RADAR AND MICROWAVE RADIOMETRIC TECHNIQUES FOR GEOSCIENCE EXPERIMENTS

The Ohio State University

ElectroScience Laboratory

(formerly Antenna Laboratory)
Department of Electrical Engineering
Columbus, Ohio 43212

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REPORT
by
THE OHIO STATE UNIVERSITY ELECTROSCIENCE LABORATORY
(Formerly Antenna Laboratory)
COLUMBUS, OHIO 43212

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ABSTRACT

This report reviews work performed under NASA Contract NSR-36-008-027. It provides brief descriptions of the equipment developed to measure backscattering cross-sections and brightness temperature of terrestrial surfaces at microwave frequencies, of the measurements made with the equipment, and of the interpretation of the measurements in terms of surface parameters such as dielectric constant and roughness. Techniques for measuring dielectric constant of natural materials at microwave frequencies are described.

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This report summarizes work performed at the ElectroScience Laboratory under Contract NSR-36-008-027 between the National Aeronautics and Space Administration and the Ohio State University Research Foundation. The actual results of the investigations are presented in a series of technical reports (References 1-9) to which the reader is referred for details. This final report reviews the motivation for the work, gives brief descriptions of the results, and some recommendations for future studies.

I. INTRODUCTION

During the past several years, there has been an extensive program to develop remote sensors for spacecraft and aircraft, particularly for surveys of the surface of the earth. Many of these sensors (e.g. conventional photography) have a long history of image interpretation for special purposes. In others, for example radar and microwave radiometry, the relation between the quantitative aspect of the sensor output and those of the interrogated surface are not so well understood. Futhermore, because the imagery from such sensors has not been widely distributed in the past, there is a lack of awareness of the potential application of the sensors to such disciplines as geology, agronomy, etc. Thus along with the program of sensor development there must be pursued a program of interpretation and calibration, in the widest sense of the terms, to demonstrate the feasibility of using the sensor for scientific or technological purposes.

In discussing remote sensors, particularly for geoscience applications, two rather different kinds of sensor output must be considered. The first, the imaging function of the sensor, utilizes suitable scanning and display techniques to produce an image of the area under consideration. Because of the many processing steps, it has often proved rather difficult to use such images quantitatively, (except for quantitative length scales). The true value of the image is that it provides patterns, upon the recognition and interpretation of which all the manifold skills of a trained human interpreter may be brought to bear. The imaging function should then permit us to recognize areas of special interest for further quantitative study. It is only to these smaller areas that the second type of sensor study, detailed quantitative measurements of surface characteristics, would be made; and such measurements may then lead to some interpretation of surface properties, in terms of previous calibration of the sensor.

In using images, a number of devices or techniques which can aid the psychological aspects of interpretation (variable intensity contrast, edge sharpening, synthetic colour contrast based on frequency or polarization differences, selective dynamic range expansion, etc.) can be exploited. It is clear that this class of sensor output is most likely to require a human operator for the equipment, as well as a human interpreter of the output. From such a sensor output one may expect to discover many features of significance, without necessarily being able to explain them. At the present time only optical photography, some single parameter maps (magnetometer, gravity field) and to a lesser extent infrared imagery, has any extensive history of interpretation, although some work has been started on the interpretation of radar images with geological objectives.

The second class of sensor output should provide quantitative data, accurate and well calibrated. From the numerical outputs of such sensors, in coordination with a previous knowledge of the behavior of the same sensor with respect to well understood test surfaces, the process of identification can begin. In the field of radar (and to a lesser extent microwave radiometer) sensors, a considerable amount of information is available about the quantitative response of certain kinds of surfaces; but these data have been gathered primarily to aid in system design, rather than for the study of the surfaces themselves.

The studies reported here are related to both kinds of sensor utilization. In connection with the quantitative use of imagery, a number of measurements of typical surface responses were made, which should permit the calibration of image gray-scales in terms of absolute backscattering cross-sections. Although these measurements were made as a service function under the contract (with the calibration to be made at certain designated test sites) the data have also proven useful for the second type of sensor utilization; the more detailed studies of the relation of surface properties to sensor response.

The succeeding sections give brief specifications of the truck-mounted radar-radiometer measurement facility used to make these measurements (Section 2). A summary description of data taken and surfaces investigated, both at the test sites and during the subsequent studies of back-scattering cross-sections and brightness temperatures of prototype surfaces is given in Section 3. Because the data were not easy to interpret unless accompanied by adequate descriptions of the surface (the "ground-truth") considerable effort was made to provide complete surface descriptions. This required estimates of the dielectric constants of the surface materials, and some of this work is reported in Section 4. Theoretical studies, mainly concerned with the interpretation of sensor responses are described in Section 5. Some geologically oriented studies in the interpretation of radar imagery are described in Section 6. Finally, in Section 7, a number of conclusions and recommendations are made.

II. THE MOBILE RADAR-RADIOMETER FACILITY

One of the major tasks undertaken during the contract was the provision of a facility for obtaining accurate sensor calibration levels at certain prescribed test sites, and for investigating the relations between surface characteristics and sensor response over carefully controlled prototype surfaces. The equipment used to collect this surface response data is fully described in Reference 6.

Briefly it consists of four truck-mounted c-w doppler radar systems, operating at 1.8 GHz, 10GHz, 15GHz and 35GHz, and two Dicke type radiometers operating at 10GHz and 35GHz (0.5GHz r.f. bandwidth). The r.f. portions of each of these six sensors is packaged in a box, which may be mounted at the end of a boom on the truck. Rotation of the box provides any linear polarization for the system. The audio and digital processing and data collection units are housed in a small laboratory built into the rear of the truck, which also carries an electrical generator. Thus the entire facility is self-contained and may be driven to any accessible site. The radar measurements require that the truck be driven a distance of about 100 feet alongside the surface to be measured, so that there will be sufficiently many independent samples to provide statistically significant averages.

During the first few months of the contract the radar system at 1.8 GHz and the radiometers at 10 GHz and 35 GHz were designed and constructed. Previously existing radars at 10, 15 and 35 GHz were updated during this period. During the first year's measurements, an existing (see Ref. 10) recording and data analysis system was used. This was completely rebuilt during the second year to provide automatic data recording, suitable for computer processing, for the radar systems. These improvements made possible rapid data handling, and computer generated output in tabular or graphical form (see Ref. 6). During this period the 10 GHz radar was provided with a cross polarized channel.

The radar systems are designed to measure the parameter $\sigma_0(\theta)$, the back scattering cross-section per unit area of terrain, as a function of incidence angle, for any linear (or, at 10 GHz crossed-linear) polarization. Thus it provides the sensor response corresponding to the "scatterometer" experiment, and establishes absolute levels for image calibration. The usable spread of angles of incidence is from 10^o to 70^o, the limit of 10^o being established by the truck speed needed to generate suitable doppler shift, and the limit of 70^o, (near grazing) being established by geometrical considerations which are particularly restrictive for vegetation (e.g. corn or sudan grass) whose height is a significant fraction of the working range of the radars (20 ft.). The range of the radar return parameter $\gamma_0(\theta_0) = \sigma_0 \sec\theta_0$ which can be measured extends from $\gamma_0 = +3$ dB (determined by the local oscillator power available) to better than $\gamma_0 = -35$ dB for the radars at 1.8, 10, and 15 GHz and to better than $\gamma_0 = -30$ dB at 35 GHz. The half power antenna beamwidths are 12^o, 5.2^o, 3.8^o, 2.0^o and the illuminated spot sizes on the ground are 13.7 sq. ft., 2.6 sq. ft., 1.5 sq. ft., and 0.4 sq. ft. respectively. Absolute calibration is by means of radar targets of known cross-section, an oscillating sphere being used for the direct polarized channel and a uniaxially conducting screen, rotated to provide sideband signals to simulate doppler shift, for the cross-polarized channel.

The radiometers, also described in detail in Ref. 6, are of standard Dicke type, and were designed to measure absolute brightness temperatures with a precision comparable to the minimum detectable temperature difference measurable by the instrument. For this reason particular emphasis was placed on an antenna design with low and well controlled side and back lobes, in order to permit efficient inversion of the integral equation relating antenna temperature to brightness temperature. However, for reasons of economy and simplicity, the original instruments utilized the zenith sky temperature as one calibration point and were operated in this configuration during the first year. They were subsequently converted to more conventional hot-cold oven loads in order to permit an independent check of the zenith calibration.

The radiometers have minimum detectable temperature differences of less than 1.5°K and 3°K, with beam widths of 3.5° and 1.5° at 10 GHz and 35 GHz respectively. Estimated precision in measuring the true surface brightness temperatures is approximately 3°K and 5°K respectively after inversion, in the range of antenna temperatures between 200°K and 350°K with poorer performance below 200°K because of the relatively small difference between hot and cold load temperatures.

III. THE MEASUREMENT PROGRAMS

The major part of the work carried out under this contract has been an extensive series of measurements of the radar and radiometer response of terrestrial surfaces at microwave frequencies, using the equipment described in the previous section. The first set of measurements, carried out in the summer of 1965, has as its objective the calibration of certain designated test sites. The sites at which measurements were actually made included 1) The Purdue Agronomy Farm (Agronomy Test Site) 2) Pisgah crater and Lavic Lake (Geology Test Site) and Mono Craters (Geology Test Site). In addition, measurements were planned at the Wilcox Playa Site (Special Radar Test Site) but at the time the mobile radar-radiometer equipment was stationed at Wilcox (1-3 July 1965), the site preparation was not complete.

The measurements made at these sites are reported in detail in Ref. 7 (geological radar data), Ref. 9 (agricultural radar data), Ref. 2 (radiometer data) and Ref. 3 (interpretation), together with appropriate ground truth data. Measurements at the Pisgah site included one smooth surface (Lavic Lake, a dry lake bed) and a number of lava surfaces of differing small scale roughness, distributed over the northern edge of Lavic Lake. Measurements at the Mono site also included one smooth surface (a lapilli plain at the base of one of the cones) and a number of rougher surfaces on the cones (large blocks of pumice or obsidian). Measurements of both the first (1965) and second (1966) series at the Purdue Agronomy Farm covered only agricultural surfaces (wheat, oats, soybeans, alfalfa, corn) under various stages of growth and cultural practice.

The second part of the measurement program had as its objective the collection of data over a wide range of surface prototypes, in order to produce a catalogue of surface responses, to provide data for comparison with theoretical models of surface response, and to suggest applications to the problem of surface identification or characterization with microwave sensors. Again the radar data are reported in Refs. 7 and 9 with radiometer data in Ref. 2. In each case, again, appropriate surface descriptions were provided. Among the sites measured were; the Purdue Agronomy Farm and the Purdue "Sand Farm" (where irrigated and non-irrigated crops could be measured in environments almost identical except for soil moisture); an exposed, glacially polished limestone surface in Marblehead, Ohio; an exposed coal bed in a strip mine near Cadiz, Ohio; and a number of vegetated surfaces in the vicinity of Columbus, Ohio.

Although the data are of considerable interest in themselves, particularly for system designers, they have also led to a number of interpretations of surface response, discussed more fully in References 2, 3, 7 and 8. For example, radiometer measurements over the limestone and coal surfaces mentioned above have established that at least for surfaces as smooth as these, the sensor can produce a rather good estimate of the dielectric constant of the surface. More surprisingly, a comparison of the vertical and horizontal radar returns from the limestone surfaces established that the dielectric constant could also be measured, though somewhat less accurately, with the radar sensor. Similarly, comparison of measurements with both radar and radiometer sensors over diffusely scattering surfaces have established experimentally the close connection between albedo and back-scattering described in Ref. 3. Further analysis of measurements made over a sequence of diffusely scattering pumice blocks of different densities has established that one can even estimate the density of the pumice reasonably well from the brightness temperature. Other examples of the use of these data include the analysis of the seasonal behavior of such crops as oats, wheat, soybeans, estimates of the optical depth of vegetation layers, etc.. It is believed that the extensive collection of radar data in References 7 and 9 will provide scientists in a number of disciplines with material for assessing the value of radar as a remote sensor, and for interpreting imagery.

IV. DIELECTRIC CONSTANT MEASUREMENTS

It was recognized at an early stage in the measurement program that among the most important of the supporting "ground-truth" data would be the complex dielectric constants (ε) of the surface materials, since very little information was available about the values of ε for natural materials. Standard methods for determining ε were not suitable due to the irregular shape and texture of the samples. Thus two types of measurement systems, appropriate for these irregular samples, were investigated.

The first was directed at the problem of the dielectric constant of vegetation, particularly as it depended on the moisture content of the sample, since ε is predominantly determined by water at microwave frequencies. A cavity perturbation technique described in detail in Ref. 5, was developed which permitted reasonably accurate measurements (limited mainly by the precision with which the sample size could be determined).

Samples of a number of types of vegetation (grass, corn, taxus, spruce) were measured as they dried out, and the values of complex dielectric constant plotted against the moisture content. It was found that the variation was almost linear over the range of moisture contents in the samples. This result is of particular value in supporting the view that the bistatic cross-section, and thus both the radar return and the brightness temperature of vegetated surfaces, can be dependent on moisture content as well as on structure. In addition, a simple formula for the dielectric constant of vegetation based on the measurements has provided a convenient input parameter for theoretical models of vegetated surfaces.

A second class of natural materials for which special methods are required to measure ε is that of rocks and minerals. Here there is another difficulty since many such materials contain ferromagnetic compounds. Thus the relative magnetic permeability, μ, must also be measured, again for samples which may be neither homogeneous nor isotropic. The technique developed for this kind of sample, described in detail in Ref. 4, is also, in a sense, a perturbation method in that it requires the measurement of the fields scattered in two orthogonal directions by a small spherical sample. The advantage over conventional waveguide and transmission line or cavity techniques is that rotation of the sample permits estimates of anisotropy and inhomegeneity. A second advantage is that, for sufficiently small spheres, the electric and magnetic scattering is decoupled, avoiding the requirement to solve the complex transcendental equations encountered in waveguide methods. Measurements made by this technique indicate that accuracies of a few per cent are attainable for materials with dielectric constants in the range $1.5 < |\varepsilon| < 20$ likely to be encountered in nature.

V. THEORETICAL STUDIES

During the course of the contract, a number of theoretical studies were undertaken in support of both the measurement and the interpretation programs.

a) Polychromatic Imagery

One of the techniques for increasing the information content of an image, and simplifying the problems of image interpretation, is the use of color. The most obvious application at microwave frequencies, as was suggested some years ago, is to combine black and white images made at several different frequencies, to produce a synthetic color. In order to demonstrate the feasibility of this approach at a time when multiband radar imagery was not available, it was decided to construct synthetic black and white images, using $\sigma_0(\theta)$ vs. θ data taken with the mobile radar system. These were combined in various ways (for details see Ref. 1) to produce the final simulated color images of a typical terrain. It was found that distinctive differences in color were developed, as between vegetated ground, bare ground, and man-made surfaces, and that these differences were preserved over a wide range of look angles.

Although more sophisticated schemes, using electronic processing, have since been developed by other investigators, the color images obtained by the simple scheme of Ref. 1 offered positive indication of the feasibility of polychromatic imaging of terrain, and early justification for the subsequent studies in this area.

b) Mutual Interpretation of Microwave Sensor Data

A significant consequence of the fact that the radar return and the microwave albedo (and thus emissivity) are controlled by the bistatic pattern is that the mutual interpretation of active and passive sensor data can often lead to a considerably more detailed and less ambiguous interpretation of surface characteristics than could be made from either sensor alone. A detailed study of the consequences of this point of view is given in References 3 and 12. It was found that, for example, by using the radiometer response to establish that a surface was a member of the "slightly-rough" class, the actual roughness could be estimated from the radar return. Another example involved the use of the radar return to classify a surface (pumice blocks at Mono craters) as unambigously Lambertian, and then making use of the radiometer response to estimate the density of the pumice. Other applications, to vegetated surfaces, to determining the kinetic temperature of a surface, etc., are also reviewed in References 3 and 12.

c) Applications of Microwave Radiometry

During the course of the radiometer measurement program, it became apparent that very little published information on the fundamentals of microwave radiometry was available to the non-specialist interested in potential applications of the sensor, and that a number of misconceptions existed, based on faulty analogies between the microwave and the infrared or optical region of the spectrum. Furthermore, there was not available a comprehensive survey of the possibilities for using this sensor as a quantitative scientific tool. To fill this gap. Ref. 8 was prepared. This report surveys the fundamental principals of radiometry, considers some of the limitations imposed by instrument design, reviews the relation between surface properties of scientific interest (such as soil moisture, crop moisture, sea state etc.) and the corresponding brightness temperatures, and outlines the more important technical and scientific applications of radiometry to date.

VI. RADAR IMAGERY

As an adjunct study, 12 flights of K-band side-looking airborne radar (SLAR) imagery were evaluated for geologic content and related radar anomalies. Table 1 below lists the flight numbers and general geographic areas covered. Copies of the original imagery, which was generated by Westinghouse for the U.S.A.F. Systems Command, were provided by NASA-MSC. Results of these studies are reported in part in references 13, 14, and 15. The major advantages of radar imagery over other sensors that produce

TABLE I
K-BAND SLAR IMAGERY FLIGHTS MADE BY WESTINGHOUSE FOR U.S.A.F. SYSTEM COMMAND AND USED IN THIS STUDY

Flight No.	Date Collected	General Geographic Location
82	9/65	Hagerstown, Md. to Dayton, Ohio
89,94	10/65	Yellowstone, Beartooths, Absarokas, Tetons, Idaho
100	10/65	Mono Craters, NW. Nevada
101	11/65	Mono Craters, San Francisco, Pisgah Crater, Las Vegas
102	11/65	SW. Nevada, Pisgah Crater, San Diego, Los Angeles
125,125,129, 122,123,124	7/66	Mid-west, central Appalachians, New England

a photo-like display, is that it is active, illuminates the subject or target at an oblique angle, and is synoptic. This greatly enhances topography and the overall view of landform distribution. Topographic form and distribution in turn can be interpreted in terms of the lithology and rock structure underlying the surface. In addition, lithology and rock composition in part control small scale roughness and vegetative cover, which significantly affect radar backscatter. It has been found that "ground truth" as read from geologic maps is reflected in a general way at least on radar imagery. This is especially true of structural configuration of the bedrock, and in a few cases structural features have been detected that were unknown previously. This interpretive work is continuing with modest confidence in further enhancing the value of radar imagery in geologic interpretation.

VII. CONCLUSIONS AND RECOMMENDATIONS

On the basis of the work described in the preceding sections, it may be concluded that:

a) The construction of the mobile radar radiometer measurement system has made it possible to provide absolute radar cross-section (σ_0) and brightness temperature (T_a) measurements which can serve as accurate calibrations for aircraft or spacecraft borne sensor programs, and which may also be used to establish at least a part of the grey-scale range of radar or radiometer imagery. It is recommended that calibrations of this type be made for at least some of the forthcoming flight tests of imaging sensors, so that the very large amount of information which such systems can generate may be utilized by those scientists and engineers interested in quantitative evaluation of the imagery or the system.

b) The large amount of data gathered under the program have provided considerable insight into the connections between sensor response and those surface properties, such as moisture content, roughness etc. which are of more direct interest to users of the sensor output. The data have been important in developing theoretical or model surfaces and checking consistency between theory and measurement. A number of direct quantitative relations have been established between sensor response and surface parameters such as dielectric constant and small scale roughness; those have led in turn to indirect relations between response and such parameters as density or moisture content. A number of qualitative associations (e.g. that between moisture content and sensor response for vegetation) have been suggested by the data, but have not yet been established quantitatively. It is recommended that, although in many cases sensor data can be gathered in much greater quantity from aircraft or space craft, there is still a role for measurements with ground-based equipment. This is especially true where precise sensing of the response of rather small, homogeneous areas, with complete synoptic ground truth data, or where extensive time sequences (as in crop development studies) are required.

c) It has been shown that there are significant improvements in the interpretation process when simultaneous active and passive microwave sensors are used. Some specific examples, based on rather simple surface models, have been exhibited. However, many natural surfaces are not well described by these simple models, making it difficult to exploit the advantages of the combined active-passive interpretation procedure. It is suggested that theoretical studies of these more complex surfaces would extend the range of applicability of this interpretation process.

d) Two perturbation methods convenient for determining the dielectric constant of vegetation and rocks or minerals, respectively, have been developed. It is recommended that, because of the great influence of the dielectric constant in determining sensor response, and the rather scanty information available about this parameter for many natural materials, such measurements continue to be made in connection with the ground-truth studies in support of flight tests. Of particular importance is the accurate determination of loss tangent, since it determines the skin depth, i.e., the thickness of the layer to which the sensor responds.

e) Convenient methods for inverting the integral equation relating brightness temperature to antenna temperature have been developed.

However successful and economical use of the inversion procedure requires specially designed antennas. It is recommended that a study of antenna designs to simplify or eliminate the inversion process be undertaken with attention to the effects of the radome on pattern and brightness temperature, and of the possibility of designing beamless antennas for post-detection side lobe cancellation.

REFERENCES

1. Shephard, G.G., "Polychromatic Terrain Imaging," Report 1903-1, 31 May 1965, Ohio State University, ElectroScience Laboratory

2. Riegler, R.L., "Microwave Radiometric Temperatures of Terrain," Report 1903-2, 30 June 1966, Ohio State University, ElectroScience Laboratory, (Thesis).

3. Peake, W.H., Shultz, C.H., Riegler, R.L., "The Mutual Interpretation of Active and Passive Microwave Sensor Outputs," Report 1903-3, 15 July 1966, Ohio State University, ElectroScience Laboratory.

4. Young, J.D., "Constitutive Parameter Measurements Using the Scattering Technique, Report 1903-4, 6 February 1967, Ohio State University, ElectroScience Laboratory.

5. Carlson, N.L., "Dielectric Constant of Vegetation at 8.5 GHz," Report 1903-5, 31 March 1967, Ohio State University, ElectroScience Laboratory, (Thesis).

6. Oliver, T.L., "A Mobile Facility for Measuring the Backscattering and Brightness Temperature of Terrain at Microwave Frequencies," Report 1903-6, 4 October 1968, Ohio State University, ElectroScience Laboratory, (Thesis).

7. Peake, W.H., "Radar Backscattering Data from Geological Surfaces at Microwave Frequencies," Report 1903-7, in process, Ohio State University, ElectroScience Laboratory.

8. Peake, W.H., "The Microwave Radiometer as a Remote Sensing Instrument," Report 1903-8, in process, Ohio State University, ElectroScience Laboratory.

9. Peake, W.H. and Oliver T.L., "Radar Backscattering Data from Agricultural Surfaces at Microwave Frequencies," Report 1903-9, in process, Ohio State University, ElectroScience Laboratory.

10. Cosgriff, R.L., Peake, W.H., Taylor,R.C., Terrain Scattering Properties for Sensor System Design, (Terrain Handbook II), Engineering Experiment Station Bulletin, Number 181.

11. Moore, R.K. Radar Scatterometry - An Active Remote Sensing Tool, 4th Symposium on Remote Sensing of Environment, University of Michigan, April 1966.

12. Peake, W.H., Shultz, C.H., Riegler, R.L., "The Mutual Interpretation of Active and Passive Microwave Sensor Output," Report 1903-3, 15 July 1966, Ohio State University, ElectroScience Laboratory, 4th Symposium on Remote Sensing of Environment, University of Michigan, April 1966.

13. Shultz, C.H., "Radar Imagery of Coastal Features and the Potential for Automatic Data Processing," paper in preparation.

14. Shultz, C.H., "Geologic Content of Radar Imagery in Ohio," paper in preparation.

15. Shultz, C.H. "Stratigraphic and Structural Geologic Data from Radar Imagery of the Central Appalachians," paper in preparation.