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APPLICATION OF DIELECTRIC CONSTANT MEASUREMENTS TO RADAR IMAGERY INTERPRETATION

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Abstract

Although it is readily recognized that there is a need for ground truth to provide adequate guidance for remote sensing data interpretation, it is also noted that, in terms of radar remote sensing, this ground truth is often inadequate. Because radar "views the world" at relatively long wavelengths which have some penetration capability but also are affected by the electrical and physical properties of the surface upon which they are impinging, it is considered necessary to make basic electrical and physical measurements of this surface and to some depth below it. This paper presents a brief outline of such a ground-truth scheme, specifically, the measurement of the dielectric constant. Two portable instruments were designed specifically for this purpose; these are (1) a Q-meter for measurement of dielectric constant and loss tangent and (2) an instrument to measure electrical properties of the two operating frequencies of our imaging radar. Although extensive data are lacking, several general cases of radar-earth surface and interaction are described; also, examples of radar imagery and some data on ice and snow are presented. The paper concludes that the next logical step is to begin to quantify the radar ground truth in preparation for machine interpretation and automatic data processing of the radar imagery.

Introduction

One of the prime requirements for proper utilization and interpretation of remotely-sensed data, that is, the conversion of raw data into useful and usable information is the collection of ground-truth data. The direct relationship between what is seen visually (but not necessarily perceived) and that collected by panchromatic photography is obvious. A difficulty in the remote sensing field is often the change in perspective of the two views (ground truth vs. remote sensing). With the longer wavelengths of thermal infrared, it is often difficult to relate the two views. Our eyes observe one aspect of the scene (i.e., the visible) but the remote sensor detects another (e.g., heat). Small and portable instruments are available to aid us in the collection of thermal data at selected sites (e.g., thermal radiometers, thermometers). At even longer wavelenths, the problems of relating the visible scene and that sensed by the remote-sensing apparatus becomes increasingly difficult, and, at the radar wavelengths of concern in this paper (3 and 20 cm), the relationship is not at all obvious. In addition, because persons attempting to interpret radar imagery and those providing the ground-truth information are often from entirely different backgrounds and training, it is of pressing importance that we proceed to quantify both the ground truth and the remotely-sensed data. Only after quantification will we be able to successfully store, retrive, and statistically analyze the data and thus properly attack the problem of environmental monitoring and measurement using airborne radars.

The problem is not only the quantification of both types of data but also the need to make these data collections as simultaneously as possible. If the concern were only for the size, shape, and relative location of buildings, forests, or highways, it would be possible to do the ground truth measurements at any time within several days (or even months) of the remotely-sensed data collection. Conversely, when dealing with features which are more unstable and ephemeral, it is necessary to make the time lag between the two data collections as short as possible.

Finally, although it is often possible to remove portions of the scene from their natural locations and study them at the laboratory bench, this may subject the sample to changes during collection, storage, and transportation. For example, the collection of a soil sample for later testing can lead to greatly altered structure, porosity, permeability, and moisture conditions, whereas the chemical constituents and, in general, the grain-sized distribution of the sample will have remained unaltered. In the case of snow, time along is sufficient to alter the physical properties [1]. Thus, the nature of the study determines, to a large degree, the nature of the applicable ground truth which should be used in support of the remote-sensing operation. The organization and conduct of the ground-truth portion of a complete remote sensing study are discussed in several recent papers [2,3].

Numerous papers concerning the interpretation of radar imagery and the nature of radar backscatter from the ground are available [e.g., 4,5]. There is no need to reiterate these at length. However, it is instructive to simply present the radar equation [6] to illustrate the nature of the parameters affecting the backscatter or reflection of radar waves.

$$S = \frac{P_t\, G^2\, \lambda^2\, \sigma}{(4\pi)^3\, R^4}$$

in which:

S = received power (i.e., backscatter)

P_t = transmitted power

G = antenna gain

λ = wavelength of emitted EM wave

σ = echoing (scattering) cross section

R = range

Several of these parameters (P_t, G, λ) are functions of the radar instrument design and operation, one (R) is concerned with the relative location of the scene to the radar antenna, and the other (σ) is a function of the nature of the target. Basically, the scattering cross-section, σ, is determined by:

(a) the roughness of the surface relative to λ

(b) the electrical properties of the material in the scene

(c) the roughness of any subsurface layers prior to which the attenuation is insignificant [7].

Many studies have been conducted in which both theoretical and empirical measurements of the scattering cross-section are considered [e.g., 8]. However, there have been few attempts to relate measurements of the surface electrical properties (specifically the dielectric constant) to the radar images.

An example of the type of feature which we are attempting to ground truth and image is given in Figure 1. Figure 1a, illustrating ice in Lake superior, clearly shows the open water and ice floes. Figure 1b, an enlargement of a portion of Figure 1a, indicates, in addition, a series of tonal variations on one ice floe. The cause of these variations is unknown because ground truth is lacking and because the panchromatic photography showed a continuous white with no detectable variations in tonal signature across this floe. It is suggested that these variations are old crusted snow surfaces, now presumably buried by more recent drifting and falling snow. Thus, the variations noted on the radar images probably reflect variations in both density and electrical properties throughout the snow drifts. A complete report on this particular radar project is available [9]. It is also hypothesized that, given the proper conditions, radar could detect moisture changes in snow cover; should this prove correct, it would be of considerable importance in forecasting runoff from hydrologic basins having significant snow cover during hte late winter and early spring period. It has been suggested [10] that radars (in this case, K-band) can detect changes in soil moisture over an area; it is also recognized that snowfields can be detected on K-band radar imagery [11]. The next logical step, it would appear, is to approach the question of quantification of both the ground truth and the radar image in order to prepare these data for machine analysis.

Review of Work

Most active microwave imaging systems that have been developed and flown are designed to operate at a single frequency, utilizing only the bandwidth necessary to realize the range resolution required. These radars have been used for a wide variety of applications, including military uses, cartography, and a variety of earth science studies. The literature contains many applications, both real and potential. For example, uses for radar imagery have been defined for cartography [12,13], local geology [14,15], geomorphology [16], and for ice studies [17,18]. Relatively complete bibliographies listing numerous geoscience applications of radar are available [e.g., 19].

Multi-parameter radar systems have been used to obtain a measure of the cross-polarization (i.e,, dipolarization) ratio of the back-scattered signal. Because this ratio is strongly dependent upon the electrical properties of the scene [20], studies and experiments have been conducted attempting to use this ratio to determine additional information about the scattering surface. Such imagery (of the Pisgah Crater, CA. region) has been obtained and studied at various polarizations [21]. Geologic studies comparing optical and multi-polarization radar imagery showing such features as faults, fractures, and lineaments are also available [22,23].

Very interesting experiments have also been conducted using the cross-polarization ratio obtained from radar backscatter from the moon [24]. These experiments provide a measure of the cross-polarization ratio (Q) as a function of the incident angle (θ_i). The resulting curve (Q vs. θ_i) is a function of the dielectric constant of the scattering surface [25]. Estimates have been made of the dielectric consant of the surface of the moon using such data.

The lunar radar experiment does not result in a microwave "image" such as we are planning to utilize, but it is clear that the implementation and results are applicable. This is also true of the work reported by Brown [26] on an experiment designed to study the use of microwave backscattering to determine electrical properties of the earth's surface. The work of Lundien [27] and Dickey, et al. [28] is also of importance at this juncture. In both cases, the techniques and results are applicable to our efforts.

Multi-wavelength radar systems have also been used to provide near-simultaneous images from which a measure of the roughness of the scattering surface can be inferred. For example, the U.S. Navy and U.S. Coast Guard have conducted experiments using a four-frquency radar system to identify areas of varying sea surface roughness [29,30].

It is clear from a consideration of the results of the many related experiments using active microwave sensors that the interpretive potential of microwave imaging radar has not been fully realized. The system parameters to be utilized, in addition to the image of the surface, are (a) multi-wavelengths, (b) multi-polarization, and (c) amplitude calibration. It is expected that by obtaining measurements utilizing as many of the parameters as possible within a single sensor system, considerable additional information can be obtained by conducting the proper analysis of the radar signal. This analysis will require digital computation.

Clearly, the credibility of interpretation of microwave data requires a good foundation based upon proper ground-truth examples. This paper presents such an experiment and the results from the first phase of a long-term program.

The Radar System

The Environmental Research Institute of Michigan, under a NASA contract (NAS9-12967) with MSC, Houston, Texas, has instrumented a radar system which operates simultaneously at wavelengths of 3 cm and 20 cm, and receives both parallel and cross-polarized signals at both wavelengths. This equipment is presently installed in a C-46 aircraft. Although the system will transmit only one polarization during any given data collection pass, it may be configured to transmit either with horizontal or vertical polarization. Microwave backscattering data will thus be available to provide four separate images of a mapped area for each aircraft pass, e.g., X(HH,HV) and L(HH,HV) [31]. The radar signal is then converted into an output image by utilizing optical data processing techniques [32].

Hardware is available to convert the output map into digital form for analysis. This consists of an image dissector tube to scan the output image and an AD (analog-to-digital) converter whose output is recorded on magnetic digital tape. The software will be designed for each particular data-processing algorithm. Of primary interest in this work will be the cross-polarization ratio obtained for the operating wavelengths. These data are expected to provide the greatest insights into remotely measuring the dielectric constant of the earth's surface materials, and, through analogy, obtaining a measure of the moisture content of these materials.

An additional important capability of the new multi-wavelength, multi-polarization radar is its resolution capability. Resolution as fine as 10 meters in both azimuth and range can be realized. Thus, an integral part of the overall objective of the work is to utilize the parameter of fine resolution in the interpretation of the imagery.

The microwave signature will consist of measurements of (a) the cross-polarization ratio Q at both wavelengths, (b) the value of backscattered energy at the two wavelengths S_L and S_X, parallel-polarized (HH,VV), (c) the ratio of the values of S_L and S_X, and (d) the ratio of the values of Q obtained at the two wavelengths ($P = Q_X/Q_L$). The value of the signature parameters will be obtained as spatial statistical averages over the area of interest. Clearly, this will be obtained using the digital techniques described above.

The Experiment

The questions to be answered utlimately by means of the information obtained during the complete experiment are:

(a) Are the ground truthing techniques used adequate? That is, can the ground parameters be determined in the field with sufficient accuracy and consistency?

(b) Can characteristic signatures of ice and snow types be determined by using the four signatures proposed (X-band, HH, HV; L-band, HH, HV)?

(c) What is the sensitivity of the radar system, i.e., how much variation in the electrical properties and geometrical properties can be recognized with this technique?

(d) Is this type of data applicable to digitization, digital processing, and automatic interpretation?

(e) Can analog optical techniques be used in data reduction?

The first phase of the experiment emphasized in this paper is concerned with questions (a) and (b) above. Instruments are available to measure physical parameters of the ice-snow (e.g., SIPRE Snow Kit). In addition, two instruments have been designed and constructed with which to obtain measures of the electrical properties of snow and ice. These instruments provide a measure at both frequencies of operation of the radar and at 100 MHz using a simple

Q-meter designed for this application (Figure 2). The Q-meter will provide measurements for the control or reference values and also the measurement of fine structure of the snow and ice (on the order of a wavelength), to determine roughness characteristics.

As stated in the introduction, there exists a need to determine particular characteristics of ice and snow for environmental resource studies. Microwave measurements, both active and passive [e.g., 33, 34], have been applied to various aspects of the problem with overall encouraging results. In order to evaluate the potential of imagery from microwave sensors, additional imagery is required with (a) pre-flight ground truth for planning, (b) simultaneous ground truth during the flight, and (c) carefully documented post-flight ground-truth data from areas of interest identified on the imagery. A study of existing radar imagery covering ice and snow regions of Lake Superior (Figure 1) has shown several interesting features which have not been adequately explained using aerial photographs [35]. Several possible explanations exist for the observed features. Two particular cases will be discussed, although it is expected that the experiment will reveal other interesting facts to add to the information obtainable by proper interpretation of radar imagery.

Case I: The roughness of the scattering surface, defined in terms of the sensor wavelength, determines the magnitude of the backscattered power [36]. The scattering surface is defined as the first discontinuity within the media along the propagation path. The earth-air boundary is usually the scattering surface for the radiation transmitted from an imaging radar system, although there are isolated situations where the scattering surface may not coincide with the optical surface (e.g., dry soil above wet clays). A measure of the reflection coefficient [37] at a discontinuity can be obtained from a comparison of the relative dielectric constant on each side of the discontinuity.

Recall: (a) that the index of refraction is related to the dielectric constant ε by $\eta = \sqrt{\varepsilon}$ (for air ε = 1); (b) the reflection is in excess of 50% for waves incident normal to a surface slope with ε = 10. The reflection coefficient is a function of the polarization. Thus, for values of $\varepsilon \lesssim 4$ the reflection is very small and most of the incident energy is transmitted across the boundary to be reflected at the next surface discontinuity.

Measurements of the relative dielectric constant of dry snow and ice [38,39] gives $\varepsilon < 4$, so that transmission into the subsurface media can be expected. An estimate of the propagation loss in a material can be obtained from a measure of the loss tangent (tan δ) of the material. Again, with reference to measurements made on snow and ice [38], the values of tan δ obtained indicate that penetration on the order of meters for 3 cm wavelength is realized, with even greater penetration for the 20 cm wavelengths. The relationship for the field strength E (i.e., the value of the radiation from the radar) at a given wavelength λ when propagating in a medium with loss tangent tan δ and relative dielectric constant ε is given by

$$E(X) = E_o e^{-\left(\frac{\pi \tan}{\lambda} \sqrt{\varepsilon}\right) X}$$

Examples of measured values of tan δ and ε for snow are given in Table I. Values for x_d given in Table I are such that:

$$E(x_d) = E_o \frac{1}{e}$$

Temp	λ (cm)	tan δ	ε	x_d
-6°C	3	5×10^{-4}	2	10 m
	30	10^{-3}	2	60 m

Table I. Examples of measured values of tan λ and ε_i for snow.

An example of results obtained from one series of ground truth measurements for snow is given in Figure 3. Values of density, temperature, and dielectric constant are obtained relative to the depth in to the snow pack. A pit is dug and measurements are made down the shadowed side in order to minimize heating effects. Loss tangent values were also obtained but not shown in Figure 3.

A second example of ground truth measurements to be used is given in Figure 4. A plot of relative dielectric constant contours is shown, obtained from measurements using the Q-meter described above. The grid is approximately 3 by 3 meters, with samples obtained at 30 cm increments. Values given were obtained in new snow about 15-20 cms deep over the ice surface of Douglas Lake, Michigan. Fine scale measurements can be used to determine the roughness of the dielectric variations.

A second instrument is used to provide a measure of the electrical properties at the frequencies of the imaging radar, i.e., at approximately 1.3 GHz and 9.6 GHz. This instrument is illustrated schematically in Figure 5. A solid state source is provided at both frequencies. Power is coupled through slotted lines, one for each frequency, and then radiated through simple waveguide antennas. The slotted-line sections are used to obtain a measure of reflected power and phase shift when the antenna apertures are placed on the surface of snow or ice. The complete measurement system is mounted in a large metal ground plane, which is supported at each corner to avoid compressing the snow.

Values of reflected power and phase shift can be used to obtain estimates of the electrical properties at the radar operating frequencies. Reduction of the data is realized by obtaining an approximate solution for the radiation admittance of the waveguide antennas when radiating into a homogeneous or layered media of particular dielectric values. This method of measuring electrical properties is similar to techniques used for plasma diagnostics and electron density measurements. Although the technique is not extremely accurate, it will provide a reference measure of the electrical properties at the imaging radar frequencies. It should also be pointed out that the scattering is a volume effect for the situations considered.

By careful ground-truth studies, it is expected that the various structures and features of the snow and ice can be correlated with backscatter characteristics (i.e., the radar image) and used as a basis for interpretation.

Case II: The second case will make use of the cross-polarization ratio Q as measured by the radar systems in addition to the roughness characteristics. Ideally, one would want to obtain a measure of Q as a function of angle as discussed above. This can be accomplished to some degree with an imaging radar but requires two or more imaging passes over the area of interest to obtain the multiple look angle. This is illustrated in Figure 6, and is similar to a scheme for stereo radar [40]. (It is pointed out, as a matter of interest, that a radar technique is available that can provide multi-angle looks simultaneously over a fairly wide range of incident angles from normal to 45° [41]. The field of view of this system is similar to that of infrared and photographic systems.)

Values of the cross-polarization ratio are dependent upon (a) the slopes of the scattering surface, (b) the Fresnel reflection coefficients, and (c) geometry [42]. The Fresnel coefficients are dependent on the dielectric constant of the reflecting material. Measures of Q obtained from the radar measurements when correlated with the radar imagery will "pin point" the area of interest within the resolution element of the radar. Ground truth will be obtained, using techniques described above, and correlations made.

The objective of "Case II" is to obtain the polarization characteristic signatures of the various ice-snow types and distribution.

Conclusions and Future Work

The research scheme in toto was outlined above, and it was noted that this paper is concerned only with parts (a) and (b). That is, can we adequately conduct our ground truth and, if so, can we detect characteristic signatures for the various types of ice and snow of interest? By types of ice and snow, the concern is not only for fresh water ice (e.g., black ice, white ice, slush, etc.) but also for sea ice (often defined as first year, annual, polar, etc.). As concerns snow, the variations in density, moisture content, structure, and depth are all of major importance to persons concerned with predicting stream runoff from snow covered hydrologic basins. An introductory discussion of the variables and problems in such studies is available [43].

The scheme of quantification of ground truth for aid in interpreting imaging-radar remote-sensing data has been briefly discussed. Although it is recognized that numerous problems will be encountered, and thus demand solutions, it is felt that to continue to concern ourselves primarily with the theory and thus avoid the real-world conditions would be to fail to discover insights into some of the data which are available on radar imagery. It is not difficult to see the obvious parallels between the type of work reported here (and the scheme of which it is a larger part) and the development of the interpretation of aerial photographic and multi-spectral scanner data. What makes radar somewhat unique is the fact that it is active. It also views the world at entirely different wavelengths; these are very long wavelengths which have the ability to penetrate to some depth below the optical (visible) surface and thus identify subsurface structures.

In addition, it is recognized that, with the present rapid rise in the use of remote sensors and the speed with which they are able to collect data and present it to the interpreters, there is a continuing serious problem of a

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data overload which is entirely beyond the capabilities of human manipulation. Hence, we encounter the problem of machine analysis. This problem has been and is continually being attacked; in many cases, it has been resolved [44]. However, prior to determining the ultimate algorithm for machine analysis of radar imagery, it is obviously necessary to obtain a set of "spectral signatures" from the various surfaces which are of primary interest [e.g., 45]. In this paper, the application of the method for ice and snow has been the major stress; however, it must be recognized that these surfaces were selected for rather selfish reasons--they closely approach the isotropic plane which geographers often discuss. That is, we effectively remove much of the surface roughness and are thus able to empirically approach the problem of the effect of dielectric constant on backscattering of radar energy.

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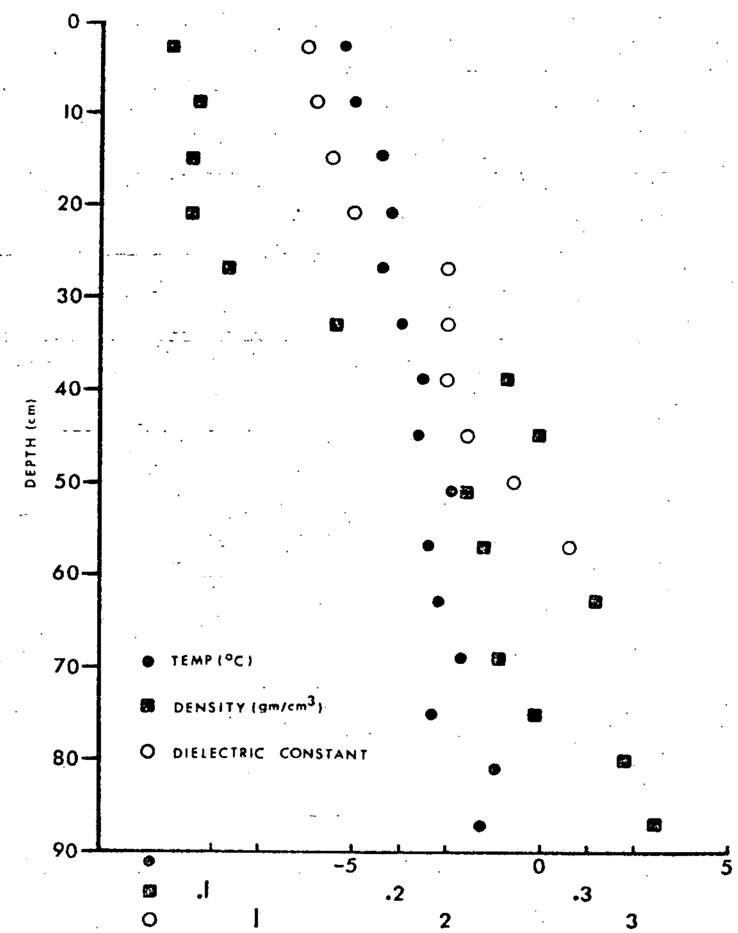

FIGURE 3. Profile of Temperature, Density, and Dielectric Constant of a Snow Bank. Douglas Lake, Michigan. 22FEB73.

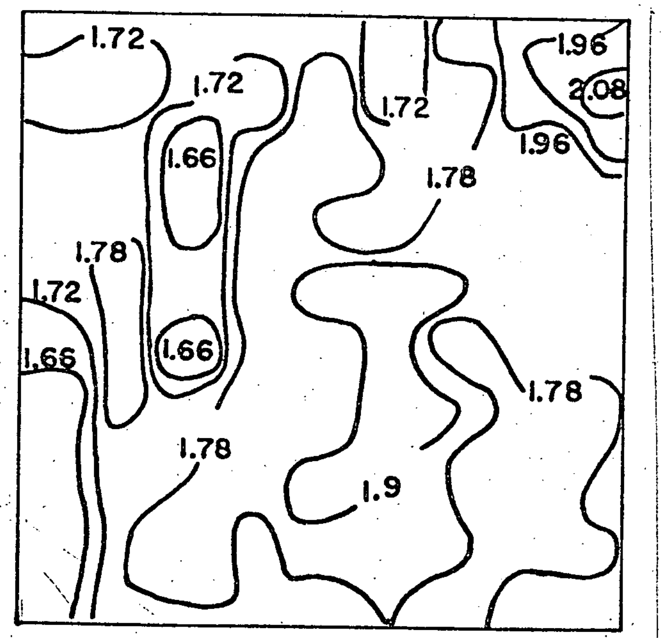

FIGURE 4. Contour Plot of Relative Dielectric Constant Values Obtained in a 3 x 3 m^2 in New Snow over Lake Ice. Measurements Made February, 1973.

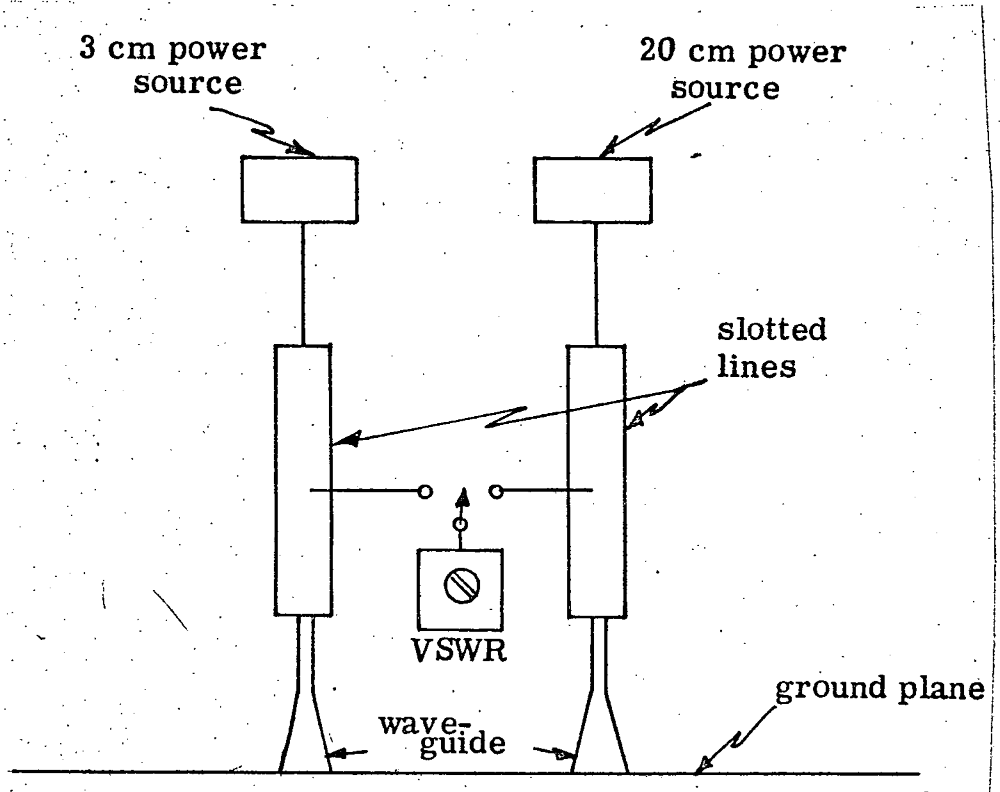

FIGURE 5. Diagram of Instrumentation Used to Measure Electrical Properties at Wavelengths of 3 cm and 20 cm.

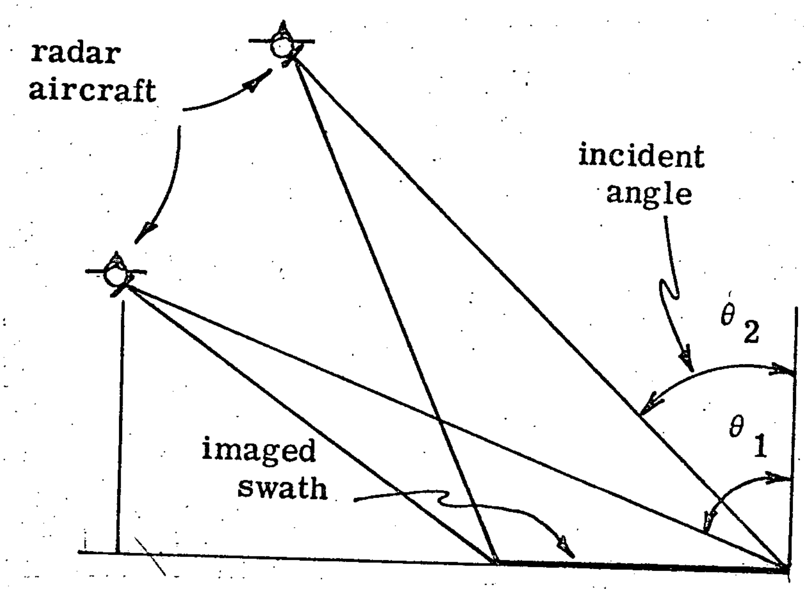

FIGURE 6. Sidelooking, Imaging Radar Geometry. Geometry for Two Imaging Passes are Shown.

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