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Summary

Studies sponsored by NASA at the University of Kansas in cooperation with several other universities and government research agencies are substantiating the applicability of remote sensing by radar to many fields within the earth sciences, agriculture, and oceanography.[1] The purpose of this paper is to show how the properties of the radar return are used to provide geoscience information.

Introduction

Radar is scanning a new horizon. The "ground clutter" that radar engineers have, by tradition, sought to suppress has taken on a new and exciting significance. Geoscientists, motivated by the tremendous potential of orbiting research platforms, are utilizing radar as a scientific tool for geoscience investigations. Consequently radar engineers must take a fresh look at radar so as to enhance its geoscience value. To stimulate this, NASA recently organized a Remote Sensing Program to focus the technology of a variety of remote sensors including photography, infrared and microwave radiometry, and radar on the areas of interest to the geoscientists.

Parker and Wolff[2] have prepared an excellent summary of the numerous geoscience applications of remote sensors in general. In the following sections of this paper we will summarize the geoscience applications of radar in particular. Basically, we will examine the techniques used to record, interpret, and hence, ideally at least, extract the geoscience information content of the radar return. These techniques are (1) scatterometry: a newly defined field of study dealing with the scattering coefficients of terrain targets; (2) imagery: a photo-like presentation of the radar return; (3) altimetry; and (4) penetration measurements.

It is very helpful in discussing these techniques to first examine the character of the radar return in such a way as to show its capacity to yield geoscience information. Thus, this paper is organized so as to briefly review the radar return character and then show, by example, how and why it is useful to the geoscientist.

Radar Return

Radar return is directly related to the nature of the terrain illuminated by the transmitted electromagnetic wave. The relationship is complex, since the terrain parameters affecting the radar return are complex. It has been demonstrated that radar return amplitude is affected by the composition of the illuminated area, its moisture content, vegetation extent and type, surface roughness, and even temperature in certain circumstances. The relationship between return and terrain is further complicated by the fact that it is a function of the angle of incidence of the transmitted wave, the wave polarization, and frequency. At this time the relationship between return signal and terrain is not easily quantified. The effort to catalog land types by examination of radar return relies on the readily distinguishable radar return changes caused by variations in incidence angle, polarization, and frequency.

Scattering Coefficient

Radar return is that portion of the transmitted radar energy which returns to the radar receiver. For our discussion of the terrain parameters affecting the return, it is helpful to examine only the radar cross-section, σ, which is directly proportional to the radar return. More specifically, we will consider the radar cross-section per unit area, or scattering coefficient, σ_o. This parameter contains all the geoscience information about the illuminated terrain that the radar is capable of sensing, except for location.

The radar cross-section is defined for two types of reradiation processes: scattering and specular (mirror-like). Specular reflection is seldom present in the backscattered return from natural terrain, and then only at vertical incidence. The radar scattering cross-section for one point scatterer is related to the radar return power by the familiar radar equation,

$$\sigma_m = \frac{P_r (4\pi)^3 R_m^{\ 4}}{P_t G_m^{\ 2} \lambda^2} \qquad (1)$$

where: P_r = received signal power
P_t = transmitted signal power
R_m = slant range to the m^{th} scatterer
λ = wavelength of transmitted signal
G_m = gain of antenna in direction of m^{th} scatterer.

In actuality the radar return is the resultant of the return from many scatterers which contribute more or less equally. Therefore (1) must be expressed as the sum over all the scatterers contributing to the return.

$$\sigma = \sum_{m=1}^{M} \frac{P_r (4\pi)^3 R_m^{\ 4}}{P_t G_m^{\ 2} \lambda^2} \qquad (2)$$

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The transmitted wave induces a scattered reradiation field pattern due to the sum of the returns from all of the individual scatterers. This field pattern has minima and maxima at various angles from a reference. Figure 1 shows a scattered reradiation pattern for a model with a two-dimensionally rough surface.

ensionless real number whose magnitude is a function of the terrain parameters. It can be expressed as

$$\sigma_o = f(\lambda, \Theta, \phi, \epsilon, \Gamma, P) \quad (4)$$

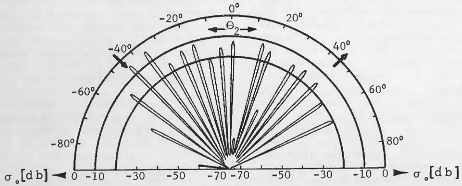

Figure 1. Scattering by a Perfectly Conducting Sinusoidal Surface, Period = 10 λ, Incidence Angle = 45°, Peak-to-trough Height = 1.6 λ (After Brekhovskikh, 1952.)

The angular positions and amplitudes of minima and maxima are dependent on surface roughness and on the complex dielectric of the terrain. These in turn are dependent on the wavelength, polarization, and angle of incidence of the transmitted signal. Backscatter measurements, with which this paper is primarily concerned, obtain only the amplitude of the reradiated lobe in the direction of the transmitted signal. Thus, radar return magnitude changes can be caused by changes in the position of the lobes and/or in changes of amplitude of a fixed backscatter lobe. Backscatter measurements alone do not separate these two possibilities.

As the radar moves relative to an incremental area on the ground, the receiving antenna intercepts minima and maxima of the reradiation patterns due to the continual changing of the lobes as the orientation of the incident wave changes with respect to the individual scatterers. The reorientation of the lobes is essentially random on a pulse-to-pulse basis. Therefore the effects of lobe reorientation, or fading as it is more commonly called, can be smoothed by statistically averaging over many pulses.[3] We define the average scattering cross-section per unit area as

$$\sigma_o \triangleq \sum_{m=1}^{M} \frac{\overline{\sigma}_m}{\Delta A} \quad (3)$$

where σ_m is defined in (1), except that it is averaged over several pulses; M is the total number of individual scatterers contributing to the radar returns; and ΔA is the incremental area containing the M scatterers, subject to the restriction that is is small enough that the incident power, the antenna gain, the range from the angenna can be considered a constant over Δ A.[3]

The average differential scattering cross-section, or scattering coefficient σ_o, is a dimensionless real number whose magnitude is a function of the terrain parameters.

where:

λ = wavelength
Θ = angle of incidence
φ = aspect angle
P = polarization of incident wave
ε = complex dielectric constant
Γ denotes surface texture or roughness.

An analytical expression for equation (4) is not readily obtainable without employing certain simplifying assumptions. Considerable controversy exists over what set of assumptions yields an expression for (4) which holds for natural terrain. Many investigators are attempting to determine the interdependence of the variables;[4,5] some of these activity is discussed in III. We will summarize here the known effects on σ_o due to changes in the variables.

Dependence of Scattering Coefficient

It is well recognized that the surface texture or roughness has the greatest effect on the magnitude of the scattering coefficient: consequently, considerable theoretical study has been devoted to this topic.[6,7] The degree of roughness dictates the extent of scattering which forms the reradiation field pattern. "Degree of roughness" is a relative expression--that is, a surface is rough or smooth relative to the wavelength of the incident energy. If we define a surface by its root mean square surface roughness, Γ, then a surface having

$$\Gamma > \frac{\lambda}{10}, \quad \text{(Rayleigh Criterion)} \quad (5)$$

where λ = wavelength of incident wave, is sufficiently rough that the incident wave scatters. Depending on roughness, a surface can be classed between the extremes of a perfect specular reflector (no scattering), where backscatter exists only at vertical incidence, to an isotropic scatterer ($\Gamma >> \lambda$), where the scattering coefficient is independent of the angle of incidence. These two extremes can be visualized by referring to Figure 1; a specular surface has only one lobe (obeying Snell's law), and an isotropic scattering surface has all maxima equal to all minima throughout the hemisphere (i.e. no fading). Varying the frequency of the wave incident upon a surface of any roughness, Γ_s, produces a similar effect to variations in Γ. In addition, however, variations in frequency affect σ_0 due to the frequency dependence of the complex dielectric of the terrain. For two very rough surfaces, Γs_1, $\Gamma s_2 >> \lambda$ the difference in their scattering coefficients is a measure of the difference of their complex dielectric. The complex dielectric is proportional to moisture content and porosity of the surface material.[8,9]

The scattering coefficient varies as the angle of incidence of the transmitted wave is varied. The scattering coefficient at near-vertical incidence is primarily determined by the large-scale features of the terrain, whereas σ_0 at near grazing incidence is primarily determined by the small-scale structure.[10] For very rough terrain, σ_0 is independent of the angle of incidence.

The dependence of σ_0 on the polarization of the transmitted wave is not readily generalized. It can be stated that the scattering coefficient becomes independent of polarization for very rough terrain. However, for slightly rough terrain σ_0 may be greater for vertically-polarized waves than horizontally-polarized waves or conversely (depending on the wavelength, angle of incidence, and type of terrain--cultural or natural). The cross-polarized return (orthogonal component of the depolarized return wave) should be independent of the polarization of the incident wave: that is, by reciprocity, the cross-polarized return component of a horizontally polarized incident wave from one terrain element is equal to the cross-polarized return component of a vertically polarized incident wave. The extent of depolarization of the incident wave appears to give as much information about the nature of the terrain as do the horizontal and vertical linear polarization differences;[11] however, to date very little has been done with either type of information. It is interesting to note that until recently[12] no scattering theories existed which accounted for the existance of depolarized backscattering, and for purposes of calculation it was generally assumed that no such component existed.[7]

It is quite evident from the above discussion that we do not have sufficient knowledge to express the scattering coefficient in an analytical form. One reason for this is that, except for work at Ohio State University,[13] no experimenters have adequately controlled the terrain parameters while varying the radar parameters. But the fact that the scattering coefficient is not as yet well defined does not substantially deter the use of radar as a remote sensor any more than the similar lack of definition of optical spatial emissivity and reflectivity deters the use of eyes or cameras.

Interpretation of Radar Return

Radar returns are recorded in various forms to aid in their analysis. The forms having primary geoscience interest can be classed in one of the following categories: (1) scattering coefficients, which are arranged in many forms and which we will place in a category called "scatterometry data"; (2) radar images; (3) altimetry data; and (4) penetration measurements. Of these forms, images have created the greatest excitement in the geoscience community, due to the fact that well-developed photographic interpretation techniques are applicable to radar image analysis. Radars capable of producing high-quality image representations of the earth have been developed. Scatterometry data, although not as amenable to interpretation by the geoscientist, is a powerful research tool in studying the nature of the radar return, and it has been directly applied to oceanic surface studies. The ability of radar to penetrate, especially at low frequencies, has been utilized for mineral exploration, and holds great promise for exploration through the lunar debris layer and through dense forests on earth.

Scatterometry

The experiments conducted to define the interaction of electromagnetic waves with rough surfaces have been grouped into a field of study called Scatterometry (R. K. Moore, University of Kansas). The basic objective is to determine the scattering coefficient as expressed in equation (4) by controlling the terrain parameters, Γ and ϵ while varying the radar parameters, λ, Θ, and P. The second step is to vary the terrain parameters in a controlled manner. Some very limited work has been done in this way by Waterways Experiment Station.[9] However the greatest interest in this regard has to do with the ocean, where both the dielectric constant and conductivity are constant. The conventional σ_0 versus Θ plot in Figure 2 demonstrates the effect of surface roughness, or sea-state, on the scattering coefficient. Such information can be used to determine some properties of the wave spectra of the ocean surface.

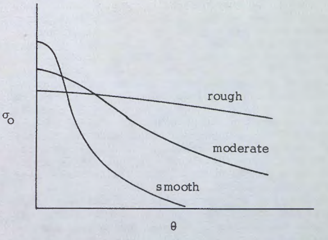

Figure 2. Scattering Coefficient and Variations with Angle of Incidence for Various Sea-State

Correlation of the scattering coefficient with wave height and surface wind speed has been established,[14] but detailed calibration has not been accomplished. This calibration should be forthcoming from an experiment conducted in 1965 by I. Katz, Johns Hopkins University Applied Physics Laboratory, F. C. Macdonald, Naval Research Laboratory, and W. Marks, Oceanics, Inc. The capability of radar to measure ocean wave heights from high altitudes has immediate application to oceanography and meteorology. A scatterometer in polar orbit can survey the entire world ocean at least twice a day, supplying information on wave height every 60 miles or so. Quantitative wave observations are presently made routinely only by one British weather ship and by the U.S. Naval Oceanographic Office at Argus Island, supplemented by qualitative reports from ships at sea. Wave height information can be used to establish the surface wind field, thus aiding in wave forecasting and surface weather forecasting.

The application of scatterometry information to identifying the "state" of a terrain, because of its myriad blending of discontinuities and inhomogeneities, is not nearly as clear as when dealing with the sea. Ohio State University has conducted extensive studies on homogeneous terrain such as roadways and vegetation patches, and has found that relative identification of the terrain using only σ_0 versus Θ information is possible in many cases. For example, concrete roads are distinct from asphalt roads, and both are distinct from gravel roads. This work led to the formulation of an analytical expression for the scattering coefficient with the parameters of equation (4), which predicted the empirical results reasonably well for several types of terrain.[3]

The approach to the scattering problem which Ohio State University and Waterways Experiment Station use--that is, examination of small samples of homogeneous terrain--is mandatory if an understanding of the relationship between the scattering coefficient and the terrain parameters is to be obtained. However, before scattering coefficient information can take on a significant geoscience value, a "composite" approach to the scattering problem is necessary. That is, an area can be homogeneous from a geologic point of view, yet have concrete, asphalt, and gravel roads across it! An attempt to define large-scale homogeneous areas was made by the University of Kansas, using data obtained by F. C. Macdonald, Naval Research Laboratories, over Pisgah Crater, California (1965). Using the incidence angle and polarization dependence of the scattering coefficient homogeneous regions were defined along the radar flight line. Later comparison with geologic field information and photographs showed that the radar-defined regions conformed with the actual terrain boundaries: however, it was not possible to catalog the individual regions by specific terrain type because of the limited amount of radar data available.

The use of multi-frequency, multi-polarization radar return data combined with n-dimensional pattern recognition techniques may allow identification and cataloging of terrain types by surface texture and electromagnetic properties. (N-dimensional pattern recognition, a type of which is being developed at the University of Kansas and the University of Michigan, consists of assigning a separate vector to the terrain response to each frequency, polarization, and angle of incidence.) However, until the refinement of these advanced techniques, and perhaps after, the principal geoscience application of scatterometry data from land is as supplementary information to aid in interpretation of photographs and radar imagery.

Radar Imagery

In previous sections we have devoted our attention to the magnitude of the radar return. Of course the return contains other information; specifically, information on the location of a terrain element with respect to other terrain elements and to the radar itself. Radar imagery is a record of both the magnitude and location information contained in the return. Imagery generally presents the optimum geoscience information content of radar return and hence it is not surprising that it has received a great deal of attention by the geoscientists.

The image record of the terrain return is effected by the frequency, angle of incidence, and polarization of the radar signal exactly as mentioned for Scatterometry, however some of the effects take on somewhat different significance when recorded as imagery. For example if the terrain being imaged is covered by vegetation, a K-band (35 gc) signal will record the vegetation, whereas a P-band (0.4 gc) signal will likely penetrate the vegetation and thus record a combination of vegetation and the soil surface. In general each frequency band represents a potential source of unique data. The angle of incidence of the incident wave will affect the image because of radar shadowing on the backside of protruding objects. Although information is lost in the shadow region, the extent of the shadow indicates the height of the object and hence has been useful in emphasizing linear features such as faults and lineations reflecting joint systems. The polarization of the radar signal affects the image by emphasizing terrain elements (particularly cultural objects) having certain favored orientations with respect to the radar. This effect is primarily due to target resonances. Another radar parameter of importance when dealing with imagery is resolution. The resolution of a system is the distance between two objects which are individually distinguishable on the radar image. Resolution is expressed in both range and azimuth. The optimum quality of the resolution depends on the geoscience application of the particular image, for example, lineations in the southern Boston Mountains are more distinct on AN/APQ-69 imagery than on AN/APQ-97 imagery even though the latter has much better azimuth resolution.

It is difficult, but very necessary, for the radar engineer to appreciate just what the geoscientist is attempting to determine from the radar return data. We will briefly examine several radar images which contain information applicable to geology, agriculture, and sea-ice studies, among others.

Geologic Interpretation of AN/APQ-69 Radar Imagery in the Faulkner County Area, Arkansas. Interpretation and analysis of regional geologic structural features is dependent upon the recognition of the trend, continuity, and interrelationships of key surface features. The curvilinear, northwest-southeast trending lines in areas A, B, C, and E in Figure 3 are ridges which generally stand 300 to 400 feet above adjoining valleys. Deformed, alternating sandstone and shale beds have been differentially eroded resulting in sandstone ridges and shale valleys. On the radar image, light tones are characteristic of the sandstone ridges and moderate tones are characteristic of the shale valleys and lowlands. The magnitude of the radar return, seen as contrasting gray tones, is dependent on a number of complexly interrelated variables which have been mentioned previously. In this hilly region, the interaction between radar beam incidence angle, regional terrain, and vegetation is important in interpreting regional geology. Rock type is considered to be of less significance than the other factors because most of the sandstones and shales are covered with soil and moderate to heavy vegetation. Some of the areas of strongest returns are located along the northern slopes of ridges, which are near-normal to the incident radar energy, and are heavily timbered as well (an example is at D-2). The valley and lowland areas contain more crop and pastureland than do the ridges, as shown by the field geometry and moderate gray tones, although some large timber areas are present.

The curvilinear sandstone ridges in areas B through F (Figure 3) define a series of moderate to steeply plunging anticlines (originally horizontal rock strata which are now convex upward as a result of deformation) and synclines (deformed strata which are convex downward). A qualitative determination of bed attitude is based on recognition of dip slopes and scarps, spatial relationships and character of radar return. Along the ridge in area D-1, for example, a southwest, moderately sloping surface approximates the dip of the underlying beds. In a similar manner, the sandstone beds that support the ridge on the south side of the valley at D-2 dip to the northeast at a high angle, forming the southern limb of syncline D. The same type of analysis defines the structure at B as a syncline. The axis of the syncline changes from west to northwest as the angle of plunge decreases along the trend until in area B-1 closure of the beds indicates that syncline B converges with another syncline plunging to the south. The sandstone-capped hill at D-3 is an erosional remnant in the valley of Cyprus Bayou, and probably approximates the axial position of syncline D. Other fold axes are easily located where they bisect "noses" of anticlines and synclines. Ridge displacements or offsets at C-1 in all probability represent fractures and rotated segments of crustal blocks.

The image can be readily divided into three distinct structural provinces as illustrated by Figure 7: (1) the Arkansas Valley structural province; (2) the Ouachita Mountains structural province; and (3) the Mississippi Embayment.

The Arkansas Valley structural province is dominated by relatively narrow, unbroken, sharply defined ridges which are the topographic expression of moderate to steeply plunging anticlines and synclines. The Ouachita Mountains structural province is similar to the Arkansas Valley province in the character of the structures and rock types but this large province is restricted to a single syncline at A. The ridges flanking syncline A are not as clearly defined as the ridges in the Arkansas Valley province and appear to be broken in numerous places. Since the ridges are poorly expressed only rough estimates of bedding dips and synclinal plunge can be made. In the Mississippi Embayment, the relative relief is 100 to 150 feet and much of the area is very gently rolling. The sedimentary rocks here are not well exposed at the surface because of their near horizontal attitude.

The separation of the Ouachita Mountains structural province from the Arkansas Valley structural province is expressed as an irregular northwest-southeast trending ridge located between A-1 and A-2. The separation is across a major thrust fault zone in which a crustal block has moved northward. The thrust fault recognition is based on several criteria:

(1) abrupt termination of ridges with minor displacement or buckling approximately midway between A-1 and A-2;
(2) the absence of an anticline between two synclines (synclines A and B);
(3) contrasting texture between the two areas. Radar return from syncline A gives a "grainy" appearance while that of the Arkansas Valley province is more smooth and uniform.

The separation of the Arkansas Valley and Ouachita Mountains structural provinces from the Mississippi Embayment is marked by an irregular southwest-northeast trending line between G-1 and G-2 on Figure 6. The line is believed to be the trace of an angular unconformity, the ancient erosional surface separating the near horizontally-bedded sediments of the Mississippi Embayment from the folded sedimentary rocks of the Arkansas Valley province, which project beneath the Mississippi Embayment.

Fifteen rock units were isolated on the basis of relative ages. In an area where a sequence of sedimentary rocks has been disrupted by folding and subsequently differentially eroded, the younger beds can be located in syncline centers and the older beds can be located in anticline centers. Age relationships of rock units can be thus established on the basis of relative position, and correlations from area to area enable a map of relative ages to be constructed (Figure 6). This map satisfies our immediate aim of obtaining a regional geologic map and focuses attention on areas needing more detailed study. In preparing such maps, it soon becomes clear to geologists that a major advantage of radar imagery is the ease with which the continuity of structures may be traced and correlated, a matter of no small importance in economic geology.

Vegetation Interpretation of Radar Imagery. Many parts of the world are inadequately covered by vegetation maps. Poor coverage is particularly true of remote, relatively inaccessible and cloud-covered regions as in rainforest, savannah, and desert belts, mountainous areas and Arctic latitudes. Radar image derived vegetation maps, even at gross scale, should be a valuable addition for resource evaluation.

Figure 9 is a radar-derived vegetation map in the vicinity of Jackson Hole, Wyoming indicating the quality and quantity of information presently obtainable from the imagery. In general, the radar-derived vegetation categories and boundaries are very similar to those mapped in 1936 by James.[17]

Ice Interpretation of Radar Imagery. Numerous possibilities exist for using imaging radars as tools for basic and applied research problems in Arctic and Antarctic regions. Continued surveillance, particularly from an orbiting platform, of sea ice, pack ice, floes, and so on would enable regular updating of charts. Frequent poor-weather and poor-light conditions often limit regular aerial photographic surveys and similarly, ground surveys are limited by remoteness and poor trafficability.

The fine scale distinction of sea ice by radars would aid shipping forecasts and routing of ships (particularly in iceberg areas).

Figure 10 is AN/APQ-56 radar imagery (negative) with a range resolution of 50 feet and with azimuth resolution of approximately 200 feet of Prudhoe Sound, Alaska (approximately at 148° longitude and 70°30' latitude), showing several types of off-shore ice. Figure 11 is a map giving an interpretation of this image. The terminology used to describe ice types is tentative because no field observations were made at the time of overflight.

Polarization Differences Observed on Radar Imagery. Most radar analyses to date have been based on imagery from radar systems capable of transmitting and receiving but one polarization mode, usually horizontal transmit and horizontal receive. Extension of the polarization capability to include the full polarization (amplitude) matrix may significantly increase the ability to identify and catalog certain terrain features.

Figure 12 is radar imagery recently acquired by an airborne radar system capable of transmitting linear polarization and receiving both linear and cross-polarized returns synchronously. The two images were taken over an area dominated by volcanic flows known as the Pisgah Crater area, located in the Mojave Desert approximately 40 miles southeast of Barstow, California. Compare the aerial photograph index, Figure 13, with the imagery segments. The contrast in information is particularly evident in the vicinity of the Lava Bed Mountains where the outline of the lava is not as clearly differentiated on the like-polarized image (A) as it is on the cross-polarized image (B). Delicate stream patterns on alluvial fan sediments south of Lavic Lake can be likewise more easily delineated on the cross-polarized image.

Precipitation Penetration on Cross-Polarized Radar Imagery. Radar is often heralded for its all-weather capability. Obviously, however, radar signals do not always penetrate clouds; in fact, storm-tracking radars depend on the radar signal not penetrating dense clouds. The upper radar image in Figure 14 shows a K-band image containing dense clouds or, more likely, heavy precipitation. The lower image in Figure 14 is the cross-polarized return and was recorded simultaneously with the upper image. In the lower image the only evidence of precipitation is slight attenuation in the heavy rain regions. This example emphasizes the potential of orbital multi-polarization radar to provide meteorological and terrain information concurrently.

Altimetry

Radar altimeters have long been used to determine the locations or altitude of aircraft with respect to the ground below. The use of altimetry on spacecraft immediately suggests the possibility of not only locating the vehicle with respect to the ground, but of profiling, or locating the ground with respect to the vehicle path.

The value of this data to the geoscientist will of course be dependent upon the accuracy and precision of the measurement. Before discussing specific applications let us review the general factors affecting altimeter accuracy.

Altimeter error may be of both the bias and random variety and will depend not only on the instrumental factors of the radar itself, but upon the variations in elevation within the total illuminated area and the fading characteristic of the return. These factors are not unrelated; averaging of independent fading returns may be used to reduce the random error of instrumental factors and signal fading. This averaging will of course increase the total illuminated area, and will be effective only under the assumption of constant mean elevation within the total area. This offers the possibility of greatly increased precision over relatively homogeneous areas such as flat plains and oceans.[18]

The general application of orbital altimetry will be to provide data for improved orbit calculation and, with the orbit as a reference baseline, reconstruction of the size and shape of the planetary or lunar body. From this, altitude control networks based on the revised planetary figure may be established and contour maps prepared. In addition altimetry will serve to provide the nadir elevation and vertical datum for scaling and contour relation of concurrently obtained photographs.

The value of this data for extra-terrestrial studies where conventional and more accurate means may be used at only a limited number of points on an entire planetary surface is easily seen. Less obvious are earth applications wherein conventional methods are inadequate.

Perhaps the most challenging use to which radar altimetry may be put is that of determining sea slope and small scale undulations of the geoid. Both the oceans of the earth and the path of the satellite tend to conform to the local geoid. The orbital inertia of the satellite will prevent its following relatively small scale fluctuations of the geoid while the mean elevation of the oceans will depart from the geoid for a variety of reasons such as tidal forces, geostrophic currents, storm surges, etc. Accurate altimetry will provide a measure of the combined deviation from the geoid of both the satellite and the ocean. With repeated coverage of the same areas it should be possible to separate these variations on a time scale. The precision required for sea-slope measurement must be in the order of 50 cm over areas in the neighborhood of 1000 square kilometers. At first glance this appears to be well beyond the present capability of radar altimetry; however the large areas involved will allow averaging of thousands of returns with a consequent improvement in precision. The importance of this measurement to oceanographers is best illustrated by a quote from the 1964 Woods Hole Conference on Oceanography from Space, "The most general and fundamental contribution to the science of physical oceanography would be the determination of precise sea level information."[19]

The height of tides and storm surges along remote coastal regions may be measured by repeated observation of the elevation differences across the land-water boundaries.

Glaciologists are intensely interested in a means of defining the mass budget of the Antarctic and Greenland ice sheets. One of the first requirements for the solution of this problem must be the accurate profiling of the surface at repeated intervals. Accurate measurements from traverses have been obtained but the amount of data is inadequate for estimation of the total budget and provides even less information on rates of growth or shrinkage. Aerial surveys in these regions are hampered not onlyby inclement weather but in dealing with a dynamic surface. With orbital altimetry near-synchronous profiling of these ice sheets will be possible.

Penetration

The reflection and transmission of an electromagnetic wave at the boundary of a plane dielectric surface is a classic wave problem. The solution to the boundary value problem shows the magnitude of the penetration portion of the wave to vary inversely with dielectric constant and the attenuation of the wave increases with frequency.[20]

Laboratory measurements of the dielectric constant and conductivity of soil as a function of moisture content and density have been conducted over a wide range of radar frequencies. These measurements have shown the skin depth at 297 mc to be 1 to 2 feet for the range of conditions normally encountered on earth, with even less penetration occuring at the higher frequencies (C-, X-, and, K-band).[7] Under these conditions the penetrating wave is normally assumed to be totally absorbed in the media and contributes nothing to the radar return. The magnitude of the scattering coefficient for surfaces smooth with respect to wavelength is then considered a function of the complex dielectric constant of the material and may be used to determine soil type and moisture content.

The most striking example of error in neglecting sub-surface return has occurred in altimeter measurements over large ice sheets.[21] The decreased conductivity of ice gives a skin depth of several hundred meters. In the case of gradual surface transition due to snow cover the sub-surface return may exceed that from the surface. This property has been extensively exploited for sub-surface profiling of the Antarctic and Greenland ice caps to a depth of 15,000 feet with short pulse ground-based systems.[22,23] Aircraft-borne systems are currently under development which greatly increase the coverage obtainable by this method and allow still better definition of the mass budget of polar ice sheets. In addition penetrating VHF systems have also been used for mineral prospecting by detection of highly conducting sub-surface layers such as copper ore. The extension of this sub-surface profiling capability to spacecraft will require narrow beam or short pulse techniques to discriminate between sub-surface and equivalent slant range surface returns.

The value of this technique for sub-surface investigation in lunar orbit is greatly increased, for the expected penetration is several hundred meters due to the low moisture content. The lower lunar orbital altitudes will reduce the problem of discrimination.

The most significant contribution the penetrating capability of radar may make in the near future will, in all probability, be that of vegetation penetration. The use of low frequency imaging radar will enable a geological analysis of the ground surface in areas of dense vegetation cover. In the even more remote future the penetrating capability of radar may offer the only possibility for imaging the surface of Venus through its cloud cover.

Conclusion

Whether as a scatterometer, altimeter, or imager, radar is a very usable tool for geoscience purposes. The tremendous increase in coverage possible from orbital altitudes greatly increases this usability. Radar is not a panacea for geoscience problems, but as one of a family of orbiting remote sensors, including photography, infrared imagers, and others, the prospects for learning more about the earth and subsequently about extra-terrestrial bodies are substantially enhanced.

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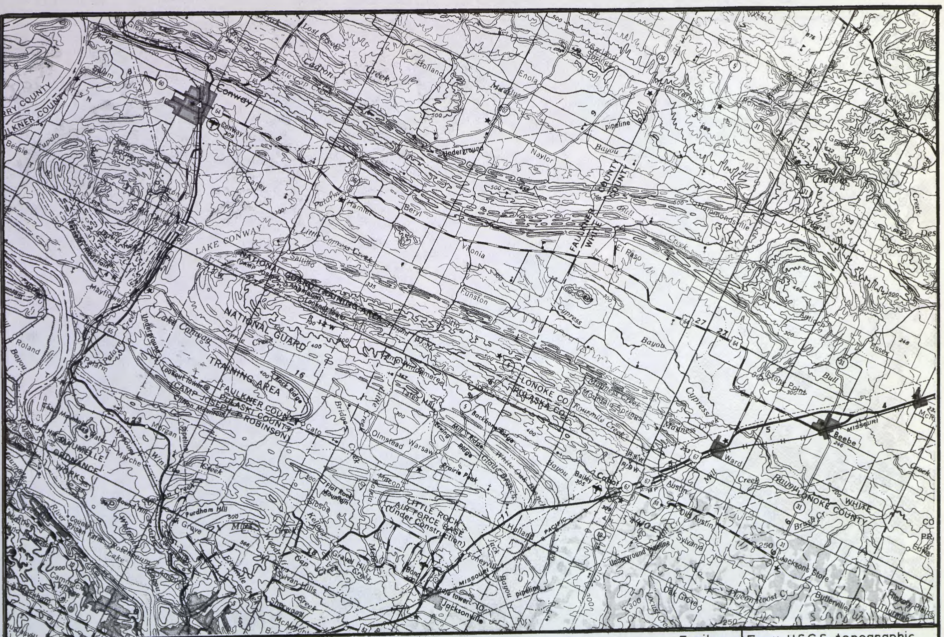

CRES-1966	CONTOUR INTERVAL 100 FEET With supplementary contours at 50 foot intervals

0 — 5 miles
SCALE

From U.S.G.S. topographic series

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FIGURE 4 TOPOGRAPHIC MAP OF THE FAULKNER COUNTY AREA, ARKANSAS

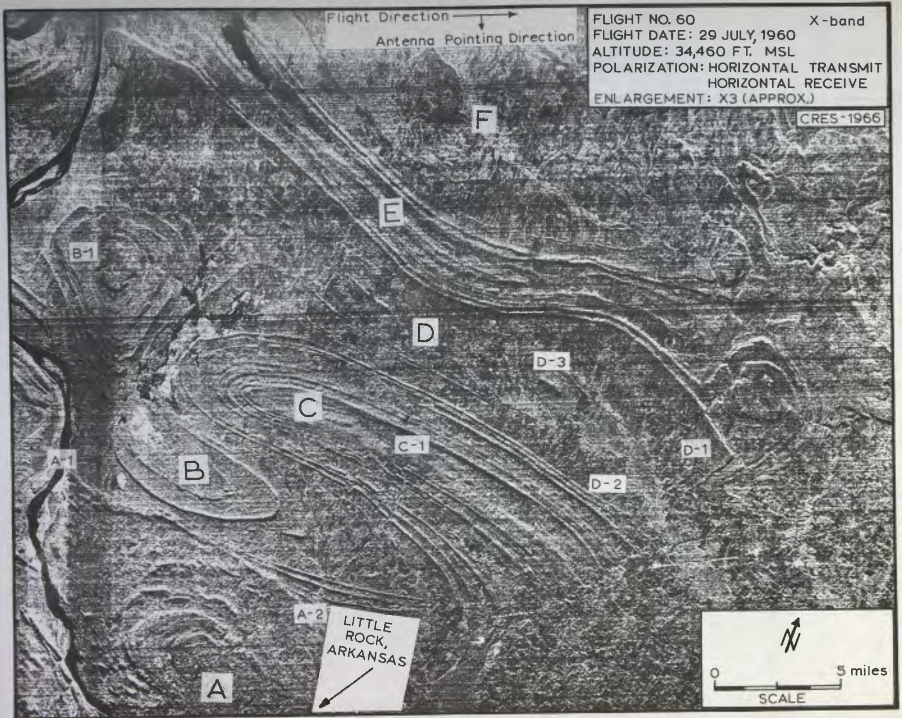


Figure 3 AN/APQ-69 Radar Imagery of the Faulkner County Area, Arkansas

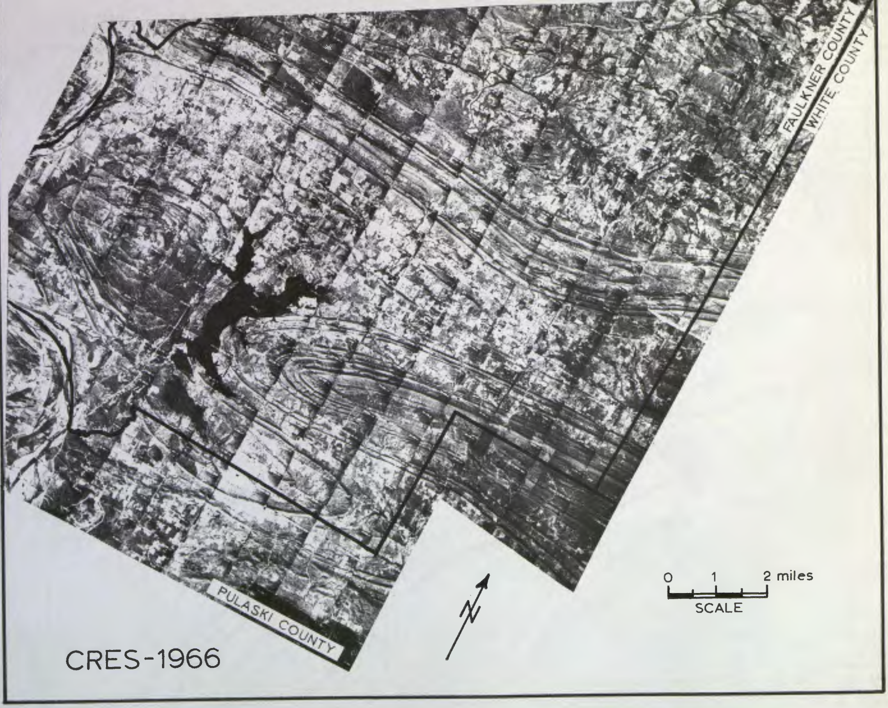
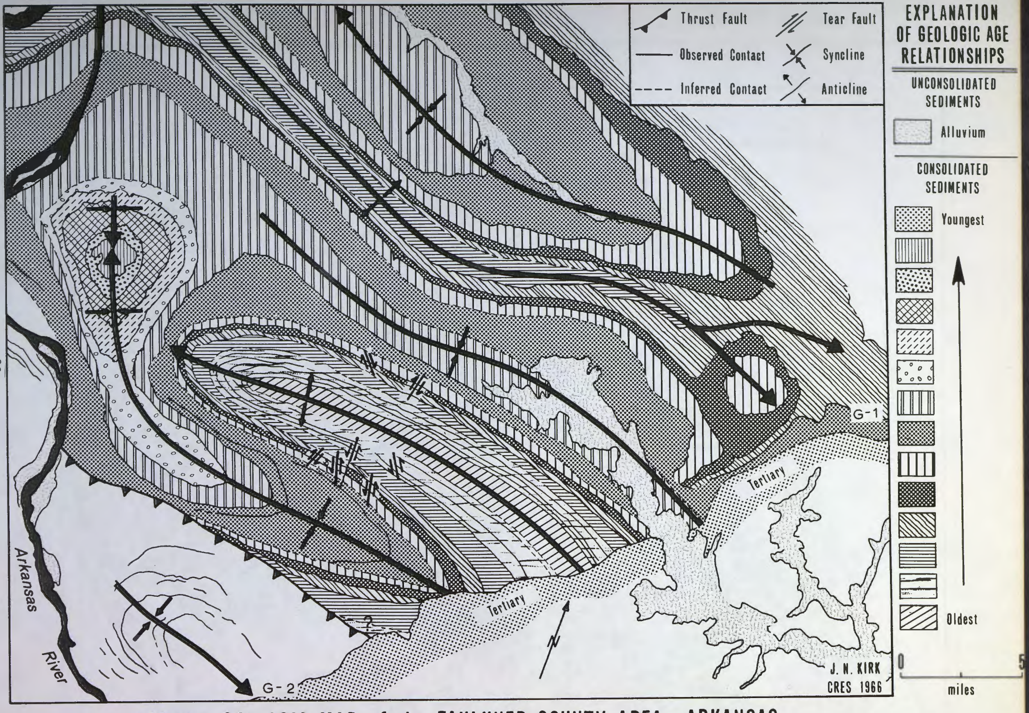


Figure 5 Aerial Photograph Mosaic of a Part of the Faulkner County Area, Arkansas (reduced X3)



RADAR — GEOLOGIC MAP of the FAULKNER COUNTY AREA, ARKANSAS

FIGURE 6

PREPARED FROM MONOSCOPIC AN/APQ-69 RADAR IMAGERY

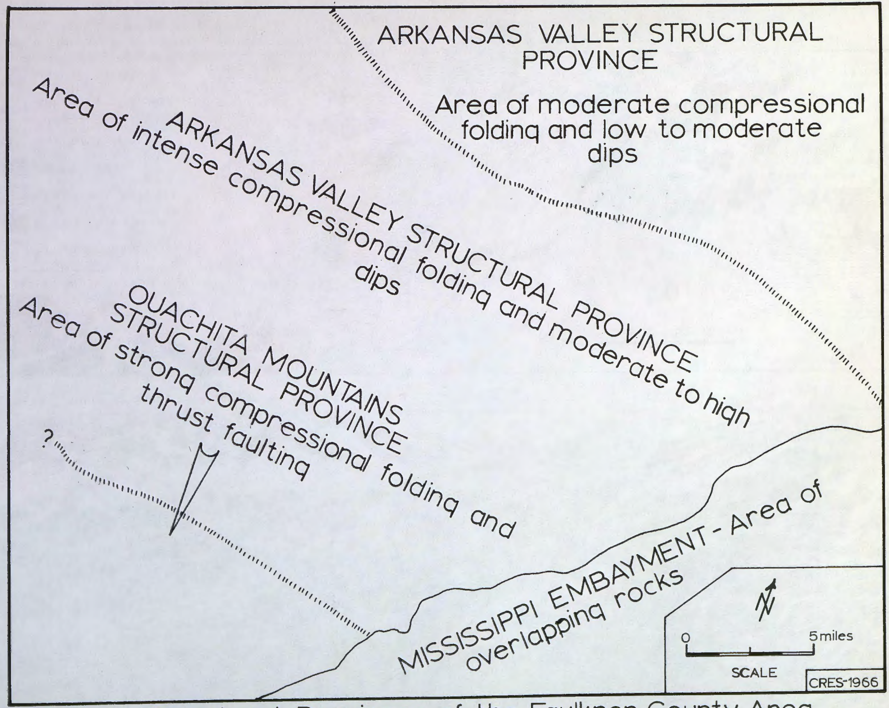


Figure 7 Structural Provinces of the Faulkner County Area, Arkansas (modified from Diggs, W. E., 1961)[15]

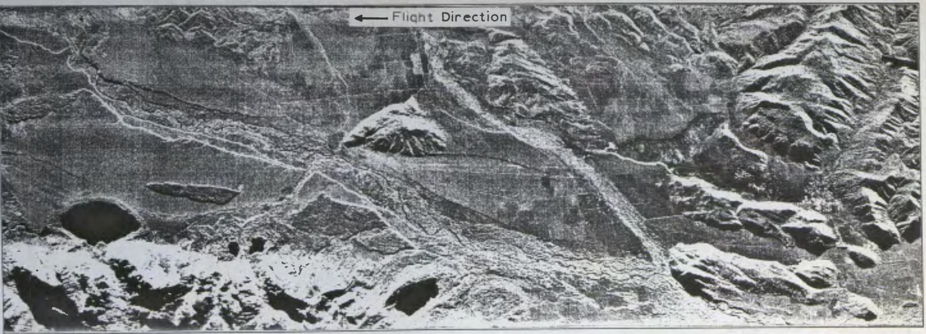


Figure 8 Radar Imagery of Jackson Hole, Wyoming

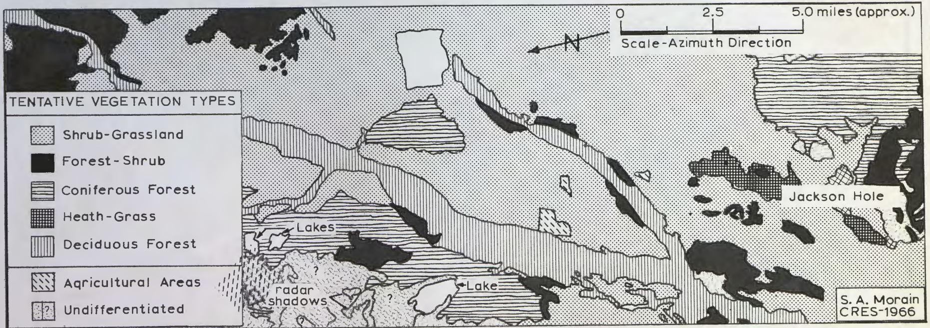


Figure 9 Major Physiognomic Vegetation Zones of Jackson Hole, Wyoming Prepared From Radar Imagery

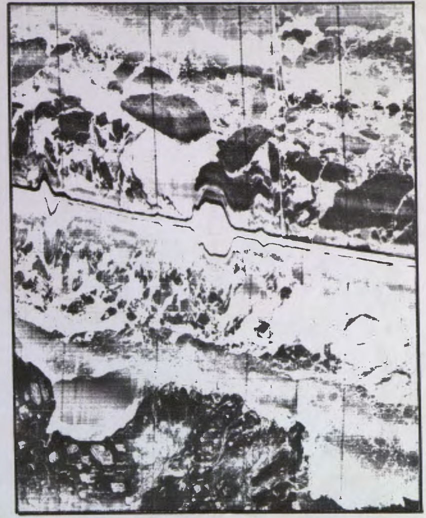


FIGURE 10 AN/APQ-56 Radar Imagery (Negative) of Prudhoe Sound, Alaska

K_a-Band (0.86 cm.)

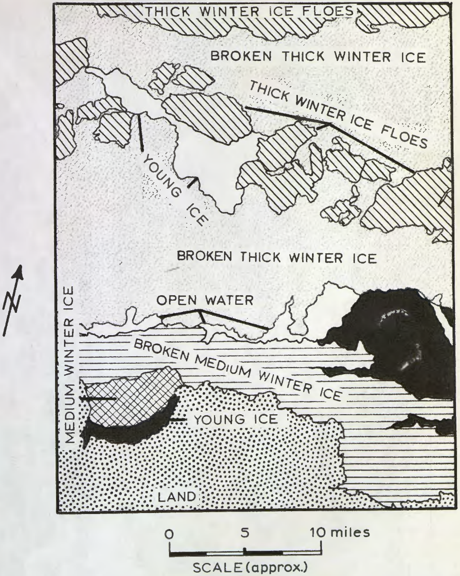


FIGURE 11 Tentative Ice Types Derived From AN/APQ-56 Radar Imagery (Interpretation From Beatty, F. D., et al, 1965)[16] of Prudhoe Sound, Alaska

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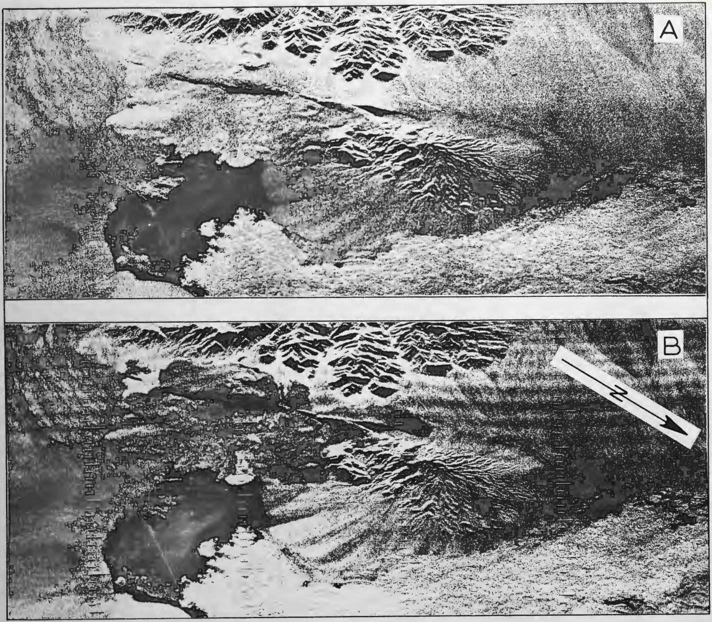
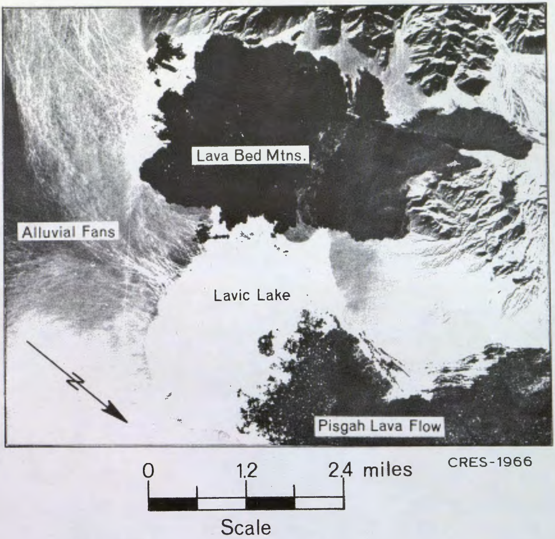


Figure 12 Radar Imagery of the Pisgah Crater–Lavic Lake Area, California

Polarization: Image A: Horizontal Transmit
Horizontal Receive

Image B: Horizontal Transmit
Vertical Receive



Fiqure 13 Aerial Photoqraph of the Pisqah Crater-Lavic Lake Area, California

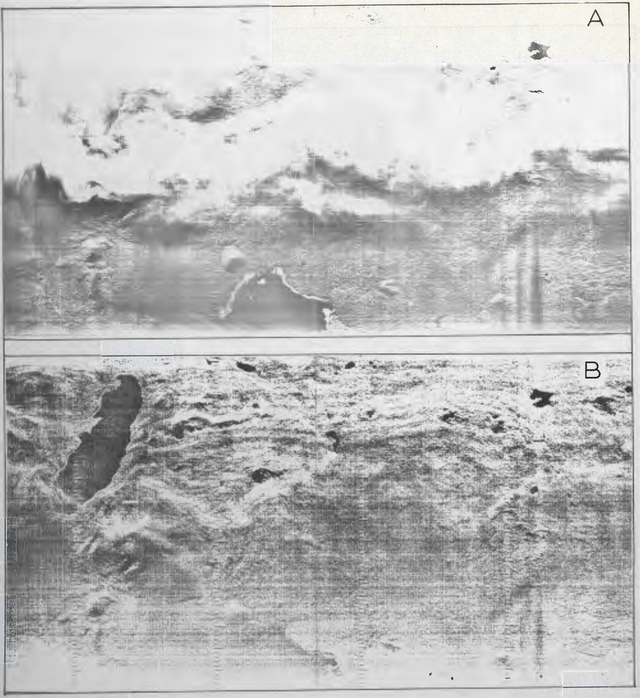


Figure 14 Precipitation Penetration Observed on Cross-Polarized Radar Imagery

POLARIZATION - IMAGE A: Horizontal Transmit
Horizontal Receive

IMAGE B: Horizontal Transmit
Vertical Receive

CRES-1966