MICROWAVE RADIOMETRIC SENSING
OF THE PHYSICAL PARAMETERS OF SNOW [1]

By

J. M. Kennedy, R. T. Sakamoto, and A. T. Edgerton

Introduction

During the past four years, Space-General has been engaged in research concerning microwave radiometers as geophysical tools. As a significant part of this program, the Office of Naval Research, in conjunction with the Cold Regions Research and Engineering Laboratory and the Air Force Cambridge Research Laboratories, has sponsored a field and laboratory program to determine the response of microwave radiometers to various snow conditions. The field portion of this program was carried out within the confines of Crater Lake National Park. Much of the data presented here would have been very difficult to obtain, if not impossible, had it not been for the assistance of the Park Rangers and the Department of Interior.

The fundamental experiments that have been performed, along with laboratory data, indicate there is great potential use, in the field of snow hydrology, for microwave radiometry. Indeed, these instruments may be used to obtain data to determine the melt condition of in situ snow, the thickness of snow packs, and possibly snow density along with the point in time when water bodies begin to freeze. The fact that these data may be obtained from remote platforms, such as aircraft or satellites, may revolutionize the study of snow hydrology.

Theory

Before discussing the radiometric data, it may be best to briefly review what it is that microwave radiometers measure.

All objects with temperatures above absolute zero emit electro-magnetic energy due to the random thermal agitation of the charged particles within them. The intensity of this radiation depends on the temperature of the object, certain physical properties, and on the frequency of observation. If a body is totally non-reflecting, the object is called a black body. That is, if a black object has a finite temperature, it will emit radiation whose intensity distribution is a function of observation frequency, as given by Planck's radiation law. It should be noted that in the microwave spectral region, as in the infrared, measurements can be separated into two general classes, continuum and spectral. Continuum radiation does not exhibit resonance conditions as a function of frequency and applies to most natural radiation from materials, such as snow, soil, and rock. To greatly simplify the subject, microwave radiometers measure the thermal noise emitted by objects at preselected frequencies. Most natural occurring objects are not black bodies so a term which relates them to black body radiation must be defined. This term is called emissivity and is the ratio of the observed emission to that of a true black body. From a conservation of energy point of view, all electromagnetic energy incident on an object is either reflected, absorbed, or transmitted, and if an object is in thermal equilibrium the absorbed energy is equal to the emitted energy or the emissivity. Also, if the object is thick, the transmitted energy will approach zero, leading to the conclusion that the only important components are the energy absorbed and the energy reflected. Slide #1 illustrates the manner in which microwave energy is propagated. The measured brightness temperature, T_A (in degrees Kelvin), can be separated into two components; the emitted energy and the reflected energy. The energy emitted by an object such as the earth's surface is the product of the thermometric temperature of the object, T_G, and the emissivity of the object. The energy reflected by the earth's surface is the product of the apparent brightness temperature of the sky, T_S, and the reflection coefficient, $1 - \epsilon$, of the surface. Thus, the measured brightness temperature is given as $T_A = \epsilon T_G + (1 - \epsilon) T_S$.

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The energy emitted from all objects in the form of electromagnetic waves can be measured at great distances. In the microwave and millimeter regions of the spectrum, such measurements are particularly convenient. This is true because the power emitted by a unit area of black body varies directly with temperature and inversely with the square of the wavelength. However, the beamwidth of almost any form of antenna varies directly with the square of the wavelength. If the range is increased, the power received from a unit area decreases as the square, but the total area seen increases as the square of the range. Thus, the power at the antenna is directly proportional to the temperature of the emitter.

Equipment

The equipment employed for both the laboratory measurements and the field measurements is a self-contained truck and trailer combination shown in Slide #2. Mounted on the truck bed is a twelve-foot hydraulic boom with a head mount which is steerable through a 180° azimuth sector. A closed loop control system is provided for incremental step-scanning in elevation. Three independent microwave radiometers are mounted on the head so that measurements may be made simultaneously at three frequencies. A closer view of the radiometers and the mount system are shown in Slide #3. All three radiometers are modulated superheterodyne types that feed directly to a data acquisition system, which, in turn, drives a digital incremental tape recorder. The tape format is compatible with existing programs for processing on a digital computer. The geophysical support data, which is gathered to define environmental conditions, is also directly fed to the data acquisition system simultaneously with the radiometric data.

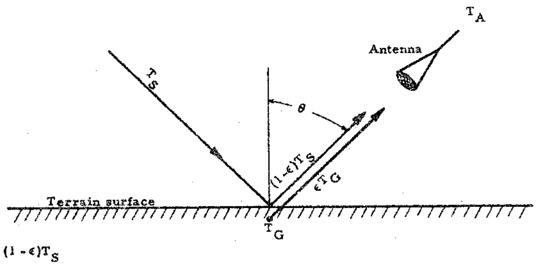
Field Measurements of Snow

Three field measurements programs have been carried out in natural environments. One during the 1964-65 winter season on old metamorphosed snow, and the second on newly fallen snow and powder during the early phases of the 1965-66 season. A third set of measurements were conducted in Colorado during March of this year. Measurements were of comparatively wet snow and of snow over lake ice. These data will be reported at a later date. A typical radiometric scan at two different frequencies which compares radiometric brightness temperatures to the viewing angle is shown in Slide #4. As the incidence angle increases, that is, the angle from nadir increases, the reflectivity slowly changes causing a slow decrease in temperature to about the 60° point. At this point, the reflectivity begins to change rapidly causing a rapid decrease in the apparent temperature due to increasing contributions from sky emissions. Slide #5 shows a typical comparison between the changing radiometric temperature as a function of time compared to the change in snow moisture content as a function of time. The different numbered curves in the upper part of the slide represent the apparent moisture content of different layers of snow in this particular stratigraphic sequence. Data points occur as both symbols and numbers to prevent confusion. From these data, it is apparent that radiometric temperature varies with moisture content. That this variation is a function of moisture and not thermometric temperature is shown in Slide #6. This shows that the received energy is an integrated depth function and the majority of energy comes from a depth where the temperature is invariant. This slide also illustrates the depth penetrating capabilities of microwave energy. The curves on the left were obtained by scanning across an exposed aluminum sheet in 2° increments. The center scan is the same aluminum sheet in the same position after 11-1/2 inches of dry snow was naturally deposited. It is of special note that snow attenuates the different frequencies to different degrees, indicating the electrical properties are variable with frequency. The curve on the far right is a scan across the same plate in the same position after the new snow had started the metamorphic process and additional snow had accumulated and begun to melt. The plate is still visible to the radiometers. However, the apparent behavior, which seems to be that old, high density, high-water-content snow greatly attenuates microwave emissions, is not wholly true. The attenuation is greatly exaggerated because the plate acted as a barrier to downward percolating water and a slush layer 3/4 of an inch thick with water content in excess of 40% was found to exist at the snow-plate interface. Water is highly dispersive at these frequencies and the effective reflectivity of the plate was greatly reduced.

Laboratory Measurements

Laboratory measurements of artificial snow have also been made in an attempt to relate changes in the physical parameters of snow directly to the apparent radiometric temperature at various frequencies and to also examine the possibility of polarization

Sources of Measured Energy



$$T_A = \epsilon T_G + (1 - \epsilon)T_S$$

where:

T_A = apparent brightness temperature (degrees Kelvin)
T_S = brightness temperature of sky (degrees Kelvin)
T_G = thermometric temperature of ground (degrees Kelvin)
ϵ = emissivity (dimensionless)
$1 - \epsilon$ = reflection coefficient (dimensionless)
θ = antenna viewing angle

Figure 1.

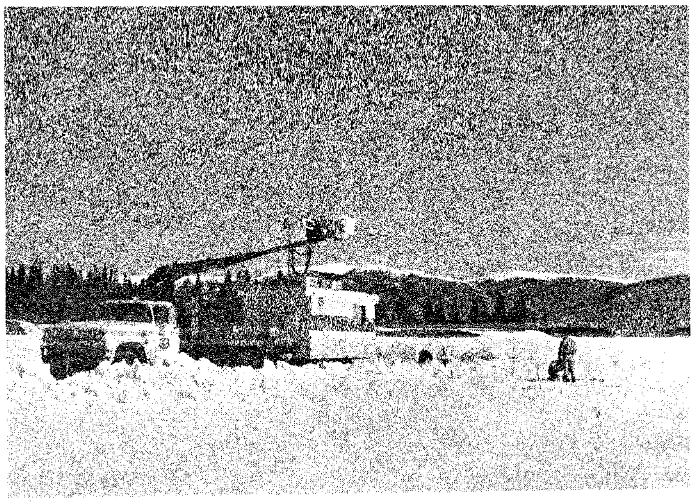


Figure 2. View of Field Laboratory

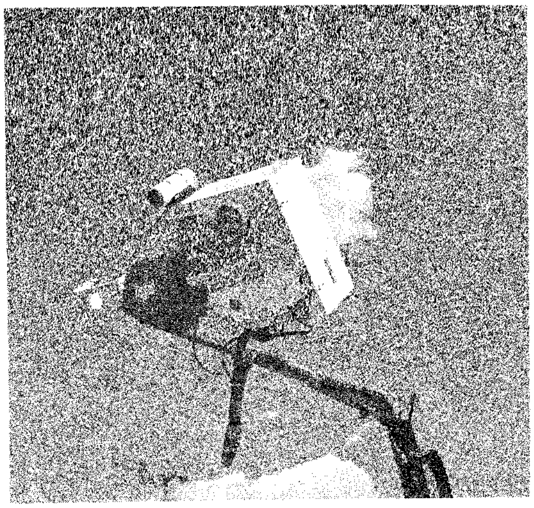


Figure 3. Close-Up View of Radiometers

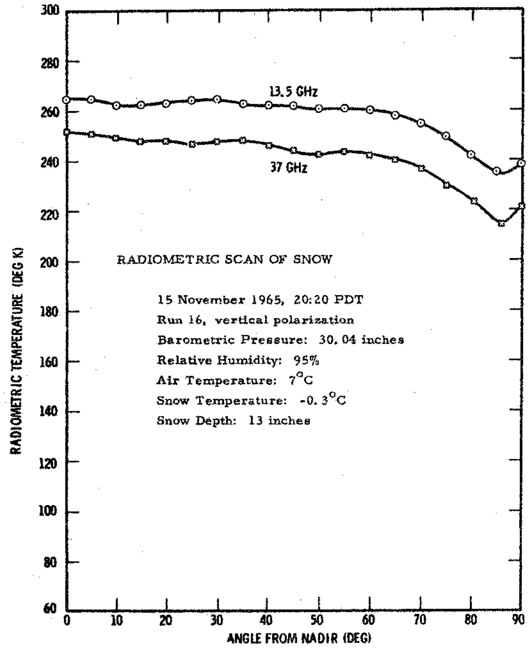


Figure 4.

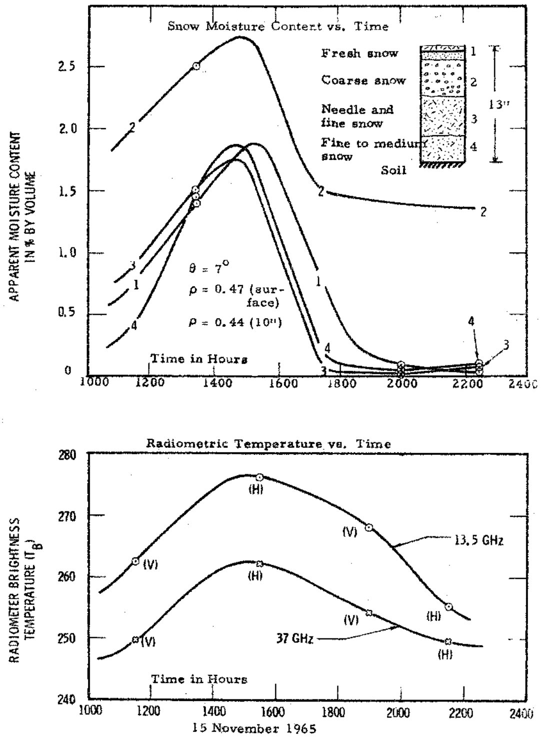


Figure 5.

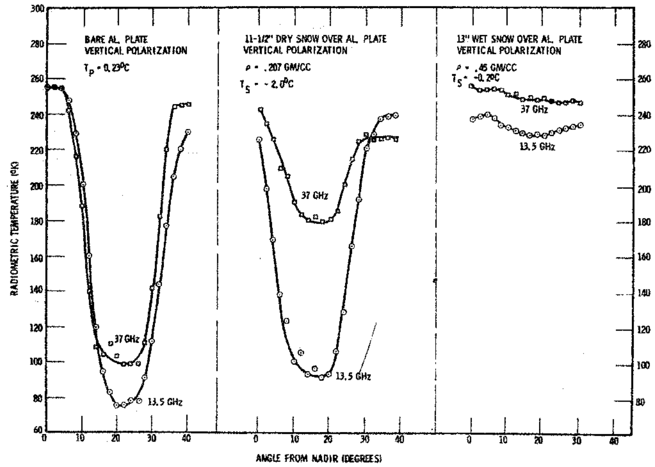


Figure 6.

effects. Slide #7 was derived from measurements performed in a snow chamber. The experiment consisted of monitoring, simultaneously, the radiometric temperature, apparent free water content, thermometric temperature, and snow density. The curves are seen to be quite steep until the water reaches about 10%. Beyond this point, the temperature curves begin to level off, becoming nearly constant above 20%, which is in very close agreement with the obtained field data and theoretical predictions. However, a linear relation also existed between the snow moisture content and the snow density. The percentage radiometric temperature change attributable to density change has not been established. Additional experiments in which differing initial snow densities are being used are planned. Other experiments involving measurements of layered snow-ice-water systems will also be conducted later this year.

Theoretical Considerations

The two interrelated factors, density and structure, enter into the emission differences between new and old snow. While these are thought to be second order effects, as compared to moisture, their contributions are significant and it is necessary to be able to determine their contributions to total emitted energy if snow packs are to be completely described from a remote platform. As mentioned earlier, the microwave temperature of snow is dependent on the reflectivity and absorptance, as with any substance. Both of these parameters are functions of the dielectric constant, which, in turn, is dependent on the physical state of the ice, air, and water mixture. The primary stumbling block in calculating the brightness temperature of snow from physical measurements is the determination of the dielectric constant. The Weiner theory of dielectric mixtures has a structure dependent parameter called the form factor. The present thought is that by making a sufficient number of dielectric constant measurements of different types of snow, we can obtain a form factor or form factors as a function of the structure and age of the snow.

The dielectric constant of dry snow can be obtained from the mixing formula by considering snow as a mixture of ice and air. The electrical dispersion of ice lies in the audio range and therefore dry snow has negligible loss at microwave frequencies. That is, the dielectric constant has no imaginary part. Water, however, is electrically dipersive in the microwave region and when it is added to the mixture to form wet snow, its frequency dependence must be considered. A Debye expression is used to obtain this dependence with constants as determined by Saxton and Lane. If the frequency dependence of the individual components of the ice-water-air mixture and the correct form factor are known, the dielectric constant of the mixture is obtainable. From these considerations, theoretical models have been established to show the variation of dielectric constant as a function of increasing moisture content. Slide #8 shows this relation for several frequencies. In this slide, attention is directed to the small change in dielectric constant between 10 MHz and 13 GHz, which is three orders of magnitude in frequency. Much larger difference exists between 13 GHz and 94 GHz, which is only a factor of seven in frequency. The theoretical model shows good agreement with microwave measurements of fresh low density snow.

Recent improvements in instrumentation will make it possible to measure dielectric constants at microwave frequencies in the near future. An instrument system for performing these measurements is now under construction at Space-General. These measurements will provide a much better understanding of the relationships between microwave measurements and the physical properties of snow systems.

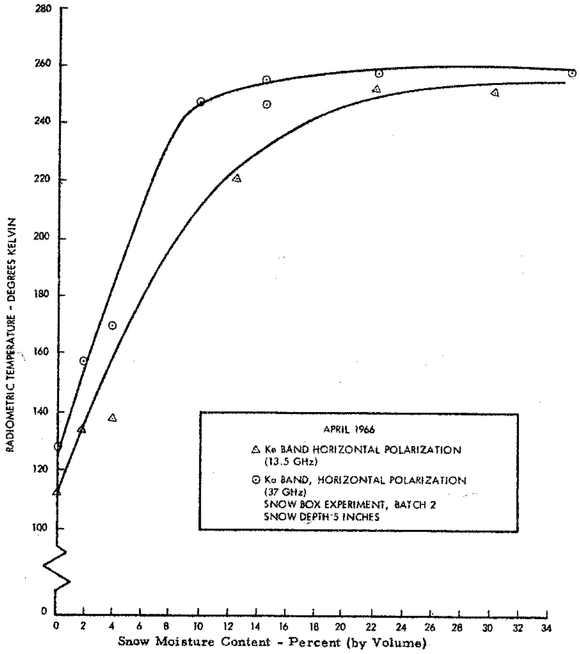


Figure 7.

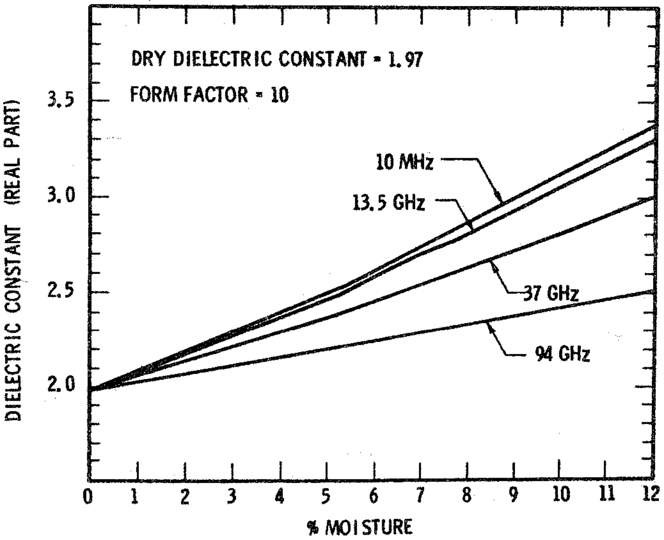


Figure 8.