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Microwave Remote Sensing of Snowpack Properties: Potential and Limitations

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This review explores from a user's viewpoint the possibilities and limitations of microwave-based techniques for the remote sensing of snowpack properties. Mapping of dry snowpacks and detection of melt onset can be achieved with combinations of readings taken at different frequencies with passive microwave sensors. A combination of readings from both passive and active sensors coupled with ground truth data will be required to estimate snow water equivalent under most snow conditions. Snowpack structure and overlying vegetation still present major problems in the estimation of snowpack water equivalent from microwave remote sensing devices.

Introduction

Snow is a major component of the hydrological cycle in temperate and boreal countries. Yet, traditional measurement techniques fail to provide accurate and routine estimates of snow water equivalent over moderate to large areas. This problem is well felt on our experimental basin, in the Canadian Rockies. where a highly variable snowpack in the wind-swept alpine zone has prevented the computation of an accurate annual water balance. The impetus for this review was a perceived potential of microwave remote sensing techniques as a solution to our snow measurement problems.

The purpose of this review is to explore from a user's viewpoint the possibilities and current limitations of microwaves for the remote sensing of snowpack properties. Hopefully, it will also help to direct the attention of researchers on the problems that prevent operational use of these techniques. Studies where the main emphasis was on sea or glacier ice were omitted in order to maintain the focus of this review on snow. Interested readers can find recent examples of sea ice work in Comiso *et al.* (1984), Kim *et al.* (1984), Hollinger *et al.* (1984), and Swift and Cavalieri (1985). Wavelengths (λ) in centimeters are used throughout the text. The conversion to frequency in gigahertz (GHz) is

$$\text{Frequency (GHz)} = \frac{30}{\text{Wavelength (cm)}}$$

Microwaves and Snow

Microwaves occupy a portion of the electromagnetic spectrum between 0.1 and 100 cm (300 to 0.3 GHz). Microwaves that fall within certain regions of the spectrum travel almost unimpeded through the atmosphere (Fig. 1). These regions of atmospheric transparency are called "atmospheric windows". Because of the type of interactions involved between snowpacks and electromagnetic waves, the most appropriate wavelengths for probing snowpacks fall within such windows and are, in addition, largely unaffected by clouds.

Snow is composed principally of air and ice. At temperatures below 0 °C, snow also contains "liquid-like" water in thin films around, and bound to, ice crystals (Hobbs 1974). The calculated thickness of these films varies from about 100 to 400 nanometers at temperatures from -6 to -1 °C. The microwave literature does not appear to make any reference to the influence of these "liquid-like" films on the microwave/snow interactions. In this review snow below 0 °C is said to be dry since it contains no "free" liquid water.

The air and ice that make up dry snow have different electrical properties, but using a dielectric mixing formula, one can estimate the relative dielectric constant (ε) of dry snow as a function of its density. The combination of air ($\varepsilon = 1$) and ice ($\varepsilon = 3.2$) gives dry snow an ε of about 2.0 (Cumming 1952; Evans 1965) at a density of 0.5 g/cm^3. If snow was a homogeneous body, this bulk electrical property would give it an emissivity of 0.98 over most of the microwave range (Schmugge 1980), very much like that of dry or frozen soil. However, two factors give dry snow a unique behaviour with respect to microwaves. First, at microwave wavelengths, dry snow is not very "lossy" (Mätzler *et al.* 1984), meaning that microwaves can penetrate deep into the pack without being absorbed. Secondly, because of this penetration, microwaves can be subjected to volume scattering within the pack.

Volume scattering in snow is caused by dielectric discontinuities or differences in dielectric properties between air and ice crystals. Wavelengths shorter than snow crystal size (0.05 to 1 mm) are strongly scattered even by the thinnest snowpack,

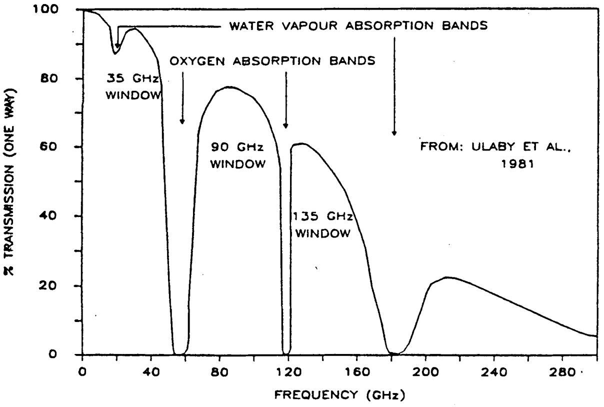

Fig. 1.
Atmospheric transmissivity at microwave frequencies.

while wavelengths longer than 10 or 15 cm travel unaffected through most dry seasonal snowpacks.

Microwaves at wavelengths between these two extremes penetrate and are scattered by dry snow, the level of scattering being greatly influenced by the amount of snow on the ground (more snow, more discontinuities for scattering). Microwave remote sensing systems attempt to measure this level of scattering so that analysts can detect the presence of snow on the ground and compute its quantity.

Instruments and Methods

Techniques for microwave remote sensing of snowpacks are classified as passive or active. Passive systems use a radiometer that points toward the ground from a tower, plane or satellite, and measures energy levels of natural upwelling microwave emission. Such systems have been studied extensively since their inclusion on board satellites, particularly those of the NIMBUS series (Ulaby *et al.* 1981, Vol. 1). Readings from passive systems are expressed as microwave brightness temperatures (T_b), the temperature in °K at which a blackbody (a perfect emitter) would cause a similar sensor response. Dry or frozen ground is a good microwave emitter and the main source of the microwaves sensed by passive systems. When snow covers the radiometrically "warm" ground, volume scattering within the pack causes some of the upwelling microwaves to be scattered back towards the ground and absorbed. Multiple scattering within the pack also increases absorption of microwaves by the snow itself. The higher the scattering due to snowpack, the greater the absorption of microwaves, and the "colder" the ground will look to the radiometer.

The ideal passive microwave reading should contain only surface-emitted microwaves. Real readings, however, also contain a small amount of atmospheric microwaves, either backscattered by the snow to the sensor, or emitted directly towards the sensor. Real readings are also altered somewhat by the absorptive properties of the atmosphere (e.g. Hofer and Good 1979). These uncorrected readings are sometimes called "apparent brightness temperature" or T_{ap} (e.g., Ulaby and Stiles 1980a). In this review, I use the more common notation, T_b for the uncorrected readings. Table 1 summarizes the location, platform, wavelengths and snowpack conditions for most of the experiments done with passive microwave systems.

Active systems use a radar or scatterometer that sends microwaves toward the ground and measures the reflected signal. The amount of backscattered energy received by the antenna is the sum of surface scattering at the snow-air interface, a very small component at angles other than perpendicular (Ulaby 1982), volume scattering within the pack, and surface scattering at the snow-soil interface (Ulaby and Stiles 1980a). In general, conditions that favor a high T_b in passive systems will yield a low backscattered signal with active ones. Table 2 lists most of the active microwave experiments on snowpacks, showing the types of radar and the platforms used. Descriptions of radar types and methods of analysis are provided below only to help the unfamiliar reader along in the discussion (see Ulaby *et al.* 1981, and Ulaby 1982, for a more complete treatment of the subject).

Pulse radars send nanoseconds pulses of energy toward the scene (the unit of land that the instrument "sees"). The pulses contain all wavelengths within a narrow band characteristic of the emitter. Information is obtained from the amplitude and the time delay of the returned signal. Frequency-modulated or FM radars send a signal whose wavelenght is continously swept across a bandwidth characteristic of the emitter. Information is obtained from the amplitude of the returning signal and its shift in phase with respect to the currently outgoing signal.

Energy returning to the receiving antenna is analyzed in either the time domain or the frequency domain. In time domain analyses, returning energy from a signal is averaged over the frequencies of the pulse or sweep and plotted over time. Individual layers or discontinuities such as air-snow, air-soil boundaries, and layers of different densities within the pack appear as peaks of returning signal amplitude as a function of time (Vickers and Rose 1974; Ellerbruch *et al.* 1977; Ellerbruch and Boyne 1980, Boyne and Ellerbruch 1979, 1980).

In the more common frequency domain analysis, the returning energy from a signal is summed over time and expressed as a function of signal wavelength. With FM radars, averaging of the signal over a narrow wavelength band and over time is done to reduce scintillation (fading) (Ulaby *et al.* 1977). Results are expressed as a function of the central wavelength of the band. The scattering cross-section area or backscatter coefficient (σ_o), the final measure of scene brightness in the frequency domain, is a function of the ratio of incident to backscattered energy. Values of σ_o are in $m^2\ m^{-2}$, or dimensionless. The logarithmic transform to decibels (dB) yields negative values when σ_o is less than unity.

Table 1 ‒ Summary of experiments on the remote sensing of snow with passive microwaves

Reference (S)	Location & Platform	Wavelengths (cm)	Scene Type
Meier and Edgerton 1971	laboratory	0.81, 2.2, 6, 21	artificially piled snow
Meier 1972	Mt Rainer, air-borne	1.55	alpine snowpack
Schmugge *et al.* 1973	Western USA air-borne	1.55	dry snow over lake ice, wet soil, glacier ice, firn and wet snow
Künzi and Staelin 1975 Künzi *et al.* 1976	NIMBUS-5 NEMS	0.95, 1.35	snow cover over northern hemisphere
Hall *et al.* 1978 Chang *et al.* 1979	Colorado Rockies, plane	0.8, 1.4, 1.7, 21	shallow natural snowpacks
Shiue *et al.* 1978	Colorado Rockies, truck	0.81, 1.66, 2.8, 6	alpine pack, 60-70 cm deep
Rango *et al.* 1979 Chang *et al.* 1979	Canadian Plains and US sites. NIMBUS-6 ESMR	0.81	shallow natural snowpacks
Foster *et al.* 1980	NIMBUS-5 ESMR NIMBUS-6 ESMR	1.55 0.81	Packs on US, Canadian plains & Russian steppes
Chang *et al.* 1980	Colorado Rockies, truck	0.81, 1.6, 3, 6	natural alpine packs, 70 cm deep
Schanda and Hofer 1977 Hofer and Schanda 1978 Hofer and Good 1979 Mätzler *et al.* 1979 Hofer and Mätzler 1980 Mätzler *et al.* 1982	Swiss Alps, tower	0.8, 1.4, 2.8, 6.1	deep alpine pack with depth hoar
Ulaby and Stiles 1980a Ulaby and Stiles 1980b Stiles and Ulaby 1979	Colorado Rockies, truck	0.3, .81, 2.8	thin natural packs and artificially piled snow
Rotman *et al.* 1981 Rotman *et al.* 1982	NIMBUS-6 SCAMS	0.94 1.34	Artic, Antartic and Greenland
Tiuri and Hallikainen 1981 Hallikainen 1984	NIMBUS-7 SMMR	0.8, 1.4, 1.66	Finland: forests, bogs and farmland
Tiuri 1982	Finland, tower	0.81, 2.5, 6.0	thin natural snowpack

cont.

Table 1 – cont.

Reference (S)	Location & Platform	Wavelengths (cm)	Scene Type
Künzi *et al.* 1982	NIMBUS-7 SMMR	0.81, 1.67, 2.8, 4.55	Northern hemisphere, winter
Hall *et al.* 1982	Michigan NIMBUS-7 SMMR	0.81, 1.67, 2.8, 4.55	Forest covered snowpacks
Goodison *et al.* in print	Airborne and NIMBUS-7 SMMR	0.81, 1.67	Thin snowpacks over Prairies

Table 2 – Summary of experiments on the remote sensing of snow with active microwave systems.

Reference (S)	Type of radar	Platform	Wavelengths (cm)	Location and scene type
Cumming 1952	Pulse	Tower	3.0	Canada, up to 25 cm of snow over sand or aluminiun
Vickers and Rose 1974	FM-CW	Tower, Snow-Cat	11.1	Colorado, 170 cm of snow over snow pillow
Ulaby *et al.* 1977	FM-CW	Truck	3.75 to 30	Kansas, up to 15 cm of snow over short grass
Ellerbruch *et al.* 1977 Ellerbruch and Boyne 1980	FM-CW ANA	Tobaggan	2.5 to 3.75 1.7 to 60	Colorado, up to 170 cm of snow in alpine area
Boyne and Ellerbruch 1980	FM-CW	Ground	2.5 to 3.75	Colorado, from 140 to 385 cm of snow over pillows
Ulaby and Stiles 1980b Stiles and Ulaby 1980a, b Stiles and Ulaby 1979	FM-CW FM-CW FM-CW	Truck	3.75 to 30 1.67 to 3.75 0.84	Colorado, 48 cm deep natural snowpack, snow artificially piled up to 170 cm
Goodison *et al.* 1980	SAR	Plane	3.2 and 23.5	Ottawa, up to 90 cm of snow in field with varied ground cover and land use
Mätzler *et al.* 1982		Tower	2.88	Switzerland, summer snow
Mätzler and Schanda 1984	SAR	Plane	3.0	Switzerland, wet snow

Scene and Instrument Parameters

Brightness temperatures and scattering coefficients are a function of scene parameters, not controlled by the observer, and instrument parameters, under the control of the observer. Scene parameters include snow depth, snow water equivalent, snow density, crystal size and layering, liquid water content of the snow and of the underlying soil, and overlying vegetation. Instrument parameters include wavelength, view angle, polarization, and, during snowmelt, timing of data acquisition. The goal of research in microwave remote sensing of snowpacks is to determine the optimum setting(s) of instrument parameters for obtaining the maximum information on selected scene parameters.

Snow Depth or Water Equivalent: a scene parameter

Snow depth and snow water equivalent are not equated here, but both have been used in the various studies as a measure of the "quantity" of snow on the ground. From a microwave's perspective, a more meaningfull unit would be the number of discontinuities or scatterers in a vertical cross-section of the pack.

All other things being equal, as more and more dry snow is piled up on dry or frozen soil, a passive microwave sensor looking down from above receives a decreasing amount of emitted energy (smaller T_b, "colder" reading in °K). Conversely, an active system receives an increasing amount of its own energy backscattered by the snow cover (higher σ_o). This interaction is the basis for the microwave remote sensing of snowpacks.

Passive systems – Inverse relationships between T_b and snow depth or water equivalent have been reported for artifically piled snow (Meier and Edgerton 1971; Shiue *et al.* 1978; Ulaby and Stiles 1980a, b), and for natural, relatively thin snow covers (Hall *et al.* 1978; Rango *et al.* 1979; Foster *et al.* 1980). Fig. 2, from Meier and Edgerton (1971), shows decreases in T_b from about 265 °K (snow free reading) to 200 °K as dry snow piled up to a water equivalent of 40 cm. The relationship of T_b to snow quantity is not unique as other scene parameters also influence it. With increasing pack thickness, brightness temperature decreases to that of the snow itself as ground contributions become less important.

Active systems – Backscatter increases with an increase in snow quantity. Data from Stiles and Ulaby (1979) show a increase of σ_o at $\lambda=3.3$ cm from -16 to -11 dB with snow manually piled from 14 to 70 cm, and a smaller increase from -11 to -9 dB with an additional meter of dry snow. As with passive readings, the relation between σ_o and snow quantity is not unique, but depends also on a host of other parameters.

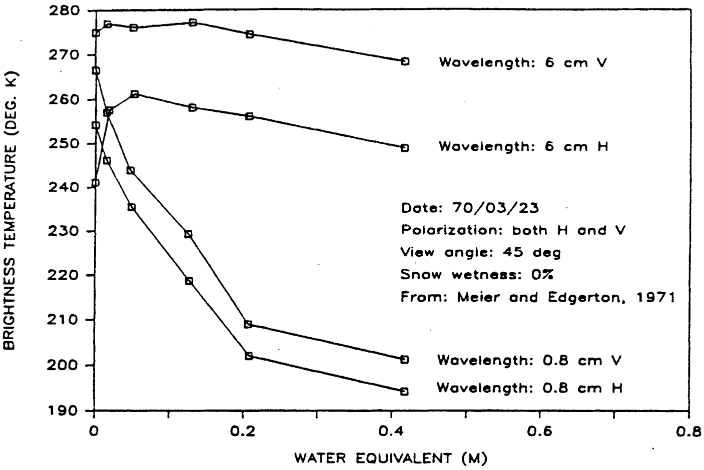

Fig. 2. Changes in the brightness temperatures at $\lambda \equiv 0.8$ and 6 cm, H and V components, with increasing snow water equivalent.

Snowpack Structure: a scene parameter

For a given wavelength, scattering increases with snow grain size and layering. Data interpretation is thus difficult when metamorphism and weather conditions, such as melt/refreeze, create multilayered packs, or where there is large spatial variations in the average snow grain size of the pack. For example, Shiue *et al.* (1978) reports a 45 °K difference in T_b, $\lambda = 0.8$ cm, between a fine-grained snowdrift and a coarse-grained metamorphosed snowpack of equal depth and density.

Passive systems – Readings from stratified packs can be problematic. At their alpine research site, Swiss workers observed a positive relation between T_b and snow water equivalent beyond a pack accumulation of 15 to 20 cm of water equivalent (Hofer and Mätzler 1980; Mätzler *et al.* 1980; Mätzler *et al.* 1982). Apparently, the initial 20 cm of the snow cover metamorphosed into depth hoar, a coarse-grained (Langham 1981), good microwave scatterer, very early in the winter and was gradually covered by finer snow over the rest of the winter. With ground emissions highly scattered by the depth hoar, emissions from the increasingly thick, radiometrically "warmer" fine snow generated the positive relationship between measured T_b's and the water equivalent of the finer snow.

Künzi *et al.* (1982) observed a similar reversal of slope in the relation between T_b and snow depth at 50 cm of snow depth accumulation in their work with microwave data from the NIMBUS-7 Scanning Multichannel Microwave Radiometer (SMMR). They also attributed this reversal to the formation of a coarser snow layer subsequently covered by finer snow.

Active systems – Goodison *et al.* (1980) reported highest return signals from dense packs and ice-covered ground. Ellerbruch and Boyne (1980), using an Automatic Network Analyzer (very much like an FM-CW radar) operating in the $\lambda = 15$ to 125 cm band, found a peak in return from a layer of denser snow 10 cm below the surface of the pack.

Liquid Water: a scene parameter

Liquid water in the snow causes a double problem to microwave remote sensing. First, even in small amounts, it turns snow into a lossy medium, meaning that wet snow readily absorbs (and emits) microwaves so that scattering is drastically reduced (Schmugge 1980). Secondly, snow liquid water content itself is very difficult to measure in the field (e.g. Colbeck 1978), especially at the low levels where its influence on microwaves is the greatest. The latest technique for the direct measurement of liquid water content is based on dilution of a solution added to the snow (Davis *et al.* 1985). Many calorimetric and electromagnetic (Denoth *et al.* 1984) methods have been tried over the years with varying degrees of success.

Passive systems – The appearance of 1 % liquid water content has caused T_b ($\lambda = 0.8$ cm) to increase by 35 to 70 °K from dry snow readings of around 210 °K (Meier and Edgerton 1971; Hall *et al.* 1978; Rango *et al.* 1979). T_b does not appear to increase further with additional liquid water (Hofer and Schanda 1978; Meier and Edgerton 1971). Changes in T_b caused by liquid water are less at greater wavelengths (Stiles and Ulaby 1980b).

During snowmelt, liquid water first appears at the surface of the pack and masks any relation between snowpack depth and T_b. Fig. 3 shows measured and modeled penetration depths of microwaves in a dry snowpack. Mätzler *et al.* (1979) report penetration depths less than 15 cm at all frequencies shown in Fig. 3 with a free liquid water content of 1-3 % in the first few centimeters of the pack.

Liquid water in the bare soil decreases the microwave emissivity of the soil (Künzi and Staelin 1975; Hall *et al.* 1978; Rango *et al.* 1979). As a result, “cold” readings can be obtained from dry snow and from wet bare soil, while “warm” readings can be obtained from dry or frozen ground and from wet snow. This overlap in the microwave signatures of bare soil and snowpacks can make differentiation of the two very difficult (Mätzler *et al.* 1982).

The very abrupt rise in T_b when dry snow acquires liquid water is easily detected in successive observations, making the onset of melt easy to detect. Day/night observations by Hofer and Mätzler (1980) show the large daily oscillations in T_b’s of the shorter wavelengths as the pack went from a daytime, near-blackbody condition to a nighttime refrozen, coarse-grained scatterer. On a much larger scale, onset of melt over the northern hemisphere was detected by Künzi *et al.* (1982) from NIMBUS-7 radiometer data taken during five successive passes.

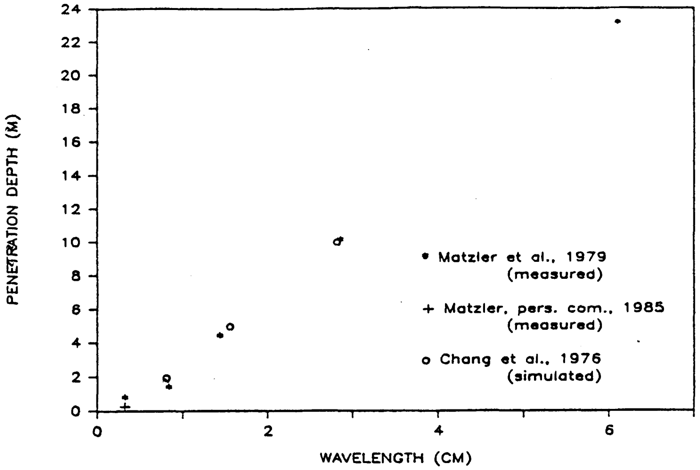

Fig. 3. Modeled and measured penetration depths of microwaves in a dry snowpack.

Active systems – Liquid water in the snow reduces the penetration depth of active microwaves. This was demonstrated by Goodison *et al.* (1980) when ground-level reflectors, visible with λ=3.2 cm imagery under 80 to 90 cm of dry snow, could not be detected after onset of melt.

The increased absorption of incoming microwaves by wet snow also decreases the backscatter coefficient. Stiles and Ulaby (1979) showed a drop of σ_0, $\lambda = 0.8$ cm, from 5 dB to -10 dB when the liquid water content in the upper 5 cm of the dry snow increased to 1.5 %. Using the low σ_0 of wet snow, Mätzler and Schanda (1984) accurately mapped wet snow cover around their research site in the Swiss Alps using a radar operating at the 3 cm wavelength.

Stiles and Ulaby (1979) also showed that the decrease of σ_0 with increasing wetness was linear up to 5 % liquid water content. This sensitivity to variations in liquid water, much higher than that of passive microwave systems, indicates that active systems may by usable to obtain information on the liquid water content of wet snowpacks. As with passive systems, Stiles and Ulaby (1979) report that the effect of liquid water decreases with increasing wavelengths.

Overlying Vegetation: a scene parameter

Vegetation is a good emitter and scatterer of microwaves. As a consequence, vegetation overlying the pack will affect readings obtained with either active or passive systems, the magnitude of the effect depending on the density, composition and structure of the cover. The large natural spatial variation in these cover properties can mask variations in microwave readings caused by variations in the snowpack.

Passive systems – Tiuri and Hallikainen (1981) were able to detect the presence of snow in scenes with up to 70 % forest cover by testing for a decrease in T_b with microwave frequency, but the sensitivity of the T_b gradient to snow cover was 35 % lower than that of a scene with more farmland. They also showed that the decrease in T_b with accumulating snowpack was preserved in successive observations of selected scenes, in spite of a heavy forest cover.

Hall *et al.* (1982) observed a positive relationship between snow depth and T_b in Nimbus-7 SMMR data covering the Michigan peninsula which, they inferred, was due to a geographical correlation between forest cover and snow depth. They restored an inverse relationship by subtracting a forest microwave emision calculated from average air temperature, emissivity of trees at microwave wavelengths, and forest cover for the individual SMMR images.

In a promising approach, Hallikainen (1984) developed algorithms from multi-frequency response and fall snow-free readings to remove the effect of ground cover on winter T_b. He reported correlation coefficients (R^2) of 0.70 and 0.76 between actual and calculated snow water equivalents over varied terrain.

Active systems – Agricultural researchers have been studying microwave-vegetation interactions for some time because of the potential of the technique for crop classification and evaluation of crop vigour (Ulaby 1982). Of particular interest is the work by Ulaby *et al.* (1983), who combined passive (λ=21 cm) and active (λ=7 cm) readings to estimate the soil moisture content under a corn cover. Dealing with trees and shrubs, however, Goodison *et al.* (1980) found that the returns from deciduous trees at 3.2 cm were greater than those obtained from adjacent 80-90 cm snowpacks, masking any variations in return signal due to the presence of snow. No technique was suggested for the removal of vegetation effects.

Wavelength: an instrument parameter

By increasing wavelength, the observer decreases the relative size of the dielectric discontinuities, and thus reduces scattering. In passive systems, reduced scattering increases the thickness of snow cover through which the "warmer" ground emissions can be perceived, and, in active systems, it increases the thickness of snow that can be penetrated by the radar pulse (Fig. 3).

Passive systems – The brightness temperature of snow covered ground decreases with decreasing wavelength (Fig. 2). This unique microwave signature (Tiuri 1982) has been used to accurately map the areal extent of snow cover various portions of the world with microwave data from satellite-borne sensors (Künzi and Staelin 1975; Künzi *et al.* 1976; Künzi *et al.* 1982).

Hall *et al.* (1978) suggested using readings at λ=21 cm to evaluate the emittive

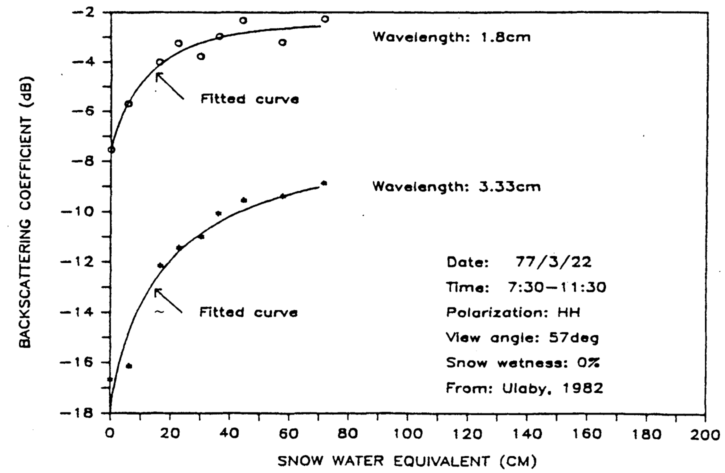

Fig. 4. Changes in the backscattering coefficients at λ=1.8 and 3.33 cm with increasing snow water equivalent.

conditions of the underlying ground and readings at a shorter wavelength (λ=0.81 or 1.55 cm) to measure the attenuation due to the dry snow. Ground emissions of microwaves depend on the temperature and liquid water content of the soil, and are the baseline from which scattering levels can be infered.

Active systems – The influence of wavelength on σ_0 is illustrated in Fig. 4 (plotted from Ulaby 1982, Fig. 24). The data was obtained from dry snow that was manually piled to a water equivalent of 70 cm with a constant density of 0.41 g cm^{-3}. From the figure, we see that backscatter increases as signal wavelength decreases toward the size of snow crystals. At a water equivalent of about 40 cm, the λ=1.8 cm curve levels as it reaches the saturation limit. This means that the pack now appears semi-infinite in depth to the sensor at that wavelength. Goodison *et al.* (1980) shows that readings at λ=23.5 cm are unaffected by the presence of a medium depth (up to 90 cm) dry or wet snow cover.

Timing of the Observation: an instrument parameter

The presence of liquid water in the top few centimeters of the pack masks any relation between T_b or σ_0 and pack depth. During early snowmelt when liquid water still occurs only in the top of the snowpack, colder night temperatures can refreeze all the liquid water. By taking readings at night, the observer can still get readings from the pack in a dry state.

Passive systems – The effect of the time of observation on T_b was briefly mentioned above with respect to the detection of onset of melt. Observations early in the snowmelt period clearly show the variations in T_b as the pack surface undergoes day-night melt and refreeze (Meier and Edgerton 1971; Hofer and Schanda 1978; Hofer and Good 1979; Stiles and Ulaby 1980b).

Active systems – Stiles and Ulaby (1980b) show the strong cycles of σ_o *at* $\lambda = 0.8$ cm in response to the varying liquid water content of the pack in day-night melt-refreeze cycles. There is, however, a degree of hysteresis in this cycle: snow that underwent some melt cannot re-freeze back to a structure comparable to its pre-melt state and will interact with microwaves in a manner that is very different from that of the original dry snow. In an example of that phenomenon, Ellerbruch and Boyne, using their FM-CW (λ=2.5-3.75 cm) radar readings recorded a strong response from a melt/refreeze surface crust. This example also shows the need for frequent collection of ground truth data as snowpack structure can change overnight.

View Angle: an instrument parameter

Instruments looking straight down at a horizontal scene are said to have a 0° view angle, the angle increasing as the line of view departs from the perpendicular. In active systems where the source of microwaves and the receiving antenna are located on the same platform, the view angle denotes the angle of both illumination and backscattering. Any scene or instrument parameter that increases scattering of microwaves within or at the surface of snowpacks, such as larger snow grains or shorter microwave wavelength, will reduce the effect of view angle on either passive or active readings. Although classified here as an instrument parameter, view angle can also be a scene parameter when acquiring data from mountainous basins.

Passive systems – Brightest T_b's from dry winter snow are usually obtained at 0° view angle. Brightest T_b's from coarse-grained refrozen snow can be obtained at much larger view angles, possibly because of specular reflection of atmospheric microwaves (Hofer and Schanda 1978). On fine-grained snowpacks, variations in T_b remain small for view angles between 0 and 30° (Ulaby and Stiles 1980a) and, therefore, readings taken at these angles are little influenced by the local slope of the land. However, many spaceborne sensors, notably the SMMR on board the NIMBUS-7 satellite, have a view angle of 50° (Künzi *et al.* 1982). Consequently, ground-based studies are often also performed at a 50° angle in order to improve the interpretation of satellite-acquired data.

Active systems – Stiles and Ulaby (1979), working on a dry 27-cm snowpack, showed that the σ_o obtained at λ=0.8 cm (short wavelength, high scattering) varied little with view angle, while σ_o at $\lambda=1.7$ cm and 11.5 cm decreased as the view angle went from 0° to 20°. Beyond a view angle of about 20°, only the readings taken at $\lambda=11.5$ cm still decreased slightly with view angle.

The presence of liquid water decreases penetration depth of the beam, thus increasing the dependency of σ_o on angle of incidence at milimeter and centimeter wavelengths. This anglular dependency seems to be quite unique to wet snow and has been proposed by Mätzler *et al.* (1982) as a way to differentiate wet snowpacks from bare soil. Such differentiation is very difficult with passive microwave radiometry because of the overlap in microwave signatures caused by liquid water.

Polarization: an instrument parameter

Polarization describes how the electric field vectors of a wave traveling in the z direction are oriented in the xy plane. When there is no rotation of the electric field vectors in the xy plane, the wave is said to be linearly polarized. In that case, horizontal (H) and vertical (V) polarization denote the orientation of the vectors. In snowpacks, as microwaves interact with large plane features such as the snow-air interface or ice layers within the pack, part of their H or V components are selectively absorbed. Sensors can record either the H or V component of any wavelength. At 0° view angle, there is no distinction between horizontal and vertical components.

Passive systems – With a view angle substantially different from 0°, vertical polarization always yields higher brightness temperatures (e.g., Fig. 1 and Shiue *et al.* 1978; Hofer and Schanda 1978, Figs. 1 and 2). This difference occurs because horizontal features of the snowpack tend to absorb the horizontal component of the microwave's electric field. Mätzler *et al.* (1982) measured a T_{bV}-T_{bH} of 62 °K at $\lambda=1.4$ cm with a 50° view angle, and attributed this difference to thin ice lamella formed by alternating warm and cold weather.

Some experimenters have used both polarizations in scene interpretation, either as a composite H and V reading (Rotman *et al.* 1981), or as the difference in H and V T_b's (Rango *et al.* 1979). There appears to be no consensus in the current literature on how to use this instrument parameter most effectively.

Active systems – At angles other than 0°, both the transmitting and receiving antennas can be polarized independently to give radars three different modes of operation: the like-polarized HH and VV, and the cross-polarized VH or HV (from the reciprocity theorem, cross-polarized backscatter coefficients (σ_{HVo} and σ_{VHo}) are equal (Ulaby 1982)).

The modeling results of Kong *et al.* (1980) show that the two like-polarized backscatter coefficients should behave differently with increasing pack depth.

However, Stiles and Ulaby (1980b) report a "nearly identical behaviour" of the two like polarizations in their fieldwork, a claim well supported by the results of Mätzler *et al.* (1982, Figs. 8 and 9). It thus appears that little additional information is to be gained by using more one like- and one cross-polarization. It also appears that work is still needed to make models match reality more closely.

Most experimenters use only one polarization type in their work, with two exceptions. Stiles and Ulaby (1980b) plot the "depolarization ratio" ($\sigma_{VHo}/\sigma_{HHo}$) against view angle over a thin natural snowpack. The graph indicates a much lower cross-polarized reading. Mätzler *et al.* (1982) report like- and cross-polarized readings also showing the lower cross-polarized response. In spite of these efforts, it is still unclear in the current literature how like- and cross-polarized active readings complement each other.

Spatial Resolution

Spatial resolution denotes the size of the smallest unit of area that a radiometer or a radar can descriminate. Although not a scene or instrument parameter in the sense used in this view, spatial resolution is an important variable for the eventual user of microwave remote sensing devices.

The spatial resolution of a radiometric system increases at the ratio of antenna size to wavelength increases. Because of the relatively long wavelengths of microwaves, and of the physical limitations on the antenna size, the spatial resolution of passive microwave systems is low. It will vary from a few centimeters for tower-mounted radiometers to about 30 km for the NIMBUS-7 SMMR at λ=0.8 cm wavelength (Künzi *et al.* 1982).

In active system, the limitation on antenna size is circumvented in the Synthetic Aperture Radars, or SARs. SARs are Side Looking Airborne Radars (see Jensen *et al.* 1977, for a discription of SLARs) that combine a large number of returned signals from FM pulse to simulate the effect of a very long antenna. Spatial resolution achieved with SARs in on the order of tens of metres, even from a satellite. SARs have a problem with speckle (random variations of the return signal from individual picture elements or pixels) (Ulaby *et al.*, Vol 2, 1981) and special care must be taken in image processing to overcome this difficulty.

Discussion and Conclusion

It appears that stand-alone active and passive systems are sufficient to map the extent of dry (e.g., Künzi *el al.* 1982) and wet (Mätzler and Schanda 1984) snow cover, and to detect the onset of snowmelt. However, because of the many factors influencing microwave scattering in snowpacks, it is certain that extensive ground truth on pack structure and overlying vegetation will be needed to estimate snowpack water equivalent. Mältzer *et al.* (1982) suggest the following sensors:

1) For mapping dry snow, two radiometers, one operating in the λ=.66 to 1.2 cm range or in the λ=.33 cm window, and a second one operating at a longer wavelength.
2) For mapping wet snow, a radar or scatterometer operating at a wavelength of 3 cm or less, with a view angle of at least 30°.
3) For estimating snow water equivalent, a combination of 1) and 2) coupled with ground thruth, and possible night (refrozen conditions) measurements in the early melt season.

The influence of vegetation on the detectability and assessment of the snow cover requires further investigation. Forested lands in North America and elsewhere play a dominant role in water production and irrigation as hydro-electric and flood diversion projects often use or control streamflow from partially or totally forested basins. These project would benefit from accurate areal estimates of snow water equivalent on their basin. The work of Hall *et al.* (1982) and of Tiuri and Hallikainen (1981) indicate that passive microwave readings can be corrected for vegetation cover. Work needs to be done with active microwave systems to see if a similar potential exists.

The importance of ground truth measurements of snowpack structure to interpret microwave measurements clearly emerges from the papers reviewed. The problem of ground truth is three-fold. First, what aspect of snowpack structure should be measured? Are the proper type of ground truth measurements available? Thin ice lamellae have been shown to affect microwave-snow interactions. Can such structures be resolved in the field with current techniques? What degree of resolution is necessary? Secondly, what should be the spatial density of the ground station network? How variable is snowpack structure over the area monitored? And what is the trade-off between network density and accuracy if ground truth? Finally, how often should readings be made in order to keep up with metamorphism? It is apparent that much work on these questions is still needed, and basic work on snow properties and metamorphism such as that by Colbeck (1983a and b) is crucial to the eventual interpretation of microwave measurements.

In past studies, the approach has been to induce or measure variations in one of the parameters and to observe or hopefully infer the resulting changes in microwave readings. In operational remote sensing, the approach has to be reversed, that is, the microwave reading is known, and the state of scence parameters has to be inferred. And since many different sets of scene parameters yield identical microwave responses, the inference problem becomes very complex. What I see as lacking is a general framework into which current research results fit and complement each other in such a way as to make the inference of scene parameters possible. In most other fields, physically-based simulators serve as such frameworks. Therefore, I think that the next step towards making microwave techniques operational should be one of modeling in a physically-meaningful way the complex microwave-snowpack interactions.

It seems unlikely that such a model would become the final interpretative tool since the input requirements of physical models are generally beyond the capacity of an operational data-gathering network. Simulation results could possibly be regionalized and, from ground truth data, searched using a type of maximum-likelihood procedure. Multivariate analysis will surely play an important role in the long run. But for now, further descriptive research is of limited use unless it either addresses a special problem, such as vegetation cover, or its conception and results are tied into a general interpretative framework.

References

Boyne, H. S., and Ellerbruch, D. A. (1979) Microwave measurements of snow stratigraphy and water equivalence, Proc. of the 47th Western Snow Conference, Sparks, Nevada, pp. 20-26.

Boyne, H. S., and Ellerbruch, D. A. (1980) Active microwave water equivalent measurements, Microwave Remote Sensing of Snowpack Properties, Proc. of a Workshop, A. Rango, ed., NASA Conf. Publ. 2153, pp. 119-130.

Chang, A. T. C., Hall, D. K., Foster, J. L., Rango, A. and Shiue, J. C. (1979) Passive microwave sensing of snow characteristics over land, Satellite hydrology, M. Deutsh, D. R. Weisnet and A. Rango, eds., Fifth Annual W. T. Pecora Memorial Symp. on Remote Sensing, AWRA, Sioux Falls, South Dakota, pp. 213-217.

Chang, A. T. C., Rango A., and Shiue, J. C. (1980) Remote sensing of snowpack properties by passive microwaves: GSFC truck experiment, Microwave Remote Sensing of Snowpack Properties, Proc. Workshop, A. Rango, ed., NASA Conf. Publ. 2153, pp. 169-186.

Colbeck, S. C. (1978) The difficulties of measuring the water saturation and porosity of snow, *J. Glaciol., Vol. 20*, pp. 189-201.

Colbeck, S. C. (1983a) Snow particle morphology in the seasonal snow cover, *Bull. Am. Met. Soc., Vol. 64*, pp. 602-609.

Colbeck, S. C. (1983b) Theory on the metamorphism of dry snow, *J. Geophys. Res., Vol. 88*, pp. 5475-5482.

Comiso, J. C., Ackley, S. F., and Gordon, A. L. (1984) Antarctic sea ice microwave signatures and their correlation with in situ ice observations, *J. Geophys. Res., Vol. 89*, pp. 662-672.

Cumming, W. A. (1952) The dielectric properties of ice and snow at 3.2 centimeters, *J. Appl. Phys., Vol. 23*, pp. 768-773.

Davis, R. E., Dozier, J., Lachapelle, E. R., and Perla, R. (1985) Field and laboratory measurements of snow liquid water by dilution, *Water Resour. Res., Vol. 21*, pp. 1415-1420.

Denoth, A., Foglar, A., Weiland, P., Mätzler, C., Aebischer, H., Tiuri, M., and Sihvola,

A. (1984) A comparative study of instruments for measuring the liquid water content of snow, *J. Appl. Phys., Vol. 56*, pp. 2154-2160.

Ellerbruch, D. A., Little, W. E., Boyne, H. S., and Bachman, D. D. (1977) Microwave characteristics of snow, Proc. of the 45th Western Snow Conference, pp. 68-75.

Ellerbruch, D. A., and Boyne, H. S. (1980) Snow stratigraphy and water equivalence measured with an active microwave system. *J. Glaciol., Vol. 26*, pp. 225-233.

Evans, S. (1965) Dielectric properties of ice and snow – a review. *J. Glaciol., Vol. 5*, pp. 773-792.

Foster, J. L., Rango, A., Hall, D. K., Chang, A. T. C., Allison, L. J., and Diesen, B. C. III (1980) Snowpack monitoring in North America and Eurasia using passive microwave satellite data, *Remote Sensing Environ., Vol. 10*, pp. 285-298.

Goodison, B. E., Waterman, S. E., and Langham, E. J. (1980) Application of synthetic aperture radar data to snow cover monitoring, Proc. of the 6th Canadian Symp. on Remote Sensing, Halifax, N. S., pp. 263-271.

Goodison, B. E., Rubinstein, I., Thirkettle, F. W., and Langham, E. J. in print. Determination of snow water equivalent on the Canadian Prairies using microwave radiometry. Presented at the IAHS Meeting, Budapest, 2-10 July 1986.

Hall, D. K., Chang, A., Foster, J. L., Rango, A., and Schmugge, T. (1978) Passive microwave studies of snowpack properties, Proc. of the 46th Western Snow Conference, Otter Rock, Oregon, pp. 33-39.

Hall, D. K., Foster, J. L., and Chang, A. T. C. (1982) Measurement and modeling of microwave emission from forested snowfields in Michigan, *Nordic Hydrology, Vol. 13*, pp. 129-138.

Hallikainen, M. T. (1984) Retrieval of snow water equivalent from Nimbus-7 SMMR data: Effect of land-cover categories and weather conditions, *IEEE J. Oceanic Eng., Vol. OE-9(5)*, pp. 372-376.

Hobbs, P. V. (1974) *Ice physics*, Clarendon Press, Oxford, U. K., 837 p.

Hofer, R., and Good, W. (1979) Snow parameter determination by multichannel microwave radiometry, *Remote Sensing Environ., Vol. 8*, pp. 211-224.

Hofer, R., and Mätzler, C. (1980) Investigations of snow parameters by radiometry in the 3 to 60 mm wavelength region. *J. Geophys. Res., Vol. 85*, pp. 453-460.

Hofer, R., and Schanda, E. (1978) Signatures of snow in the 5 to 94 GHz range. *Radio Science, Vol. 13*, pp. 365-369.

Hollinger, J. P., Troy, B. E., Ramseier, R. O., Asmus, K. W., Hartman, M. F., and Luther, C. A. (1984) Microwave emission from high arctic sea ice during freeze-up, *J. Geophys. Res., Vol. 89*, pp. 8104-8122.

Jensen, H., Graham, L. C., Porcello, L. J., and Leith, E. N. (1977) Side-looking airborne radar, *Sci. Am.*, October 1977, pp. 84-95.

Kim, Y. S., Onstott, R. G., and Moore, R. K. (1984) The effect of a snowcover on microwave backscatter from sea ice, *IEEE J. Oceanic. Eng., Vol. OE-9,* pp. 383-389.

Kong, J. A., Shin, R., Chuang, S. L., and Tsang, L. (1980) Theoretical models microwave snow response and application to remote sensing, Microwave Remote Sensing of Snowpack Properties, Proc. of a Workshop, NASA Conf. Publ. 2153, pp. 147-168.

Künzi, K. F., and Staelin, D. H. (1975) Measurements of snow cover over land with the NIMBUS-5 microwave spectrometer, Proc. of the 10th International Symp. on Remote Sensing of the Environment, Ann Arbor, Michigan, pp. 1245-1253.

Künzi, K. F., Fisher, A. D., Staelin, D. H., and Waters, J. W. (1976), Snow and ice surfaces measured by the NIMBUS-5 microwave spectrometer. *J. Geophys. Res., Vol. 81*, pp. 4965-4980.

Künzi, K. F., Patil, S., and Rott, H. (1982) Snow-cover parameters retrieved from NIMBUS-7 Scanning Multichannel Microwave Radiometer (SMMR), *IEEE Trans. Geosci. Remote Sensing, Vol. GE-20(4)*, pp. 542-467.

Langham, E. J. (1981) *Physics and properties of snowcower*, Handbook of Snow-Principles, Processes, Management & Use, D. M. Gray and D. H. Male, eds., Pergamon Press, Toronto Ontario, 776 pp.

Lowry, W. P. (1969) *Weather and Life*; *an introduction to biometeorology.* Academic Press, N.Y., 305 p.

Mätzler, C., Aebischer, H., and Schanda, E. (1984) Microwave dielectric properties of surface snow, *IEEE J. Oceanic Eng. Vol. OE-9(5)*, pp. 366-371.

Mätzler, C., Hofer, R., Wyssen, D., and Schanda, E. (1979) On the penetration of microwaves in snow and soil. Proc. of the 13th International Symp. on Remote Sensing of the Environment, Ann Arbor, Michigan, pp. 1243-1249.

Mätzler, C., Schanda, E., and Good, W. (1982) Towards the definition of optimum sensor specifications for microwave remote sensing of snow, *IEEE Trans. Geosci. Rem. Sens., Vol. GE-20(1)*, pp. 57-66.

Mätzler, C., Schanda, E., Hofer, R., and Good, W. (1980) Microwave signatures of the natural snow cover at Weissflujoch, Microwave Remote Sensing of Snowpack Properties, Proc. of a Workshop, A. Rango, ed., NASA Conf. Publ. 2153, pp. 203-224.

Mätzler, C., and Schanda, E. (1984) Snow mapping with active microwave sensors, *Int. J. Remote Sensing, Vol. 5*, pp. 409-422.

Meier, M. F. (1972) Measurement of snow cover using passive microwave radiation, Proc. Symp. on Role of Snow and Ice in Hydrology, Banff, Canada, September 1972, pp. 739-750.

Meier, M. F., and Edgerton, A. T. (1971) Microwave emission from snow-a progress report, Proc. of the 7th International Symp. on Remote Sensing of the Environment, Ann Arbor, Michigan, pp. 1155-1163.

Rango, A., Chang, A. T. C., and Foster, J. L. (1979) The utilization of spaceborne radiometers for monitoring snowpack properties, *Nordic Hydrol., Vol. 10*, pp. 25-40.

Rotman, S. R., Fisher, A. D., and Staelin, D. H. (1981) Analysis of multiple-angle microwave obserbarions of snow and ice using cluster-analysis techniques, *J. Glaciol., Vol. 27*, pp. 89-97.

Rotman, S. R., Fisher, A. D., and Staelin, D. H. (1982) Inversion for physical characteristics of snow using passive radiometric observations, *J. Glaciol., Vol. 28*, pp. 179-185.

Schanda, E., and Hofer, R. (1977) Microwave multispectral investigations of snow, Proc. of the 11th International Symp. on the Remote Sensing of the Environment, Ann Arbor, Michigan, pp. 601-607.

Schmugge, T. J. (1980) Microwave approaches in hydrology, *Photogramm. Eng. and Remote Sensing, Vol. 46*, pp. 495-507.

Schmugge, T. J., Wilheit, T. T., Gloersen, P., Meier, M. F., Frand, D., and Dirmhirn, I. (1973), Microwave signatures of snow and fresh water ice, *In* "Advanced Concepts and Techniques in the Study of Snow and Air Resources", National Academy of Science, Washington, D.C., pp. 551-563.

Shiue, J. C., Chang, A. T. C., Boyne, H., and Ellerbruch, D. (1978) Remote sensing of snowpack with microwave radiometers for hydrologic applications, Proc. of the 12th International Symp. on the Remote Sensing of the Environment, Ann Arbor, Michigan, pp. 877-886.

Stiles, W. H., and Ulaby, F. T. (1979) Monitoring snow with microwaves. Satellite Hydrology. M. Deutsh, D. R. Weisnet and A. Rango, eds., Fifth Annual W. T. Pecora Memorial Symp. on Remote Sensing. AWRA, Sioux Falls, S. Dakota, June 10-16, pp. 225-229.

Stiles, W. H., and Ulaby, F. T. (1980a) Radar observation of snowpacks, Micowave Remote Sensing of Snowpack Properties, A. Rango, ed., Proc, of a Workshop, NASA Conf. Publ. 2153, pp. 131-146.

Stiles, W. H., and Ulaby, F. T. (1980b) The active and passive microwave response to snow parameters – 1, Wetness. *J. Geophys. Res., Vol. 85*, pp. 1037-1044.

Swift, T. C., and Cavalieri, D. J. (1985) Passive microwave remote sensing for sea ice research, *EOS Trans. Amer. Geophys. Union, Vol. 66(49)*, pp. 1210-1212.

Tiuri, M. E., (1982) Theoretical and experimental studies of microwave emission signature of snow, *IEEE Trans. Geosci. Rem. Sens., Vol. Ge-20(1)*, pp. 51-57.

Tiuri, M. E., and Hallikainen, M. (1981) Microwave emission characteristics of snov covered earth surfaces measured by the Nimbus-7 satellite, Pros. 11th European Microwave Conference, Amsterdam, pp. 233-238.

Ulaby, F. T. (1982) Radar signatures of terrain: useful monitors of renewable resources, *Proc. IEEE, Vol. 70*: pp. 1410-1428.

Ulaby, F. T., and Stiles, W. H. (1980a). Microwave radiometric observation of snowpacks. Microwave Remote Sensing of Snowpack Properties, A. Rango, ed., Proc. of a Workshop, NASA Conf. Publ. 2153, pp: 187-202.

Ulaby, F. T., and Stiles, W. H. (1980b). The active and passive microwave response to snow parameters-2, water equivalent of dry snow, *J. Geophys. Res., Vol. 85*, pp. 1045-1049.

Ulaby, F. T., Dobson, M. C., and Brunfeldt, D. B. (1983) Improvement of moisture estimation accuracy of vegetation-covered soil by combined active/passive microwave remote sensing, *IEEE Trans. Geosci. Remote Sensing, Vol. GE-21(3)*, pp. 300-305.

Ulaby, F. T., Moore, R. K., and Fung, A. K. (1981) Microwave remote sensing – active and passive. Addison-Wesley Publishing Co., Reading, Massachusetts, 3 vols.

Ulaby, F. T., Stiles, W. H., Delwig, L. F., and Hanson, B. C. (1977) Experiments on the backscatter of snow. *IEEE Trans. Geosci. Electron., Ge-15*, pp. 185-189.

Vickers, R. S., and Rose, G. C. (1974) High resolution measurements of snowpack stratigraphy using a short pulse radar. Proc. of the 8th International Symp. on the Remote Sensing of the Environment, Ann Arbor, Mich., pp. 261-177.

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