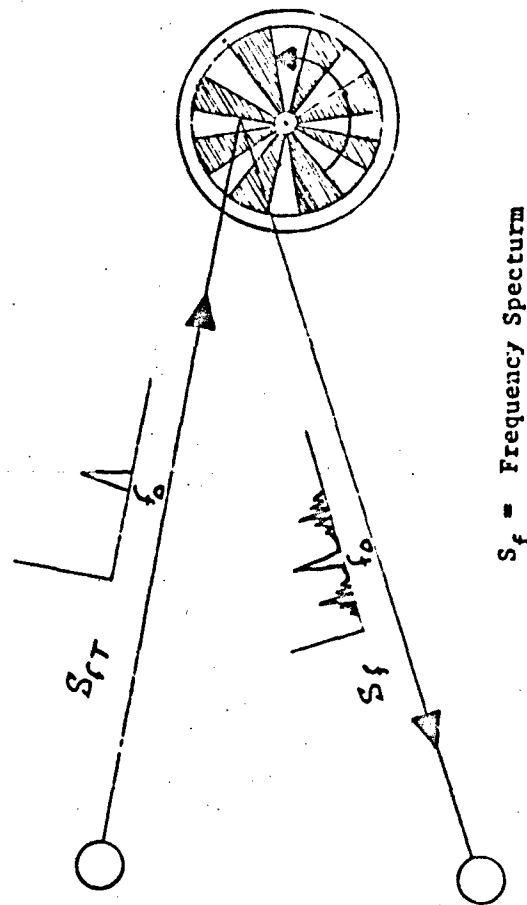
S_f = Frequency Specturm

Figure 2.13.8.1

2.14 Range and Velocity Measurement

In a pulse Doppler radar, range is generally determined by a process called range gating in which a series of switches are closed, one at a time, at measured intervals after the radar pulse is transmitted. Target range is determined by noting which switch was closed at the time the target return arrived. This arrangement is shown in Figure 2.14.1. An advantage of the range gate method is that the background noise entering the receiver in competition with the target signal is limited to that which enters while that one range gate is open, thus improving the signal-to-noise ratio considerably.

One method of determining the Doppler shift (frequency) of the target return, and hence the relative velocity of the target, is to pass it, in parallel, through a bank of narrow-band, bandpass filters as shown in Figure 2.14.1. The Doppler shift is then determined by noting which of the filters passed the signal. As in the case of range gating, this method of "sorting" the target returns eliminates much of the background noise, thereby greatly improving the signal-to-noise ratio.

The range gating and Doppler filtering processes create range "bins" and velocity "bins" as shown in Figure 2.14.2(a) and 2.14.2(b), respectively. The corresponding "footprint" for an air-to-ground radar is shown in Figure 2.14.3. The overall block diagram for a typical pulse Doppler radar is presented in Figure 2.14.4. In this arrangement the return signal is first heterodyned down to intermediate frequency and passed

Range Gating
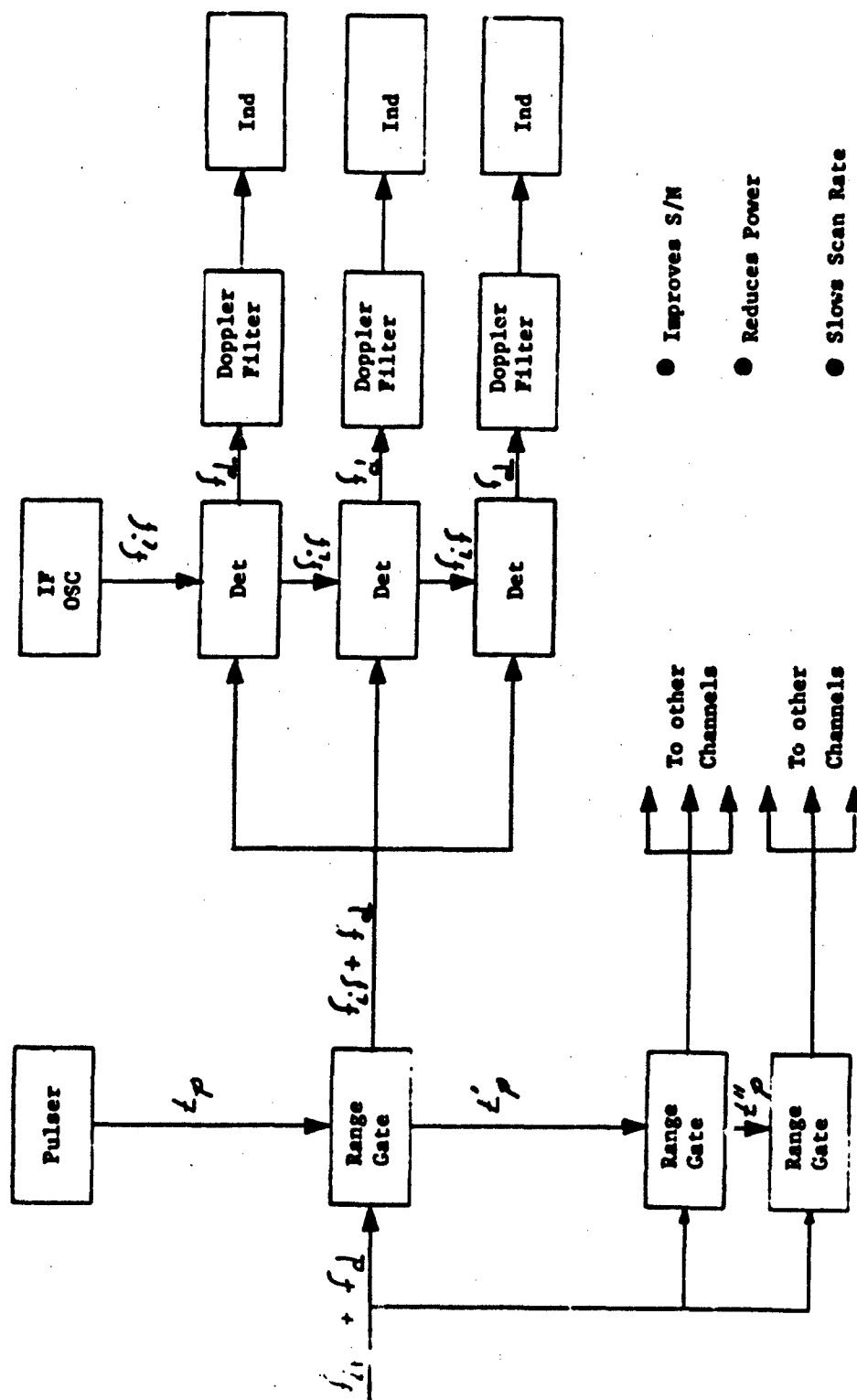
Figure 2.14.1

(a) TEMPORAL RETURN (PULSE)

Airborne Doppler Return Spectrum

TRANSMIT PULSE

ALTITUDE MARK

SIDE LOBES

MAIN LOBE

TARGET

RANGE GATES

time ⟶

(b) SPECTRAL RETURN

ALTITUDE LINE (ZERO DOPPLER)

SIDE LOBES

MAIN LOBE

DOPPLER FILTERS

MOVING TARGET ECHO

$$f_0 - \frac{2V_a}{\lambda}$$

$$f_0$$

$$\frac{2V_a}{\lambda}\cos\eta_t$$

FREQUENCY

$$f_0 + \frac{2V_a}{\lambda}$$
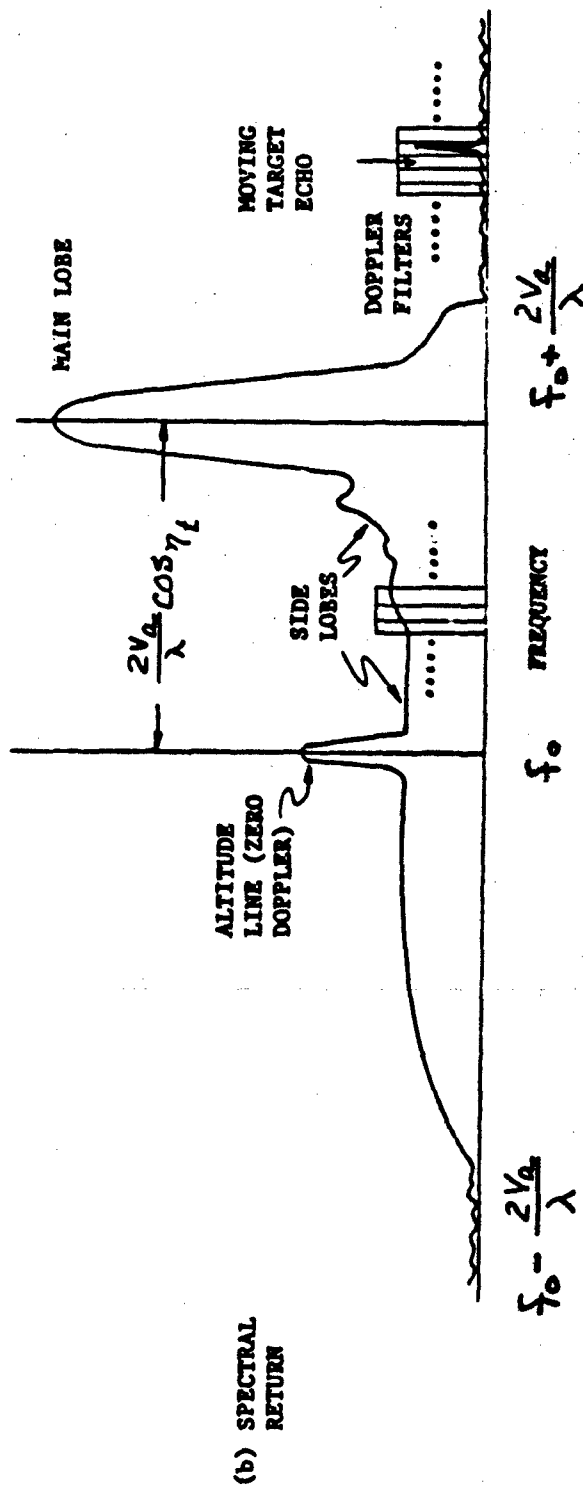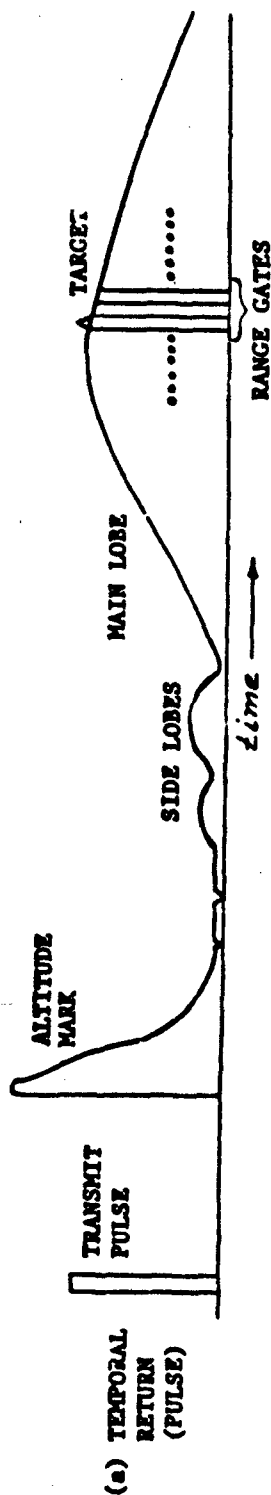
PULSED DOPPLER RADAR – RANGE GATING AND DOPPLER FILTERING

Figure 2.14.2

2.44b

DOPPLER RETURN IN AIRBORNE RADAR

MAX DOPPLER

η_ℓ = NOMINAL CONE ANGLE TO TARGET

DOPPLER BINS

RANGE BINS

η_2

η_1

V_{ac}

$\Delta\lambda$

$$\Delta f = \left(\frac{2V_{ac}}{\lambda}\right)\Delta\eta \; \sin(\eta_\ell)$$
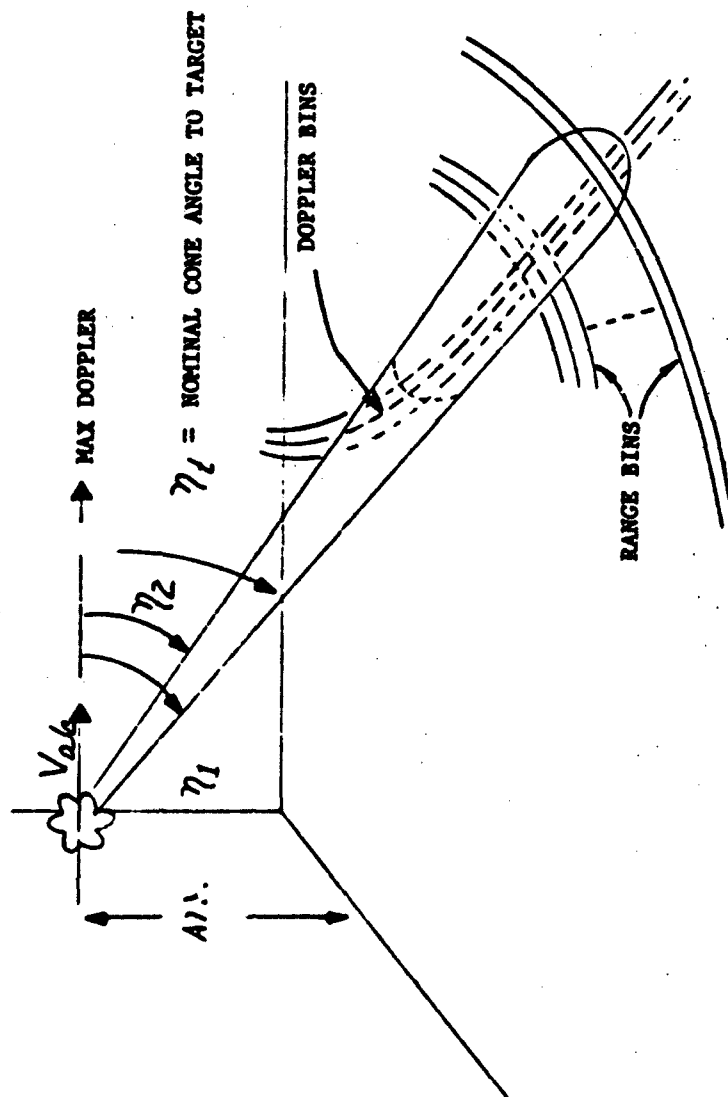
WHERE λ = RADAR WAVELENGTH

θ_η = ANTENNA BEAMWIDTH

Δf = DOPPLER BANDWIDTH OF MAIN LOBE RETURN

Figure 2.14.3

Generic Pulse Doppler Radar
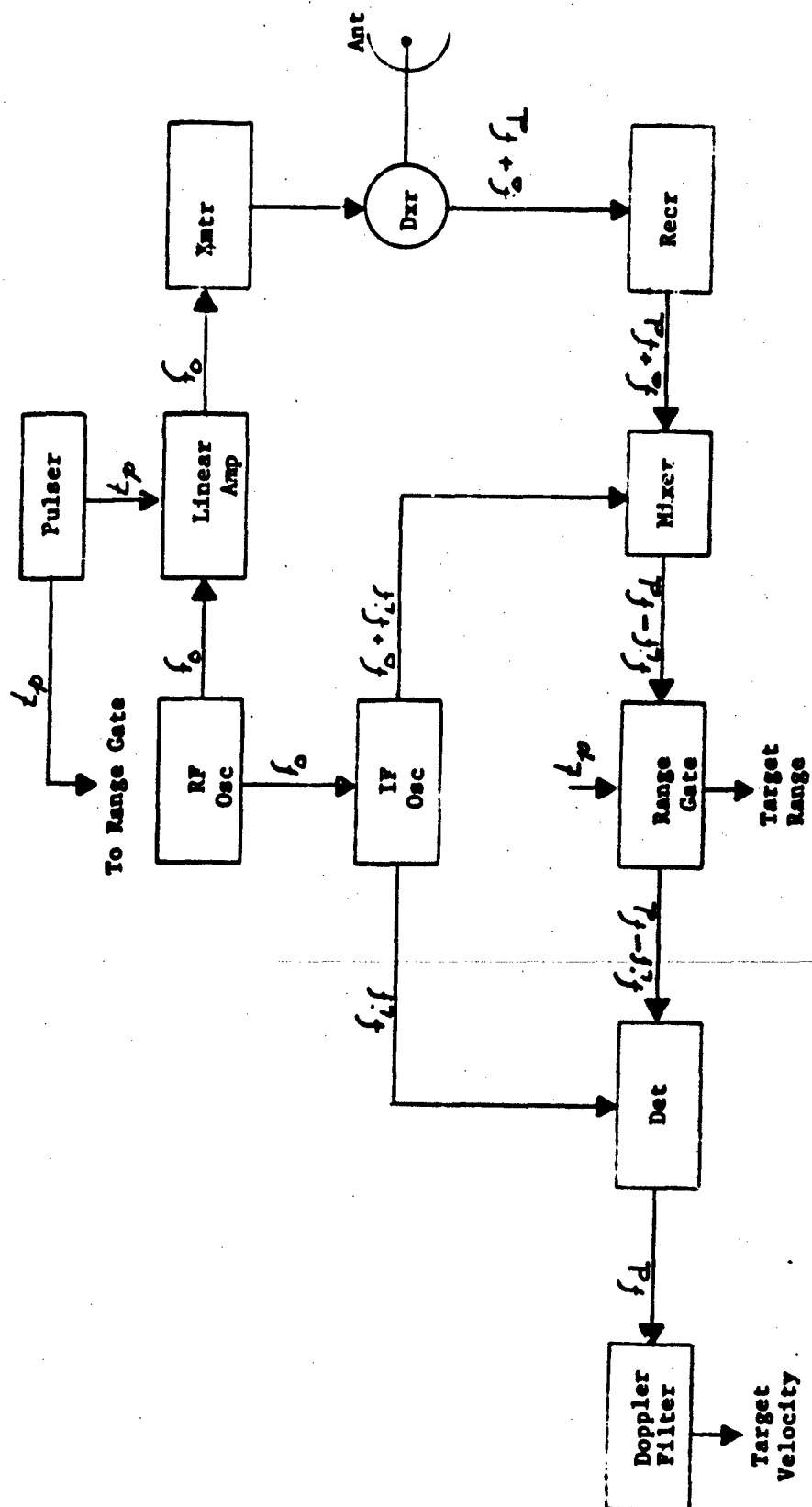
Figure 2.14.4

through the range gates to determine range. It is then heterodyned down

to Doppler shift frequency, (all carrier removed), and passed through

the Doppler filters to determine velocity.

2.15 The Radar Range Equation for Pulse Doppler Radar

The radar range equation as developed in Section 2.4 applies to pulse Doppler radar if the effects of pulsing, Doppler filtering, and range gating are taken into account. This is accomplished by inserting two factors into Equation 2.4.13.

Due to pulsing of the signal and the band-pass Doppler filtering employed, the effective energy utilized is proportional to d_s^2, where d_s is the duty cycle of the radar return signal. (For a more detailed explanation, see Radar Handbook by M. I. Skolnik, Pp 19-22). Thus, a factor d_s^2 must be inserted into the numerator of Equation 2.4.13. Due to range gating, the signal-to-noise ratio is improved by a factor d_g, where d_g is the range gate duty cycle. Thus, a factor d_g must be inserted into the denominator of Equation 2.4.13.

The radar range equation for pulse doppler radar with range gating then becomes:

$$R_{Max} = \left[\frac{P G \sigma A d_s^2}{(4\pi)^2 L k T B_n F_n (S/N)_{Min} d_g} \right]^{1/4} \qquad [2.15.1]$$

where:

P = Peak Transmitted Power

G = Transmitting Antenna Gain

σ = Target Radar Cross Section

A = Receiving Antenna Effective Area

d_s = Return Signal Duty Cycle

L = System Loss Factor

k = Boltzmann's Constant

T = Absolute Temperature

Bn = Noise Bandwidth of System

Fn = Noise Figure of Receiver

(S/N)Min = Minimum Acceptable Signal-to-Noise Ratio

dg = Range Gating Duty Cycle

2.16 Moving Target Indicator Radar

2.16.1 Advantages of Moving Target Indicators-- The purpose of a moving target indicator (MTI) is to detect a target moving with respect to some reference. That reference may be the radar itself, the ground, or any other fixed or moving object. In airborne radar applications, the principal advantage of an MTI is, generally, not that it detects that a target is in motion (nearly everything is moving with respect to an aircraft in flight), but that it can detect moving objects in the presence of background clutter returns two or three orders of magnitude larger. Common applications are the air-to-ground detection of moving vehicles and the air-to-air detection of other aircraft in a low-level, look-down situation.

2.16.2 The Area MTI

The most rudimentary type of MTI is the so-called area MTI. In a sense, any position-indicating radar with some scan-to-scan memory is an MTI. That is, if there is a difference between the returns from successive antenna scans, something must have moved. An example of area-type MTI is the ability of a radar operator to detect moving targets on a PPI display by noting "comet tails" on their indications. In this case, the long-persistence screen of the PPI provides the memory and the operator provides the differencing function.

2.16.3 Coherent Doppler Signal Processing -- A Doppler radar that uses an internally generated signal as a reference for detecting the Doppler shift requires an extremely stable internal oscillator called a coherent oscillator (COHO) as shown in Figure 2.16.3.1. The COHO signal is mixed with the signal from another stable oscillator (STALO) to create the carrier frequency as shown. The signals from these oscillators are then used to remove the carrier from the target returns, thereby determining the Doppler shift due to the relative, radial motion of the target with respect to the radar.

2.16.4 The Doppler Filter MTI -- A Doppler radar is, by its very nature, a moving target indicator. The Doppler shift provides a direct indication of instantaneous velocity, a fundamentally different process from that of inferring velocity from movement between scans. Thus, one type of moving target indicator, the Doppler Filter MTI, is the pulse Doppler radar previously discussed in Section 2.14 and shown again in Figure 2.16.4.1 The Doppler Filter shown in that figure would, in the case of an MTI, be a bandpass filter designed to filter out the clutter pedestal and pass the clear region. The frequency response for a Doppler filter MTI is shown superimposed upon the clutter spectrum in Figure 2.16.4.2.

2.16.5 The Airborne MTI -- In an airborne MTI the frequency of the main lobe clutter signal is a function of aircraft velocity, altitude, attitude and position as well as antenna scan angles and terrain contours. In

Coherent Signal Processing

COHO = Coherent Oscillator
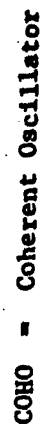
STALO = Stable Local Oscillator

● Stable Oscillators Determine Transmitted Frequency and Phase.

Figure 2.16.3.1

2.49a

Generic Pulse Doppler Radar

Pulser

Linear Amp

Xmtr

t_p

f_o

f_o

t_p

To Range Gate

RF Osc

f_o

IF Osc

f_o

$f_o + f_d$

Recr

$f_c + f_{if}$

f_{if}

Mixer

$f_o + f_d$

$f_{if} + f_d$

Range Gate

t_p

Target Range

$f_{if} + f_d$

Det

f_d

Doppler Filter

Target Velocity
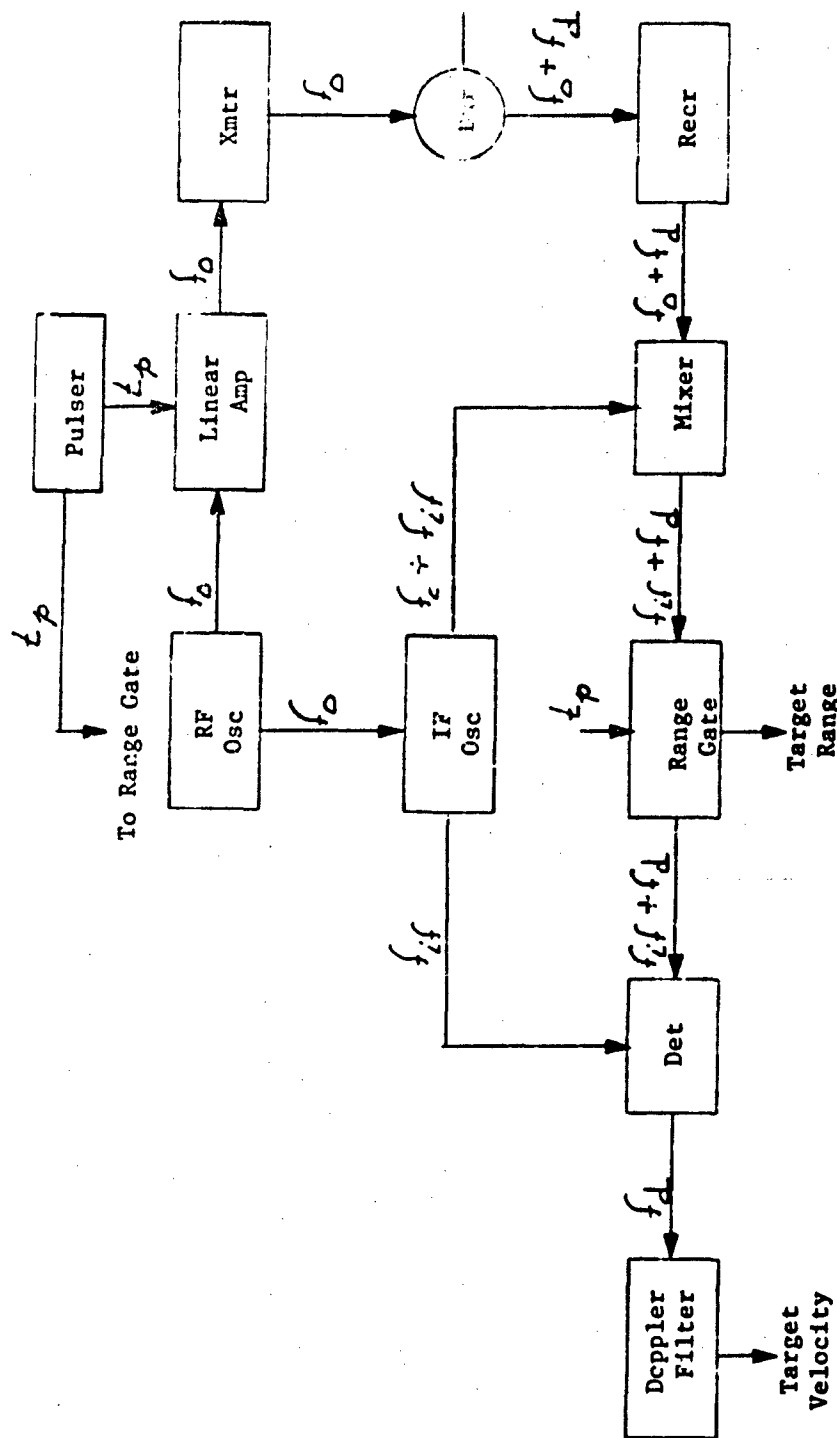
Figure 2.16.4.1

Range Gate/Doppler Filter MTI

• Frequency Response
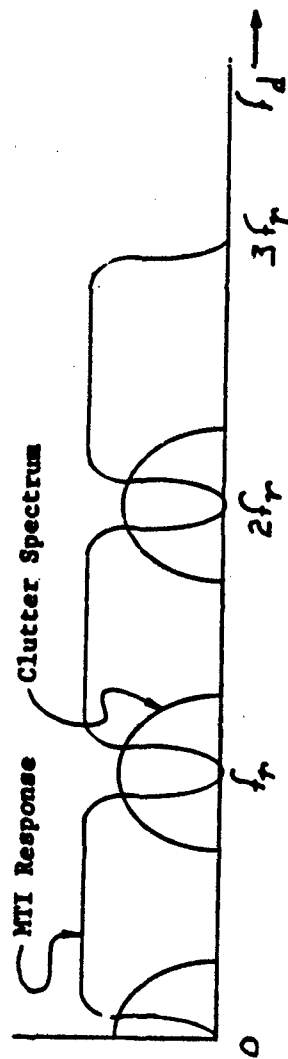
Figure 2.16.4.2

order for the clutter-rejection filters to perform their function, they must sense these parameters and somehow track the constantly-changing clutter frequency. One method of achieving the required tracking would be to use a variable-frequency filter. A simpler method is to employ a constant-frequency filter and shift the entire frequency spectrum of the filtered signal by changing the intermediate frequency reference signal as required. In Figure 2.16.5.1 is shown an airborne MTI with that pro-vision.

2.16.6 The Delay Canceller -- One method of removing the returns due to non-moving targets (clutter) from an MTI radar return signal is to employ a device known as a delay canceller. In this device, shown in Figure 2.16.6.1, the input signal, e(t), is routed in parallel, through two paths, one of which introduces a time delay equal to one interpulse period, T_r. The two signals are then differenced. The amplitude of the difference signal is, then, a measure of the time rate of change of e(t). (The delay canceller can be considered a first approximation to a time differentiating network). If there is no moving target and e(t) is, therefore, constant, the output Δe(t) will be zero.

A more detailed block diagram for a delay canceller is shown in Figure 2.16.6.2. In this figure, it can be seen that several refinements are required in the simple arrangement shown in Figure 2.16.6.1. The first refinement is the incorporation of a compensating filter and amplifier in the non-delayed path. This amplifier and filter have characteristics

2.50

Generic Pulse Doppler Radar
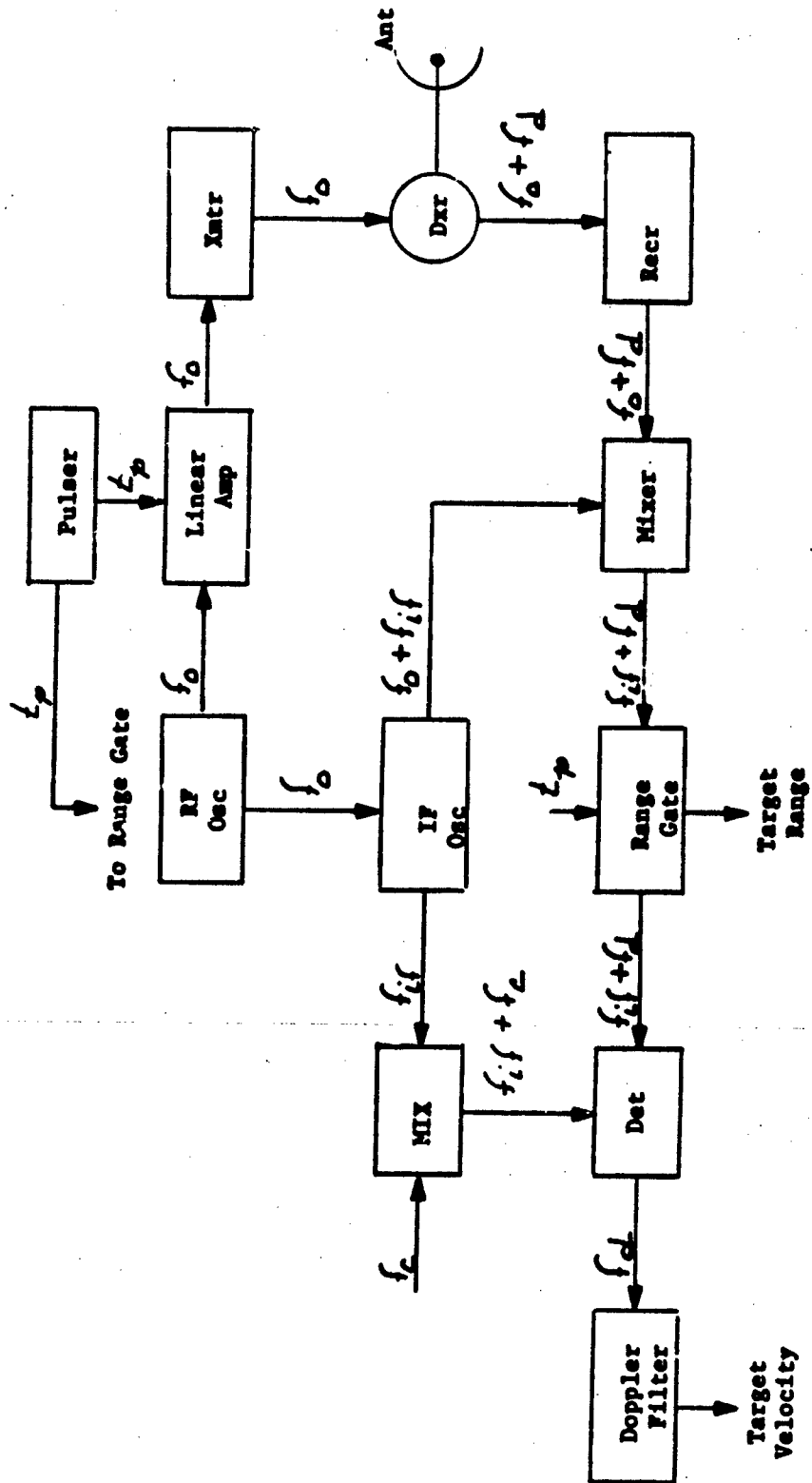
Figure 2.16.5.1

Delay Canceller
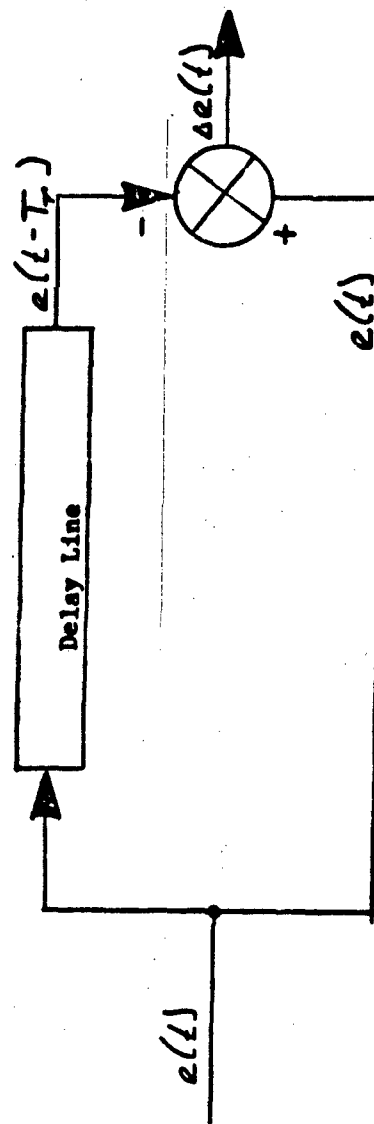
Figure 2.16.6.1

Delay-Line Cancellation

PRF
Trigger

Trigger
Gen

LPF

AGC

Amp

Det

$e(t-T_{pr})$ $(f_{if}+f_1)$

$e(t-T_{pr})$

f_{if}

Delay
Line

$e(t)$ $(f_{if}+f_1)$

Comp
Filter

Comp
Amp

$e(t)$ $(f_{if}+f_2)$

Det

$e(t)$

f_{if}

$\Delta e(t)$

(f_1)

$+$ $-$

$\otimes$

MOD

f_1

f_{if}

IF
Osc
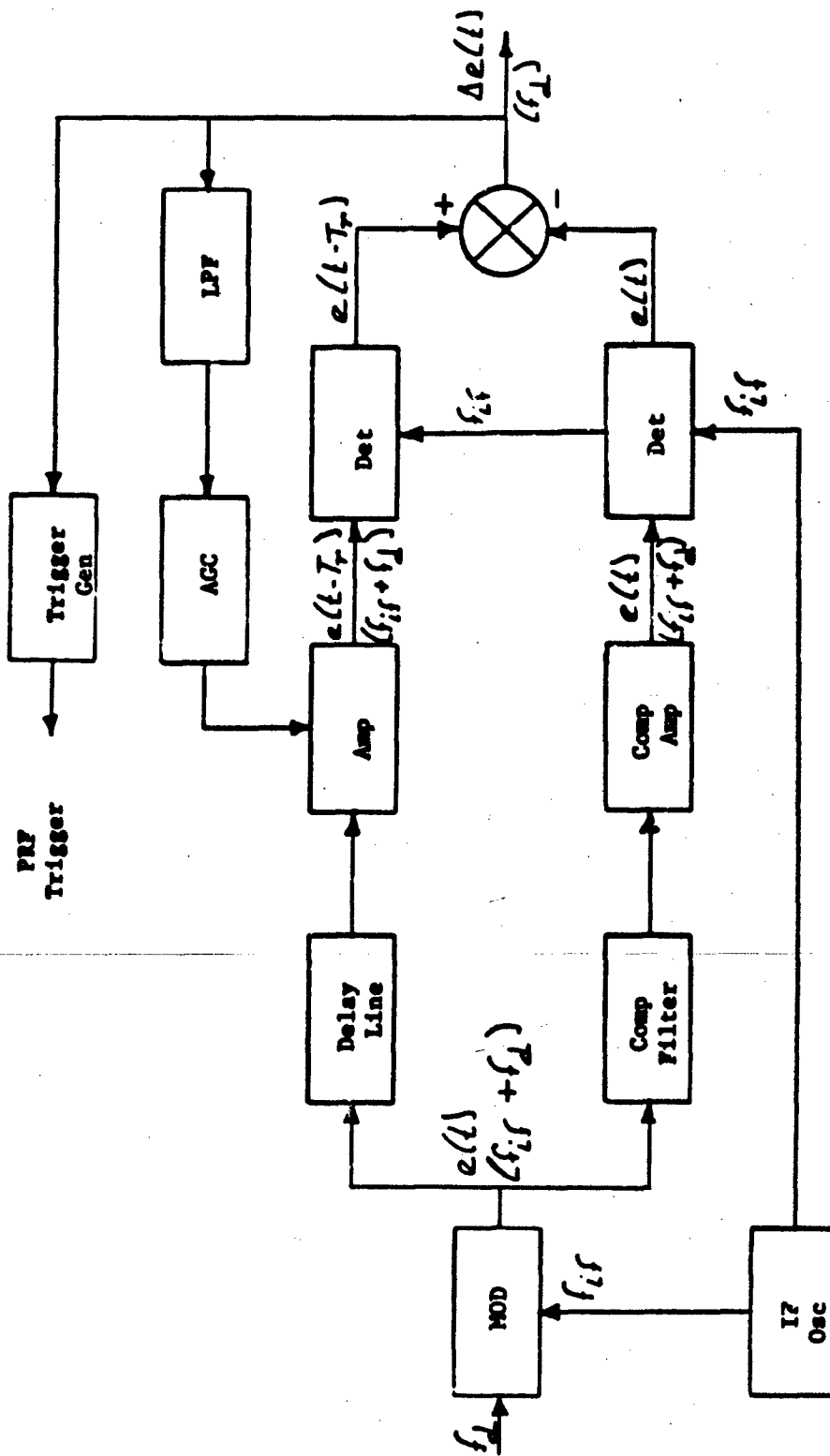
Figure 2.16.6.2

identical to those of the delay line, but without the delay. The second
refinement is the use of a low-pass filter (LPF) and automatic gain con-
trol (AGC) to remove long-term gain fluctuations in both branches. The
third refinement is the use of a trigger generator which controls the
pulse repetition frequency of the transmitter, thereby matching it to
the delay time of the delay canceller. Also shown explicitly is the
insertion of an intermediate frequency carrier.

2.16.7 The Coherent Doppler Delay Canceller MTI -- A delay canceller
is often used in a coherent Doppler MTI radar to suppress the clutter
(zero Doppler frequency) signal as shown in Figure 2.16.7.1. This
method of moving-target detection requires coherent signal processing as
discussed in Section 2.16.3. That is, the phase relationships of the
transmitted, return, and internal reference signals must be preserved.
Since an internal reference signal is used, this type of MTI indicates
target velocity with respect to the radar.

2.16.8 The Interferometer or Non-Coherent Delay Canceller MTI -- An
alternate method of determining Doppler shift in the target return signal
is shown in Figure 2.16.8.1. In this arrangement, known as non-coherent
Doppler processing, the incoming target return signal is not heterodyned
with an internal oscillator reference signal to determine Doppler shift.
It is heterodyned with the incoming return signal from the ground, there-
by deriving the target radial velocity with respect to the ground. Since
the phase relationships of the return signals to the internal signals are
not important, phase-sensitive detection is not necessary and, therefore,

2.51

Coherent Delay-Canceller MTI
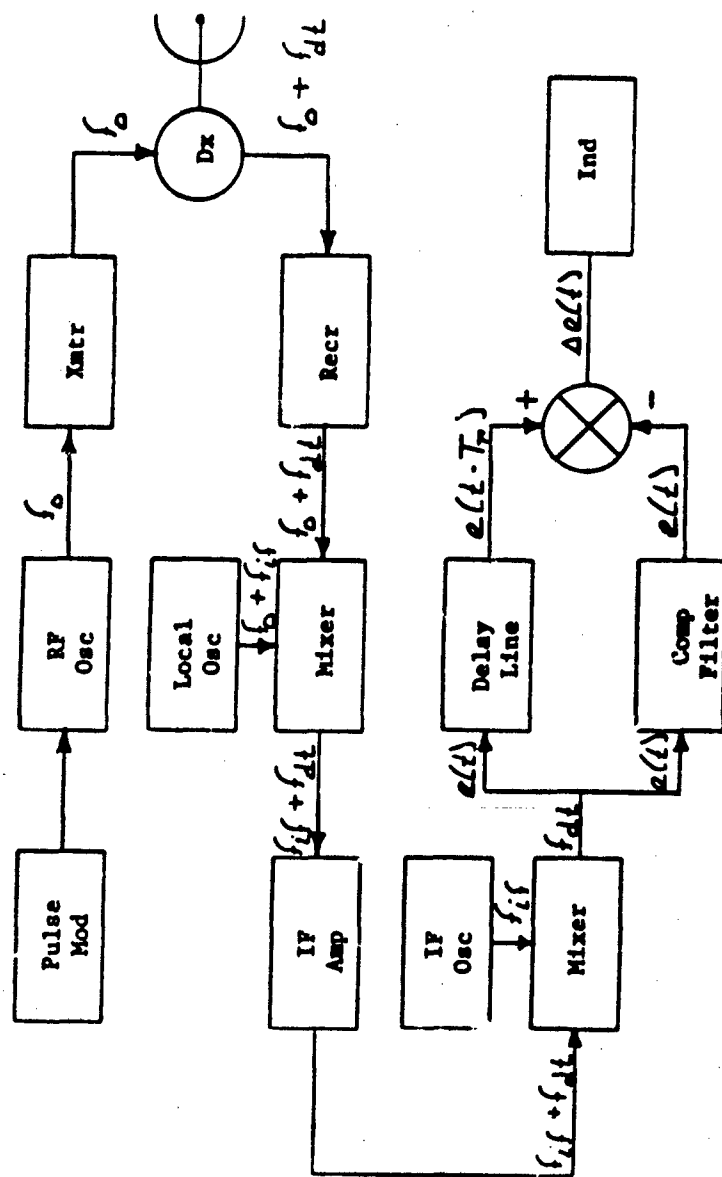
f_o = Transmitted Frequency

f_{df} = Doppler Shift Frequency of Target Return

f_{if} = Intermediate Frequency

$e(t)$ = Signal Voltage

Figure 2.16.7.1

2.51a

Non-Coherent Delay-Canceller MTI

(Interferometer)

Pulse Mod	

RF Osc

IF Osc

Mixer

Xmtr

Rec'r

IF Amp

Env Det

Delay Line

Comp Filter

Ind

Ant

Dx

f_o

f_o

$f_o + f_{dc}$
$f_o + f_{dt}$

$f_o + f_{dc}$
$f_o + f_{dt}$

$f_o + f_{if}$

$f_{if} + f_{dc}$
$f_{if} + f_{dt}$

$f_{if} + f_{dc}$
$f_{if} + f_{dt}$

f_b $e_b(t)$

$e_b(t-T_r)$

$e_b(t)$

Δe_b
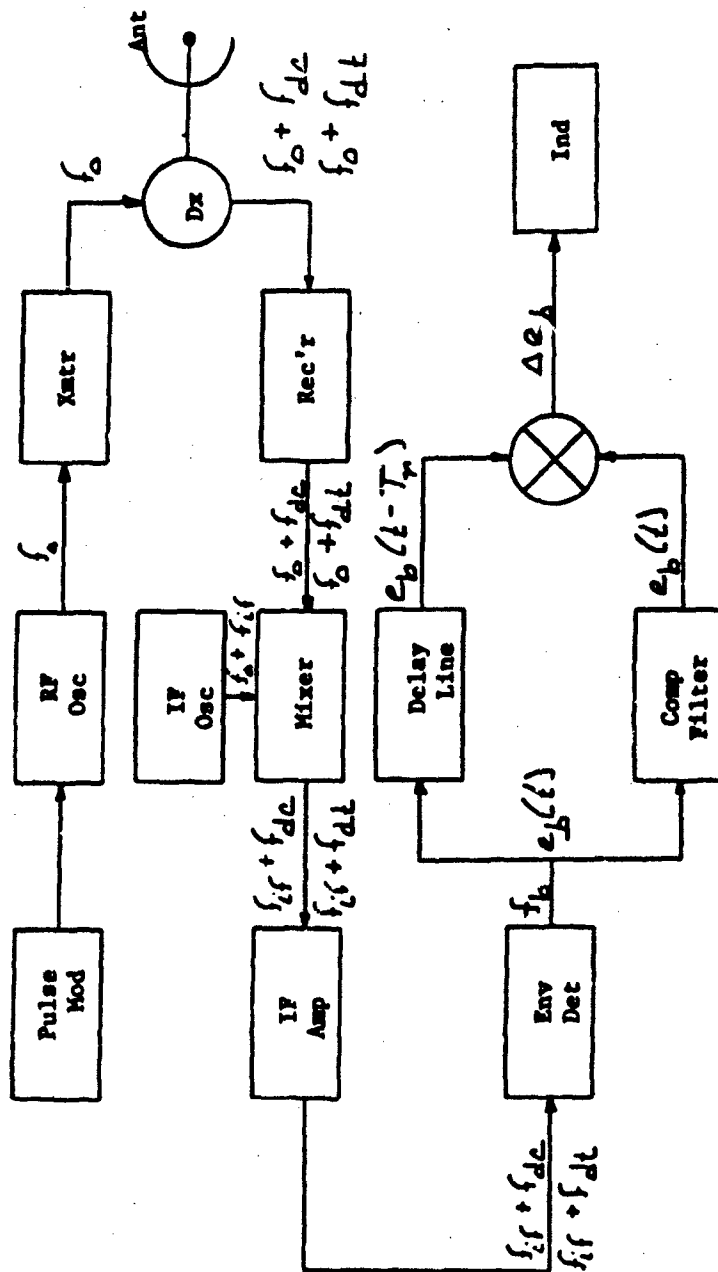
f_o = Transmitted Frequency

f_{dc} = Doppler Shift of Clutter Return

f_{dt} = Doppler Shift of Target Return

f_b = Beat (Difference) Frequency $(f_{dt}-f_{dc})$

f_{if} = Intermediate Frequency

$e_b(t)$ = Beat Frequency Signal Voltage

T_r = Pulse Repetition Interval

Figure 2.16.8.1

2.51b

a simple envelope detector is used to obtain the difference (beat) frequency between the target and ground returns. As in the coherent system shown in Figure 2.16.7.1, a delay canceller is used to suppress the zero frequency (clutter) signal.

2.16.9 Multiple-Delay Cancellers -- Multiple delay cancellers, as shown in Figure 2.16.9.1 are sometimes employed to suppress the clutter signal in a pulse Doppler MTI radar. The effect of multiple cancellers can best be appreciated by comparing the cancellers to differentiating networks. The effect of differentiation on a time-varying signal is to accentuate the time variations. The effect of additional differentiations, then, would be to further accentuate these variations. In figure 2.16.9.2(a) is shown the frequency response of a single-delay canceller superimposed upon the spectrum of the clutter signal for a pulse Doppler radar. (Note that the delay canceller frequency response is periodic, of period $T_r = 1/f_r$.)

In Figure 2.16.9.2(b) is shown the frequency response of a dual-delay canceller. The advantage of the dual delay canceller is apparent from the figures. While the clutter pedestal will be considerably attenuated by the response for a single-delay canceller, the attenuation for the dual-delay canceller is much greater.

2.16.10 Delay Canceller Blind Speeds -- It is apparent from the response curves in Figure 2.16.9.2 that target returns with Doppler shifts that place their returns in one of the filter response notches will be invisible.

2.52

Multiple – Delay Cancellers

● **Double Delay**
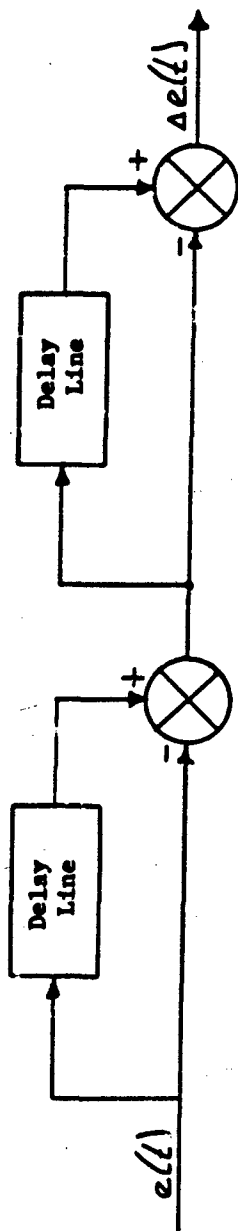
● **Three-Pulse Comparator**
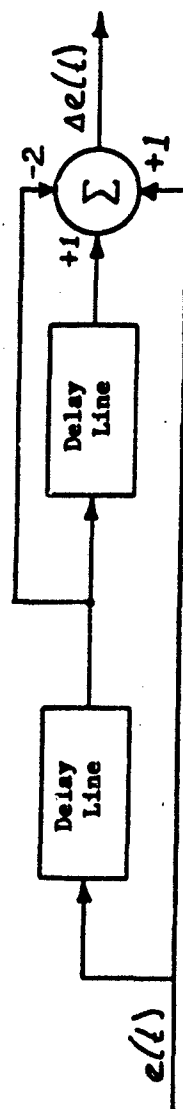
● **Canonical Configuration**
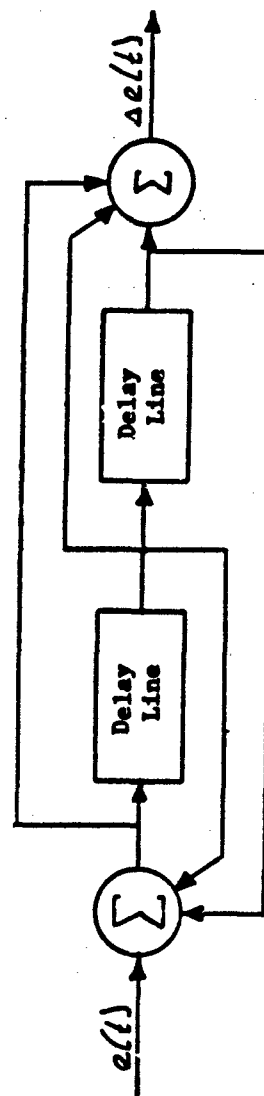
Figure 2.16.9.1

2.52a

Frequency Response of Delay Cancellers

Figure 2.16.9.2

(a) Single Delay

Clutter

$Sin^2\left(\dfrac{\pi f}{f_r}\right)$

Response

O f_r $2f_r$ f

(b) Double Delay

Clutter

$1 + Sin\left(\dfrac{2\pi f}{f_r}\right)$

Response

O f_r $2f_r$ f

2.52b
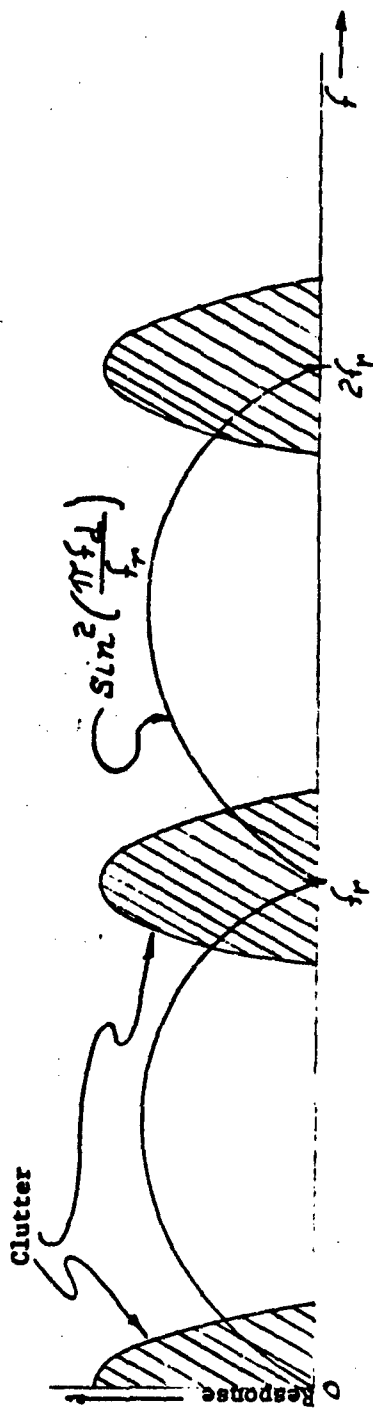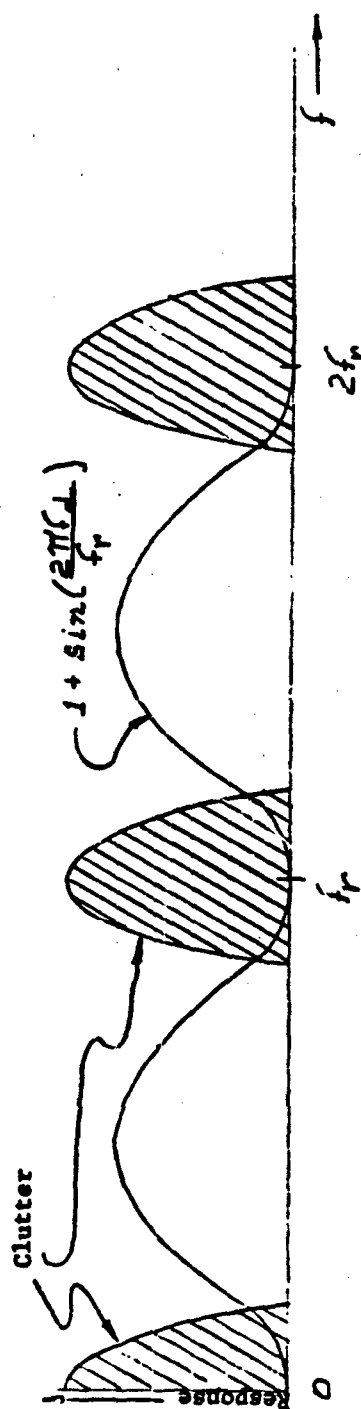
The corresponding target velocities are, thus, blind speeds for that
MTI. The blind speeds, V_b, for a given pulse repetition rate, f_r, and
radar wavelength, λ_o, are given by:

$$V_b = \frac{n\,\lambda_o\,f_r}{2}$$

[2.16.10.1]

when n is an integer, zero or greater.

MTI response (visibility) at the blind speeds can be improved, at the
cost of a degradation in MTI clutter rejection, by utilizing a "staggered"
pulse repetition frequency as shown in Figure 2.16.10.1(a). In Figure
2.16.10.1(b) are shown the MTI responses corresponding to each of the
two pulse repetition frequencies (periods) as well as the composite
response for the staggered PRF. As shown, the response for the staggered
PRF MTI does not go to zero at the blind speeds. Thus, the MTI is able
to detect targets at those speeds, but also sees more clutter.

2.16.11 Clutter Improvement Factor -- The figure of merit for a moving
target indicator is the clutter improvement factor, defined as the ratio
of the moving target signal-to-noise ratio with clutter rejection to
that quantity without clutter rejection.

There are numerous factors which adversely affect MTI clutter rejection.
That is, there are many factors which cause pulse-to-pulse variations
in target returns, other than relative target motion. Typical factors

Dual (Staggered) PRI Delay Cancellation

(a) Pulse Train

(b) Frequency Response of Delay Canceller

$T_r = T_1$

$T_r = T_2$

Staggered
$\dfrac{T_1}{T_2} = \dfrac{4}{5}$

RELATIVE RESPONSE
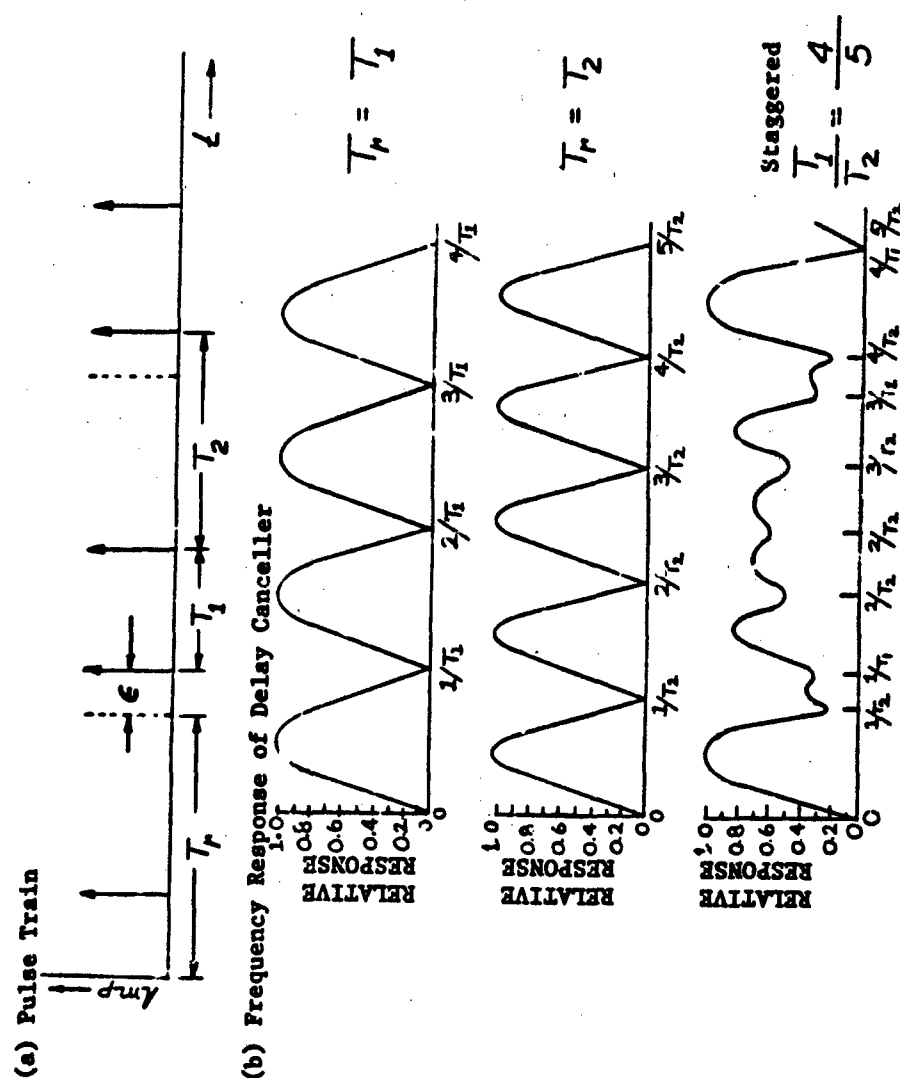
Figure 2.15.10.1

are: antenna platform motion, antenna scanning, radar frequency instability, the use of pulse integration, the use of staggered PRF, and, finally, anything that widens the frequency spread of the clutter pedestal. External factors that increase the width of the clutter spectrum are: atmospherics, non-stationary clutter such as swaying trees or waves at sea, and chaff.

2.17 Tracking Radar

2.17.1 Principle of Operation -- A modern radar typically determines target azimuth, elevation, range, and velocity. A tracking radar continually and automatically stores and updates those quantities while keeping the target in the field of view. Some radars physically track position parameters such as azimuth by changing antenna orientation to keep the target on boresight. Other radars, of the track-while-scan variety, do not "point" the antenna boresight at the target; but, nevertheless, maintain the tracked quantities in memory. In all cases, the principle of tracking is the same, the tracker operates in the manner of a feedback control system. Three distinct operations are involved:

(1) An incremental change is made in the tracked quantity.

(2) The new target return is compared to the last (stored) target return and the difference is used to generate a tracking error signal.

(3) A change is made in the tracked quantity so as to reduce the error signal.

The above steps are continually iterated, thereby providing quasi-continuous tracking. This process is sometimes called gradient tracking because the system responds to the rate of change of the target return with respect to a change in the tracked quantity. As indicated above, the tracked quantity may be antenna position in the case of azimuth and elevation. In the case of range or velocity, it may be the "position" of a range or velocity gate.

2.55

The block diagram of a generic line-of-sight tracking radar is shown in Figure 2.17.1.1. The system therein is seen to consist of a basic radar, (the two upper branches containing the transmitting, receiving, and ranging components), and a tracking loop (the lower branch containing the tracking error-generating and antenna drive components). The operation of the basic radar has been described in previous sections. The operation of the tracking loop is as follows.

    (1) The scan drive imparts an incremental change to the boresight of the antenna.

    (2) The error detector, utilizing antenna position information from the scan reference generator as well as return signal information from the basic radar, generates error signals for the azimuth and elevation controllers.

    (3) The controllers, through the azimuth and elevation drives, change the boresight position of the antenna so as to reduce the error signals.

The only change required in this tracking radar diagram for range or velocity tracking would be in the tracking loop component names. Instead of azimuth and elevation controls and drives, the loop would contain range gate and velocity gate controls and drives. In turn, the drives would change the positions of the tracking gates rather than the position of the antenna.

Typical Line-of-Sight Tracking Radar

Figure 2.17.1.1

2.56a
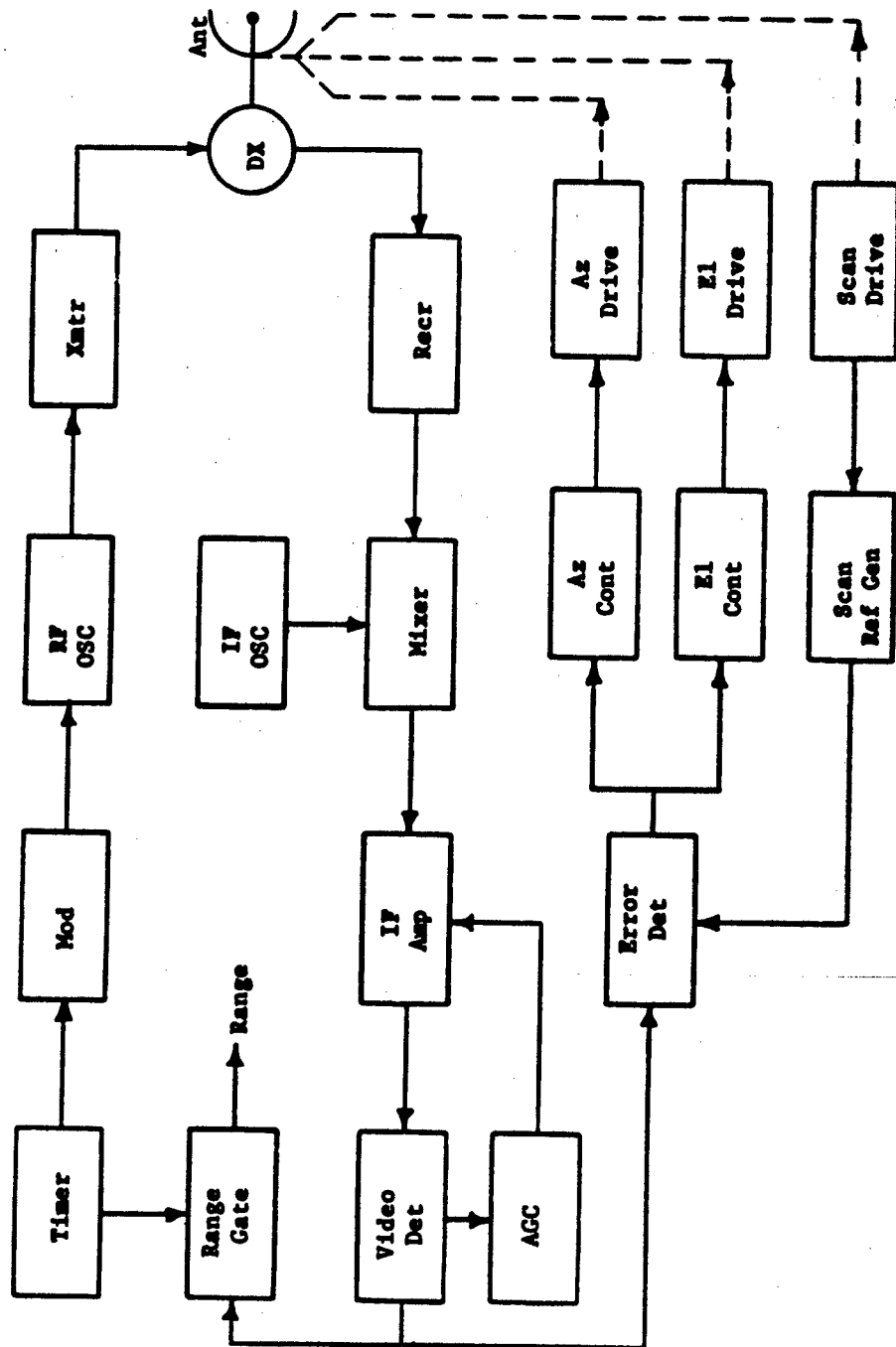
In addition to continually updating the tracked quantities, a tracking radar often has the capability of predicting future values of the tracked quantities, based upon stored information. This capability allows the system to "track" the target during periods of momentary loss-of-signal such as those due to target scintillation.

High frequency noise (rapid fluctuation of signal level) is reduced by the use of low-pass filters such as sample-and-hold circuits. Low frequency noise is reduced by the use of automatic gain control (AGC). Both low-and high-frequency filtering are possible because the only frequency range of interest is that produced by the incremental scanning process.

2.17.2 Characteristics of Tracking Radars -- A tracking radar derives most of its characteristics from the radar itself, rather than from the tracking loop. One characteristic peculiar to the tracking loop, however. is the dynamic "following" error exhibited by all such closed-loop control mechanisms.

2.17.3 Target Acquisition -- In order to track a target, a tracking radar must have the target in the field of view. Attaining that condition is referred to as target acquisition. Target acquisition is accomplished by imposing a search pattern on the change imparted to the tracked quantity. When a target return is detected, the search pattern is terminated, (except for track-while-scan radars), and the incremental scanning is initiated. The more common types of sector scanning patterns are shown in Figures 2.17.3.1

2.57

ANTENNA SCAN CHARACTERISTICS

SPIRAL SCAN

Spiral Scan employs a circular scan in
a vertical dimension.

Final Squint Angle

α

Boresight Line
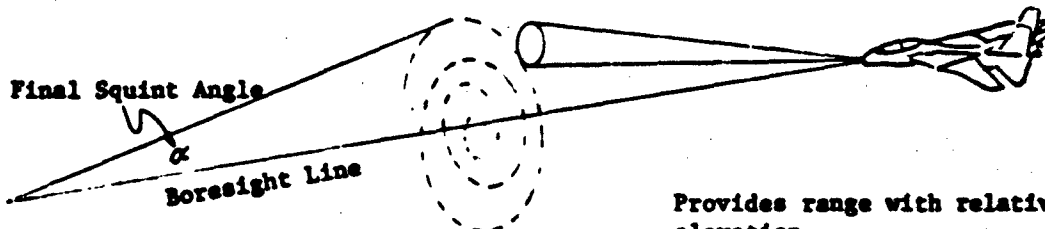
Provides range with relative azimuth and
elevation.
Used as an acquisition mode of some
threat radars.

RASTER SCAN

Note: Raster Scan is used in the "Acquisition"
(Search) mode by some Airborne Intercept radars.

"6 Bar"
Pattern
shown

Target is displayed
in relative Azimuth
and Elevation by
a rapidly moving
sweep.

Typical Display

"C" Scope
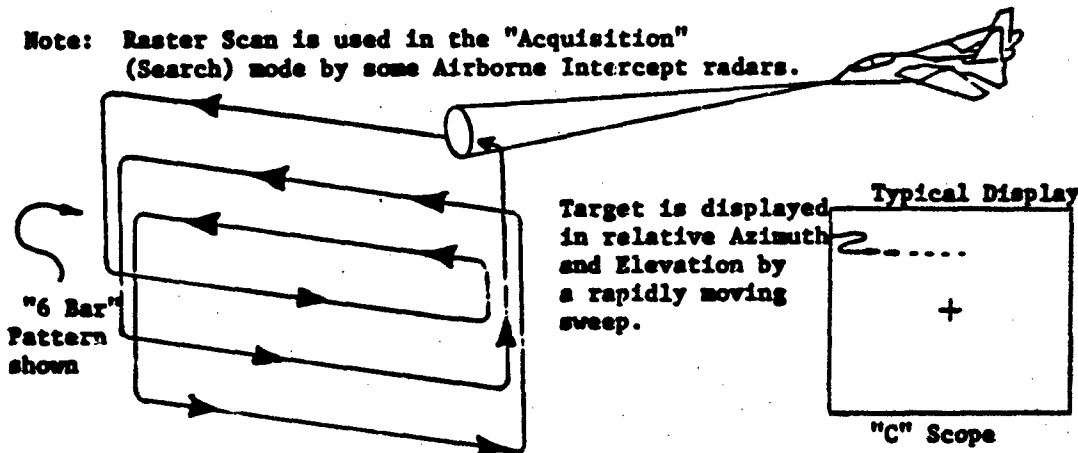
CONICAL SCAN

Note: Conical Scan is employed by some
Automatic AA radars and Airborne
Intercept radars.

Antenna Azimuth and Elevation are read
from the mechanical position of the
dish, for inputs to the automatic
tracking computer.

"Delayed" sweep
starts and ends
at some range as
adjusted

**RANGE
DISPLAY**

Adjustable Range
Cursor

Expanded "A" Scope

Maximum
Range

Zero
Range

Range

Target

"J" Scope
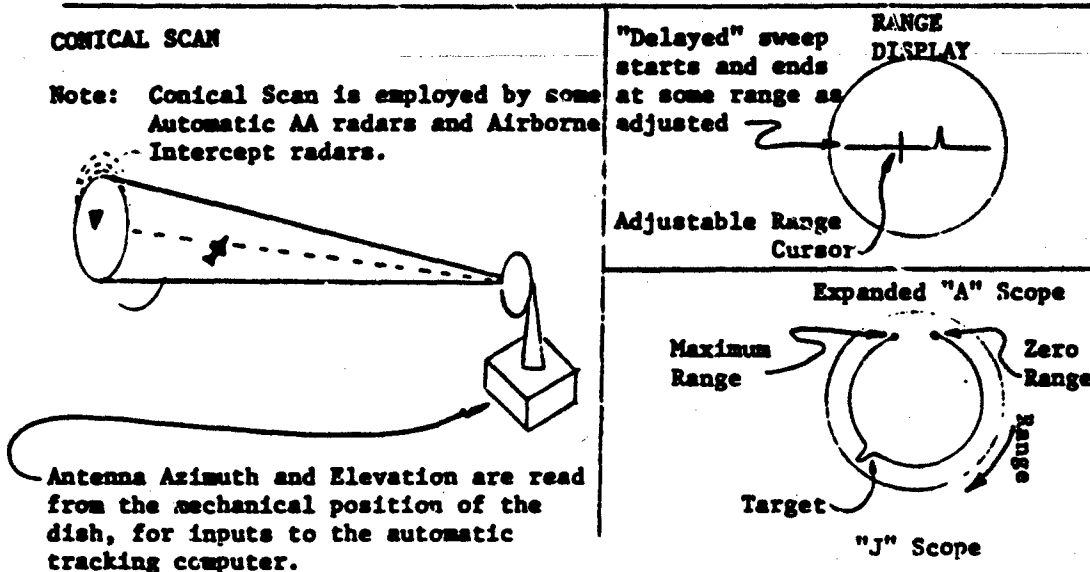
Figure 2.17.3.1(...)

2.57a

Antenna Scan Characteristics

PALMER SCAN (Conical Scan superimposed on some other scan)

Palmer-Circular or
Palmer-Sector Scan

"2-Bar" Palmer-Raster Scan
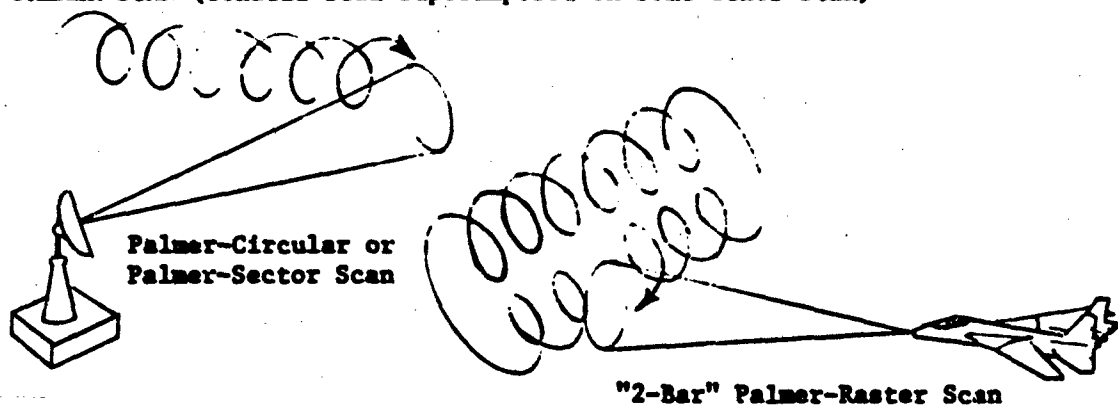
LOBE-SWITCHING

Lobe-Switching Scan is employed as an
automatic tracking mode on some threat
radar control systems.

Produced by switching a
narrow beam around an axis
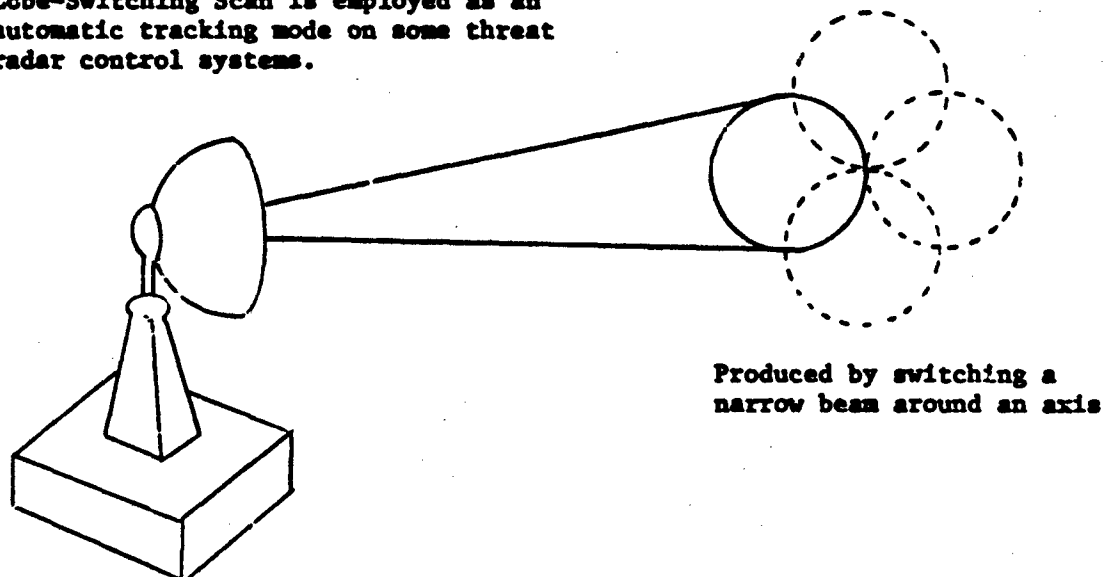
Figure 2.17.3.1(b)

2.17.4 Conical Scan Radar -- The most common line of-sight scanning method employed today is the conical scan with mechanical positioning of the antenna. This method, shown in Figure 2.17.4.1 rotates a pencil beam in a conical motion about the boresight of the system. Unless the target is on the axis of rotation, (antenna boresight), the target returns will be amplitude modulated as shown in the same figure. Also as shown, the azimuth and elevation error signals can be generated, by resolvers, from the returns. The error signals are then used to move the antenna system boresight in the proper direction to put it on the target. The block diagram of Figure 2.17.1.1 is directly applicable to conical scan radars.

The conical-scan antenna has a number of major disadvantages with respect to other systems. The first is that mechanical conical scanning requires rotating hardware. Generally, the feed horn nutates. Rotating hardware tends to be bulky, heavy, and unreliable. The second disadvantage is that the conical scan is designed to place the half-power point of the antenna pattern on the axis of rotation. Thus, a perfectly tracked target receives only one half the illumination it would receive at the peak of the pattern. The most serious disadvantage of the conical scan radar is the fact that at least three pulses per orbit (scan) are required for tracking. (Three points determine a circle). This requirement means that any change in pulse-to-pulse amplitude of the target returns, such as that due to scintillation or jamming, will interfere with the tracking process.

2.58
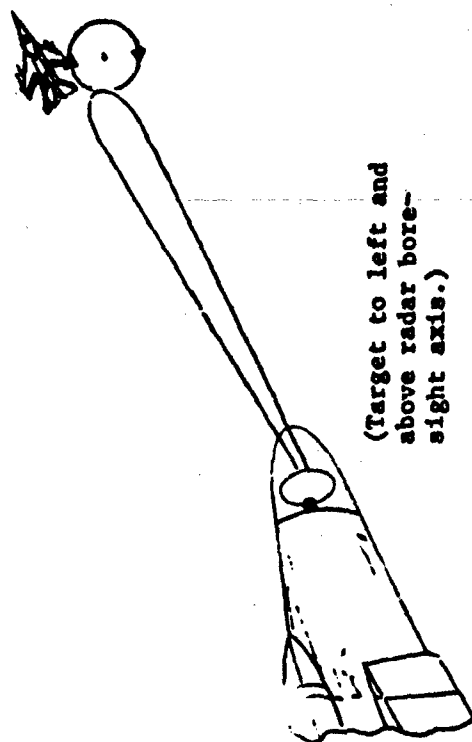
Conical - Scan Radar

(Target to left and above radar bore-sight axis.)

Figure 2.17.4.1

2.58a
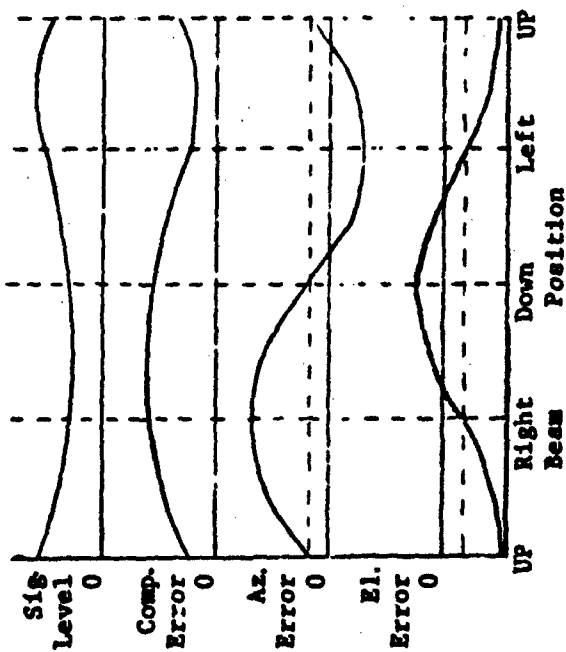
2.17.5 Sequential Lobing Radar -- Sequential lobing is accomplished by sequentially positioning the antenna beam in each of four discrete, equally-spaced positions in a conical scan pattern as indicated in Figure 2.17.5.1. The signal processing is the same as for a conical scan radar and yields performance equal to that of conical scan but without moving hardware for scanning. The four antenna beam patterns are achieved using four antenna horns or a phased-array antenna. The block diagram for a sequential lobing radar, shown in Figure 2.17.5.2, differs from that for a conical scan radar only in that an RF switch is used in place of a conical antenna scan drive. A disadvantage of sequential lobing with respect to other scanning methods is the necessity of switching high-power radio frequency signals.

2.17.6 Monopulse Radar -- The monopulse scanning method incorporates the best features of sequential lobing while eliminating its most severe limitations. As shown in Figure 2.17.6.1, the same four-position pattern is employed as with sequential lobing, but with all four positions illuminated simultaneously by each pulse and also sensed simultaneously by the four horns. Thus, the same information is obtained as with sequential lobing but without the time dependence of the latter. Since the returns from all four quadrants are sampled simultaneously, pulse-to-pulse variations due to scintillation or other causes have no effect. Sometimes a fifth antenna, not shown in the figure, is used to illuminate all four quadrants.

2.59

Sequential - Lobing Radar

Sig.
Level 0

Comp.
Error 0

Az.
Error 0

El.
Error 0

Up Left	Up Right	Down Right	Down Left

Beam Position

(Only two beam
positions shown)

(Target to left of and
above radar bore-sight axis)

Figure 2.17.5.1

2.59a
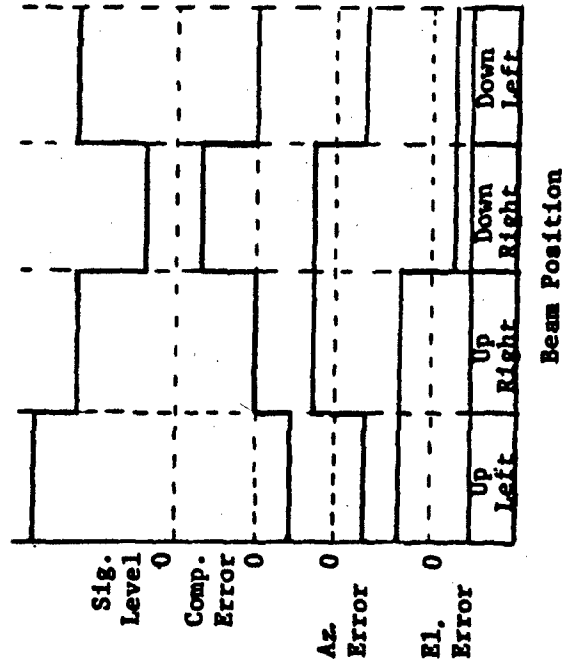
Sequential - Lobing Radar

Figure 2.17.5.2

2.59b

Monopulse Radar

B   D

A   C

Pattern

B   D

A   C
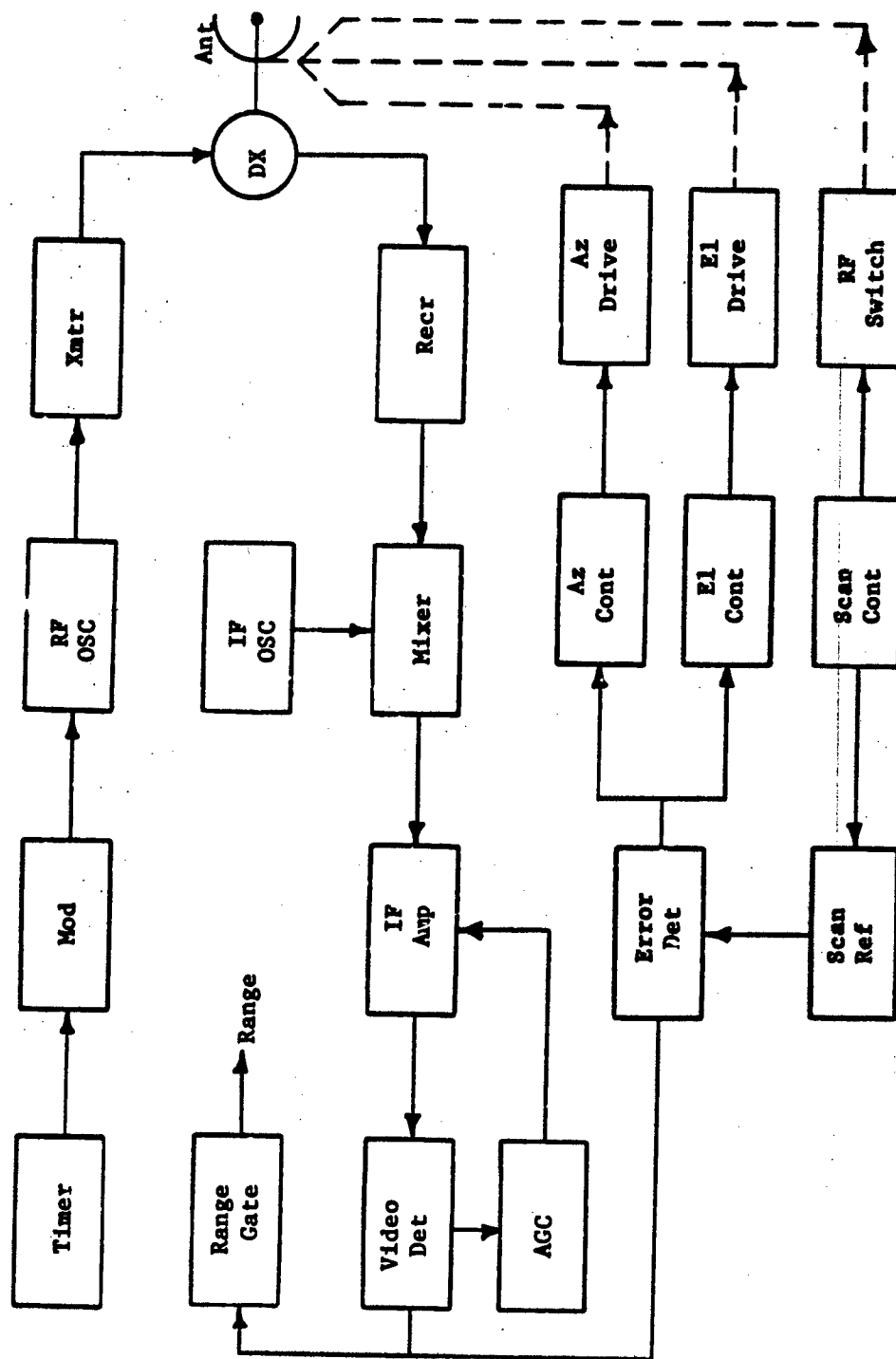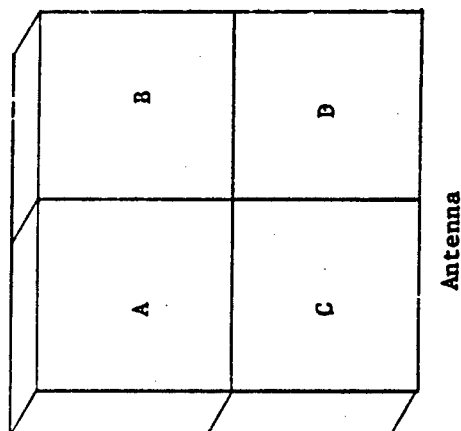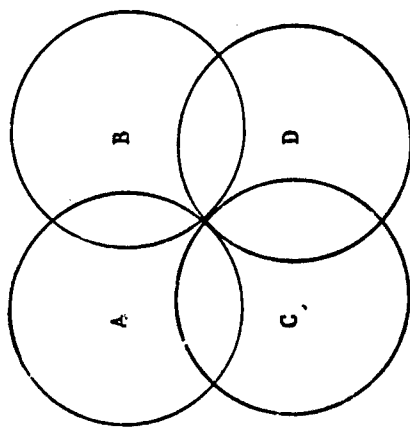
Antenna

Figure 2.17.6.1

The monopulse principle of operation depends upon the fact that a target not on the array centerline (boresight) will produce return signals in the four antennas that have phase relationships and amplitudes which depend on the angle off boresight. There are two types of monopulse radar, amplitude comparison and phase comparison.

The amplitude comparison monopulse radar receiver shown in Figure 2.17.6.2 employs the error signal equations:

$$V_E (Az) = [V_B + V_D] - [V_A + V_C]$$
$$V_E (El) = [V_A + V_B] - [V_C + V_D]$$

[2.17.6.1]

where V_A, V_B, V_C, and V_D are the target return signal voltages from horns A, B, C, and D as shown in Figure 2.17.6.1 and V_E is an error signal voltage. It should be noted that the only purpose of the phase-sensitive detectors is to determine the sign as well as the magnitude of the error signals.

The block diagram for a single axis (azimuth) phase comparison monopulse radar receiver is shown in Figure 2.17.6.3. The output of the phase comparator is given by the error signal equation:

$$V_{E(Az)} = \left(\frac{Kd}{\lambda_o} \right) \theta_{Az}$$

[2.17.6.2]

where K is the system gain, d is the distance between the two antennas, λ_o is the radar wavelength, and θ_{Az} is the target azimuth angle.

The monopulse or interferometer radar has several advantages over other types of radar. One advantage is its insensitivity to pulse-to-pulse

Monopulse Tracking Radar Receiver
(Amplitude Comparison)
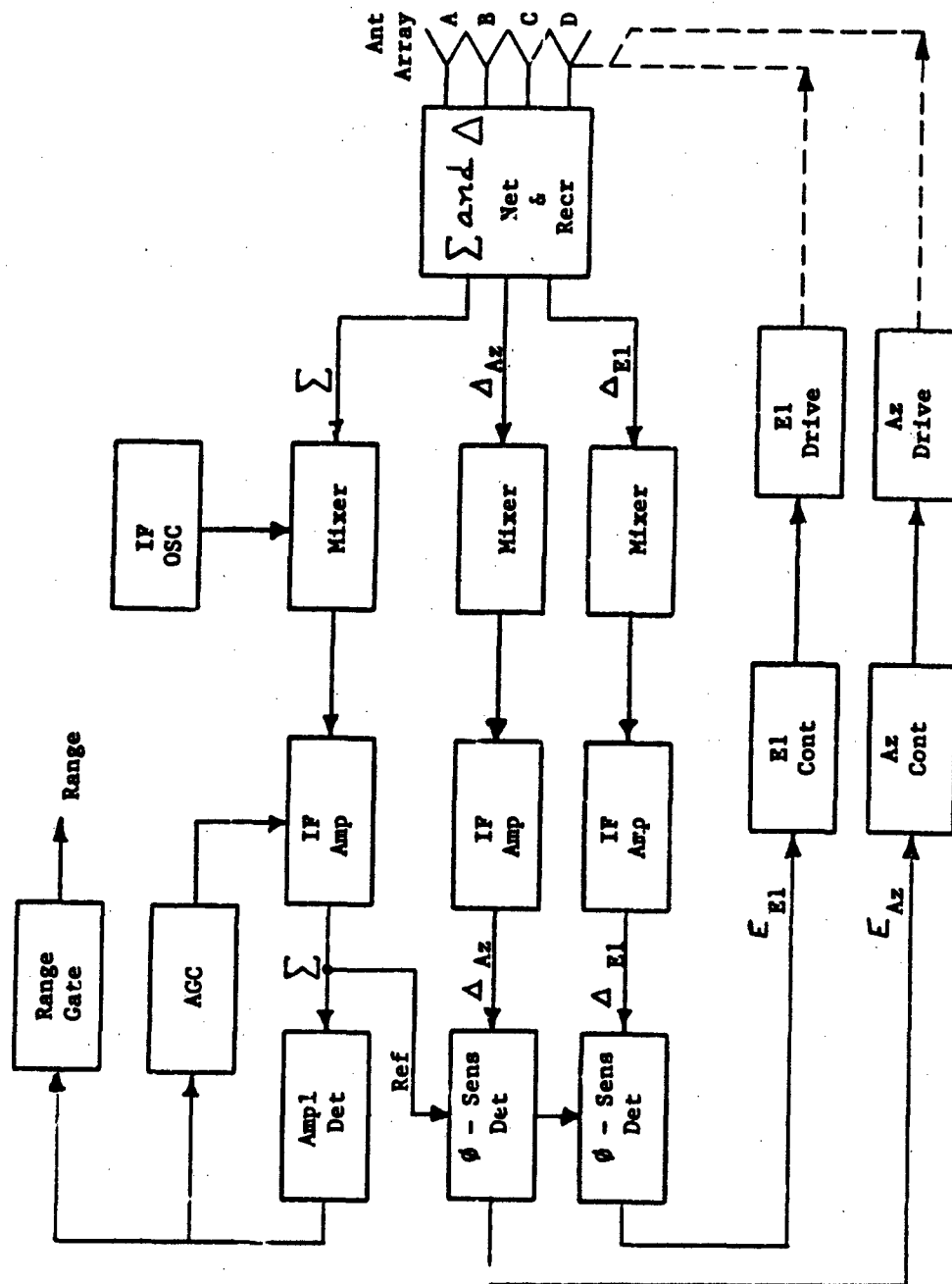
Figure 2.17.6.2

Monopulse Tracking Radar Receiver
(Phase Comparison)
(Azimuth Only)

Figure 2.17.6.3

2.60b
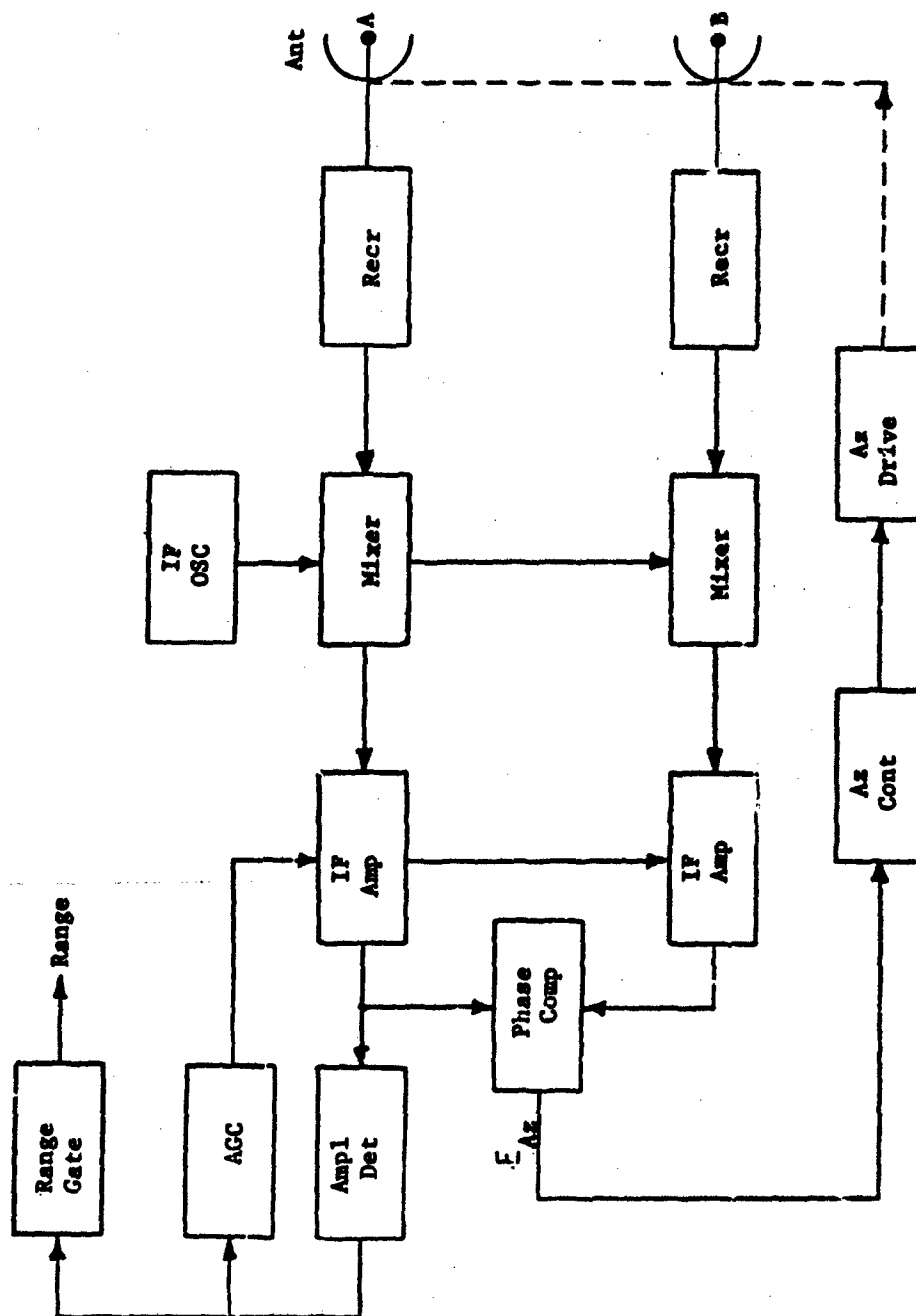
amplitude fluctuations in the target return. Another advantage is the fact that its angular accuracy and resolution are independent of individual antenna beam width, being derived entirely from phase relationships. Other advantages are its mechanical simplicity (no scanning mechanism) and electrical simplicity (no high-power RF switches). The performance of monopulse radar is generally superior to that of both conical-scan and sequential-lobing radars.

2.17.7 Track-While-Scan Radar — Unlike other types of tracking radar, the track-while-scan (TWS) radar does not impart a separate line-of-sight scanning motion to the antenna. The sector-search scanning motion shown in Figure 2.17.7.1, provides the "incremental" changes necessary for tracking. Furthermore, the TWS radar does not change antenna position so as to place any given target on the antenna boresight. Instead, target azimuth and elevation are stored in a "track file" in computer memory and updated on each scan. Range and velocity are treated in a similar manner. These quantities, stored in computer memory, constitute the tracked quantities in a TWS radar. A block diagram for a track-while-scan radar is shown in Figure 2.17.7.2. All error signals and tracking control quantities are generated by equations programmed into the computer.

Since the track-while-scan radar continuously scans a given sector, it can track, (in computer memory), more than one target at a time. This multiple-target capability is its principal advantage over other radars. In order to provide the necessary computational processing and storage

Track-While-Scan Radar

A— Scope Presentation
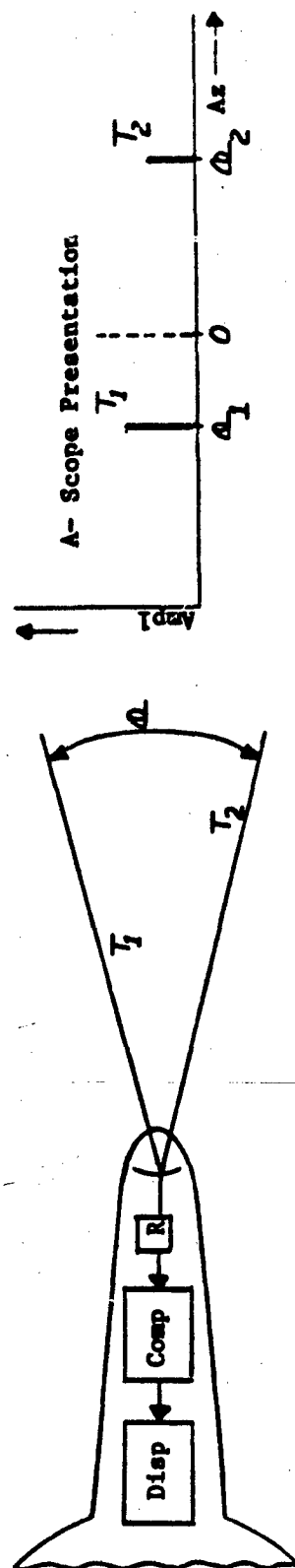
Figure 2.17.7.1

2.61a

Track-While-Scan Radar
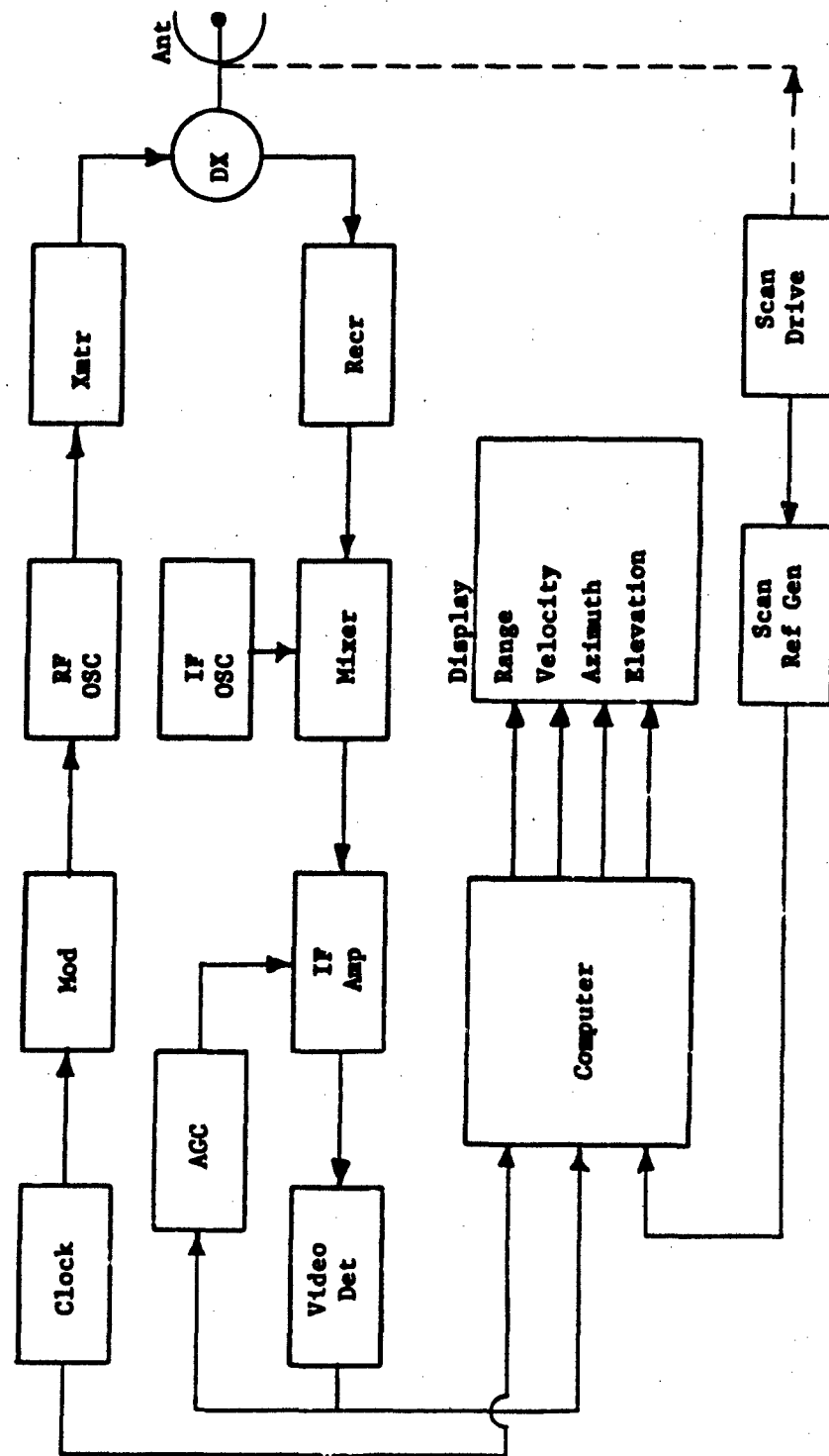
Figure 2.17.7.2
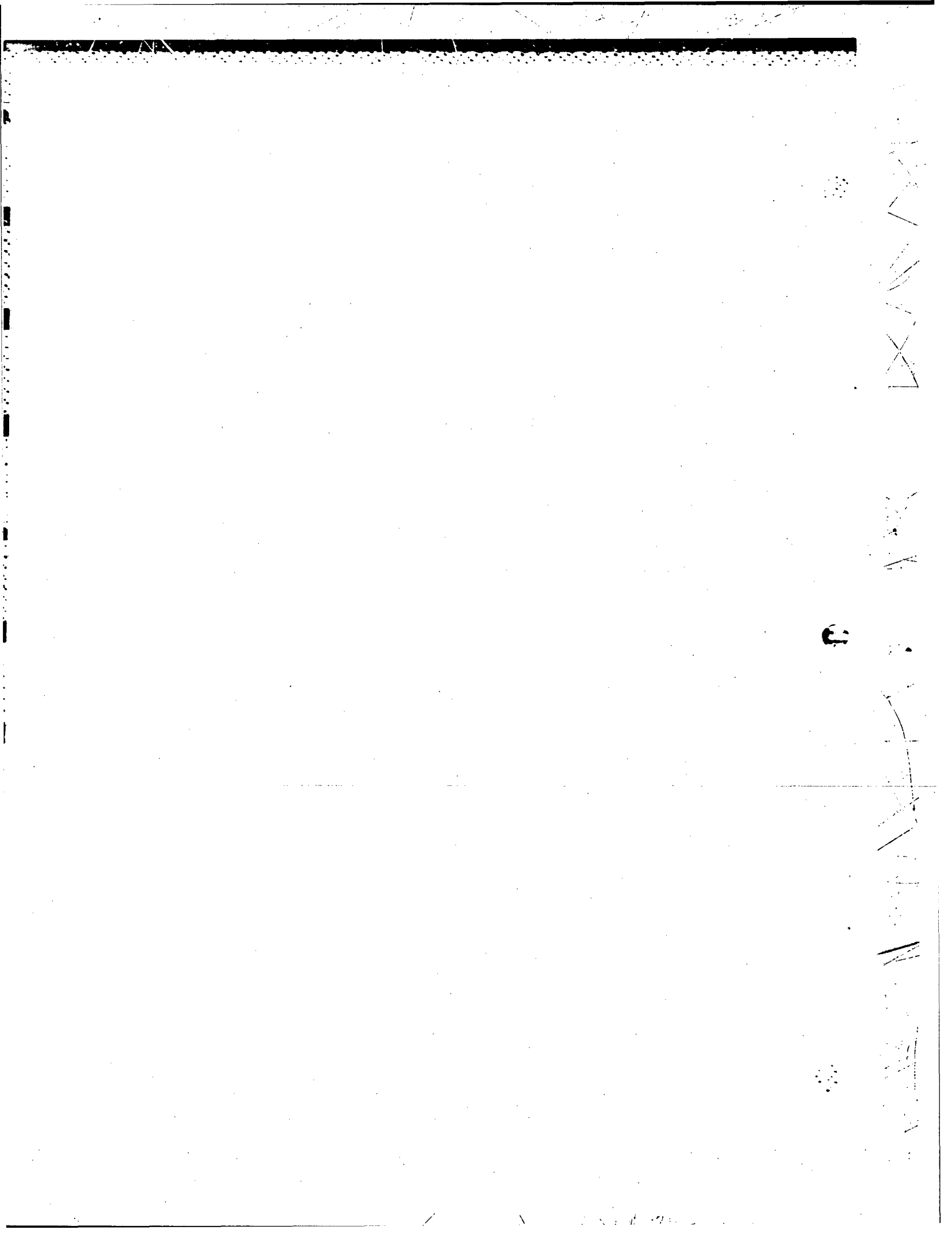
to allow multiple-target tracking, a relatively powerful computer is re-
quired. This computational ability, in turn, allows such sophisticated
data processing as predictive tracking, statistical data processing
(e.g. Kalman filtering), and threat assessment.

The principal disadvantage of TWS radar is the fact that only a minute
fraction of the radiated power is used to illuminate any given target.
Furthermore, the dwell time on any given target is extremely short.
These factors reduce the probability of detection for a given range.
Also the sampled-data nature of the target information complicates the
tracking process.

2.17.8 The Range Gate -- Tracking radars generally employ the range-tracking arrangement, known as a range gate, discussed in Section 2.14 of this text. In Figure 2.17.8.1(a) is shown the block diagram of a typical range gate. Actually, there are two gates, consisting of electronic switches, sequentially actuated by signals from the gate time generating circuit. At time t_1, the early gate is closed. At time t_g, the late gate is closed and the early gate is opened. The target return pulse energies that pass through the early and late gates are differenced in the gate time generator and the gate times, t_1 and t_g, are jointly advanced or retarded depending upon the algebraic sign of the difference. If more energy passes through the late gate than through the early gate, the gate times are retarded, thus increasing t_g and increasing the computed (tracked) range. When the gates split the pulse energy equally between them as shown in Figure 2.17.8.1(b), the range-tracking error signal t_e is zero, and no further change is made in the gate times. The corresponding value of t_g is then utilized to compute range to the target.

(a) Range Gate Block Diagram

t_1 = Time of Early Gate Closure

t_g = Time of Late Gate Closure, Early Gate Opening, and Target Pulse Return

V_e = Error Voltage

(b) Radar A-Scope Display

$t_1 \rightarrow t_g$ = Early Gate

$t_g \rightarrow t_2$ = Late Gate
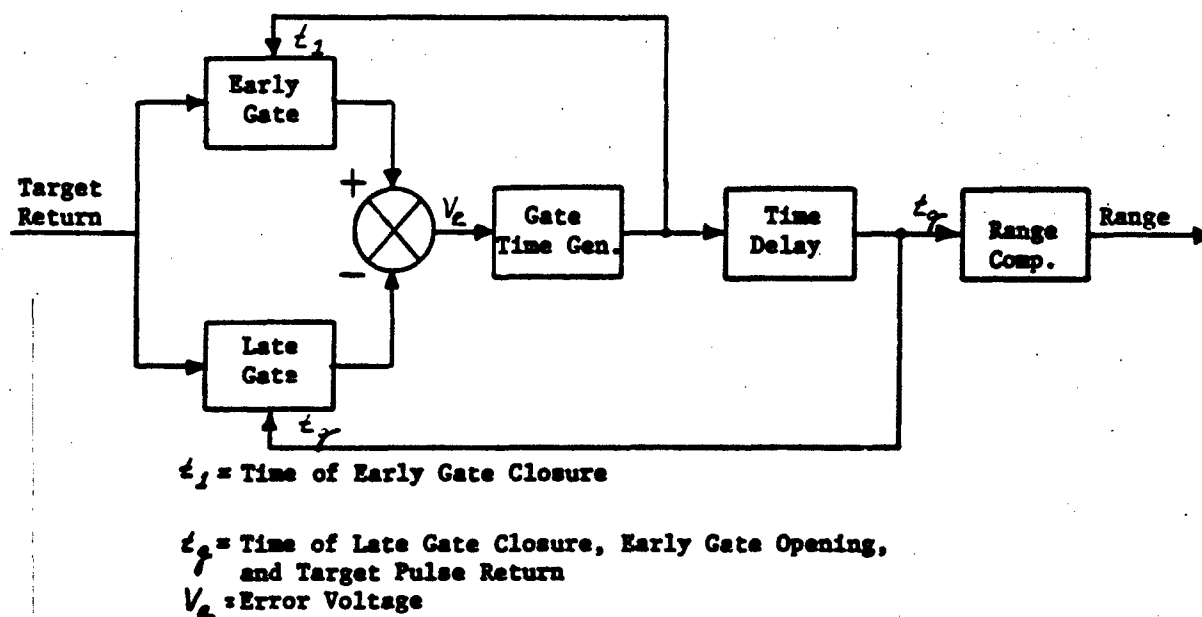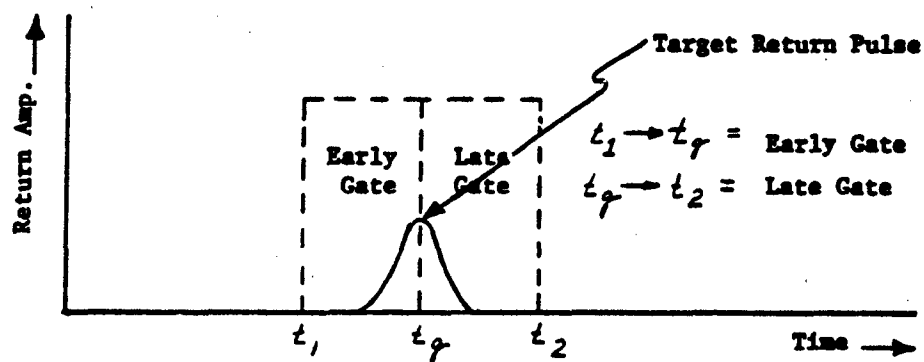
Figure 2.17.8.1 -- Radar Range Gate

2.63a

2.17.9 The Velocity Gate -- The velocity or speed gate employs the closed-loop frequency-tracking system shown in Figure 2.17.9.1. As indicated in the block diagram of Figure 2.17.9.1(a), the target return at the Doppler frequency, fd, is input to a mixer the other input to which is the output of a voltage-controlled oscillator (VCO). The output of the mixer, at the difference frequency, f_f, is then passed through a narrow-band band-pass filter, the purpose of which is to filter out extraneous signals on the basis of frequency. The filtered signal is then input to a frequency discriminator, the characteristics of which, (output voltage, V_d, as a function of input frequency, f_f), are shown in Figure 2.17.9.1(c). The output of the discriminator drives the voltage controlled oscillator, (the characteristics of which are shown in Figure 2.17.9.1(b)), thus completing the tracking loop. It should be noted that the gain of the tracking loop is such that the voltage V_d varies considerably, thus providing an output voltage proportional to the input frequency, f_d. In some systems, the filtered signal, at frequency f_f, is also output for further signal processing.

(a) Velocity Gate Block Diagram

Voltage – Controlled Oscillator

Frequency Discriminator

Band-Pass Filter

Mixer

$f_{VCO} = f_d - f_f$

f_f

f_d

V_d
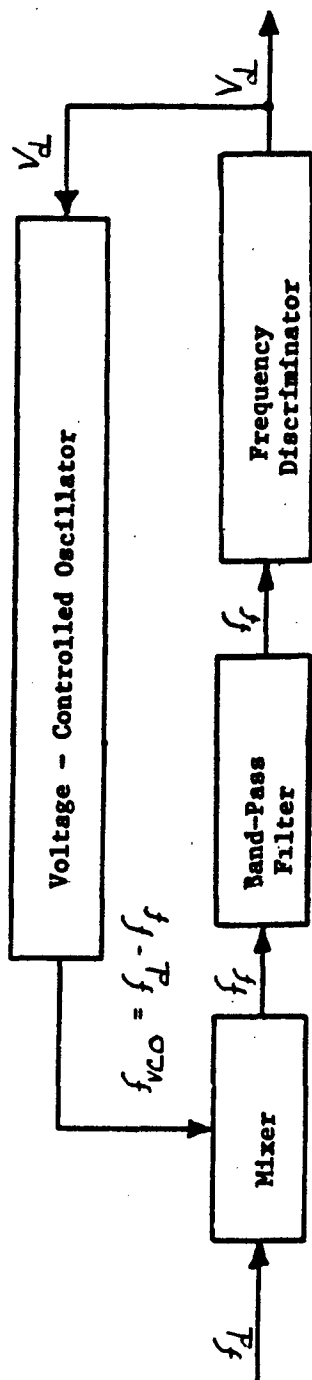
(b) VCO Characteristics
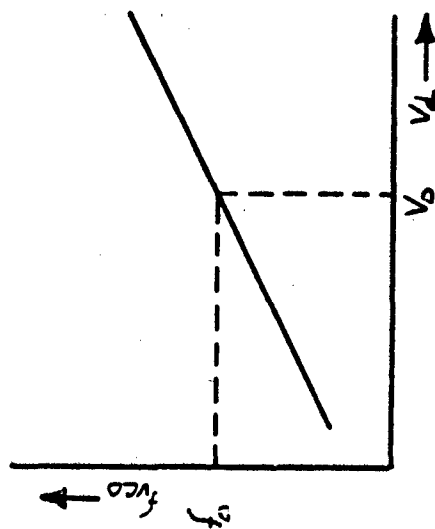
(c) Discriminator Characteristics
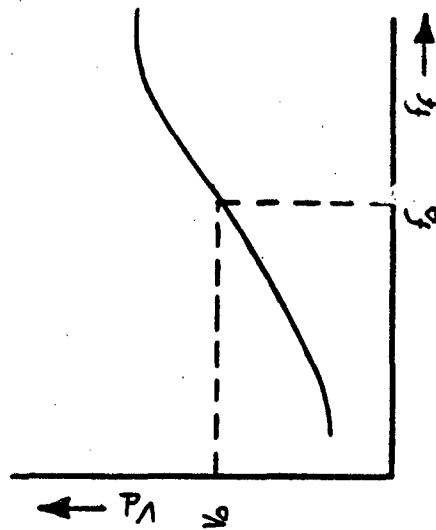
Figure 2.17.9.1 — Velocity (Speed) Gate

2.17.10 The Angle Gate -- The angle gate employed in a track-while-scan radar, shown in Figure 2.17.10.1(a), functions in a manner similar to that of the range gate discussed in Section 2.17.8 of this text. A major difference, however, is that, while the range gate operates on a single pulse, the angle gate operates on the returns of many pulses. As indicated in Figure 2.17.10.1(b), the early and late gates are not contiguous as in the range gate, but are separated in time (angle) so as to be positioned, during track, on different sides of the main lobe pattern generated at the receiver by a scanning radar, as shown in Figure 2.17.10.1(b). When the main lobe is not "centered" between the gates, the difference in energy entering the early and late gates produces a change in the joint gate times such as to equalize those energies. When the early and late gates are positioned at equal "heights" on the main lobe return pattern, equal energies enter the two gates, no further change is made in the gate times, and t_g is then used to compute target angular position by relating scan time (t_g) with scan position.

(a) Angle Gate Block Diagram

t_e = Early Gate Time

t_ℓ = Late Gate Time

t_g = Angle Gate Time
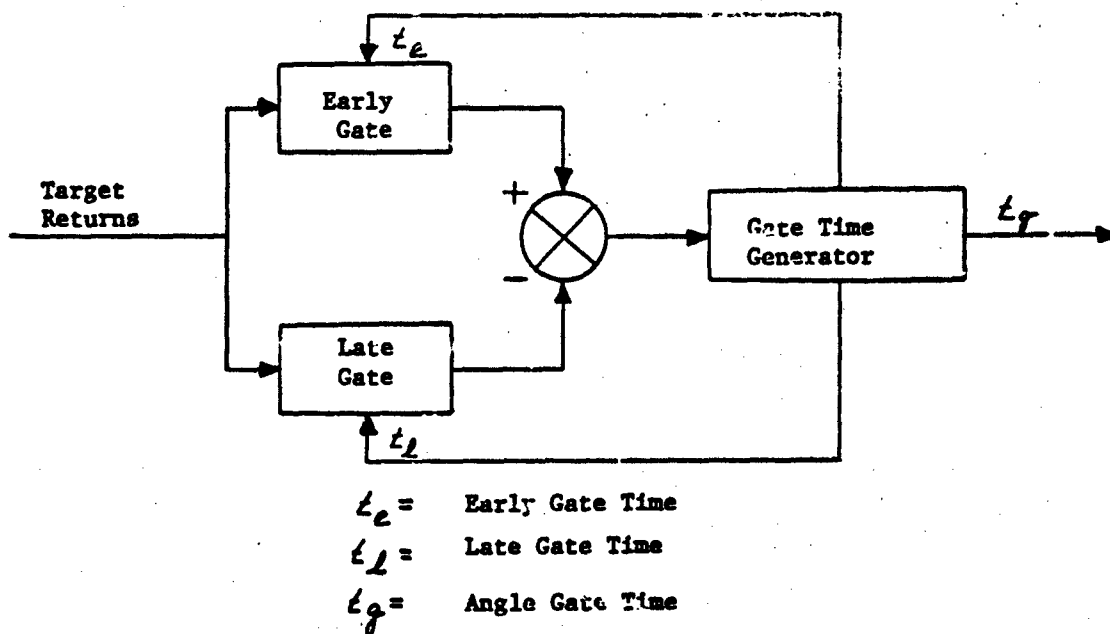
(b) Track - While-Scan Radar Returns
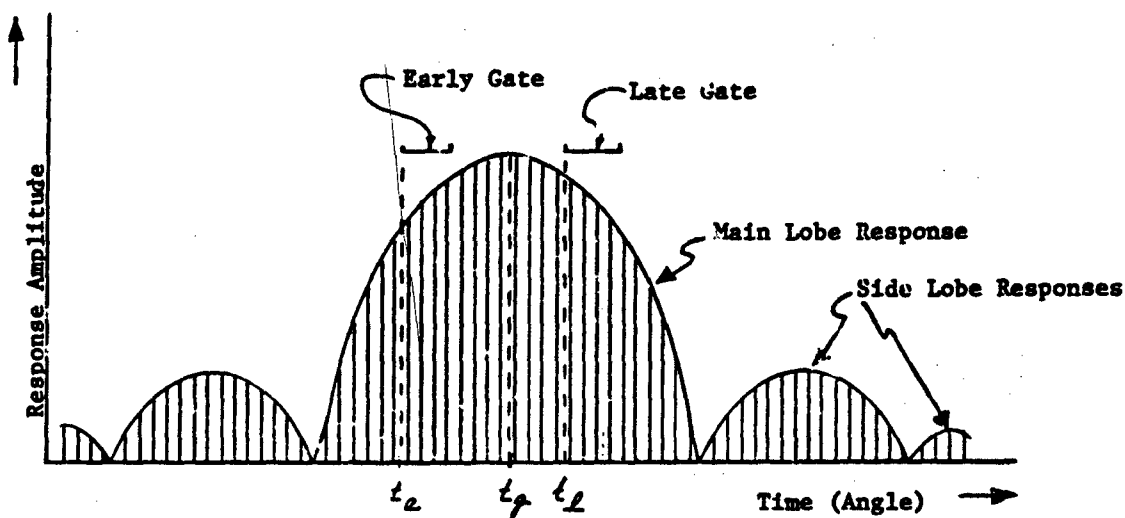
Figure 2.17.10.1 -- The Angle Gate

..65a

2.18 Doppler Beam Sharpening

As noted in Section 2.3.5, the angular (bearing) resolution of a radar
is generally much poorer than its range resolution. Thus, when an air-
borne radar is used for ground mapping, the overall clarity of the picture
is severely degraded by poor detail in azimuth. Fortunately, there exists
a method, ideally suited to ground mapping, by which angular resolution
can be improved by a factor of from fifteen-to-one to seventy-to-one.
That method depends upon the Doppler frequency shift of the ground return
and, therefore, is called Doppler beam sharpening (DBS).

Briefly, Doppler beam sharpening makes use of the difference in their
Doppler shift to distinguish between two ground points that would other-
wise not be distinguishable, due to the angular resolution (beam width)
of the radar antenna. In Figure 2.18.1 is shown the footprint of a radar
beam (the area where the main lobe intercepts the ground). The resolution
of the radar in range is a function of the timing circuits and is shown
in the figure as a "Range Bin". If the resolution of the radar in
azimuth were dependent upon the beam width, the azimuthal resolution
would be equal to the beamwidth, θ_B , and the resolution cell of the
radar would be the hatched area shown in the figure. With Doppler beam
sharpening, the azimuthal resolution of the radar is equal to the much
smaller angle $\Delta\theta$, and the resolution cell is, therefore, the cross-
hatched area shown.

Doppler Beam Sharpening

$\Delta f_1, \Delta f_2$

Beam Footprint

f_{d_1}, f_{d_2}

Range Bin (Range Resolution)

Isodop

$\Delta \alpha$

Flight Path

α_B

α

$\vec{v}$

f_{d_1}, f_{d_2} = Doppler Shift Frequencies for Two Isodops Bordering Resolution Cell

$\vec{v}$ = Ground Velocity of Aircraft

α = Azimuth of Resolution Cell

α_B = Antenna Beam Width

Δf_d = Doppler Filter Bandwidth

$\Delta \alpha$ = DBS Beam Width (Azimuth Resolution)

Figure 2.18.1

2.66a
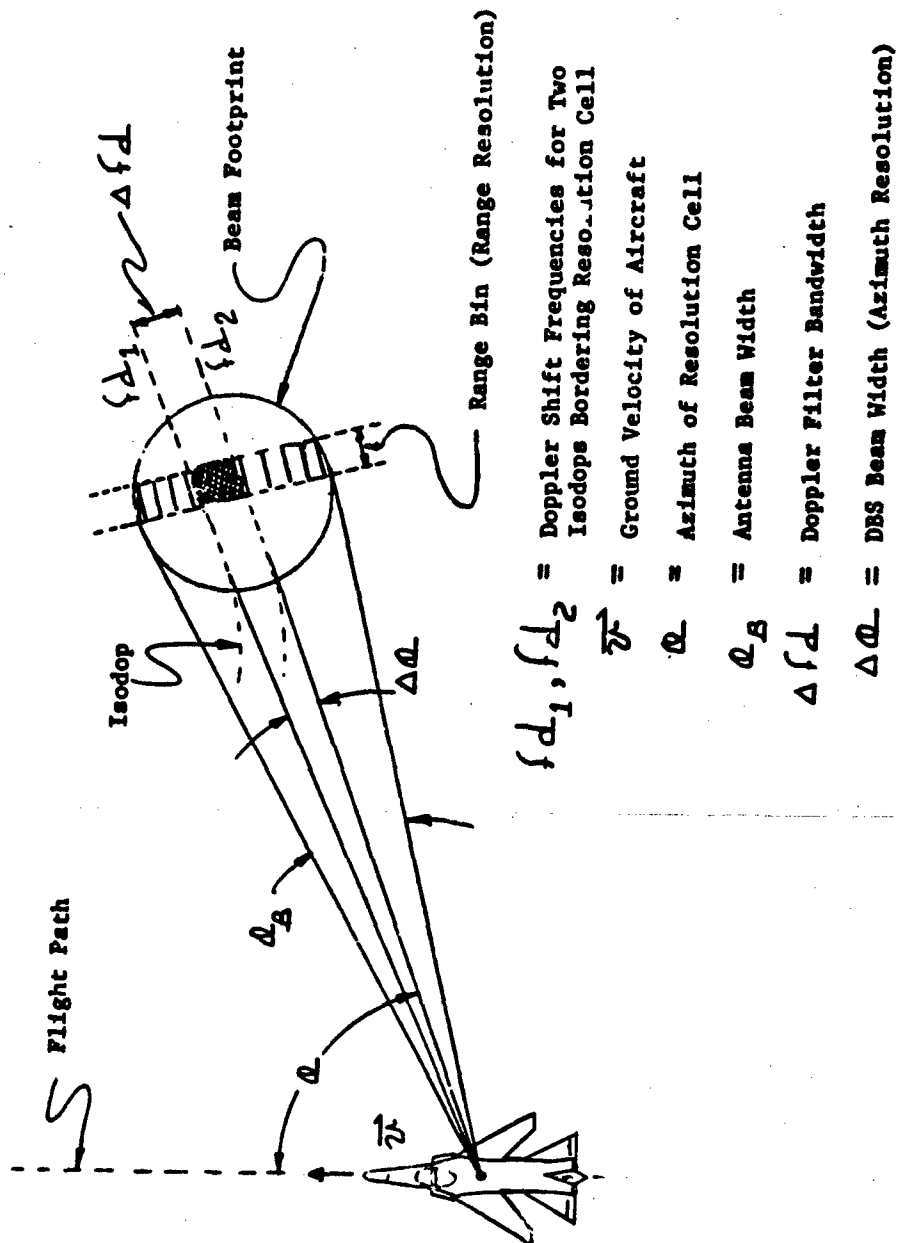
In Figure 2.18.1, two isodops, (loci of constant Doppler shift on the earth's surface), are shown labeled by their Doppler shift frequencies, f_{d1} and f_{d2}. The Doppler shift frequency along an isodop is given by:

$$f_d = \left(\frac{2v}{\lambda_o}\right) \cos\theta \, \cos\gamma \qquad [2.18.1]$$

where v is the aircraft's ground speed, λ_o is the radar wavelength, θ is the DBS resolution cell azimuth and γ is the DBS resolution cell depression angle, all measured from the direction of the velocity vector. For simplicity, the beam depression angle, γ, will be assumed to be zero for the following development. Thus:

$$f_d = \left(\frac{2v}{\lambda_o}\right) \cos\theta \qquad [2.18.2]$$

The differential Doppler shift, Δfd, for a given differential azimuth, $\Delta\theta$, is then:

$$\Delta fd = -\left(\frac{2v}{\lambda_o}\right) \sin\theta \, \Delta\theta \qquad [2.18.3]$$

If the frequency resolution (ability to distinguish two signals close in frequency) of the radar is Δfd, then the radar should be able to distinguish two targets separated by $\Delta\theta$ in azimuth on the basis of their difference in return frequency, where:

$$\Delta\theta = \frac{\lambda_o \, \Delta fd}{2 \, v \, \sin\theta} \qquad [2.18.4]$$

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According to the principles of information theory, the limiting factor
in determining the frequency resolution, Δf, of a measuring system is
the time interval, ΔT, during which the frequencies can be observed.[1]
Specifically:

$$\Delta f = \frac{1}{\Delta T}$$ [2.18.5]

For the case illustrated in Figure 2.18.1, the observation time is pro-
portional to the beam width (if the beam is held at a fixed angle θ).
Thus, we have the apparently anomalous, but accurate, result that, in
this case, a larger beam width produces better angular resolution.

As indicated by Equation [2.18.4], DBS resolution is best when the mapping
beam is pointed at right angles to the flight path. Conversely, the
resolution becomes very poor as θ approaches zero. For that reason,
Doppler beam sharpening is not applied within limits that extend for
several degrees to either side of the direction of flight.

---

(1) This analysis assumes good frequency stability throughout the system
during the transmission/observation period. Such stability is a
requirement of DBS radar.

2.68

3.0 Radar System Characteristics

3.1 General Radar System Characteristics

3.1.1 General Description -- The block diagram of a generalized radar system
is shown in Figure 3.1.1.1. As indicated therein, the amplitude and/or fre-
quency (phase) of the carrier are modified by modulation in accordance with a
modulation signal designed to impart, to the transmitted signal, characteris-
tics that will make observable the target parameters of interest, such as
position, velocity, shape, and reflectivity. The characteristics of the radar
signal (modulation, polarization, direction of propagation, etc.) are then
modified by reflection from the target, thus impressing the desired information
upon the reflected signal. Upon being received, the information-bearing signal
is demodulated, thus extracting the information signal from the modulated
carrier. (The figure indicates coherent detection.) The information-bearing
signal is then compared with the original modulation by time and/or frequency
correlation. Finally, the results of the correlation are displayed to the
user and/or passed on to other systems such as navigation or weapon-delivery
systems. Detailed discussions of modulation, demodulation, correlation, and
other signal processing operations commonly employed in radar systems are pre-
sented in the text on communications and in earlier sections of this text.
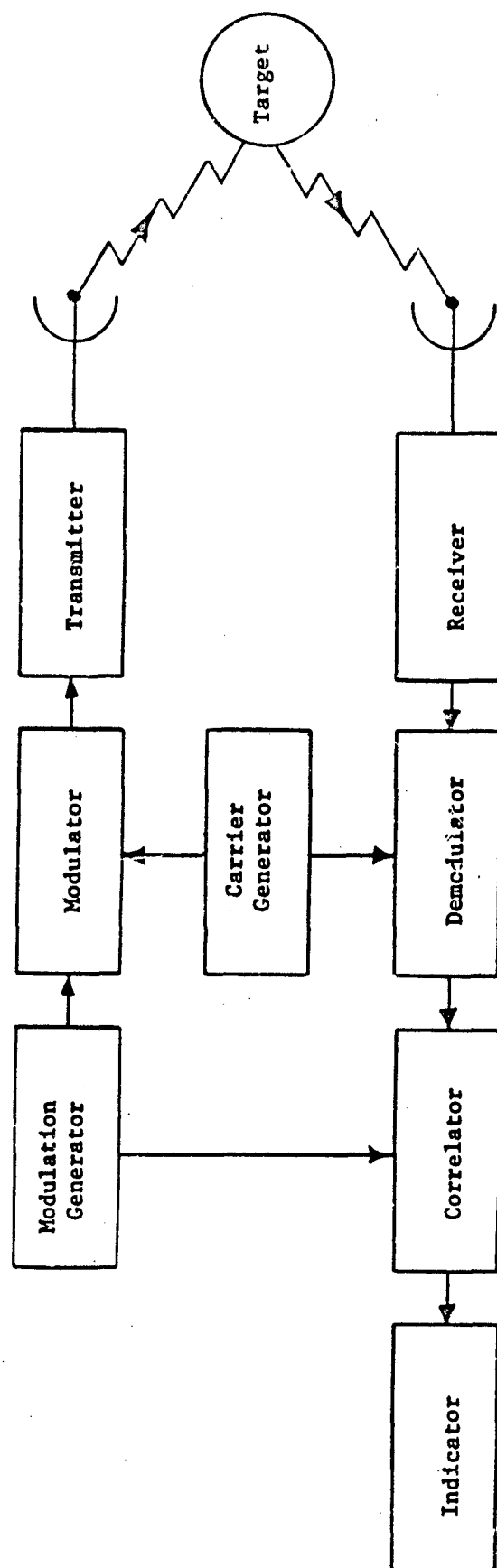
Figure 3.1.1.1.—Generalized Radar System

3.1a

3.1.2 Radar System Requirements -- The operation of a radar system involves

the transmission of information from one point (the target) to another (the

radar receiver). Thus, a radar is a specialized type of communications system.

Therefore, the communications system requirements discussed in Section 3.1.2

of the communications text apply to radar systems. These requirements are listed

below and discussed, in terms of radar systems, in the following paragraphs.

    Range (Distance)
    Transmitting Media
    Carrier Constraints
    Modulation Constraints
    Information Signal Content
    Information Rate
    Interference Rejection
    Fidelity
    Acceptable Error Rate
    Operational Constraints
    Electronic Counter-Countermeasures
    Secure Operation
    Covert Operation
    Reliability and Maintainability
    Electromagnetic Compatibility
    Environmental Tolerance
    Hardware Constraints
    Development, Production, and Operation Costs

Range -- For a radar system, several maximum functional operating ranges are

involved, each specifying the maximum range at which a particular function can

be performed. Typical functions are detection, track acquisition, and tracking,

the last two obviously applying only to tracking radars. The maximum functional

ranges depend upon the signal-to-noise ratios required for the various functions

and upon other factors indicated by the radar range equations presented in

Sections 2.4 and 2.15 of this text.

Transmitting Media -- In this text, the propagation path is assumed to lie,

almost entirely, in the atmosphere or in free space. The exceptions are

transmission through radomes and other structures of little extent. The atmospheric effects are, however, quite complex, exhibiting reflection, refraction, diffraction, and absorption as discussed in Section 2.4 of the text on Communications.

Carrier Constraints -- In this text, the carrier is assumed to consist of radio-frequency electromagnetic waves. Sensors utilizing other carriers, such as optical-frequency waves (laser "radar") and acoustic waves (sonar) are treated in other texts. Constraints are commonly placed, by outside authority, upon radar systems, with respect to carrier frequency, bandwidth, and power.

Modulation Constraints -- As discussed in Section 1.0 of this text, the modulation employed in radar signals is primarily determined by the need to optimize the recovery of information. Some constraints are, however, imposed by outside authority.

Information Signal Content -- In radar, the information content is impressed upon the carrier not at the transmitter but, rather, at the target. The reflected signal (target return) is amplitude and frequency modulated as a result of the target's position, size, shape, reflectivity, and motion. At the receiver, the reflected signal is demodulated to recover those target characteristics. The information signal requirements are, therefore, imposed indirectly by specifying the desired target parameters and the dynamic ranges anticipated.

Information Rate -- The required information rate of a radar is specified indirectly by specifying the rate of change of the target characteristics to be determined. The radar must be designed with the proper pulse rate, pulse width,

3.3

scan rate, and display rate to accommodate the resulting information rate.

Interference Rejection -- Requirements for the rejection of interference (noise) are increasingly common in radar systems because of two factors: deliberate jamming and background clutter. Whether due to jamming or to clutter, the noise must be rejected on the basis of time (range gating), frequency (narrow-band filtering, Doppler filtering, and coherent processing), position (narrow-beam antennas), or amplitude (threshold devices).

Fidelity -- Fidelity is the accuracy with which a system indicates the desired information. For a radar system, that information generally consists of range, bearing (azimuth and elevation), and velocity. The measures of radar fidelity are the accuracy, repeatability, and resolution with which the information is indicated.

Acceptable Error Rate -- For a radar, the acceptable error rate is specified in terms of Probability of Detection, Probability of False Alarm, and Blip-to-Scan Ratio. It is necessary to employ statistical terms (probabilities) because random noise renders the detection process stochastic. It should be noted that Probability of Detection and Maximum Detection Range are alternate ways in which to express the ability of the radar to detect a target.

Operational Constraints -- Constraints, other than those due to performance limitations, are often placed upon radar systems. Such constraints may result from technical, operational, or political considerations.

Electronic Counter-Countermeasures -- In the radar field, requirements are
imposed for electronic counter-countermeasures to prevent an adversary from
jamming or deceiving the system. Electronic counter-countermeasures are
discussed in the text on Electronic Warfare.

Secure Operation -- Design requirements often are imposed on radar systems
to prevent an adversary from recovering, from the intercepted signals, such
system parameters as carrier frequency, pulse repetition frequency, modulation,
and scan rate. Such requirements are discussed in the text on Electronic
Warfare.

Encryption of radar transmission also is sometimes required for purposes of
target identification. (Encryption is discussed in Section 2.5.8 of the
communications text.)

Covert Operation -- A low probability of intercept is of great importance in
many tactical situations. Corresponding requirements are being placed on
radar systems with increasing frequency.

As with all airborne systems, radar systems are required to meet exacting
standards with respect to reliability, maintainability, electromagnetic
compatibility, environmental tolerance, hardware constraints, and life-cycle
costs.

3.1.3 Radar System Design Features -- The communication system design features presented in Section 3.1.3 of the text on Communications Systems apply to radar systems. These design features are listed below, and discussed in terms of radar systems, in the following paragraphs.

    Carrier Type
    Carrier Frequency and Bandwidth
    Carrier Power
    Propagation Mode
    Antenna Design
    Number of Channels
    Multiplexing
    Redundancy
    Modulation
    Spectral (Frequency-Dependent) Filtering
    Nonlinear (Amplitude-Dependent) Filtering
    Digital Encoding
    Signal Correlation
    Statistical Signal Processing
    Encryption
    Spread-Spectrum Signal Processing
    Operational Techniques

Carrier Type -- As previously stated, the carrier is assumed, in this text, to be a radio frequency electromagnetic wave. Both plane and circularly-polarized waves are employed. The target signal-to-clutter signal ratio is enhanced by employing vertical or horizontal polarization for certain targets. The clutter signal due to rain is greatly reduced by employing circular polarization because the sense (direction of rotation) of the signal is reversed by reflection from the raindrops but is not reversed by reflection from a solid target, thus allowing discrimination by the receiving antenna. Change of polarization also is sometimes used as an electronic counter-countermeasure. Electronic countermeasures are discussed in the text on Electronic Warfare.

Carrier Frequency and Bandwidth -- Carrier frequency is determined primarily by considerations of wave propagation, target cross section, required beam width,

and airborne space limitations. As discussed in Section 2.4.3 of the text on Communications Systems, such factors as atmospheric absorption are greatly affected by frequency. For that reason, long-range radars employ relatively low carrier frequencies to minimize absorption.

As discussed in Section 2.5 of this text, a large target return requires that the wavelength of a radar signal be small in comparison with the dimensions of the intended target. For most airborne radar targets, that fact indicates a relatively high carrier frequency.

A high carrier frequency is also required for good angular resolution. For non-interferometric radars, good angular resolution requires a small beam width. (See Section 2.3.6 of this text for a detailed discussion of angular resolution.) The beam width of an antenna is roughly proportional to the wavelength of the signal and inversely proportional to the size of the antenna. (Refer to Section 2.6.7 of the text on Communications Systems.) Since space for airborne systems is severely limited, a high carrier frequency is required to achieve a narrow radar beam, and hence good resolution. A narrow beam is also required for a high antenna directive gain, often required to obtain a high target signal-to-clutter signal ratio.

A relatively high bandwidth is required for good range resolution in radar systems. Good range resolution in a pulsed radar requires short, sharp pulses which in turn contain high frequencies. An FM-ranging radar requires a large frequency excursion to obtain high resolution. In either case, a large bandwidth is required.

Carrier Power -- As discussed in Sections 2.4 and 2.15 of this text, the maximum range of a radar is a function of the carrier power. Radar performance is almost always enhanced by an increase in available power.

Propagation Mode -- Most radar applications employ direct, line-of-sight propagation. The exceptions are some long-range radars which employ relatively low frequencies and utilize sky-wave and ducted-wave propagation as discussed in Section 2.4.4 of the text on Communications Systems.

Antenna Design -- As indicated in the discussion of carrier frequency considerations, antenna gain and beam width are determined largely by antenna size, which is severely limited in airborne applications. Antenna design is, therefore, a difficult aspect of radar system design. Advances in phased-array antennas, (see Section 2.6.12 of the text on Communications Systems), have somewhat alleviated the problems of achieving the required scan patterns and rates, but the beam width is still dictated by available space.

Number of Channels -- Multiple site radars and multiple transmitting and/or receiving antennas are sometimes employed, their signals being combined to yield an optimal solution. Monopulse radar is an example of a multiple-antenna radar technique.

Multiplexing -- Time and frequency multiplexing are used in radar systems to improve performance and as an electronic counter-countermeasure. For example, time switching of carrier frequency is used both to eliminate blind speeds in a Doppler radar and to counter jamming.

3.8

Redundancy -- Redundancy (multiple, identical channels) is employed in air-borne radar systems for reliability.

Modulation -- As previously indicated, it is the modulation applied to the carrier by reflection from the target that impresses the desired information upon the radar return. The modulation applied to the carrier at the transmitter is, however, one of the most powerful design features employed by the radar designer. The most obvious example is the time-coloring (pulsing, frequency modulating, etc.) employed to provide for ranging. Another example is the use of a time-varying pulse repetition interval and carrier frequency used to avoid blind ranges and blind speeds. Still another example is the use of frequency modulation within the pulse to allow compression of the pulse to improve range resolution. Most spread-spectrum techniques involve the use of special carrier modulations. (All of these examples are discussed in Section 2.0 of this text.)

Spectral Filtering -- Frequency-dependent filtering is one of the most frequently employed signal processing techniques. It is, of course, used to select a signal of given carrier frequency from others of different frequency. It is also used to attenuate interfering signals (noise) of known frequency content. In Doppler radar systems, spectral filtering is used to determine the Doppler shift of the radar return, and therefore, the relative range rate of the target. (Doppler radar is discussed in Sections 2.11 to 2.16 of this text). As indicated in Section 2.18 of this text, narrow-band frequency filtering is the basis for Doppler beam sharpening.

Nonlinear Filtering -- Amplitude-dependent filtering is employed in the radar field to discriminate between the information signal and noise on the basis of amplitude. The most common example is the processing of a radar return through a device that rejects all returns below a set threshold level, on the assumption that the target return will be larger than the background noise. Another type of amplitude-dependent device is the automatic gain control (AGC), which reduces the gain in the presence of a large-amplitude signal, thereby preventing saturation of the system. Clipping (truncation of all signals above a set level) is also employed to prevent saturation or overload.

Digital Encoding -- Digital encoding of radar signals is increasingly employed. The usual purpose of digitization is to allow processing of the signal by means of a digital computer. As indicated in Section 2.2 of the text on Communications Systems, digital techniques and equipment have advanced to the point where many operations, formerly impossible, are now highly practicable. Doppler beam sharpening and spread-spectrum signal processing are examples of such operations.

Signal Correlation -- As discussed in Section 2.8 of this text, correlation detectors are currently employed in the radar field to "recognize" radar returns in the presence of noise. As digital radar signal processing becomes more universal, the powerful techniques of signal correlation will become more widely used.

Statistical Signal Processing -- Pulse integration, as discussed in Section 2.7 of this text, is the most commonly employed statistical processing technique. A more complex techniqu   the use of an optimal estimation filter, such as

3.10

the Kalman filter. The Kalman filter is a device that inputs various system measurements, (with noise), and combines them, via statistically-weighted averaging and dynamic modeling, to obtain the best estimate of the desired system parameters and outputs.

Spread Spectrum Signal Processing -- Spread spectrum techniques are employed for several purposes in radar signal processing. Those purposes include covert operation, rejection of interfering signals, and encryption. A description of spread spectrum methods and the purposes for which they are employed is presented in Section 2.5.8 of the text on Communications Systems. Techniques peculiar to radar systems are the use of spread spectrum techniques (complex amplitude and frequency modulation) to avoid blind target ranges and velocities and to improve range resolution.

Operational Techniques -- Constraints are often imposed, by the designer, upon radar systems, precluding (or requiring) specific operational techniques under certain circumstances. A typical designer-imposed operational constraint is that precluding the use of Doppler-beam-sharpened ground-mapping radars in directions approaching that of the ground track. Another example is the constraint prohibiting the use of some air-to-air radars in a look-down situation or below a certain altitude, because of ground clutter.

3.2 Definitions of Radar System Characteristics

The general communications system characteristics defined in Section 3.2.2 of the text on communications systems are applicable to radar systems. Other characteristics, peculiar to radar systems, are listed below and defined in the following paragraphs.

3.2.1 Pulse Radar Characteristics

Antenna Beamwidth
Antenna Boresight Accuracy
Bearing Accuracy
Bearing Resolution
Blind Ranges
Blip-to-Scan Ratio
Display Type
Duty Cycle
Max Detection Range
Max Unambiguous Range
Min. Detection Range
Probability of Detection
Probability of False Alarm
Range Accuracy
Range Resolution
Scan Field-of-View
Scan Rate
Scan Pattern
Scan/Display Stabilization Limits
Scan Volume

3.2.2 Pulse Doppler Radar Characteristics (Additional)

Blind Speeds (Velocities)
Max. Target Velocity
Max. Unambiguous Target Velocity
Min. Target Detection Velocity
Range Rate Accuracy
Range Rate Resolution

3.2.3 Continuous-Wave, Frequency-Modulated Radar Characteristics (Additional)

Frequency Modulation Bandwidth
Frequency Modulation Rate
Frequency Modulation Repetition Interval
Frequency Modulation Waveform

3.2.4 Tracking Radar Characteristics (Additional)

Max. Acquisition Line-of-Sight Slew Rate
Max. Acquisition Time
Max. Number of Missiles In-Flight
Max. Number of Targets Displayed (TWS)
Max. Number of Track Files (TWS)
Min. and Max. Acquisition Ranges
Min. and Max. Acquisition Range Rates
Velocity Accuracy
Velocity Resolution

Pulse Radar Characteristics

Antenna Beam width -- The angular subtence of radial lines through the half-power points on the antenna pattern. Elevation and azimuth beamwidths are, in general, independent. Antenna beamwidth depends upon carrier frequency and effective antenna size and determines the angular resolution of a non-interferometric radar.

Antenna Boresight Accuracy -- The accuracy of angular alignment between the radiation main lobe and the antenna mechanical pointing reference line. Antenna boresight accuracy depends upon the electrical and mechanical properties of the antenna and determines, in part, the accuracy with which radar target bearing may be determined.

Bearing Accuracy -- The maximum error within which a tracking radar is capable of determining the bearing (azimuth or elevation) of a target. For a non-interferometric radar, angular accuracy depends upon the characteristics of the antenna pattern, (primarily boresight accuracy and beamwidth), and includes measurement error due to finite angular resolution. For an interferometric radar, bearing accuracy depends upon antenna boresight accuracy, (but not beam-width), and depends on the accuracy with which the radar signal processing equipment can measure differences in signal amplitude or phase.

Bearing Resolution -- The minimum separation in bearing for which two targets can be distinguished. For a non-interferometric radar, bearing resolution depends upon antenna beamwidth. For an interferometric radar it depends upon the minimum signal amplitude or phase difference that can be discerned, as discussed in Section 2.3.6 of this text.

3.14

Blind Ranges -- The ranges at which a pulse radar cannot detect a target due to eclipsing of the target return by the transmission period. Blind ranges depend upon the pulse repetition frequency and affect the probability of detection.

Blip-to-Scan Ratio -- The ratio of the number of target detections divided by the number of times an actual target was scanned. Blip-to-scan ratio depends upon probability of detection and is a measure of overall radar system performance.

Display Type -- The manner in which the target information (system output) is visually presented to the crew. The most common types of radar displays are shown in Figure 3.2.4.1.

Duty Cycle -- The fraction of time that a pulse radar is transmitting. The duty cycle is equal to the ratio of pulse width to pulse repetition interval and determines the relationship between peak power and average power.

Maximum Detection Range -- The maximum range at which a radar can detect a target of given cross section with a given probability. Maximum detection range is given by the range equations presented in Sections 2.12 and 2.15 of this text.

Maximum Unambiguous Range -- The maximum range at which the return from a target will arrive back at the receiver before another pulse is transmitted. Maximum unambiguous range depends upon the pulse repetition interval.

A-DISPLAY
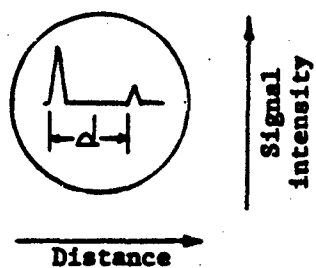
B-DISPLAY
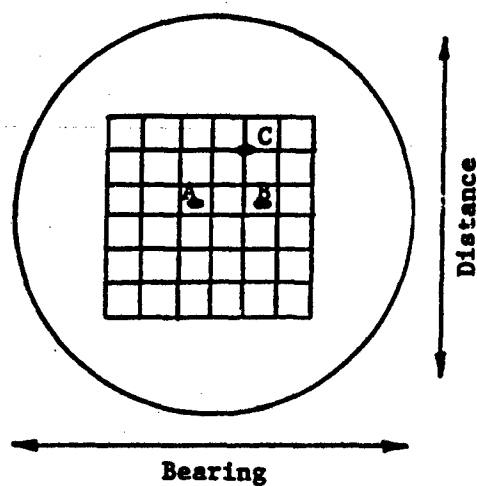
C-DISPLAY
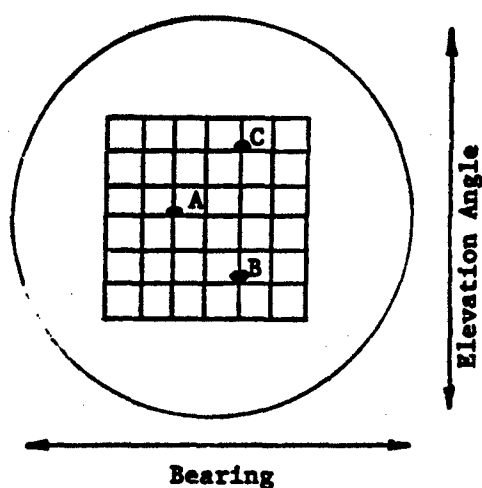
Figure 3.2.4.1(a)—Airborne Radar Displays

3.15a

D-DISPLAY

E-DISPLAY

Elevation Angle

Bearing

Elevation Angle

Distance

E SCAN

F-DISPLAY

Target is bright spot

Elevation

Range

Vertical Aiming Error

Horizontal Aiming Error
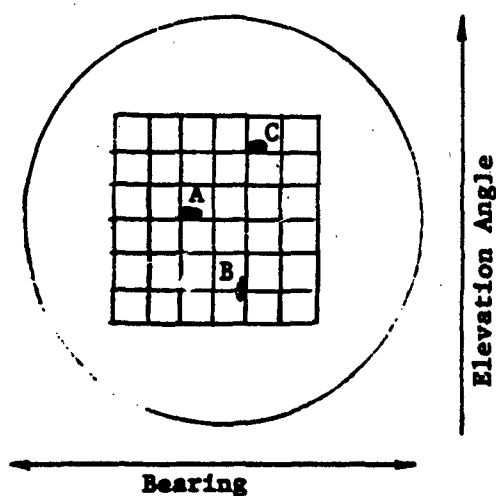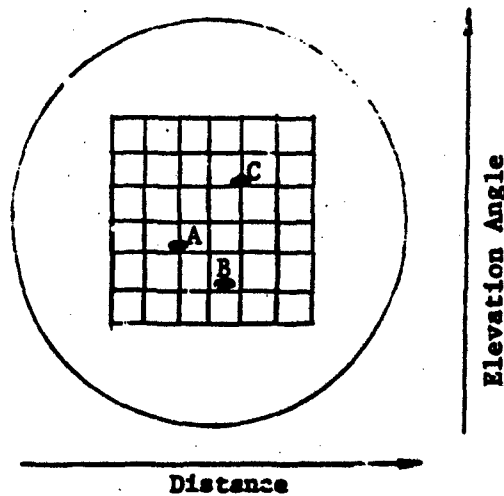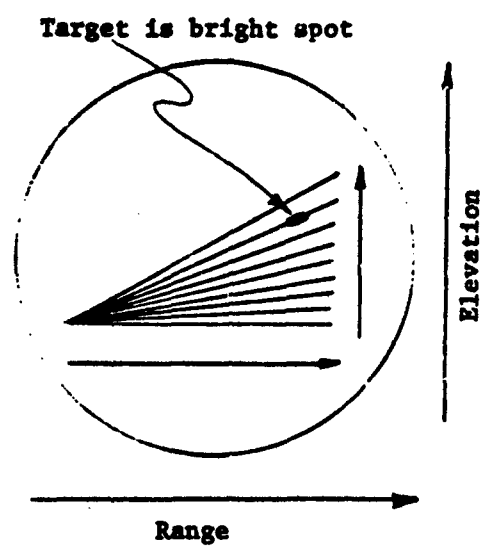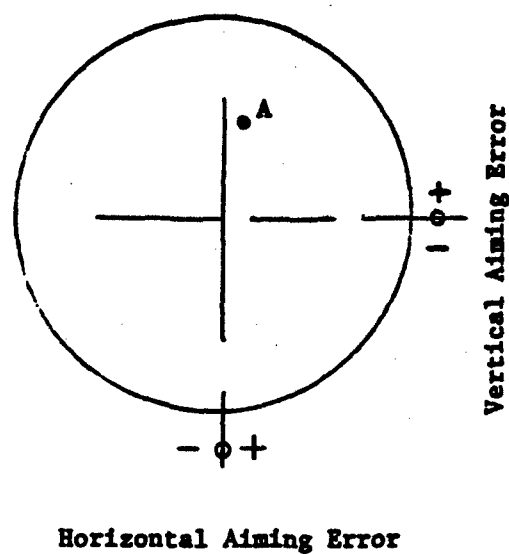
Figure 3.2.4.1(b)--Airborne Radar Displays

3.15b

H-DISPLAY

Distance

Bearing

G-DISPLAY

Vertical Aiming Error

Azimuth Aiming Error

J-DISPLAY

Two targets (A,B) at different distances.

I-DISPLAY

Two targets (A,B) at different distances.
Radar is aimed on target A.
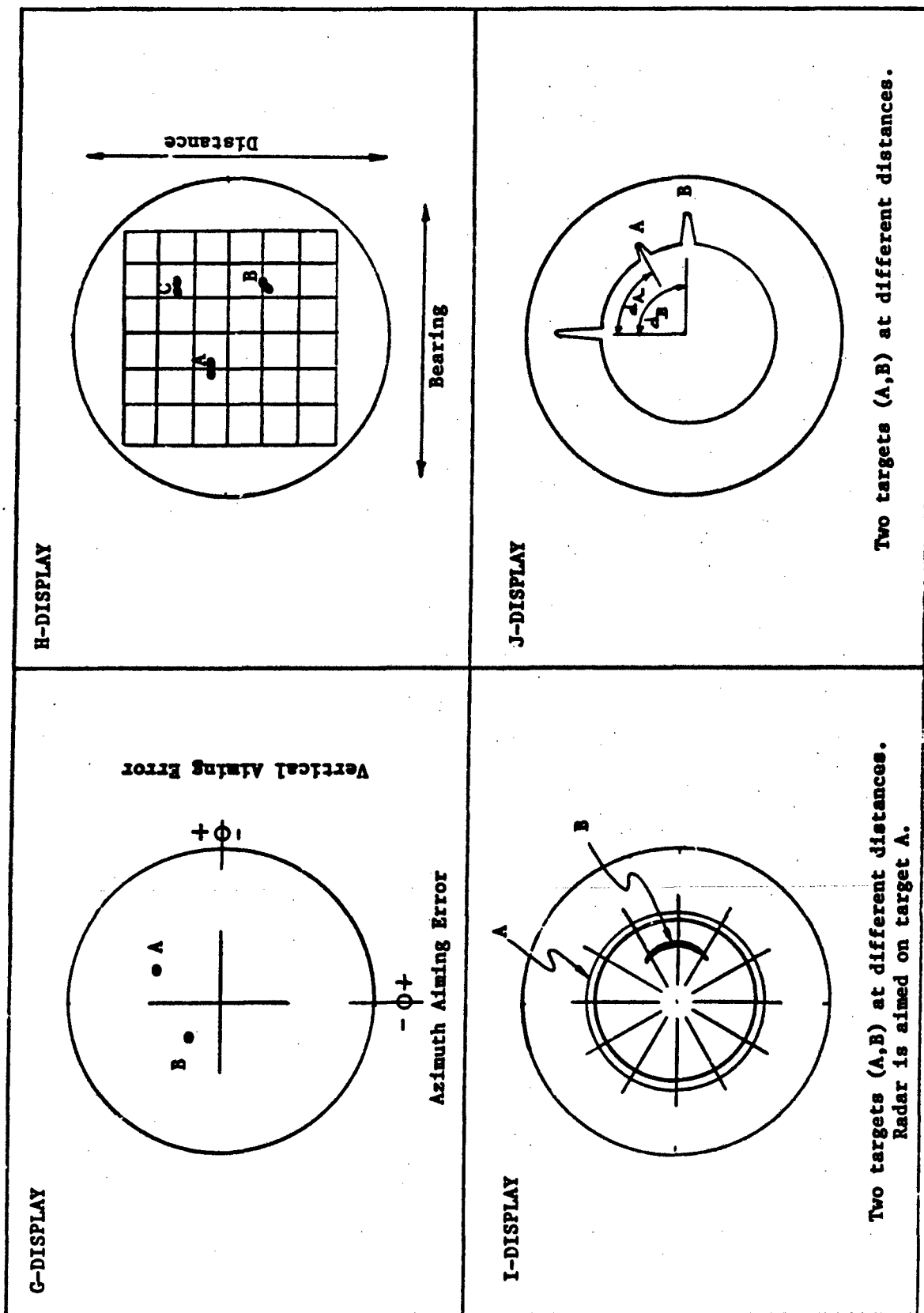
Figure 3.2.4.1(c)—Airborne Radar Displays

3.15c
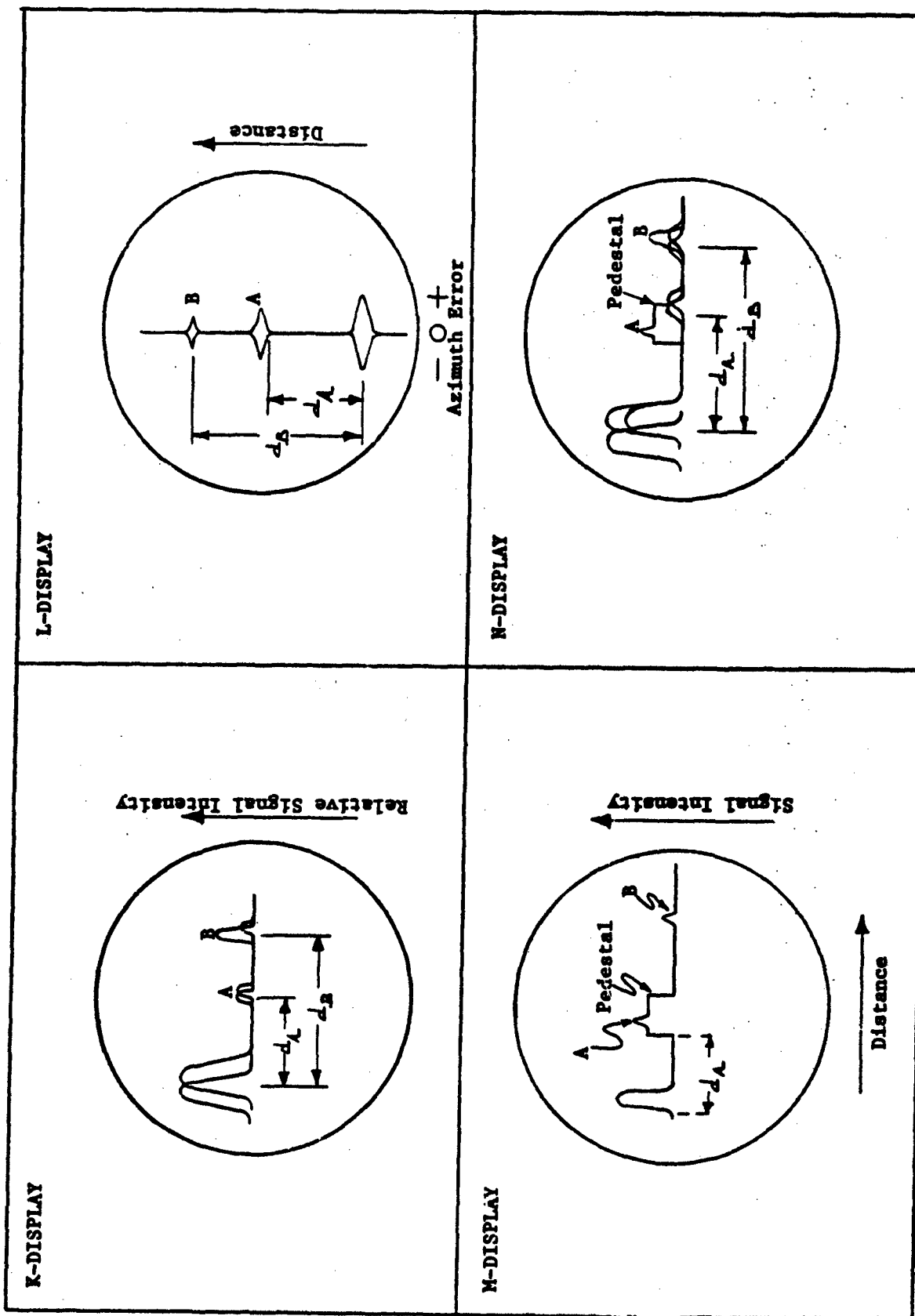
Figure 3.2.4.1(d)—Airborne Radar Displays

(a)

(b)
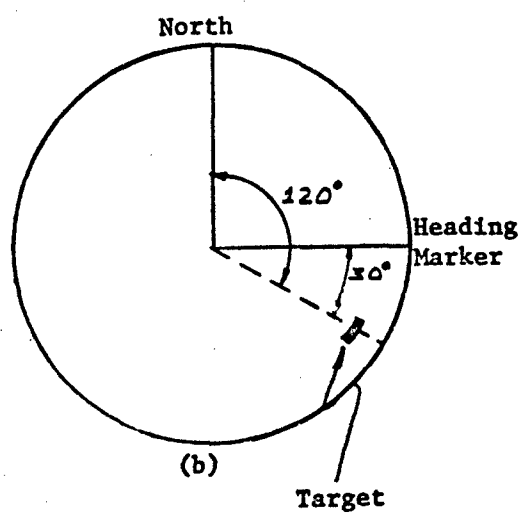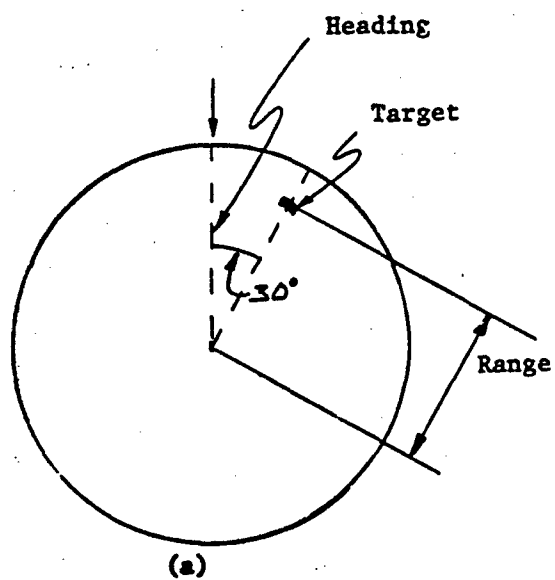
Figure 3.2.4.1 (e) -- Airborne Radar Displays

Minimum Detection Range -- The minimum range at which a target return will not

arrive back at the receiver before the transmission period has ended. The

minimum detection range depends upon pulse width.

Probability of Detection -- The statistical probability that a target will be

detected when an actual target is scanned. The probability of detection depends

upon many factors and is a measure of overall radar system performance.

Probability of False Alarm -- The probability that a target will be detected when

no actual target is scanned. The probability of false alarm depends upon many

factors and generally increases with probability of detection. It is an

inverse measure of radar system performance.

Range Accuracy -- The maximum error within which a radar is capable of determining

the range of a target. Range accuracy depends upon pulse width (range resolution)

and upon the accuracy with which the radar signal timing circuits can measure

pulse time intervals.

Range Resolution -- The minimum separation in range for which two targets can be

distinguished. Range resolution depends upon effective pulse width. (The

actual pulse may be time-colored to allow effective pulse compression.)

Scan Field-of-View -- The extent, in two dimensions, of the region in which a

target can be detected. The scan field of view depends upon the instantaneous

field-of-view, scan rate, and scan time.

Scan Rate -- The rate at which a scan variable (range, bearing, velocity) is varied during scan. The scan rate affects scan field-of-view, target dwell time, and scan-to-scan period.

Scan Pattern -- The scan variable time sequence executed in one scan period. Various scan patterns are presented .- Section 2.17 of this text.

Scan/Display Stabilization Limits -- The maximum aircraft attitude and position excursions for which the scan pattern and display can be isolated from aircraft motion. The scan and display are generally stabilized with respect to the horizon.

Scan Volume -- The extent, in three dimensions, of the region in which a target can be detected.

Pulse Doppler Radar Characteristics (Additional)

Blind Speeds (Velocities) -- The relative range rates for which targets cannot be detected by a pulsed moving target indicator due to frequency aliasing of the pulsed returns, as discussed in Sections 2.13.6 and 2.16.10 of this text.

Maximum Target Velocity -- The maximum target relative range rate for which a Doppler radar can measure and display that rate.

Maximum Unambiguous Target Velocity -- The maximum target relative range rate for which the target return frequency falls within the primary spectral region of a pulse Doppler radar, as discussed in Section 2.12.2 of this text.

Minimum Target Detection Velocity -- The minimum target relative range rate for which the target return is not filtered out by the Doppler filter or delay canceller of a moving target indicator, as indicated by the MTI frequency response curves presented in Sections 2.16.4 and 2.16.9 of this text.

Range Rate Accuracy -- The maximum error within which a Doppler radar is capable of determining the range rate of a target. The range rate accuracy of a Doppler radar depends upon the capability of the signal processing equipment to measure the Doppler frequency shift of target returns, as discussed in Section 2.13 of this text.

Range Rate Resolution -- The minimum separation in range rate for which two targets can be distinguished. Range rate resolution depends upon the same factors that affect range rate accuracy.

3.18

Continuous-Wave, Frequency-Modulated Radar
Characteristics (Additional)

Frequency Modulation Bandwidth -- The width of the frequency spectrum covered by the frequency modulated carrier of an FM radar.

Frequency Modulation Rate -- The time-rate-of-change of the carrier frequency of an FM radar.

Frequency Modulation Repetition Interval -- The period of the frequency modulation cycle of an FM radar.

Frequency Modulation Waveform -- The frequency-versus-time characteristic of the frequency modulation applied to the carrier of an FM radar.

Tracking Radar Characteristics (Additional)

Maximum Acquisition Line-of-Sight Slew Rate -- The maximum time-rate-of-change of bearing for which track may be acquired on a moving target.

Maximum Acquisition Time - The maximum time required to acquire track on a target within the field-of-view.

Maximum Number of Missiles Inflight -- The maximum number of guided missiles that can be controlled simultaneously by a weapon delivery system.

Maximum Number of Targets Displayed -- The maximum number of targets that can be displayed simultaneously by a track-while-scan radar.

Maximum Number of Track Files -- The maximum number of targets that can be tracked simultaneously by a track-while-scan radar.

Minimum and Maximum Acquisition Ranges -- The minimum and maximum ranges for which range track may be acquired on a target.

Minimum and Maximum Acquisition Range Rates -- The minimum and maximum range rates for which velocity track may be acquired on a target.

Velocity Accuracy -- The maximum error within which a tracking radar is capable of determining the velocity of a target.

Velocity Resolution -- The minimum difference in target velocity discernible by a tracking radar.

3.3 Specialized Radar System Characteristics

3.3.1 Types of Radar Systems -- The major types of airborne radar systems are listed below and their salient features and characteristics are discussed in the following paragraphs.

    Tactical, Air-to-Air
    Tactical, Air-to-Ground
    Tactical, Multi-Mission
    Airborne Early Warning
    Ground Mapping
    Terrain Avoidance/Following
    Radar Altimeter
    Weather Avoidance
    Doppler Navigation

Most tactical airborne radars operate in two distinct modes: search and track. In the search mode, the tracked parameters (range, azimuth, elevation, velocity) are scanned in pre-programmed patterns. When a target is acquired (track acquisition), the tracked parameters are locked onto the target and updated with continuing data. (In a track-while-scan system, the tracked parameters exist only in computer memory.) The features of search and track radars are discussed in Section 2.17 of this text.

3.3.2 Tactical, Air-to-Air Radar -- The task of a tactical, air-to-air radar
is quite unlike that of an air-to-ground radar. The target is likely to be
rapidly moving, is highly maneuverable, and is not constrained to move on
the surface of the earth. In search, the maximum target range is likely to
be much greater (200 miles, or more) than that for an air-to-ground radar.
In the track mode, the radar is designed to operate in conjunction with
current air-to-air missiles which do not require precise aiming information.
The background clutter problem for an air-to-air radar is much less severe
than that for an air-to-ground radar, (except for look-down situations at
low altitudes). Furthermore, the tracking accuracy and resolution require-
ments for radar-controlled airborne weapon delivery generally are less severe
than those required for air-to-ground weapon delivery. All of these con-
siderations affect the characteristics of a typical tactical, air-to-air
radar as noted below.

Operating Modes and Functions -- Typical air-to-air radar search modes are
range search, velocity search, and track while scan. Typical track modes are
single-target track and track while scan (multiple-target track).

Carrier Frequency -- Tactical air-to-air radars generally operate in the X Band
(9-10 GHz) for compatibility with such air-to-air missiles as the Sparrow and
the Phoenix. X-Band frequencies also are low enough to avoid the severe
atmospheric absorption, prevalent at higher frequencies, but high enough to
provide adequate angular resolution for air-to-air detection and weapon delivery.
(In an air-to-air radar, high resolution is required primarily for raid
assessment.)

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Carrier Polarization -- Air-to-air radars generally utilize vertical polarization to reduce the ground returns in a look-down or low-altitude situation.

Bandwidth -- Despite the relatively large pulsewidth utilized and the absence of requirements for high-resolution (sharp) pulses, the bandwidth of air-to-air radars is generally narrow (about 1 MHz) in order to provide improved anti-jam performance (interference rejection).

Carrier Power -- In order to achieve the ralatively large detection ard track ranges required, air-to-air radars employ relatively large peak power for both search and track (about 160 kilowatts).

Modulation -- Air-to-air radars are typically pulsed. Some employ frequency modulation for ranging.

Pulse Width -- In order to attain relatively large detection range (high pulse energy), air-to-air radars employ relatively large pulse widths (about 2 microseconds) for search. In order to obtain adequate range resolution for weapon delivery, they employ smaller pulsewidths (about 0.4 microseconds) for track. In order to trade range resolution for range at large ranges, pulse width is often varied with range. The pulse repetition frequency is also varied to maintain a constant duty cycle. Pulse compression techniques, as discussed in Section 2.10 of this text, are employed in some recent air-to-air radars.

Pulse Repetition Frequency -- In order to avoid velocity ambiguity, air-to-air Doppler radars employ large pulse repetition frequencies (about 300 KHz). As

previously indicated, PRF and pulse width are often varied together to obtain constant duty cycle. The large pulse repetition frequencies generally used in air-to-air radars would produce severe range ambiguity problems if some method were not employed to overcome them. Typically, PRF jitter (time-varying pulse repetition intervals) is employed for that purpose, as discussed in Sections 2.3.4 and 2.13.7. The F-14 uses a superimposed frequency modulation for ranging, thereby avoiding the range ambiguity due to its high PRF.

Antenna Beamwidth -- The large scan area needed for air-to-air search requires a relatively large beam width (or unacceptably large scan rate). Furthermore, except for raid assessment, a narrow beam is not required for high angular resolution. For those reasons, a relatively wide beam antenna (about 4 degrees) is commonly used.

Antenna Scan -- Tactical, air-to-air radars typically employ raster-scan search patterns as shown in Section 2.11.3 of this text. The limits of the search patterns are relatively large because of the wide field-of-view required. The F-4 uses a conical scan. Multiple target radars, like that of the F-14, employ track-while-scan. The F-14 also has a single-target-track mode that employs randomly-switched sequential lobing. The random switching prevents an adversary jammer from locking onto a fixed scan rate, thus affording a pseudo-monopulse operation. Future air-to-air radars are likely to employ true monopulse and track-while-scan.

Moving Target Indication -- Air-to-air moving target indicators are typically coherent, Doppler filter radars, as discussed in Section 2.16 of this text.

Displays -- Air-to-air radars typically employ multiple displays, most often including B-Scope (azimuth and range), PPI (plan-position indicator), and, for Doppler radars, azimuth and velocity.

3.3.3 Tactical, Air-to-Ground Radar -- The task of a tactical, air-to-ground search radar is to detect and locate a stationary or slow-moving target constrained to the surface of the earth and at relatively short maximum range (generally, less than 50 miles). The detection typically must be performed, however, from a rapidly-moving vehicle and in the presence of heavy clutter, entirely surrounding the target. Such detection requires either a ground-oriented moving target indicator or a high-resolution (almost imaging) detector. (Ground mapping requires high-resolution imaging). The task of a tactical, air-to-ground tracking radar is to determine the weapon-release parameters, (range, bearing, and velocity), with sufficient accuracy to allow the delivery of unguided weapons (about 50 feet in range, 5 mils in bearing, and 2 feet per second in velocity). The characteristics of a typical tactical air-to-ground radar are briefly discussed in the following paragraphs.

Operating Modes and Functions -- Typical air-to-ground search modes are range search and airborne moving target indication. (The A-6 has a track-while-scan mode). Typically air-to-ground track modes do not actually track a ground target but merely "track" a point on the surface of the earth, as designated by the crew, utilizing aircraft position and attitude information determined by an inertial navigation system or other navigator.

Carrier Frequency -- In order to obtain the high angular resolution required for target detection and weapon delivery, air-to-ground radars typically operate in the Ku-Band (16 GHz) or Ka-Band (35 GHz). (At the relatively short ranges typically involved, atmospheric absorption is acceptable.)

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Carrier Polarization -- Air-to-ground radars generally utilize horizontal polarization to enhance ground returns. Circular polarization is sometimes used to improve all-weather (rain) operation.

Bandwidth -- The narrow, sharp pulses needed for range resolution, require that the air-to-ground radar employ a narrow bandwidth (about 2 MHz).

Carrier Power -- In order to achieve adequate range, air-to-ground search radars employ medium peak power (about 120 kilowatts). Because of the relatively short weapon delivery ranges involved, typical air-to-ground track radars generally employ relatively low peak power (about 60 kikowatts). The lower peak power decreases the possibility of detection by the adversary.

Modulation -- Air-to-ground radars are typically pulsed.

Pulse Width - In order to achieve the requisite range resolution for detection and weapon delivery, air-to-ground radars utilize short (about 0.4 microsecond), sharp pulses. The pulse width is often varied with range and with PRF to attain a constant duty factor. Pulse compression, as discussed in Section 2.10 of this text is now generally employed.

Pulse Repetition Frequency -- In order to avoid range ambiguity, an air-to-ground radar employs a low pulse repetition frequency (about 1000 Hz). Typically, the PRF is varied with range, being decreased as range increases in order to avoid range ambiguity. Velocity ambiguity due to low PRF is often avoided by utilizing PRF jitter as discussed in Section 2.3.4 of this text.

Antenna Beamwidth -- The high angular resolution required for air-to-ground target detection and weapon delivery require a narrow antenna beam in azimuth (typically about 1.5 degrees). Since the required scan area is relatively small, a relatively narrow beam can be used in search as well as track. In the elevation direction, a spoiled (cosecant-squared) beam is generally employed in order to obtain uniform illumination of the ground at all ranges.

Antenna Scan -- Tactical air-to-ground radars typically employ an azimuth (PPI) scan. No scan is needed in elevation since the wide antenna beamwidth in elevation illuminates a large range spread. The orthogonal scanning parameter is range. (The A-6 employs a monopulse technique in elevation for precise ranging.) The A-6 employs air-to-ground track-while-scan.

Moving Target Indication -- Air-to-ground moving target indicators are typically non-coherent, delay-canceller MTI's, as discussed in Section 2.16.8 of this text. Future air-to-ground MTI's are likely to be coherent Doppler.

Displays -- Modern air-to-ground radars typically employ the sector plan-position-indicator (PPI). Older radars employed the B-Scope (azimuth and range) greatly distorting the short-range picture.

3.3.4 Tactical, Multi-Mission Radar — The task of a tactical, multi-mission radar encompasses those of both the air-to-air and the air-to-ground radars already discussed. The operational and functional requirements placed upon those two types of radar are often incompatible. When such is the case, the conflicting requirements can sometimes be met, in a single radar, by switching radar parameters as required. When the conflicting requirements occur simultaneously, however, so that switching is not feasible, an alternative method must be employed that meets both sets of requirements. One such method is to employ a medium-PRF radar with extensive signal processing designed to meet the conflicting requirements. Various signal processing techniques are employed to achieve, simultaneously, long range, large unambiguous range, high range resolution, high angular resolution, and large scan volume. The medium PRF alone would yield neither a sufficiently large maximum unambiguous range nor a sufficiently large maximum unambiguous velocity. These requirements are met by the use of a time-varying PRF as previously discussed. The pulse width is chosen to attain the required maximum range. It would not, generally, provide adequate range resolution. Range resolution is attained by utilizing the pulse compression technique discussed in Section 2.10 of this text. The carrier frequency (X-Band for missile compatibility) and antenna size (small for minimum space) are such that adequate angular resolution would not be obtained with the resulting antenna beam width. Air-to-air angular resolution is attained utilizing interferometer (monopulse) techniques as discussed in Section 2.17.6 of this text. Air-to-ground angular resolution is attained employing Doppler beam sharpening as discussed in Section 2.18 of this text.

The principal parameters of a typical, modern, multi-mission radar are presented below.

Operating Modes: A to A--Range-While-Search, Velocity search, Pulse Doppler Single Target Track, Track-While-Scan. A to G--Ranging, Fixed-Target Track, Ground Moving Target Indicator, Real Beam Ground Map, Doppler Beam Sharpened Ground Map.

Carrier Frequency: X-Band (10 GHz)

Carrier Polarization: Vertical

Carrier Power: 20K Watts (Peak)

Pulse Width: Variable

Pulse Repetition Frequency: Variable

Antenna Beamwidth: 3.3 degrees (RB); 0.1° (DBS); (10° Spoiled Beam in Elevation for A to G).

Antenna Scan: A to A--Bar Scan (Azimuth and Elevation). A to G -- Azimuth only, at set elevations.

Moving Target Indication: A-A -- Doppler Filter. A to G -- Doppler Filter

Display Types: A to A -- B-Scan (Azimuth and Range). A to G -- PPI

Max. Number of Track Files (TWS): 8

3.3.5 **Airborne Early Warning Radar** — The task of an airborne early warning radar is similar to that of an air-to-air radar. The exceptions are (1) the AEW radar must have much greater maximum detection and tracking ranges, (2) the AEW radar must have the capability of scanning a much greater area, and (3) the AEW radar must be able to simultaneously track many targets. The required maximum ranges are attained by the use of a low (UHF, i.e. 0.3 to 3 GHz) carrier frequency. Signal correlation techniques (see Section 2.8 of this text and Section 2.5.7 of the text on Communications Systems) are employed to enhance target detection and noise rejection. A very large rotating antenna is employed to get angular resolution and 360° azimuth scan. Track-while-scan tracking is utilized to attain multi-target-track capability.

The parameters of a typical AEW radar are presented below.

Operating Modes: Track-While-Scan with Delay-Canceller Moving Target Indicator and pulse compression.

Carrier Frequency: UHF (B-Band) (406 to 450 MHz)

Carrier Polarization: Horizontal

Carrier Power: 1.0 Megawatts

Pulse Width: 12.8 microseconds (0.27 μ sec. with pulse compression)

Pulse Repetition Frequency: 285 to 315 Hz (Staggered)

Antenna Beamwidth: 6.8° Azimuth,   21° Elevation

Antenna Scan: Azimuth only. (6 RPM)

Moving Target Indication: Double-Delay Canceller.

Display Type: PPI.

3.3.6 Ground Mapping Radar -- The task of a ground-mapping radar is similar to that of the tactical, air-to-ground radar already discussed. The principal differences are: (1) the extremely high resolution required, and (2) the distortion compensation required because of the large scanned area and the aircraft motion.

Real beam plan-position-indicators have been used for mapping purposes. The resolution obtained thereby was limited by the dimensions of the rotating airborne antenna. An improved method is the sidescan radar which employs a long antenna mounted parallel to the longitudinal axis of the aircraft, thus producing a very narrow "fan" beam to give good azimuth resolution. Range resolution is achieved by the use of very short pulses or by pulse compression.

The most advanced method of radar ground mapping utilizes Doppler beam sharpening as described in Section 2.18 of this text. Utilizing Doppler beam sharpening, bearing resolutions of less than $0.1°$ are possible, employing a two-foot diameter X-band antenna. The principal parameters of a typical Doppler-beam-sharpened ground mapping radar are presented below.

Carrier Frequency: X-Band (10GHz)

Carrier Polarization: Vertical

Carrier Power: 2 K Watts (Peak)

Pulse Width: 1 Microsecond

3.34

Pulse Repetition Frequency: 300 KHz.

Antenna Beam Width (Unsharpened):   3.0°

Antenna Beam Width (Sharpened):   0.1°

Antenna Scan: Fixed antenna, aircraft motion (snow plow); PPI Azimuth Sector Scan

Display Types: PPI

3.3.7 Terrain Following/Avoidance Radar -- The problem of avoiding ground impact in all-weather low-level operation requires the use of a sensor such as radar. Five types of ground impact avoidance systems have been employed. They are listed and defined below.

Radar Altimeter -- A system that determines the distance between the aircraft and the ground directly below the aircraft.

Terrain Warning -- A system that detects terrain directly in the flight path and provide a warning to the crew.

Terrain Clearance -- A system that detects and provides clearance from terrain peaks along the flight path.

Terrain Following -- A system that senses and follows terrain contours by altering aircraft altitude only.

Terrain Avoidance -- A system that senses terrain contours and avoids ground impact by maneuvering the aircraft in both altitude and direction.

A terrain following system employs a narrow, vertically-scanned radar beam directed ahead of and below the aircraft. The range to the highest terrain point for each scan is computed, and an aircraft command in elevation is giver such as to clear that point by a fixed vertical distance.

A terrain avoidance system employs a beam scanned in the horizontal plane to determine the elevation of the terrain ahead of the aircraft as a function of

azimuth and range.   A typical terrain avoidance radar employs a search mode that scans $\pm 30°$ in azimuth with respect to the aircraft datum line.   Range is scanned out to 8.5 nautical miles.   Elevation at a given range is determined by phase-comparison monopulse.   The terrain avoidance display exhibits constant-range contours, on an elevation-angle versus-azimuth display, in varying shades of gray.   Terrain clearance directly below the aircraft is indicated by an "altitude curtain" on the display.   The flight path of the aircraft is directed in both azimuth and elevation so as to fly between the peaks.

All types of ground clearance radars are subject to problems due to the fact that the information sensed at some distance ahead of the aircraft may not provide clearance from objects or terrain directly below the aircraft.

The principal parameters of a typical terrain avoidance radar are presented below.

Carrier Frequency: Band (16 GHz)

Carrier Polarization:

Carrier Power: 60 Kilowatts (Peak)

Pulse Width: Variable (0.2 to 3.0 μ secs.)

Pulse Repetition Frequency: Variable (300 to 2400 Hz)

3.37

Antenna Beamwidth

    Azimuth: 1.5°

    Elevation: Spoiled (CSC^2) Beam

Antenna Scan: Sector Scan in Azimuth

                Phase Monopulse in Elevation

Display types: Elevation Angle vs Azimuth with range contours indicated by

                 shades of grey.

3.3.8 Radar Altimeters -- Two types of radar altimeters are commonly employed: frequency modulated, continuous-wave radar and narrow-pulse, low-pulse repetition frequency pulse radar. Each has relative advantages and disadvantages. The FM-CW radar avoids "altitude holes" (blind ranges) but requires a higher average power. The pulse radar requires a lower average power, but suffers from "altitude holes" due to eclipsing. Very narrow pulses and staggered pulse repetition intervals are used to alleviate the eclipsing problem.

Low-gain, wide beamwidth antennas are employed for radar altimeter systems. The wide beamwidth is required to allow adequate illumination of the ground directly below the aircraft during maneuvers. The low antenna gain (and low radiated power) are possible because of the large radar cross section of the earth.

The characteristics of a typical FM-CW radar altimeter are presented in the following table.

Carrier Frequency: 4.3 GHz.

Carrier Power: 1.5 Watts (Average)

Modulation: Frequency Modulated Continuous Wave

Frequency Modulation Bandwidth: 70 MHz.

Antenna Beamwidth: 60 Degrees.

Altitude Range: 0 to 5,000 Feet.

The characteristics of a typical pulse radar altimeter are presented in the following table.

Carrier Frequency: 4.3 GHz.

Carrier Power: 0 to 170 Ft. -- 5 Watts (Peak)

　　　　　　　　　170 to 5K Ft. -- 1 Kilowatt (Peak)

Modulation: Pulse

Pulse Width: 0 to 170 Ft. -- 6 Nanoseconds.

　　　　　　　170 to 5K Ft. -- 85 Nanoseconds.

Pulse Repetition Frequency: 0 to 170 Ft. -- 1500 Hz.

　　　　　　　　　　　　　　　170 to 5K Ft. -- 3000 Hz.

Antenna Beamwidth: About roll axis -- $\pm$ 30°

　　　　　　　　　　About pitch axis -- $\pm$ 50°

Altitude Range: 0 to 5000 Feet

3.3.9 Weather Avoidance Radars -- Weather avoidance radars are search radars

designed to optimize backscatter from particulate moisture in the atmosphere.

Because the radar wavelength is much larger than the water particles, reflection

is by Rayleigh scattering. (See Section 2.5 of this text.) Therefore, the

scattering cross section of large raindrops, such as would be encountered in

thunderstorms, is much greater than that of cloud droplets. The scattering

cross section of hailstones is also very large. Violent weather processes are,

thus, made evident on the display.

The characteristics of a typical weather-avoidance radar are presented in the following table.

Carrier Frequency: X-Band (10 GHz)

Carrier Power: 75 Kilowatts (Peak)

Pulse Width: 5 Microseconds

Pulse Repetition Frequency: 200 Hz

Antenna Beamwidth: 3° (Pencil)

Antenna Scan: Sector Scan ($\pm$ 90° in Azimuth)

Display Type: PPI

Range: 600 N   Miles

3.3.10 Doppler Navigation Radar -- Doppler navigation radar is discussed in the text on navigation systems.

4.0 Radar System Performance Test and Evaluation

4.1 Levels of Testing

4.1.1 Stages of Testing -- Testing can be categorized as developmental, functional, or operational, depending upon the stage of development of the test item. Developmental testing is concerned with the evaluation of design features for the purpose of design development. The end result of developmental testing is the proposed final design. Functional testing is concerned with the performance evaluation of the final design as a whole. The principal method of evaluation is the quantitative measurement of the ability of the test item to perform its intended functions. The end result of functional testing is final design acceptance or rejection. Operational testing is concerned with the evaluation of the final design and production implementation of the test item. Of primary interest is the ability of the test item to accomplish its intended operational mission. The end result of operational testing is acceptance or rejection of the test item for service use and the recommendation of operational procedures.

4.1.2 Testing Criteria -- The basic purpose of any stage of testing determines the criteria used to evaluate the test results. The testing criteria, in turn, are reflected in the tests to be performed and the test methods employed. Testing criteria derive from one of three objectives: data acquisition, determination of specification compliance, and evaluation of mission performance. In developmental testing the intent is to acquire comprehensive information on the

characteristics of the item under test. Usually, no a-priori criteria are imposed for performance acceptance or rejection. Functional testing, however, is primarily intended to evaluate the performance of the test item against specific criteria -- that is, for specification compliance. As previously indicated, operational testing is primarily concerned with mission performance. While some specific, quantitative requirements are imposed, test criteria for operational testing often are of a qualitative nature.

It should be recognized that the three stages of testing; developmental, functional, and operational; are not mutually exclusive. That is, the differences are primarily ones of emphasis. For example, functional testing often produces data that result in a design change. Thus, functional testing often takes on some aspects of developmental testing. For that reason, it is necessary, in functional testing, to test to a depth sufficient to allow engineering analysis of the problem. A "go" or "no-go" answer often is not sufficient. On the other hand, functional testing cannot ignore mission suitability in evaluating a new design. Compliance with published specifications is not sufficient if functional testing reveals an operational problem. Thus, while the following sections of this text will be concerned primarily with quantitative tests for specification compliance, it should be noted that functional testing should reflect mission requirements, including non-quantitative considerations when appropriate.

4.1.3 Test Regimes -- Functional airborne system tests are performed in the laboratory, in the aircraft on the ground, and in flight. For various reasons, testing is usually performed in that order. Tests performed on the bench in the laboratory are most convenient, quickest, cheapest, and safest. Flight

4.2

tests are least convenient, take the longest time, are most costly, and present the greatest danger to personnel and equipment. They also are most susceptible to uncertainties in the weather and availability of equipment. For the above reasons, tests should be performed in the laboratory, before installation in the aircraft, when feasible. Tests that can only be performed installed in the aircraft should be performed on the ground when feasible. Flight tests should be performed only when necessary and only when laboratory and ground tests have reduced the uncertainties to the greatest extent feasible. Of course, some tests can be performed only in flight; and, in any event, flight performance eventually must be demonstrated.

In the following sections, brief descriptions will be given of the methods employed to determine system compliance with the major radar system functional specifications. General testing, such as environmental, electromagnetic compatibility, reliability, and maintainability testing, is discussed in a separate text devoted to tests common to all airborne systems.

Flight tests sometimes can be performed in a test-bed aircraft. Such an arrangement allows in-flight tests to be performed with instrumentation far more extensive than would be possible with the system installed in the aircraft for which it was intended. In addition, a test bed aircraft can be employed for which flight operations are more convenient, less hazardous, and less costly. Testing in a test bed aircraft, however, cannot satisfy all flight testing requirements. The performance characteristics of all airborne systems are, to some extent, susceptible to the environment of the installation. The radiating characteristics of an airborne antenna are especially sensitive to the installation. Other

factors influenced by the vehicle are the electrical power, cooling, electro-magnetic interference, vibration, acceleration, and other environmental effects.

An alternative to some flight testing is flight simulation testing. The most useful "simulations" incorporate actual flight hardware for the system under test, utilizing simulations only for generating external stimuli. Such a hybrid test simulation can, in fact, perform tests not possible in actual flight. Test "flights" can, for example, be rerun exactly, or with controlled modifications. The ability of a simulation to exactly duplicate test conditions is especially valuable in testing digital systems, where one-at-a-time modifications of the inputs are necessary to exercise the various logic branches of the software. Furthermore, real-time interrupts in a test simulation make possible the examination of internal system quantities not available in an actual flight situation.

This text is devoted to test methods peculiar to radar system parameter determination and performance testing. Topics of general concern to airborne systems test and evaluation, such as test planning, test performance, instrumentation, data acquisition, and data analysis, are discussed in the text on Integrated Airborne Systems Test and Evaluation.

4.2 Radar System Performance Test Methods

4.2.1 Laboratory Measurements (Uninstalled)

Figure 4.2.1.1 shows the test setup for radar system measurements in the laboratory. The dummy load is provided to avoid external radiation and to provide a non-reflecting (matched) load. The RF coupler in the transmitter waveguide taps off a known fraction of the transmitter power. (Sometimes in-line attenuators are used to further reduce the power level.) The RF power and carrier frequency can be measured at the point shown. (RF power also can be measured utilizing a dummy load with built-in calorimeter.) The transmitted signal is also detected, typically by an amplitude detector as shown, and the video (detected) signal is examined on an oscilloscope to determine waveform (pulse width, pulse rise and fall times, pulse repetition interval, pulse amplitude, etc.). A counter is sometimes used, as shown, to measure pulse repetition frequency.

In order to determine ranging accuracy and other parameters requiring a radar return, the detected transmitter pulse is used to generate simulated radar returns, utilizing a double-pulse RF pulse generator. The generator has pro-vision for varying the time interval between the transmitted pulse and the target return pulse and also the time interval between two return pulses. Thus the pulse generator can be used for determination of ranging accuracy and range resolution. For an interferometer (monopulse) radar, two pulses can be injected, separately, into the two channels, in order to determine angular accuracy and resolution. The angular accuracy and resolution can also be determined utilizing an RF pulse generator synchronized to the transmitter pulse and to the antenna scanning mechanism.
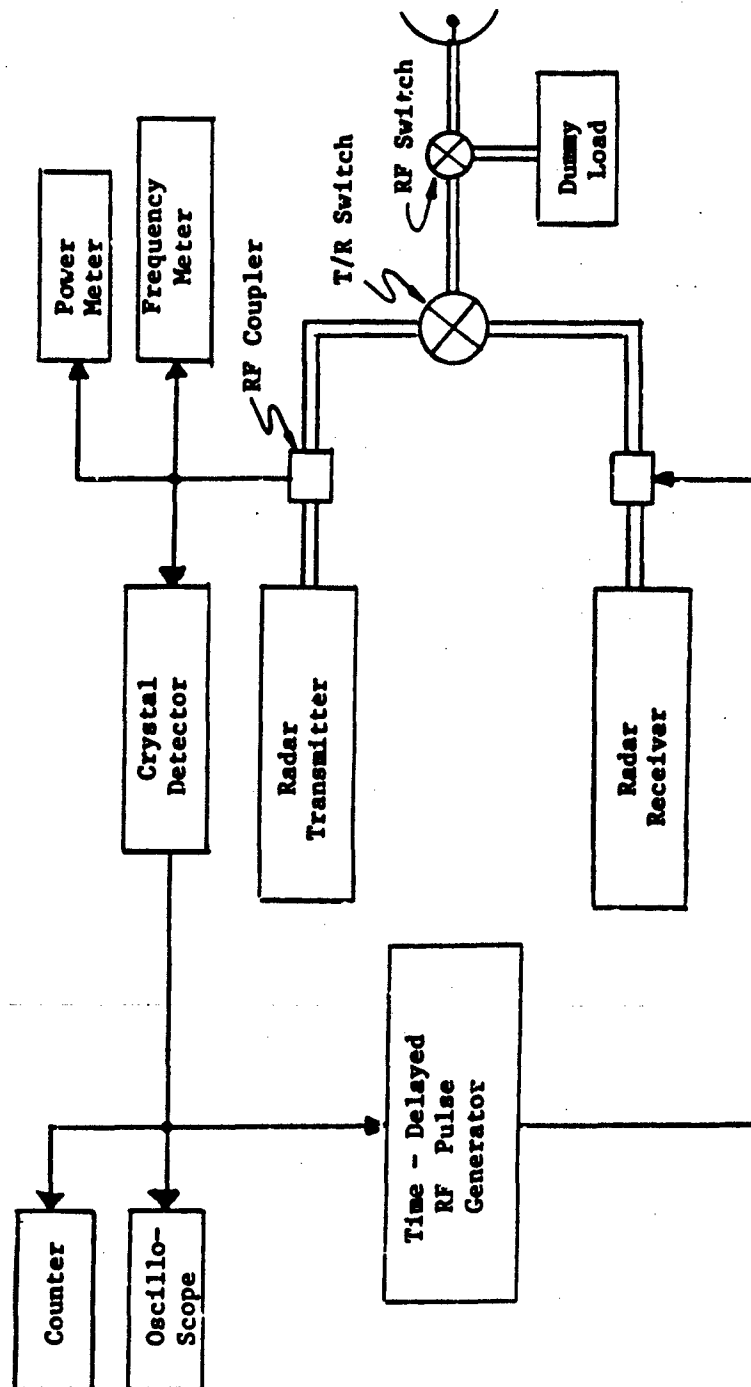
4.5

Figure 4.2.1.1—Radar System Laboratory Measurement Test Setup

4.5a

Minimum detection range and maximum unambiguous range can be determined by varying the transmit-to-receive time interval to the minimum and maximum allowable limits, respectively.

The system variables measured during performance testing may be normal system outputs to the crew (e.g., radar displays, digital indicators, etc.); they may be normal system outputs to other avionics systems (e.g., range and range-rate voltages to a weapon delivery computer); and they may be signals internal to the radar system, specifically instrumented for the tests. When the system is digital, especially if it employs an integrated data bus, the task of monitoring both internal and external signals is greatly simplified. The relevant digital words can be recorded and decoded as required. It is common practice to monitor not only the variables being measured, but also other variables that might yield information significant to the test in progress.

The provisions for Built-In-Test (BIT) of a radar system are most conveniently tested during bench testing. BIT tests are performed by "inserting" faults into the system and evaluating the ability of the BIT to detect the faults. Such fault-insertion often requires access to the internal mechanism of the equipment under test.

Electronic counter-countermeasures also can be evaluated by signal injection during bench testing. Multiple-pulse and random noise generators are used to generate the ECM signals. Similar methods are used to evaluate clutter-rejection by a moving-target-indicator radar.

It should be noted that most of the above "laboratory" measurements can be performed installed in the aircraft and even in flight. Waveguide RF couplers, dummy loads, and power meters often are permanently incorporated into radar installations.

4.2.2 Ground Measurements (Installed in the Aircraft)

The range and bearing determination performance of an installed radar can be tested on the ground, utilizing targets of known position with respect to the system under test. The reflectivity of the targets is usually augmented by means of corner reflectors.

For range accuracy tests, the radar antenna is "aimed" directly at the target. For boresight and bearing accuracy tests, the radar antenna is "aimed" at known offset angles from the line-of-sight to the target. Range and bearing resolution can be determined using two closely-spaced targets, one of which is moveable with respect to the other. The targets must be sufficiently far from the radar to be in the far field and to provide favorable "geometry".

In all ground testing, care must be taken to avoid erroneous or ambiguous results due to multi-path caused by ground (or other) reflections. One method of minimizing ground returns is to mount the target (reflector) on a tower of sufficient height to put the horizon (ground level) at the first null of the antenna pattern.

Minimum range and other "blind" ranges can be determined utilizing moveable targets. A suitable means of determining the actual position of the targets ·(truth data) must be provided.

The field-of-view of a radar may be determined by boresighting on a distant target and then slewing the radar antenna so as to place the target "image" at the limits of the radar display. The angular offsets corresponding to those limits can then be measured.

4.8

Measurements involving determination of the antenna radiation pattern (beam width, side lobes, scan patterns, radome effects, etc.) are difficult due to reflections from the ground and other nearby objects. Accurate measurements require the use of an anechoic chamber.

4.2.3 In-Flight Measurements

1. Range and Bearing Accuracy (Air-to-Ground)

a. Scenario -- Fly prescribed flight path, at constant altitude, toward
well-defined ground target. Acquire target on radar. Continue to track target
while varying range and bearing to target. Vary radar modes and parameters as
required.

b. Test Data -- Measure test aircraft position and target position via range
instrumentation (truth data); target bearing via bore-sighted camera or test
aircraft attitude via on-board IMU or other instrumentation; radar imagery via
cockpit camera; radar data via video recorder; time.

c. Data Reduction -- Derive actual range and bearing versus time from range
data. Derive indicated range and bearing versus time from test radar data.
Compare to determine range and bearing accuracy. Care must be exercised to
identify and discard false data due to ground clutter and multipath caused by
ground reflections.

2. Range and Bearing Accuracy (Air-to-Air)

a. Scenario -- Fly prescribed flight path with respect to target aircraft.
Acquire target on radar. Continue to track target while varying range and
bearing (azimuth and elevation) to target. Vary radar modes and parameters as
required.

b. Test Data -- Measure test aircraft position and target aircraft position
via range instrumentation (truth data); target bearing via bore-sighted camera or
test aircraft attitude via on-board IMU or other instrumentation; radar imagery
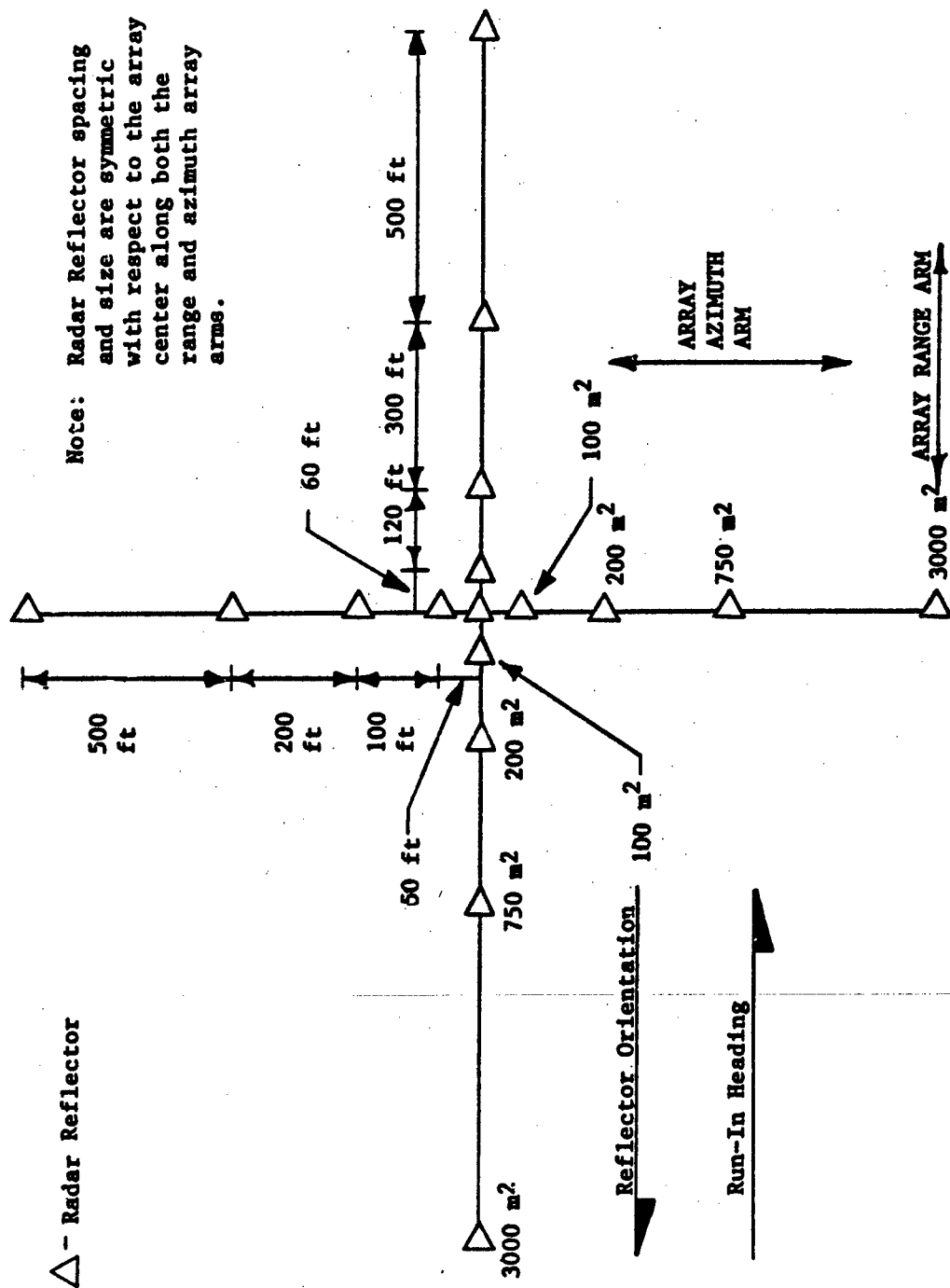via cockpit camera; radar data via video recorder; time.

c. Data Reduction -- Derive actual range and bearing versus time from range
data. Derive indicated range and bearing versus time from test radar data.
Compare to determine range and bearing accuracy.

4.10

3. Range and Bearing Resolution (Air-to-Ground)

a. Scenario -- Fly prescribed flight path, at constant altitude, toward
an air-to-ground radar target array such as that shown in Figure 4.2.3.1.
Acquire target. Continue to track target while "running in" on target, at
constant altitude, as shown in Figure 4.2.3.2. Vary radar modes and parameters
as required.

b. Test Data -- Measure test aircraft position via range instrumentation;
radar imagery via cockpit camera; radar data via recorder; time.

c. Data Reduction -- Derive test aircraft range from target, versus time,
from range data. Derive radar resolution (range and azimuth) versus time from
radar data. (Number of reflectors resolvable at a given time indicates resolution
as shown in table in Figure 4.2.3.2.) Correlate times to determine resolution
versus range. Azimuth resolution can be converted from linear separation to
angular separation by taking the arctangent of the linear separation-to-range
ratio.

4. Range and Bearing Resolution (Air-to-Air)

a. Scenario -- Fly prescribed flight path with respect to two target aircraft
as shown in Figure 4.2.3.3 for range resolution test and Figure 4.2.3.4 for
azimuth resolution test. Acquire targets. Continue to track targets until two
targets are resolved (in range or azimuth). Vary radar modes and parameters and
target separation as required.

b. Test Data -- Measure test aircraft position and two target aircraft
positions via range instrumentation; range imagery via cockpit camera; radar data
via recorder; time.

c. Data Reduction -- Derive test aircraft-to-target range and target separation,
versus time, from range data. Determine target resolution time from test data.
Correlate times to determine target resolution versus range.

4.11

Note: Radar Reflector spacing and size are symmetric with respect to the array center along both the range and azimuth array arms.

△ - Radar Reflector

Figure 4.2.3.1—Air-to-Ground Radar Target Array

4.11a

Determination of Range Resolution

Number of Reflectors Resolved	Range Resolution
5	Less Than 60 ft
4	120 ft
3	300 ft
2	500 ft
1	Greater Than 500 ft

α = Antenna/Beam Depression Angle

= Reflector Elevation Angle

Radar Reflectors

Test Altitude (ft AGL)

Ground Level

60 ft   120 ft   300 ft   500 ft

Radar Reflector Spacing
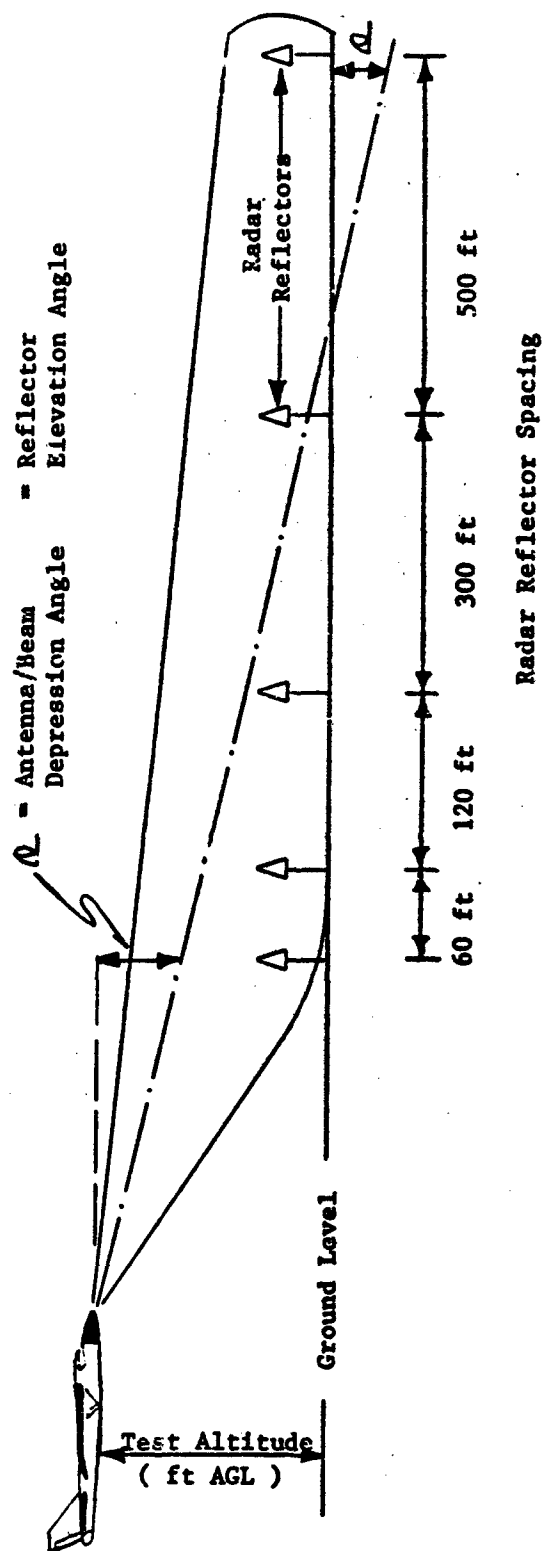
Figure 4.2.3.2--Air-to-Ground Radar Range Resolution Test

4.11b

Target Altitude (ft MSL x 1,000)

50   40   30   20   10   0

Range Tracking
Radars

TARGET
#2
Motion

Range
Resolution
(ft)

- Target #1 Constant Airspeed
             Constant Altitude

- Target #2 Constant Altitude
             Vary Airspeed to
             Open & Close
             Target #1

Co-Altitude Tests

$$R_{RES} = \frac{PW \times 'C'}{2}$$

Test must be conducted within fighter maximum detection
range (nmi) for that target, geometry & radar mode
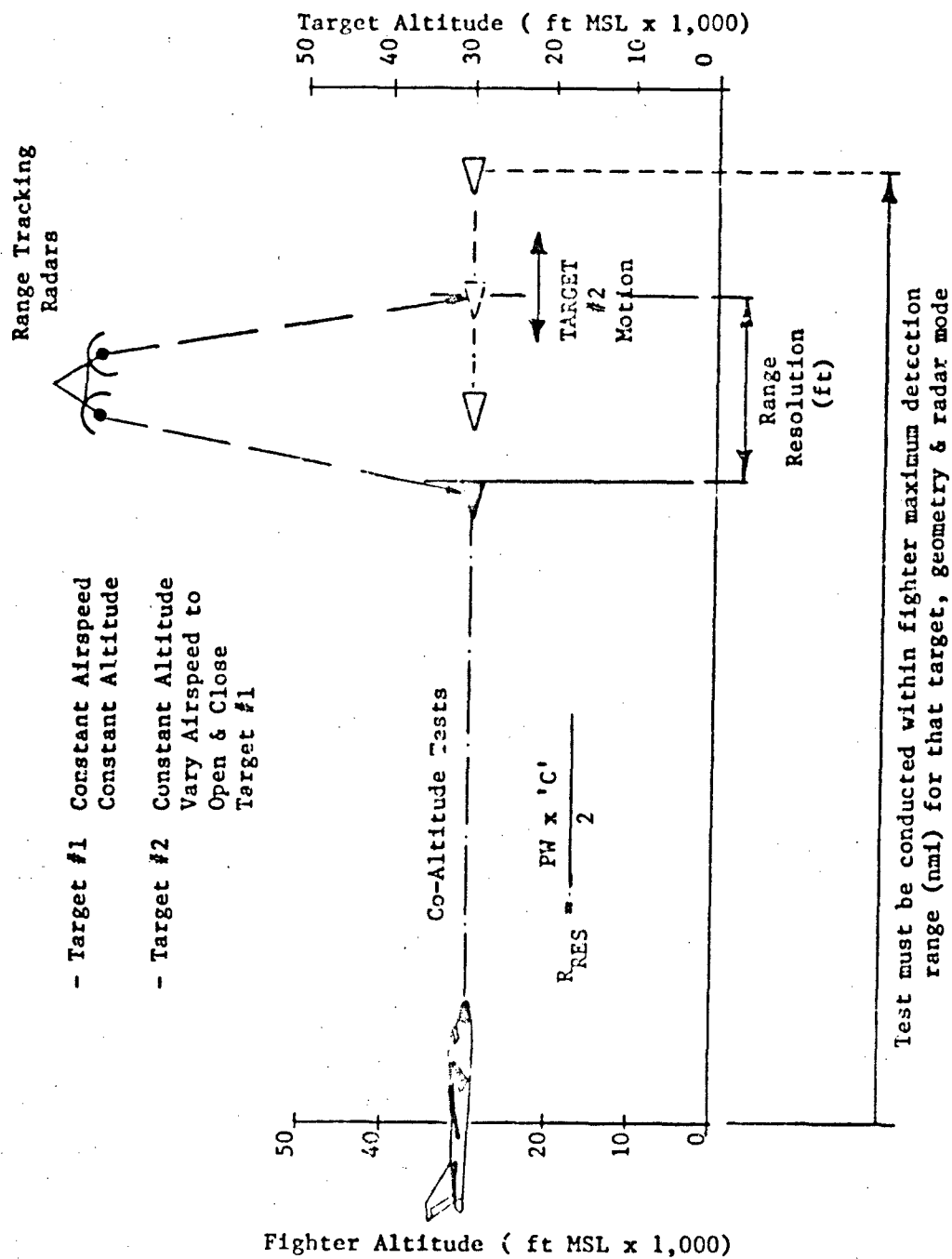
Figure 4.3.3—Air-to-Air Radar Range Resolution Test

Fighter Altitude (ft MSL x 1,000)

50   40   20   10   0

4.11c

Figure 4.2.3.4--Air-to-Air Radar Azimuth Resolution Test

4.11d

5. Maximum Range for Detection (Air-to-Ground)

a. Scenario -- Fly prescribed flight path, at constant altitude, toward fixed, well-defined target of prescribed radar cross section, as shown in Figure 4.2.3.5. Continue run-in until detection is achieved. Vary radar modes and parameters and flight altitudes as required.

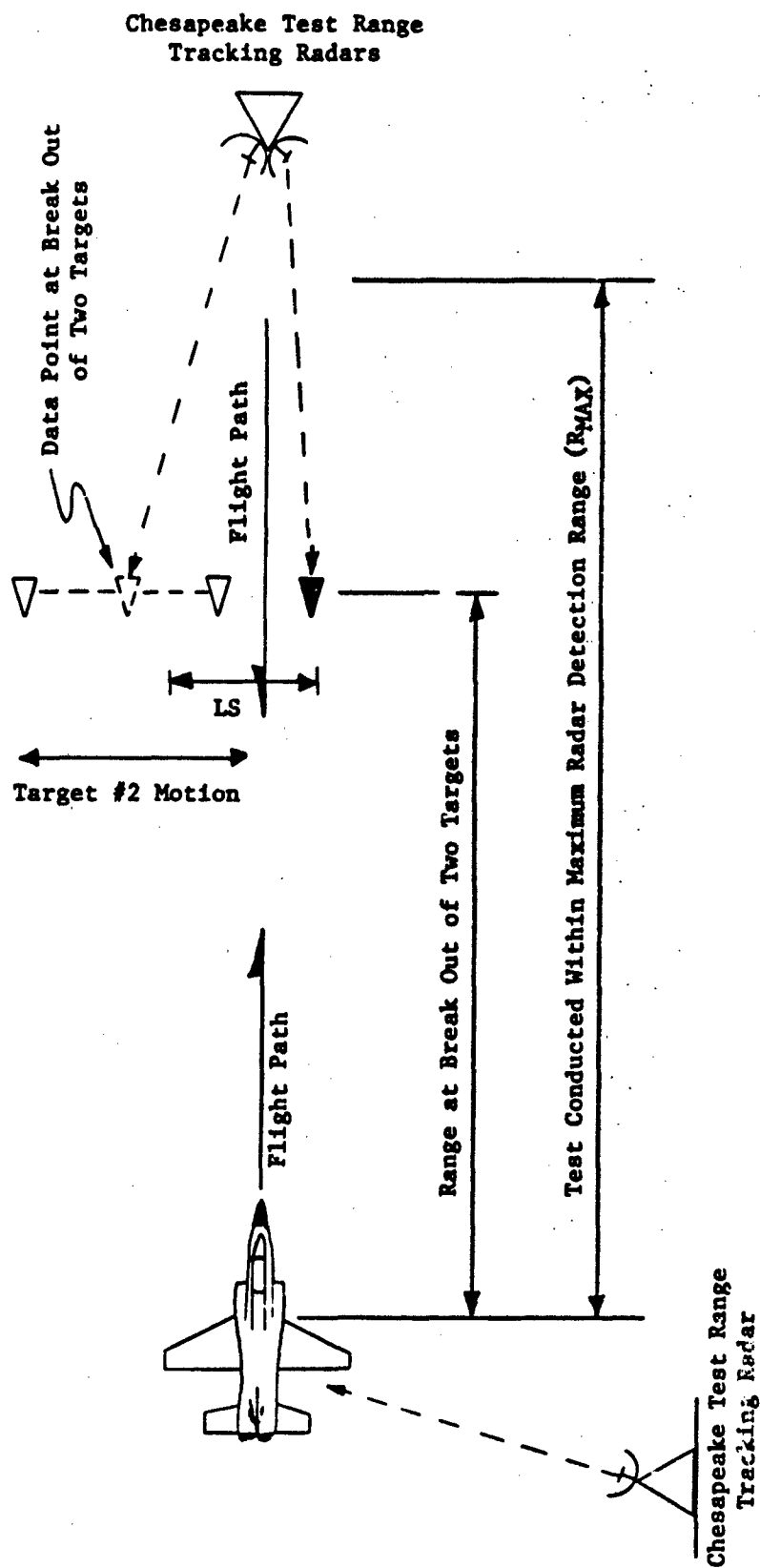b. Test Data -- Measure test aircraft position via range instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

c. Data Reduction -- Derive test aircraft-to-target range versus time from range data. Determine time of detection from test data. Correlate times to determine maximum target detection range. Care must be exercised to identify false data due to ground clutter, multipath, and anomalous wave propagation (ducting).

6. Maximum Ranges for Detection and Track Acquisition (Air-to-Air)

a. Scenario -- Fly prescribed flight path toward target aircraft of prescribed radar cross section, as shown in Figure 4.2.3.6. Continue closing until detection is achieved. Continue closing until track acquisition is achieved. Vary radar modes and parameters and test aircraft-to-target aircraft relative altitudes as required.

b. Test Data -- Measure test aircraft position and target aircraft position via range or on-board instrumentation such as air-to-air Tacan; radar imagery via cockpit camera; radar data via recorder; time.

c. Data Reduction -- Derive test aircraft-to-target aircraft range versus time from range data. Determine detection and track acquisition times from test data. Correlate times to determine maximum target detection and track acquisition ranges.
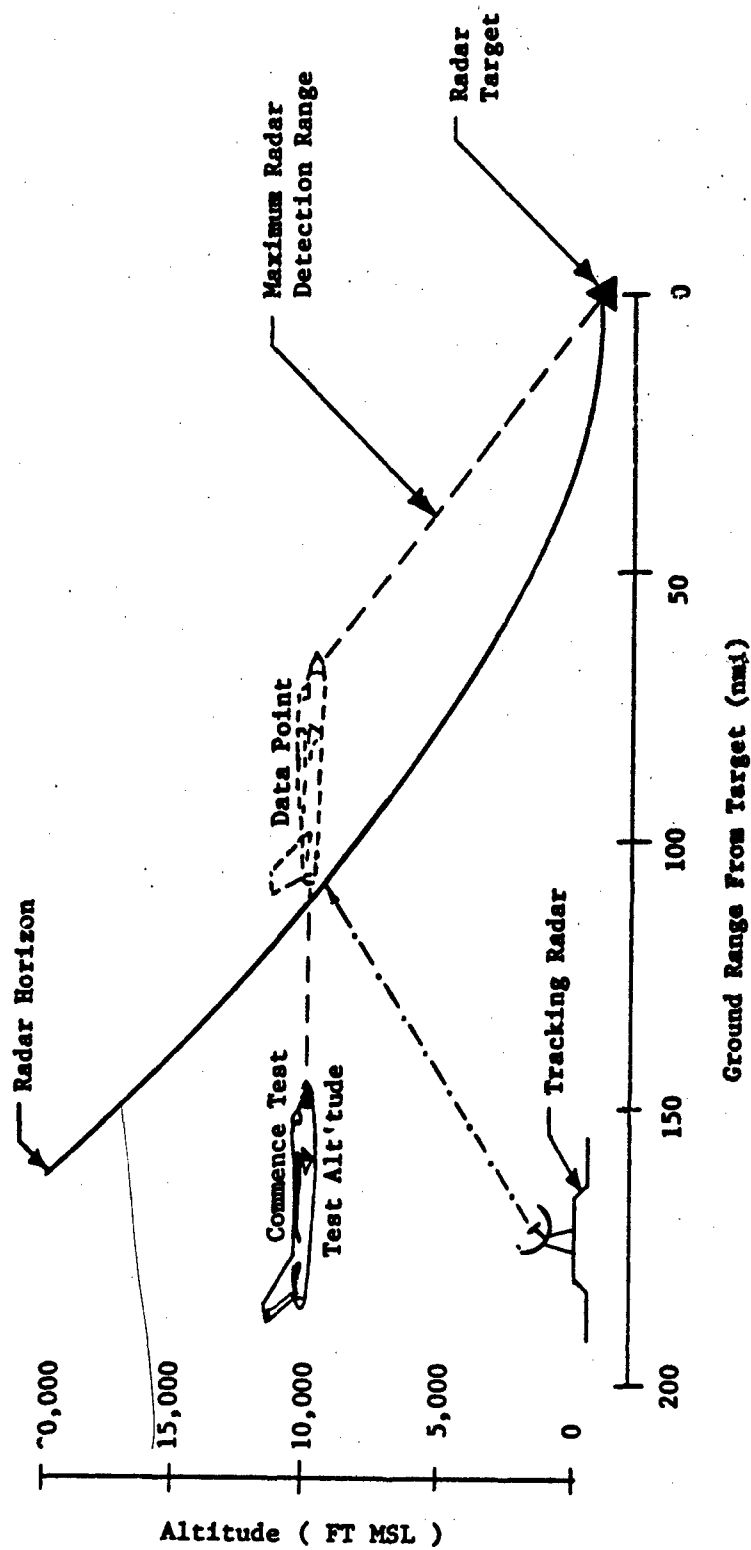
4.12

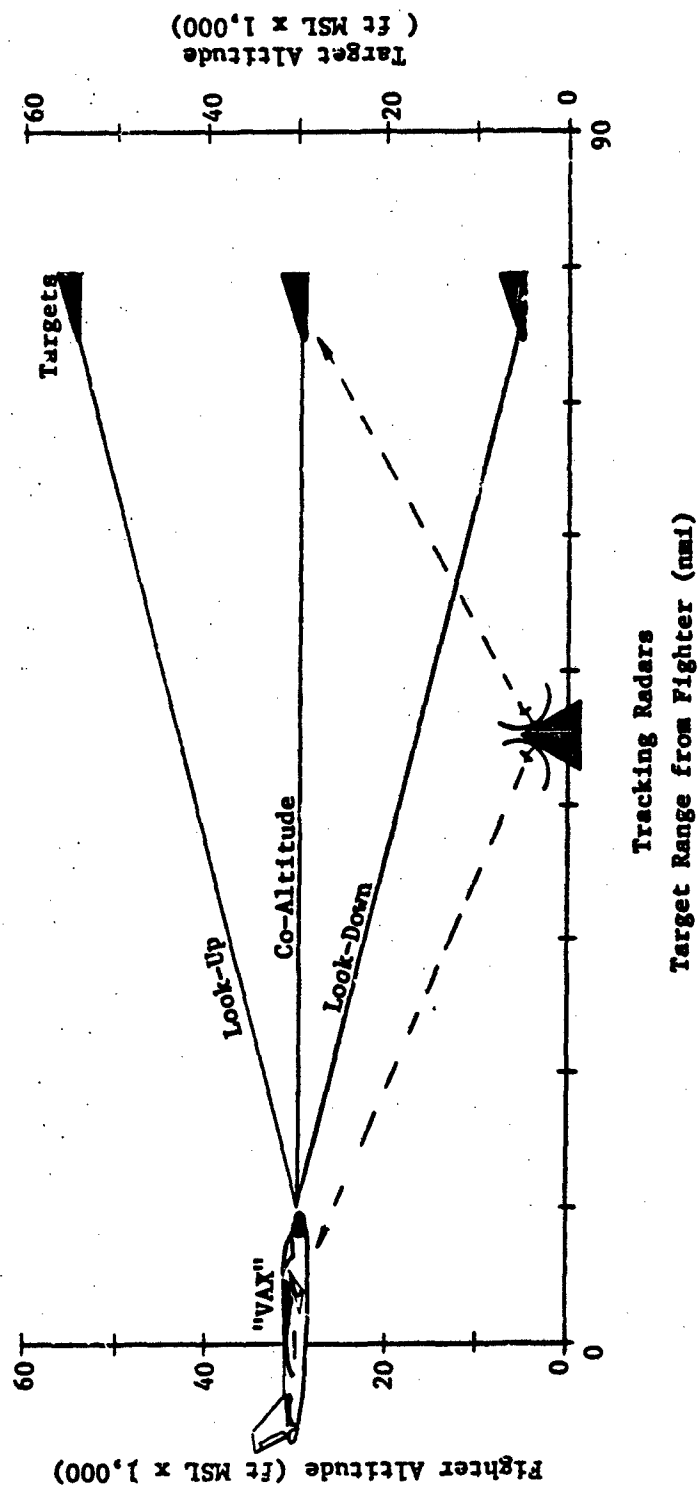Figure 4.2.3.5—Air-to-Ground Radar Maximum Detection Range Test

4.12a

Figure 4.2.3.6—Air-to-Air Maximum Detection and Track Acquisition Range Tests

4.12b

7. Minimum Ranges for Detection and Track (Air-to-Air)

a. Scenario -- Fly prescribed flight path with respect to target aircraft as shown in Figure 4.2.3.7. Acquire track on target. Continue closing until "break-lock" occurs. Continue closing until loss-of-target occurs. Vary radar modes and parameters as required.

b. Test Data -- Measure test aircraft position and target aircraft position via range or on-board instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

c. Data Reduction -- Derive aircraft separation versus time from range data. Determine times of break-lock and loss-of-target from test data. Correlate times to determine minimum range for detection and minimum range for track.

8. Maximum Unambiguous Range (Air-to-Ground and Air-to-Air)

a. Scenario -- Fly prescribed flight path closing on well-defined target beyond detection range. Continue closing until radar acquisition of target. Note any anomalous range indications. Vary radar modes and parameters as required.

b. Test Data -- Measure test aircraft position and target position via range instrumentation (truth data); radar imagery via cockpit camera; radar data via recorder; time.

c. Data Reduction -- Derive test aircraft-to-target range versus time from range data. Determine target detection times and ranges from test data. Correlate times to identify any anomalous range indications.
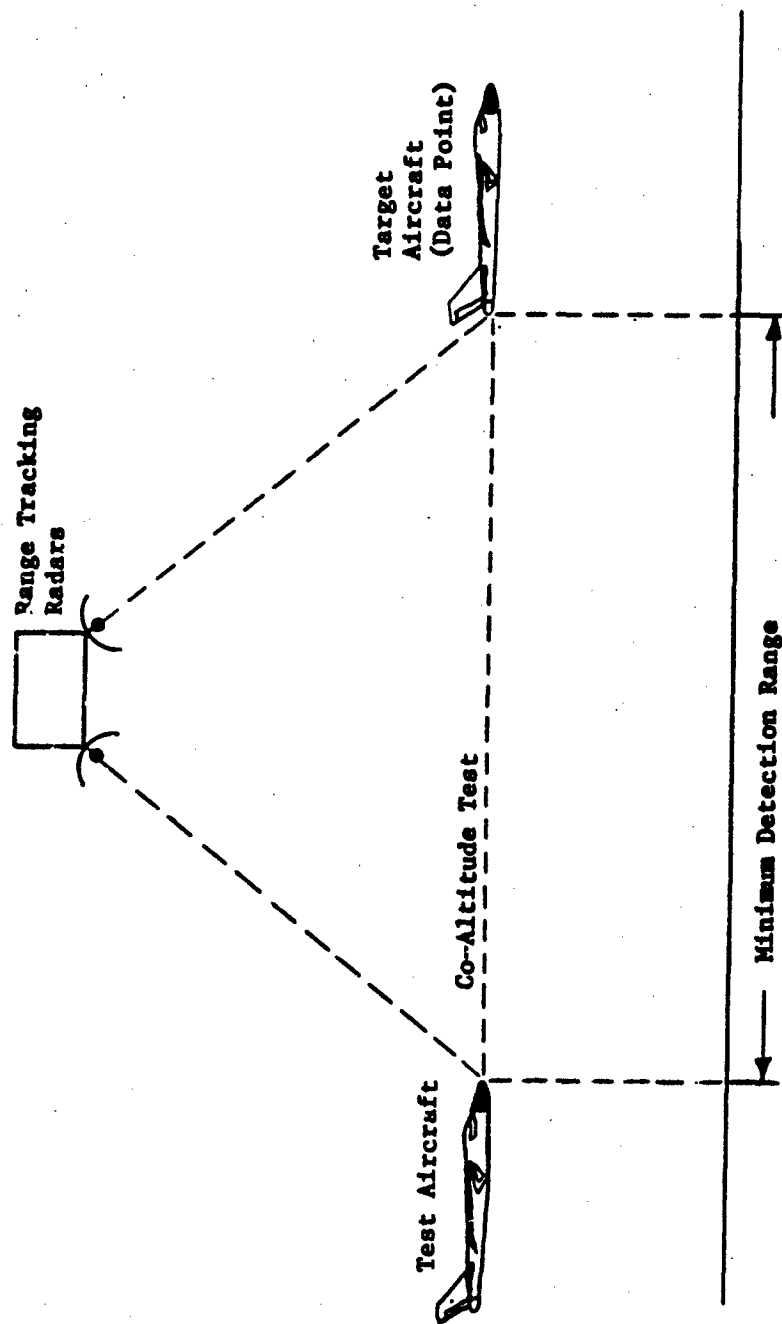
Figure 4.2.3.7--Air-to-Air Radar Minimum
Detection Range Test

4.13a

9. Target Imaging Definition (Air-to-Ground)

a. Scenario -- Fly prescribed flight path with respect to known ground target. Map area of target in ground mapping mode. Vary radar modes and parameters as required.

b. Test Data -- Photograph area including target via airborne camera or use detailed map of area (truth data); recorded radar ground map of area including target, via cockpit camera or video recorder.

c. Data Reduction -- Compare test radar image of target area with photograph or other truth data.

10. Field-of-View (Air-to-Ground and Air-to-Air)

a. Scenario -- Fly prescribed flight path toward a known, well-defined target. Acquire target. Continue to track target while altering test aircraft attitude to place the target at the extremes of the display. Vary radar modes and parameters as required.

b. Test Data -- Measure test aircraft attitude (pitch and yaw) via on-board instrumentation; radar imagery and instrument indications via cockpit camera. (Note instrument indications with target at limits of display.)

c. Data Reduction -- Determine field-of-view directly from test data.

11. Scan Patterns and Rates (Air-to-Ground and Air-to-Air)

a. Scenario -- Fly prescribed flight path. Vary radar modes and parameters as required.

b. Test Data -- Measure antenna deflection angles via on-board instrumentation (gimbal angle pickoffs for gimballed antenna; beam deflection voltages for electronically-scanned antennas); radar mode and parameter settings.

c. Data Reduction -- Determine scan patterns directly from test data.

4.14

12. Antenna/Display Stabilization Limits (Air-to-Ground and Air-to-Air)

a. Scenario -- Fly prescribed flight path toward a known, well-defined target. Acquire track on target. Maneuver test aircraft in pitch and roll, one axis at a time, until display destabilizes. Vary radar modes and parameters as required.

b. Test Data -- Measure test aircraft attitude via on-board instrumentation (inertial platform, vertical gyro, etc.); radar imagery and instrument indications via cockpit camera; radar and instrument data via recorder. Note aircraft attitude excursions at display stabilization limits. Also note any stabilization drift during tests.

c. Data Reduction -- Determine radar antenna/display stabilization limits directly from test data.

13. Antenna Beam Patterns and Sidelobes (Air-to-Ground and Air-to-Air)

a. Scenario -- Fly prescribed flight path with respect to ground receiving station while transmitting via radar antenna boresighted to aircraft datum line. Maneuver test aircraft to cover required ranges of azimuth and elevation angles. Vary radar modes and parameters as required.

b. Test Data -- Measure radar antenna beam signal strength via ground receiving station instrumentation; test aircraft space position via range instrumentation; test aircraft attitude via on-board instrumentation; time.

c. Data Reduction -- Derive radar antenna position and orientation with respect to receiving station versus time from range and on-board instrument data. Derive radar antenna signal strength versus time from ground station data. Correlate times to determine radar antenna pattern. (The functional adequacy of an air-to-ground radar spoiled (CSC^2) beam can be verified by examining the radar display for uniform illumination).

14. Velocity (Range-Rate) Accuracy (Air-to-Air)

a. Scenario -- Fly prescribed flight path toward target aircraft. Acquire track on target aircraft and continue track while target aircraft maneuvers in such a way as to provide required range of velocities relative to the test aircraft. Test data should include relative velocities varying continuously between positive and nc ive values. Vary radar modes and parameters as required.

b. Test Data -- Measure test aircraft and target aircraft position and velocity via range or on-board instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

c. Data Reduction -- Derive actual test aircraft-to-target aircraft relative velocity versus time from position data. Determine radar-indicated velocity versus time from test data. Correlate times to determine radar velocity accuracy.

15. Velocity (Range-Rate) Resolution (Air-to-Air)

a. Scenario -- Fly prescribed flight path toward two target aircraft. Acquire track on targets and continue track while one target aircraft alters airspeed to establish velocity differential relative to the other. Repeat test, at increasing velocity differentials until radar resolves the two aircraft in velocity. Vary radar modes and parameters as required.

b. Test Data -- Measure test aircraft and target aircraft position and velocity via range and/or on-board instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

c. Data Reduction -- Derive target velocity differentials from position or velocity data. Determine target breakout (velocity resolution) from radar data. Determine radar velocity resolution directly from data.

4.16

16. Maximum Velocity Indication Limit and Maximum Unambiguous Target Velocity (Air-to-Ground and Air-to-Air)

   a. Scenario -- Fly prescribed flight path toward target. Acquire target on (pulsed Doppler) radar. Gradually increase rate of target closure to designated value beyond maximum velocity indication limit. Note any anomalous velocity indications. Vary radar modes and parameters as required.

   b. Test Data -- Measure test aircraft and target position and velocity via range or on-board instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

   c. Data Reduction -- Derive test aircraft-to-target rate of closure versus time from range or on-board data. Derive radar target velocity indications versus time from radar data. Correlate times to verify maximum velocity indication and to identify any anomalous velocity indications.

17. Blind Ranges (Air-to-Ground and Air-to-Air)

   a. Scenario -- Fly prescribed flight path toward known, well-defined target. Acquire target on radar. Close on target to designated minimum range while monitoring radar target indication for drop-out. Vary radar modes and parameters as required.

   b. Test Data -- Measure test aircraft and target position via range or on-board instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

   c. Derive test aircraft-to-target range versus time from position data. Determine radar target indication drop-out times from radar data. Correlate times to determine radar blind ranges.

18. Blind Target Speeds (Air-to-Ground and Air-to-Air)

a. Scenario -- Fly prescribed flight path toward well-defined target. Acquire target on radar. Gradually increase rate of closure on target to designated value beyond maximum velocity indication limit. Monitor radar target indication for drop-out. Vary radar modes and parameters as required.

b. Test Data -- Measure test aircraft-to-target position and velocity via range or on-board instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

c. Data Reduction -- Derive test-aircraft-to-target velocity versus time from velocity data. Determine times of radar indication drop-outs from radar data. Correlate times to determine radar target blind velocities (speeds).

19. Minimum Target Ground Speed (Air-to-Ground)

a. Scenario -- Fly prescribed flight path toward moving ground target. Acquire target on air-to-ground interferometer-type moving target indicator radar. Gradually decrease target ground speed. Monitor MTI target indication for drop-out. Vary radar modes and parameters as required.

b. Test Data -- Measure test aircraft position via range instrumentation; target ground speed via ground instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

c. Data Reduction -- Derive target radial component of ground speed versus time from range and ground instrumentation. Determine time of MTI indication drop-out from radar data. Correlate times to determine MTI minimun ground speed.

20. Minimum Target Range Rate (Air-to-Air)

    a. Scenario -- Fly prescribed flight path toward target aircraft (tail chase). Acquire target on air-to-air Doppler-filter-type MTI radar. Gradually decrease target closing rate. Monitor MTI target indication for drop-out. Vary radar modes and parameters as required.

    b. Test Data -- Measure test aircraft and target aircraft positions and velocities via range or on-board instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

    c. Data Reduction -- Derive test aircraft-to-target aircraft range rate versus time from range or on-board data. Determine time of MTI target indication drop-out from radar data. Correlate times to determine MTI minimum range rate.

21. Maximum Number of Track Files and Maximum Number of Targets Displayed
(Air-to-Air)

    a. Scenario -- Fly prescribed flight path toward multiple target aircraft. Acquire target aircraft on track-while-scan radar. Verify ability of radar to maintain simultaneous track on, and to display, specified numbers of targets. Vary radar modes and parameters as required.

    b. Test Data -- Measure test aircraft and target aircraft positions via range instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

    c. Data Reduction -- Verify maximum numbers of targets simultaneously tracked and displayed with sufficient targets within tracking field-of-view and range.

4.19

22. Maximum Tracking Line-of-Sight Slew Rate (Air-to-Air)

    a. Scenario -- Fly prescribed flight path with respect to target aircraft (tail chase). Acquire track on target. Assume specified longitudinal and lateral separation from target. Maneuver test aircraft to opposite side of target aircraft (reverse lateral separation) at prescribed rate. Reduce longitudinal separation and repeat lateral maneuver until break-lock (track drop-out) occurs. Note drop-out value of lateral rate. Vary radar modes and parameters as required.

    b. Test Data -- Measure longitudinal and lateral separations and rates via on-board instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

    c. Data Reduction -- Determine maximum tracking antenna line-of-sight slew rate directly from test observations. Determine lateral rates from excursions and times.

23. Probability of Detection and Probability of False Alarm (Air-to-Ground and Air-to-Air)

    a. Scenario -- Fly prescribed flight path toward well-defined target of known radar cross section. Starting from a point beyond detection range, decrease range while monitoring radar blip-to-scan ratio. Continue closing until blip-to-scan ratio is essentially unity. Vary radar modes and parameters as required.

    b. Test Data -- Measure test aircraft and target positions via range or on-board instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

    c. Data Reduction -- Derive test aircraft-to-target range, versus time, from range or on-board data. Derive blip-to-scan ratio from radar data. Determine probabilities of detection and false alarm by correlation of target indications to actual targets.

4.20

24. MTI Clutter Rejection (Air-to-Ground)

a. Scenario -- Fly prescribed flight path toward well-defined, moving ground target of known radar cross section, in a background of stationary "clutter" targets of known radar cross section. Acquire moving target on MTI radar. Simultaneously observe returns from moving target and stationary clutter. Vary radar parameters, radar-to-target geometry, and target ground speeds as required.

b. Test Data -- Measure test aircraft and target positions and velocities via range and on-board instrumentation; radar imagery via cockpit camera; radar data via recorder; time.

c. Data Reduction -- Derive radar-to-target range and geometry from range data. Derive target ground speed from ground instrumentation. Determine moving target and clutter "target" return amplitudes from radar data. Determine clutter rejection attenuation of stationary targets as ratio of moving target-to-stationary target amplitudes.

25. Electronic Counter-Countermeasures

Electronic counter-countermeasures evaluation tests are discussed in the text on Electronic Warfare.