MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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AIRBORNE RADARS FOR SURVEILLANCE AND WEAPON DELIVERY

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ABSTRACT

Airborne radars such as AWACS capable of large area surveillance of aircraft over both land and sea have become a reality in the past few years. Soon to follow are radars capable of large area surveillance of moving ground traffic. Through their ability to accurately report enemy movement and to target individual enemy ground vehicles, these radars will undoubtedly have a large impact on intelligence gathering, resource allocation, command, control and the damage assessment functions.

This report describes relationships and trade-offs fundamental in the design of airborne surveillance radars in various operational roles. It describes radar capabilities which can be achieved using modern technology including array antennas, advanced waveforms and advanced signal processing techniques.

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AIRBORNE RADARS FOR SURVEILLANCE AND WEAPON DELIVERY*

I. INTRODUCTION

Microwave radars play a vital role in modern air warfare. They are the only sensors capable of performing long range, all weather, day or night surveillance and target acquisition. Microwaves easily penetrate rain, clouds and fog and lower microwave frequencies will even penetrate forests. Because radars provide their own source of illumination, they are not dependent on sunlight and perform well both day and night.

The major wartime role of the Air Force is to seek out and destroy the enemy. Radars are thus designed to perform the surveillance role and to aid in target acquisition and weapon delivery.

In this paper we describe radars designed to meet present and future operational needs. Recent technological developments and physical principles are discussed in some detail since they influence the design and capabilities of radar used to fulfill operational requirements.

Figure 1 shows the principal elements considered in evolving any particular radar design. The design is influenced by new technology such as solid-state power sources, phased array antennas and digital signal processing. New technology is simultaneously evolving in other modern weapon systems such as infra-red imaging seekers for missiles, cluster munitions, glide bombs, advanced bombing systems and laser guidance, and these too have an influence. The design is also influenced by developments in radar science wherein physical principles are discovered or better understood and measurements are made of radar target or clutter characteristics. We will in this paper discuss the physical principles and measurements which influence radar design and then the modern surveillance and weapon system requirements. First, however, a brief historical discussion is in order.

Historically, airborne radars were first designed to map the ground to aid in finding ground targets for attack using conventional bombs. The targets were large and saturation bombing was employed. Target location accuracy

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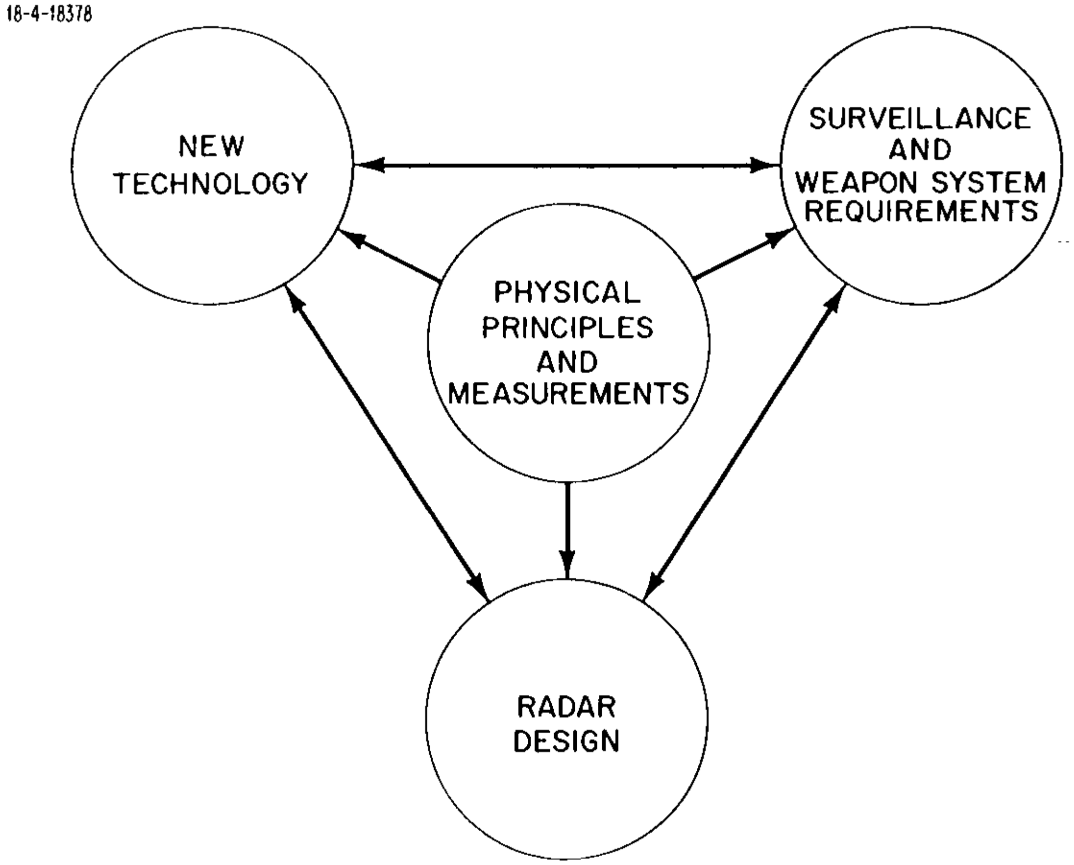

Fig.1. Elements which enter into radar design.

depended on the azimuth antenna beamwidth that could be obtained using reasonable sized antennas where the beamwidth is inversely proportional to the antenna dimension. These early radars were noncoherent; that is they did not use the phase information contained in the signal return.

The first airborne radars to employ phase information are the so called "noncoherent MTI" (Moving Target Indicator) radars. These radars detect targets with motion relative to the ground. The radar signal reflected from any object is offset from the carrier frequency due to the "doppler effect". When a source is aboard an object with a closing velocity there is an increase in the observers received frequency of v/λ where v is the relative velocity and λ is the wavelength. If the object is receding, the doppler offset is negative. In radar, because the signal travels a two-way path (radar to target and return), the doppler offset is doubled to $2v/\lambda$. Thus, in an airborne radar there is a difference in doppler frequency between the ground clutter return and the return from a ground vehicle moving with some radial velocity with respect to the ground. In a noncoherent MTI radar the return signal containing both target and ground return (clutter) is passed through a nonlinear device such as a square-law detector where the target return beats with the ground clutter causing a difference frequency which can be filtered using simple high pass filters.

Noncoherent MTI radars did not prove to be very reliable in detecting ground vehicles because, by their nature, these radars require a ground clutter return for detection. The amplitude of the beat signal produced in the square-law detector is directly proportional to the clutter signal. If the ground clutter is too low in amplitude an inadequate beat signal is produced and the target is lost in noise. If the ground clutter is too high it is difficult to filter from the desired signal.

To overcome these difficulties, the first airborne, coherent MTI radars were developed in the 1950's. They were first used for the detection of other aircraft. In these radars a correction loop was employed to lock the frequency of a local coherent oscillator with the signals reflected from the ground. This local oscillator signal was then beat with the return signal to translate clutter to a convenient frequency where it could be removed by filtering leaving only the aircraft return. Early airborne radars of this class worked well over the sea but poorly over land where the amplitude of ground clutter returns is typically 20 to 30 dB higher and where the ground clutter is very nonhomogeneous.

The 1960's saw the genesis of two important airborne radar techniques:

(1) the development of medium and high PRF pulse-doppler radars for aircraft detection over land, and

(2) the development of Synthetic Aperture Radar (SAR) to provide finer resolution maps of the ground. We will describe each in some detail.

A. Medium and High PRF Pulse-Doppler Radar(1)

To understand the rationale for the development of medium and high PRF airborne radars one must understand what is known as the "range-doppler ambiguity problem". In an airborne radar ambiguity may exist in the doppler frequency and/or range of the target and ground clutter being observed.

Doppler frequency ambiguity arises whenever the range of doppler frequencies from targets or clutter exceeds the radar's pulse repetition frequency (PRF). For instance, a sine wave with a frequency exactly equal to the PRF, when sampled at the PRF, will give a constant value so cannot be distinguished from a zero frequency (DC) signal. Doppler frequencies are ambiguous modulo the PRF.

Range will be ambiguous if the transit time of the signals from radar to target and return is greater than the spacing between pulses (the reciprocal of the PRF). The range ambiguity arises because the radar does not know which pulse was reflected from the target. Thus, the transit time to the target is ambiguous modulo the reciprocal of the PRF.

We see that a high PRF is desirable to remove doppler ambiguities and a low PRF is desirable to remove range ambiguities. Unfortunately in the microwave region, for the range and velocity of airborne targets of interest, it is impossible to design a single PRF radar which avoids both types of ambiguities. This condition has led to the development of three radar classes:

(1) Low PRF radars which are unambiguous in target range,

(2) High PRF radars which are unambiguous in target doppler (velocity),

(3) Medium PRF radars which are ambiguous in both target range and doppler.

Generally speaking, the difficulty with doppler or range ambiguity is not in determining the true target range and doppler. The ambiguities can be removed by observing the target successively on two or more different PRF's. The apparent range and/or doppler are different on each PRF and enough information is available to resolve the ambiguities.

The difficulty with doppler ambiguities arises when clutter returns are considered. Figure 2 shows the ground clutter spectrum and its aliases for a 10-GHz radar with a 0.6-meter-diameter antenna mounted in the nose of a fighter aircraft flying at a speed of 200 m/sec and observing targets 45 degrees off its nose. A reasonable range for such a radar is 75 km. To obtain unambiguous range the PRF must be 2000 Hz or below. With this low PRF, less than 50% of all velocities are available for target detection (see Figure 2). Even if two or three different PRF's around 2000 Hz are employed, there still will be significant blind regions.

To overcome these blind speed problems several recent airborne air search radars have been designed using medium or high PRF's. With an increase in PRF to 8000 Hz the target visible regions increase to about 85 percent, but both range and doppler become ambiguous. Using two or three different PRF's the ambiguity can be resolved. Finally, some radars are designed with high enough PRF (100 kHz in our case) so that doppler will be completely unambiguous. Again, the PRF is varied to determine the correct target range.

The penalty paid when using medium or high PRF's is an increase in the ground clutter level since ground clutter returns are received from all ambiguous ranges. The long range target must compete with very strong clutter returns received from close-in ground clutter illuminated by the last pulses transmitted.

Besides providing a higher percentage of target visible dopplers, the medium and high PRF radars also filter out more easily returns from moving clutter such as rain and bird flocks as well as that from ground vehicles. All of these types of clutter must be considered in the final radar design.

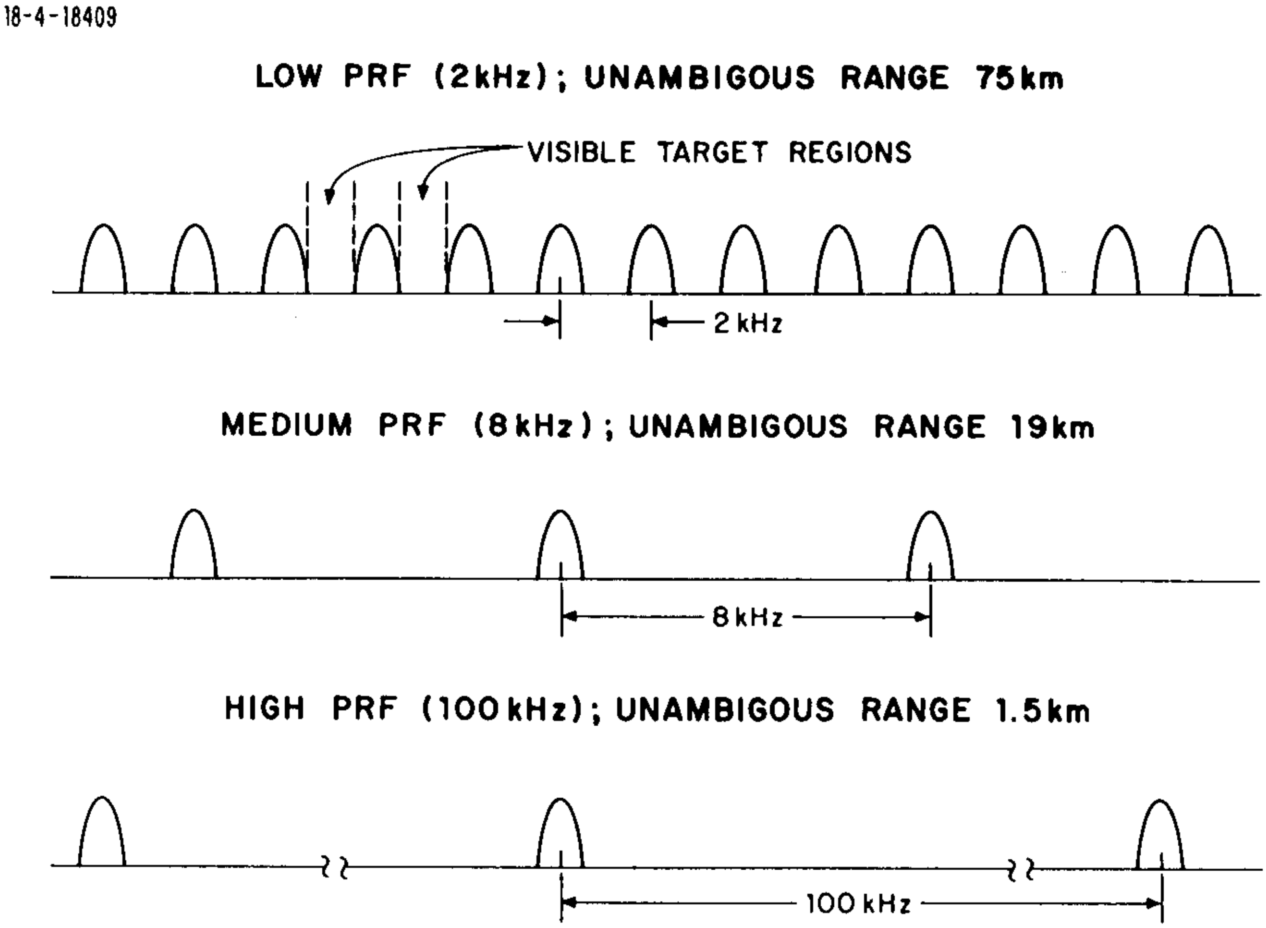

Fig.2. Ground clutter spectra for low, medium and high PRF radars.

The challenges in making the medium and high PRF radars perform well are in designing circuits and filters which have very wide dynamic range to reject main beam clutter and in designing antennas with extremely low side lobes so that the radar will have visibility for targets whose dopplers fall in the same doppler region as antenna side lobe clutter. These challenges have been met successfully, as exemplified in the AWACS radar, through the use of wide dynamic range digital processing and the development of precision slotted-waveguide array antennas. Considerable improvement in oscillator and amplifier stability was also required.

B. Synthetic Aperture Radar(2)

Synthetic Aperture Radar (SAR), also developed in the 1960's and early 1970's, makes use of doppler signals to produce a map of the terrain which has much finer resolution than that which can be obtained using antennas whose aperture size is limited by aircraft mounting considerations. SAR makes use of the aircraft's motion to produce a synthetic antenna aperture in space essentially by using sequential observations from a small moving antenna to simulate a much larger antenna.

As explained earlier, the doppler frequency of a radar return is $2v/\lambda$, where $v = V \cos \theta$. V is the aircraft's velocity and θ is the angle between the aircraft's velocity vector and the line of sight to the ground object to be imaged. The frequency of the fixed object varies as shown in Figure 3 as the radar flies past. Near broadside the return is almost a linear function of position in the beam. For each spot on the ground the SAR's signal processor provides a filter matched to the expected frequency slope at each radar range. For this purpose, the return signal is sampled at intervals corresponding to the effective pulse width of the radar. These samples are collected for a time T producing a synthetic aperture of length VT which provides an azimuth resolution of the synthetic aperture of $\lambda/2VT$ in radians. In Section II we will discuss the resolution limits of SAR and in Section III its relation to MTI radar.

The challenges in developing SAR have been in the areas of signal processing, motion compensation and radar system stability. Early signal processing

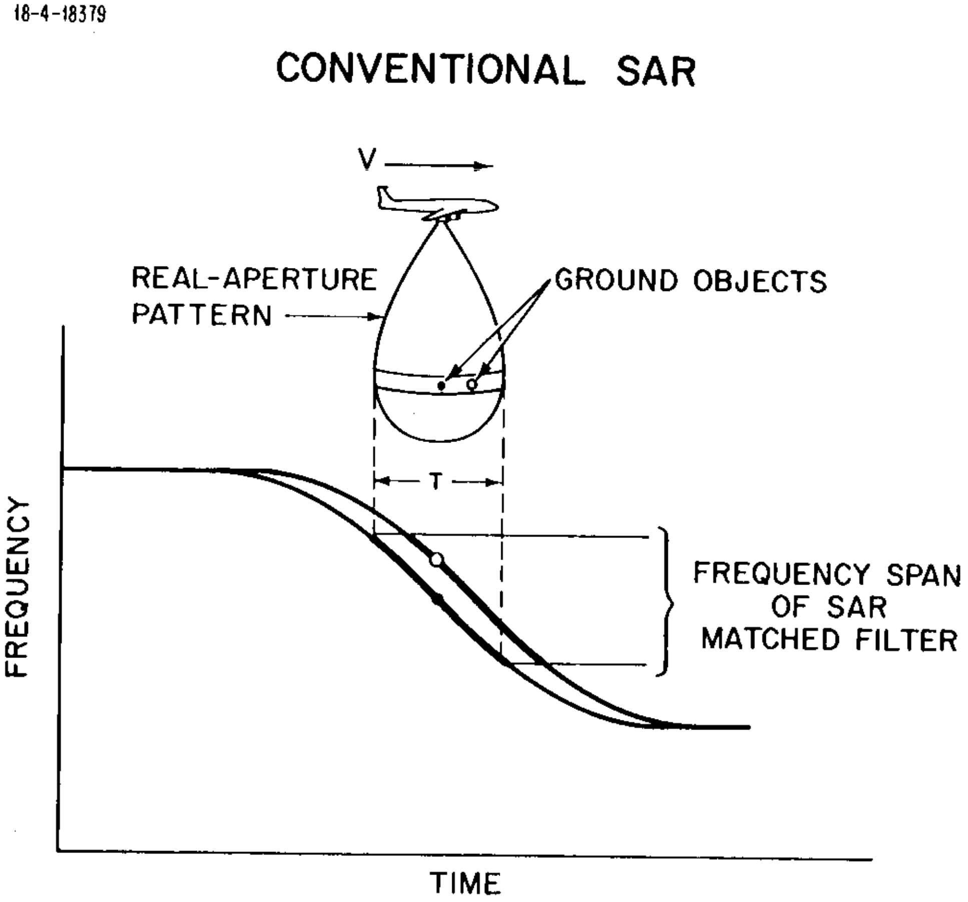

Fig.3. Frequency variation of fixed ground objects.

was done on signals recorded on film using optical techniques. More recently, digital storage and processing have been developed so as to allow SAR to perform in real time and more nearly match the surveillance and weapons delivery requirements of a modern tactical Air Force. Adequate motion compensation for SAR requires the use of state-of-the-art inertial navigation techniques.

In the 1970's, besides the work on SAR and MTI for aircraft targets, development of airborne radar for the detection of slowly moving ground vehicles continued with the development of the advanced Displaced Phase Center Antenna (DPCA)(3,4).

One of the limiting factors of conventional airborne MTI is the spectral spread of the ground clutter returns caused by platform motion. The same spectral spread used by SAR to distinguish returns at different azimuth angles causes difficulty with the separation of ground moving vehicles from fixed objects.

The DPCA solution to this problem is to artificially move the phase center of the antenna backwards as much as the aircraft flies forward, making it appear as if the antenna aperture hadn't moved; in some sense, the opposite of the SAR approach.

DPCA was first used in the 1950's on Airborne Early Warning radars to produce 10 to 20 dB better clutter cancellation for the worst clutter spread situation when the antenna is aimed broadside from the aircraft. More recently, using an array mounted along the side of an aircraft, excellent clutter cancellation has been demonstrated using DPCA with precise phase center switching. Again, advanced digital processing and array antenna techniques have contributed to the success of the demonstration. Figure 4 is a photograph of the aircraft carrying the experimental DPCA array.

As is evident from the above historical review, the complete topic of Airborne Radar is too extensive for a complete review in a paper as long as this one. Therefore, we will not discuss further the radar techniques to provide surveillance of other aircraft, but will instead concentrate on radars designed to map ground objects. In Section II we describe radar performance

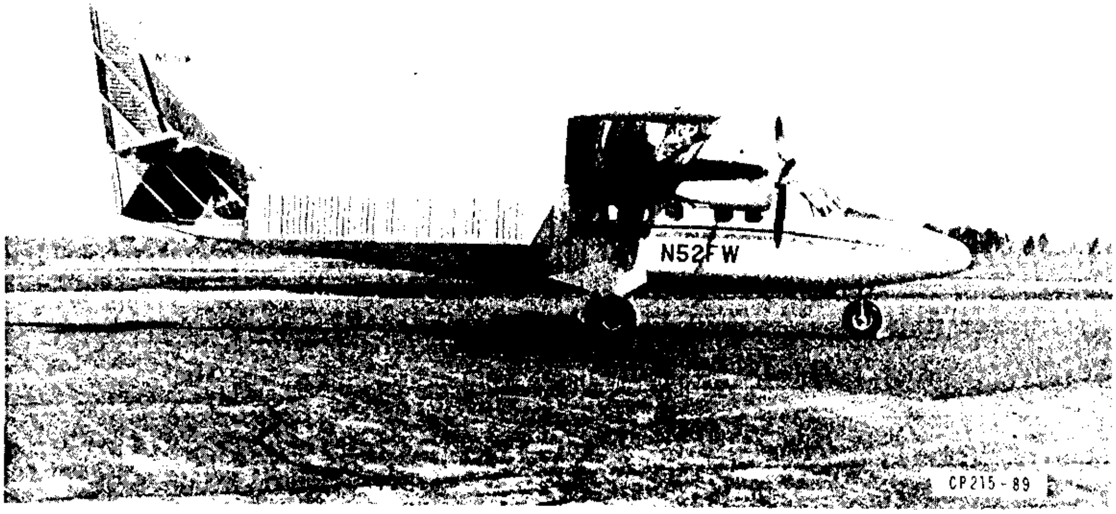

Fig. 4. Experimental DPCA Radar.

capabilities against fixed ground objects and in Section III concentrate on objects moving on the ground. Radar surveillance and weapon delivery requirements for ground objects are discussed in Section IV.

II. OBSERVING FIXED GROUND OBJECTS

As noted in the Introduction, Synthetic Aperture Radar (SAR) was invented to overcome the difficulty of airborne radars in achieving fine azimuth resolution. In this section we will discuss limitations on SAR resolution and accuracy when observing fixed ground objects and the effect of attenuation which is experienced in the propagation path under various circumstances.

A. Resolution

Radar resolution, defined as the ability to discriminate between two equal sized closely spaced objects, is four dimensional as shown in Table I. Fine resolution is often desired to separate targets or to reduce the clutter returns so as to improve the detection of targets in a clutter background.

TABLE I

Measured Quantity	Resolution
Range	$\frac{1}{\text{Signal Bandwidth}}$
Azimuth Angle	$\frac{\text{Wavelength}}{\text{Antenna Width}}$
Elevation Angle	$\frac{\text{Wavelength}}{\text{Antenna Height}}$
Doppler Frequency	$\frac{1}{\text{Coherent Integration Time}}$

At medium and long ranges it is difficult to achieve cross range (azimuth) resolution comparable to range resolution. This is particularly true for airborne radars where antenna size is limited. So called "range-doppler" mapping provides a solution to this problem whenever there is adequate relative motion between the radar and the object to be mapped. Range-doppler mapping has been used to map the surfaces of the moon and the nearby planets. It has been used to provide two-dimensional pictures of satellites. In this paper we are particularly interested in the form of range-doppler mapping called "synthetic aperture radar" (SAR) which takes advantage of the doppler produced by the relative motion of an aircraft as it flies by a portion of the ground to be mapped.

Figure 3 shows how the doppler frequency of signals reflected from an object on the ground varies as an aircraft flies by. If the radar's antenna is looking in a generally broadside direction (instead of directly fore and aft) the reflected signal collected by the antenna is a linear FM waveform. A filter matched to this expected signal is used to coherently integrate the returned signal and cause the fixed ground object to stand out and be separated from its surroundings. It is not difficult to show that in the absence of imperfections a theoretical cross-range resolution can be achieved equal to half of the actual antenna's projected physical width in the direction being mapped. Imperfections generally limit the theoretically expected cross-range resolution.

The most important imperfections limiting SAR cross-range resolution[2,5] are:

1. Aircraft velocity uncertainties
2. Aircraft radial acceleration uncertainties
3. Internal motion of the object being mapped
4. Phase shifts due to variations in the wave propagation path between radar and objects being mapped.

The resolution limits set by aircraft velocity and acceleration uncertainties are derived in Appendix A. Cross-range resolution limits have been plotted against wavelength in Figure 5 for velocity errors associated with modern inertial platforms. The acceleration errors typically turn out to be less than the velocity errors.

If the SAR is to be employed in wooded areas or where radar objects to be mapped are near tree lines, a degradation in resolution will be experienced because of the motion of the trees in the wind. Figure 6 shows the typical doppler spectrum of tree motion at various frequencies and its effect on SAR resolution is plotted in Figure 5. At low carrier frequencies the tree motion is only a fraction of a wavelength so produces a low order phase modulation on the carrier. The return then consists of a strong component at the carrier plus side bands which faithfully represent the spectrum of tree motion. A tree acts pretty much like a damped oscillator with a resonant frequency of about 0.4 Hz.

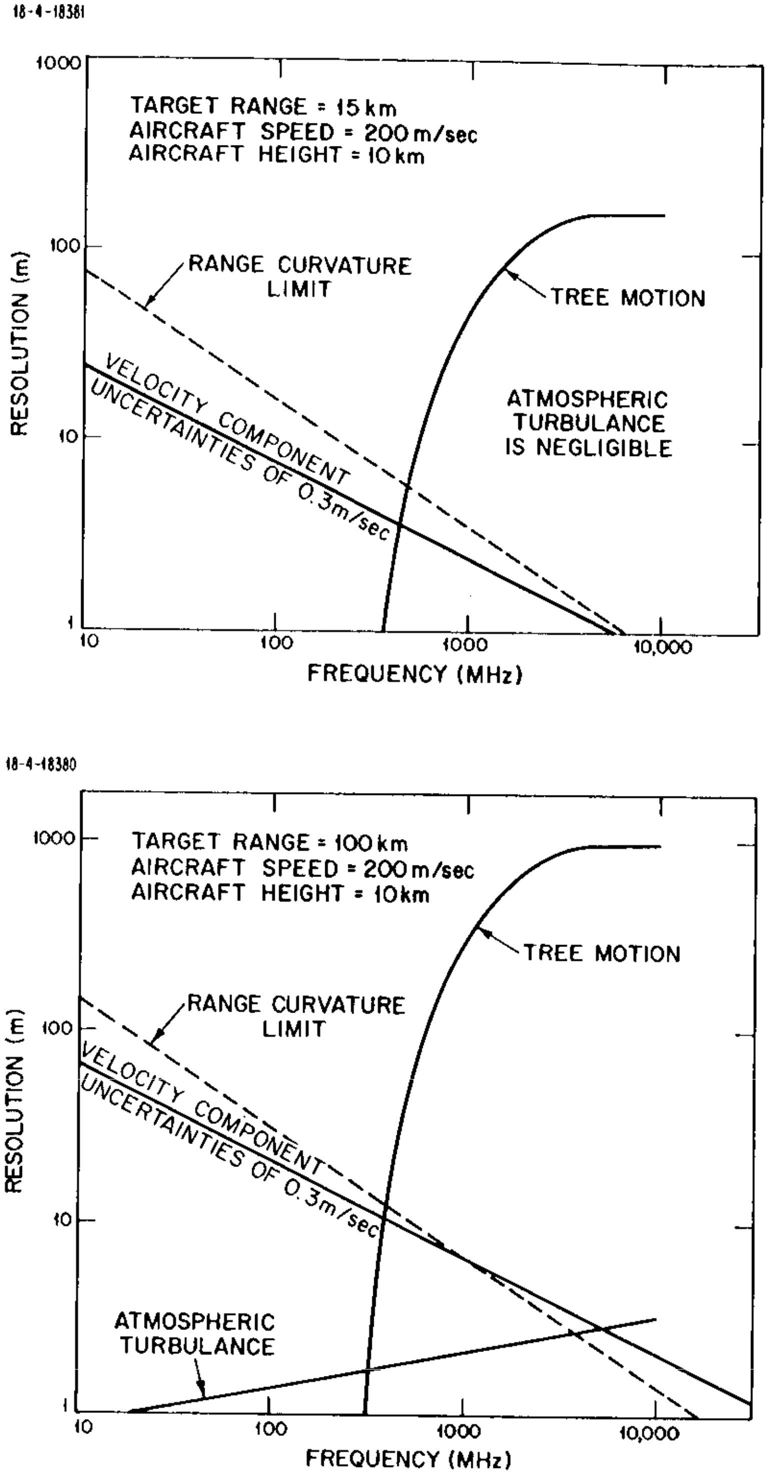

Fig.5. SAR resolution limits imposed by various effects at ranges of 15 and 100 km.

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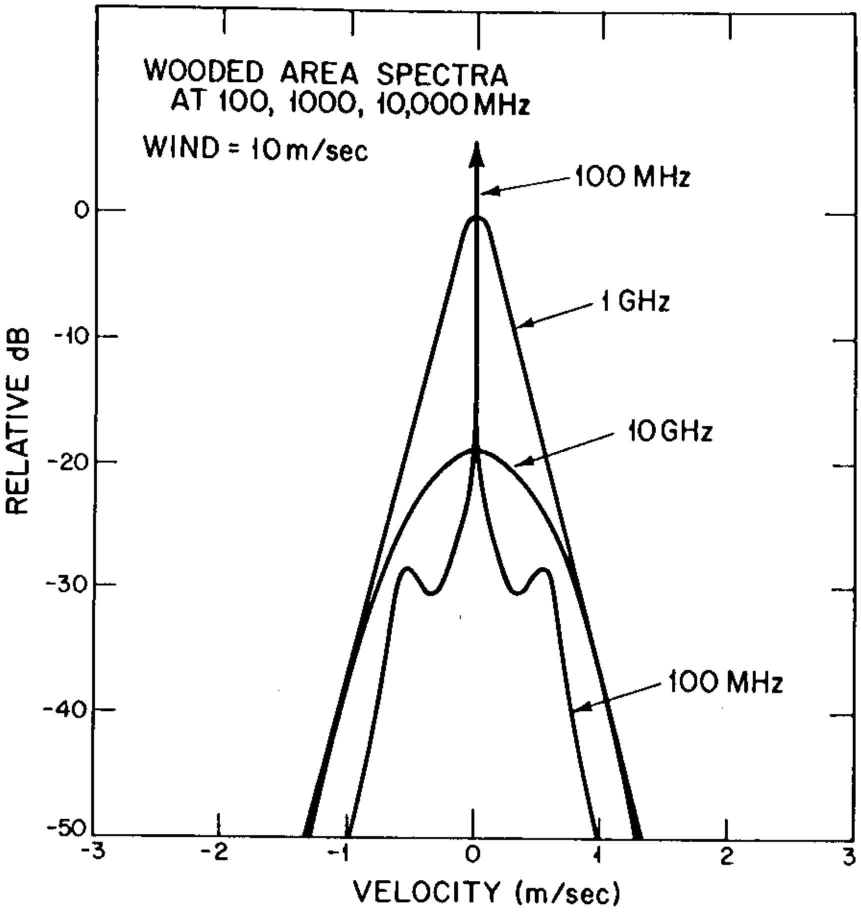

Fig.6. Doppler spectra of tree motion converted to velocity.

As the carrier frequency is increased the modulation or AC component increases and at about one GHz the index of modulation becomes an appreciable portion of a wavelength. Higher order modulation terms appear. At still higher frequencies reflections occur from the leaves and higher tree branches. At 10 GHz these represent independent scatterers so the spectrum becomes Gaussian in shape. Thus, at frequencies where the AC component of the spectrum predominates, resolution at moderate winds in or near trees is quite limited.

When SAR is attempting to image objects under the trees the waves must propagate through the trees and a modulation is imparted to the reflected signals. If the frequency is low enough to image the trees blowing in the wind and if the attenuation of the reflected wave from the desired target is not too great, then target resolution should not be degraded by propagation effects through the trees.

Figure 5 indicates that by choosing a suitable frequency in the UHF band a resolution of approximately 20 m should be achievable when mapping in or near wooded areas at 100 km.

Simple propagation of the radar wave through a normal atmoshpere adds phase errors which affect SAR resolution. Studies show(5) that atmospheric turbulence limits SAR resolution (see Figure 5) only at long ranges and at high microwave frequencies.

So called "range curvature" is still another factor which, although not limiting resolution, complicates SAR signal processing. As the aircraft flies by, the range to a particular ground object follows a curved path so that the range sampling must be gradually modified during the sampling period. This effect is analyzed in Appendix B and the corresponding resolution limit plotted in Figure 5.

B. Accuracy

Most airborne radars are range gated. The return signals are sampled in range at a rate somewhat greater than the range resolution. By comparing target signal strengths after filtering in successive range gates, range can be estimated to a small fraction of the radar's range resolution.

Similarly, the signals from a scanning antenna and from a doppler filter bank can be interpolated to provide accuracies to a small fraction of the radar's resolution in angle or doppler. Alternately sum and difference antenna patterns (monopulse) may be employed to measure the target's distance off the antenna boresite.

When an airborne SAR observes a fixed object on the ground, azimuth can be determined by measuring the doppler frequency of the object:

$$f_d = \frac{2V}{\lambda} \cos \theta$$

where, θ is the angle of the object measured with respect to the aircraft's velocity vector.

The error in determining the true azimuth angle of fixed ground objects arises chiefly due to error in the aircraft's radial velocity:

$$f_d = \frac{2V}{\lambda} \cos\theta + \frac{2\ v_r}{\lambda} \qquad (1)$$

and

$$\Delta\theta = \frac{v_r}{V \sin \theta} \qquad (2)$$

C. Forest Attenuation and Ground Lobing

A major factor in choosing a radar's frequency when it is to observe targets in a forested environment is the amount of attenuation experienced by the radar signal on its way to and from the target.

Figure 7 shows the two-way* attenuation which should be experienced by radar signals at various wavelengths for an airborne radar at 10-km altitude.

Besides foliage attenuation, there is a serious loss of signal strengths at lower frequencies due to multipath effects off the ground. The target is

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*"Two-way" is a term applied to the radar case where due account must be taken of the attenuation experienced by the electromagnetic wave as it propagates from radar to target and back.

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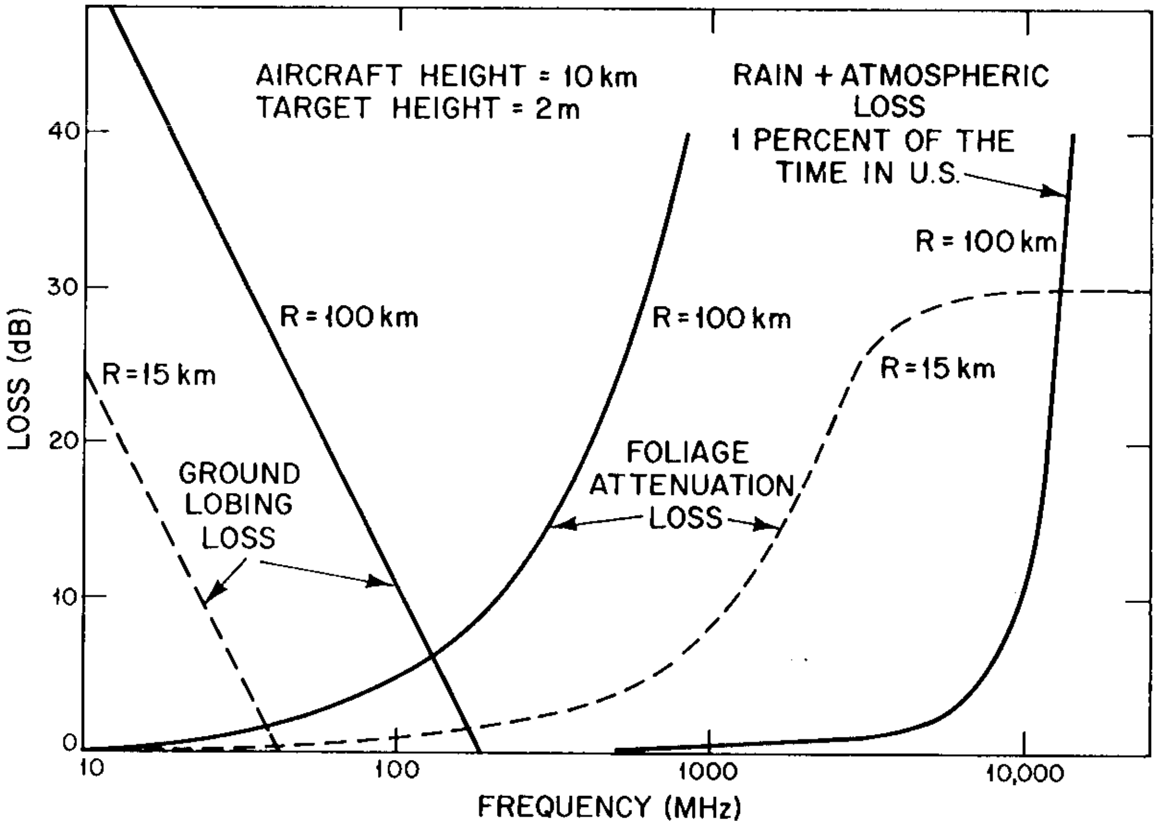

Fig.7. Radar propagation losses at ranges of 15 and 100 km.

illuminated by two rays, a direct ray and one that has suffered a 180-degree phase shift upon being reflected from the ground.

If we assume noncoherent scattering centers evenly distributed in height over the target of interest, we arrive at the ground multipath loss curve shown in Figure 7 for a target height of 2 m. The solid curves in Figure 7 are for a range of 100 km, while the dashed are for 15 km. Notice that both suggest the use of a low frequency in the VHF or UHF bands.

In some tactical situations the ability to observe objects amongst the trees is not important. The next attenuation limit is set by rain(6). Figure 7 indicates that frequencies up to 10 GHz could be used. At higher frequencies due consideration must also be given to rain backscatter.

III. OBSERVING MOVING GROUND OBJECTS

As described in the Introduction, early radars used so called "noncoherent MTI" to observe moving vehicles on the ground from an airborne platform. Recent emphasis has been on achieving finer resolution through doppler filtering. In this section we discuss resolution achievable through doppler filtering and techniques such as narrow antenna beamwidths and DPCA for further reducing ground clutter. We then discuss methods for achieving azimuth accuracy on moving vehicles.

A. Resolution on Moving Objects

The discussion of fixed-object resolution limits set by radial acceleration and velocity errors applies whether the error is on the part of the target or the radar. If in the previous discussion we interpret these velocity and acceleration errors as those of the moving ground vehicle, we obtain the curves in Figure 8 which show the resolution limits for unfocused SAR where no correction is made for the quadratic phase shift, and for focused SAR where the quadratic phase shift is corrected but no correction is made for unknown vehicle velocity with speeds up to 30 m/sec (60 knots). It is interesting to observe that the same resolution limit applies

$$\rho = \sqrt{\frac{v}{V} R \lambda} \qquad (3)$$

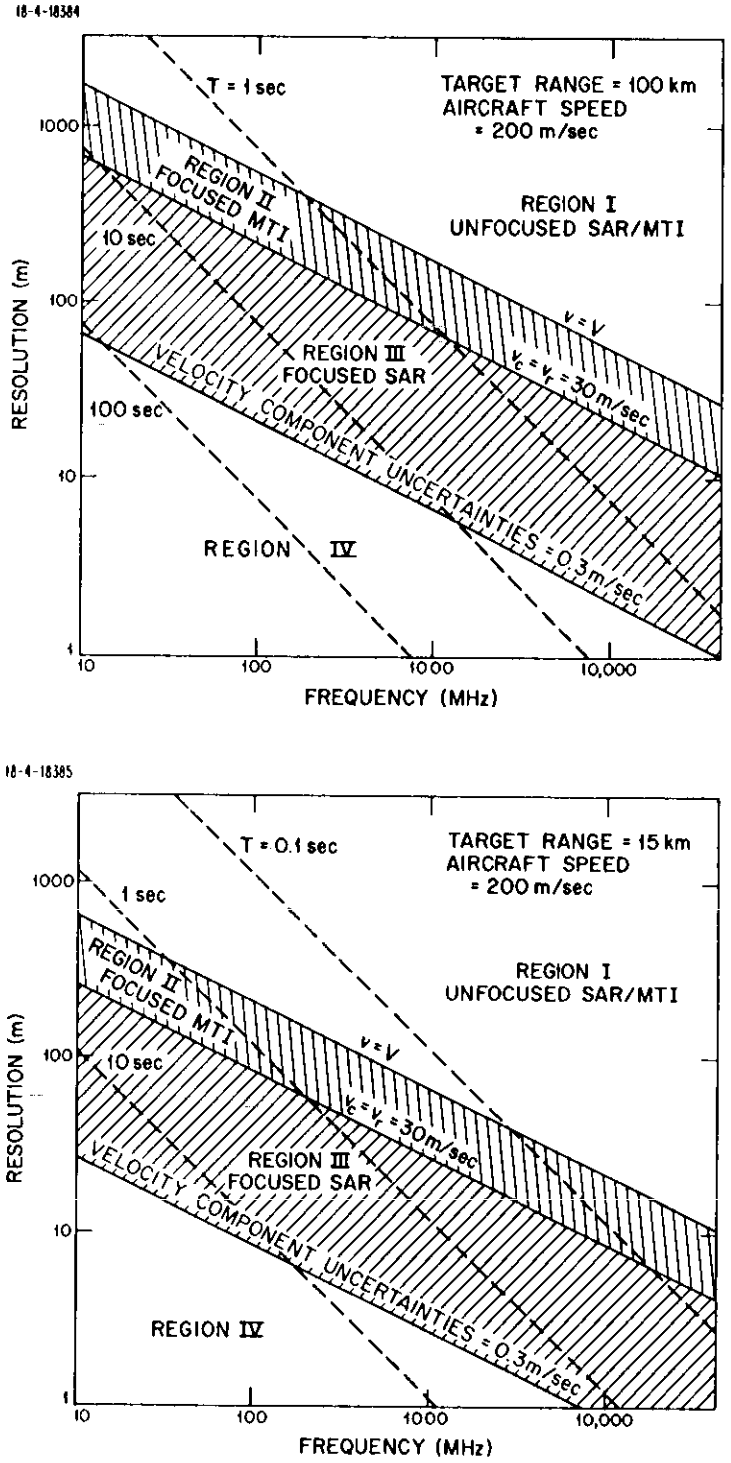

Fig.8. Resolution limits for SAR and MTI radars at ranges of 15 and 100 km.

whether v is a radial or cross-range vehicle velocity. Four regions can be delineated in Figure 8 as follows:

Region I - Unfocused SAR or MTI. In this region no attempt is made to correct for the quadratic phase history of the signals. Each filter is matched to a target with uniform radial velocity. This mode is sometimes called doppler beam sharpening. It is also used when detecting high velocity targets such as aircraft.

Region II - Focused MTI. In this region the quadratic term is corrected and moving targets with speed uncertainties up to 30 m/sec are imaged. The image will be displaced from its true azimuth according to its radial velocity component as discussed below under Accuracy.

Region III - Focused SAR. In this region fixed ground objects are properly focused but moving targets are not. They are smeared out in range and/or azimuth and therefore may not be detected at all.

Region IV - In this region uncorrected aircraft velocity or acceleration will blur the image of even fixed ground objects.

The suggestion has been made at various times that matched filters could be implemented to focus ground moving vehicles. If one realizes what a wide variety of velocities and accelerations various ground vehicles can possess, one quickly becomes disabused of the idea.

B. Clutter Considerations

The range-walk equation (Eq. A2) shows that in all the regions of Figure 8 the resolution cell area is given by:

$$A = \rho_r \rho_c = \frac{v}{V} \frac{\lambda R}{2} \qquad (4)$$

This expression assumes that a coherent integration time is employed just equal to that for an object walking through a range gate.

The above expression says that the clutter area after doppler filtering depends on parameters which, except perhaps for wavelength, are specified by the desired application. For instance, if vehicles up to 30 m/sec at a range of 100 km are to be imaged from an aircraft flying at 200 m/sec and if we have chosen a 2-m wavelength (frequency, 150 MHz) to achieve good foliage penetration, we find the resolution area is 30,000 sq. meters. The same clutter area is achieved using a fine range resolution and a short integration time or a fine azimuth resolution corresponding to a longer integration time. At this wavelength, the clutter reflectivity is such that the radar cross section of a typical clutter cell is approximately 1/300 that of the physical area and the clutter cross section will be 100 m^2. The vehicle return cross section may be 10 m^2 but when attenuated through the foliage (see Figure 7) would be only about 1.5 m^2. Since the return from the clutter approaches 100 times the magnitude of the competing target return, clearly some other mechanism would be required to improve the detection of the moving vehicle. Two such mechanisms may be applied:

1. Narrow Azimuth Beamwidth

If the doppler frequency of the lowest velocity ground target is outside of the doppler frequency spread of the ground returns each will appear in different doppler filters so the moving ground vehicle can be detected. Vehicles will be detected with radial velocity:

$$v_r > \theta_B V \sin \theta \qquad (5)$$

where θ_B is the antenna one-way, 3-dB beamwidth. Thus, looking sideways ($\theta = 90^o$) from an aircraft at 200 m/sec with a one-degree beamwidth, vehicles with radial velocities above 3.3 m/sec should be detectable.

2. DPCA

At medium or lower frequencies or on smaller high speed aircraft where narrow azimuth beamwidths are difficult to achieve this minimum velocity may be too high. Another technique called Displaced Phase Center Antenna, DPCA(3,4), may be employed to filter out and detect ground moving vehicles whose doppler frequencies fall within the main beam clutter doppler spread. As the name implies, a DPCA has a movable phase center. Consider an antenna mounted on the side of an aircraft. As the aircraft flies forward the phase center is electronically shifted rearward at exactly the same rate so the antenna appears stationary.

The simplest DPCA has two phase centers, successive pulses being transmitted and received on each one alternately. The received signal from the rearward phase center is subtracted from that from the forward phase center. In principle, the ground clutter signals will subtract to zero, but signals from any moving target will produce a measurable result if the target has moved even a small fraction of a wavelength. Effects which may degrade the cancellation are:

a. timing of the pulses not corresponding exactly to the forward motion of the aircraft,

b. the two antenna patterns differing from each other,

c. the aircraft crabbing in the wind so the phase center is not moved directly along the velocity vector, and

d. electrical differences existing in the receiver channels from the phase centers.

Considerable development work in recent years has overcome these possible deficiencies so that better than 40 dB clutter cancellation has been routinely achieved with the DPCA.

Subtraction using the two-phase-center DPCA reduces the target signal strength according to a sine-squared function similar to the response of a two-pulse canceller. By using several unequally spaced phase centers it is possible to obtain target responses similar to that from multiple pulse cancellers on staggered PRF's.

C. Accuracy

How can a moving ground vehicle be accurately located using an airborne radar? Before discussing useful location techniques we wish to warn the reader of one often suggested technique which cannot locate moving vehicles.

First, it is fairly well known that the image of a ground moving object on an SAR map is displaced from its true azimuth in proportion to its radial velocity. This can be inferred from Eq. (2) in Section II if we interpret the radial velocity error in azimuth to be just the ground vehicle's radial velocity. The suggestion is then made that the moving vehicle be observed on several successive SAR images and that the vehicle's azimuth position be corrected using its apparent motion on these SAR maps. Appendix C shows the futility of that approach. It turns out that four parameters must be estimated but there is only enough information to estimate three.

We will now describe two techniques which can be used to improve the accuracy in determining the azimuth of moving ground vehicles with respect to the radar platform. They are monopulse and three-phase-center DPCA.

1. Monopulse

Monopulse is basically an antenna technique and operates directly in estimation of azimuth. Two antenna patterns are provided, a sum pattern with a single lobe and a difference pattern with two lobes spaced equally on either side of the center of the sum pattern. The difference pattern lobes are 180 degrees out of phase with each other. An object is observed by both patterns and the difference to sum ratio is calculated. This ratio is calibrated to give the position of the object off the boresite of the sum pattern.

Monopulse angle accuracy is proportional to the sum pattern beamwidth divided by the square root of the signal-to-noise ratio.

2. Three-Phase-Center DPCA

The three-phase-center DPCA essentially provides a mechanism for estimating the fourth unknown. If a DPCA is arranged to have three phase centers, samples can be taken which, if processed properly, will yield the radial velocity of a moving target. The three phase centers cause samples to be taken when the antenna is nearly stationary in space. Following ordinary doppler filtering the second sample is subtracted from the first after any correction for sideways drift toward the clutter patch is made. Then the third sample is subtracted from the second. The subtraction process eliminates virtually all of the ground clutter. Any residual signal is due to a moving target. The phase shift observed between the two difference signals after subtraction divided by the time between pulses gives the doppler frequency in radians per second of the moving target. This can be used to correct its apparent azimuth determined by doppler filtering.

When using the three-phase-center DPCA technique the true target position θ is given by:

$$\frac{2V}{\lambda} \cos \theta = f_{dm} - \frac{\Delta\phi}{2\pi T} \quad (\text{modulo } f_r) \qquad (6)$$

where f_{dm} is the measured doppler from doppler mapping of the ground using the replies from a single phase center and $\Delta\phi$ is the phase of the second difference (pulse 3 compared to pulse 2) minus the phase of the first difference (pulse 2 compared to pulse 1) and T is the time between samples taken at the three phase centers.

From the above equation we note that ambiguities in θ may arise if too low a PRF is employed. The PRF for a single phase center must be higher than the spread of the ground clutter spectrum in the main beam so that any angular ambiguity can be resolved by the fact that the target must be within the main beam. To avoid range and angle ambiguities in the three-phase-center DPCA the PRF must lie between two limits:

$$\frac{5V}{a} < f_r < \frac{c}{2R} \qquad (7)$$

where c is the velocity of light and a is the antenna aperture.

An error analysis of Eq. (6) shows that when the PRF is chosen so that $f_r = 5\ V/a$, the azimuth accuracy is comparable to that achievable by configuring the same aperture as a monopulse antenna. Worse accuracy is achieved if the PRF is raised above this value.

Since both of these schemes provide cross-range accuracies on moving vehicles considerably worse than the resolution available when mapping fixed objects using SAR, it is improbable that moving objects can be placed accurately (within the resolution) on an SAR map. One must, therefore, include other schemes such as those above to deliver weapons against moving vehicles.

In comparing the above two methods, we observe that the monopulse method measures azimuth angle directly and does not depend on the resolution of any doppler ambiguities. It thus may be more appropriate for use at higher carrier frequencies where very narrow azimuth beamwidths are attainable in an airborne antenna and where it is often difficult to use a PRF high enough to avoid all doppler ambiguities.

IV. SURVEILLANCE AND WEAPON DELIVERY

With the radar performance descriptions presented in Sections II and III we consider in this section the application of airborne radar to typical surveillance and weapon delivery missions. As far as surveillance is concerned, it is clear that two kinds of targets exist; fixed and moving targets.

The required update rate for fixed targets is quite low. The most severe requirement would be to find targets which have recently moved into their present position. Typical targets are SAM sites, AAA and artillery batteries, tanks, APC's, etc. which are sometimes called transient targets. The really fixed targets such as buildings and bridges are located more effectively during good weather using photographic techniques. A radar reconnaissance for transient targets may be profitable at intervals of a half hour or so. The difficult task here is the interpretation of the radar output. Fine resolution focused SAR gives the most information concerning fixed and non-moving transient objects. An automated process called change detection can aid the radar image interpreter in deciding where there are interesting targets. Change detection uses a computer system to simultaneously examine two images of the same area at different times and pick out significant differences.

In a dynamic tactical environment target acquisition and observation of enemy movement are greatly aided by continuous radar surveillance. For continuous observation of specific ground moving vehicles, an update rate of 4 to 30 seconds is required depending on the density of targets and the detection quality of the radar. During an attack mode the radar may update moving target position once per second or faster.

The resolution requirements for moving targets are based on the required clutter suppression and the ability of the radar to suppress clutter as described in Section III as well as the requisite location accuracy. A moving target radar mode can be used to maintain continuous surveillance of a large area and the information so derived can be used to show areas of enemy activity and to actually count vehicles as they enter or leave a critical area such as a supply base. In most tactical situations mobility is restricted by mountain passes, swamps, river crossings, etc. Large area, continuous surveillance of moving vehicles can give the area Air Force Commander the information needed to direct his strike forces to those areas where they can be used most effectively.

Weapon delivery against fixed ground targets can be carried out using information derived from an SAR map. For example, by using beacons which have been provided in the attack area. The beacons are pictured on the SAR image and the attack is carried out using the offset measurements of the target from the beacons.

A similar arrangement cannot be used to attack moving vehicles because the offset continually changes. Because of the relatively poor azimuth accuracy afforded by airborne radar, a system called Multilateration Radar Surveillance and Strike System (MRS^3) has been under development within the Air Force. This system uses only range measurements from several aircraft to accurately locate a moving target. This system has, of course, the disadvantage of greater complexity and for that reason, perhaps higher vulnerability than one would like to see in a radar-based weapon delivery system.

In what follows we describe the accuracy problems associated with the use of a weapon delivery system employing a single, long range radar platform.

A. Single Aircraft Weapon Delivery System

The simplest standoff weapon delivery system would consist of one standoff aircraft which would locate the target and direct an attack vehicle (cruise missile, glide bomb, RPV or manned aircraft) against the target. Such a system would be completely aircraft oriented and except for altitude corrections for the missile and standoff aircraft, need have no relation to an earth oriented measurement grid. Only if target coordinates are to be transmitted to a command post for reference to other surveillance data, must the target coordinates be put into a common measurements grid.

The questions which this section addresses are:

1. How accurately must the target and missile be located to effect target acquisition and kill by the missile?
2. What is the best mode of attack by the missile?

We first observe that with high tens of kilometers standoff range from the target, the standoff aircraft would be outside of the range of tactical surface-to-air missiles, and would have warning time of impending attack by enemy fighters. Although this system would still be useful at shorter ranges, we have chosen 100 km as the range which would largely meet the above objectives.

Azimuth is the least accurate measurement which an airborne radar makes. We thus concentrate on inaccuracies of weapon delivery caused by errors in measuring the angle between the missile and the target. We will consider a two-dimensional problem in a plane defined by the missile, target and standoff aircraft knowing that altitude corrections must also be made for the third dimension.

It is clear from known weapon effects that a single aircraft at long range cannot guide a missile close enough to a hard target such as a tank or armored personnel carrier to effect significant damage with high probability. A missile with some form of terminal homing must be employed. Almost all terminal homing devices have a limited field of view. For instance, IR and optical devices narrow the field of view to secure greater target magnification and thus target recognition at longer ranges. The difficulty is to provide sufficient accuracy from measurements made by the standoff aircraft so that it can direct the seeker aboard the missile accurately enough to acquire the target.

Figure 9 shows the results of an error analysis. It is assumed that the radar aboard the standoff aircraft measures the missile range, the target range and the angle between them. Each of these three measurements are subject to error. Figure 9 shows sets of error circles caused by azimuth errors of 2-mrad and ranging errors of 10 m. The error circles all pass through the target position. The diameter of the circle due to azimuth error equals the radar-to-target range divided by the angular error magnification at the missile

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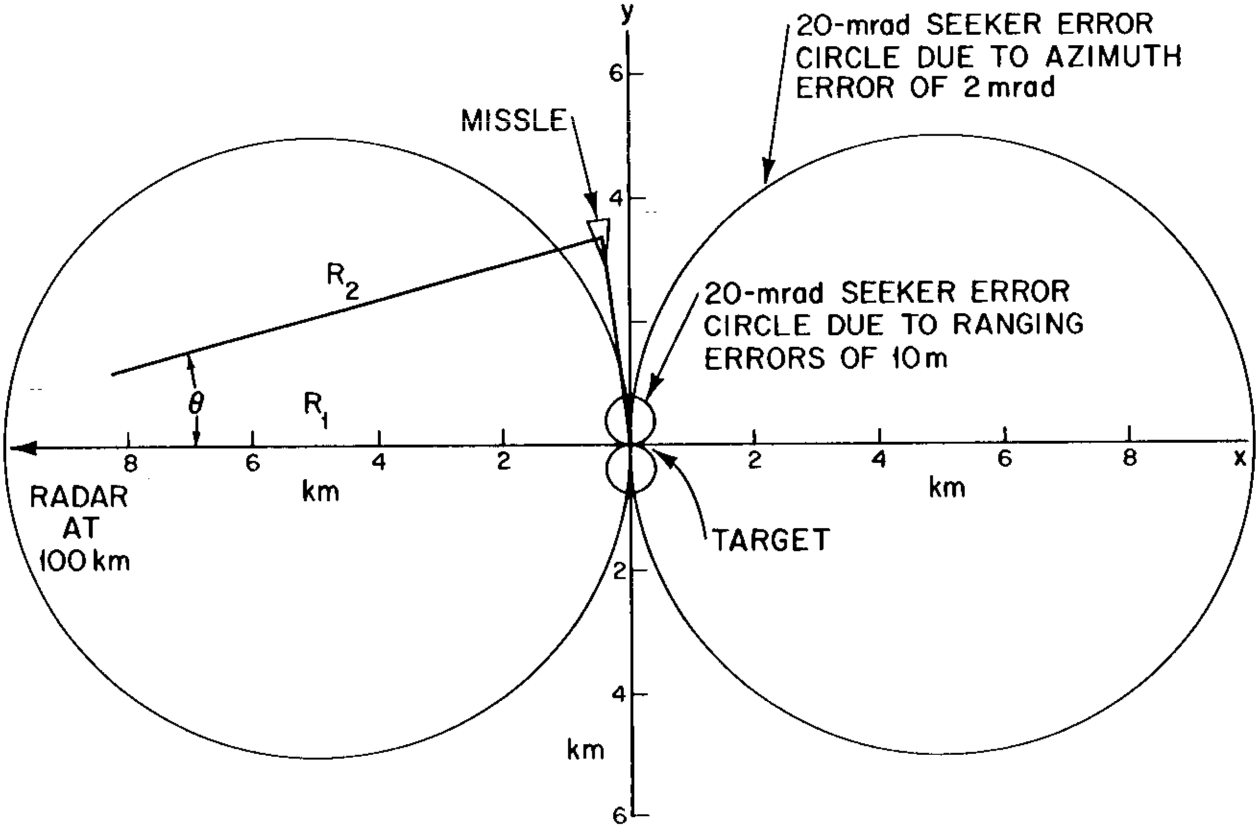

Fig. 9. Error circles for radar-directed missile attack.

seeker. We have drawn these error circles for a magnification of ten; 20 mrads (1.2 deg) at the seeker for 2 mrad at the radar. The error circles due to range errors have a diameter equal to the total range error divided by the seeker angular error.

The missile angular error circles, due to radar azimuth error, have their centers on the x axis. Thus, if the missile is in the plane which is normal to the line joining the radar and target (along the y axis of Figure 9), the angular error magnification is zero. The magnification is small if the missile is close to this plane.

The missile angular error circles due to radar ranging errors have their centers in the normal plane mentioned above. Thus, if the missile is colinear with the radar and target, or very close to this line, the angular error at the missile due to ranging error is minimized.

Since the ranging errors are very small compared to the azimuth errors, the angular errors at the missile will be minimized if the missile acquires the target close to the normal plane described above (along the y axis). Figure 10 shows schematically the missile and target errors. It seems obvious that the best solution is for the two elipses to merge end on.

Since the azimuth errors are at a right angle to the ranging errors, their combined effects can be estimated in an rms fashion. A cruise missile, RPV or manned aircraft could fly out to the range of the target, fly at constant range until it approached the target, acquire the target with its seeker and, finally, close on the target in a homing attack. Alternately, an aircraft could launch a shorter range missile such as the Maverick along the y axis while it remained high and out of range of at least the low altitude SAM's and AAA batteries.

The critical point in the attack is the acquisition range between missile and target. In the case shown in Figure 9 with an rms error of about 1.2 degree, the seeker should have at least a 6-degree field of view. This would allow the target to be within the 2 sigma error uncertainty and would allow about a one degree error in missile orientation. With this 6-degree field of

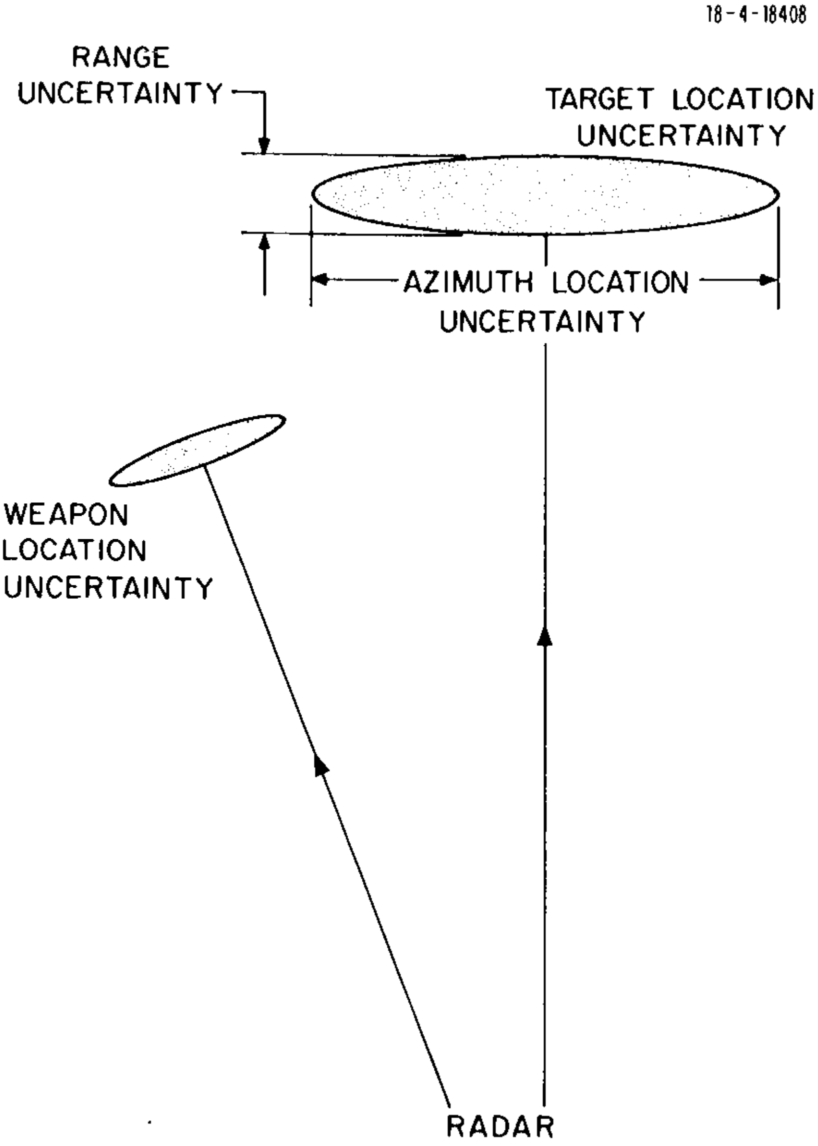

Fig.10. Error ellipses for missile and target location.

view target acquisition and lock-on must take place while the missile range to the target is greater than 700 m. For a smaller angular seeker error, the circles in Figure 9 would be proportionately larger and the field of view of the seeker could be smaller.

In the above discussion, we have dwelt on the azimuth seeker error and found that it is within reasonable bounds if the missile attacks the target along the y axis. Now let us consider the target position as presented to the missile seeker in the vertical or elevation plane. Due to the assumed azimuth error in the radar, the range between missile and radar will have a one sigma error of about 200 meters. Since the radar measures azimuth angle, this error is really an error in the projection of the missile's position on the ground relative to the target. If the missile is attacking at a small angle relative to the ground, the ground field of view of its sensor is elongated. This elongation would not be sufficient to encompass the target unless the angle of attack were very low. An effective means of attack is to fly the missile at about 300 m height above the ground with its seeker aimed 700 to 1000 m ahead. It will then sweep out a path about 70-m wide. When the target is acquired, it is immediately attacked at a steeper dive angle. In cases where the recognition and lock-on ranges are longer, the missile can fly at a proportionately higher altitude prior to lock-on.

Besides the above constraint, the achievable missile dynamics must be such that the missile can reach the target after lock-on takes place at the lock-on range. In the last 700 m the missile may have to correct up to 3 degrees or 35 m in cross-range. This implies that

$$\frac{aR}{v^2} > 0.1 \tag{8}$$

where: a is the available missile acceleration, v is its velocity and R is the lock-on range. For $a = 30\ \text{m/sec}^2$, $v = 300$ m/sec and $R = 700$ m

$$\frac{aR}{v^2} = 0.23 \tag{9}$$

and the inequality is easily satisfied. Target lock-on at longer ranges or using a slower missile would allow lower accelerations.

In conclusion, we have described a single aircraft, standoff location and attack system which is simple and compatible with many missiles and air-to-ground weapon delivery systems already in the Air Force inventory or under development. The system described envisions the use of radar, either MTI or SAR, for target location.

V. CONCLUSIONS

In this paper we have reviewed the role of airborne radar in modern air warfare. We have stressed basic physical principles as these ultimately limit the applicability of radar in a particular situation. Besides this, hardware development applicable to airborne radar has been so rapid in the past ten years that we can almost say that hardware is no longer a limitation. Airborne radars can now be designed and built limited only by radar physical principles and by the size and character of the signals reflected from targets and clutter (ground, rain, birds, etc.).

We have discussed in detail the resolution, accuracy and clutter performance limitations and have shown how these affect airborne radar in the air-to-ground mode. The studies show that it is possible to build fine resolution ground mapping radars to locate fixed targets not under foliage. Relatively low frequencies must be used to see targets under foliage. We have seen that synthetic aperture radar is best suited to providing fine resolution of fixed ground objects.

For moving ground objects doppler filtering does not provide as fine a resolution as SAR by a factor of about 10. We have further seen that the true azimuth of a moving object on the ground is difficult to determine and accuracies are limited to those achievable using monopulse techniques with the size of antenna available aboard an aircraft.

Because narrower antenna beamwidths are achieved with a given antenna size, good accuracy tends to drive the radar design toward higher microwave frequencies.

However, if foliage penetration is desired lower frequencies must be used. It appears that two classes of air-to-ground radars should be developed; a higher frequency radar without foliage penetration and a lower frequency radar with foliage penetration. The frequency of the foliage penetration radar may be higher than desired for good foliage penetration so as to give it good azimuth accuracy. The largest possible antenna should be used for foliage penetration since this will influence its maximum useful range.

We have described radar's role as a surveillance tool and, finally, we have described one useful standoff, all-weather weapon delivery system and shown that accuracies can be achieved suitable for effective weapon delivery using many weapons presently in use or under development within the Air Force.

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APPENDIX A

SAR RESOLUTION LIMITS SET BY VELOCITY AND ACCELERATION UNCERTAINTIES

To give a concrete example, consider an SAR mapping an area 100 km on the ground at a right angle to the aircraft's velocity vector. The received signal from any point on the ground is a linear FM waveform. The range to the target when expanded retaining only quadratic terms has the form:

$$R(t) = R_o - v_r t + \quad (V - v_c)^2 - R_o \, a_r \quad \frac{t^2}{2\,R_o} \qquad \text{(A1)}$$

where: v_r and v_c are the radial and cross range velocity errors and a_r is the radial acceleration error. Any cross acceleration causes higher order error terms. R_o is the range of the closest approach, V is the aircraft's velocity and t is the time.

The radial velocity v_r can be removed by proper processing. Because the waveform is a linear FM waveform, residual uncompensated radial velocity causes a cross-range shift in target position without affecting azimuth resolution. There remains, however, a so called "range-walk" problem wherein the object appears to move through a range resolution cell. Best range resolution ρ_r is achieved when the object walks through one range gate in the coherent integration time, T.

$$\rho_r = T\,v_r$$

and, since the cross-range resolution $\rho_c = \frac{R\lambda}{2VT}$:

$$\rho_r\,\rho_c = \frac{v_r}{V}\,\frac{\lambda R}{2} \qquad \text{(A2)}$$

A similar cross-range walk occurs in the cross-range dimension limiting cross-range resolution to:

$$\rho_c = \sqrt{\frac{v_c}{V}\,\lambda R} \qquad \text{(A3)}$$

where the resolution has been increased by $\sqrt{2}$ since two effects, cross-range walk and integration time are acting simultaneously.

Eq. (1) also shows that quadratic phase error across the synthetic aperture is introduced by radial acceleration a_r and cross-range velocity v_c errors.

When the error due to either of these equals λ/4 over half of the synthetic aperture, resolution is significantly degraded. Thus,

$$\frac{a_r \left(\frac{T}{2}\right)^2}{2} = \frac{\lambda}{4} \qquad \text{(A4)}$$

or

$$\frac{V \; v_c \left(\frac{T}{2}\right)^2}{R_o} = \frac{\lambda}{4} \qquad \text{(A5)}$$

are the resolution limits yielding for cross-range resolution:

$$\rho_c = \sqrt{\frac{R_o \lambda \;\; v_c}{V}} \qquad \text{(A6)}$$

and

$$\rho_c = \frac{R_o}{V} \sqrt{\frac{a_r \; \lambda}{2}} \qquad \text{(A7)}$$

It is interesting to observe that cross-range walk (Eq. 3) and quadratic phase distortion (Eq. 6) cause the same limit on cross-range resolution. Cross-range resolution limits have been plotted against wavelength in Figure 5 for velocity errors associated with modern inertial platforms. The acceleration errors typically turn out to be less than the velocity errors.

APPENDIX B

RANGE CURVATURE

Still another factor which, although not limiting resolution, complicates SAR signal processing is the phenomena called "range curvature". Equation (A1) indicates that the range changes with time by $V^2t^2/2R_o$. Different range cells must be sampled to properly image an object unless $V^2\ (T/2)^2/2R_o$ is less than the range resolution. This leads to the relation,

$$\rho_r = \frac{V^2T^2}{8\ R_o} = \frac{\lambda^2\ R}{32\ \rho_c{}^2} \qquad \text{(B1)}$$

If we set $\rho_r = \rho_c = \rho$

$$\rho = \frac{1}{2}\ (\frac{\lambda^2\ R}{4})^{1/3} \qquad \text{(B2)}$$

This condition is also plotted in Figure 5.

APPENDIX C

FUTILITY OF MOVING-TARGET AZIMUTH CORRECTION USING SAR MAP ALONE

Consider the radar platform moving along the x axis at velocity V starting at the origin at time t equals zero. At t = 0, the moving ground vehicle is at (x_o, y_o) and moves with x and y velocities v_x and v_y. The range between radar and ground vehicle is then:

$$
\begin{aligned}
R^2 &= (x_o + v_x t - VT)^2 + (y_o + v_y t)^2 \\
&= (x_o{}^2 + y_o{}^2) + (2x_o v_x - 2\,x_o V + 2y_o\,v_y)\,t \qquad \text{(C1)} \\
&\quad + (v_x{}^2 + V^2 - 2v_x V + v_y{}^2)\,t^2 \\
R &= (R_o + At + Bt^2)^{1/2} \qquad \text{(C2)}
\end{aligned}
$$

Notice that if the range variation with time were to be fitted to the above expression, only three parameters (R_o, A and B) would be determined whereas there are four unknown parameters (x_o, y_o, v_x and v_y) associated with the ground vehicle. Therefore, one cannot determine the vehicle parameters using this technique. It does not help to use target doppler since this is just a measure of dR/dt and adds no more information to the range-time history.

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Airborne radars such as AWACS capable of large area surveillance of aircraft over both land and sea have become a reality in the past few years. Soon to follow are radars capable of large area surveillance of moving ground traffic. Through their ability to accurately report enemy movement and to target individual enemy ground vehicles, these radars will undoubtedly have a large impact on intelligence gathering, resource allocation, command, control and the damage assessment functions.

This report describes relationships and trade-offs fundamental in the design of airborne surveillance radars in various operational roles. It describes radar capabilities which can be achieved using modern technology including array antennas, advanced waveforms and advanced signal processing techniques.