PASSIVE MICROWAVE STUDIES OF SNOWPACK PROPERTIES [1]

By

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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 cloudcover, 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-surface reflectances are detected.

Microwave data have the potential to provide information regarding internal snowpack properties, even through cloudcover because of the penetrating character of the radiation. 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 (Schmugge et al., 1973; Schmugge, 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 over Colorado will be discussed in this paper.

Test Sites, Mission Objectives and Instrumentation

During the winters of 1976 and 1977 a NASA P-3 aircraft equipped with passive microwave sensors (radiometers) and a color infrared aerial camera was flown over several flight lines in the Colorado Rockies, Figure 1. Steamboat Springs and Walden, Colorado were the major study sites. These sites were chosen because of differing snow conditions: the Yampa Valley south of Steamboat Springs generally has a deep, continual snowpack whereas Walden has a shallow, transient snowpack.

Steamboat Springs (elevation 2140 m (6900 ft) is located in northwestern Colorado on the western flank (windward side) of the Park Range Mountains. The Steamboat Springs flight line is approximately 8 km (5 mi) in length in the Yampa River Valley, a few miles south of the town of Steamboat Springs. The Steamboat Springs flight line is located in an area of flat pasture and meadow land with the southernmost mile being hilly and covered by sagebrush and grasses. Steamboat Springs receives about 445 cm (175 in) of snow in an average year because of its windward location and the fact that there are no major mountain ranges in the immediate vicinity to intercept precipitation coming from the west.

Walden is located 65 km (40 mi) northeast of Steamboat Springs on a high plateau (elevation 2540 m (8200 ft)) surrounded by mountains and drained by tributaries of the North Platte River. Two lines were overflown at Walden, one oriented in an east-west direction (6.0 km (3.8 mi) long), and the other in a north-south direction (7.3 km (4.5 mi)

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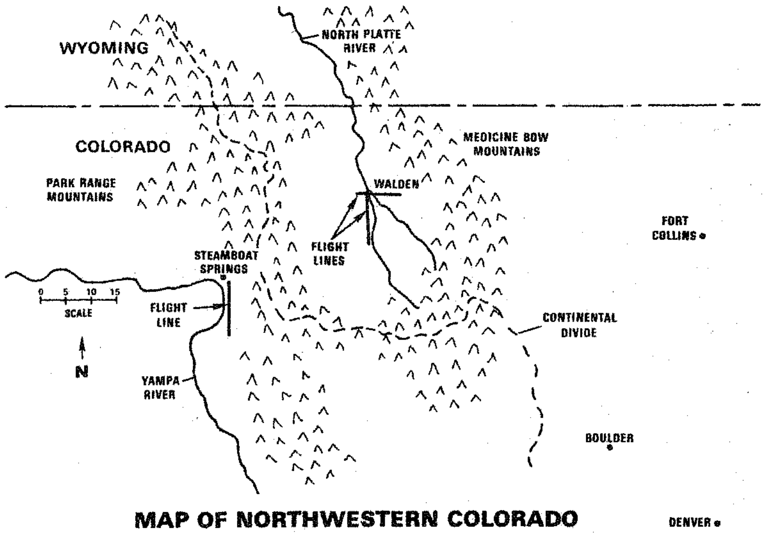
long). The land is comprised of open, low hills and is used primarily for pasture and grazing land. Walden receives much less precipitation than does Steamboat Springs and generally does not maintain a seasonal snowpack. This is because Walden is located downwind of the Park Range Mountains which intercept most of the precipitation. The average snowfall for Walden is about 89 cm (35 in).



MAP OF NORTHWESTERN COLORADO SHOWING LOCATION OF STUDY AREAS

Figure 1

Ground truth data for both the Steamboat Springs and Walden flight lines are summarized in Table 1. For the purposes of this study the data were averaged for an entire flight line for better comparison with average values obtained from the aircraft.

Table 1

Snow and Ground Measurements Taken During the Study Period Along the Steamboat Springs and Walden Flight Lines

Data Obtained	Steamboat Springs	Walden
Density and Water Equivalent	intervals of 305 m (1000 ft)	intervals of 800 m (2640 ft)
Grain Size, Wetness Etc.	intervals of 305 m (1000 ft)	intervals of 800 m (2640 ft)
Depth	intervals of 30.5 m (100 ft)	intervals of 160 m (528 ft)
Layer Classification	in 7 pits dug at 1 km intervals	N/A
Soil Moisture	at bottoms of pits only	intervals of 800 m (2640 ft)

Seven snow classification pits were dug at Steamboat Springs; because of inadequate snow depth, no pits were established at Walden. The following data were obtained from the snow pits: temperature, free water, density, structure and soil moisture.

The winter of 1976 had nearly normal snow conditions both at Steamboat Springs and at Walden; in 1977, however, the snowfall was far below normal and consequently various snow depths were observed at the two sites during the two year study period. The aforementioned areas will be overflown and studied again using microwave instrumentation during the 1978 winter along with additional test areas.

The NASA P-3 aircraft was equipped with four non-imaging, microwave radiometers known as the Multifrequency Microwave Radiometer (MFMR). The characteristics of the MFMR are shown in Table 2. The radiometers are calibrated prior to each flight by a pass over a water target which has a known emissivity.

Table 2

MFMR Characteristics

Wavelength cm	Frequency GHz	Beamwidth	Angle*	Resolution at an Aircraft Altitude of 600 m
0.8	37.0	6°	48°	91 x 143 m
1.4	22.2	6°	48°	91 x 143 m
1.7	18.0	6°	48°	91 x 143 m
21.0	1.4	15°	48°	229 x 335 m

*MFMR points forward of the aircraft.

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 (Chang and Gleorsen, 1975). The average emissivity ($\bar{e}$) and the average temperature ($\bar{t}$) of the snowpack affect the measured radiation, known as the brightness temperature (T_B). The following approximation has been found to hold true for snow: $T_B = \bar{e}\ \bar{t}$ (Chang et al., 1976). 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 of the pack, 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. As 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 statements are generalizations which apply to the snow depths encountered at Steamboat Springs and Walden during the study period.

Many factors influence the microwave response to snow including snow depth, density, water equivalent, free water within the pack, grain and crystal sizes, average temperature, surface topography, and emission due to microwave radiational scattering.

In addition to snow depths, snow grain and crystal sizes plus 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 (1-5%) 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 ($\sim$0.90-0.95) with a T_B of $\sim$ 260°K whereas unfrozen wet ground has a much lower emissivity ($\sim$ 0.7) with possible brightness temperatures as low as 200°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.

Snow depth, free water within the pack, and underlying conditions will be stressed 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 years. 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.

Observational Results

Snow Depth. Table 3 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 increasing snow depth as shown in Figure 2. Figure 2 graphically illustrates the responses of the 0.8 and 1.4 cm channels of the MFMR to the various snow depths shown in Table 3.

Table 3

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

The greater T_B decrease evident in the plot of the 0.8 cm channel is due to the fact that more particles are present which can scatter the 0.8 cm radiation than the 1.4 cm radiation 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.

Figure 3 shows microwave responses to the well-developed snowpack at Steamboat Springs in March of 1976 and in January of 1977. The primary reason for the lower, $\sim$35°K overall T_B for all wavelengths in the 1976 data is due to deeper snow in 1976 (average 39.3 cm deeper in March 1976 than in January 1977). Also in Figure 3 it is interesting to note the response of the 0.8 cm channel in both years. It is $\sim$33°K lower in both years than the 1.4 cm channel brightness temperature. This is undoubtedly due to the many fine, newly fallen snow crystals comprising the top layers of snow which scatter the 0.8 cm radiation and lower the emission and the T_B, but do not as greatly affect the emission in the longer wavelength ranges. For the 21 cm wavelength the January 1977 T_B is higher because the frozen ground has a warmer signature than the unfrozen wet ground in March 1976.

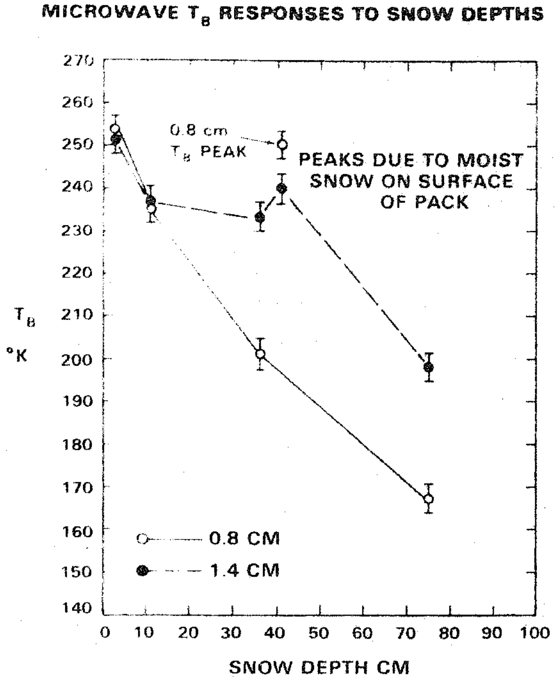


Figure 2

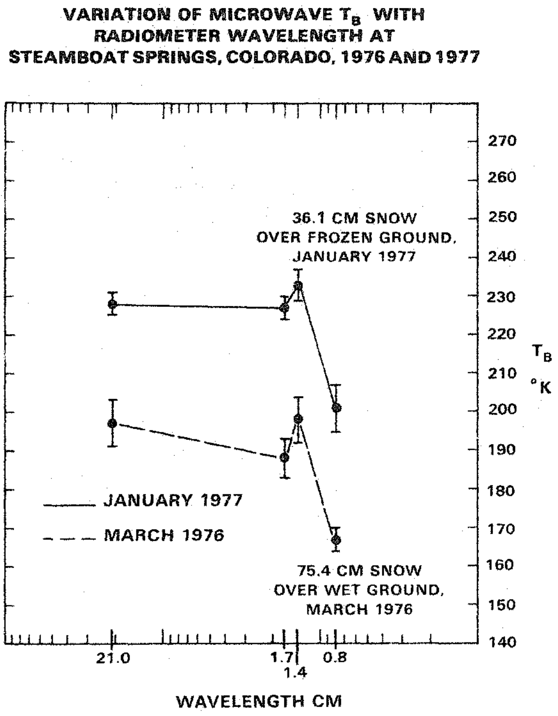


Figure 3

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 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 41.0 cm depth snow in Figure 2, (this was the March 1977 snowpack at Steamboat Springs). The peak is apparently caused by surface melting 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 detect emission from deeper, drier layers within the snowpack, If all wavelengths were to show the peak, hypothetically the snowpack would be ripe.

Figure 4 compares the responses of all four wavelengths over frozen ground in January, 1977 to that over shallow (2.5 cm), moist snow and wet ground at Walden in March 1977. The shortest wavelengths, 0.8 and 1.4 cm, have slightly higher average brightness temperatures for moist snow than for the frozen ground because they are affected by emission of the moist snow. While the 1.7 cm channel shows approximately the same T_B for frozen ground and moist snow, the difference in the 21 cm T_B between moist snow and frozen ground is 58°K. The 21.0 cm radiation is apparently unaffected by the moist snow because it is so shallow and reflects the T_B of the wet ground beneath the snow.

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 aircraft experiments. An average T_B decrease for the shorter wavelengths studied (0.8, 1.4 and 1.7 cm) of 35°K has been shown to correspond with a 39.4 cm greater snow depth for the March 1976 as compared to the January 1977 snowpack. A T_B decrease of the same magnitude for the 21 cm wavelength is attributed to wet soil conditions in March 1976. Furthermore, a sharp rise, ∿ 49°K, in the 0.8 cm T_B corresponds to moist snow on the surface of the Walden snowpack in March 1977 demonstrating the sensitivity of microwave 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 strongly 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 <1 mm. 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.

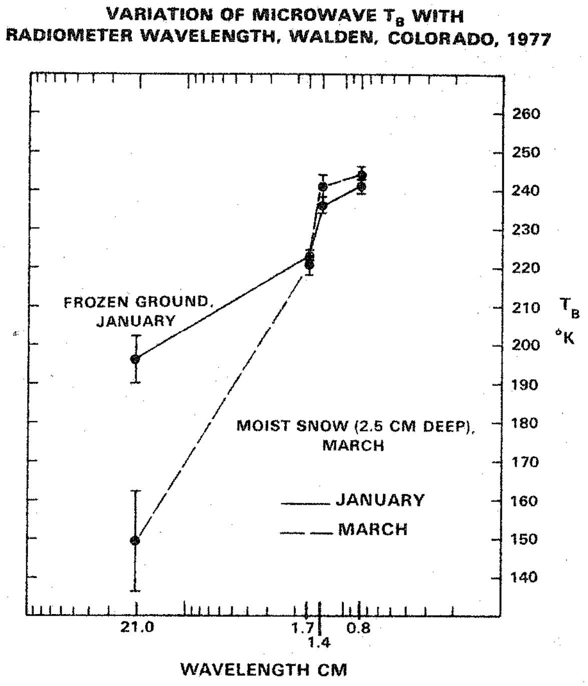


Figure 4

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.

Passive microwave sensors appear to have the potential to sense internal and surficial snowpack properties. For example, brightness temperatures increase when the snow is moist and decrease with increasing snow depth as demonstrated. Advantages of the multifrequency approach employed herein relate to characterization of conditions not only at the bottom, but in the middle and at the top of the snowpack. This is because longer wavelength radiation tends to be dependent upon conditions at greater depths or beneath the snowcover whereas shorter wavelength radiation is dependent upon the more shallow portions of a snowpack.

A strong potential exists in which microwave radiation could augment the currently used visual and near-infrared techniques by sensing internal snowpack properties and by delineation of snowcovered area even through cloudcover. This latter apparent potential will have to be corroborated by the analysis of more experimental data and through the development of larger antennas that afford better spatial resolution than is obtainable with the current state-of-the art passive microwave sensors.

During 1978 two satellites, Nimbus-G and Seasat-A, will be launched with multifrequency imaging radiometers on-board. These radiometers will not be optimum for snow studies because they will have spatial resolutions extending from 25 to 150 km. These additional satellite data will be studied to determine the extent of snowcovered areas, thus supplementing the visual observations available from other satellites, and additionally to make inferences regarding water equivalent and the presence of free water in the snow.

REFERENCES

Chang, T. C. and P. Gloersen, 1975: Microwave Emission from Dry and Wet Snow, in Operational Applications of Satellite Snowcover Observations, NASA SP-391, Washington, DC pp. 399-407.

Chang, T. C., P. Gloersen, T. Schmugge, T. T. Wilheit and H. J. Zwally, 1976: Microwave Emission from Snow and Glacier Ice, Journal Glaciology, V. 16, No. 74, pp. 23-39.

Egerton, A. T., A. Stogryn and G. Poe, 1971: Microwave Radiometric Investigations of Snowpacks, Aerojet General Corp. Final Report 1285R-4.

Ellerbruch, D. A., W. E. Little, H. S. Boyne and D. D. Bachman, 1977: Microwave Characteristics of Snow, Proceedings of the 45th Annual Western Snow Conference, Albuquerque, New Mexico, pp. 68-74.

Hoekstra, P. and D. Spanogle, 1972: Radar Cross Section Measurements of Snow and Ice. Cold Regions Research and Engineering Laboratory, Technical Report TR 235, Hanover, New Hampshire, 39 oo.

Rango, A. (ed), 1975: Operational Applications of Satellite Snowcover Observations, National Aeronautics and Space Administration, NASA SP-391, Washington, DC, 430 pp.

Rango, A., 1978: Pilot Tests of Satellite Snowcover/Runoff Forecasting Systems, Proceedings of the 46th Annual Western Snow Conference, Otter Rock, Oregon, 10 pp.

Schmugge, T., 1973: Microwave Signature of Snow. Proceedings of the Annual Science and Technology Review GSFC, National Aeronautics and Space Administration, NASA SP-361, pp. 193-195.

Schmugge, T., T. T. Wilheit, P. Gloersen, M. F. Meier, D. Frank and I. Dirmhirn, 1974: Microwave Signatures of Snow and Fresh Water Ice, in Advanced Concepts and Techniques in the Study of Snow and Ice Resources, National Academy of Sciences, Washington, DC, pp. 551-562.