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Measurement and Modeling of Microwave Emission from Forested Snowfields in Michigan

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Forest cover was found to confuse the normally inverse relationship between microwave brightness temperature (T_B) and snow depth in dry snowpacks in the lower peninsula of Michigan during February of 1979 and 1980. However, even in the presence of forest cover, consisting of a mixture of hardwoods and softwoods, the average Nimbus-7 SMMR 37 GHz vertically and horizontally polarized T_Bs were 11° and 19° K lower during the study period in February of 1979 versus February of 1980. This is attributed to deeper average snowcover for the study period in 1979 (43.8 cm) as compared to 1980 (9.9 cm) since lower T_Bs accompany deeper snow under dry snowpack conditions. 37 GHz brightness temperature was correlated with snow depth for the study periods in 1979 and 1980, resulting in positive relationships instead of the expected inverse relationships. Because the snow depth increased with increasing forest cover in the lower peninsula of Michigan, it was assumed that the emissivity of the forest cover overwhelmed that of the snow – both in 1979 and 1980 causing higher T_Bs in more heavily forested areas. Using a simple model, we removed the effects of the trees from the T_B/snow depth relationship. A new value, T_{BR}, residual brightness temperature, derived from the 37 GHz data, was correlated with snow depth for selected time periods in February 1979 and 1980 resulting in inverse relationships of $R \equiv .82$ and .77 respectively. In addition, SMMR data of August 1979 were correlated with percent forest cover to determine the T_B of the study area in the absence of snow. The lower SMMR frequencies (10.69 and 6.6 GHz) showed statistically significant inverse relationships with forest cover during the August study period. These inverse relationships were probably due to increased soil moisture in the more heavily forested areas in the northern half of lower peninsula of Michigan thus causing lower T_Bs.

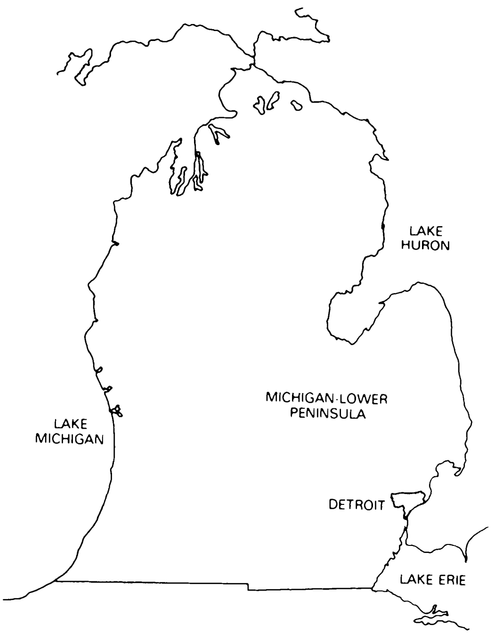

Fig. 1. Lower Peninsula of Michigan.

Introduction

An inverse relationship has been found to exist between satellite-derived microwave brightness temperature (T_B) and snow depth in dry snowpacks in homogeneous prairie areas (Rango et. al. 1979 and Foster et. al. 1980). Because of this relationship, hydrologists may ultimately be able to use satellite-borne microwave sensors to assess the water equivalent of snowpacks – an important parameter in forecasting the quantity of expected runoff. However, the presence of forest cover confuses the relationship between T_B and snow depth in many areas. In this paper, we analyze the microwave emissivity of snowcovered forests, and subsequently employ Nimbus-7 SMMR (Scanning Multichannel Microwave Radiometer) data in a microscopic scattering model (similar to that discussed in Chang et.al. (1976)) to subtract the effects of the forest cover from the T_B/snow depth relationship in the lower peninsula of Michigan.

During February of 1979 and 1980, and August of 1979, Nimbus-7 SMMR data were obtained of the lower peninsula of Michigan. The winter of 1978-79 had a record high amount of snowfall and thus provided a good basis for comparison with the following winter (1979-80) which had a lower than normal amount of snow. The microwave T_Bs for the study area were quite different for the three time periods. The physical basis for the T_B differences is the subject of this paper.

The lower peninsula of Michigan is surrounded by Lake Michigan to the west, Lake Huron to the north and east and Lake Erie to the southeast (Fig. 1). The topography of the lower peninsula consists of smooth plains in the south and east, rolling plains in the central part and hills in the north. Elevations range from about 150 to 500 m. There are numerous small lakes (< about 5 km^2) scattered throughout the southern half of the lower peninsula with somewhat larger lakes being more prevalent in the northern half. In southern and central Michigan, the forests are generally comprised of northern hardwoods (oak-hickory, elm-ash, beech-maple and aspen-birch associations); and in the northern parts of the lower peninsula, the forests are generally comprised of softwoods (pine and spruce-fir associations). Soils are classified as being cool and moist (mean annual soil temperature < 8°C) in the northern part, and warm and dry (mean annual soil temperature > 8°C) in the central and southern parts of the lower peninsula (U.S. Department of the Interior 1970).

Interpretation of Passive Microwave Data and Description of the SMMR

Since December of 1972, the Nimbus satellites have been acquiring passive microwave data of the surface of the Earth; the Nimbus-5 and -6 satellites each carried an Electrically Scanning Microwave Radiometer (ESMR) on board sensing naturally emitted radiation with 25 km resolution. In October of 1978, the Nimbus-7 satellite was launched with a SMMR on board operating in five different frequencies, from 37 GHz to 6.6 GHz with resolutions ranging from 30 km (for the 37 GHz data), to 156 km (for the 6.6 GHz data). Some pertinent characteristics of the SMMR are given in Table 1. A more detailed description of the SMMR can be found in Gloersen and Barath (1977).

Microwave radiation emanates from features on the surface of the Earth in an intensity that is proportional to the product of the temperature and the emissivity of the surface at an altitude (H) above the surface. The measured value referred to as the brightness temperature is

$$T_B \equiv \tau(H,\theta)[R\,T_{\mathrm{SKY}} + (1-R)T_{\mathrm{SURF}}] + T_{\mathrm{ATM}}(H,\theta)$$

where τ is the atmospheric transmission and R is the surface reflectivity, T_{SKY} is reflected sky radiation, T_{SURF} is the thermal emission from the surface, and T_{ATM}

Table 1 – Characteristics of the Nimbus-7 SMMR (after Gloersen and Barath 1977).

Wavelength	4.54	2.80	1.66	1.36	0.81
Frequency (GHz)	6.60	10.69	18.00	21.00	37.00
Spatial resolution (km)	156	97.5	60	60	30
Temperature resolution T_{rms} (°K) (per IFOV)	0.9	0.9	1.2	1.5	1.5
Antenna beam width (degree)	4.2	2.6	1.6	1.4	0.8

is the emission from the intervening atmosphere (Schmugge et.al. 1976).

Previous work has shown that surface cover will influence the passive microwave response to snow (Abrahms and Edgerton 1977 and Tiuri and Hallikainen 1981). However, the type and amount of surface cover must be quantified so that the effects of the surface cover, on the microwave response, can be assessed and removed in order to analyze the snow conditions. Tirui and Hallikainen (1981) used Nimbus-7 18 and 37 GHz data to analyze snowcovered areas in different types of terrain, e.g. farmland, bogland and forests. They used a value derived from subtracting the T_B of the 18 GHz sensor from the T_B of the 37 GHz sensor ($T_{37} - T_{18}$). They obtained negative values due to scattering in dry snow and concluded that, even with 35% shadowing due to trees, it was still possible to remotely sense snowcover through forests.

Snowpack Studies

Numerous studies (Abrahms and Edgerton 1977; Hall et. al. 1978; Rango et. al. 1979) have shown that the 37 GHz frequency is useful for studying internal snowpack properties. The wavelengths of the higher SMMR frequencies (37, 21 and 18 GHz) are more comparable in size to the snow grains and crystals and are more strongly scattered by internal snowpack particles than are the lower SMMR frequencies (10.69 and 6.6 GHz) for which the wavelenghts are too large with respect to snow crystals and grains to be significantly scattered. The lower frequencies are more useful for analyzing conditions beneath the snowpack such as the state (frozen or thawed) of the ground below the snow. This is true because these lower frequencies emanate from deeper within the medium.

In dry snow conditions, the T_B decreases with increasing snow depth because greater thicknesses of snow contain proportionally more snow crystals which scatter upwelling radiation. Less radiation is received by the sensor as scattering increases because the radiation is dispersed.

Results of SMMR Measurements of Snowcovered Forest Areas in Michigan

Snow depths were obtained from NOAA climatological data for the State of Michigan (NOAA 1979 and 1980). (Snow water equivalent (SWE) measurements would be more useful to the hydrologist than snow depth measurements, however SWE was not available for most of the study area.) Isolines of snow depth were drawn onto a map of Michigan and percent of forest cover of each county (Chase et. al. 1970) was superimposed on the map. These data were correlated with Nimbus-7 brightness temperature data for selected time periods in February 1979 and 1980.

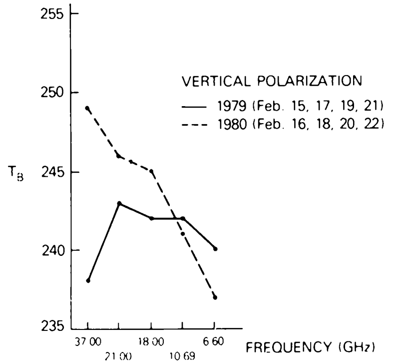

Fig. 2. Plot of average SMMR T_Bs for the study area – 1979 and 1980 vertical polarization.

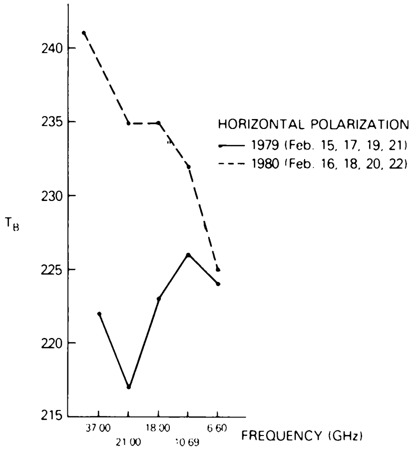

Fig. 3. Plot of average SMMR T_Bs for the study area – 1979 and 1980 horizontal polarization.

The average T_Bs for the vertical and horizontal polarizations at all the SMMR wavelengths for the 1979 and 1980 snow study areas are plotted in Figs. 2 and 3. Note the differences in T_B in the 37 GHz frequency v (vertical) and h (horizontal) polarizations between February 1979 and February 1980. In the case of the horizontal polarization, the T_B is 19° K lower in 1979 than in 1980, and for the vertical polarization, the T_B is 11° K lower in 1979 than in 1980. The average snow depth was greater in the study area in 1979 (43.8 cm ± 17.24) than in 1980 (9.9 cm ± 5.65) thus explaining the lower average T_B in 1979 because T_B should be lower in a deeper snowpack. The average maximum air temperature for the study period was also lower in 1979 (266° K) as compared to 1980 (273° K) but not enough lower (only 7° K) to account for the large differences in average T_B between the two years. Therefore, the 37 GHz T_B must have been largely influenced by the snow beneath the trees.

Note that the average maximum air temperature for the study period in 1979 is well below freezing and therefore melting within the snowpack should not be an influencing factor on the T_B. However, in 1980 with an average maximum air temperature at the freezing point, 273° K, slight melting of the snowpack might have been present to influence the 1980 brightness temperatures.

Coefficient of correlation (R) values for forest cover versus snow depth are +.83 for February 1979 (Fig. 4) and +.75 for February 1980. These positive relationships show that the areas of denser forests are also areas of deeper snow. This is reasonable since greater precipitation in these areas (mainly the northern portion of the lower peninsula of Michigan) allows for greater available soil moisture which tends to promote denser forest cover. It should be noted that type of

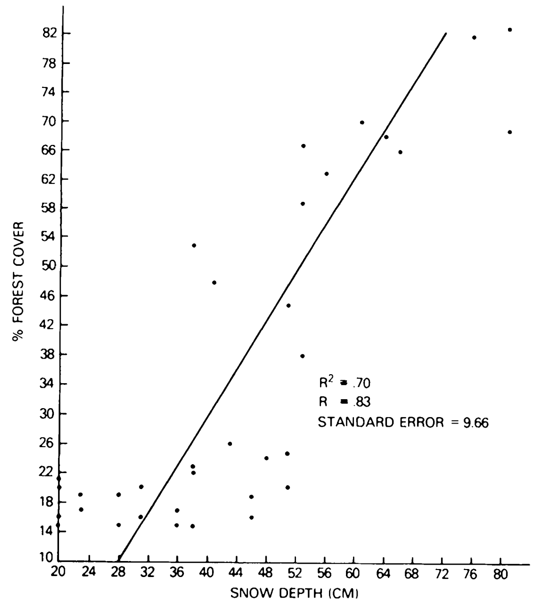

Fig. 4.
Relationship between snow depth and percent forest cover – lower peninsula of Michigan – February 1979.

forest (hardwood versus softwood) was not correlated with T_B because the areas of pure forests were not large enough for statistically significant correlations.

The horizontally polarized data display more sensitivity to vegetation and forest cover than do the vertically polarized data. This can be seen in Table 2. Relationships are generally positive and significant at the .01 level between T_B and forest cover at frequencies from 37 to 10.69 GHz in the 1979 data. Positive relationships (however with lower *R* values) were also found between T_B and snow depth (also see Table 2). This is consistent with the rather strong positive (R = .83) relationship found between forest cover and snow depth in February 1979. The influence of the forest cover is apparently overriding the effect of snow depth on the microwave T_B causing the positive relationships between T_B and snow depth.

In February of 1980 (Table 3), the *R* values are rather low both for snow versus T_B and for forest cover versus T_B. This is probably because the snow cover was so thin (average depth = 9.9 cm), that there was low vegetative ground cover protruding through the snow thus raising the microwave T_B of the snow closer to that of the forest cover. In addition, the snow did not vary enough in depth to allow for a good statistical comparison with T_B.

The August 1979 SMMR data were correlated with percent forest cover in the lower peninsula of Michigan to determine if a relationship existed in the absence of snowcover. *R* values were very low and not significant in the 37, 21 and 18 GHz frequencies; this was probably because the sensors were unable to differentiate between the forest cover and low vegetative ground cover which have similar emissivities. However, the 10.69 and 6.6 GHz *v* and *h* data gave *R* values signifi-

Table 2 – Coefficient of Correlation (R) values for T_B versus Snow Depth and for T_B versus Forest Cover – February 1979

T_B	37v	37h	21v	21h	18v	18h	10.69v	10.69h	6.6v	6.6h
Snow depth	No +.35	+.71	No 0	+.69	No −.05	+.72	−.43	+.62	No −.76	−.30
Forest cover	No +.16	+.78	No 0	+.86	No −.21	+.84	−.56	+.81	−.69	No −.01

No – not significant at .01 level

Table 3 – Coefficient of Correlation (R) Values for T_B versus Snow Depth and for T_B versus Forest Cover – February 1980

T_B	37v	37h	21v	21h	18v	18h	10.69v	10.69h	6.6v	6.6h
Snow depth	No −.18	NO +.25	No +.26	No +.42	No +.19	No +.40	No −.34	No −.01	−.56	−.61
Forest cover	No +.20	+.57	No +.32	+.66	No +.32	+.68	No −.31	No +.07	−.50	−.44

No – not significant at .01 level

cance at the .01 level; the 10.69 GHz v and h R values were −.55 and −.47 respectively, and the 6.6 GHz v and h R values were −.75 and −.74 respectively. These inverse relationships at the higher frequencies may be due to greater soil moisture and cooler physical temperatures in the areas of denser forests causing a lowering of the T_B. Surface water in these areas may also cause a lowering of the T_B. Microwave radiation emanating from beneath the forest cover comes from a greater depth at the higher frequencies thus the low T_B of the ground is sensed offering an explanation for the negative correlations of forest cover and T_B at the higher frequencies.

Model Results

We have developed a simple model to separate the effects of the forest cover from the effects of the snow depth on the 37 GHz T_B data for the February 1979 and 1980 study periods. This was necessary because the T_B/snow depth relationship was positive (Table 2) when in fact T_B should vary inversely with snow depth as shown in previous studies. It was assumed that the trees were primarily influenc-

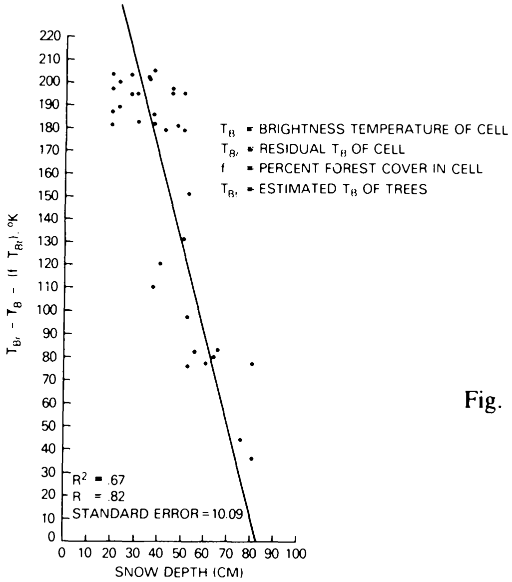

Fig. 5. Relationship between T_{Br} (from model) and snow depth from 37 GHz data February 1979.

ing the T_B/snow depth relationship and causing the positive correlations. The following formula was used to subtract the influence of the trees from the 37 GHz T_B data

$$T_{BR} = T_B - (f\ T_{BT})$$

where T_{BR} represents the residual 37 GHz T_B from which the effects of forest cover have been removed. T_B is the brightness temperature of a particular cell block, f is percent forest cover determined from Chase et al. (1970); T_{Bt} is the assumed brightness temperature of the trees which is calculated by multiplying the emissivity of the trees (.90) by the average maximum air temperature of the study period which were 266° K and 273° K for February 1979 and 1980 respectively.

T_{Br} was calculated for each of the 34 cell blocks and correlated with snow depth in each cell block which is 97.5 km^2 in size for the February 1979 and 1980 37 GHz v and h data. An inverse relationship with an R value of .82 was found for the 1979 correlations calculated using the 37 GHz v data (Fig. 5). For the 1980 data, the relationship was also inverse with an R value of .77. For both the 1979 and 1980 data, the R values were quite similar in both polarizations (Table 4).

Note that the snow depth was correlated with T_B (Tables 2 and 3), the R values were quite different in the horizonal and vertical polarizations. This shows that the forest cover was strongly influencing the relationships because surface cover effects are more pronounced in horizontally polarized data than in vertically polarized data. When snow depth was correlated with T_{Br} (Table 4) this was not the case; there was no longer a large polarization effect. Thus, our model appears

Table 4 – Coefficient of determination (R^2) and coefficient of correlation (R) values for February 1979 and 1980 – T_{B_r} versus snow depth.

	1979		1980	
	37v	37h	37v	37h
R^2	.67	.68	.59	.59
R	−.82	−.83	−.77	−.77
Standard Error	10.09	9.89	3.12	3.09

to be consistent with theory which does not favor a large polarization effect in snow.

Conclusions

Many snowcovered areas are not homogeneous prairie areas, but have surface cover that may confuse the microwave response to the snow underneath. Thus, it is necessary to determine the emissivity or T_B of confusion factors (such as trees) so that the T_B variations that remain can be attributed to snow depth or water equivalent variations and not to surface cover effects. This appears to be possible through modeling whereby the effects of confusion factors can be removed. Ultimately, the hydrologist will use microwave data from satellites in conjunction with in-situ measurements to estimate snow water equivalent over large areas with homogeneous and non homogeneous surface covers.

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