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## STUDIES OF SNOWPACK PROPERTIES BY PASSIVE MICROWAVE RADIOMETRY

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### ABSTRACT

Research involving the microwave characteristics of snow was undertaken in order to expand the information content currently available from remote sensing, namely the measurement of snowcovered area. Microwave radiation emitted from beneath the snow surface can be sensed and thus permits information on internal snowpack properties to be inferred. The intensity of radiation received is a function of the average temperature and emissivity of the snow layers and is commonly referred to as the brightness temperature ( $T_B$ ). The  $T_B$  varies with snow grain and crystal sizes, liquid water content and snowpack temperature.

The  $T_B$  of the 0.8 cm wavelength channel was found to decrease more so with increasing snow depth than the 1.4 cm channel. More scattering of the shorter wavelength radiation occurs thus resulting in a lower  $T_B$  for shorter wavelengths in a dry snowpack. The longer 21.0 cm wavelength was used to assess the condition of the underlying ground. Ultimately it may be possible to estimate snow volume over large areas using calibrated brightness temperatures and consequently improve snowmelt runoff predictions.

### INTRODUCTION

The use of remotely-acquired microwave data, in conjunction with essential ground measurements will most likely lead to improved information extraction regarding snowpack properties beyond that available by conventional techniques. Landsat visible and near-infrared satellite data have recently come into near operational use for performing snowcovered area measurements (Rango, 1975; 1978). However, Landsat data acquisition is hampered by cloud cover, sometimes at critical times when a snowpack is ripe. Furthermore, information on water equivalent, free water content, and other snowpack properties germane to accurate runoff predictions is not currently obtainable using Landsat data alone because only surface and very near-surfaces reflectances are detected.

Microwaves are mostly unaffected by clouds and can penetrate through various snow depths depending on the wavelength. Hence, microwave sensors are potentially capable of determining the internal snowpack properties such as snow depth and snow water equivalent (Hall et al., 1978; Rango, et al., 1978). However, operational use of remotely-collected microwave data for snowpack analysis is not imminent because of complexities involved in the data analysis. Snowpack and soil properties are highly variable and their effects on microwave emission are still being

explored. Nevertheless much work is being done to develop both active microwave (Hoekstra and Spangle, 1972; Ellerbruch, et al., 1977) and passive microwave techniques (Edgerton, et al., 1971; Schmutge et al., 1973; Schmutge, 1973; Linlor et al., 1974; and Chang et al., 1976) for analysis of snowpack properties. Passive microwave data obtained during recent flights by NASA aircraft and measurements made by University of Kansas in Colorado will be discussed. Recent results from analyzing the Nimbus Electrically Scanned Microwave Radiometer (ESMR) data with snowpack depth will also be discussed.

### Passive Microwave Experiments

During the winter of 1976 and 1977 the NASA P-3 aircraft equipped with Multifrequency Microwave Radiometer (MFMR), cameras and other support instruments was flown over test sites near Steamboat Springs and Walden, Colorado. Ground truth which includes snow depth and temperature, free water content, density, structure and soil moisture was taken along the flight lines. In February and March 1977 a mobile microwave system was used to conduct a snow experiment in Steamboat Springs (Stiles et al., 1977). This experiment was supported by NASA Goddard Space Flight Center. The microwave equipment was mounted atop truck-mounted booms. Ground truth data were also taken during the experiment.

Passive microwave data from space have been available since December 1972 when Nimbus 5 was launched with the Electrically Scanning Microwave Radiometer (ESMR) onboard sensing at the 1.55 cm wavelength. Further data became available in June 1975 with the launch of Nimbus 6 with an ESMR instrument capable of receiving dual-polarized microwave radiation from the earth at 0.8 cm wavelength. Due to the coarse spatial resolution of these two instruments, a large homogeneous area in Canada was selected for analysis.

### Interpretation of Microwave Emission from Snow

Snow particles act as scattering centers for microwave radiation. Computational results indicate that scattering from individual snow particles within a snowpack is the dominant source of upwelling emission in the case of dry snow. This type of radiation upwelling through snow is governed by Mie scattering theories for which a good description can be found in Chang et al. (1976). Microwave radiation emanating from snow originates from a depth of ~10-100 times the wavelength used (Chang et al., 1976). However, when the snowpack thickness is less than the microwave penetration, the underlying surface will contribute to the  $T_B$  (Chang and Gloersen, 1975).

Using the multifrequency analysis approach, one can make inferences regarding not only the thickness of the snowpack, but the moisture conditions and the condition of the underlying soil (wet versus dry). The shorter wavelengths such as the 0.8 cm, sense near-surface temperature and emissivity, and surface roughness. At the intermediate wavelengths, 1.4 and 1.7 cm, the radiation is less affected by the surface and more information is obtained on the characteristics of the mid-pack. Longer wavelengths such as 21 cm, represent greater penetration through a snowpack and receive a strong contribution of emission from the underlying ground. All of the above generalizations apply to the snow depths encountered at Steamboat Springs and Walden during the study period.

In addition to snow depths, snow grain and crystal sizes, ice lenses and layers within the snowpacks were measured in the snow pits. Grains, crystals, lenses and layers act as scatterers to the microwave radiation if their size is

comparable to the wavelength. Short wavelength radiation tends to be scattered by snow crystals and grains (~ 1 mm) which are comparable to the wavelength, as well as by the larger ones. Longer wavelengths are not affected by the very fine crystals and grains, but will be affected by lenses and layers, the result of snow metamorphism.

The presence of free water in the snowpack and the condition of the ground below the pack were also measured. Free water in snow (5%) will cause a sharp increase in the  $T_B$  (Chang and Gloersen, 1975). This is because the effects of scattering of individual snow particles are reduced when free water coats the crystals, and emission increases.

The condition of the ground beneath the snow will determine the intensity of the radiation incident from below. Dry or frozen ground has a high emissivity (~0.9-0.95) with a  $T_B$  of ~260°K whereas unfrozen wet ground has a much lower emissivity (~0.7) with brightness temperatures as low as 150°K. Knowledge of the condition of the ground underlying the snow is important for the interpretation of observed brightness temperatures and can generally be determined from the 21 cm observations.

### Observational Results

**Snow Depth.** Table 1 shows the various snow depths and average wetness conditions of the snow encountered at the two sites in 1976 and 1977. When the snowpack is dry (< 1% free water present), the  $T_B$  should decrease with increased snow depth as shown in Figure 1. Figure 1 graphically illustrates the responses of the 0.8 and 1.4 cm channels of the MFMR to the various snow depths shown in Table 1.

The greater  $T_B$  decrease evident in the plot of the 0.8 cm channel (solid line in Figure 1) is due to the fact that more particles are present which can scatter the 0.8 cm radiation than the 1.4 cm radiation (dashed line) because of the size range of particles within a snowpack. A deep snowpack obviously has more crystals and/or grains than does a shallow pack. Crystals and grains large enough to scatter the 1.4 cm and longer wavelength emission are inherently fewer.

Table 1

Average Snow and Ground Conditions at the Study Areas

	depth cm	snow condition	ground condition
March 1976			
Steamboat Springs	75.4	dry	wet
Walden	10.5	moist	frozen
January 1977			
Steamboat Springs	36.1	dry	frozen
Walden	trace	N/A	frozen
March 1977			
Steamboat Springs	41.1	dry to moist	frozen
Walden	2.5	moist	wet

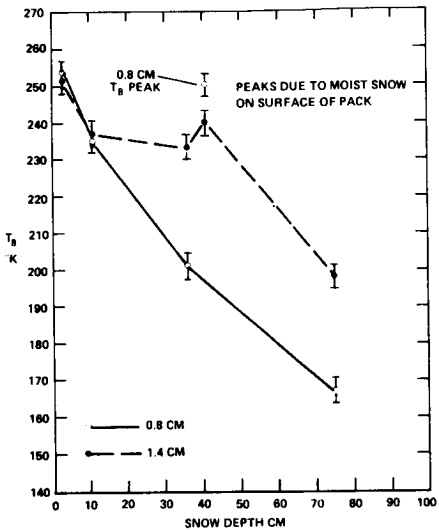


Figure 1. Horizontally Polarized Microwave  $T_B$  Responses to Snow Depths

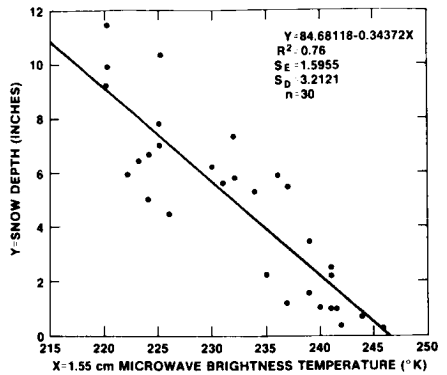


Figure 2. Nimbus 5 Microwave Brightness Temperature versus Snow Depth on the Canadian High Plains

Recently, a study has been performed to derive relationships between the snow depth and brightness temperature measured by ESMR on board the Nimbus 5 and 6 satellites. The area studied was a homogeneous area located on the Canadian high plains near southern Alberta and Saskatchewan. Figure 2 illustrates the snow depth versus brightness temperature data for Nimbus 5 and the resulting significant (at the .002 level) regression line and statistics. The Nimbus 5 data are from the nighttime pass on 14 March 1976 and the snow depth data are from 15 March 1976. Air temperatures prior to 15 March were well below  $0^{\circ}\text{C}$  with little chance of significant melting, and as a result, dry snow conditions were assumed. Figure 3 presents a comparable plot for snow depth and Nimbus 6 vertically polarized brightness temperature from the daytime pass on 15 March 1976. It does appear that in simple regression analysis that the Nimbus 6 data produce better relationships than the Nimbus 5 data. This most likely results from the fact that the emission from the relatively thin snowcover at 1.55 cm contains a more significant contribution from the variable underlying soil layer than at 0.81 cm.

Snowpack and Soil Moisture Conditions. The response of the MFMR data to snow moisture has also been analyzed. Snow wetness is very important to runoff forecasting, as is the condition (wet or dry) of the underlying ground. Variations in snow moisture have been measured using a freezing calorimeter technique during the 1976 and 1977 aircraft experiments and it has been found that free water in a snowpack will raise the 0.8 cm  $T_B$ . Note the peak in the response of the 0.8 channel to the 41.1 cm depth snow in Figure 1 (open circle  $\sim 250^{\circ}\text{K}$ ). This is the March 1977 snowpack at Steamboat Springs. The peak is apparently caused by surface moisture to which the 0.8 cm radiation is very sensitive. The longer wavelengths did not respond as markedly (i.e., show the sharp  $T_B$  increase) because they emanate from deeper, drier layers within the snowpack. If all wavelengths were to show the peak, theoretically the snowpack would be ripe.

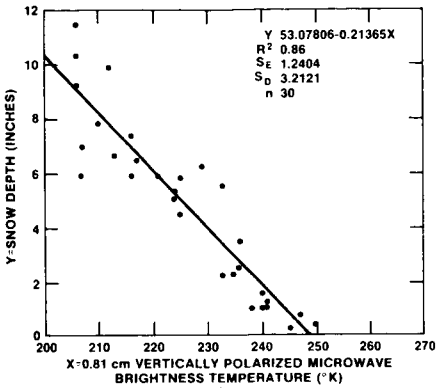


Figure 3. Nimbus 6 Vertically Polarized Microwave Brightness Temperature versus Snow Depth on the Canadian High Plains

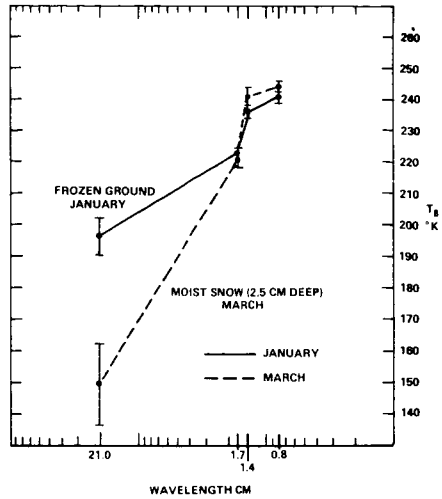


Figure 4. Variation of Microwave  $T_B$  with Radiometer Wavelength, Walden, Colorado, 1977

Figure 4 compares the responses of all four wavelengths over frozen ground in January, 1977 (solid line) to that over shallow (2.5 cm), moist snow and wet ground at Walden in March 1977 (dashed line). The shortest wavelengths, 0.8 and 1.4 cm, have slightly higher average brightness temperatures for moist snow (March) than for the frozen ground (January). The 1.7 cm channel shows approximately the same  $T_B$  for frozen ground and moist snow while the difference in the 21 cm  $T_B$  between moist snow and frozen ground is  $47^\circ\text{K}$ . The 21.0 cm radiation is apparently unaffected by the moist snow because the snow is so shallow. The low  $T_B$  of the 21 cm wavelength in March results from the wet ground beneath the snow.

Figure 5 shows the variation of brightness temperature as a function of time for 2.8 cm and 0.8 cm wavelengths (Stiles et al., 1977). When the free water content within the snow pack increased to approximately 4% the brightness temperature jumped from 140K to 260K at the 0.8 cm wavelength with  $50^\circ$  incidence angle. This is consistent with the aircraft measurements.

### Summary and Conclusions

It has been demonstrated that there are differences in the microwave brightness temperatures for the snowpacks studied at Walden and Steamboat Springs, Colorado during the 1976 and 1977 experiments. An average  $T_B$  decrease for the shorter wavelengths (0.8, 1.4 and 1.7 cm) of  $35^\circ\text{K}$  has been shown to correspond with a 39.3 cm greater snow depth for the March 1976 as compared to the January 1977 Steamboat Springs snowpack. A  $T_B$  decrease of  $50^\circ\text{K}$  for the 21 cm wavelength is attributed to wet soil conditions in March 1976. Furthermore, a sharp rise,  $\sim 49^\circ\text{K}$ , in the 0.8 cm  $T_B$  corresponds to moist snow on a surface of the Walden snowpack in March 1977 demonstrating the sensitivity of microwave

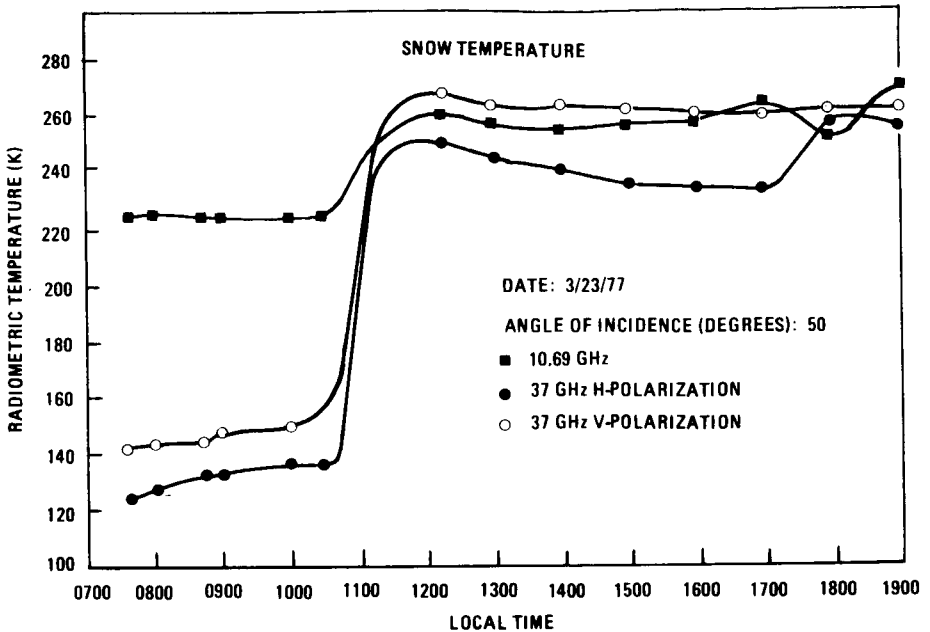


Figure 5. Microwave TB Variation with Time  
(University of Kansas)

radiation to moist snow. Also, a greater  $T_B$  decrease for a given snowpack is evident for the short, 0.8 cm, as compared to the longer, 1.4 cm, wavelength. This is due to the fact that shorter wavelength radiation is scattered more so than longer wavelength radiation thereby resulting in a lower emissivity and a lower  $T_B$  for the short wavelengths. A dry snowpack has particle sizes typically  $< 0.1$  cm. As the wavelength of the radiation approaches the particle size, the scattering will increase. This greater scattering lowers the  $T_B$  and the emissivity of a snowpack.

Snow depth, free water within the pack, and underlying conditions were addressed in this paper. Varying conditions of these parameters were encountered in the study areas and subsequent correlations made with the microwave data were consistent between different measurements. The challenge in the analysis of the microwave response to snowpack properties lies in the fact that snowpack conditions are complex and their interaction with microwave radiation is not completely understood. The fact that snowpack character can change so rapidly, and, is in fact constantly changing, adds a complicating factor to data analysis. It is believed that with additional measurements in the coming years a more quantitative relationship between brightness temperatures and snow depth will be possible for snowpacks of known wetness condition. The near-term goal is to understand the microwave emission from snow so that a system for improved snowpack monitoring from a remote platform can be defined.

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