A REVIEW OF MICROWAVE REMOTE SENSING OF SNOW

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INTRODUCTION

Repetitive coverage of snow conditions can be obtained at microwave frequencies, unrestricted by cloud cover or lighting conditions throughout the winter season. Microwave sensors have the ability to penetrate deep into the snowpack providing subsurface information, thereby offering additional information on snowpack properties which cannot be obtained from optical or infrared sensors, sensing only surface information.
Passive microwave radiometers measure energy levels of naturally upwelling surface radiation. Over a snow surface the signal received will contain information from two sources; 1) emission by snow-volume, and, 2) emission from the underlying ground (Stiles & Ulaby 1981). Readings of natural microwave emission are recorded as brightness temperatures (Tb's); a function of the emissivity of the surface and its physical temperature.
Active microwave sensing utilises a radar system that sends microwave pulses towards the ground and then measures the energy reflected or backscattered back to the sensor. The total amount of energy received by the antenna per unit surface area is the sum from several contributions; 1) Surface backscattering at the air-snow interface, (a very small component at angles other than perpendicular), 2) volume scattering within the snowpack, and 3) surface scattering a the snow-ground interface, (Ulaby & Stiles 1980). Contributions to sensor readings of both systems are governed by the transmission and reflection properties of the air-snow and snow-ground interfaces, and by the absorption and scattering properties of the snow layer itself.

SNOW MICROWAVE REMOTE SENSING

The emissivity and reflection or backscatter coefficient of the surface cover are the two most important parameters governing microwave remote sensing. These parameters are governed in snow research by the electromagnetic and scattering properties of the snowpack. These properties vary with a number of physical features such as; grain size, snow density, snow temperature, free water content, snow depth, soil state, stratification, ice lenses, snow surface roughness and vegetation cover (Foster et al. 1984). Apart from the natural properties of snow itself, several controllable instrument and uncontrollable scene parameters will determine active and passive microwave return (Bernier 1987).
Instrument parameters include: 1) sensing frequency or wavelength, 2) polarization of propagated or received signal, and 3) the view or incidence angle. **Scene parameters** include; 1) the extent of the snow cover, 2) the snow depth and water equivalent, 3) the timing of the onset of melt, 4) the free water content and finally, 4) the effect of a vegetation cover on the sensor readings.

Frequency

The scatter component of microwave remote sensing is highly dependent on frequency. By increasing wavelength, (decreasing frequency) the relative size of the dielectric discontinuities are decreased and the scattering and attenuation from within the snowpack will be small, with most of the scattering occurring at the snow-ground interface. On the other hand as the wavelength of the signal approaches the size of the snow crystals the contribution to scatter from within the snowpack increases.
Multifrequency measurements offer the capability of sampling at various locations within a homogeneous snowpack. While a single frequency offers the capability of distinguishing differing structures and properties within the snowpack, or between several snowpacks.

Polarization

Polarization describes the orientation in the xy plane of the electric field vectors travelling in the z direction. In active microwave sensing, both the propagated and received signals are polarized. Sensing can take place in either a like or cross polarized mode of operation. Kong et al. (1980) indicated that the two like-polarized backscatter coefficients behave differently with increasing snow depth. However Ulaby & Stiles (1980) reported nearly identical behaviour of the two modes. The effects of cross-polarization remains relatively unclear. In passive systems on the other hand, vertical and horizontal sensor polarizations have been shown to respond differently to snowpack. At view angles greater than zero degrees, vertical polarizations will always produce higher brightness temperature readings, while horizontally polarized sensors tend to have more information.

View Angle

The view angle in active systems furnishes both the illumination and backscattering angles to which the signal received is highly sensitive. Passive systems, on the other hand, are relatively insensitive to changes in view angle. Any instrument or scene parameter that increases the scattering of microwaves within or at the surface of the snowpack, will reduce the effect of view angle in both active and passive systems. The exception exists with active microwave where the presence of liquid water in the snow layer will result in the view angle being relatively important. This angular dependence of wet snow can be useful when trying to distinguish wet and dry snowpacks (Matzler 1984).

Snow Extent

Snow boundaries can easily be defined using passive systems, because of the sharp decrease in brightness temperature between dry land and a dry snow surface. Kunzi et al. (1982) demonstrated that snow-free areas can be discriminated against dry snow areas using a gradient between the 19 and 37 GHz channels in either a vertical or horizontal polarization. The algorithm's physical basis is derived from the fact that the apparent dry snow brightness temperature is a strong function of frequency and is relatively insensitive to physical temperature changes in the snowpack.

$$GT = \frac{\underline{Tb(f1) - T(f2)}}{(f1) - (f2)} \text{ K/GHz}$$

where if GT <= D then dry snow is present
GT >= D then dry snow is not present

f1 and f2 are the higher and lower frequencies in gigahertz, and can be either horizontally or vertically polarized. The value of D (-0.2) was determined empirically, then adjusted for the best correspondence between horizontally polarized SMMR data and ground data (kunzi 1982).
Based on active microwave theory, it seems that the distinction of dry snow from frozen ground could be made routinely using active systems.

Snow Depth - Water Equivalent

Both the scattering coefficient and brightness temperatures are sensitive to changes in snow depth. Active microwave backscatter data will rise exponentially with increasing depth. Passive microwave brightness temperatures will, on the other hand, fall exponentially with increasing depth, giving a 'colder' signature. It should be kept in mind that the relationships between depth and backscatter or brightness temperatures are not unique as they also depend upon a multitude of other factors.
Kunzi extended his gradient algorithm for the determination of snowpack thicknesses.

$$\text{depth} = \frac{\underline{(GT - 0.085)}}{0.036} \text{ cm}$$

Water equivalent is a better measure of the quantity of snow due to the significant regional variations often observed in snowpack densities. The water equivalence of a snow cover can be calculated by:

water equivalent = Q * depth

where Q is the snow density in grams per cubic centimetre. Bilello (1966) derived the following relationship for determining the average dry snow density for a given climatic imatic region:

$Q = 0.152 - 0.0031*T + 0.019*W$

Where: Q = average seasonal snow cover density (g/cm^3)
T = average seasonal air temperature (°C)
W = average seasonal wind speed (m/sec^2)

The term 'seasonal' refers to the period during which a snow cover is present.

Liquid Water Content - Onset Of Melt

At microwave frequencies, the dielectrics of ice and water are markedly different, (water is much higher) rendering the signature of dry and wet snowpack strikingly different. Previously described relationships are essentially masked by the high attenuation of the wet layer. Liquid water in snow affects active microwave by reducing the penetration depth of the propagated signal. This is done by increasing the amount of absorption taking place which then causes the backscatter coefficient to fall. Stiles and Ulaby (1979) reported that the decrease in backscatter was linear with increasing liquid water content up to about 5%. In passive microwave radiometry, the initial effect of small amounts of water is to increase microwave absorption within the snowpack so that less emission from the soil penetrates through the snow. With the addition of 1% free water brightness temperatures will increase by roughly 70 degrees. Detection of the onset of melt is best accomplished from multi-temporal observations of signature fluctuations. Before melting, the snowpack will undergo a wetting and freezing cycle. Strong cycles in brightness temperature and backscatter response are observed.

The Effect Of A Vegetation Cover

Large spatial variations in cover properties will mask variations in microwave signal caused by variations in the snow cover. The magnitude of that effect will depend on the density, composition and structure of the cover. Heavily vegetated areas have a two-fold effect on microwave readings; 1) the emissivity of the vegetation cover will shadow that of the snow, in return causing higher values than would otherwise be recorded. 2) a dense vegetation cover will increase soil moisture and result in a cooler physical surface temperature. In order to restore the normally inverse relationship between temperature brightness and depth in passive microwave signal, Foster and Hall. (1984) suggest a method of subtracting forest microwave emission from the observed readings. The observed brightness temperature will be made up of contributions from both the forest and the snow.

$$Tbr = Tb - (F*Tbf)$$

where: Tbr = residual brightness temperature
Tb = temperature brightness of the scene
F = the percentage of the scene covered by forest
Tbf = temperature brightness of the forest

$$Tbf = Ef*T$$

where: Ef = emissivity of the forest, approximately 0.90
T = average of the maximum air temperature.

These algorithms were successfully used by Hall et al. (1982) to remove forest effects from SMMR data, using the 37 GHz channel.

CONCLUSION

Microwave remote sensing of a surface snow cover holds great potential. Microwave radiation is sufficiently penetrating to be responsive to a wide range of snowpack properties. Emission characteristics are influenced by the surface and bulk snow properties, as well as the properties of the base materials. Sensitivity to the occurrence of snow properties such as free water, varying snow density, ice lenses, non constant thermal temperatures, gives an indication as to the amount of information that could be extracted from properly designed instruments. An understanding of the nature of snow-microwave interaction permits optimal sensor configuration to be achieved. Proper choice of sensing wavelength, view angle and polarization will allow the maximum amount of information to be obtained from a varying snow cover. Relationships have been derived, linking microwave theory and surface conditions, proliferating a wide range of possible applications to snow monitoring. Snow extent, depth, water equivalent and melt-freeze conditions are all surface states that can be determined using both active and passive sensors. However, relationships derived in one region are not directly transferable to another, without, significant knowledge of the physical and climatic differences between the region of algorithm development and algorithm application.

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