Snow Probe for *In Situ* Determination of Wetness and Density

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***Abstract*—The amount of water present in liquid form in a snowpack exercises a strong influence on the radar and radiometric responses of snow. Conventional techniques for measuring the liquid water content m_v suffer from various shortcomings, which include poor accuracy, long analysis time, poor spatial resolution, and/or cumbersome and inconvenient procedures. This paper describes the development of a hand-held electromagnetic sensor for quick and easy determination of snow liquid water content and density. A novel design of this probe affords several important advantages over existing similar sensors. Among these are improved spatial resolution and accuracy, and reduced sensitivity to interference by objects or media outside the sample volume of the sensor. The sensor actually measures the complex dielectric constant of the snow medium, and the water content and density must be obtained through the use of empirical or semi-empirical relations. To test the suitability of existing models and allow the development of new models, the snow probe was tested against the freezing calorimeter and gravimetric density determinations. From these comparisons, valid models were selected or developed. Based on the use of these models, the following specifications were established for the snow probe: 1) liquid water content measurement accuracy = ±0.66% in the wetness range from 0 to 10% by volume and 2) wet snow density measurement accuracy = ±0.05 g/cm^3 in the density range from 0.1 to 0.6 g/cm^3.**

I. Introduction

In the study of microwave remote sensing of snow, it is necessary to consider the presence of liquid water in the snowpack. The dielectric constant of water is large (e.g., $\epsilon_w = 88 - j9.8$ at 1 GHz [1]) relative to that of ice ($\epsilon_i \approx 3.15 - j0.001$ [2]), and therefore even a very small amount of water will cause a substantial change in the overall dielectric properties of the snow medium, particularly with respect to the imaginary part. These changes will, in turn, influence the radar backscatter and microwave emission responses of the snowpack.

Among instruments available for measuring the volumetric liquid-water content of snow, m_v, under field conditions, the freezing calorimeter [3]–[5] offers the best accuracy (≈1%) and has been one of the most widely used in support of quantitative snow-research investigations. In practice, however, the freezing calorimeter technique suffers from a number of drawbacks. First, the time required to perform an individual measurement of m_v is about thirty minutes. Improving the temporal resolution to a shorter interval would require the use of multiple instruments, thereby increasing the cost and necessary manpower. Second, the technique is rather involved, requiring the use of a freezing agent and the careful execution of several steps. Third, the freezing calorimeter actually measures the mass fraction of liquid water in the snow sample, W, not the volumetric water content m_v. To convert W to m_v, a separate measurement of snow density is required. Fourth, because a relatively large snow sample (about 250 cm^3) is needed to achieve acceptable measurement accuracy, it is difficult to obtain the sample from a thin horizontal layer, thereby rendering the technique impractical for profiling the variation of m_v with depth. Yet, the depth profile of m_v, which can exhibit rapid spatial and temporal variations [6], [7], is one of the most important parameters of a snowpack, both in terms of the snowpack hydrology and the effect that m_v has on the microwave emission and scattering behavior of the snow layer.

In experimental investigations of the radar response of snow-covered ground, it is essential to measure the depth profile of m_v with good spatial resolution (2–3 cm) and adequate temporal resolution (a few minutes), particularly during the rapid melting and freezing intervals of the diurnal cycle. There have in recent years appeared a host of instruments [8] which retrieve snow parameters quickly and nondestructively, by measuring the dielectric constant of snow and relating it to the physical parameters. Of these techniques, the most attractive candidate has been the "Snow Fork," a microwave instrument developed in Finland [1]. The strengths of this technique are the simplicity of the equipment and speed of the measurement, high spatial resolution, and the ability to measure both the real and imaginary parts of the dielectric constant of snow, allowing for more powerful algorithms allowing determination of snow wetness and density with a single measurement. In the process of examining the Snow Fork approach, we decided to modify the basic design to improve the sensitivity of the instrument to m_v and reduce the effective sampled volume of the snow medium, thereby improving the spatial resolution of the sensor. Our modified design, which we shall refer to as the "Snow Probe" is described in Section II. The snow probe measures the real and imaginary parts of the relative dielectric constant of the snow medium, from which the liquid water content m_v and the snow density ρ_s are calculated through the use of empirical or semi-empirical relations. The degree to which such relations are valid is established through a comparison with direct techniques. Therefore, in the process of developing a snow probe algorithm, it was necessary to perform independent measurements of ρ_s and m_v. Density measurements were performed with a standard tube of known volume, whose weight is measured both empty

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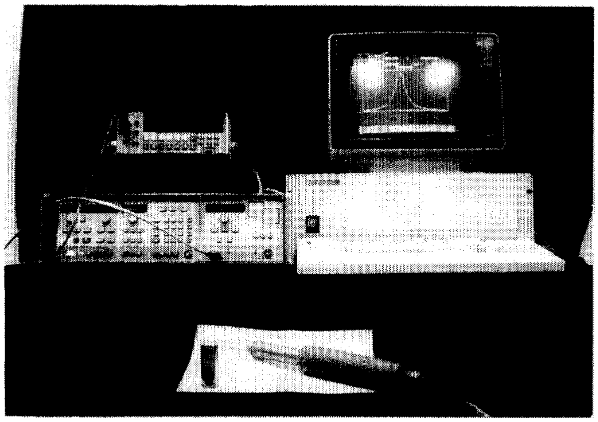

Fig. 1. Photograph of snow probe system.

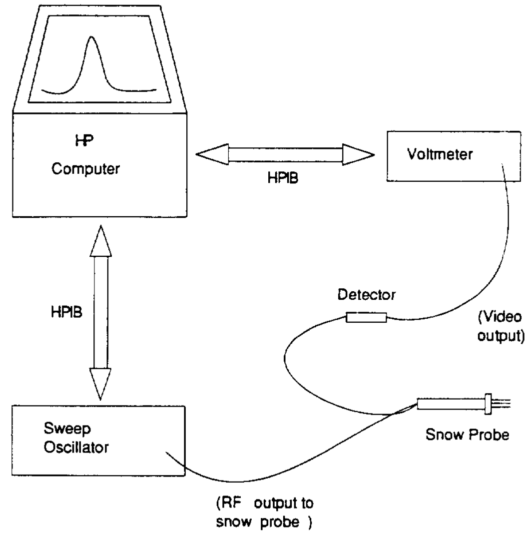

Fig. 2. Schematic diagram of snow probe system.

and full of snow. For a direct technique for measuring m_v we evaluated two candidates: 1) the freezing calorimeter; and 2) the dilatometer [9], which measures the change in volume that occurs as a sample melts completely. The dilatometer approach was rejected because of poor measurement accuracy and long measurement time (about one hour). The form of the relations which were ultimately established as a result of these comparison studies is described in Section III.

II. Snow Dielectric Probe

A. Snow Probe Measurement System

Figs. 1 and 2 show a photograph of the snow probe measurement system, and a schematic diagram, respectively. The sweep oscillator, under computer control, sweeps (in discrete 10 MHz steps) over a relatively large frequency range. This serves to determine, within ± 5 MHz, the frequency at which the detected voltage is a maximum, corresponding to the resonant frequency of the probe. The RF power transmitted through the snow probe is converted to video by the crystal detector, measured by the voltmeter, which in turn sends the voltage values to the computer. The frequency spectrum is generated in real-time on the monitor of the computer. In the second pass, a much narrower frequency range is centered around the peak location and swept with a finer step size (≈ 1 MHz). The center frequency and the 3-dB bandwidth around it are found, and from these, first the dielectric constant and then the snow parameters m_v and ρ_s are determined according to procedures described in detail in Section III of this paper.

As it is depicted in these figures, the snow probe is connected to a coaxial cable approximately 15 meters long. This arrangement is suitable, for example, for cases in which measurements are required in an area fairly local to truck mounted radars. For more remote field applications, the functions of the hardware shown would need to be combined into a portable unit. The technology for building a compact unit is well established.

B. Sensor Design

The snow probe is essentially a transmission-type electromagnetic resonator. The resonant structure used in the original design [1] was a twin-pronged fork. This structure behaves as a two wire transmission line shorted on one end and open on the other. It is resonant at the frequency for which the length of the resonant structure is equivalent to $\lambda/4$ in the surrounding medium. The RF power is fed in and out of the structure using coupling loops.

For our design, we used a coaxial type resonator, as illustrated in Fig. 3. The skeleton of the outer conductor is achieved using four prongs. The principle is basically the same: a quarter wavelength cavity, open on one end, shorted on the other, with power delivered in and out through coupling loops. The coaxial design was chosen for purposes of spatial resolution. Being a shielded design, the electric field is confined to the volume contained within the resonant cavity, as opposed to the original design, which used only two prongs. The coaxial design also had a much higher quality factor, (≈ 110 versus 40–70 for the original design) which, as discussed below, allows for more accurate determination of the complex dielectric constant. A photograph of the snow probe is shown in Fig. 4. The stainless-steel band encircling the resonant structure near the bottom is necessary to defeat competing two-wire resonances which are otherwise excited between any given pair of the outer prongs.

The real part of the dielectric constant is determined by the resonant frequency of the transmission spectrum, or equivalently, the frequency at which maximum transmission occurs. As mentioned above, this corresponds to the frequency for which the wavelength *in the medium* is equal to four times the length of the resonator. If the measured resonant frequency is f_a in air and f_s in snow, then the real part of the dielectric constant is given by

$$\epsilon_s' = \left(\frac{f_a}{f_s}\right)^2. \tag{1}$$

The imaginary part of ϵ_s is determined from the change in Q_m, the measured quality factor of the resonator. The quality factor may be determined by measuring Δf, the half-power

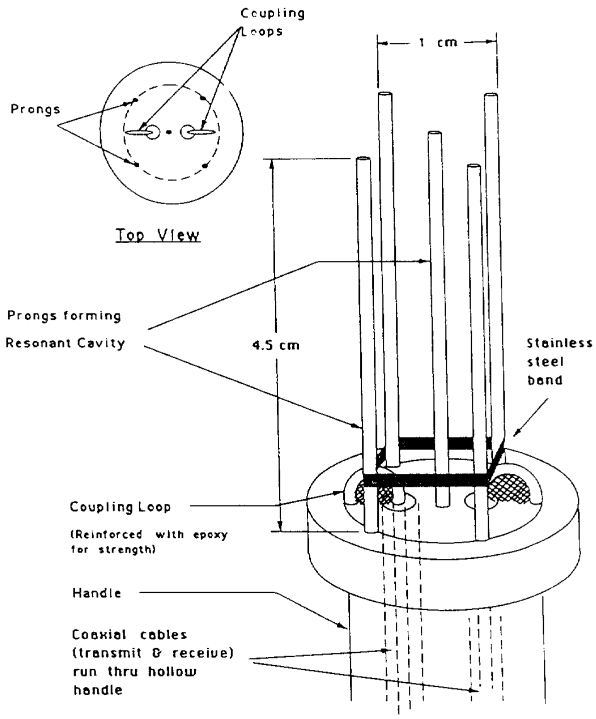

Fig. 3. Illustration of snow probe. Coaxial transmission lines extend through handle. At the face of the snow probe, the center conductors of the coaxial lines extend beyond and curl over to form coupling loops.

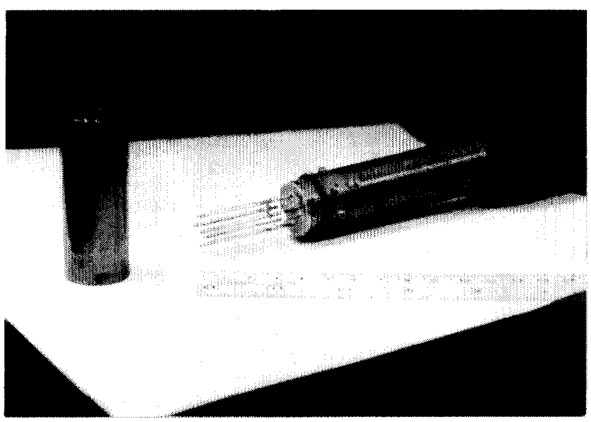

Fig. 4. Photograph of snow probe with cap.

bandwidth [10]:

$$Q_m = \frac{f_r}{\Delta f} \tag{2}$$

where f_r is the resonant frequency (f_a or f_s, depending on whether the medium is air or snow). For the snow probe, power losses exist because of radiation, finite conductivity of the conductors, coupling mechanisms (i.e., coupling loops), and dissipation in a lossy dielectric. Thus the measured Q is

TABLE I
SUMMARY OF TEST MATERIAL PROPERTIES AND MEASUREMENTS

Material	$\bar{\epsilon}$	(GHz) f_R	Q_m
Air	$1.0 - j0.0$	1.716	125.2
Sand	$2.78 - j3.70e^{-2}$	1.036	51.7
Sugar	$1.98 - j7.8e^{-3}$	1.229	89.3
Coffee	$1.50 - j3.32e^{-2}$	1.431	30.4
Wax	$2.26 - j0.3e^{-3}$	1.150	137.0

given by [10]

$$\frac{1}{Q_m} = \frac{1}{Q_R} + \frac{\epsilon''}{\epsilon'} \tag{3}$$

where Q_m is the measured Q when the probe is inserted in the snow medium, and Q_R is the quality factor describing collectively radiation losses, losses due to the finite conductivity of the conductors, and the power losses due to the external coupling mechanisms for the dielectric-filled snow probe. To calculate ϵ'', from (3), one must not only measure Q_m and know ϵ', but the value of Q_R should be known also. As long as $\tan\delta = \epsilon''/\epsilon'$ is very small, which is the case for snow, it is reasonable to assume that Q_R is a function of ϵ' only. This assumption was verified experimentally by measuring Q_R for each of five materials with known dielectric properties (Table I). For each material, Q_m was calculated by (2) on the basis of measurements of Δf and f_r and then it was used in (3) to compute Q_R. The values of ϵ' and ϵ'' of the test materials given in Table I were measured with an L-band cavity resonator. This process not only validated the assumption that Q_R is dependent on ϵ' only, but it also produced an expression for computing it:

$$\frac{1}{Q_R} = \frac{(pf_r + b) \times 10^{-3}}{f_r} \tag{4}$$

where p and b are constants and f_r is the resonant frequency associated with the material under test (which is related to ϵ' by $\epsilon' = (f_a/f_r)^2$). For the probe used in this study, $p = 8.381$ and $b = 0.7426$ when f_r is in GHz. Combining (2), (3), and (4) and specializing the notation to snow (by adding a subscript s to ϵ'' and replacing the subscript r by s in f_r) we obtain the expression

$$\epsilon'' = \left(\frac{f_a}{f_s}\right)^2 \left[\frac{\Delta f_s}{f_s} - \left(p + \frac{b}{f_s}\right)\right]. \tag{5}$$

Equations (1) and (5) constitute the basic relations used for determining ϵ_s' and ϵ_s'' from measurements of f_a, the resonant frequency when the probe is in air, and f_s and Δf_s, the resonant frequency and associated 3-dB bandwidth measured when the probe is inserted in the snow sample.

C. Spatial Resolution/Outside Interference

As mentioned earlier, the partially shielded design of this sensor reduces its sensitivity to permittivity variations outside the sample volume. By sample volume, we refer to the volume inside the cylinder described by the four outside prongs (Fig.

3). The coaxial design will tend to produce greater field confinement relative to a twin-prong structure.

The effective sample volume was tested in the following way: a cardboard box (30 cm × 30 cm) was filled with sugar to a depth of ≈16 cm. The snow probe was inserted into the sugar at a position in the center of the top surface, and then the dielectric constant was measured. Next, a thin metal plate (square, ≈25 cm on a side) was inserted into the sugar, parallel to and resting against one side of the box. The dielectric constant was remeasured. The metal plate was incrementally moved closer to the sensor position, with dielectric measurements recorded at each sensor-to-plate distance. The results of the experiment are shown in Fig. 5, in which ϵ'' is plotted as a function of the sensor-to-plate separation.

The plate appears to have a weak influence on the measurement, even at a distance of only 0.6 cm. To put this variation into perspective, had the material been snow, and using the relations given in Section III-A, the fluctuation in the estimate of liquid water would have ranged from $m_v = 0.6\%$ to $m_v = 0.8\ \%$. The real part of the dielectric constant (not shown in Fig. 5) stayed within the range 2.00–2.01 during the experiment. The results of this experiment, which essentially confirm the expectation that the electric field is confined to the volume enclosed by the four prongs, translate into a vertical resolution of about 2 cm when the snow probe is inserted into the snowpack horizontally (the snow probe cross section is 1 cm × 1 cm).

There is necessarily a compromise between the ability to make high spatial resolution measurements and maximum ruggedness of design. The overall small size of the probe requires the use of small diameter prongs as well to insure that the snow volume which is being sampled is not compressed to the point of compromising the measurement. Though we used stainless steel for the prongs to afford maximum strength, it is still possible—for snow samples which are especially dense, coarse, or icy—to have some bending of the prongs occur. For some extreme cases the probe might not be a practical option for a measuring device. In these cases, it may also be the case that the simple relationships (which will be described in Section III) between dielectric constant and snow parameters no longer hold.

III. Retrieval of Snow Density and Liquid Water Content

The preceding section described the design and operation of the snow probe and the procedure used for measuring ϵ'_s and ϵ''_s of the snow medium. The next step is to use these measurements to determine the density ρ_s and liquid-water content m_v. This is accomplished by using a set of empirical or semi-empirical relationships relating the dielectric constant of wet snow to its density and liquid-water content. These relationships express the dielectric constant of wet snow ϵ_{ws} in terms of ϵ_{ds}, the dielectric constant of the snow in the absence of liquid water, plus additional terms that account for the increase in ϵ' and ϵ'' due to the presence of liquid water:

$$\epsilon'_{ws} = \epsilon'_{ds} + \Delta' \tag{6}$$

$$\epsilon''_{ws} = \epsilon''_{ds} + \Delta'' \tag{7}$$

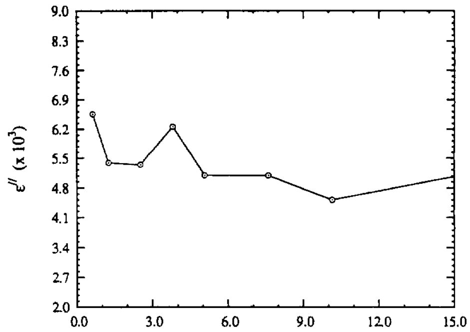

Fig. 5. Variation in measurement of ϵ'' of suger as a function of sensor proximity to metal plate. (Real part ϵ' stayed in the range 2.00–2.01.)

where Δ' and Δ'' represent the incremental increases due to m_v. The particular expressions for these quantities which we adopt for evaluation are based on the dispersion behavior of liquid water [2]:

$$\Delta' = 0.02m_v^{1.015} + \frac{0.073m_v^{1.31}}{1 + (f_s/f_w)^2} \tag{8}$$

$$\Delta'' = \frac{0.073(f_s/f_w)m_v^{1.31}}{1 + (f/f_w)^2} \tag{9}$$

where f_s is the resonant frequency at which ϵ'_{ws} and ϵ''_{ws} are measured by the probe, $f_w = 9.07$ GHz is the relaxation frequency of water at 0°C, and m_v is expressed in percent. Thus, the quantities measured by the snow probe are ϵ'_{ws}, ϵ''_{ws}, and f_s, and the quantities we wish to retrieve are m_v and ρ_{ws}, the latter being the density of the wet snow medium.

A. Liquid-Water Content

In the frequency range around 1 GHz, which is the operational frequency range of the probe, the dielectric loss factor of dry snow ϵ''_{ds} is less than 4×10^{-4} (for a snow density ρ_{ds} less than 0.5 g/cm³). For $m_v = 1\%$, the increment Δ'' given by (9) is equal to 7.5×10^{-3}, which is approximately 20 times larger than the first term. Hence, ϵ''_{ds} may be ignored in (7) and the equation can be solved to express m_v in terms of ϵ''_{ws}:

$$m_v = \left\{ \frac{\epsilon''_{ws}[1 + (f_s/f_w)^2]}{0.073(f_s/f_w)} \right\}^{\frac{1}{1.31}}. \tag{10}$$

The applicability of this retrieval procedure was evaluated by comparing the results obtained using (10) on the basis of the snow-probe measurements with those measured with a freezing calorimeter. The freezing calorimeter measures the liquid water mass fraction W, from which m_v was calculated by using the relationship

$$m_v = 100\rho_{ws}W \tag{11}$$

where ρ_{ws} is the density of the wet snow sample, which was measured gravimetrically.

The results for the liquid water content comparison are shown in Fig. 6. The error bars associated with the freezing calorimeter data points show the range of results obtained

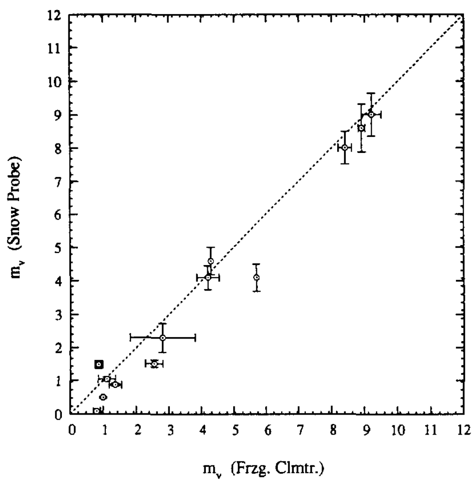

Fig. 6. Comparison of snow wetness results obtained via snow probe and freezing calorimetry, respectively. Snow probe data points are based on an average of twelve separate measurements.

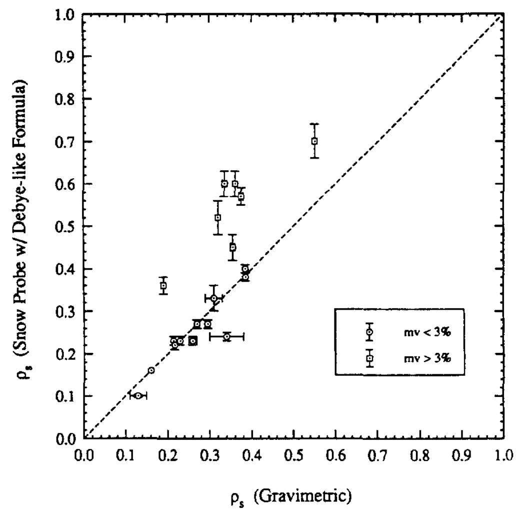

Fig. 7. Comparison of snow density results obtained via snow probe (in conjuction with Debye-like relation) and gravimetric measurements. Data points represented with squares were from snowpacks having volumetric wetness levels of >3%; with circles, <3%.

from typically two separate (and usually simultaneous) determinations. (Data points with no error bars indicate only a single measurement or that only the mean value of a set was available.) The freezing calorimeter has generally excellent precision.

The values for m_v obtained from the snow-probe dielectric measurements are computed by (10). The data points and error bars shown for the snow probe are based on an average of twelve separate measurements made for each snow sample and the uncertainty of the estimate of the mean value as represented by the error bars was computed as $\pm\sigma/\sqrt{N}$ where σ is the standard deviation of the set of measurements and N is the number of measurements in that set. From the figure, the agreement between the two techniques is generally very good, and, with the exception of an outlier at the 6% level, the use of the snow probe and (9) gives results which are within $\pm 0.5\%$ of the freezing calorimeter results. This result strongly supports the validity of (9).

B. Snow Density

With m_v known, through the retrieval procedure described in the preceding section, we now turn our attention to using (6) and (8) in order to retrieve the wet snow density ρ_{ws} from ϵ'_{ws}, the dielectric constant of the wet snow medium measured by the snow probe. To do so, we first express ρ_{ws} in terms of ρ_{ds}, the density of the snow had the liquid water been removed,

$$\rho_{ws} = \rho_{ds} + m_v/100. \tag{12}$$

Next, we use the expression [11],

$$\epsilon'_{ds} = 1 + 1.7\rho_{ds} + 0.7\rho_{ds}^2, \tag{13}$$

and combine it with (6) to obtain the result:

$$\epsilon'_{ws} = 1 + 1.7\rho_{ds} + 0.7\rho_{ds}^2 + \Delta', \tag{14}$$

where Δ' is given in (8). Upon combining (12) and (14) and solving for ρ_{ws}, we obtain the expression

$$\rho_{ws} = (m_v/100) - 1.214 + \sqrt{1.474 - 1.428(1 - \epsilon'_{ws} + \Delta')}, \tag{15}$$

in which only the positive root is considered. To compute ρ_{ws} from (15), we use the value of m_v determined in the previous section through (10), the value of ϵ'_{ws} measured by the snow probe, and the value of Δ' calculated from (8). The values of ρ_s (for both wet and dry snow) determined through this procedure are compared with gravimetric measurements of ρ_s in Fig. 7. The data points for which good agreement is found correspond to snow samples having low wetness levels, <3%, for which the contribution Δ' is small anyway. For the samples in which the m_v is more appreciable, there is a significant disagreement between the measurements and the model given by (8).

The errors in density estimates are caused by the model underestimating the incremental increase $\Delta\epsilon'_{ws}$ for the higher wetness cases. Shown in Fig. 8 is a plot of $\Delta\epsilon'_{ws}$ as a function of m_v computed on the basis of (8), and the measurement points were calculated from $\Delta\epsilon'_{ws} = \epsilon'_{ws} - \epsilon'_{ds}$, with ϵ'_{ws} being the value measured by the probe and ϵ'_{ds} determined from (12) and (13). The curve drawn through the data points is generated using a simple polynomial fit, given by

$$\Delta\epsilon'_{ws} = 0.187m_v + 0.0045m_v^2. \tag{16}$$

The agreement between the gravimetric density technique and the snow probe using (16) is shown in Fig. 10. A very good fit can also be obtained via (8) by modifying the term $0.02m_v^{1.015}$ to $0.08m_v^{1.015}$; however, an arbitrary adjustment defeats the purpose of using a model which is based on physical arguments. The Debye-like model of (8) has essentially the same frequency dependance as the real part

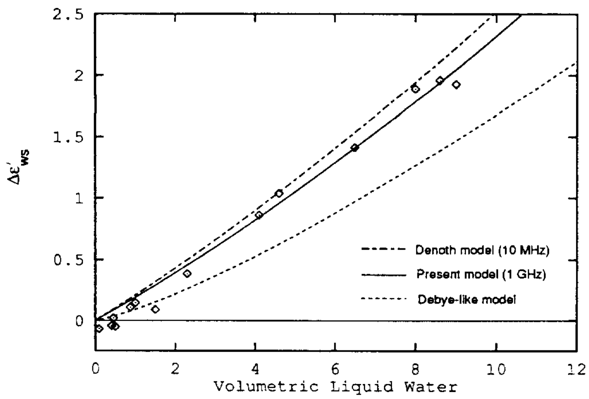

Fig. 8. $\Delta\epsilon'_{ws}$ versus m_v. Shown is data and best fit curve, plus a model obtained from a comparable study at 10 MHz, and Debye-like model.

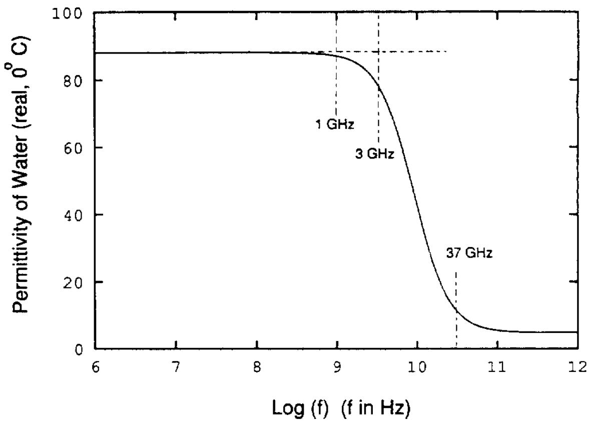

Fig. 9. Real part of permittivity of water at 0°C.

of the dielectric constant of water, and its empirically-derived coefficients—which effectively reduce the value of this quantity from the theoretical value of the pure material—account for the water being distributed in particle form within a host having a dielectric constant somewhere between those of air and ice. With this understanding, there does not appear to be any reason why a model which works well between 3 and (at least) 15 GHz should need to be significantly modified to work at 1 GHz; physically speaking, the only difference between 3 GHz and 1 GHz is that the dielectric constant of water increases from ≈80 to ≈87.

The literature contains certain pertinent experimental results that should be considered. Tiuri *et al.* [11] report measurements also at 1 GHz. In these measurements, a dilatometer technique was primarily employed for wetness measurements, but a capacitor technique was used for some of the samples corresponding to the lowest m_v levels. The dielectric measurements were made with the Snow Fork developed at the Helsinki University of Technology. The relationship they report is,

$$\Delta\epsilon'_{ws} = 0.089m_v + 0.72m_v^2. \tag{17}$$

This function, when plotted, closely resembles the Debye-like model (8) evaluated at 1 GHz. Most recently Denoth [12] reported measurements made at 10 MHz, in which dielectric measurements were made using a simple plate capacitor and liquid water measurements were made using a freezing calorimeter. The relation he reports is,

$$\Delta\epsilon'_{ws} = 0.206m_v + 0.0046m_v^2. \tag{18}$$

Denoth observes that this relation should continue to be valid up to approximately 2 GHz, since ϵ' of the constituents of wet snow—ice, air, and water—are all exactly or nearly frequency-independent in this range. In particular, for water, as seen in Fig. 9, the real part of the dielectric constant of water, ϵ'_w, at 1 GHz differs from that of 10 MHz by only 1.1%. Also noted on the figure is the region through which the Debye-like model of [2] was reported to be valid (although above 15 GHz, the empirical coefficients shown in (8) are slightly modified as a function of frequency). The best fit function for the 10 MHz data, given by (18), is also shown in Fig. 8. The close agreement between the results at 10 MHz and 1 GHz tends to bear out Denoth's prediction and suggest that at these frequencies, where scattering is an unimportant factor in calculating the dielectric constant, ϵ'_{ws} is directly relatable to ϵ'_w. In effect, a model like (8) *should* be expected to work, but, in its present form, does not appear to. Regarding the discrepancy between our results and those of [11], a possible explanation is that they used a dilatometer to measure wetness (we found the dilatometer to give very unsatisfactory performance), whereas our standard (which was also used in [12]) was the freezing calorimeter technique whose accuracy and precision has been demonstrated.

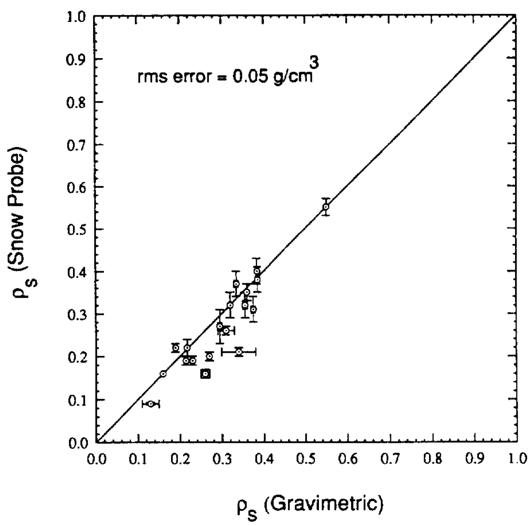

Fig. 10. Comparison of snow density results obtained via snow probe (with associated empirical algorithm) and gravimetric measurements.

IV. Application

Fig. 11 is a nomogram, based on these equations which have been found to be valid in the specified ranges. It consists of contours of constant m_v and ρ_{ds}, respectively, in a two-dimensional representation bounded by the two parameters

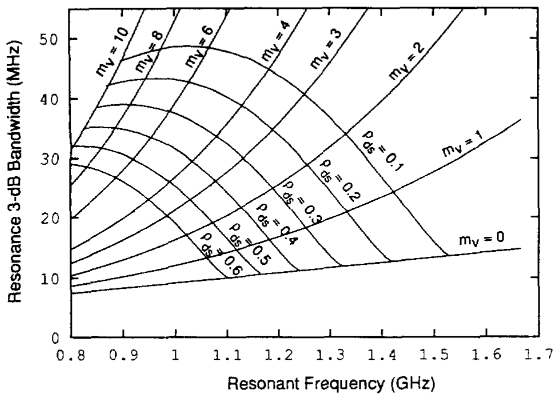

Fig. 11. Nomogram giving snow liquid water content (m_v) and equivalent dry snow density (ρ_{ds}) in terms of two parameters directly measured by the snow probe: resonant frequency (f) and resonance (3-dB) bandwidth (Δf).

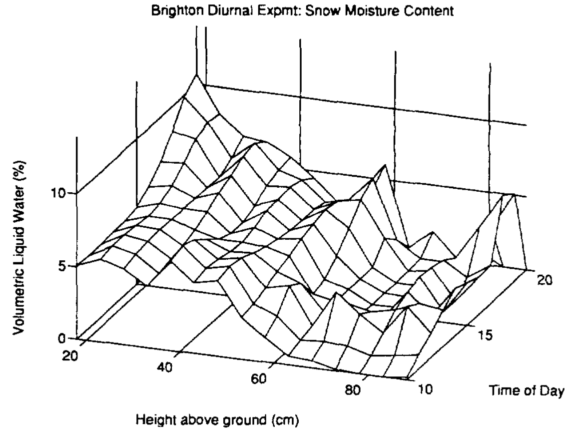

Fig. 12. Snow moisture measured via the snow probe in a 0.88-m snowpack over a diurnal cycle, shown as a function of time and height above the ground.

which are directly obtained by the snow probe: resonant frequency and bandwidth (3-dB) of the resonance spectrum. With the measurement of these two quantities, m_v and ρ_{ds} may be uniquely specified. Dry-snow density, ρ_{ds}, is related through (12) to wet-snow density ρ_{ws}.

As an example of the utility of the snow probe for elucidating snowpack character and behavior, we present in Fig. 12 snow wetness data measured for an 0.88-m deep snowpack over a diurnal cycle. During the period shown, from 10 a.m. to 8 p.m., the temperature rose from freezing to 6°C and down to −3°C again at 8 p.m.. The lowest 16-cm of the pack was solid ice; therefore measurements start at 18-cm above ground, and were made at roughly 5-cm intervals. Among the interesting features in the figure, even at 10 a.m., after subfreezing night temperatures, and while the surface is still completely dry, there is appreciable moisture deeper down in the snowpack. At the top surface, between the hours of 6 and 8 p.m., there was significant wetness which then quickly froze at about 8 p.m.

V. Summary

This paper has described the development and validation of an electromagnetic sensor and associated algorithm for the purpose of rapid (≈20 s) and nondestructive determination of snow liquid water content and density. The sensor is similar in principle to an existing device known as a "Snow Fork," but offers additional advantages in spatial resolution and accuracy owing to a novel coaxial-cavity design. Also, the algorithm employed with that device [1] for relating complex dielectric constant to snow parameters does not agree with the results of the present study. We have consequently developed new relations for that purpose.

Direct methods of snow wetness determination were evaluated for their suitability as standards against which the snow probe could be tested. The dilatometer, though simple in principle, was found to give very unfavorable performance. The freezing calorimeter, which has, as a system, been brought to a high degree of sophistication in our lab, was found capable of delivering accuracy better than ±1%, and excellent precision.

The snow probe determines the dielectric constant directly. Empirical and semi-empirical models are used with this information to compute liquid water volume fraction and density. To test the suitability of existing models and/or allow the development of new models, the snow probe was tested against the freezing calorimeter and gravimetric density determinations. Originally, The relations set forth by Hallikainen *et al.* [2] were employed to translate measured dielectric constant to snow parameters. The equation relating ϵ''_{ws} to m_v and frequency was found to be entirely valid. However, the equation predicting $\Delta\epsilon'$ in terms of m_v and frequency was found to underestimate this quantity, leading to substantial errors in the estimates of ρ_{ds}. A purely empirical relation, given in (16) was obtained instead, and will be used in our parameter retrieval algorithm for the snow probe. Through the use of these functions, in association with the complex dielectric measurements of the snow probe, the following specifications are established: liquid water content measurement accuracy ±0.66% in the wetness range from 0 to 10% by volume; wet snow density measurement accuracy ±0.05 g/cm^3 in the density range from 0.1 to 0.6 g/cm^3.

Two examples of pertinent experimental results were compared against ours: Denoth's measurements [12] at 10 MHz are very similar to ours; those reported by Tiuri *et al.* [11] at 1 GHz differ considerably from ours but agree well with the model given by (8), our own starting point. Denoth [12], noting the diversity of empirical relations for the dielectric constant of wet snow suggests that because of the influence of the shape of the water component, and the stage of metamorphism of the snow sample, "a valid simple relation between $\Delta\epsilon'$ or ϵ'' and liquid water content W may not exist." This may be the case, but the results of the present study are very consistent with results presented in [12] for the case of $\Delta\epsilon'$, and in [2] for the case of ϵ''. Accurate snow measurements of dielectric constant and liquid water content are notoriously difficult to make. This has doubtlessly been a factor in the diversity of results, and is motivation for the development of instruments such as has been the focus of this present investigation.

REFERENCES

[1] A. Sihvola and M. Tiuri, "Snow fork for field determination of the density and wetness profiles of a snow pack," *IEEE Trans. Geosci. Remote Sensing*, vol. Ge-24, pp. 717–721, 1986.
[2] M. Hallikainen, F. T. Ulaby, and M. Abdelrazik, "Dielectric properties of snow in the 3 to 37 GHz range," *IEEE Trans. Antennas Propagat.*, vol. AP-34, pp. 1329–1339, 1986.
[3] R. T. Austin, "Determination of the liquid water content of snow by freezing calorimetry," Univ. of Michigan Radiation Lab Report 022872-2, Jan. 1990.
[4] E. B. Jones, A. Rango, and S. M. Howell, "Snowpack liquid water determinations using freezing calorimetry," *Nordic Hydrol.*, vol. 14, pp. 113–126, 1983.
[5] W. H. Stiles and F. T. Ulaby, "Microwave remote sensing of snowpacks," NASA Contractor Report 3263, June 1980.
[6] S. C. Colbeck, "The layered character of snow covers," *Revs. of Geophys.*, vol. 29, pp. 81–96, 1991.
[7] D. A. Ellerbruch and H. S. Boyne, "Snow stratigraphy and water equivalence measured with an active microwave system," *J. Glaciol.*, vol. 26, pp. 225–233, 1980.
[8] A. Denoth *et al.*, "A comparative study of instruments for measuring the liquid water content of snow," *J. Appl. Phys.*, vol. 56, no. 7, 1984.
[9] M. A. H. Leino, P. Pihkala, and E. Spring, "A device for practical determination of the free water content of snow," *Acta Polytechnica Scandinavica*, Applied Physics Series No. 135, 1982.
[10] R. E. Collin, *Foundations for Microwave Engineering*. New York: McGraw-Hill, 1966.
[11] M. E. Tiuri, A. H. Sihvola, E. G. Nyfors, and M. T. Hallikainen, "The complex dielectric constant of snow at microwave frequencies," *IEEE J. Oceanic Eng.*, vol. OE-9, pp. 377–382, 1984.
[12] A. Denoth, "Snow dielectric measurements," *Adv. Space Res.*, vol. 9, no. 1, pp. 233–243, 1989.

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