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RADAR AS A REMOTE SENSOR

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ABSTRACT

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Radar is a self-illuminating sensor operating over a wide wavelength range, but especially in the microwave region. Because of control over illumination, techniques not available to passive sensors can be used to measure range, azimuth, and radial velocity. These techniques are described.

Radar return is determined by many parameters, especially wavelength, roughness, and dielectric properties. Fundamental techniques used in theoretical descriptions of the scattering process are described briefly. Experiments have indicated radar return is influenced near the vertical by relatively flat parts of the surface and near the horizontal by surface elements with smaller radii, but numerous additional measurements are needed to describe radar return from natural surfaces and to relate to theory.

Imaging radar systems can be very useful even without complete knowledge of scattering coefficient theory. Measurements under conditions controlled by earth scientists are also needed in this field before full interpretation is possible.

AUTHOR

RADAR AS A SENSOR

Table of Contents

RADAR AS A REMOTE SENSOR

A remote sensor is a device that detects some property of an object or a group of objects at a distance by measuring some type of radiation or emanation from the object. Thus, our eyes, ears, and nose are all remote sensors. Cameras, infra-red detectors, telescopes, sonars, and radars are all remote sensors. They are distinguished from our sense of touch, from a meter connected to a circuit, a balance used in weighing, or a measuring tape, all of which are direct rather than remote sensors.

Radar is one of the few remote sensors providing its own source illumination. Because of this, it is capable of measuring range by time measurements rather than by angle measurements. This results in improved resolution for many purposes. Radars are less sensitive to clouds and atmospheric attenuation because of the wavelengths customarily used, but these longer wavelengths result in more difficulty in obtaining angular resolution with reasonably sized equipment. The use of the synthetic aperture technique for radars carried on moving vehicles permits great improvement in angular resolution without tremendous increase in the size of the equipment.

Radar signals are customarily returned to the receiver by a scattering process, with pure reflection being encountered only in rare situations. When the target area is a rough surface such as the surface of the earth or moon, the theory of scattering may be treated as if the surface were described statistically rather than deterministically. Numerous theories have been developed using different statistical models for the surface and some fair degree of agreement has been achieved between a few of the theories and some simple surfaces. Natural surfaces, on the other hand, are usually considerably more complex than any of the models feasible for use in the theory so that a great deal of work has been done empirically and many of the useful results are obtainable only by empirical means. Proper understanding of the radar scattering phenomenon involves both theoretical and experimental treatments, with the theory leading the way but the experiment being required for surfaces too complex to be described theoretically.

In spite of many previous programs for radar cross section measurement and many programs involving imaging systems, we still lack good measurements closely correlated with terrain types. Such measurements are presently being conducted under NASA sponsorship, with geographers and geologists working closely with the radar engineers to achieve proper correlation in experiment design.

This paper deals exclusively with radar returns from surfaces. The subject of radar returns from objects such as aircraft and spacecraft has received extensive treatment in the literature but is not discussed here.

Classification of Remote Sensors

So that the place of radar among the remote sensors is clearly established, let us first consider classification of remote sensors by source of emission, by wavelength, and by imaging method and resolution, noting the way in which radar fits in each of these categories.

Table 1 lists examples of remote sensors as classified by primary source of radiation. No attempt has been made to list the sensors exhaustively. Sensors that detect thermal radiation are the most common sensors using self-emission. However, both photographic and other techniques can be used to detect chemical or biochemical luminesence and radioactive decay is occasionally used as a source for remote sensors. Of course, many sensors of acoustic waves depend upon self emission of sound but these are not considered here.

TABLE 1

CLASSIFICATION OF REMOTE SENSORS BY PRIMARY SOURCE OF RADIATION

- SELF-EMITTING
  - RADIOACTIVE DECAY
  - CHEMICAL OR BIOCHEMICAL LUMINESCENCE
  - THERMAL RADIATION
- RERADIATION OF NATURAL AND NON-COHERENT MAN-MADE SOURCES
  - SOLAR RERADIATION
  - RERADIATION OF ATMOSPHERIC THERMAL RADIATION
  - RERADIATION FROM FLASHBULBS, FLARES, ETC.
- RERADIATION FROM COHERENT SOURCE PART OF SENSOR
  - RADAR - MONOSTATIC
  - RADAR - BISTATIC

Re-radiation, in the visible spectrum especially, is probably the most widely used type of radiation detected by remote sensors. Natural and man-made sources not connected with the sensor are lumped together in this category; thus, nearly all photography (even in the infra-red region) depends primarily on radiation from the sun or from flash bulbs. In some wavelength regions the atmospheric thermal radiation is important.

When the signal received is re-radiated from a source whose time variation is controlled as a part of the sensor operation, we call the system a radar. "Monostatic" radar systems have the receiver and transmitter (illuminator) in the same general location. Sometimes the same antenna is used for both but a radar altimeter having a transmitting antenna on one wing and a receiving antenna on the other wing of an airplane would also be classed as a monostatic system -- although it certainly is not static if it is on an airplane.

"Bistatic" radar systems have receivers located significant distances from the source of illumination. Such systems are often used for air defense and satellite surveillance. Sometimes guidance radars also are bistatic.

Because the radar provides its own source, it is often called an "active" sensor as distinct from a "passive" sensor that uses illumination present whether the sensor is in use or not. Some bistatic radar guidance systems use a ground based transmitter and a receiver on a moving vehicle. The equipment on the moving vehicle is then called a "semi-active" system.

Table 2 lists the classification of sensors by wavelength. The sensors considered are those using electromagnetic radiation; sound waves would probably call for a different classification. A remote sensor may use any wavelength that can be detected. Thus, one can use wavelengths as short as those of gamma rays and wavelengths as long as the hundreds and thousands of kilometers at the lower frequency extremes of the radio spectrum. Radars are presently in use at wavelengths from those of visible light (fractions of a micron) to long radio wavelengths (kilometers). The great majority of modern radar systems, however, operate in the microwave region (0.5 cm to 100 cm).

TABLE 2

ELECTROMAGNETIC REMOTE SENSOR CLASSIFICATION BY WAVELENGTH

GAMMA-RAYS	
X-RAYS	
ULTRAVIOLET	
VISIBLE LIGHT	- RADAR USING LASER
INFRARED	- RADAR WHERE LASER AVAILABLE
MICROWAVE	- RADAR
VHF, HF	- RADAR
LOWER FREQUENCIES	- RADAR

Table 3 summarizes classification of sensors by imaging methods and resolution. The crudest sensors are essentially non-directional although they may be either deliberately or inescapably directional to some extent. These sensors detect the presence of some radiation source without attempting to tell the direction except in a gross sense. Combinations of these, of course, may be used to achieve an interferometric effect for directional sensing.

Other types of sensors are highly directional in their pickup, detecting the presence of remote objects only in a particular small angular cone such as the field of view of a telescope. Normally the output of such sensors is either a decision as to the presence or absence of an object or some kind of a record as a function of time, either of the passage of objects through the beam or of the passage of the beam over objects. Thus, a fixed radio telescope may provide, with respect to an earth reference, a record of the passage of astronomical objects through its beam, whereas a movable telescope with a photo cell may either scan across the sky determining the brightness in different areas, or may remain aimed at a particular celestial object.

TABLE 3

ELECTROMAGNETIC REMOTE SENSOR

CLASSIFICATION BY IMAGING METHOD AND RESOLUTION

ONLY SLIGHTLY DIRECTIONAL :

- GEIGER COUNTER, SCINTILLATOR, PHOTOCELL, ANTENNA SMALL COMPARED WITH WAVELENGTH

HIGHLY DIRECTIONAL, NON-IMAGING :

- PHOTOCELL ON TELESCOPE
- NON-SCANNING RADAR OR RADIO-TELESCOPE

SCANNING IMAGE

- TELEVISION CAMERA
- ROTATING MIRROR WITH PHOTOCELL, BOLOMETERS, ETC.
- IMAGING RADAR

SIMULTANEOUS IMAGE

- CAMERA
- MULTIPLE ANTENNA OR LENS RADAR OR RADIOMETER
- DATA-PROCESSING ANTENNA RADAR

Devices providing two-dimensional display sequentially by scanning are listed next. Certainly the most familiar of these today is the television camera, but various rotating mirror devices are used in different parts of the electromagnetic spectrum to provide similar scanned images. Both ground based and airborne imaging radars are widely used.

Conceptually, the most sophisticated sensor and certainly the one which provides information most quickly, provided the signal intensities are strong enough, is the sensor providing all elements of an image simultaneously or essentially so. The camera is the most familiar example of this, but radars are also capable of producing simultaneous images either with multiple antennas, each of which provides an output corresponding to a particular direction, or with data processing antennas in which the signals coming from many directions are simultaneously processed so that only signals from a particular direction are enhanced at a particular point on the image.

Radar is distinguished as the device that provides its own illumination. Radars are found in a wide variety of wavelengths although the microwave region is most commonly used. Radars are used with everything from the crudest to the most complicated imaging method depending upon the application and the complexity permissible.

Fundamental Radar Principles

This section summarizes some of the basic ideas behind radar operation. A reader familiar with the operation of radar systems may find this useful for organizing his thoughts. Hopefully, it will also be simple enough so that one unfamiliar with radars can follow the fundamental ideas even though he would be lost in the details of a radar system.

Since radar depends upon re-radiation of energy supplied by the radar system, the factors determining the strength of this re-radiation may be conveniently divided into factors determined by the properties of the source and receiver and those that are determined strictly by the particular surface. In fact, the parameters of the surface are themselves a function of the source parameters in many cases.

TABLE 4

FACTORS DETERMINING RERADIATION OF ELECTROMAGNETIC WAVES

- PARAMETERS OF SOURCE (or receiver):
  - WAVELENGTH
  - POLARIZATION
  - DIRECTION
- PARAMETERS OF SURFACE
  - DIELECTRIC AND CONDUCTING PROPERTIES, INCLUDING QUANTUM RESONANCES
  - SURFACE ROUGHNESS IN WAVELENGTH UNITS
  - PHYSICAL RESONANCES
  - SURFACE SLOPES
  - SUBSURFACE EFFECTS

THESE FACTORS APPLY ALSO TO SELF-EMISSION, EXCEPT THAT TEMPERATURE AND OTHER CAUSES OF SELF-EMISSION MUST BE ADDED.

Table 4 summarizes the factors determining re-radiation. Source and receiver parameters include the wavelength of the radiation and its polarization. In a sense, the direction with which the object is illuminated and from which it is viewed are parameters of the source as well. Certainly the re-radiation depends upon all of these.

The re-radiation for any particular surface depends upon its dielectric and conducting properties -- often expressed in terms of the complex permittivity or complex conductivity of the material. Sometimes these properties appear in the form of reflection and transmission coefficients computed using the Fresnel relations. Also included in the same class of properties is the quantum resonances, like those that determine the color of a particular material.

Perhaps even more important to radar than the dielectric and conducting properties is the degree of roughness of the surface. Actually, it is not the absolute roughness that is so important, but rather the roughness expressed in units of a wavelength. Roughness is a geometric property of the surface. It can be expressed for most surfaces in statistical terms involving variance of height about the mean, correlation distances and correlation functions, slope distributions, etc.

Presence of structures within the surface having resonant dimensions can give rise to strong radar signals from apparently small objects if they are properly oriented and can also result in weaker signals with improper orientation. Surface slopes are, in a sense, measures of roughness but relatively flat facets at different slopes are significant by themselves in some of the theories; hence, the surface slopes are listed separately here.

If the radar signal can penetrate a significant distance into the surface material all parameters significant for the surface may also be significant at various subsurfaces. The re-radiation then will be determined by the combination of the surface and the subsurface parameters. Furthermore, inhomogenieties within the surface material itself at some depth will have a significant effect if penetration of the signal is sufficient.

These factors determine re-radiation whether the source is a part of the remote sensor or not. Therefore, they are not unique to radar. Normally parameters of an outside source that effect re-radiation are the same as those for a radar transmitter.

Any remote sensor detects certain information about the remote object, the simplest information being merely the presence or absence of the object. Table 5 lists the information sensed by a radar. Numerous properties of the remote object may of course be inferred but the information listed in the table is, in fact, all that is sensed directly for a given wavelength and polarization. The signal strength and angle from the sensor to the object are of course detected by the passive sensors as well. Unique to radar is measurement of the distance to the object by measuring the delay time between the transmitted signal and the one received from the object. Also unique is the measurement of the relative velocity of the object and the observer by measuring the Doppler frequency shift of the received signal as compared to that which was transmitted. Of course, a similar technique has been used by astronomers for a long time to measure velocities, using the assumption that the transmitted frequency for a particular spectral line is known. Except for this, however, radar appears to be the only sensor capable of Doppler measurement of velocity.

TABLE 5

INFORMATION SENSED BY A RADAR

SIGNAL STRENGTH ANGLE TO OBJECT	(SAME AS PASSIVE SENSORS)
DISTANCE TO OBJECT, BY TIME MEASUREMENT RELATIVE VELOCITY OF OBJECT BY DOPPLER MEASUREMENT	(UNIQUE TO RADAR)

Because range and velocity measurements are possible independent of angle measurement, the radar system can have improved resolution at any particular wavelength relative to a passive system that must determine position by angle measurements.

Furthermore, correlation of received and transmitted signal properties permits "pre-detection integration" which results in enhanced signal-to-noise ratio compared with that obtainable using systems depending upon "post-detection integration".

Angle measurement in sensors dependent upon electromagnetic or acoustic waves is normally achieved by observing the difference in phase between signals received at two or more locations. This technique is used explicitly in interferometry and antenna arrays and implicitly with lenses, parabolic reflectors, and similar devices.

The interferometer with two receptors (antennas, transducers, etc.) is the simplest angle measurement device and readily illustrates the fundamental principle. Figure 1 shows such an interferometer. The assumption is usually made as here that the base line of the interferometer (d) is sufficiently small, compared with the distance to the source of radiation, that lines joining the two receptors with the source may be considered parallel. This is not a necessary condition, but the processing of information in the interferometer is more complicated if this condition is not satisfied.

As illustrated in the Figure, the extra distance traveled by a wave from the source to the left-hand receptor is given by

$$d \sin \theta$$

Thus the two distances are the same when $\theta = 0$ and the source is on a line perpendicular to the base line. In that case, the signals add up in phase whereas for any other direction, one must calculate the relative phase shift to determine whether they add or subtract. The relative phase shift is, of course, given by

$$\text{relative phase shift} = (2\pi d/\lambda) \sin \theta$$

If the signals at the two points on the interferometer experience the same delay in traveling from the receptors to the combining point, the relative phase shift at the combining point is just that associated with the receptors. Enforcement occurs when they add in phase:

$$(2\pi d/\lambda) \sin \theta = 2n\pi \quad \text{or} \quad \sin \theta = n\lambda/d$$

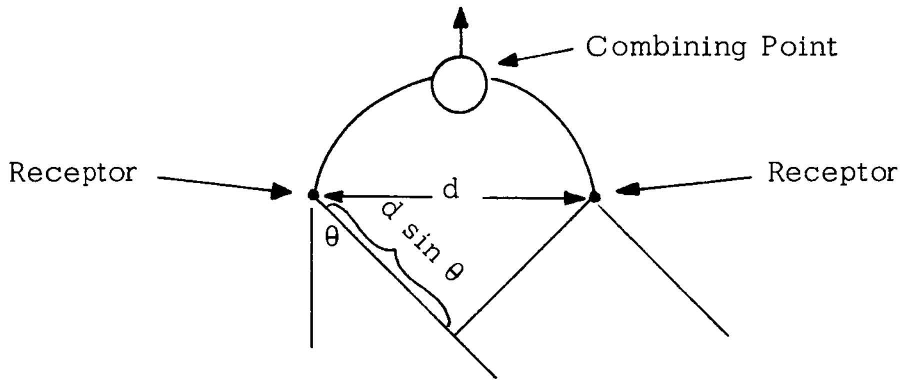
Cancellation occurs when the relative distance is such that the two signals are out of phase:

$$(2\pi d/\lambda)\ \sin\theta = (2n + 1)\,\pi \qquad \text{or } \sin\theta = (2n + 1)\,\lambda/2d$$

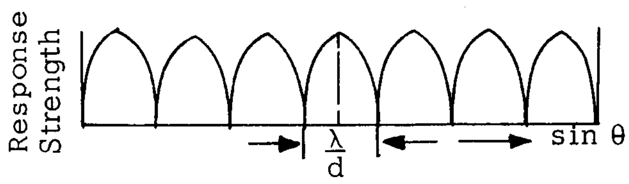
Thus, the spacing between nulls or between peaks is just an increase of sin θ by (λ/d). The interferometer pattern is indicated in Figure 1 b. Sin θ may be replaced by θ over the region of small θ.

The difference between the interferometer indicated in Figures 1a and 1b and an antenna or lens designed to have a single lobe at θ = 0, rather than the multiple lobes of the interferometer, is that the space between the ends of the apertrue (d) is filled in by additional receptors (antennas or transducers). In fact, it may be filled continuously as in the case of the lens or parabolic reflector. Ideally, one would hope this would suppress all the lobes except the central one in Figure 1b, and would enhance it. In practice, the subsidiary lobes are not easy to suppress completely. The result is a pattern of the sort indicated in Figure 1c.

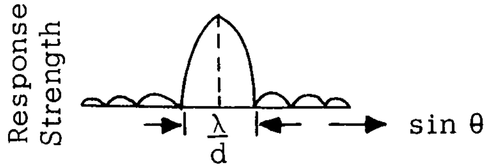
Figure 1. Antenna Pattern Principles



(a) Interferometer Geometry



(b) Interferometer Pattern



(c) Antenna or Lens Pattern
(Space filled with elements)

The minimum width of the lobe for a large antenna or interferometer is determined by the total length of the aperture. It is given approximately by

minimum lobe width for large antennas $\cong \lambda$ /length

This well known relation is extremely significant for all remote sensors and particularly so for the radar. Since the wavelengths are moderately long for radar as compared with other sensors, the aperture lengths must either be extremely long or must be fewer wavelengths long than for, say, optical sensors.

The radar measures range by comparing the received signal with the signal transmitted earlier. If the comparison is made by adjusting the delay for the preserved transmitted signal, the proper range is that for which the correlation between the received and transmitted signal is the greatest. Thus, measurement of this delay time permits determination of the range.

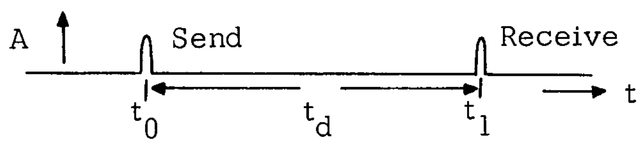
Figure 2 illustrates three techniques for measuring the range to the point target. The most commonly used radar system transmits a short pulse. The time at which the pulse is received from the remote object (target) is measured and the range determined because of the known velocity of electromagnetic waves. Figure 2(a) illustrates this. The received signal coincides in shape with the transmitted signal so the direct comparison and correlation is performed by the eye if the amplitude is presented as a function of time on an oscilloscope.

Figure 2(b) shows another range measurement technique using a frequency-modulated continuous-wave transmitter. Here the transmitted frequency is shown as a function of time along with the received frequency. At time t_o the transmitted frequency is f_{ot}. The delay time for transmission to the target and back is t_d. Thus, at t_1, f_{ot} is received. By this time, however, the transmitted signal has increased in frequency to f_{1t}. The received signal is therefore a replica of the transmitted signal delayed by an amount t_d. Although one could delay the transmitted signal in a delay line by differing amounts and determine that which gave maximum correlation, the usual practice is merely to measure the difference between the frequencies of the signal being transmitted and that being received at time t_1. Thus, the difference between frequencies transmitted at time t_o and t_1 is the same as the difference between the frequency of signals transmitted and received at time t_1, and this difference frequency can be measured to determine range.

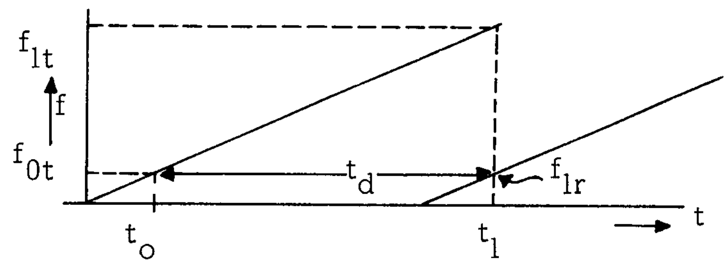
There are a number of variations for these two most commonly used systems. Another system that can be used, however, is shown in Figure 2c. Here the signal transmitted is just the carrier of the transmitter modulated (in either amplitude, phase, or frequency) by a noise signal. The received signal is a replica of the

Figure 2. Principles of Radar Range Measurement - Point Target

Compare received signal with earlier transmitted signal. When they match, time of transmission is found.



(a) Pulse



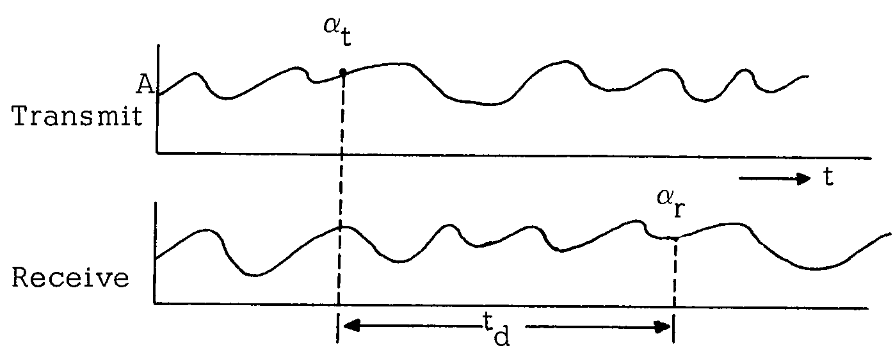
t_d Measured by $f_{1t} - f_{ot} = f_{1t} - f_{1r}$

(b) FM-CW

(c) Noise:

α_t = Arbitrary point on waveform

$ct_d = 2R$



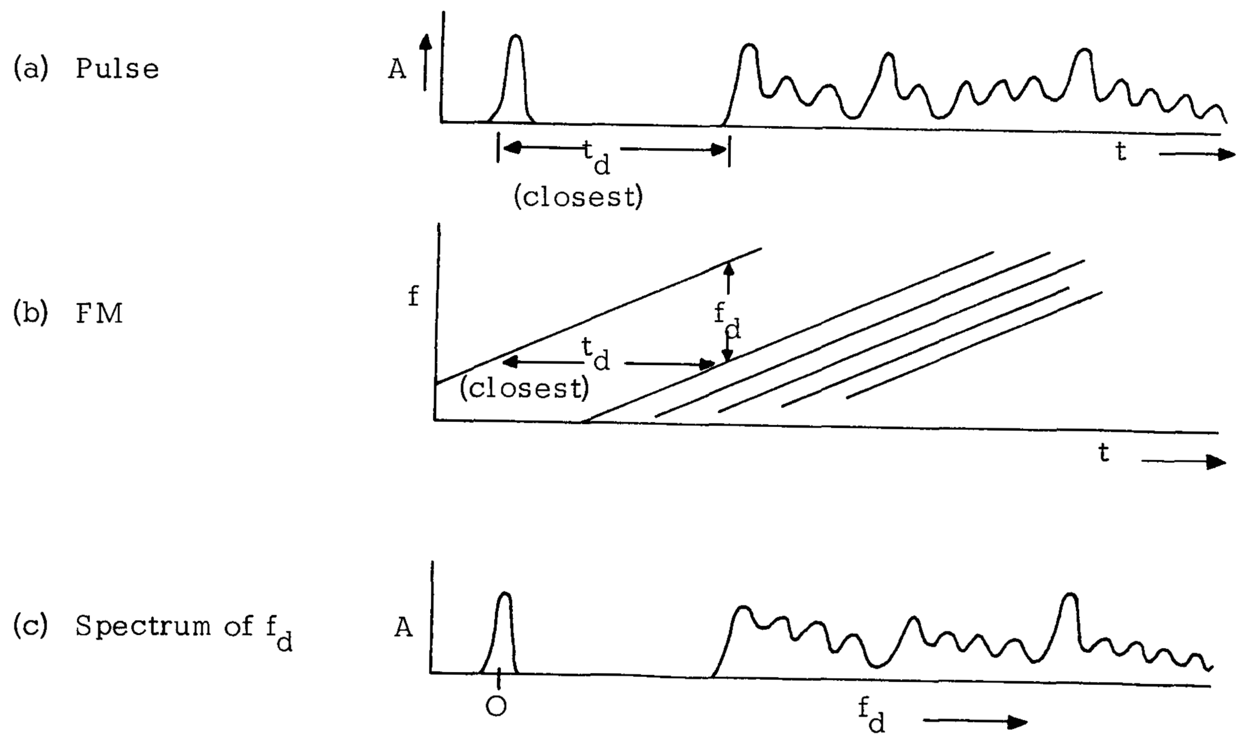
transmitted signal delayed by an amount t_d. Here one could visually match up the transmitted and received signals by simply sliding the graph of the transmitted signal along the graph of the received signal. He could also do this automatically by electronically performing a correlation with variable delay inserted in the transmitted signal replica. The delay corresponding to maximum correlation would then be established as the time delay determining the distance to the target.

The illustrations of Figure 2 were based upon a point target and most of the written material on radar is, in fact, based upon this. A terrain sensor, however, works against an extended target, so that signals are received at successive time delays from different portions of the terrain. Thus, one cannot maximize a simple correlation to determine the "range" to a target; in fact, what one must do is to establish separately the signal from each particular range. By presenting the signals at many ranges and also sweeping in angle or linearly in distance normal to the range dimension, an image can be produced. Figure 3 illustrates the signals received by the pulse and F M systems of Figure 2 from an extended target. It is difficult to show the signal received by the noise modulated system from an extended target although this does not preclude its use for extended targets.

Figure 3(a) shows the amplitude as a function of time as it would be presented on an oscilloscope if the signal from the output of a pulse radar were used to deflect the oscilloscope beam. The time corresponding to the closest target is t_d. If the radar were on the ground, of course, the closest target would be essentially on the radar because it would be the ground in the immediate vicinity of the antenna. With an airborne radar, however, the closest target (presuming the antenna permits its illumination) is the ground directly beneath. This part of Figure 3 is the same as Figure 2(a). However, as the signal passes over additional parts of the ground, additional returns are observed and this is indicated by the stretched out received pulse. Each time interval equal to the width of the transmitted pulse corresponds to signals received from a different part of the terrain. The amplitudes are different partly because the terrain properties are different and partly because fading that is caused by cancellation or addition of the returns from the components of each ground patch.

Figure 3(b) shows the frequency versus time plot of Figure 2(b); this time for an extended target. The signal received from the closest point is, of course, a replica of the transmitted signal, delayed by an amount t_d. Signals received from points further away are indicated, and these are replicas of the transmitted signal but delayed by larger times. The signal received at a particular instant contains frequencies associated with replicas of signals transmitted at a number of earlier times corresponding to the different time delays associated with the different terrain elements. Thus, a spectrum is received at a particular instant as indicated at the bottom of the figure. This spectrum in essence takes the same form as the amplitude versus time plot for the pulse system. If the sweep of the transmitted signal went on forever, the transmitted signal would appear on the difference frequency spectrum as a single line at 0. Of course, there must be a finite duration for the sweep and the effect of this is to broaden the spectrum of a line to an envelope as indicated in the diagram.

Figure 3. Radar Range Measurement - Extended Target



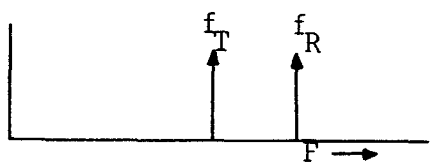
Speed measurement for a point target is quite simple. Of course, it is the relative speed, dependent on magnitude and direction of radar and target velocities. Multiple radars would be required to determine the velocity vector. Figure 4(a) illustrates what happens for a target coming toward the radar. It is assumed that a single frequency is transmitted. The signal received is shifted to a higher frequency. If the target were receding, the shift would be toward a lower frequency. Although only a single frequency is shown, in fact, the same shift occurs for all components of the transmitted signal. A second order effect is present such that lower frequency components are shifted a smaller amount than higher frequency components, but this may often be neglected.

For an airborne radar used against an area-extensive target, a multiplicity of Doppler frequencies is present because the relative velocity between the carrier of the radar and the different points on the ground depends upon the angles between the radar velocity vector and a line joining the point observed with the radar. Thus, the line spectrum indicated in Figure 4(a) becomes a distributed spectrum as in 4(b), where the higher frequencies correspond to points for which the relative velocity is higher. The maximum relative velocity occurs along the flight track at the horizon. The relative velocity is 0 to both sides and negative behind the vehicle. Thus, the spectrum shown in Figure 4(b) corresponds to an antenna illuminating an area ahead of the radar since neither the 0 frequency corresponding to the side or the negative frequencies corresponding to the rear are present.

Figure 4. Radar Velocity Measurement

(a) Single Target:

A(f)



f_T Transmitted

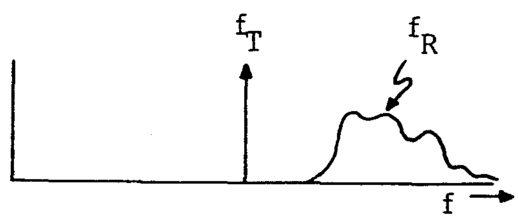
f_R Received

$f_R - f_T$ = Doppler Shift

Relative Velocity Toward Radar Makes $f_R > f_T$

(b) Extended Target:

A(f)



Signals simultaneously received from object with differing relative velocities toward radar.

The use of radar for angle, range, and velocity measurement has been summarized. The width of the lobe used for angular measurement is determined by the length of the aperture, with a larger aperture being required for a smaller lobe. Resolution in range may be improved by shortening the transmitted pulse or widening the F M sweep width or noise bandwidth. Thus, a fine range-resolution system corresponds with a large bandwidth and a coarse range-resolution system with a small bandwidth. Fine resolution in velocity however, corresponds with a narrow bandwidth.

Resolution

The term resolution is widely used in discussion of remote sensors. The correct definition and the usage are not necessarily the same. In fact, it is often difficult to make a correct definition of general applicability.

Figure 5 illustrates one definition for resolution. If two objects giving signals of equal intensity are sensed by a radar or other remote sensor as a single object, their spacing is less than the resolution distance. If the same two objects are sensed separately, their spacing is equal to or greater than the resolution distance. Usually, when two adjacent objects present signals of different intensity, they must be further apart in order that the small one can show up as distinct from the large one. Thus, the concept of resolution distance is not an easy one to apply to natural surfaces for which some pairs of objects may be of equal intensity but others may be of greatly different intensity.

Figure 5. Definition of Resolution

D = resolution distance

```
   o    o
|----D----|                 o |------D------| o

Appear as one object          Appear as two objects
```

In imaging radar, the term resolution is often loosely used to mean distinguishable spot size as calculated on some arbitrary basis such as a contour of half-power illumination, determined by the half-power width of the antenna pattern and the half-power width of the pulse, or perhaps that of a Doppler or FM filter. This quantity is certainly related to the resolution distance and is of the same order of magnitude, but it is not necessarily equal to the resolution distance. Nevertheless, it is much more commonly used than the properly defined resolution distance.

A distinction should be made between resolution, detectability, and precision. It may not be possible to resolve two objects a hundred feet apart. Yet, one of the objects may be detectable even though it is only a foot across. Thus, the fact that an object is smaller than the resolution distance does not mean it goes undetected. For example, a metal fence post may be resonant to the wavelength of the radar. If so, and if the illumination is at the correct angle, the fence post will show up clearly but one will not be able to distinguish between fence posts spaced so closely that they are within the resolution distance.

With an infinite signal-to-noise ratio, range can in theory be measured to any desired degree of precision, independent of bandwidth. Thus, a radar with a resolution distance of 100 ft. could, in theory at least, measure the range from the radar to the target to a precision of one foot. This is not especially important for imaging systems but altimeters frequently have a precision of measurement much finer than their range resolution. Thus, a one microsecond pulse altimeter would have a range resolution of about 150 meters; however, it could be expected to measure altitude over a flat area to a precision of a few meters. In theory, it could even measure to a precision of a few centimeters, although achieving this in practice would be extremely difficult.

Passive sensors must achieve all their resolution by angular measurements. The radar, in addition to angle measurement capability, has both range and velocity measurement capabilities. Figure 6 illustrates this. A passive system, or a radar system using continuous transmission with no modulation and no relative velocity, depends upon angular resolution set by the antenna beam as shown in Figure 6(a). Since a narrow beam is required for a small resolvable area, a large antenna must be used for the longer wavelengths. An antenna to achieve a small resolvable area at any significant distance becomes very large indeed.

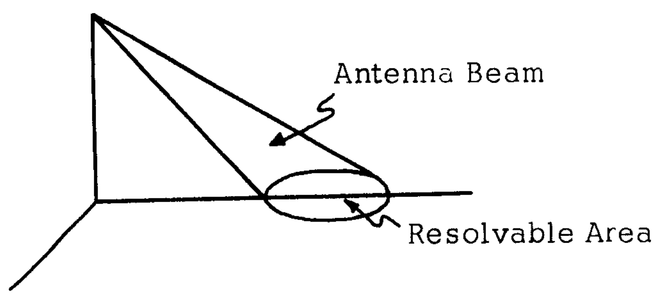
With a pulse radar system resolution may be achieved in range even if the antenna radiates isotropically. Figure 6(b) shows this. If the pulse duration is t, the signal energy received during any time interval of duration t has to be back-scattered from the region between two concentric spheres a distance ct/2 apart as shown by the figure. When these spheres contact a surface, they outline the scattering region contributing at a particular delay time. For a plane surface or spherical surface, (as illustrated) the resolvable area is, therefore, a ring between the concentric circles formed by intersections of the spheres with the surface. Any of the other systems for discriminating radar range achieves the same sort of resolvable areas. Practical applications of this wide-beam system are to radar altimeters whose antenna beam must be wide to accomodate motions of the vehicle and to planetary radars whose antenna beam cannot be confined to a solid angle as small as that occupied by the planet. Most but not all of the lunar experiments fall in this category.

A radar can combine the angle discrimination with the range discrimination to get a smaller resolvable area as indicated in Figure 6(c). Thus, with a narrow beam and a narrow pulse a resolvable region can be established that is approximately rectangular. This technique is ordinarily used in radar systems for looking at the ground. A similar technique is used for radar systems that look at objects in space. In that case, however, resolution in angle is two-dimensional with the third space dimension being provided by the range resolution.

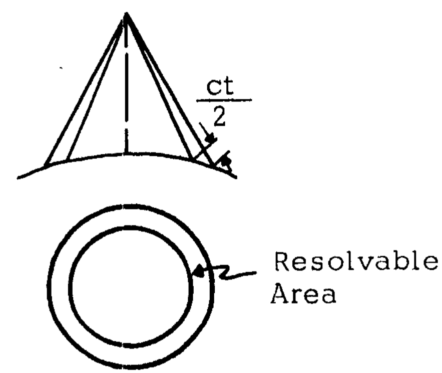
Resolvable areas may also be reduced by combining range resolution and velocity resolution as indicated in Figure 6(d). This technique has been used for studying the moon and extremely small (relatively speaking) resolvable areas on the moon have been established in this manner, even though the antenna beams are relatively large. Shown in Figure 6(d) are the concentric circles defining the resolvable area set by pulse duration and the adjacent constant-relative-velocity hyperbolas for radar motion parallel to the surface. Since each relative velocity is associated with a given frequency, all signals lying between the two Doppler frequencies defined by the hyperbolas may be passed by a filter, and only those components present at the appropriate time corresponding with the pulse length need by examined; thus the small resolvable areas. There is an ambiguity indicated because of the dual intersections of a constant Doppler line and a constant range line. Moderate antenna directivity can be used to eliminate this ambiguity. In the lunar experiment, the relative

Figure 6. Radar Resolution

(a) CW System - No resolution by Modulation or Doppler (same as radiometer)

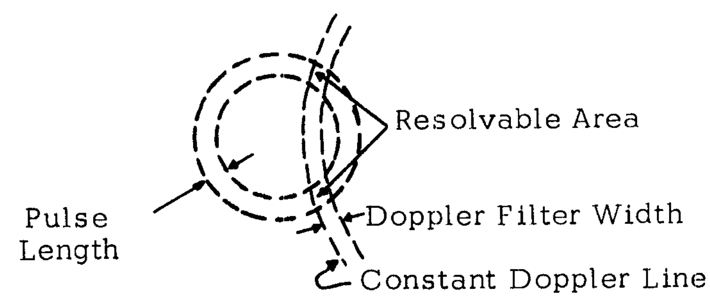


(b) Pulse System - Isotropic Antenna (Radar altimeter or planetary radar with beam wider than planet)



(c) Combination - Narrow Beam and Narrow Pulse

(d) Combination - Narrow Pulse and Doppler Filter (Evans and Pettengill lunar work)



velocity is determined by the libration of the moon about its axis. Thus, the lines of constant Doppler frequency are straight lines parallel to the axis in this plot rather than hyperbolas that are appropriate for linear motion over a plane.

The numerous possibilities inherent in combination of angular resolution, range resolution, and velocity resolution make the radar more versatile as a sensor than other sensors that must depend strictly upon angular resolution.

Unfortunately, because of the long wavelength customarily used, radar angular resolution is poorer than that of optical and infra-red sensors. A considerable improvement can be achieved by the use the synthetic aperture technique so that effective antenna size is greatly increased over that physically realizable in a structure.

The principles of a synthetic aperture system are moderately simple; the implementation is not. Consider the seven element linear antenna array in Figure 7. The total aperture occupied is d; so, as indicated above, the beam width is approximately λ/d. If we use the array for receiving, we arrange to add all the voltages (or currents) at some point that is the input to the receiver. The usual broadside array (one whose maximum reception is from a direction normal to the line of the array) adds all of these signals in phase. In order to do this, the path length from each of the elements to the feed point must be the same length so that the shift due to traveling along different distances will not appear. This can be achieved as shown in Figure 7, by making all the feed lines of equal length; but it can also be achieved, and usually is, by adjusting their length to be equal except for an integral number of wavelengths. That is, the shorter lines are 1, 2, 3, or more wavelengths shorter than the longest one. Since the phase is the same for lines differing in length by an integer number of wavelengths, the effect is the same as that illustrated in Figure 7(b). The only problem is that such an array works only at a particular wavelength because the extra phase shifts inserted are different than 2π radians at any wavelength other than that for which the array was designed.

The voltage received at the output of the addition point is given by

$$V = V_1 + V_2 + \dots V_7$$

If the signal arriving is of the same amplitude at all elements of the array, the sum performed at the addition point can be expressed as

$$V = V_o \left[e^{i\phi_1} + e^{i\phi_2} + \ldots . e^{i\phi_7} \right].$$

The maximum voltage occurs when all the phase angles are the same; that is

$\phi_i = \phi_o$, so that

$$V = 7\, V_o e^{i\phi_o} .$$

At any angle other than normal to the line of the array, the phases received at the different elements are different because of the difference in path length indicated in Figure 1 (a). Thus, the maximum is normal to the line of the array ("broadside"). If the elements are not spaced closely enough, there are other maxima of significant size as in an interferometer. If, however, they are spaced closely enough, these do not occur and a single major lobe as indicated in Figure 1 (c) is the result, with the side lobes greatly reduced in amplitude. This is the desirable condition.

With the physical array, the summations occur simultaneously as indicated in Figures 7 (b) and (c). With the synthetic array, a single real antenna is successively placed at the different positions of array elements. At each position, the signal is received and stored complete with phase information. The signals could, for example, be stored in a digital computer memory; they could be stored on a storage tube, in a delay line, or on film. Regardless of the method of storage, processing the signals consists of calling them out of storage and adding them all together in such a way that phase is important. Thus, the signals received at each element from a source broadside to the array add together in phase whereas the signals that were received from some other direction will partially cancel because of their differing phases. Hence the greatest contribution to the output of the adder is from the broadside source. Relative contributions from other directions may be determined by computing the array pattern in the normal way.

By use of the synthetic array, therefore, a relatively small physical antenna has been transported to enough positions so that the total aperture length, d, is big enough to cause a very narrow antenna beam as compared with what could be achieved reasonably with a physical antenna.

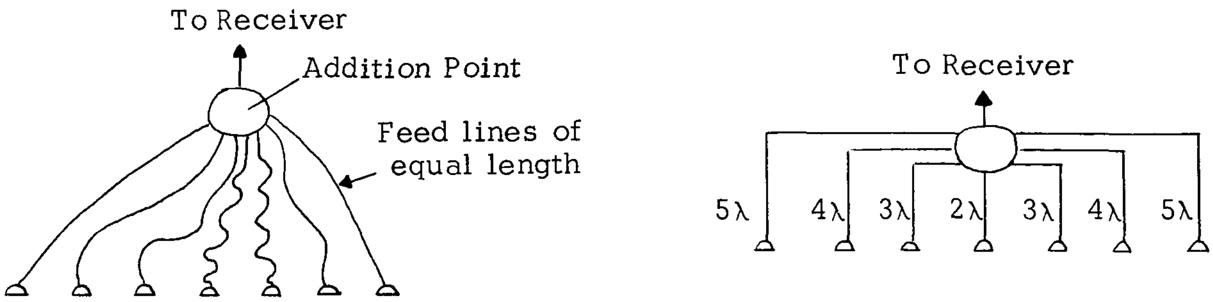
Figure 7. Linear Array Principles

|---------d---------|

x x x x x x x

1 2 3 4 5 6 7

(a) Element location



(b) Equal length feed lines

(c) Equivalent phase-shift feed lines example

The synthetic array description given above is correct when the length of the array is sufficiently short compared with the distance to the target (or source) that the difference between the distance from the target to the center of the array and that from the target to the end of the array is a small fraction of a wavelength. When this condition is satisfied, the rays may be considered parallel for all practical purposes. In antenna theory, this is known as the Fraunhofer region. When the rays may not be considered parallel because this difference in distance is significant compared with the wavelength, it is necessary to focus the antenna. The source is then said to be in the Fresnel region. This situation is illustrated in Figure 8.

If the array had its elements along a circle instead of along a straight line, the distance from each element to the center of the circle would be the same so the phase shift would be the same. The signals would all add up in phase if they came from the center of the circle but would add up in some other way with some cancellation if they came from another point. Thus, to focus on a particular point, one should fly a circle about that point, store the signals received at the various locations, and add them up to obtain the net array output. Unfortunately, flying in such a circle is not convenient, especially since a different radius is required for each focal point.

The focused synthetic array solves this problem by inserting corrective phase shift for each element so that the effective flight path is the indicated circle even though the actual flight path is a straight line. Figure 8 shows this; here the phase shift due to the normal distance, is $2\pi R/\lambda$. The additional phase shift at array element number 1 is $2\pi \delta_1/\lambda$. In processing, this extra phase lag is compensated with a leading phase correction so that the signal presented to the adder has the phase $2\pi R/\lambda$. The appropriate correction is made for each element in the array so that the signals added together are in phase just as they would be in a linear array with a target far enough away so that the distances to the various elements could be considered equal.

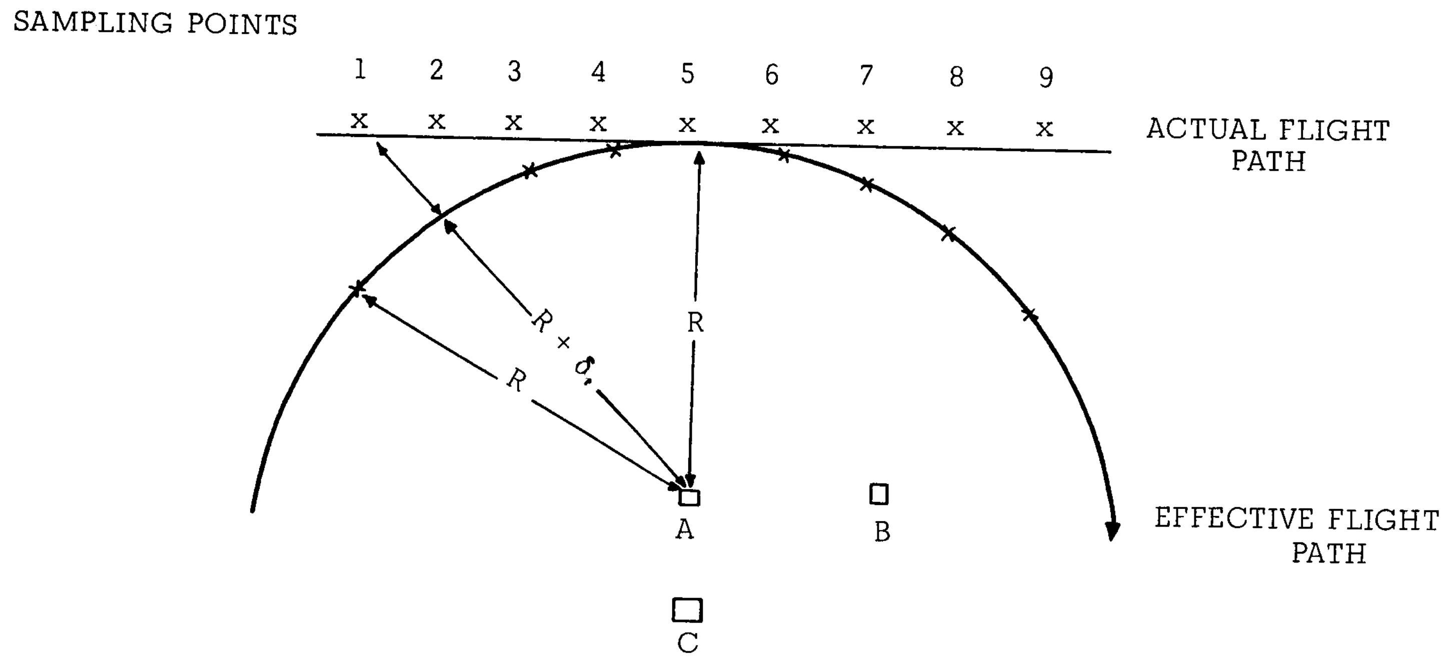
Array element number 5 in Figure 8 requires no correction for target element A. Target element B is in a comparable position for array element number 7 so that to observe target element B no correction is applied to array element number 7 but a phase correction is applied to number 5; this correction being the same as that applied to element number 3 when looking at target element A. Since the information is stored in the memory without correction, the signal associated with each array element may be used for looking at many different targets by applying a different phase correction for each target.

Target element C also requires no correction for array element 5. However, the corrections necessary for the other elements are not the same as those at target element A. The effective flight path circle for a focused array has a different radius; hence, a different correction is applied to each element for focusing on target element C than that on target element A or that on target element B.

Numerous schemes have been developed for applying the corrections and focusing the synthetic aperture array for different target elements at different ranges. The techniques themselves are not discussed here; it is sufficient to note several are indeed practical.

Use of synthetic arrays makes it possible to achieve extremely good resolutions from long distances, such as the distance from a spacecraft to the ground, without using the physical antennas that would be required. In theory, the focused synthetic array has a minimum resolution distance equal to half the length of the physical aperture used for each element in the array. Since this is independent of range the resolvable patch for the synthetic aperture system is the same size regardless of the distance from the target to the radar.

Figure 8. Focussed Synthetic Array Principle



PHASE SHIFT DUE TO NORMAL DISTANCE = $\frac{2\pi R}{\lambda}$

CORRECT PHASE OF ANTENNA 1 BY $\frac{2\pi\delta_1}{\lambda}$

BY CORRECTING SEPARATELY FOR EACH R, SIMULTANEOUS FOCUS ACHIEVED AT ALL RANGES

This is achieved by using longer and longer focused arrays as the range is increased. If the actual length of the synthetic array were to be kept constant as the distance varied, the resolution would correspond to a constant angular increment and the resolvable patch would increase linearly with distance.

These comments refer to the resolution in the direction along the flight path. This is determined by the angular resolution of the array. The resolution for the radar perpendicular to the flight path is determined by the pulse duration or other ranging technique.

Radar Presentations

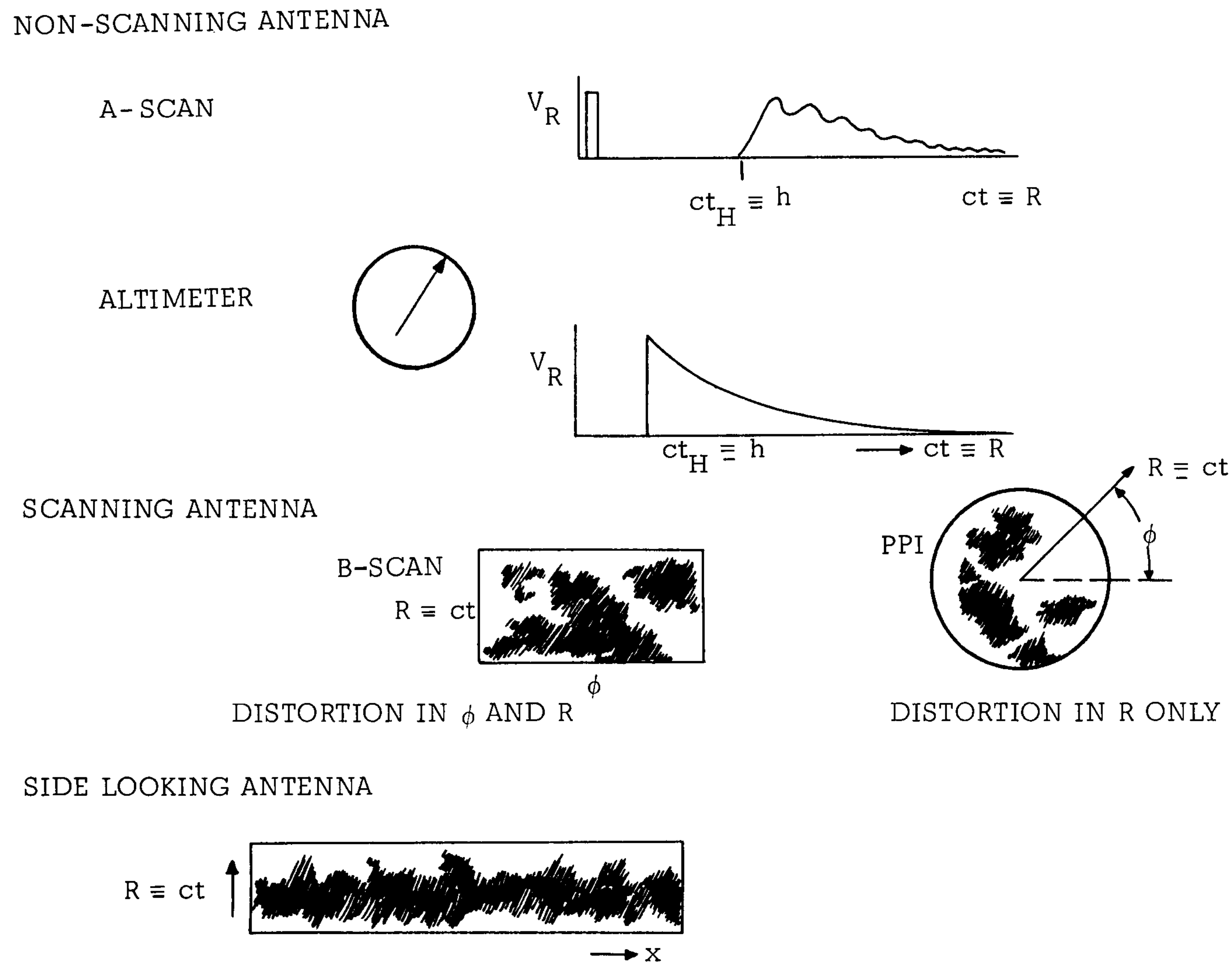
Many types of presentation have been developed for radar systems. Some of these are particularly appropriate to special purposes such as airport landing systems, or mapping radars.

Figure 9 shows some of the more common radar presentations. Probably the earliest one is a simple oscilloscope picture of received voltage versus time, and consequently versus range. This is called the A-scan. One of the earliest presentations for radar altimetry is simply in the form of a meter indicating altitude. Meters indicating speed are also common.

A variation of the A-scan is frequently used in discussing radar astronomy data and in radar system design. In this presentation, an average of received power is presented as a function of delay time, with the graph representing the average of many pulses received at different times whose typical shape might be more like that shown for the A-scan.

Two mapping presentations for rotating antennas were developed early in World War II. The B-scan is used with an antenna scanning a limited sector ahead of the vehicle using it. The coordinates are range (as represented by time delay) and angle. The signal strength is presented as light intensity on the cathode ray tube. The B-scan is a distorted map because the distances corresponding to a given change in angle are function of range. Hence the PPI (Plan Position Indicator) was developed. The PPI presents a true map for radars on the ground. Airborne radars using a PPI have a distortion because the time sweep from the center of the tube to the outer edge is proportional to slant range rather than to ground range. Sometimes a compensating electronic circuit is used so that this sweep is non-linear in time but linear in ground range. As the antenna sweeps around a complete circle, the scan follows it

Figure 9. Radar Displays



so that the map is then painted on the cathode ray tube. Long persistence phosphors must be used on B-scan and PPI displays because of the relatively slow motion of any feasible antenna system.

The highest resolution airborne systems use a fixed side-looking antenna or a synthetic aperture (equivalent to a longer side-looking physical antenna). The presentation commonly used for these, at least for recording and later viewing, is one in which the sweep across a cathode ray tube is intensity modulated by the signal but is always on the same line (at the center of the tube); thus, rather than scanning an area as with television, a single line is scanned. The other dimension in the map is achieved by moving a film past this line in synchronism with the motion of the vehicle. Thus, the first sweep appears as a line on the film. When the second sweep comes along, the film has advanced so it appears as a different parallel line on the film. In this way a map-like image is produced.

Elements of Radar Theory

This section provides a brief resumé of the types of theory used to describe radar return and some of the results of use of these theories.

The relations between parameters effecting a radar system are best seen in the "radar equation". The properties of the target itself are given in terms of a scattering cross section (σ). All other parameters in the equation are associated with either the radar or the geometry.

The radar equation for a point target and a bistatic system (transmitter and receiver at different places) is given in Eq. 1.

$$W_R = \left(\frac{W_T G_T}{4\pi R_T^2} \right) \sigma \left(\frac{1}{4\pi R_R^2} \right) \left(\frac{G_R \lambda^2}{4\pi} \right) \qquad (1)$$

Here W_R = received power

W_T = transmitted power

G_T = gain of the transmitting antenna

R_T = distance from the transmitter to the target

σ = scattering cross-section per unit solid angle toward the receiver for the target

G_R = gain of the receiving antenna

R_R = distance from the target to the receiving antenna

λ = wavelength

Here

$\left(\frac{W_T G_T}{4\pi R_T^2}\right)$ = power density in watts per square meter at the target due to the radar transmitter. Multiplying this by σ gives the strength of the equivalent source for re-radiation toward the receiver. Thus, we may think of this product as the strength of a transmitter located at the target and illuminating the receiver.

$\left(\frac{1}{4\pi R_R^2}\right)$ is the factor associated with spreading of the re-radiated signal.

The product of $\left(\frac{W_T G_T}{4\pi R_T^2}\right)\sigma$ and $\left(\frac{1}{4\pi R_R^2}\right)$ is the power per unit area at the receiver.

$\left(\frac{G_R \lambda^2}{4\pi}\right)$ = equivalent area of the receiving antenna. Multiplying this by power per unit area gives the total received power.

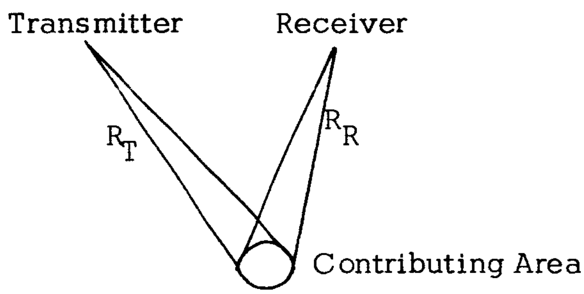
Eq. 1 is the defining equation for σ. One could describe σ in terms of the receiving capability of the target, the amount of energy absorbed, and the transmitting capability in the direction of the receiver. However, the definition is established using eq. (1) without any concern for these factors that go to make up the value for σ. Thus, a measurement of the known parameters in Eq. 1 permits establishing σ for a given target without any knowledge of the individual factors. Of course, theoretical analyses must consider the various contributions of absorption and receiving and transmitting directivity.

Figure 10 shows the situation when an area target rather than a point target is illuminated. The power received from an incremental area ΔA is given by Eq. (2).

$$W_R = \frac{\lambda^2}{(4\pi)^3} \frac{W_T G_T G_R}{R_T^2 R_R^2} (\sigma_o \Delta A) \tag{2}$$

Here the cross-section of the incremental area is described in terms of an average cross-section per unit area σ_o multiplied by the area itself. This mean differential scattering cross-section is a very useful descriptor for radar return from the ground. Its use presumes that the ground return is due to a significant number of independent contributors having random relative phases so that power superposition may be used. The concept would not apply, for example, to reflection from a perfectly smooth plane, where one would have to use voltage superposition rather than power superposition, because phases are not random.

Figure 10. Radar Equation Geometry



The differential scattering cross section σ_o is the scattering cross-section per unit target area per unit solid angle in the direction of the receiver. It is determined not only by the properties of the target itself, but by the angle with which the target is illuminated and the angle to the receiver, as well as by the polarization and wavelength of the incident radiation, as was indicated in Table 4.

If the illuminated area is sufficiently large that either the type of terrain illuminated is diverse or some of the parameters associated with the radar and the geometry may vary, a summation must be performed over the various elemental areas. The usual procedure is to pass to the limit in Eq. (2) and replace the sum by the integral

$$W_R = \frac{\lambda^2}{(4\pi)^3} \int \frac{W_T G_T G_R}{R_T^{\,2} R_R^{\,2}} \sigma_o \, dA \qquad (3)$$

Strictly speaking, this integral is not correct because the concept of average scattering cross-section assumes an area element large enough to contain several scatterers so that a vanishingly small differential area element would not fit the concept. Nevertheless, the results obtained by evaluating the integral can be shown to be equivalent to those that would be obtained by summation, because of the fact that σ_o is, indeed, an average.

The usual radar is a monostatic one, for which transmitter and receiver are at the same location and use either the same or identical antennas. For this situation Eq. (3) becomes

$$W_R = \frac{\lambda^2}{(4\pi)^3} \int \frac{W_T G_T G_R}{R^4} \sigma_o \, dA \tag{4}$$

Although a curve of σ_o vs. angle of incidence is a smooth curve, and the mean power calculated by Eqs. 2 through 4 for a pulse spreading out on the ground varies smoothly, in fact, the instantaneous signal received at any particular point from any particular part of the ground can only be described statistically for it is subject to extreme fading. A common way to describe this fading is in terms of its noise-like character; that is, any particular surface illuminated area contains a number of facets contributing to the received signal. Since these are at slightly different angles with respect to the velocity vector of the radar-carrying vehicle, the relative velocities and consequently Doppler frequencies are different. Hence, as far as the receiver is concerned, the ground may be considered a source containing a number of more or less randomly phased oscillators at slightly different frequencies. Since this is just one of the models for random noise the statistics of random noise are also statistics of the fading, with the bandwidth for the fading being determined by maximum difference in Doppler frequency between objects within the illuminated area.

The reason this fading occurs is that the signals from the various facets add in phase at some times and out of phase at other times. The same phenomenon occurs if one moves in space irregularly rather than at a constant velocity, although in this case the model based on oscillators at different frequencies does not apply. At any particular point in space, the distances to the various facets within an illuminated patch are fixed so that the relative phase shift between them is also fixed and the phasor sum of the fields received at the antenna from these facets is fixed. When one moves to a different point the relative distances, and consequently the relative phases, have changed so the phasor sum is different. Since this is just the process by which an antenna pattern is built up, it is apparent that each scattering region on the ground has an antenna pattern and that the fading described by the Doppler model merely represents motion through this "antenna pattern".

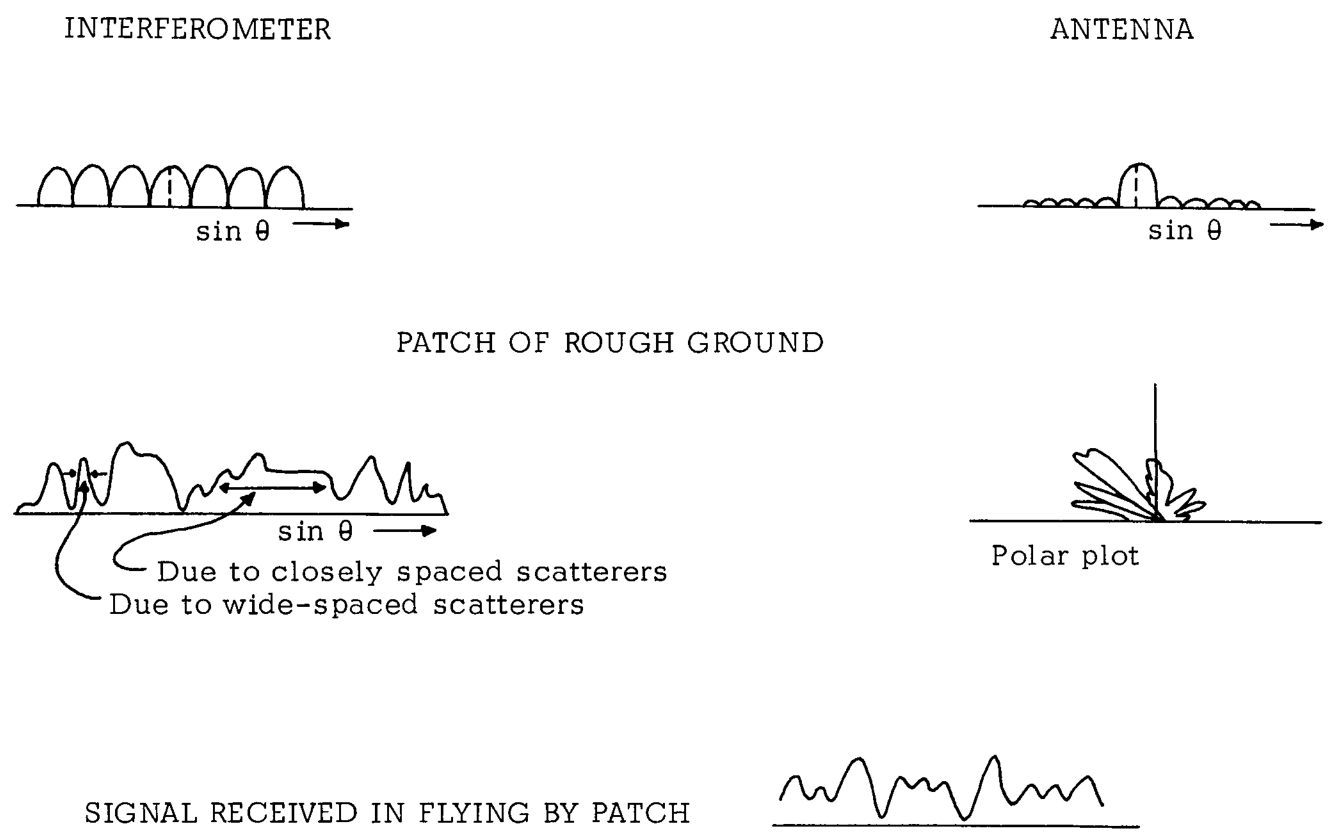
Figure 11 illustrates the way in which such an antenna pattern is generated and compares the patterns from Figure 1(b) and (c) with the pattern that might occur from a patch of rough ground. Note that fine structure in the pattern must be due to contributions from facets far apart and coarse structure could be due to contribution from closely spaced facets. The fading signal obtained by flying through such a pattern is indicated also on the figure.

Most radar scattering theories start with a model of a perfectly conducting rough surface. The situation for this model is determined and the effect of finite or zero conductivity is then introduced. In some theories, however, this effect has been introduced at the beginning. Numerous approaches have been used to determining the scattering coefficient for surfaces described by mathematical models. The most common methods are based upon the Kirchhoff-Huyghens principle, and upon the use of geometric optics with slope distributions. An extensive series of interesting papers uses surface models made up of random hemispherical or hemicylindrical bosses on a plane.

The earliest models presumed to apply to radar scatter were based on Lambert's Law of optics. For this model the scattering coefficient is proportional to the cosine of the angle of incidence. This is equivalent to saying that the surface is made up of a number of isotropic scatterers. The cosine is due to the fact that a given illuminated element size <u>on the surface</u> corresponds with a smaller <u>projected area</u> as the angle of incidence increases, and the illumination is constant for a given projected area, not for a given surface area. It was soon realized that at radar wavelengths very few surfaces are sufficiently rough that the scattering comes anywhere close to Lambert's Law.

The Kirchhoff-Huyghens approach postulates that the surface currents can be determined from the incident fields. Small elements of the surface then re-radiate as "Huyghens sources". The received field is the superposition of the fields from all of the Huyghens sources. Since each Huyghens source is located at a point on the rough surface, whose distance to the radar differs from the corresponding distance for a point on the average (smooth) surface, its signal experiences a phase shift different from the one that would occur for a smooth surface. The smooth surface would merely give the Fresnel reflected wave that is calculated in all books on electromagnetic theory as the plane wave

Figure 11. Scatter Pattern for Patch of Rough Surface



reflection. The rough surface on the other hand gives quite a different phasor combination because of these different phase shifts associated with the different Huyghens sources.

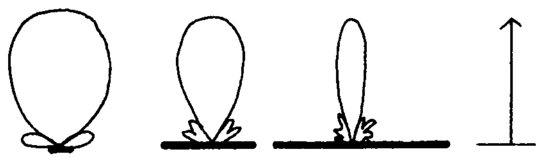
Some of the theories have been developed for sinusoidal surfaces. Because of the regularity of variations of these surfaces the scatter pattern also contains regularly spaced "interferometer lobes". Since natural surfaces are not regular, it is customary to describe them statistically. A proper description can be obtained by the use of a two-dimensional probability density function describing the probability that a certain point is at a certain height and another nearby point is at a different certain height, as a function of their difference in location. Fortunately, this two-dimensional probability distribution is not really needed, for the theory reduces the need to that for a two-dimensional autocorrelation (autocovariance) function and a variance for the height above the mean surface, at least if the assumption of a Gaussian distribution of heights is made. Most treatments further simplify the problem by assuming that the autocorrelation function is independent of direction although this certainly is not justified for many natural surfaces.

This formulation gives the fields in terms of a complex integral involving the correlation function. This integral has been evaluated for some simple correlation functions, but little attempt has been made to evaluate for correlation functions associated with natural terrain. Hayre showed that contour maps often yield an exponential correlation function for which the integrals can be evaluated. Unfortunately, interesting parts of the scattering coefficient curve depend upon information much finer than that usually obtainable from contour maps so validity of this type of correlation function over the entire range is not known.

The Kirchhoff-Huyghens formulation depends upon the assumption that the currents flowing in the surface are those that would flow in a comparable plane surface; that is, the boundary conditions for the plane surface are used to determine the currents. This is a reasonable assumption provided the radius of curvature for elements on the surface is not too small compared with the wavelength. When some the radii of curvature are small, the normal practice is to use a superposition of a Lambert Law type scatter with that obtained by applying the Kirchhoff-Huyghens approach to the portions of the surface having larger radius of curvature.

Another fairly common approach describes the surface in terms of facets having different slopes, with distributions specified for the size and slope of the facets. Figure 12 illustrates the patterns one might expect from facets of different sizes. The narrow pattern goes with the facet large in terms of the wavelength and the wide pattern with the facet small in terms of the wavelength. Most of the theoretical treatments based on facet distributions assume that all facets are large enough so the pattern may be assumed to be a narrow spike; that is, the signal from the facet is present only when the angle of reflection equals the angle of incidence and at no other angle. As Figure 12 indicates, this is not true for a finite sized facet and would only apply to an infinite sized facet. Another way to think of this is that it applies only to the zero-wavelength case; hence, it is frequently called the "geometrical optics" method. Intrinsically, this method presents more opportunity than others for relation between the physical and mathematical models, but few treatments have really considered the finite sized facet.

Figure 12. Facet Patterns
(Uniform normally incident illumination)



Infinite plane pattern

Unfortunately, natural surfaces do not join air or space with a semi-infinite medium as all the theories assume. To date, very little work has been done that considers the effect of penetration into a surface that may consist of multiple layers and also include discrete scatterers within the volume between the interfaces.

Regardless of the particular theoretical approach or surface model used, all the scattering theories agree:

1. Returns near the vertical are due to large structures, and
2. Returns near grazing angles are due to smaller structures.

Some theories state the scattering is independent of wavelength but most define "larger" and "smaller" in terms of wavelength units.

The effect of dielectric properties of the surface is to reduce the current flowing in the surface and consequently reduce the return signals. Since boundary conditions associated with Fresnel reflection coefficients are a function of angle, the dielectric properties not only affect the strength of the scattering coefficient but also its angular variation. This also means that horizontal and vertical polarization will have different scattering properties because of the difference in the reflection coefficients. Of course, there may also be differences between polarizations for geometric reasons.

The theories lead to a better understanding of the experimental results. However, a mathematical model that is truly adequate to describe most natural surfaces is not feasible; an exception may be the surface of the ocean. Hence, it is necessary to make empirical measurements of scattering coefficients and not depend upon the theory except as a means to determine the best experiments and to understand the experiments. Once experiments have verified a particular theoretical conclusion, of course, the theory can then be used to extrapolate to other situations.

Radar Measurements

Numerous measurements of radar cross-section versus angle at frequencies all the way from 30 Mc to 35 gc have been made in the past 25 years. Most of the measurement programs have been aimed at specific design objectives or the flight programs have been rather brief so that the results are not of general applicability. Thus, today we still find a lack of good scattering coefficient-versus-angle data for carefully defined surfaces of the size illuminated by airborne radars.

The difficulty of making bistatic radar measurements with aircraft has made such measurements extremely rare and incomplete. Bistatic measurements under controlled conditions of ultrasonic wave scatter from known surfaces have been made (Parkins 1965). No electromagnetic bistatic omnidirectional scatter measurements covering the complete range of angles is known.

Table 6 summarizes measurements made at angles of incidence appropriate to airborne and spaceborne radar systems. No attempt has been made to cover measurements more suitable for ground based systems. A continuing bibliography of radar theory and measurements with emphasis on ground based systems is maintained by Georgia Institute of Technology (Corriher and Pyron, 1965). Table 6 does not attempt to be complete and mentions only a few of the major programs.

Extremely careful measurements over known surfaces have been made by Ohio State University (Cosgriff, Peake, and Taylor, 1960) and U.S. Army Waterways Experiment Station (Lundien, 1965). The Ohio State measurements have been

TABLE 6

RADAR CROSS-SECTION MEASUREMENTS - BACKSCATTER

EARTH-SHORT RANGE		OHIO STATE, WATERWAYS EXPERIMENT STA.
	ADVANTAGES:	KNOWN SURFACE, UNIFORM TARGET
	DISADVANTAGES:	RESOLUTION TOO FINE TO SHOW FEATURES AS LARGE AS TREES OR LARGE SHRUBS. NO POSSIBILITY OF SHOWING EFFECTS OF LARGER STRUCTURE.
EARTH - AIRCRAFT		SANDIA-UNM (NEAR VERTICAL), NRL, GOODYEAR, TRE, GPL (NUMEROUS OTHER SMALLER EFFORTS)
	ADVANTAGES:	REALISTIC SIZE TARGETS, COMPOSITE TARGETS (LIKE NATURE) POSSIBLE.
	DISADVANTAGES:	MOST PROGRAMS LIMITED RANGE OF ANGLES. FEW PROGRAMS ATTEMPT OTHER THAN AVERAGE OVER MILES, SO IDENTIFICATION OF PROPERTIES OF SINGLE TARGET UNITS IMPOSSIBLE. MOST PROGRAMS AIMED AT ENGINEERING DESIGN LIMITS ONLY.
EARTH - ACOUSTIC SIMULATION		U OF NM, U OF KANSAS, KANSAS STATE U
	ADVANTAGES:	CONTROLLED CONDITIONS, REASONABLE SIZE OBJECTS LIKE BUILDINGS OR MOUNTAINS CAN BE SIMULATED. LOW FREQUENCY MAKES BREADBOARD TESTS EASY.
	DISADVANTAGES:	SCALAR WAVE CANNOT HANDLE POLARIZATION EFFECTS. SHEAR WAVE SET UP IN TARGET HAS DIFFERENT RESONANCES, NON-LINEAR MODELS OFTEN NECESSARY.
EARTH - SATELLITE		ALOUETTE - U. OF KANSAS, SATURN-MSFC
	DISADVANTAGES:	FREQUENCY LOW FOR COMPARISON (ALOUETTE) PULSE LONG FOR RESOLUTION (ALOUETTE) INSTRUMENT NOT DESIGNED FOR AMPLITUDE MEASUREMENT. VIDEO SIGNAL NOT AVAILABLE (SATURN)
MOON -		LINCOLN LAB, JPL, MANY OTHERS
	ADVANTAGE:	DATA BETTER THAN AIRCRAFT DATA BECAUSE OF LONG TIME OF OBSERVATION
	DISADVANTAGE:	POOR RESOLUTION, σ_0 VS θ CURVE TAKES EACH θ POINT FROM DIFFERENT REGION, NO KNOWLEDGE OF PENETRATION
VENUS -		LINCOLN LAB, JPL, OTHERS
	DISADVANTAGE:	POOR RESOLUTION AND LOW SIGNAL LEVEL CAUSE DIFFICULTY.

made at a wide range of wavelengths with both vertical and horizontal polarization and cross-polarization, and bistatic measurements for which the incident and scattered rays lie in the same plane have been made. Unfortunately, this precision is obtained by mounting the radar on a truck or in a fixed location so that the illuminated area is only about a foot square. Hence, most natural features are too large to be included within the area and certainly too large to be included on a statistical basis. The Waterways Experiment Station uses a fixed specially-prepared sample, but the preparation of the sample destroys many of its natural features. Furthermore, the illuminated area there is also only a few feet square so there is no possibility of showing the effects of large structures.

Numerous backscatter measurements have been made from aircraft. With aircraft it is, of course, possible to illuminate areas that are comparable in size with the areas used operationally. Some of the experiments, notably that of Sandia Corporation, attempted to get truly homogeneous terrains within the illuminated area, but most use composite natural targets. Unfortunately, few of the programs have attempted to identify the scattering curve with a unit as small as a single field or patch of trees or block of houses. Such identification was made when possible in the Sandia Corporation program in which the data were analyzed at the University of New Mexico, but these data are only valid out to about 20° from the vertical (Edison, Moore, and Warner, 1960). The measurements by the U.S. Naval Research Laboratory have been conducted over many years (see for example, Ament, Macdonald and Shewbridge, 1959) with a variety of frequencies and polarizations. Only a few of the measurements were made near vertical incidence, and at all angles averages have been made over wide expanses of terrain containing many different targets only loosely classified together under such headings as farmland, New Mexico desert, or city of Chicago. Similarly, many measurements have been made over the sea but the difficulty of getting adequate sea-state measurements to correlate with radar measurements makes interpretation of the results difficult. A joint program currently underway, involving U. S. Naval Research Laboratory and Johns Hopkins University Applied Physics Laboratory, is making stereo photographs of the sea surface at the same time the radar flies over it. Goodyear Aircraft used a side-looking radar (Reitz, 1959) to obtain measurements of scattering coefficient by carefully calibrating the film intensities. Unfortunately, each particular element of terrain is only illuminated at a single angle in this type of measurements, so generation of a scattering-coefficient-versus-angle curve must assume that two different target elements belong to the same class. The returns from the two elements are then combined to present two points on a curve. Furthermore, the range of angles was limited, as it was not possible to get all the way to the vertical with the system used.

Since many of the programs identified had as their aim determination of engineering design limits, they did, in fact, achieve their objectives. Unfortunately, this does not make general radar scattering cross-section curves any more available!

The use of acoustic (ultrasonic) simulation at the University of New Mexico (Edison 1960, Moore 1962) and the University of Kansas (Parkins 1965) has permitted careful measurements over areas considerably larger in terms of square wavelengths than those used by Ohio State University and U. S. Army Waterways Experiment Station. The measurements, of course, are not completely correlated with the electromagnetic measurements because the effects of polarization cannot be duplicated acoustically. These measurements have, however, been made under conditions more suitable for correlation with theory than any of the electromagnetic measurements and, in fact, some of this correlation has been successfully achieved. It is much easier, for example, to determine altitude dependence of radar scatter under the controlled conditions of the acoustic tank than under the conditions of repeated flight passes at different altitudes over what is hoped to be the same terrain. In fact, in the acoustic measurements it is possible to make a continuous traverse from high to low equivalent altitude for which an airplane would require diving! By non-linear scaling techniques the acoustic simulation also has permitted studies of lunar scatter, high altitude altimetry over mountains, and low altitude altimetry over cities. Little has been done acoustically with imaging systems other than work done in ultrasonic trainers -- and the scale factor is bad there because the time scale required for training purposes is wrong for careful experimentation.

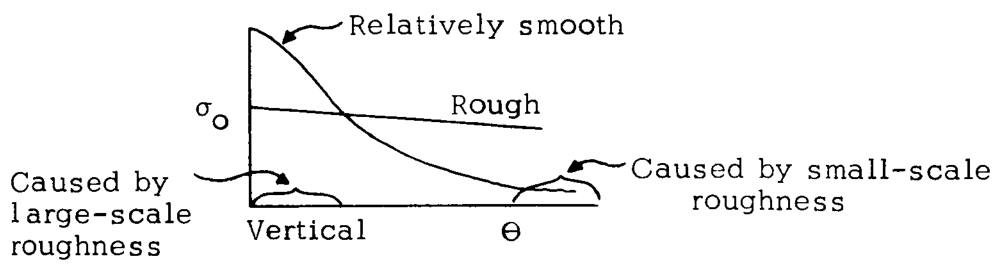
Only two measurements of radar cross section of the earth from satellite altitudes are known. One of these uses the Alouette top-side ionosphere sounder at around 30 meters wavelength (Chia, Fung, and Moore 1964). The other used the telemetry of the AGC voltage from the Saturn altimeter (Coleman, 1965). Both of these experiments suffer because the experiments were not designed to measure scattering coefficient. However, they do indicate that the extrapolation from low to high altitude is reasonable, and they give some assistance in correlating lunar and planetary echoes with earth echoes.

Many fine measurements have been made of the radar cross-section of the moon by radar astronomers at Lincoln Laboratory, Jet Propulsion Laboratory, Cornell Arecibo Laboratory, and others. Because the moon moves relatively slowly with respect to the radar telescope and because its position is accurately known, these data are in many respects better than those obtained from aircraft flying over the earth. Unfortunately, however, they suffer from the same problem that plagues the Goodyear measurements; that is, one must assume homogeniety of the surface in order to plot a curve of scattering versus angle because each point on the surface is observed only at one, or at best a relatively small set of incident angles, so the curve must be made of points obtained from many different areas on the surface. Errors in interpretation of the lunar measurements may also exist because of penetration of the radar wave through a low attenuation surface layer that is not present on the earth.

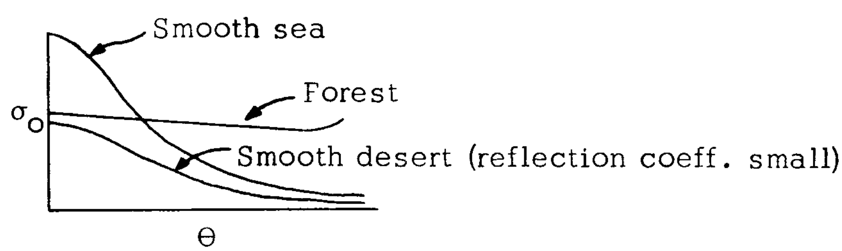
In spite of the problems of getting controlled experiments and in spite of the differences between the various theories, there are certain features that essentially all of the experiments show and that essentially all of the theories agree on. Figure 13 (a) shows the conclusions of the theories as interpreted in terms of experiment. Relatively smooth targets have values for σ_o large at the vertical but falling off rather rapidly. Rough surfaces, on the other hand, are associated with smaller values of σ_o at the vertical but less rapid fall-off; so that, in fact, well away from the vertical σ_o is larger than for the smooth surface. Furthermore, the theories are in moderate agreement that the part of the curve near the vertical is caused by roughness having a large horizontal scale and relatively small slopes whereas the part of the curve well away from the vertical is caused by roughness having a small horizontal scale and relatively steep slopes. Some sort of transition, of course, occurs between the two extremes.

Figure 13(b) shows the way this applies to experiment. A smooth sea and a smooth desert may have essentially the same surface characteristics. However, because of the smaller reflection coefficient for the desert the value of σ_o will be smaller for desert than for sea at all angles. Otherwise the shape of the curves will be the same. The curve for a forest may be somewhat above or below that for the desert at vertical incidence depending upon the density of the forest and the smoothness and dielectric properties of the desert. Although they are somewhat similar near the vertical, because the forest top is extremely rough to the radar, it will present a much larger value of σ_o for angles well away from the vertical. Cross-polarized signals are likely to be stronger when steep slopes are present, as in extremely rough surfaces. The difference between vertical and horizontal polarization is not so well documented quantitatively, but all of the experiments involving both show that the variation with angle is different for the two polarizations and that the relation between these variations is a function of the terrain type encountered.

Figure 13. Conclusions of Experiment and Theory



(a) Interpretation



(b [illegible]

Much of the inter[illegible] [illegible]olution imag[illegible] by radar depends upon contrasts [illegible] between vari[illegible] surface areas as well as changes in pat[illegible] Hence, a lack of complete knowledge of σ_o versus [illegible] does not [illegible] widespread application of the images to numerous earth science problems. Earth scientists are customed to working with aerial

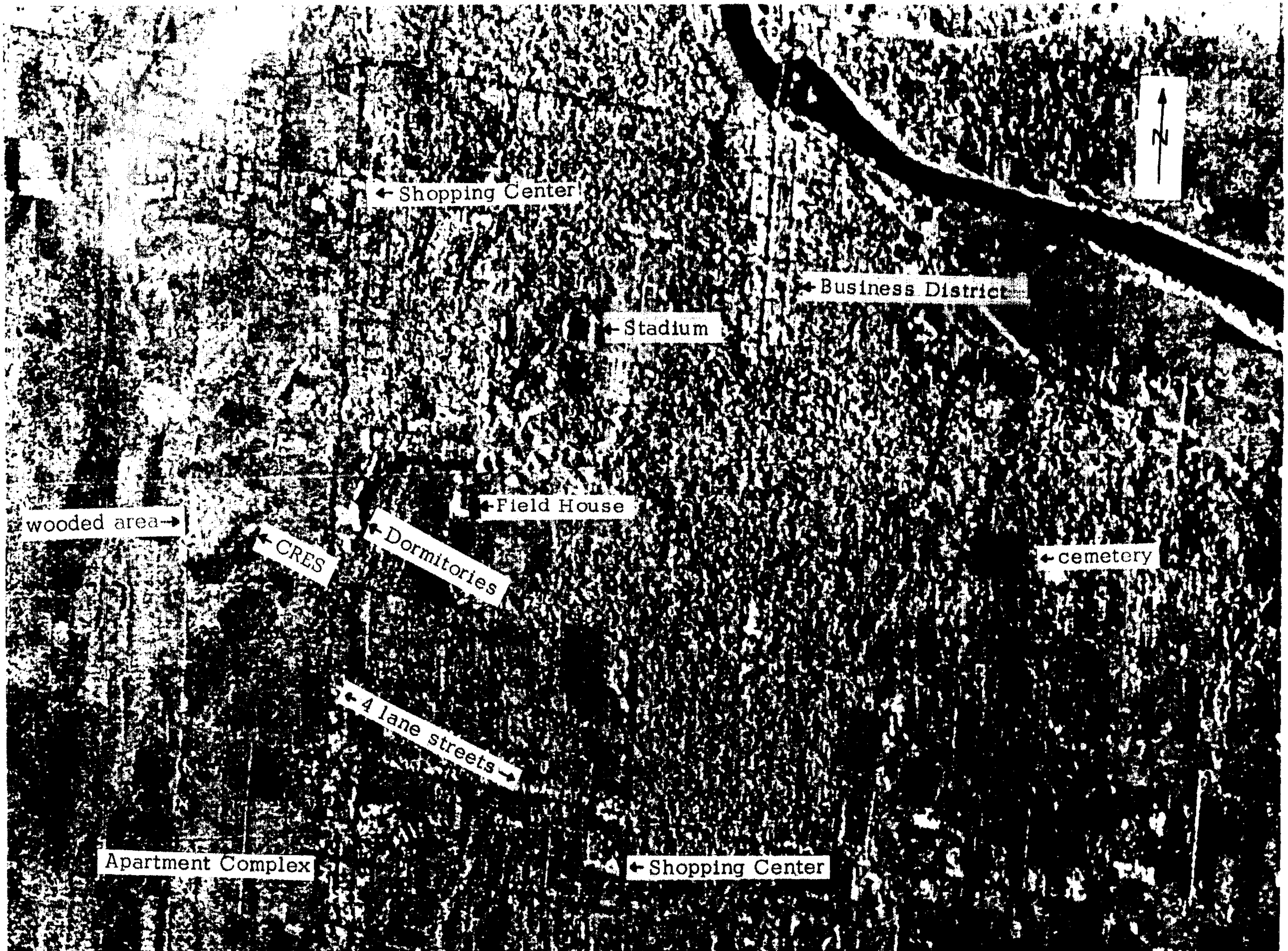


Figure 14a. Example of Images - Lawrence, Kansas including the University of Kansas

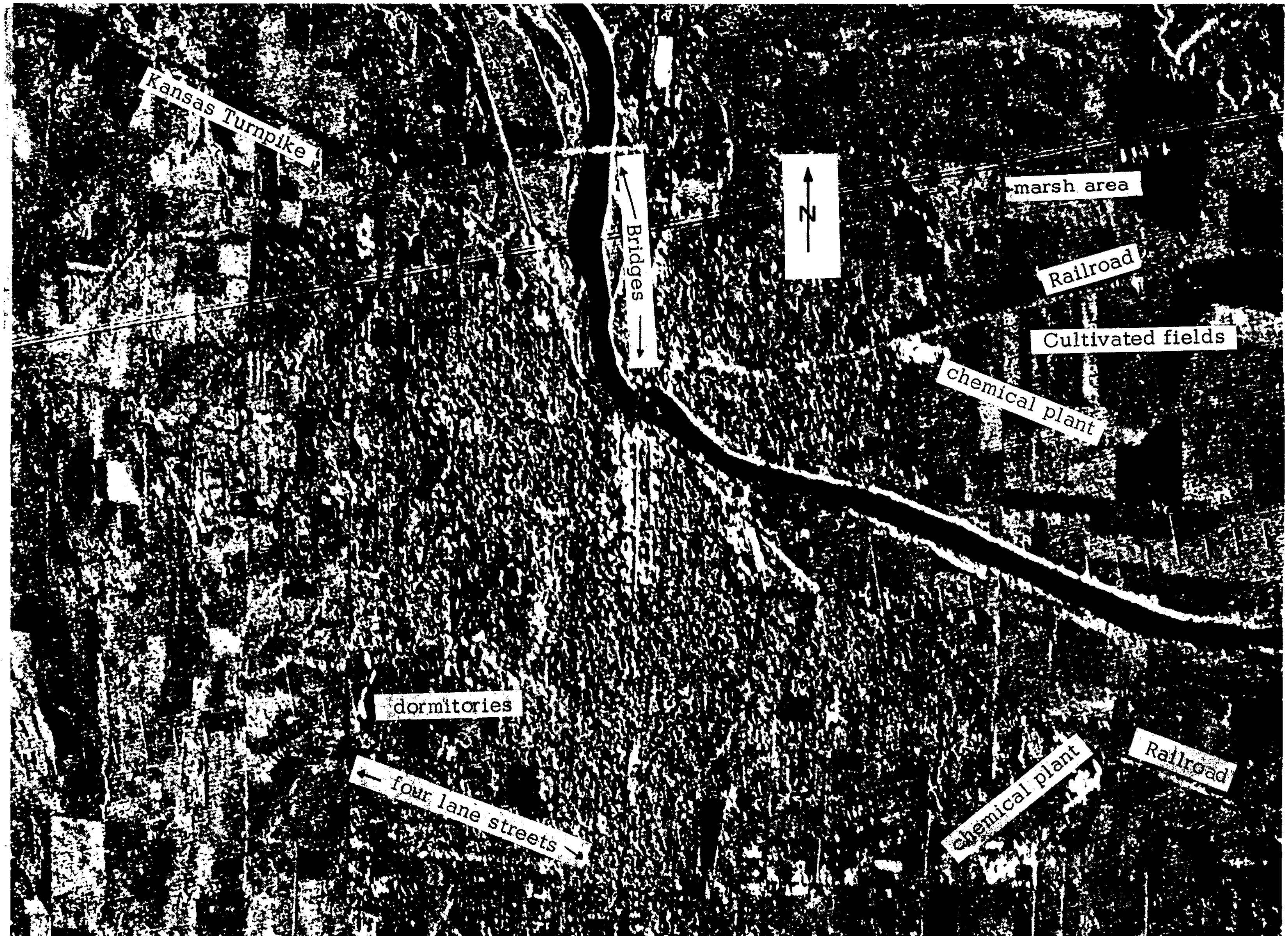


Figure 14b. Examples of Images - Lawrence, Kansas area

Photographs without attempting to quantify the gray levels used except for rare applications. For these non-quantified uses the image should be studied on an empirical basis to determine its information content and the scattering coefficient curves are not necessary. Figure 14 shows such images.

As our knowledge of the scattering coefficient curves increases, the information can be applied to images to produce corrections for the differing incident angles and to produce quantitative relations between the signals obtained at different angles, different polarizations and different wavelengths that will permit accurate identification of the target characteristics, in the same way that color permits more accurate identification of characteristics in visual photography.

Information Needed

At the present time radar is a useful sensor for many purposes. Its value can be enhanced, however, if suitable measurements are made to aid in interpretation of sensor outputs.

Table 7 summarizes part of the information needed from radar scatterometers and related devices. Probably the most important information needed is flight experiments under controlled conditions over targets for which earth scientists are obtaining simultaneous correlative information, such as moisture content, crop type, surface relief, soil type, etc. These measurements will be enhanced if short range radar measurements, like those made by Ohio State University, can be conducted simultaneously.

TABLE 7

RADAR CROSS-SECTION MEASUREMENTS - NEEDED INFORMATION

- CONTROLLED FLIGHT EXPERIMENTS OVER KNOWN SPECIFIC TARGETS WHERE GROUND TRUTH IS AVAILABLE.
- CORRELATIVE SHORT RANGE EXPERIMENTS.
- MOST PREVIOUS MEASUREMENTS ARE IN 3 CM. OR 1 CM. REGION. EFFECT OF FREQUENCY AND POLARIZATION NEEDED UP TO METER WAVELENGTHS.
- DEPTH OF PENETRATION MEASUREMENTS.
- RADAR AND ACOUSTIC MEASUREMENTS DESIGNED TO MAKE COMPARISON WITH THEORY EASY.
- GREAT EXPANSION OF BISTATIC MEASUREMENTS OF ANY TYPE.

Unfortunately, most of the radar cross section measurements in the past have been in the 3 cm wavelength region. The effects of frequency and polarization should be measured up to meter wavelengths. Some of this is being done by the U.S. Naval Research Laboratory at the present time.

Essentially nothing has been done to determine whether the radar signals come from the surface or beneath the surface, and if beneath the surface, from what depth. Both attenuation measurements in-situ through natural surfaces and radar measurements in areas where the penetration conditions are known should be made both at short and long range. A start has been made under restricted conditions at the U.S. Army Waterways Experiment Station.

Both radar and acoustic measurements made in such a way that comparison with theory is facilitated are important. A start has been made on this at The University of Kansas and Kansas State University acoustically, but few electromagnetic measurements of surfaces whose characteristics are really known statistically have been conducted to date.

Because bistatic measurements are so rare, any new measurements will greatly increase our knowledge and help us to understand not only the operation of bistatic radars but of monostatic radars since much of the energy that does not come back to the monostatic radar antenna is scattered in the other directions observed in the bistatic measurements.

Table 8 shows the kind of information needed immediately from imaging radars. Of the hundreds of thousands of square miles of radar images presently available, very few have been made with concurrent measurements of ground characteristics. Furthermore, few experiments have been conducted over the same terrain with different moisture, snow cover, and vegetation conditions. Both types of measurements are needed urgently over a wide variety of terrains. Multiple frequency, multiple polarization, high-resolution images are just becoming available now from U.S. Naval Research Laboratory and Westinghouse Corporation (multiple polarization only). Exciting differences appear in the single-frequency Westinghouse multi-polarization images. The images from Naval Research Laboratory at lower frequencies also show exciting possibilities. Such work must be expanded if we are to truly understand the nature of the radar signal and the way it can be used to benefit the earth scientist.

TABLE 8

HIGH - RESOLUTION IMAGING RADAR

INTERPRETATION DEPENDS ON CONTRASTS, INTERRELATIONS AMONG VARIOUS SURFACE AREAS, TEMPORAL CHANGES, AND EMPIRICAL CATALOG OF σ_o AT θ USED.

NEEDED INFORMATION

ANALYSIS AND CATALOGING BY GEOSCIENTISTS IN AREAS OF KNOWN GROUND TRUTH, INCLUDING EFFECTS OF CHANGING MOISTURE, SNOW COVER, AND VEGETATION.

EFFECTS OF FREQUENCY, POLARIZATION CHANGE, AND CROSS-POLARIZATION. (MOST EXISTING IMAGES SINGLE POLARIZATION IN 1 - 3 CM. WAVELENGTH RANGE.)

THEORY AND COMPLETE σ_o VS θ CURVES LESS IMPORTANT THAN FOR OTHER TYPES OF RADAR.

Concurrent theoretical studies must go forward in order that the experimental scattering coefficient and image measurements may be understood. This is particularly true in the unexplored area of the effect of the materials beneath the surface on the scattering coefficient and the image, since such effects may be extremely important for radar imagers operating in lunar and earth-polar environments.

In addition to the radar work itself, the problem of image combination and enhancement will become more important as large numbers of radar images, photographs, infra-red images, ultraviolet images, etc. become available for different terrain elements. The quantity of data to be collected by spacecraft is so tremendous that means must be found to automate as much of the process of image collation and image analysis as possible.

Conclusions

Radar is one of the most important remote sensors because it is capable of providing high resolution images independent of external illumination and of cloud cover. Furthermore, it provides this information at wavelengths not available to other sensors and in a way that permits easier electronic manipulation. We already know a great deal about the application of radar and the way in which the radar signal is returned. Many new experiments are needed, however, to aid in the use of radar as a remote sensor for the earth sciences.

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