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Microwave Measurements of Snowpack Properties

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Prior microwave measurements of snow water equivalent and liquid water content and conceptualizations of emission and backscattering models are reviewed. The results of an experiment designed to collect simultaneous passive and active microwave data to be used in interpreting and analyzing the sensitivity of the microwave spectrum to changing snowpack properties are reported. Both the scattering coefficient, σ°, and the apparent radiometric temperature, T_{ap}, were found to be sensitive to changes in snow water equivalent and liquid water content. The σ° data exhibit an exponential-like increase with increasing water equivalent, whereas, the T_{ap} data exhibit an exponential-like decrease. For both the active and passive data, the snow water equivalent at which the microwave response begins to saturate decreases as the wavelength decreases. Increasing liquid water in the snowpack causes a decrease in σ° and an increase in the T_{ap}. Diurnal data sets show the greatest σ° and T_{ap} variation in response to snowmelt at 35 and 37 GHz with correspondingly less variation at the lower frequencies. Based on research results to date, immediate formulation of a comprehensive microwave and snow research program is recommended.

Introduction

The use of remote sensing for increasing our state of knowledge about snow fields and as input data for snowmelt runoff predictions has been shown to be feasible. Techniques for remotely delineating the extent of snow cover in a basin were developed for use with high-resolution (≤ 1 km) satellite data. These satelite data were tested both in seasonal snowmelt runoff regression equations and in daily snowmelt models and were found to have the potential for reducing runoff forecast error by 6-10% on a relative basis (Rango and Peterson 1980). The success of this project led to the conclusion that remotely sensed snow-cover information was a valuable ancillary data source. A more complete remote characterization of the snowpack would result if areawide measurement of water equivalent were added to the snow-cover areal-extent data now available. A watershed estimate of snow water volume would then be possible. Further valuable information should result if the capability for sensing liquid water were added.

Although visible and infrared techniques have been examined for providing this information, very little potential is foreseen because these wavelengths are limited to sensing surface conditions. Microwave measurements are considered more promising because of the microwave capability to penetrate the snow and respond to variations in subsurface properties. The microwave portion of the spectrum is advantageous additionally because of the large difference in the dielectric constants of liquid- and frozen-water, which will cause a significant variation in the microwave signal when liquid water is present. Working in the microwave region also permits remote observation of snow under nearly all weather conditions. Microwaves will penetrate clouds and most precipitation with little attenuation, thus, reliable measurement of snow-cover extent may by possible by employing microwave sensors.

Because of these potentials in the microwave spectral interval, NASA has initiated a microwave-oriented research program for investigating the measurement of snowpack properties. It was felt that although past experiments have provided evidence of the microwave potential for snow measurements, a controlled experiment, such as is possible with a truck-mounted system of microwave sensors and coordinated detailed conventional snow observations, was needed to better specify the microwave response to varying snow properties. Conducting this experiment in a location where spring snowmelt was the major input to the total annual water supply was felt to be essential so that representative snowpack properties and processes could be measured.

The experiment described in this paper was designed to collect high-quality data which could be used to interpret and analyze the sensitivity of the microwave spectrum to changing snowpack properties. Detailed conventional snow measurements are necessary and were obtained in order to understand the physics underlying specific microwave variations. Based on the data collected and the understanding gained, development of models has been initiated which could be used eventually (after further refinements) to infer snowpack parameters based on the measured microwave responses.

Conventional Measurement

Although snow-covered area has been shown to be valuable in remote sensing and snow hydrology studies, the most commonly measured snow parameter is either snow depth or snow water equivalent. This snow water equivalent (w_n) is defined as the amount of water that would be obtained if the snow were completely melted. Measured alone, water equivalent probably provides the most complete information on snow storage in a basin at the beginning of snowmelt and, thus, can be used as an indicator of the quantity of snowmelt runoff to be expected. Snow depth (d_n) is important additionally but, because of possible significant variations in snowpack density, w_n is to be preferred for comprehensive snowpack information.

All measurements of w_n are made conventionally at scattered points in a drainage basin. Manual measurements usually are obtained by weighing snow-cores from previously established snow courses. Each snow-course observation usually includes about 10 separate measures at pre-established intervals (typically every 100 feet). The w_n value given for that snow course is an average of the 10 separate measurements. These values are not assumed to be representative of the snowpack for the entire basin, rather they are used as indices of the basin-wide snow water equivalent. Their most common application is in regression equation-based forecasts of seasonal snowmelt runoff.

In recent years automated measurements of w_n at specific points in a basin using a variety of pressure pillows or tanks, lysimeters, and radioactive sources have become more popular. Used in remote regions, these measurements usually are telemetered in real time to user agencies for runoff forecast purposes. One major advantage of these sensors is that they can be interrogated at any time thereby eliminating the need to wait until the first of the month, which is the typical time of the manual measurements. Because of this continuous w_n measurement capability, the use of automatic sensors has promoted increased emphasis on and use of snowmelt runoff models as opposed to regression equation predictions.

A further refinement in snowpack measurement is the determination of the liquid water content of the snowpack at a given time. The liquid water content m is defined as the fraction, by volume or weight, of liquid water which is contained in the interstices between snow grains but is not bound strongly to individual grains. It is free to move by capillary action or under the force of gravity. Since the snowpack must hold a certain amount of liquid water before meltwater is produced at the base of the pack, measurement of m in the spring is an indication of the readiness of the snowpack to produce runoff. In the spring m will vary diurnally as well as from day to day and, as a result, affects the timing of runoff during the snowmelt period.

Because of the dynamic nature of the snow/liquid-water mixture that makes up the snowpack, conventional measurement of m is extremely difficult. In fact, no operational m measurements are made currently. Most current observations of m are time-consuming, complicated, cumbersome, and produce highly variable data. Such information is of considerable interest for research projects but is not suited for operational observations. Various techniques have been used for or proposed to measure m and they may be broadly categorized as centrifugal, dielectric, and calorimetric approaches.

Centrifugal separation of the liquid water from a snow sample was described by Kuroda and Hurukawa (1954). Langham (1974, 1978) subsequently improved the method by isolating the amount of melt that occurs during the centrifuging process. The measurement and comparison of the dielectric constant of wet- and dry-snow has provided a method of determining the m of the snowpack (Ambach and Denoth 1974). Several calorimetric methods have been proposed including hot water (Yoshida 1960), electric (de Quervain 1946), and freezing (Radok et al. 1961; Leaf 1966) techniques. In the freezing technique the »negative heat« required to freeze the liquid water in a snow sample is monitored and related to the m. As was the case with w_n, the measurement of m using conventional techniques can be accomplished only at a point and is not representative of a large area or an entire watershed.

Associated with this absence of an operational system for measuring m is a lack of understanding of how to use the data for runoff forecasting purposes. Whereas operational agency hydrologists can readily use w_n in runoff-prediction methods and recently have started to use snow-covered area from satellites in a similar fashion (Shafer and Leaf 1980; Brown, Hannaford and Hall 1980), they have no way presently of using m for runoff forecasts, even if it were available regularly. As a consequence, microwave research results in w_n and snow-covered area will find more ready application initially than will m. Consequently, research on the techniques for applying m in snowmelt runoff forecasting will be required.

Supporting Measurements for Remote Sensing Experiments

For quantitative analysis and interpretation of microwave experiment data, a well-planned and detailed program of conventional snow measurements is necessary. These conventional snow-pack measurements often are referred to as ground truth because they provide the best possible knowledge of the snow properties at the time of the remote sensing observations. This ground truth should, as a minimum, include measurements of w_n, d_n, m, and the underlying soil conditions. Additional information on crystal-size, snowpack structure, and snow temperature is highly desirable. At this stage in our understanding of the microwave/snow interaction, the need for rigorous snowpack observations programs cannot be overemphasized.

Microwave Measurements

Two basic classes of microwave sensors are available: active and passive. The active systems provide their own scene-illumination and include radar scatterometers and imagers. These systems measure the radar reflectivity, usually referred to as the backscattering coefficient σ°, which is analagous to the optical reflectivity measured by optical sensors.

A calibrated radar imager (where variations due to system- and propagation-parameters have been removed) is essentially a two-dimensional map of σ° of the imaged scene. The power received due to backscatter by a surface of area A is given by

$$P_r = K\sigma^0 \qquad (1)$$

where the factor K is related to the radar system parameters, the range to the scene and the area A. The scattering coefficient σ° is a dimensionless quantity characterizing the average radar backscattering cross-section (m^2) per unit physical area (m^2) of the illuminated surface. It is customary to express σ° in decibels; that is, $\sigma^\circ_{dB} = 10 \log \sigma^\circ$.

Passive microwave systems are radiometers that measure radiation emitted by the scene under observation. In the microwave region, the received radiation is characterized by an apparent radiometric temperature T_{ap}, which is related to the brightness temperature of the terrain, T_b, through

$$T_{ap} = \gamma_a(T_b+T_{sc}) + T_{up} \qquad (2)$$

where

γ_a – atmospheric transmission coefficient for propagation between the terrain and the radiometer.

T_{sc} – scattered radiation, due primarily to downwelling atmospheric emission scattered (reflected) by the terrain in the direction of the radiometer.

T_{up} – upwelling radiation by the atmospheric layer between the terrain and the radiometer.

The radiometer measures T_{ap} and the quantity of interest is T_b (since it is related to the terrain parameters of interest). For a non-absorbing (and therefore non-emitting) atmosphere, $\gamma_a = 1$, and $T_{sc} = T_{up} = 0$, which leads to $T_{ap} = T_b$. To minimize atmospheric effects on the measurement of T_b, radiometric measurements usually are made at frequencies below 20 GHz (wavelengths λ longer than 1.5 cm) or in one of the microwave atmospheric windows centered around 35 GHz (λ = 8.6 mm) and 94 GHz (λ = 3.2 mm). In these frequency ranges, T_{ap} is strongly dominated by T_b even under moderate cloud conditions.

The measurements reported in this paper were made from a truck-mounted platform at a height of 20 m above the snowpack, which means that no atmospheric attenuation ($\gamma_a = 1$) and no upward atmospheric emission ($T_{up} = 0$) were involved in the measurements. Moreover, for a snowpack with an approximately uniform physical temperature T_o, T_b and T_{sc} are given by the expressions

$$T_b = \varepsilon T_0 \tag{3}$$

$$T_{sc} = r T_{dn} \cong (1-\varepsilon) T_{dn} \tag{4}$$

where ε is the snowpack emissivity, T_{dn} is the downwelling atmospheric temperature, and r is the snowpack reflectivity which may be approximated by $r = 1-\varepsilon$. Under the above conditions, Eq. (2) reduces to

$$T_{ap} = \varepsilon T_0 + (1-\varepsilon) T_{dn} \tag{5}$$

By pointing the radiometer antenna upward towards the sky (before or after measuring T_{ap} of the snowpack), T_{dn} could be measured directly and then used in Eq. (5) to compute ε. The data presented in this paper are either in the form of ε or T_{ap}.

The purpose of the present study is to relate the active (σ°) and passive (ε or T_{ap}) microwave parameters to the conventionally measured snowpack properties, with primary emphasis on water equivalent, depth and liquid water content.

Previous Microwave Measurements of Snowpacks

Reflection and scattering properties of snow have been investigated using three basic types of techniques. These are: a) bistatic reflection-coefficient measurements (Cumming 1952; Suzuki and Hasegawa 1958; Battles and Crane 1966), b) measurements of the snow vertical stratigraphy using high range-resolution radar (Vickers and Rose 1972; Venier and Cross 1972; Ellerbruch et al. 1977), and c) measurements of the backscattering coefficient, σ° (Janza et al. 1959; Cosgriff et al. 1960; Sackinger 1972; Hoekstra and Spanogle 1972; Linlor 1974; Currie et al. 1977; Ulaby et al. 1977). The first two types of measurements provide information on the electromagnetic behavior of the snow surface reflection and volume scattering properties, and such information is used in modeling the backscattering and emission behavior. That is, the backscattering coefficient σ° and brightness temperature T_b (or emissivity ε) represent the integrated behavior of the snowpack including surface effects at the snow-air and snow-ground boundaries as well as scattering, absorption and emission within the snow volume. Until recent investigations of the backscatter properties of snow (Hayes et al. 1979; Stiles and Ulaby 1980; Ulaby and Stiles 1980a), prior studies were limited in scope and in terms of the "quantitativeness" of ground-truth data acquired in support of the radar measurements. Consequently previous results provided useful, but mostly qualitative information on the dependence of σ° on snow parameters such as depth and liquid water content. This situation has been rectified by the measurement program conducted by the University of Kansas during the past few years, and a survey of the major results is given in this paper.

In contrast to the recent development of the qualitative understanding of the active microwave response to snowpack parameters, research with passive microwave sensors (radiometers) has been ongoing for many years and snow observations have been made from ground-based platforms (Meier and Edgerton 1971; Tiuri et al. 1978; Schanda and Hofer 1977; Shiue et al. 1978; Hofer and Matzler 1980); airborne platforms (Schmugge et al. 1974; Hall et al. 1978); and spaceborne platforms (Gloersen and Salomonson 1975: Kunzi et al. 1976; Rango et al. 1979). These observations have provided an understanding of the overall behavior of microwave emission from snow, but detailed understanding remains in the research phase. With the desire to improve this understanding and to evaluate the passive microwave response to snowpack parameters simultaneously with active microwave measurements of the snowpack, combined active and passive microwave investigations were conducted at a test site near Steamboat Springs, Colorado. A survey of the results is given in the sections that follow.

Emission and Backscattering Models

Microwave emission from a layer of snow over a ground-medium consists of two contributions: a) emission by the snow-volume and b) emission by the underlying ground. Both contributions 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. Basic formulation of the above problem is given by the radiative transfer method (England 1975) which has been used to compute the emission (Chang et al. 1976; Tsang and Kong 1977) from a layer of spherical scatterers, such as ice-crystals in a snow volume, and recently it has been extended to compute the backscattering coefficient σ° (Tsang and Kong 1978; Fung et al. 1980). If scattering in the snow medium is significant (in comparison to absorption), the solutions for the emissivity ε and scattering coefficient σ° are quite involved, and therefore will not be discussed in this paper. Instead, approximate expressions will be used to introduce the reader to the general behavior of ε and σ° as a function of some snow parameters. These expressions are (Ulaby and Stiles 1980b)

$$\varepsilon = \gamma_{sa}(\theta)[(1-a)(1-\Gamma(\theta')) + \gamma_{gs}(\theta')\Gamma(\theta')] \tag{6}$$

$$\sigma^0 = \gamma_{sa}^2(\theta)[\frac{\eta}{2\kappa_e}(1-\Gamma^2(\theta'))\cos\theta + \sigma^0_{\text{soil}}(\theta')\Gamma^2(\theta')] \tag{7}$$

where

θ – angle of incidence (relative to nadir)
θ' – angle of refraction in snow medium
γ_{sa} – power transmission coefficient at the snow-air boundary
γ_{gs} – power transmission coefficient at the ground-snow boundary
a – single scattering albedo of snow
$\Gamma(\theta')$ – $\exp(-\kappa_e d \sec\theta')$, where d is depth of snow layer
η – volume reflectivity of snow medium
σ^0_{soil} – backscattering coefficient of underlying soil medium
κ_e – extinction coefficient of snow medium

Except for the angle θ, the above quantities are related to the geometry (roughness) of the two snow boundaries, the geometry in the snow medium (crystal-size) and to the dielectric properties of the snow and soil media. The second term in the above two expressions represents the contribution of the underlying ground medium. The dependence on snow-depth is through $\Gamma(\theta')$ which accounts for the transmission loss between the ground and air boundaries. For d large, $\Gamma(\theta')$ approaches zero and the expressions reduce to

$$\varepsilon = \gamma_{sa}(\theta)(1-a) \qquad \kappa_e d >> 1 \tag{8}$$

$$\sigma^0 = \gamma^2_{sa}(\theta)\left(\frac{\eta}{2\kappa_e}\right)\cos\theta \qquad \kappa_e d >> 1 \tag{9}$$

These represent the limiting values corresponding to an electromagnetically semi-infinite snow medium. The rate at which these limits are approached depends on κ_e which is an increasing function of frequency and snow liquid water content. That is, for dry snow the depth of the snow layer beyond which no appreciable change is observed decreases with increasing frequency, which has been observed experimentally and is discussed in later sections. Also, as the snow gets wet, κ_e increases rapidly with m, and if the liquid water is present in the snow surface layer, the contributions of the remainder of the snow layer are essentially masked by the high attenuation of the wet surface layer. In Eq. (6), $a = \kappa_s/\kappa_e$ where κ_s is the volume scattering coefficient. Among the various quantities in the above expression, κ_e exhibits a much stronger dependence on m than any of the others do. Hence, as m increases, ε increases and σ^0 decreases. Such variations are verified by the experimental observations discussed in the section on diurnal variation.

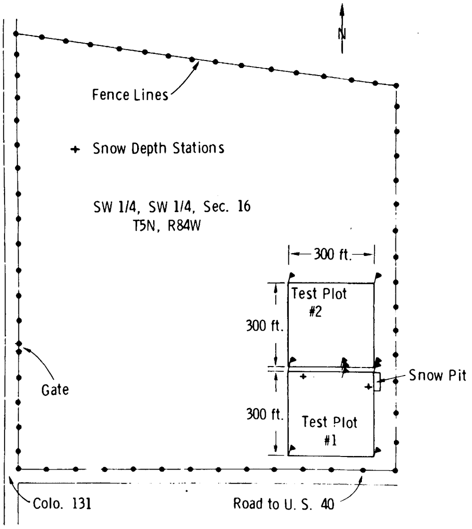

Fig. 1. Steamboat Springs test-site layout.

Experiment Description and Objective

Among the snow microwave investigations conducted to date with the University of Kansas facility, the most extensive have been two experiments, conducted in 1977 and 1980 in Colorado, and a 1979 experiment conducted in South Dakota. Results of the 1980 investigation are not yet available for inclusion in this report. The basic description is the same for the 1977 and 1979 experiments and therefore only the former will be described below.

Test Site Description

The 1977 test site was a close-cut hayfield in a valley 7 miles south of Steamboat Springs, Colorado. The hay was about 6 cm in height and was in its winter-dormant stage. Fig. 1 is a sketch of the primary observation area (Test Plot No. 1) and an alternate area (Test Plot No. 2). Also shown is the location of the snow-pit in which the snow ground-truth data were obtained. The validity of using the single-point measurements obtained in the snow-pit was verified by sampling the depth and density around the perimeter of Test Plot No. 1. This verification procedure was performed four times during the investigation period. The results indicate that the spatial variability was very small and therefore, the test area essentially was homogeneous in character.

The experiment-duration was from 2 February 1977 to 24 March 1977. Drought conditions existed during 1977 in Colorado, resulting in a much-below-normal snowpack ranging in depth (at the test site) from 26 cm to 57 cm. During the measurement period, density varied from about 0.16 g/cm^3 to 0.30 g/cm^3, and the maximum snow water equivalent was 14.6 cm. Dry-snow conditions were prevalent; however, diurnal melt cycles were observed on several days exhibiting a maximum liquid water content of 6% by volume (m_v) or 26% by weight (m_w). Snow crystal size varied both over time and depth within the snowpack. Soil conditions were found to vary from frozen to a semi-thawed, plastic-like state depending on ambient temperatures.

Microwave Sensors

The measurement systems used for obtaining the active microwave data were the University of Kansas Microwave Active Spectrometer (MAS) systems. These are truck-mounted, mobile radars capable of operating over a very wide range of the radar system parameters (Table 1). Each system is calibrated to measure the radar backscattering coefficient σ° for each of the three linear polarization configurations at angles of incidence between 0° (nadir) and 70°. Such measurements are

Table 1 – MAS 1-8 and MAS 8-18/35 GHz Nominal System Specifications

	MAS 1-8	MAS 8-18	35GHz Channel
Type	FM-CW	FM-CW	FM-CW
Modulating Waveform	Triangular	Triangular	Triangular
Frequency Range	1-8 GHz	8-18 GHz	35.6 GHz
FM Sweep: Δf	400 MHz	800 MHz	800MHz
Transmitter Power	10dBm	10dBm	1 dBm
Intermediate Frequency	50KHz	50KHz	50 KHz
IF Bandwidth	10 KHz	10 KHz	10 KHz
Antennas			
Height Above Ground	20 m	26 m	26 m
Type	122 cm Reflector	46 cm Reflector	Scalar Horn
Feeds	Crossed Log-Periodic	Quad-Ridged Horn	-
Polarization Capabilities	HH, HV, VV	HH, HV, VV	HH, HV, VV, RR, RL, LL
Beamwidth	12° at 1.25 GHz to 1.8° at 7.25 GHz	4° at 8.6 GHz 2° at 17.0 GHz	3°
Incidence Angle Range	0° (Nadir) – 80°	0° (Nadir) – 80°	0° (Nadir) – 80°
Calibration:			
Internal	Signal Injection (Delay-Line)	Signal Injection (Delay-Line)	Signal Injection (Delay-Line)
External	Luneberg Lens Reflector	Luneberg Lens Reflector	Luneberg Lens Reflector

made at nineteen frequencies between 1 GHz (λ = 30 cm) and 35 GHz (λ = 8.6 mm). Data acquisition is sequenced by a minicomputer which also provides some preprocessing of the many spatial samples necessary to reduce the effects of signal scintillation (due to the coherent nature of the radar signal).

The passive microwave systems were mounted on the truck-boom alongside one of the MAS systems. The characteristics of these systems are given in Table 2. Calibration was achieved by observation of the sky (cold temperature reference) and microwave absorber material (warm temperature reference).

Table 2 – Radiometer Specifications

	Manufacturer		
	Aerojet	Aerojet	Sperry
Frequency	10.69 GHz	37 GHz	94 GHz
Type	Dicke	Dicke	Total-Power
Polarization	H	H and V	H
Bandwidth	200 MHz	300 MHz	730 MHz
Sensitivity (Δt min)	0.2K (1-sec.)	0.5K (1-sec.)	3.5 K
Accuracy	±1K	±1K	$\pm[.05(300\text{-}T_s)+6]$
Temperature Range	50-350K	0-500K	0-500K
Approx. Gain (Volt/K)	–.012	.010	.020
AGC	No	Yes	Yes

Ground Truth

The choice of ground-truth parameters and the frequency of sampling were determined by a combination of a) the relative importance of the role each parameter was expected to play in the wave-target interaction process, b) the type of microwave experiment (as discussed below) and c) manpower limitations.

Atmospheric pressure, temperatures and relative humidity were monitored continuously by a weather station installed at the test site. Most of the snowpack- and ground-parameters were monitored at approximately two-hour intervals. The snowpack parameters included depth, stratification, density (of each observable layer), water equivalent, liquid water (of the top 5 cm snow layer and, occasionally, of other layers in the snowpack), temperature profile in 2 cm increments, grain size, and surface roughness. Liquid water was determined using a freezing calorimetric technique (Leaf 1966), grain-size and structure were determined from enlargement of microscope photographs of thin snow sections, and snow surface roughness profile was recorded on photographs of a thin metal plate (with a grid-pattern) inserted along its edge into the snowpack. The ground-truth observations were made using a snow-pit located on one edge of the field used for the microwave observations.

Data Acquisition

Three types of experiments were performed to investigate the active and passive microwave responses to snow parameters

1) *Temporal Measurements:* Approximately daily morning and afternoon datasets were acquired over the 6-week duration of the snow investigation. The purpose of this experiment was to study the overall temporal variation of the sensors' responses relative to the observed variations of the snowpack properties. Each data set consisted of backscatter and emission measurements at six angles, 0° (nadir) to 30° in 10° steps, plus 50° and 70°, and all available frequencies (19 active and 3 passive) and polarization configurations were employed. Spatial averaging was used by both types of sensors; the number of resolution cells averaged by the radar decreased from 20 for 0° measurements to 5 at 70°, and the radiometers averaged five cells at each angle of incidence. Ground-truth data acquisition was coordinated with the microwave data set, which required approximately 3 hours to record.

2) *Diurnal Measurements:* Four sequencies of continuous backscatter and emission measurements were taken to observe short-term variations in snow conditions, such as the appearance and disappearance of liquid water. Each sequence of continuous data was conducted over a 28-hour period commencing at 0600 hours. To reduce measurement time of a data set from 3 hours to 1 hour, it was necessary to reduce the number of incidence angles and polarizations observed by approximately a factor of three. The majority of the measurements were made at angles of incidence equal to 0°, 20° and 50°, and only horizontally polarized measurements were made.

3) *Snowpile Measurements:* The drought conditions that prevailed during 1977 in Colorado prevented at large accumulation of snow. Consequently, the build-up of a deep snowpack was simulated by piling snow up to 170 cm, in approximately 20 cm increments. Backscatter and emission measurements were made after the addition of each increment. A total of three such experiments were conducted.

Results

This section covers the analyses of the active and passive microwave responses to varying snowpack conditions.

Microwave Angular Response

Comparison of the angular response of the backscattering coefficient σ° for wet- and dry-snow conditions is shown in Fig. 2 at two microwave frequencies.

The frequencies selected are 2.6 GHz ($\lambda = 11.5$ cm) representing the behavior in the lower part of the microwave frequency band where scattering and attenua-

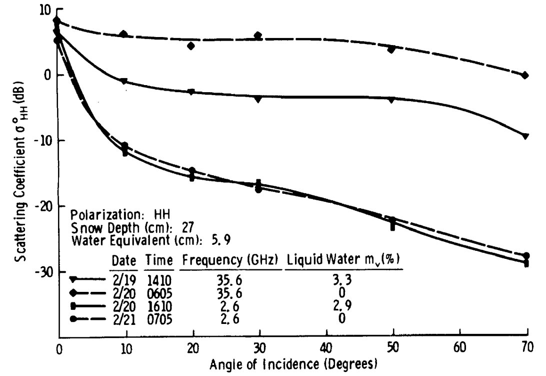

Fig. 2. Angular response of σ^0 to wet and dry snow conditions at 2.6 GHz and 35.6 GHz.

tion by snow are small in comparison to the backscatter contribution of the underlying ground, and 35.6 GHz (λ = 8.4 mm) where the backscatter contribution of the snow layer plays an important role, as evidenced by the difference in behavior of the dry- and wet-snow responses shown in Fig. 2.

The angular behavior of the passive microwave data is illustrated in Fig. 3 for wet- and dry-snow conditions. At 10.69 GHz, the apparent radiometric temperature T_{ap} shows similar angular shapes for the wet and dry cases. The approximately 5-15 K difference in level is attributed in part to the difference in snowpack thermometric temperature between the two cases. This difference in T_{ap} between wet- and dry-snow conditions is very small compared with the large change (>100K) at 37 GHz. The low magnitude of the apparent temperatures of dry snow

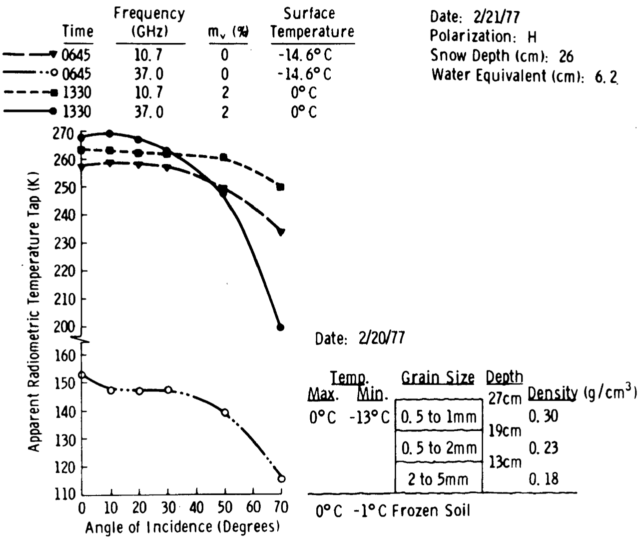

Fig. 3. Angular response of apparent radiometric temperature T_{ap} at 10.7 and 37 GHz to wet and dry snow conditions.

at 37 GHz are due to volume scattering, as discussed previously. Volume scattering is less evident at 10.69 GHz because of the longer wavelength.

Diurnal Variation

To investigate the effects of diurnal changes in snowpack conditions on σ° and T_{ap}, data were acquired over four diurnal periods. Analysis has shown that two types of behavior were observed. In the first type, the weather conditions were overcast, and the air- and snow-temperatures were continually below 0° C, and no measurable liquid water content was observed. For this case, the observed variation in σ° was very small (within system accuracy). In the second type, the temperature variation within the snowpack was such that the snow became wet in the surface layer during the daytime period. As an example of this case, the diurnal response of σ° is illustrated in Fig. 4a at five frequencies between 1.2 GHz and 35.6 GHz. The general shape of the σ° response is an inverse image of the liquid water m_v diurnal response. The magnitude of the observed dip in σ° between 1200 and 2000 hours increases with frequency from about 2 dB at 4.6 GHz to about 15 dB at 35.6 GHz.

Electromagnetically, scatter and emission by the snow scene are governed by: a) the dielectric discontinuities at the snow-air and snow-ground boundaries and b) dielectric inhomogeneity of the snow medium. Because of the large difference in magnitude of the dielectric constant of water relative to that of dry snow (ice and air), the presence of water in liquid form in the snow volume exercises a strong influence on the dielectric constant of the medium, which in turn influences the absorption, emission and scattering in the medium, and the transmission across its upper- and lower-boundaries. Furthermore, the influence of the liquid water content on the electromagnetic properties of the snow medium is strongly dependent on the microwave frequency, which is the reason for the observed increasing sensitivity of σ° to m_v with increasing frequency (Fig. 4a).

Generally speaking, a change in the dielectric properties of the snow medium results in opposite responses for active and passive microwave sensors; hence, while σ° decreases with m_v, T_{ap} increases, as shown in Fig. 4b. A substantially stronger sensitivity to m_v is observed at 37 GHz in comparison to 10.69 GHz; at 10.69 GHz T_{ap} shows a total variation of 15 K, in contrast to 120 K at 37 GHz.

A typical example depicting the observed variation of σ° with m_v is shown in Fig. 5. Empirically, the variation takes the form

$$\sigma^0_{dB} = A + Be^{-cm_v} \tag{10}$$

where A, B and c are constants for a given frequency, angle of incidence and polarization configuration. The observed target was the South Dakota State University football field, covered with a layer of snow.

The corresponding passive microwave behavior is shown in Fig. 6, along with empirically generated expressions. Part of the scatter about the regression curve is

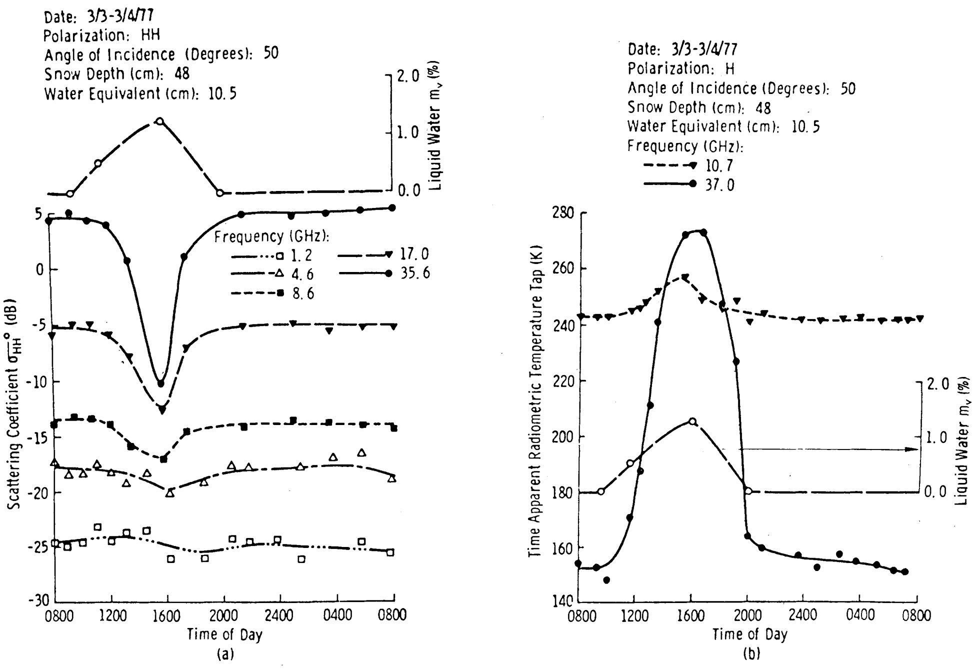

Fig. 4. Diurnal variation of liquid water and a) σ^0 and b) T_{ap} at 50° angle of incidence.

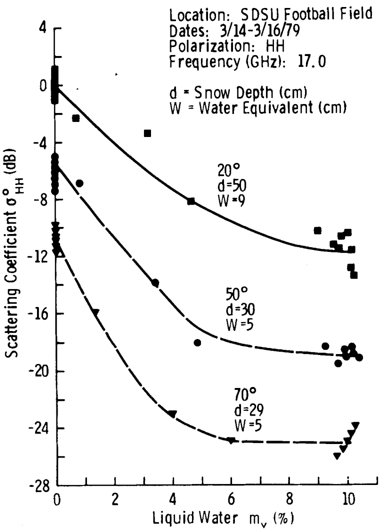

Fig. 5. Response of σ^0 to liquid water for three angles of incidence at 17 GHz.

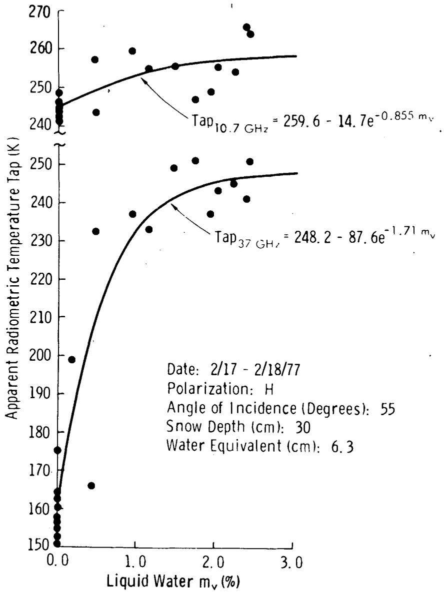

Fig. 6. T_{ap} response to liquid water at 50° angle of incidence.

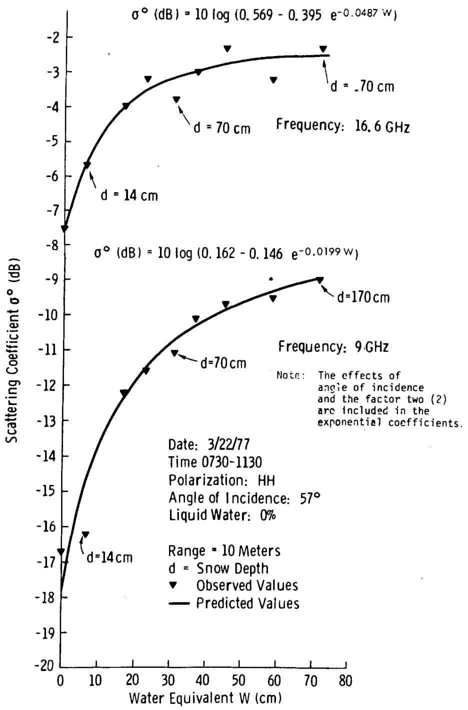

Fig. 7. Scattering coefficient response to snow water equivalent.

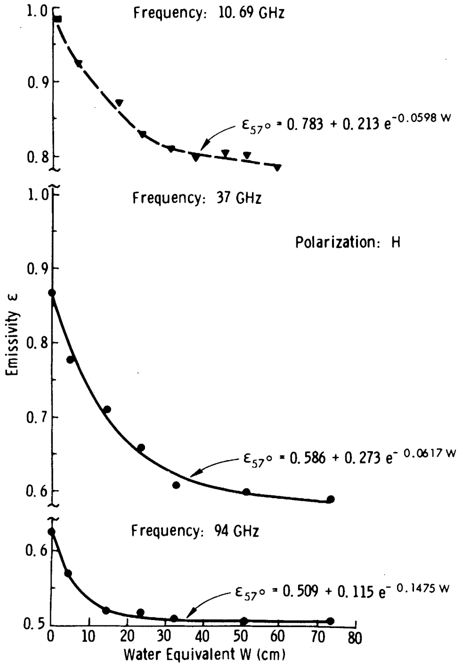

Fig. 8. Measured radiometric emissivity response to snow water equivalent.

due to the fact that T_{ap} is a function of the snow thermometric temperature, whose variation is unaccounted for in Fig. 6. Also, in the cases of both active and passive sensors, the liquid water m_v used in Figs. 5 and 6 is that measured for the top 5 cm layer of the snowpack, while the observed microwave responses may be governed by the backscatter and emission contribution of a layer whose thickness is greater or smaller than 5 cm depending on the microwave frequency and the depth profile of m_v. This point is discussed further in the section on temporal behavior.

Water-Equivalent Response

As was mentioned earlier, the microwave backscatter and emission responses to snow-depth (or water equivalent) were investigated through the construction of snowpiles. The snow was dry and its average density was 0.42 g/cm^3. Figs. 7 and 8 show, respectively, the scattering coefficient σ^0 and the emissivity ε (computed from measured values of T_{ap} and T_{dn} using Eq. (5)) as a function of w_n, the snow water equivalent. For both types of sensors, an exponential-type dependence on w_n is observed. Also, as w_n increases, σ^0 and ε approach a limiting value corresponding to the case of an electromagnetically infinitely-deep snow layer. Because the attentuation coefficient of snow increases with increasing frequency, the effective depth of the layer responsible for the majority of the backscatter and emission decreases with increasing frequency. This behavior is observed in Figs. 7 and 8.

Temporal Behavior

Fig. 9 is a typical example of the observed temporal variation of σ° for the 6-week duration of the 1977 investigation. The top part of the figure shows the variation of the liquid water content m_v (of the top 5 cm layer) as a function of time, and the bottom part shows the gradual increase in snow water equivalent from about 5 cm on 2/11/77 to about 13 cm at the end of the winter season.

The following observations are noted:

a) For the period prior to 3/17/77, σ° always responds to changes in the liquid water content m_v. During this period, whenever the top 5 cm layer was dry ($m_v = 0$), the entire snowpack was dry.

b) For the period after 3/17/77, some of the observations were made for snowpack conditions characterized by a dry surface-layer over slightly wet lower layers. With the top layer dry, the attenuation through it is small, and therefore σ° is influenced by the liquid water content of the lower layers, which explains why σ° exhibited lower values on the afternoon of 3/24/77 then would be expected for a completely dry snowpack.

c) The dashed lines in Fig. 9 represent the envelope of the σ° variation prior to 3/17/77. It is observed that $\sigma^\circ_{\text{min}}$ remains approximately constant throughout this period. That is, the limiting value of σ° for wet snow is independent of the water equivalent w_n. This is to be expected because when the top layer is wet, it masks the contributions from the remainder of the snowpack and from the underlying soil.

d) $\sigma^\circ_{\text{max}}$, corresponding to dry snowpack conditions, increases approximately monotonically with time, in response to the increase of w_n.

The temporal variation of T_{ap} at 37 GHz is shown in Fig. 10. The behavior is similar to that shown in Fig. 9 for σ° except that the trends are inverted; T_{ap} increases with m_v whereas σ° decreases.

Discussion

The potential of microwave techniques for the measurement of various snowpack characteristics, which had been indicated by prior research, has been defined more specifically by the results of this experiment. Both the scattering coefficient and the apparent temperature have been found to be sensitive to changes in snow water equivalent and liquid water content. Because of the abnormality of the

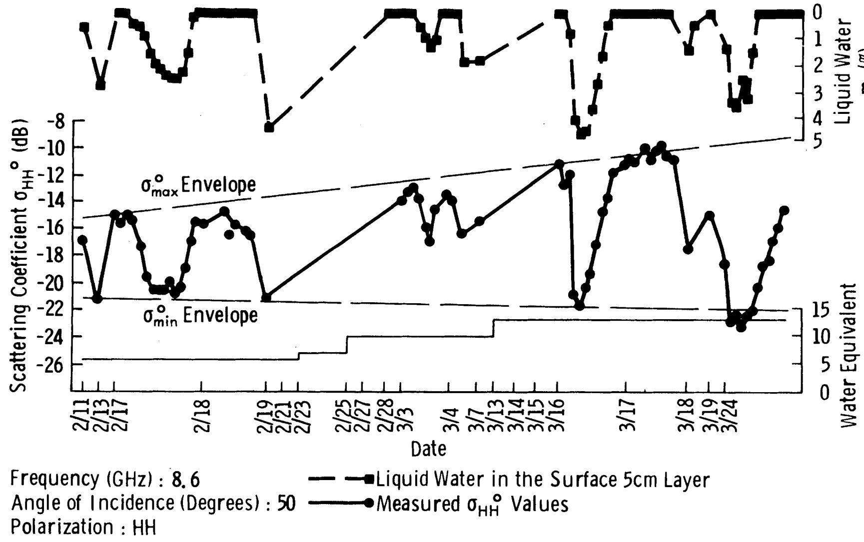

Fig. 9. Temporal variation of σ^0 over the experiment duration at 8.6 GHz and 50° angle of incidence.

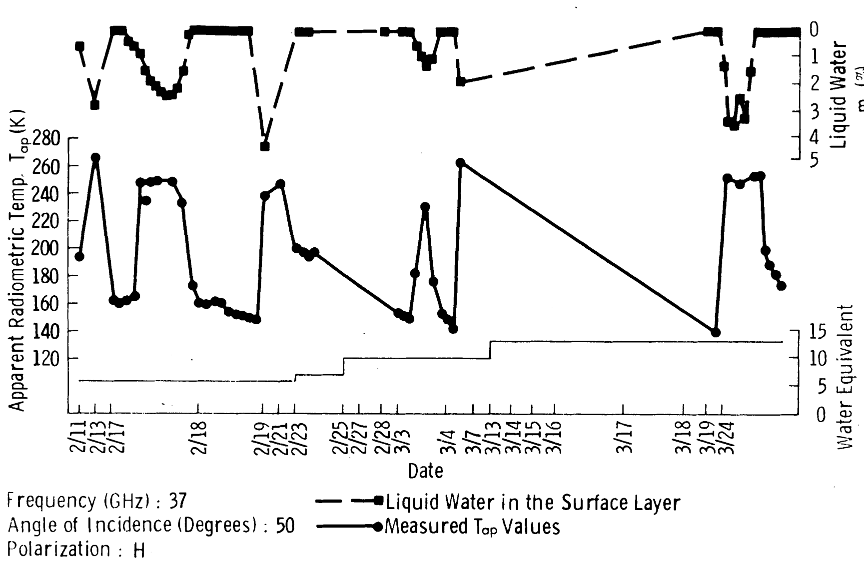

Fig. 10. Temporal variation of T_{ap} over the experiment duration at 37 GHz and 50° angle of incidence.

study-period, however, water equivalent variability had to be simulated by the artificial piling of snow to various depths. In addition, because the Colorado study-period ended March 25, 1977, the active snowmelt runoff period was not sampled and liquid water content values were limited to the 0-5% by volume range. The results of this study, however, indicate the definite possibility that microwave techniques can be used to measure liquid water content and snow water equivalent over large areas, thereby improving the existing capability of observations at a few scattered points.

The full capability of the microwave approach was not realized in this experiment because of the drought-influenced and limited snow water equivalent data-range (5.7-14.6 cm) and because the pack melt period was not observed. In order to evaluate fully the microwave potential, a wider range of data must be collected and models should be improved to allow quantitaive estimation of the significant snowpack parameters. Associated with this is the need to expand and increase the frequency of ground-truth observations in order to better interpret the microwave data. Specifically, more sites have to be measured to obtain greater natural variations in snow depth and grain size. The measurement period also should be extended to include the accumulation as well as the peak snowmelt period.

In order to take advantage of the microwave capability for sampling varying penetration depths at various frequencies (for both σ^o and T_b), the vertical spatial- and time-resolution measurements of snow wetness ground-truth should be increased. Response of the lower-frequency measurements to snow wetness in the lower layers of the snowpack should be considered. Such multifrequency measurements would enable assessment of meltwater movement through the snowpack for snowmelt modeling purposes. In order to assess the liquid water content of the various layers rapidly, improved conventional techniques and increased observer-effort must be considered.

When microwave experiments over snow are conducted, every attempt should be made to collect coordinated passive and active observational data sets. It is conceivable that the combination of information content from these different sensors will characterize more fully the snowpack conditions. Additionally, operation of a full complement of passive and active microwave instruments over the same snow conditions will permit a detailed evaluation of the optimum microwave configuration with reference to frequency, polarization, incidence angle, and sensor type.

Because of the results of the microwave research to date, it is apparent that there is now a need for closer interaction between microwave researchers and snow hydrologists and snow data users. Future development of microwave sensors for measuring snow and development of associated information extraction algorithms would benefit from a more detailed understanding of snow hydrology data needs. Information on measurement frequency, spatial density, vertical resolution, and data-delivery needs should be factored into the design of a comprehensive microwave- and snow-research program at this stage. The snow data user community subsequently would be involved in experiment-design, field measurements, data interpretation and analysis, and user testing. The first step in such interaction was the Workshop on Microwave Remote Sensing of Snowpack Properties held in Fort Collins, Colorado in 1980 (Rango and Peterson 1980). Subsequent working-group meetings will be used to develop an overall plan of research in the microwave sensing of snow properties.

Conclusions

In a field-program of microwave snow measurements performed at Steamboat Springs, Colorado during the winter of 1977, both active and passive microwave data were collected with truck-mounted instruments and the data were analyzed. Both the scattering coefficient, σ°, and the apparent temperature T_{ap}, were found to be sensitive to changes in snow water equivalent and snow liquid water. Snow water equivalent, w_n, causes σ° to increase at angles away from nadir, and at a constant angle, the σ° data exhibit an exponential-like increase with increasing w_n. The T_{ap} response is reversed, i.e., the T_{ap} data exhibit an exponential-like decrease with increasing w_n For both active and passive data, the w_n at which the microwave response begins to saturate (where further additions of snow do not affect the response) decreases as the wavelength employed decreases.

As opposed to w_n, snow liquid water content, m causes σ° to decrease at angles away from nadir. The sensitivity of σ° to m in the upper layer of the snowpack generally increases with increasing frequency and increasing angle of incidence. Although the sensitivity of T_{ap} to m_v increased with increasing frequency, it remained relatively constant with changing incidence angles. As a result, diurnal microwave data sets show the greatest σ° and T_{ap} variation in response to the daily melt cycle at 35 and 37 GHz with correspondingly less variation at the lower frequencies.

Much additional research is needed to develop recommendations for the optimum observing system and data analysis techniques for use in total snowpack monitoring. Such a research program in the long run will be most efficient and effective by the inclusion of operationally oriented snow-data users in the early stages of planning and development.

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List of Symbols

a – single scattering albedo of snow
A – illuminated area (m^2)
d_n – snow depth (cm)
m – snow liquid water content (m_v% by volume; m_w% by weight)
r – snowpack reflectivity (power reflection coefficient)
P_r – received power (mW)
T_{ap} – apparent radiometric temperature (K)
T_b – brightness temperature (K)
T_{dn} – downwelling atmospheric temperature (K)
T_{sc} – scattered radiation, primarily T_{dn} scattered by the terrain (K)
T_o – physical temperature of the snowpack (K)
T_{up} – upwelling radiation by the atmospheric layer between the sensor and the terrain (K)
w_n – snow water equivalent (cm)
$\Gamma(\theta')$ – $\exp(-\kappa_e d \sec\theta')$
ε – emissivity of snow scene
η – volume reflectivity of snow medium
θ – angle of incidence
θ' – angle of refraction in snow medium
κ_e – extinction coefficient of snow medium
κ_s – volume scattering coefficient of snow medium
λ – wavelength (cm)
σ^o – backscattering coefficient
σ^o_{soil} – backscattering coefficient of underlying medium
γ_a – atmospheric transmission coefficient for propagation (terrain to radiometer)
$\gamma_{sa}(\theta)$ – power transmission coefficient at the snow-air boundary
$\gamma_{gs}(\theta')$ – power transmission coefficient at the ground-snow boundary

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