EMISSION CHARACTERISTICS OF SNOW AND ICE IN THE MICROWAVE RANGE

by

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Snow on the ground has very important scientific, practical, and environmental consequences. Not only does it cover about one-third of the land surface of the earth at any one time, it is by far the most variable material lying on the land. Snow can cover 10,000 or even 100,000 km^2 in a matter of hours, and disappear almost as fast. Its spatial variability, especially in the mountains, is also very great.

Snow reflects solar radiation (it is the material of highest albedo over large areas of the land), causes snowmelt floods, and affects plants, animals, and people in many ways. It is also a resource of great value. For instance, the measurement of the snowpack in the mountain West alone is a program that involves thousands of people and perhaps a million dollars worth of effort each year. The cost of this effort is paid by water users--hydroelectric power developments, irrigation districts, and other groups that need to know the runoff to be expected in the streams when the mountain snowpacks melt.

This resource has important environmental implications. For instance, the amount of Feather River water that can be used to preserve San Francisco Bay vis-a-vis other diversions is directly related to the accuracy with which we can measure the winter snowpack in the Sierra Nevada.

We now know how to measure and monitor this snow at fixed points, using devices that range from the crude snow course to the sophisticated radioactive profiling snow gage. Unfortunately point measurements are not nearly enough to satisfy present day needs. We will never be able to monitor the snowpack with reliability until we can measure the snow not just at a few fixed points but also its broad distribution in time and space. Quite obviously only a synoptic remote sensing program can do this. A big problem here is the fact that the most important changes in the snowpack occur when the atmosphere is cloudy, and therefore a remote sensing system must be devised that can work through clouds. Thus only the microwave frequencies are of any interest. They are of additional advantage over infrared or visual light techniques because the microwave frequencies penetrate below the surface and can tell us something about the characteristics of the snow throughout its depth, a factor which is of great hydrologic and scientific importance.

This has been known for some time and microwave measurements of snow have been made for a number of years. Unfortunately most of the past work has raised far more questions than it has answered. We now know that snow can be distinguished from many other land surface materials in the microwave region of the spectrum. We also know that microwave brightness temperatures vary as a function of snow wetness, snow depth, snow density, ice layers, and the character of the underlying material. Until the past year most results from microwave snow measurements in the field could only be described as highly confusing.

A 2-year contract between the Geological Survey and Aerojet-General Corporation on the microwave emission from snow has just been concluded. We present here some of the results in terms of new understanding that has been derived, as well as several large enigmas that still remain which may be basic to other microwave observations of layered granular materials. This study included theoretical studies, laboratory measurements of electrical properties of snow and similar materials, numerical modelling of hypothetical and real snowpacks, analysis of microwave data obtained on overflights, and, most important, careful quantitative measurements of natural and artificial snowpacks made in the field.

The critical problem was separating the effects on microwave emission of the various individual snow characteristics. Therefore almost all of the work of the past year was directed to this problem, and the progress has been encouraging.

The results have come slowly because of a number of important difficulties. First of all, liquid water in snow has a complex effect and does not appear to behave as simply as liquid water in soil. Second, natural snowpacks are invariably inhomogeneous so that the ground truth problem is one of sampling the snow exactly where it is being seen by radiometers. Third, snow is a difficult laboratory material to work with, and because of the thermodynamic constraints it is virtually impossible to work with homogeneous wet snow in the laboratory. Fourth, we have not yet been able to find an accurate method of measuring the liquid water content of snow in the field.

Attempts were made to measure the dielectric constant of several dry snow samples using an ellipsometer. Although caution should be exercised in using the results (the snow samples were inhomogeneous and the ellipsometer is strictly valid only for homogeneous samples) a value near 1.9 was obtained for the real part of the dielectric constant for each sample. The total mass per volume of the snow samples did not vary significantly from 0.5 g cm^{-3} and the temperature during measurement was below freezing. The dielectric constants of air and ice (the limiting values for snow) are well known and our results also agree with other laboratory measurements of artificial snow. The imaginary part of the dielectric constant of dry snow was found to be so low--less than 0.01--that it could not be measured with an ellipsometer. The work of others suggests that this parameter may be a function of frequency and some tentative values have been determined. No measurements were made of dielectric constants of wet snow because this is virtually impossible to do in the laboratory; simple reflectivity measurements were made and considerable information was derived on scattering and surface reflection coefficients.

In the field we carried out experiments this past winter in which almost all snow variables could be held relatively constant except one, resulting in measurements which can be directly compared with analytic models. Figures 1A and 1B show the setup of one of our field experiments conducted at Crater Lake, Oregon. This involved measurement of an artificial snowpack made by laboriously collecting, disaggregating, and spreading snow over a bare soil surface. Field experiments were conducted at microwave wavelengths of 0.8, 2.2, 6 and 21 cm.

Perhaps the most significant experiment that we have yet performed in the field is shown in Figure 2. Microwave brightness temperatures at three different frequencies and two polarizations are plotted as a function of increasing snowpack mass or water equivalent. The smooth and pronounced response of brightness temperature as the snowpack builds up is very gratifying because it does indicate that microwave brightness temperatures can, under certain conditions, be used to directly measure the water equivalent of a snowpack. Water equivalent is the parameter of greatest hydrologic and glaciologic importance. Note that at a wavelength of 0.8 cm the brightness temperatures changed by 50° as this modest little snowpack was built up. Unfortunately the 21-cm radiometer was out of action due to a bad switch and an absolute calibration for the 6-cm radiometer was not available, but we feel that its relative values are correct. The crosses represent the probable errors in the instrumental measurement of brightness temperature and the variation of snowpack thickness and density.

Now we should ask if these changes can be explained qualitatively or quantitatively. Fortunately it is now possible to attempt a quantitative explanation. Stogryn of Aerojet-General has just developed a theory for the microwave emission from layered media, and has adapted this theory to numerical calculation of a snowpack lying over soil, using the determined electrical properties of snow. Figure 3 shows a typical result in the form of a plot of brightness temperatures versus snow depth (or water equivalent) of dry snow. The curves for other frequencies, snow densities, and soil types are similar (dry soil produces less oscillation and lower frequencies show oscillations of higher amplitude). This graph has two obviously discouraging features: first and foremost, the brightness temperature increases as depth increases and this is not what we see in nature except at the shallowest snow depths. Second, the graph shows numerous oscillations. These are apparently due to multiple reflections from the perfectly sharp, planar boundaries assumed in the numerical model. These oscillations do not occur in our results from snow measurements we then had to face the problem of modifying the theoretical or numerical model to account for more realistic boundaries. First, we tried to incorporate the effects of random inhomogeneities or scattering in the theory but this difficult job could not be accomplished in the time available. At the last minute we tried a substitute approximation. We know that all boundaries in nature are irregular and to some extent gradational so we tried numerical modelling of this field experiment using boundaries which were gradational over a range of a few centimeters. The latter model does eliminate the wild oscillations due to the smoothing effects of a continuous gradation in the dielectric constant near boundaries, but the resulting curve still does not match the field measurements.

Part of the problem is the effect of snow density. As the depth of the snowpack increases in the field, compacting of the lower layers produces an increase in density. Our numerical modelling shows that for a constant depth an increase in density causes the brightness temperature first to increase and then to decrease. A typical result is Figure 4. This effect is too small to account for the strong drop of brightness temperature with depth at high frequencies as measured in the field.

The same problem can be illustrated with an analysis of microwave data obtained from an overflight--in this case a flight over Mount Rainier by the NASA Convair 990 with a 1.55-cm microwave imager. As indicated in Figure 5, there is an enormous scatter in the data and furthermore if there is a trend in the data it does not seem to follow very closely the results predicted by theory. Unfortunately one cannot make definitive experiments out of these overflight data. The snow is different at the location of each resolution element, and we could not possibly measure all the properties of the snow at all of these places. In this case, the airplane flew over an area where no ground truth data existed and we had to extrapolate snow conditions from measurements elsewhere.

Now consider what happens when the snow warms up and liquid water begins to appear. Detection of this condition is very important to hydrologists because no runoff can occur until a water saturated condition is attained. Figure 6 shows the same snowpack as in Figure 2, but after the sun warmed the snowpack and liquid water began to appear at the surface. This produced very large changes in brightness temperatures. The brightness temperature thus indicates rather clearly whether the snow is dry or wet. However, liquid water actually increases the natural brightness temperature of snow, opposite to its behavior in soil. We have obtained virtually the same results by reflectivity measurements in the laboratory and in many other field measurements.

In this case theory and numerical modelling do lend insight into the cause for this interesting phenomena. Figure 7 shows typical numerical results. You note first a sharp rise in brightness temperature followed by a slow decline. This theory indicates that a small amount of free water will not increase the magnitude of the dielectric constant significantly while increasing the loss, so that the emission by soil is not seen. Thus, since the dielectric constant of snow is smaller than that of soil, the effect is to increase the brightness temperature. After the free water has been increased sufficiently, the magnitude of the dielectric constant of the snow begins to increase appreciably and at this stage the brightness temperature begins to decrease.

Figure 8 shows a typical field experiment in which a wet snowpack is built up. This graph is not as interesting as the dry snow results shown earlier. Only the highest frequency shows an appreciable change in brightness temperature (20-25°). However, the other frequencies all show a decrease in the difference between the horizontal and vertical polarized brightness temperatures. The very low frequency radiometer apparently sees the soil even though it is covered by an appreciable fraction of a meter of wet snow.

This program is one of those in which the practical need is very obvious and the backlog of previous work is fairly considerable. However, the problem is so complex that even a sophisticated integrated approach involving theory, laboratory, field, and overflights is yielding quantitative understanding very slowly. This progress, although slow, is gratifying and we are ever more optimistic that a fairly simple combination of microwave polarizations and frequencies can ultimately be used to monitor the water equivalent and free-water content as well as the distribution of snow. It is probable that this understanding will also shed light on the physics of microwave emission from other wet, granular, layered media.

Figure 1A.- Microwave measurements of soil before constructing a snowpack. Crater Lake, Oregon, March 22, 1970.

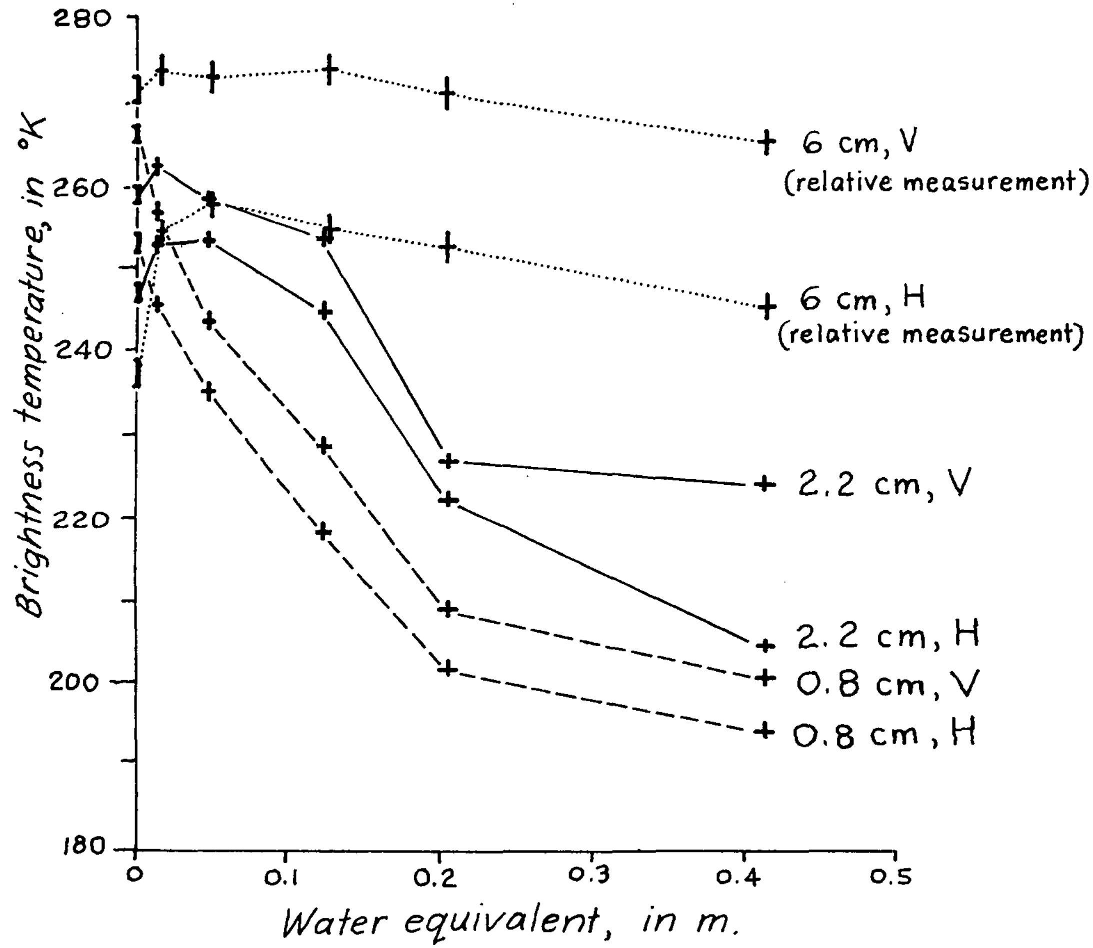

Figure 2.- Measured brightness temperature as a function of snow mass per unit area (water equivalent), for cold, dry snow.