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SECTION 53

MICROWAVE PROPERTIES OF GEOLOGICAL MATERIALS: STUDIES OF PENETRATION DEPTH AND MOISTURE EFFECTS

by

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INTRODUCTION

This paper discusses two series of ground based microwave radiometer measurements performed by the Jet Propulsion Laboratory in cooperation with the University of Nevada. The studies were conducted at three wavelengths in a variety of typical sands and gravels. In nature, the microwave radiation from an object is a complex function of composition, moisture and temperature, all as a function of depth, and of surface cover, surface geometry and sky brightness temperature. It is difficult to interpret the microwave signature from a natural site without understanding the effects contributed by each of these individual parameters. Hence, the experiments were controlled to permit examination of the effects of a single parameter at a time on the microwave radiation. The two parameters studied were penetration depth and moisture effects.

Added to the complexity of interpreting the microwave radiation is the problem of measuring it. If radiometer measurements are to be valid independent of measurement system parameters, then they must be absolutely calibrated; that is, effects due to antenna beam energy distributions and systems losses must be removed. This can be a complex operation; however, the experiment designed also permitted a simplified calibration technique. In summary, our experimental approach was to minimize the complexity of the radiometer calibrations, isolate individual target parameters, and make maximum use of existing equipment.

EXPERIMENT DESCRIPTION

The experiments were conducted for three weeks during the summer of 1970 with three dual-polarized microwave radiometers operating at 0.95, 2.8 and 21 cm wavelengths (see Figure 1). The radiometers were mounted four meters above the target on an antenna positioner on the front of a truck. They viewed a controlled target area formed by a 2.4 x 2.4m box with movable sides for accurate variable depth control. The electronics were contained in the truck. The real time data system utilized a PDP8 computer which gathered data from the data/programmer, punched it in raw form, performed real time calculations and outputted calibrated data.

The measurements were made in the vicinity of Pyramid Lake, 80 km northeast of Reno, Nevada. The lake provided a wide variety of naturally sorted and man-made sands and gravels and had low levels of RFI which is particularly important at the 21 cm wavelength.

RADIOMETER CALIBRATION

Two stages of calibration were utilized. A relative calibration valid over the short term (5-15 min) was established by periodically viewing two internal heated sources controlled at approximately 45 and 100°C. This calibration is relative because the antennas with their sidelobes and generally wide beams receive energy from sources other than the target area as indicated in Figure 2. Also, loss in the components up to and including the internal calibration switches modify the incoming radiation. To remove these effects, two point, linear absolute calibrations were accomplished externally by replacing the target area with two sources of known microwave brightness temperature. In this experiment, an aluminum sheet was the "cold" source, and a microwave absorber the "warm" source. Using the internal calibrations only, the temperature predicted for the plate is generally warmer than the correct value, 0°K, as shown in Figure 3.

The result is the use of an incorrect calibration which was off by as much as 50% for these experiments. By forcing the data to fit at the two known external points, a correct absolute calibration for the target area was established. (Note: By forcing a fit to 0°K, sky contributions are also removed. The calibration technique is more fully described in Reference 3.).

Ideally, this is a one time calibration. It was generally accomplished once or twice per experiment. Use of this technique, which greatly simplified the calibration, is subject only to the condition that the background radiation be invarient during the period between calibrations.

RESULTS: PENETRATION DEPTH

The first series of measurements was to determine the effective depth of radiation for a number of sands and gravels. Measurements were made by viewing a metal plate with varying depths of material placed on it in accurately controlled plane parallel layers. A theory based strictly on intensity of radiation predicts that the microwave brightness temperature, T_B, will increase exponentially with increasing thickness. The penetration depth is twice the thickness required to reach the 1/e extinction point (Reference 1). Consequently, the experiment was devised to use doubling thicknesses starting at one cm. It was quickly found that points did not behave smoothly as expected and the thickness increments were reduced to examine more closely what was happening. As a result, increments as low as 0.8 cm were used over the range 0-32 cm.

The results in Figure 4 show an oscillating behavior, particularily noticeable at 21 cm for this fine sand. The fringe amplitude will disappear with increasing particle size. However, it still exists at 21 cm when particle size is on the order of $\frac{1}{4}$ wavelength as seen in Figure 5.

The results can be modeled theoretically by solving for the reflectivity, which is related to emissivity and hence microwave brightness temperature. Standard textbook solutions of Maxwell's Equations (Reference 2) for reflectivity for plane parallel layered isotropic media yield the theoretical curve shown in Figure 4. Although no attempt was made to optimize a fit, correlation between the two curves is excellent as evidenced by the zero slope at the origin, broader nulls than peaks for the small values of layer thickness, and general agreement in the values of the maxima and minima.

It is noted that the theoretical maxima-minima excursions are greater than the experimental results for larger values of thickness. Since the 21-cm radiometer measurements are not at a single frequency but over a 10% band of frequencies, this "smearing" of the higher-order fringes would be expected and can easily be included in the model.

A two dimensional fit of the data to the model is being studied as a potential method of determining the microwave properties of materials in bulk. Extension of this work could lead to the definition of a technique for remotely determining layer thickness in certain naturally layered systems such as sea ice. The penetration depth measurements and results are more completely described in Reference 3.

RESULTS: MOISTURE EFFECTS

An independent series of measurements designed to isolate the effect of moisture content in a smooth uniform sand were performed in the same 2.4 x 2.4 m container without the aluminum reflector. The measurements were conducted in a ten cm thickness of material by mixing in calculated amounts of water, smoothing the surface, measuring the brightness temperature at both polarizations, and collecting five samples for determining the moisture content at the four corners and center of the target area. The results for Mono, Pyramid, and Junction Sands are shown in Figures 5 and 6. The horizontal lines represent the spread in values of moisture as a percent of dry weight obtained for the dry five samples. The curves typically show no effect until moisture is above approximately four percent. Brightness temperature then decreases with increasing moisture in a somewhat linear fashion at rates ranging from 1.5 to 4.8°K per 1% change in moisture content (see Table 1 for values). Table 2 lists the properties of the materials discussed in this report.

Wavelength (cm) / Sand	0.95	2.8	21
Mono	1.5	2.4	4.8
Pyramid	2.4	3.4	4.8
Junction	4.5	3.1	3.9

Table 1: Rate of Decrease in Brightness Temperature with Increasing Moisture Content ($-^{\circ}K/1\%$)

The shorter wavelengths with smaller penetration depths are more sensitive to the surface variations caused by evaporation, water migration, and roughness. This is especially noticeable in the rates and scatter for the data from Mono Sand which was very permeable and hence drained rapidly. Because of the deeper penetration depths at 21 cm, the wooden bottom of the container had an influence on that data. This is particularily noticeable as a "warm" anomaly in the 21 cm data for moistures around 16%.

It was difficult to obtain a perfectly smooth surface for the higher values of moisture. To check the effects of roughness, a rake was passed over the surface parallel to the direction of horizontal polarization. The spacing between the furrows was approximately two cm. As shown in Figure 7, the effects due to moisture essentially disappear at 0.95 and 2.8 cm where the wavelength is on the order of, or shorter than, the furrow spacing. At 21 cm where the furrow spacing is on the order of 0.1 wavelengths, the effect is smaller but still apparent. Vertically polarized data shows similar results.

CONCLUSION

This paper has summarized the results of two of a series of controlled experiments performed in three weeks during the summer of 1970. The first series of experiments to determine penetration depth showed the value of having a modeled response and data reduced in real time for examination in the field. This capability permitted a modification of the experimental approach when the data showed that results did not conform with expectations and lead to a detailed examination of the interference effect discussed herein. The results suggest a radiometric method for measuring the microwave properties of materials in bulk and are applicable to studies of sea ice and other naturally layered media.

The sensitivity of the microwave emission to changes in moisture content has inspired a number of airborne and ground based investigations. Although the effect is dominent under certain conditions, the complicating factors of soil type, roughness, vegetation, etc. seem to govern the conclusions regarding its application at this time. Obviously, the nature of the proposed technique affects the likelihood of its success. For instance, monitoring moisture in a smooth material has a good chance for quick application. While this may not be practical in nature, it may be in process control such as monitoring the curing of concrete.

Concerning applications in the natural environment, experiments which use repeated observations on an area as calibrations for future observations of the same area have a greater chance of success than those which propose remote determination of soil moisture over an unknown area. Consideration of roughness effects and penetration depth indicate the desirability of using longer wavelength radiometers for soil moisture and certain other applications.

REFERENCES CITED

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2. Stratton, J. A., Electromagnetic Theory, McGraw-Hill Book Co., Inc., 1941.

3. Blinn, J. C. III, Conel, J. E., and Quade, J. G., Microwave Emission from Geologic Materials: Observation of Interference Effects, Submitted for publication.

TABLE 2. Summary of Materials Studied

Material	Mineralogy		Particle Sizes, mm		Density		Surface
	Minerals	%	Mean	σ	Bulk	Specific	Characteristics
Mono sand (lake shore deposit)	Glass Devitrified glass Quartz Potash feldspar Iron oxide Elements less 1%	68 16 8 4 1 3	0.46	0.26	1.25	2.25	Coarse-grained
Junction sand (windblown)	Plagioclase Quartz Iron oxide Biotite Volcanic chips Elements less 1%	38 35 5 13 12 7	0.12	0.042	1.20	2.49	Very fine-grained
Pyramid Sand (river deposit)	Quartz Plagioclase Iron oxide Hornblende Lithic Frags. Elements less 1%	45 35 5 3 8 4	0.24	0.10	1.37	2.41	Very fine-grained
Gravel $\simeq$ 5 cm	Welded tuffs Olivine basalts Rhyolites Andesites Highly silicified rhyolites and tuffs	30 20 20 20 10	30-50		1.17		Broken, irregular

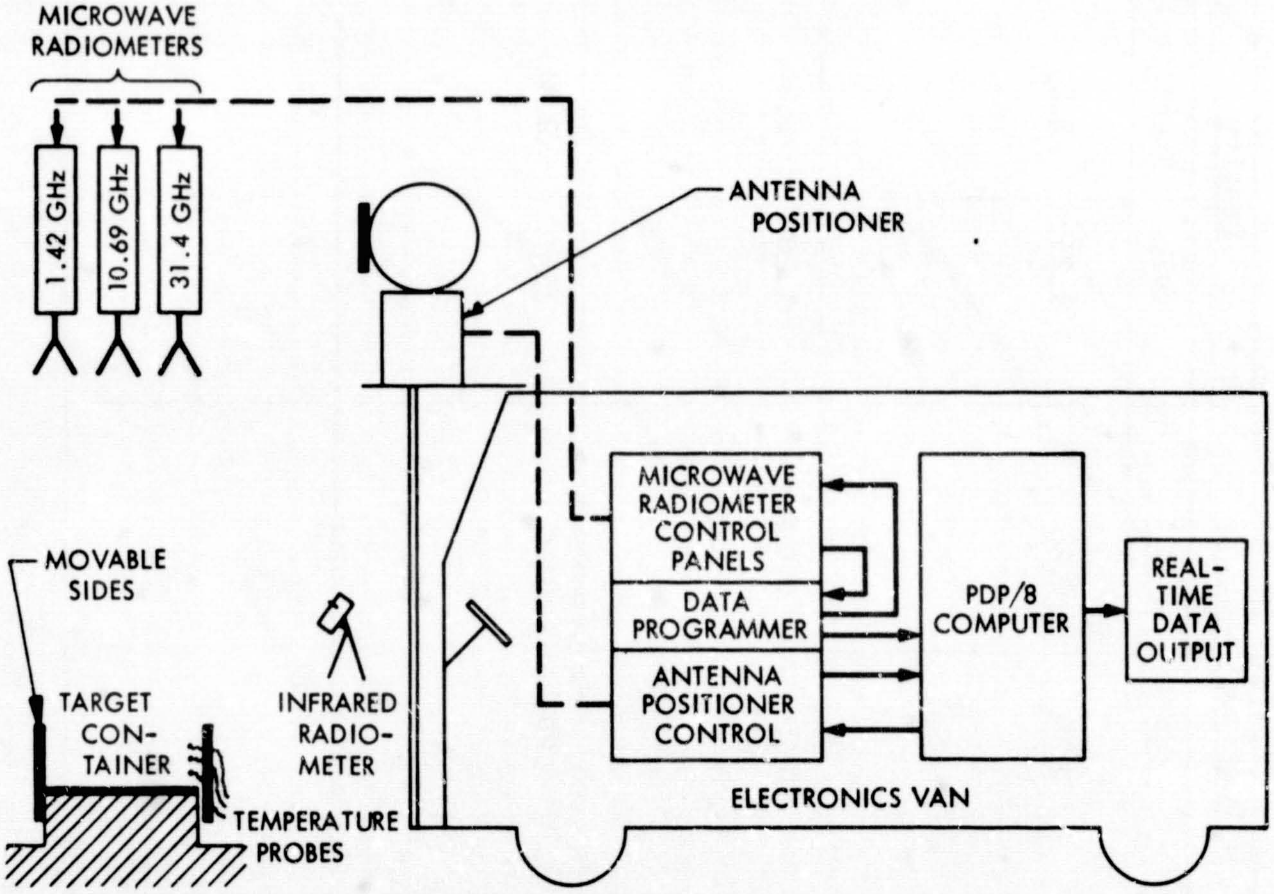

Figure 1. Microwave Radiometric Field Experiment Configuration

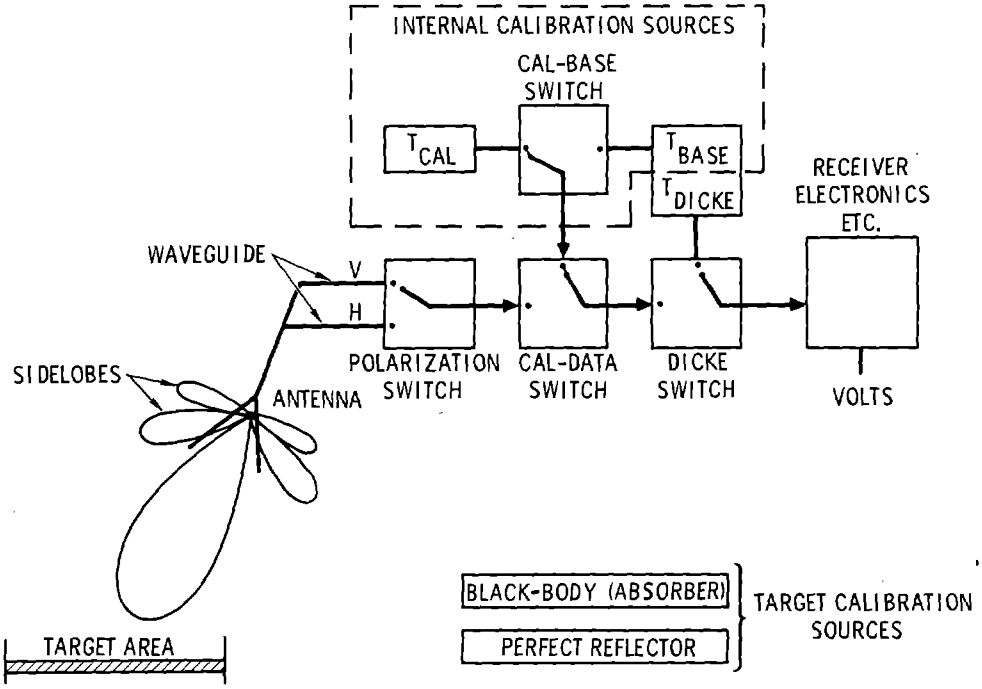

Figure 2. The Calibration Problem

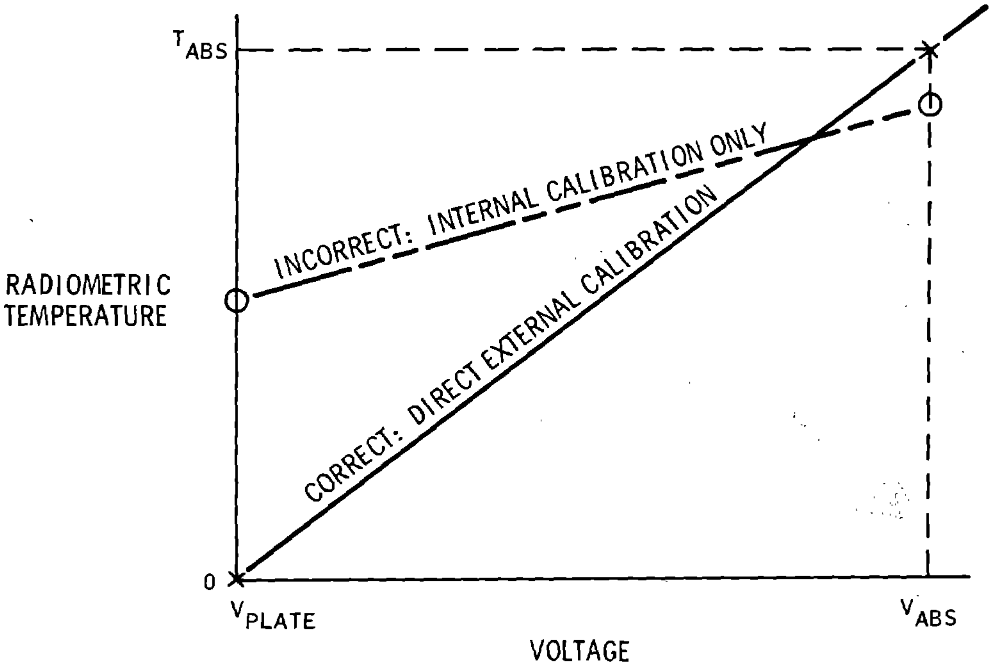

Figure 3. Target Calibration Curves

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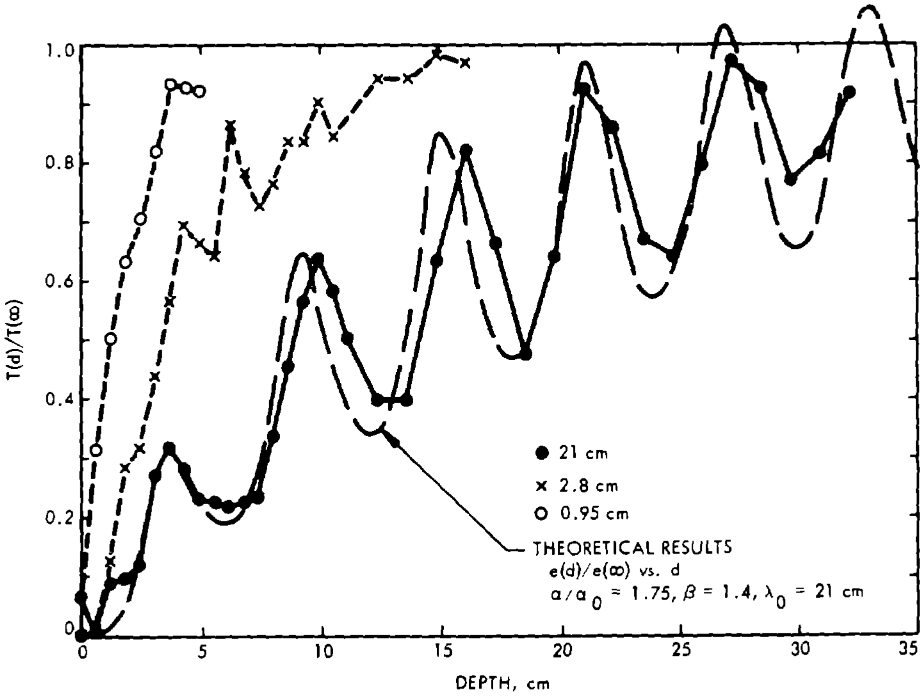

Figure 4. Plate Measurements for Junction Sand

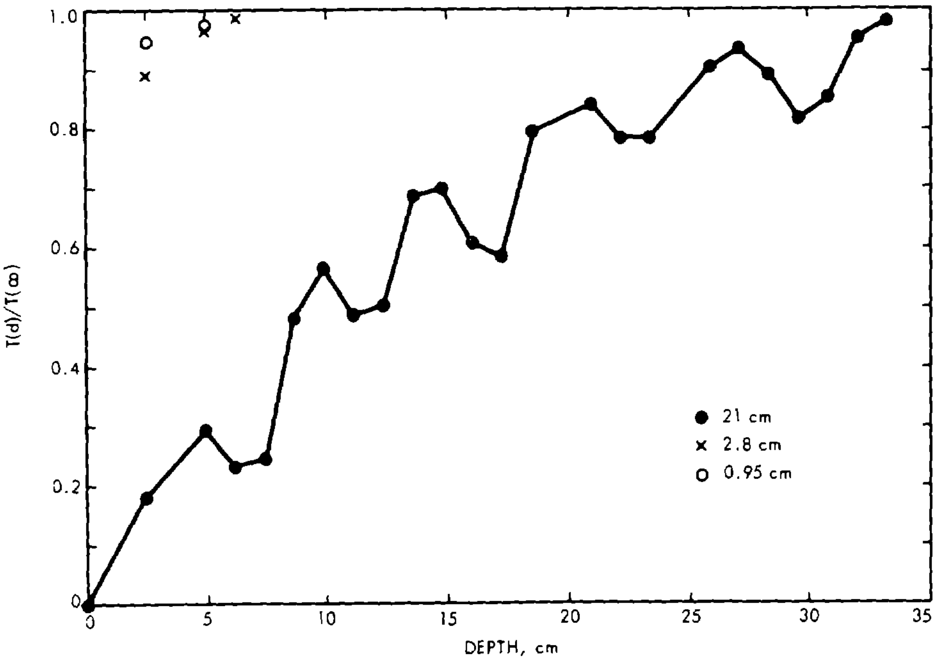

Figure 5. Plate Measurements for 2.5-10 cm Gravel

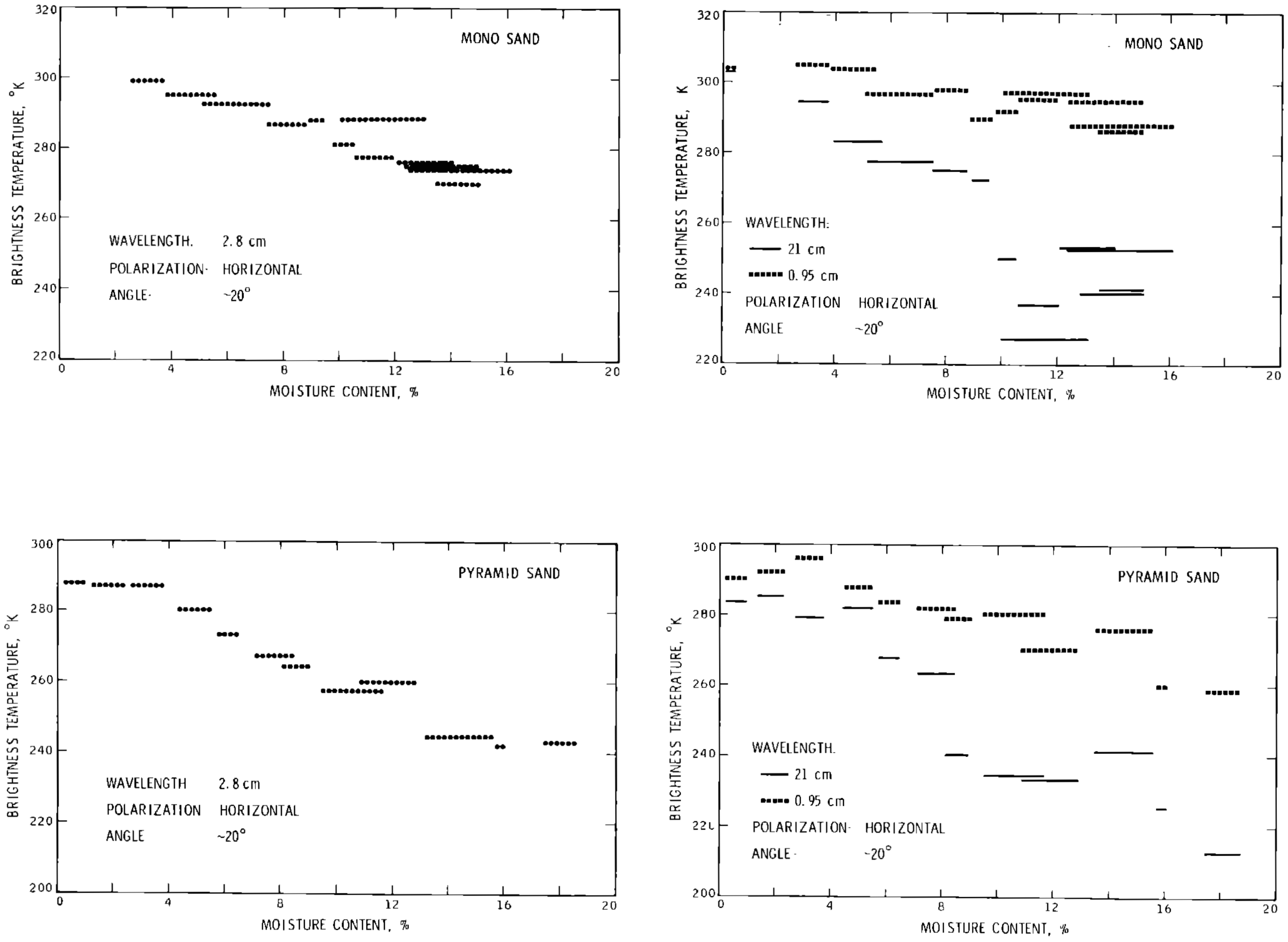

Figure 6. Moisture Effects in Mono and Pyramid Sands

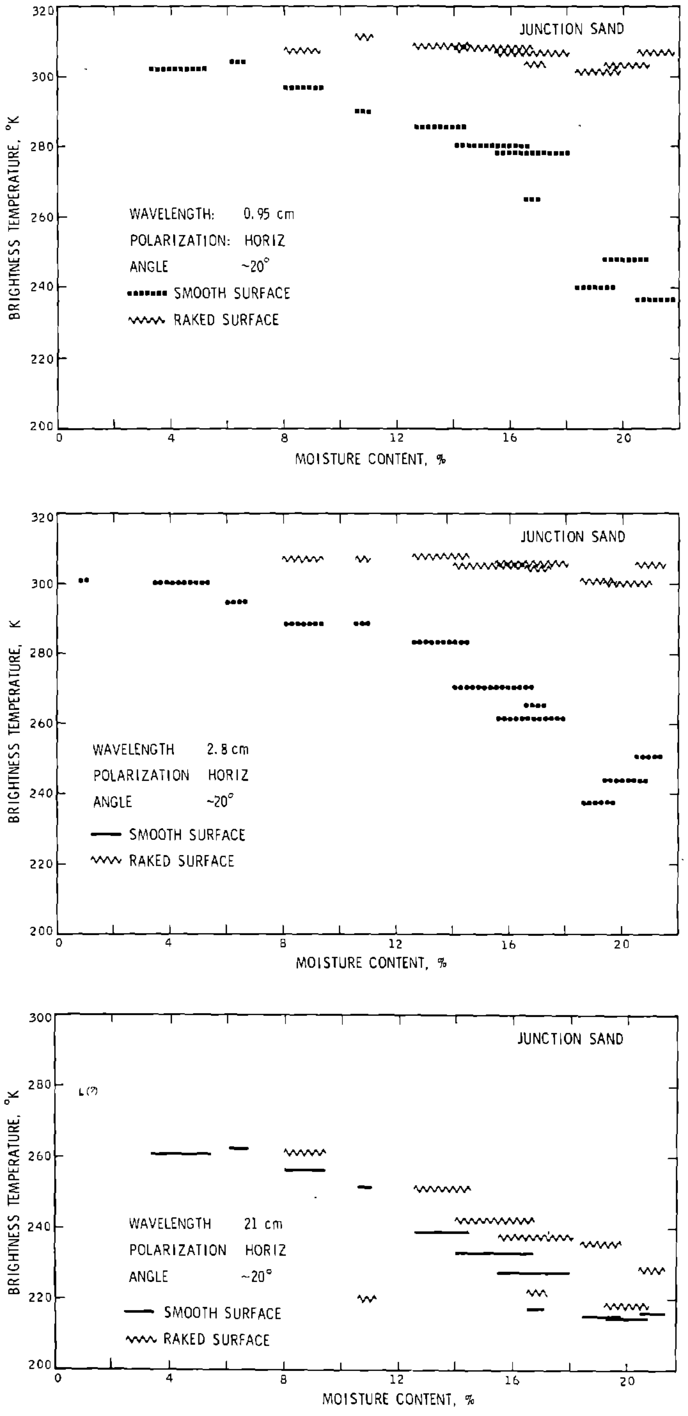

Figure 7. Moisture Effects for Smooth and Rough Junction Sand