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 $m_w$ suffer from various shortcomings, which include poor accuracy, long analysis time, poor spatial resolution, and/or cumbersome and inconvenient procedures. This report describes the development of an improved design of the “Snow Fork”, a hand-held electromagnetic sensor that was introduced by Sihvola and Tiuri [1], for quick and easy determination of snow liquid water content and density. The novel design of this sensor 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, from which the water content and density are obtained through the use of semi-empirical relations. To confirm the validity of these relations, it was necessary to conduct comparisons against reliable and accurate direct techniques. For liquid water determination, two direct procedures were investigated: freezing calorimetry and dilatometry. Of these only the freezing calorimeter was judged suitable. An extensive comparison study was then carried out between it and the snow probe. Through this comparison, the following specifications were established for the snow probe: (1) liquid water content measurement accuracy $= \pm 0.66 \%$ in the wetness range from 0 to 10\% by volume and (2) wet snow density measurement accuracy $= \pm 0.03$ g/cm$^3$ in the density range from 0.1 to 0.6 g/cm$^3$. In addition, it was found that the existing semi-empirical expressions relating dielectric constant to the snow physical parameters fail to agree with experimental observations when the snow liquid water content exceeds $\approx 3\%$. Accordingly, the expression was modified to correctly model the observed behavior.
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1 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., $\varepsilon_w = 88 - j9.8$ at 1 GHz [1]) relative to that of ice ($\varepsilon_i \approx 3.15 - j0.001$ [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, 6] offers the best accuracy ($\approx 1\%$) and is one of the more 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 on the order of 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 (on the order of 250 cm$^3$) is needed in order 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 [7, 8], is one of the most important parameters of a snowpack, both in terms of the snowpack hydrology and in terms of 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 (on the order of 2-3 cm) and adequate temporal resolution (on the order of a few minutes), particularly during the rapid melt and freeze intervals of the diurnal cycle. Examination of available techniques narrowed the list to two potential instruments: (a) the dilatometer, which measures the change in
volume that occurs as a sample melts completely, and (b) the "Snow Fork", which is a microwave instrument that was developed in Finland [1]. As discussed in Appendix A of the report, the dilatometer approach was rejected because of poor measurement accuracy and long measurement time (about one hour). In the process of examining the Snow Fork approach, we decided to modify the basic design in order 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 2. 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 $\rho_s$ are calculated through the use of semi-empirical relations that had been established by Hallikainen et al. [2] and by Sihvola and Tiuri [1]. To evaluate the performance of the snow probe, independent measurements of density were performed using a standard tube of known volume, whose weight is measured both empty and when full of snow, and of $m_v$ using a freezing calorimeter. One of the unexpected by-products of this study was the discovery that the semi-empirical relations developed by Hallikainen et al. [2] are not valid over the full ranges of snow wetness and density. Consequently, a modified set of expressions is proposed instead, as discussed in Section 3.

2 Snow Dielectric Probe

2.1 Snow Probe Measurement System

Figures 1 and 2 show a photograph of the snow probe measurement system, and a schematic of the same, 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 resonance frequency of the probe. The RF power transmitted thru 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
Figure 1: Photograph of snow probe system.
Figure 2: Schematic of snow probe system.
swept over with a finer step size ($\approx 1\ \text{MHz}$). The center frequency and the 3-dB bandwidth around it are found, and from these, first the dielectric constant and then the snow parameters $m_w$ and $\rho_s$ are determined according to procedures described in detail in Section 3 of this report.

2.2 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 $\lambda/4$ 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 Figure 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, ($\approx 120$ vs. $40 - 70$ 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 Figure 4.

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

$$\epsilon'_s = \left(\frac{f_a}{f_s}\right)^2. \quad (1)$$

The imaginary part of $\epsilon_s$ is determined from the change in $Q$, the quality factor of the resonator. The quality factor is defined as follows [9]:

$$Q = \frac{\omega (\text{time-average energy stored in system})}{\text{energy loss per second in system}}, \quad (2)$$
Figure 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.
Figure 4: Photograph of snow probe with cap.
and it may be determined by measuring $\Delta f$, the half-power bandwidth \[9\]:

$$Q = \frac{\Delta f}{f_o},$$ \hspace{1cm} (3)

where $f_o$ is the resonant frequency ($f_a$ or $f_s$, depending on whether the medium is air or snow). In the case of the snow probe, power losses exist due to radiation, coupling mechanisms (i.e. coupling loops), and to dissipation in a lossy dielectric. Thus the measured $Q$ is given by:

$$\frac{1}{Q_m} = \frac{1}{Q_{R_e}} + \frac{1}{Q_d},$$ \hspace{1cm} (4)

where $Q_m$ is the measured $Q$ when the probe is inserted in the snow medium, $Q_{R_e}$ is the quality factor describing both the radiation losses and the power losses due to the external coupling mechanisms for the dielectric-filled snow probe, and $Q_d$ pertains to the dielectric losses. It has been shown \[9\] that

$$\frac{1}{Q_d} = \tan \delta = \frac{\epsilon''}{\epsilon'},$$ \hspace{1cm} (5)

As can be seen from (4) and (5), in order to calculate $\epsilon''$ one must not only measure $Q_m$ and know $\epsilon'$, but the value of $Q_{R_e}$ should be available also. As long as $\tan \delta$ is very small, we may assume that $Q_{R_e}$, which is related to the power radiated by the snow probe, is a function of the real part of $\epsilon$ only. We can therefore define experimentally the functional dependence of $Q_{R_e}$ on $\epsilon'$, and then, for the actual test materials, having found $\epsilon'$ from the shift alone in the resonance curve, specify $Q_{R_e}$ and hence compute $\epsilon''$. The details of how the snow probe was characterized are given in the next sub-section.

We noted at the beginning of this section that our coaxial design for the snow probe had a considerably higher $Q$ than the original twin-prong design. Why this increases the precision of the dielectric measurements may be understood from an examination of the relations already cited in this section. A high $Q$ means a sharper resonance, and thus greater precision in determining the center frequency $f_s$, and from (1), $\epsilon'$. From equations (4) and (5) it is seen that $\epsilon''$ is determined from the contribution of the dielectric power loss to the total power loss. As the radiated power increases ( $Q_{R_e}$ decreases), the contribution of the dielectric loss becomes an increasingly smaller fraction of the total power loss. Thus a small change in dielectric loss, or equivalently, a small change in $\frac{1}{Q_d} = \tan \delta = \epsilon''/\epsilon'$, becomes more difficult to detect from the measured $Q$.
2.3 Characterization of Snow Probe

In order to compute the functional dependence of $Q_{R_e}$ on $\epsilon'$, it was necessary to determine very precisely the complex dielectric constants of a variety of materials. This was achieved using an L-band cavity resonator. The materials used were sand, sugar, coffee, wax, and of course, air. The cavity used was cylindrical in shape with a diameter of 13.9 cm and a height of 6.35 cm. Details of how the dielectric constant of a material is determined using such a cavity are given in Appendix B.

We now recall equation (4) which pertains to $Q$ of the snow probe:

$$\frac{1}{Q_m} = \frac{1}{Q_{R_e}} + \frac{\epsilon''}{\epsilon'}. $$

Once $Q_m$ is measured for our calibration materials, exact knowledge of the loss tangent for a given material allows isolation of the quantity $Q_{R_e}$. The quantity $Q_{R_e}$ is equivalent to $Q_m$ for a lossless material having dielectric constant $\epsilon'$. That is, for such a lossless material,

$$\frac{1}{Q_m} = \frac{1}{Q_{R_e}} = \frac{\Delta f_{\delta=0}}{f_r}. $$

The quantity $\Delta f_{\delta=0}$ is thus the 3-dB bandwidth of the resonance spectrum of the snow probe when immersed in a lossless material having dielectric constant $\epsilon'$. From our measurements of the five calibration materials, the quantity $\Delta f_{\delta=0}$ was found to be a linear function of the resonant frequency. Information pertaining to the analysis of the calibration materials is given in Table 1, and a plot of $\Delta f_{\delta=0}$ versus $f_r$ is given in Figure 5. Figure 5 also shows (triangles) the 3-dB bandwidths of each of the calibration materials before the effect of the dielectric losses was removed. We rewrite (4) to reflect the linear dependence of $\Delta f_{\delta=0}$ on $f_r$:

$$\frac{1}{Q_m} = \frac{\Delta f}{f_r} = \frac{mf_r + b}{f_r} + \frac{\epsilon''}{\epsilon'}, $$

where $m$ and $b$ are the slope and intercept respectively of the line in Figure 5 relating $\Delta f_{\delta=0}$ to $f_r$. Invoking (1) allows us to write,

$$\Delta f = mf_r + b + \frac{f_r^3 \epsilon''}{f_a^2} $$

(8)
Figure 5: Snow probe resonance bandwidth as a function of permittivity. Marks (Δ) represent 3-dB bandwidth of materials (lowest freq. to highest) sand, wax, sugar, and coffee. Squares represent bandwidth of resonances if materials are lossless ($\varepsilon'' = 0$).
<table>
<thead>
<tr>
<th>Material</th>
<th>$\varepsilon$</th>
<th>$f_R$ (GHz)</th>
<th>$Q_m$</th>
<th>$\Delta f_{\delta=0}$ (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>$1.0 - j0.0$</td>
<td>1.715776</td>
<td>125.2</td>
<td>13.700</td>
</tr>
<tr>
<td>Sand</td>
<td>$2.779 - j3.7e^{-2}$</td>
<td>1.036</td>
<td>51.7</td>
<td>6.245</td>
</tr>
<tr>
<td>Sugar</td>
<td>$1.984 - j7.778e^{-3}$</td>
<td>1.22947</td>
<td>89.3</td>
<td>8.947</td>
</tr>
<tr>
<td>Coffee</td>
<td>$1.497 - j3.32e^{-2}$</td>
<td>1.43125</td>
<td>30.4</td>
<td>15.339</td>
</tr>
<tr>
<td>Wax</td>
<td>$2.26 - j2.9e^{-4}$</td>
<td>1.150308</td>
<td>137.0</td>
<td>7.853</td>
</tr>
</tbody>
</table>

Table 1: 3-dB bandwidth of Snow Probe as a function of $\varepsilon_r$ (real part of permittivity).

where $f_a$ is the resonant frequency of the device in air. We have made use of (8) in Figure 5 to generate curves of $\Delta f$ for particular values of $\varepsilon''$.

It is clear from (7) that, given a measured $Q_m$ and resonant frequency $f_R$, and given knowledge of the constants $m$ and $b$, $\varepsilon''$ may be directly calculated as follows:

$$\varepsilon'' = \left(\frac{f_a}{f_R}\right)^2 \left[\frac{1}{Q_m} - (m + \frac{b}{f_R})\right].$$

The determination of the function parameters $m$ and $b$ therefore constitutes the “calibration” of the probe. In general, we expect this calibration to be valid as long as nothing occurs which might affect the radiating or power input/output characteristics of the device. However, if we assume that the function of $\Delta f_{\delta=0}$ versus $f_r$ is always a linear one, re-calibration may be performed at any time by measuring just two materials for which the dielectric constant is known exactly. In practice, we calibrate the device daily when used, by measuring air and heptane ($\varepsilon = 1.925 - j0.8 \times 10^{-4}$). Generally the calibration coefficients are reproduced quite closely, and the daily calibration is done mainly as a precaution. A typical calibration curve is,

$$\Delta f(\text{MHz}) = 8.381 \times f(\text{GHz}) + 0.7426$$

The determination of dielectric constant with the snow probe is summarized as follows: parameters $m$ and $b$ are obtained by measuring the $Q$ of two materials of known dielectric constant (air and heptane) and then applying (8); $\varepsilon'$ is obtained from the shift in resonance relative to air (equation (1)); and finally, $\varepsilon''$ is computed from (9).
2.4 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 (Figure 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 (30cm × 30cm) 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 (≈ 25 cm square) was inserted into the sugar, parallel to and resting against one side of the box. The dielectric constant was re-measured. 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 Figure 6, in which $\varepsilon''$ 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 centimeters. To put this variation into perspective, had the material been snow, and using the relations given in section 3.1, 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 Figure 6) 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 on the order of 2 cm when the snow probe is inserted into the snowpack horizontally (the snow probe cross section is 1cm × 1cm).

3 Liquid Water Content and Density Retrieval

3.1 Procedure

The volumetric liquid water content, $m_v$, and the snow density $\rho_s$ can be calculated from the complex dielectric constant $\varepsilon$ (and knowledge of the exact frequency at which it was measured) using a set of semi-empirical relation-
Figure 6: Variation in measurement of $\varepsilon''$ of sugar as a function of sensor proximity to metal plate. (Real part $\varepsilon'$ stayed in the range 2.00 - 2.01.)
ships [1, 2]. These equations are:

\[
\epsilon'_{ds} = 1 + 1.7 \rho_{ds} + 0.7 \rho_{ds}^2
\]

\[
\Delta \epsilon'_{ws} = \epsilon'_{ws} - \epsilon'_{ds} = 0.02 m_v^{1.015} + \frac{0.073 m_v^{1.31}}{1 + (f/f_w)^2}
\]

\[
\epsilon''_{ws} = \frac{0.075(f/f_w)m_v^{1.31}}{1 + (f/f_w)^2}
\]

where:

\[
\epsilon'_{ds} = \text{the real part of the dielectric constant of dry snow},
\]

\[
\rho_d = \text{the “dry density” of snow, which would result if all the volume occupied by water was replaced with air},
\]

\[
\epsilon'_{ws} = \text{the real part of wet-snow dielectric constant}
\]

\[
\epsilon'_{ds} = \text{the real part of dry-snow dielectric constant},
\]

\[
m_v = \text{the volumetric liquid water content (%),}
\]

\[
f_w = 9.07 \text{ GHz (related to relaxation frequency of water at 0° C)},
\]

\[
f = \text{frequency (GHz) at which } \epsilon''_{ws} \text{ is determined.}
\]

Equation (11), from [1], relates the real part of the dielectric constant of dry snow to its density. Equations (12) and (13), from [2], are semi-empirical Debye-like equations.

Upon measuring \( \epsilon''_{ws} \) (by the snow probe), \( m_v \) can be calculated directly from (13):

\[
m_v = \left\{ \frac{\epsilon''_{ws} [1 + (f/f_w)^2]}{0.075(f/f_w)} \right\}^{1/31}.
\]

Note that (13) basically relates \( \epsilon''_{ws} \) to the imaginary part of the dielectric constant of water, \( \epsilon''_w \), scaled by its volume fraction in the snow mixture, \( m_v \). This follows from the fact that \( \epsilon''_a = 0 \) for the air constituent and \( \epsilon''_i \) of the ice constituent is several orders of magnitude smaller than \( \epsilon''_w \) of water.

From (11) and (12) we may compute \( \epsilon'_{ds} \) as follows:

\[
\epsilon'_{ds} = \epsilon'_{ws} - 0.02 m_v^{1.015} - \frac{0.073 m_v^{1.31}}{1 + (f/f_w)^2}.
\]

Then from (11) and (15) we can compute \( \rho_{ds} \) from the quadratic equation:

\[
\rho_{ds} = -1.214 + \sqrt{1.474 - 1.428(1 - \epsilon'_{ds})},
\]
in which only the positive root is considered.

The dry snow density $\rho_{ds}$, and the volumetric liquid water content $m_v$ (\%) are related to the wet snow density $\rho_{ws}$ by [4]:

$$\rho_{ws} = \rho_{ds} + \frac{m_v}{100}. \quad (17)$$

3.2 Results

Since the physical snow parameters yielded by the snow probe are the results of empirical and semi-empirical equations, it was necessary to see how closely the snow probe reproduced the results obtained from well-established direct techniques. The parameters tested were density and liquid water content. The direct techniques used were a simple gravimetric density measurement and freezing calorimetry for liquid water.

It should be noted that the relations used with the snow probe (given in (11), (12), and (13)) deal with liquid water volume fraction, $m_v$. The freezing calorimeter, however, produces liquid water mass fraction ($W$) as its output. In order to compare $m_v$ as measured by the snow probe with $W$ as measured by the freezing calorimeter, we need to use the relation,

$$m_v = 100 \times \rho_s W \quad (18)$$

where $m_v$ is volumetric liquid water expressed in percent, and $\rho_s$ is the density of the snow. In our tests, we have converted the freezing calorimeter results to volume fractions using the gravimetrically determined density and (18).

3.2.1 Liquid Water Content

The results for the liquid water content comparison are shown in Figure 7. The error bars associated with the freezing calorimeter data points show the range of results obtained 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 is seen to have generally excellent precision.

The values for $m_v$ obtained from the snow-probe dielectric measurements are computed using equation (13). 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
Figure 7: Comparison of snow wetness results obtained \textit{via} snow probe (marks) and freezing calorimetry respectively. Snow probe data points are based on an average of twelve separate measurements.
value as represented by the error bars was computed as $\pm \sigma/\sqrt{N}$ where $\sigma$ is the standard deviation of the set of measurements and $N$ is the number of measurements in that set. From the figure, it is seen that 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 (13) give results which are within $\pm 0.5\%$ of the freezing calorimeter results. This result strongly supports the validity of equation (13).

3.2.2 Density

The outputs of equations (12) and (11), with dielectric information supplied by our sensor, were compared with the results of gravimetric density measurements. The comparison was conducted over a density range extending between 0.1 and 0.55 g/cm$^3$. The results are shown in Figure 8. It is seen that, with the exception of a single outlier, excellent agreement is obtained for the cases where the snow volumetric wetness level was < 3%. In contrast, density estimates made via (12) and (11) when snow wetness exceeded 3% departed markedly from the gravimetric measurements.

The procedure for the retrieval of density, outlined in Section 3, employs a conceptual quantity $\Delta \epsilon_{ws}'$ (Eq. (12)), which is defined to be a measure of the increase in the real part of the dielectric constant of snow, relative to that for dry snow, which would occur if some of the air in the snow medium was replaced by liquid water. Application of (12) to measured values of $\epsilon_{ws}'$ then allows determination of a theoretical $\epsilon_{ds}'$, from which, using (16), a theoretical dry-snow density, $\rho_{ds}$, may be determined. Wet-snow density, $\rho_{ws}$, is then related to $\rho_{ds}$ using (17).

The quantity $\Delta \epsilon_{ws}'$ is a function of both the resonant frequency $f_r$ and $m_v$. Across the frequency range over which the snow probe operates ($\approx 0.9 - 1.7$ GHz), $\epsilon'$ is approximately constant for both water and ice. Hence, $\Delta \epsilon_{ws}'$ may be examined as a function of $m_v$ alone. This function is plotted in Figure 9. Also included are experimental quantities which were generated by taking the difference between measured values of $\epsilon_{ws}'$ (averages of typically twelve independent snow probe measurements) and calculated values of $\epsilon_{ds}'$, determined through the use of (17) and (11). The solid curve drawn through the experimental quantities is seen to diverge from the behavior predicted by (12), for $m_v > 2.5\%$. 

17
Figure 8: Comparison of snow density results obtained via snow probe (with associated relations) and gravimetric measurements. Data points represented with squares were from snowpacks having volumetric wetness levels of $>3\%$; with circles, $<3\%$. 
Figure 9: $\Delta \varepsilon'_w$ (computed using snow probe-measured $\varepsilon'_w$, snow probe-determined $m_u$, and gravimetrically measured $\rho_w$) versus $m_v$ (snow probe-determined).
This curve is produced by the following function, which is based on the original formula but which is consistent with the observed behavior:

\[
\Delta \varepsilon'_{ws} = \varepsilon'_{ws} - \varepsilon'_{ds} = 0.02m_v^{1.015} + \frac{0.073m_v^{1.31}}{1 + (f/f_o)^2} + [0.155 + 0.0175(m_v - 2.5)] \{1 + (2/\pi) \tan^{-1}[4(m_v - 2.5)]\}
\]

(19)

This function accommodates the essential discontinuity which exists in the data in the neighborhood of \(\approx 2.5\%\). Note the data points shown in the figure follow this functional form given in (19) independent of density. As an example, the two data points corresponding to \(\approx 4.5\%\) liquid water had densities of 0.19 and 0.55 respectively—yet they still exhibit an incremental \(\Delta \varepsilon'_{ws}\) according to (19). Having derived (19) from the measured data, we have produced a formula relating measured dielectric constant and snow density which is valid in the region 0.1 to \(\approx 0.6 \text{ g/cm}^3\). The sensor data, re-processed using (19) and (11) is compared against the gravimetric data in Figure 10. It is seen that over the range examined, with the exception of one outlier at \(\rho \approx 0.34\), the snow probe method agrees with the gravimetric method to within \(\pm 0.03 \text{ g/cm}^3\).

The concept of dry-snow density \(\rho_{ds}\), as understood in the above context, is a conceptual quantity which cannot be measured. Its use is motivated by a desire to attach a physical basis to the dielectric behavior of wet snow; that just as \(\varepsilon''_{ws}\) may be understood in terms of the dispersion behavior of water, so may the behavior of \(\varepsilon'_{ws}\) be understood, as an addition of a quantity based on the dispersion behavior of the real part of the dielectric constant of water, namely equation (12), to \(\varepsilon'_{ds}\), for which a reliable empirical model exists. The results from the present investigation indicate that the physical reasoning put forth to explain the behavior of \(\varepsilon'_{ws}\) is incomplete; that there are important factors in addition to the real part of the dielectric constant of the water itself.

That there exists, or should exist, an abrupt transition in the dielectric constant of snow as a function of moisture is an idea which has been cited by previous researchers. Colbeck [13] describes a transition between the pendular regime, wherein “air occupies continuous paths throughout the pore space”
Figure 10: Comparison of snow density results obtained via snow probe (with associated modified relations) and gravimetric measurements. Data points represented with squares were from snowpacks having volumetric wetness levels of > 3%; with circles, < 3%.
and the *funicular* regime, wherein liquid water "occupies continuous paths throughout the pore space". Denoth [14] estimated this transition at 11 to 15% of the pore volume, which would correspond to 7 to 10% of the total volume for an average snow sample have density 0.3 g/cm$^3$.

Another description, attributed to Colbeck by Hallikainen et al. [2], suggests that such a transition occurs when liquid water inclusions in snow transform from being primarily needle-shaped (at low values of liquid water content) to being primarily disk shaped. In [2], snow dielectric constant data in the 3 to 37 GHz range was analyzed using Polder Van Santen mixing models. It was concluded that the shape factors in the models which provided the best fit to the data supported the concept of a needle-to-disk transformation of the water inclusions. The two-phase Polder Van Santen model with the shape factors (or depolarization coefficients) specified in [2] was applied to the current snow probe data. It was found however to give a result very comparable to the Debye-like model (Equ. 12), that is, it predicts no transition.

4 Conclusion

This report has described the development and validation of an electromagnetic sensor and associated algorithm for the purpose of rapid ($\approx 20$ seconds) and non-destructive determination of snow liquid water content and density. The sensor is similar in principle to an existing device known as a “Snowfork”, but offers additional advantages in spatial resolution and accuracy owing to a novel coaxial-cavity design.

Direct methods of snow wetness determination were evaluated for their suitability as standards against which the device 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 $\pm 1\%$, and excellent precision.

The snow probe determines the dielectric constant directly. Empirical and semi-empirical models use this information to compute liquid water volume fraction and density. To test the suitability of these models, the snow probe was tested against the freezing calorimeter and gravimetric density determinations. In general, excellent agreement was obtained: liquid water
measurement accuracy ±0.66 % in the wetness range from 0 to 10% by volume; wet snow density measurement accuracy ±0.03 g/cm³ in the density range from 0.1 to 0.6 g/cm³. The relations employed to translate measured dielectric constant to snow parameters were those set forth by Hallikainen [2]. The equation relating \( \epsilon''_{ws} \) to \( \rho_{vs} \) and frequency was found to be entirely valid. However, the equation predicting \( \Delta \epsilon'_{ws} \) in terms of \( \rho_{vs} \) and frequency failed to take into account an abrupt increase in \( \epsilon'_{ws} \) which occurs in the range of \( \rho_{vs} \) equal to 2.5 to 3%. This failure results in very large errors in the estimate of density. The formula was accordingly modified (equation (19)) to correctly model the observed effect.

Figure 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 \( \rho_{ds} \) and \( \rho_{ds} \) respectively, in a 2-dimensional representation bounded by the two parameters 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, \( \rho_{vs} \) and \( \rho_{ds} \) may be uniquely specified. Dry-snow density, \( \rho_{ds} \), is related thru (17) to wet-snow density \( \rho_{ws} \).
Figure 11: Nomogram giving snow liquid water content ($m_v$) and equivalent dry-snow density ($\rho_{ds}$) in terms of two parameters directly measured by the snow probe: resonance frequency ($f$) and resonance (3-dB) bandwidth ($\Delta f$).
References


APPENDIX A: Evaluation of Dilatometer and Freezing Calorimeter

A.1 Dilatometer Evaluation

Attracted by the simplicity of the concept, apparatus, and procedure, we expended considerable effort in evaluating the dilatometer technique. As we ultimately rejected it as a result of its poor performance in determining liquid water content, we will not go into the details of the apparatus itself; a complete description is provided in [12] for those interested. Instead, we will just briefly describe the method and then present some of the drawbacks that led us to reject the method.

In the method, a weighed snow sample is placed in a cooled (0°C) jar, and then the jar is completely filled with 0°C water. A lid with a graduated tube is fixed onto the jar, and the tube itself is filled with freezing water and the level noted. The jar is placed in a warm water bath to melt the snow and then the entire system is returned to a temperature very close to 0°C. The change in the volume is related to the mass of ice present, and subtracting this from the original snow mass gives the mass of water in the snow sample.

The principal drawbacks we found were the following:

- Lack of accuracy due to non-ideal behavior of the materials. We tried the following experiment: we filled the apparatus entirely up with 0°C water (no snow or ice) and cycled the temperature up and then back down as described above. In each of several trials, the volume of the water (which should have returned to its original value, about 1 liter) was found to have increased by about 0.1%, enough to cause a very significant error in an actual trial. In quantitative terms, if a 75 gram sample of snow having 5% water mass fraction was analyzed, it would appear that the sample had 20% water mass fraction. We believe this volume expansion effect may be caused by gases that are liberated when the cold water is warmed. Additional slight but critical volume changes may be caused by expansion or contraction of any of the parts of the dilatometer apparatus.

- Long analysis time. The snow, once added, can be melted relatively quickly by warming the system. However, to return back to 0°C (which
is absolutely critical to avoid unwanted volume changes in the system) the wait required is on the order of one hour. The reason is that, unlike the warming case, for the cooling there is a relatively small temperature gradient. The bath can be no less then 0°C; so when the temperature gets down to 5 or 6°C, there is very little gradient to drive it down further.

A.2 Freezing Calorimeter Evaluation

As noted earlier, the theoretical background and the procedural details of the freezing calorimeter method are thoroughly discussed in a previous Radiation Lab report [6]. Since that report was written, there have been several major improvements made in the freezing calorimeter system:

- A second calorimeter was constructed, identical to the first, to allow for duplicate measurements to be done in parallel.

- A motorized tripod-mounted mechanical shaker was constructed which is capable of shaking both calorimeters simultaneously.

- The system has been made PC–based. Software was written which handles two calorimeter channels independent of one another. Data from each channel is collected, displayed, and reduced automatically by the computer.

The method, with these improvements, was tested for precision and accuracy. To our knowledge, it is the first time a systematic test of the method precision and accuracy has been performed.

The accuracy of the method was tested at three different levels of wetness. We prepared a sample of snow with zero wetness by placing it in a freezer at −20°C for several hours. Four separated analyses were performed on the snow from this batch. To test at two other wetness levels, at the point in the procedure where the lid is removed from the calorimeter and snow added, we added—in addition to the zero-wetness snow from above—a precisely measured volume of water at exactly 0°C. In this way, we “spiked” dry snow samples at levels corresponding to 5% and 11% liquid water mass fraction. Each case was analyzed in duplicate. The results of the accuracy tests performed at these three levels are shown in Figure A.1. Shown is
Figure A.1: Calorimeter accuracy tested at three different levels of water content. Data is normalized so all results are compared to what actual level was calculated to be in each case. The two points marked “suspect” correspond to analyses noted at the time of execution as problematic.
the degree to which the experimental results deviated from the known mass fractions. Two results, one at the 0% level and one at the 11% level, come from analyses which were noted as problematic at the time of analysis, and are marked as "suspect". From these tests, it appears that the method is accurate to a level somewhat better than ±1%.

The precision of the method was clearly observed since all analyses were done in duplicate. From the results shown in Figure A.1 and the results which will be seen in the next section wherein the calorimeter is compared to the snow probe, it seems that the precision is on the order of ±0.5%.
APPENDIX B: Resonant Cavity Measurements of Dielectric Constant

The L-band cavity used for the present study was a cylindrical, transmission-type resonator, with diameter 13.9 cm and depth 6.35 cm. The $TM_{010}$ mode is resonant at 1.64618 GHz and the loaded (measured) $Q$ for the air-filled cavity was $\approx 3750$. To insure reliable, reproducible performance, the cover of the resonator was always fixed on using a torque wrench (60 ft-lbs) and following a prescribed pattern in tightening the screws.

In the most general case, the quality factor of a resonant system is given as follows:

$$\frac{1}{Q_l} = \frac{1}{Q_u} + \frac{1}{Q_{ext}} \quad \text{(B.1)}$$

where, $Q_l$ is the loaded $Q$, $Q_u$ is the unloaded $Q$, and $Q_{ext}$ the external $Q$. The unloaded $Q$ is the "real" $Q$ of the resonator but it is possible to measure it directly. The coupling devices (loops, probes) used to couple power in and out of the resonator also contribute to power leakage out (represented by $Q_{ext}$) which is a source of loss not inherently related to the resonator itself or its contents. The reciprocal of $Q_u$ may be written as the sum:

$$\frac{1}{Q_u} = \frac{1}{Q_R} + \frac{1}{Q_d} + \frac{1}{Q_m} \quad \text{(B.2)}$$

where $Q_R$ is, as before, related to the radiated losses, $Q_d$ to the dielectric losses, and $Q_m$ to the losses associated with the metal walls of the resonator having a finite conductivity. For a closed resonator, as ours is, the radiated losses are zero and we need not consider $Q_R$. Also, for the empty (air-filled) resonator, $Q_d$ is not considered. Furthermore, it can be demonstrated [10] that for a resonator filled with a dielectric $\epsilon$,

$$\frac{1}{Q_m} = \frac{\sqrt{\epsilon}}{Q_{mo}} \quad \text{(B.3)}$$

where $Q_m$ is associated with the metal losses in the dielectric-filled cavity, and $Q_{mo}$ with the metal losses in the air-filled cavity. From (5) the loss tangent $\tan \delta$ may be found from $Q_d$ which may in turn be obtained if $Q_u$ as given in (B.2) may be found and (B.3) is also used. The problem then becomes how,
upon measuring $Q_I$ (see equation (B.1)), may $Q_u$ be determined? For the most general case of the input and output coupling networks being different, Altschuler ([11]) describes a general impedance method for determining $Q_u$ from $Q_I$. If it is assumed that the input and output coupling networks are equivalent, then $Q_u$ can be directly calculated [10] from measurements of $Q_I$ and the insertion loss $a_r$ at the resonant frequency as follows:

$$Q_u = \frac{Q_I}{1 - \sqrt{a_r}}.$$  \hspace{1cm} (B.4)

For our L-band cavity, it was found that the simple method above gave very comparable results to the general impedance method in all cases. It is noted that the general impedance method detailed in [11] is considerably more involved than that given by (B.4).

Based on the above discussion, the procedure for determining dielectric constants with a resonant cavity is summarized as follows:

- Real part of dielectric is found in the same way as given in equation (1), using the resonant frequencies of the dielectric-filled and air-filled cavity.

- Imaginary part of dielectric requires determination of $Q_u$. Then for the case of equivalent input and output coupling factors, equations (5),(B.3), and (B.4) lead to,

$$\epsilon'' = \epsilon' \left\{ \frac{1}{Q_I} \left[ 1 - \sqrt{a_r} \right] - \frac{\sqrt{\epsilon'}}{Q_{mo}} \right\}$$  \hspace{1cm} (B.5)

where

$$\frac{1}{Q_{mo}} = \frac{1}{Q_{lo}} \left[ 1 - \sqrt{a_{ro}} \right] = \frac{1}{Q_{lo}} - \frac{1}{Q_{ext,o}}$$  \hspace{1cm} (B.6)

where the “o” in the subscripts refers to quantities associated with the air-filled cavity.
APPENDIX C: Snow Probe Program Listing

This appendix contains the computer program used in conjunction with the snow probe. It is written in HP Basic. See Section 3.4 for additional details of the snow probe system.

```basic
2 ! Program SNOWFORKB!
3 OPTION BASE 1
4 COM /Flag/Qflag,Cal_flag
5 COM /Values/Fstart,Prl,Det_max
6 COM /Addr/@Swp,E0vm
7 COM /Cal_vlds/Mslope,B_cept,F_air
8 COM /File_info/F_flag,Stars$(15),F_name$(12),@Path1,Dumm
9 COM /Line_loss/Patep,Pfrc,Pflag
10 MASS STORAGE IS "SNOWFORB:\CS80,700,0"
12 INITIALIZE ",", ,9 !CREATE MEMORY VOLUME TO HOLD FILE.
13 STORE KEY "KEY.DEFS," !STORE KEY DEFS'S IN FILE "KEY.DEFS"!
14 DIM A$(23)(1) !REDEFINE ALL KEYS TO Undefined.
15 SET KEY 0,A$(*) !REDEFINE ALL KEYS TO Undefined.
16 CLEAR SCREEN
17 ON KEY 0 LABEL "TAKENDATA" CALL Takedata
18 ON KEY 1 LABEL "CALIBRATES" CALL Calibrate
19 ON KEY 9 LABEL "QUIT" CALL Quit
20 ON KEY 3 LABEL "CREATE_FILE" CALL Create_file
21 ON KEY 4 LABEL "CLOSE_FILE" CALL Close_file
22 ON KEY 5 LABEL "PWR_LVL" CALL Prer_lvl
23 ON KEY 6 LABEL "START_FREQ" CALL Start_freq
24 !ON KEY 8 LABEL "SAMPLE_RATE" CALL Rate
26 !ON KEY 8 LABEL "CAL_LINE_LOSS" CALL Cal_line
27 KEY LABELS ON
28 ON ERROR RECOVER Getfree
30 PLOTTER IS CRT,"INTERNAL"
31 Pflag=0
32 Patep=2.09* .01
33 Dumm=10
34 Fstart=.95
35 Prer=0
36 Mslope=4.53
37 B_cept=5.36
38 F_air=1.663
39 PRINT "CURRENTLY, Mslope = ";Mslope; " B_cept = ";B_cept
40 PRINT "AND, F_air = ";F_air
41 F_flag=0 ! Denotes no file opened yet.
42 Cal_flag=0 ! Denotes Cal not in progress.
43 Stars$="***************" ! Dividers between file entries.
44 Qflag=0
```

C-1
Choose:  !
INPUT "WHICH DETECTOR (1,2, OR 3)?", Detect
SELECT Detect
CASE 1
   Det_max=.00500
CASE 2
   Det_max=.00089
CASE 3
   Det_max=.00056
CASE ELSE
   BEEP
   PRINT "INVALID CHOICE"
   GOTO Choose
END SELECT
ASSIGN @Dvm TO 702
ASSIGN @Sep TO 719
OUTPUT @Sep;"IP"
WHILE Qflag<>1
END WHILE
LOAD KEY "KEY_DEF$;0" ! RELOAD OLD KEY DEF$.
INITIALIZE ":,0",0 ! RECLAIM MEMORY VOLUME STORAGE.
Getfree:  !
IF F_flag=1 THEN ASSIGN @Path1 TO ✫
PRINT "Program Exit"d"
END
!
SUB TakeData
REAL B(1:250)
DIM Comment$[200]
COM /Line_loss/ Pstep,Pfrac,Pflag
COM /Addr/ @Sep,@Dvm
COM /Values/ Pstart,Purl,Det_max
COM /Results/ E1,E11,F0,Q,Mv,Pus
COM /Cal_vals/ Mslope,B_cept,F_air
COM /File_info/ F_flag,Stars$,F_name$,@Path1,Dumm
COM /Flag/ Qflag,Cal_flag
COM /Samp_rate/ Srate$[2]
Comment$=""
IF Cal_flag=1 THEN GOTO Jump1
IF F_flag=1 THEN
   PRINT "Current comment is:";
   PRINT Comment$
   INPUT "Enter comment or description if desired:"; Comment$
   PRINT "Press continue to take data:";
   PAUSE
END IF
Jump1:  !
GEDIT
GRAPHICS ON
GCLEAR
CLEAR SCREEN
N=80
FOR I=1 TO 250
   B(I)=0
C-2
101 NEXT I
102 !Pstep=INT(.209*.01/.006)*.006
103 !INPUT "ENTER POWER STEP:";Pstep
104 Pstep=.067
105 OUTPUT GSpw:"PL";Pwrl:"DM CW";Fstart:"GZ SF10MZ"
106 ! Instrument preset: power 0 dBm, start @ fstart GHz,
107 ! step size = 10 MHz.
108 ! OUTPUT @Dvm;"TL F1 R-2 M3 Z0 D3"!Int. trig., DC volts,
109 ! 30 mV DC, 3.5 digits, autozero off, display off.
110 !
111 ! DIFFERENT CMD FOR FLUKE 8842A METER:
112 OUTPUT @Dvm;"* TO F1 R5 S2 DO"!Int. trig., DC volts,
113 ! 20mV DC, fast aqu., display off.
114 !
115 VIEWPORT 10,120,25,75
116 FRAME
118 !WINDOW 1,84,-9.8E-3,1.2E-2
119 WINDOW 1,84,-5*Det_max,1.5*Det_max
120 FOR I=1 TO 84
121 ENTER @Dvm;Dum
122 B(I)=Dum
123 !OUTPUT @Spw;"PL UP CW UP"
124 OUTPUT @Spw;"UP"
125 PLOT I,B(I)
126 !PRINT B(I)
127 NEXT I
128 Bmax=MAX(B(I))
129 !PRINT "Max value:";Bmax
130 !GOTO Jump3
131 !
134 Delta=B(84)/Bmax !FRACTION OF ATTN.
135 Fdelta=.84 !gHz
136 Pfrac=Delta/Fdelta
137 IF Pflag=1 THEN
138 SUBEXIT
139 END IF
140 K=1
141 WHILE B(K)<Bmax
142 K=K+1
143 END WHILE
144 Freq=Fstart+(K-1)*.010
145 F1=Freq-.06
146 Ss=120/W
147 !Pstep=Pstep*.0015/.01
148 OUTPUT @Spw;"PL";Pwrl:"DM CW";F1;"GZ SF";Ss;"GZ"
149 !
150 FOR I=1 TO 250
151 B(I)=0
152 NEXT I
154 ! OUTPUT @Dvm;Brate$
155 FOR I=1 TO W/2
156 ENTER @Dvm;Dum
157 ! B(I)=Dum+(I-1)*.001*1.17E-2
158 B(I)=Dum
159 OUTPUT @Spw;"UP"

C-3
OUTPUT @Sw;"UP"

NEXT I

! Adjust power level for optimum snr:

! P_level=10^((Pwrl/10)

Pwrl=P_level*(Det_max/Bmax)

Pwrl=10*Log10(Pwrl)

Pwrl=INT(Pwrl/.004)*.004+10

OUTPUT @Sw;"pl":Pwrl;"DM CW";F1;"0Z"

! OUTPUT @Dvm;$rate$

FOR I=1 TO N

ENTER @Dvm:D um

B(I)=D um+(I-1)*.001+1.117E-2

B(I)=D um

OUTPUT @Sw;"UP"

NEXT I

Pwrl=3

OUTPUT @Sw;"PL":Pwrl;"DM"

Bmax=MAX(B(1))

Half=Bmax/2

K=1

Btest=B(1)

IF (Btest>Half) THEN

PRINT "Leading edge of peak not in bracketed region."

PRINT "Press Continue to proceed."

PAUSE

CLEAR SCREEN

GCLEAR

GOTO Jump3

ENDIF

WHILE Btest<Half

K=K+1

Btest=B(K)

ENDIF

WHILE Half<B(K)>

K=K+1

ENDIF

WHILE B(K)<Bmax

K=K+1

ENDIF

! Find out if there are duplicate max pts., if so, choose

! center one.

K1=K

WHILE B(K1)=Bmax

K1=K1+1

C-4
217  END WHILE
218  K=1NT((K+1)/2)
219  F0=F1+((K-1)*Ss
220  K=K
221  Btest2=B(Kk)
222  WHILE Btest2>Half
223    K=K+1
224    Btest2=B(Kk)
225    IF (Kk=M+1) THEN
226      PRINT "Trailing edge of peak not in bracketed region."
227      PRINT "Press Continue to proceed."
228      PAUSE
229      CLEAR SCREEN
230      GCLEAR
231      GOTO Jump3
232  END IF
233  END WHILE
234  IF Btest2=Half THEN
235    F3db=F2+F1+(Kk-1)*Ss
236  ELSE
237    Delta=(Half-B(Kk-1))/(B(Kk)-B(Kk-1))
238    F3db=F1+(Kk-2*Delta)*Ss
239  END IF
240  Khalf=(F3db-F1)/Ss
241  Khalf=Khalf+1
242  Khalf2=(F3db2-F1)/Ss
243  Khalf2=Khalf2+1
244  ! COMPUTE Q:
245  Fdelt=ABS(F3db-F3db2)
246  Q=F0/Fdelt
247  !
248  ! CALCULATE COMPLEX DIELECTRIC CONSTANT,
249  ! AND COMPUTE SNOW MOISTURE AND DENSITY.
250  !
251  E1=(F_air/F0)^2
252  Beta=Mslope*FO+B_cdept
253  E11=E1^((1/3)-Beta/(F0+1000))
254  IF E11<0 THEN E11=0
255  !
256  ! COMPUTE LIQUID WATER VOL. FRAC & DENSITY.
257  !
258  A1=FO/9.07
259  Mv=(E11*(1+A1^-2)/(.075*A1))^-1/(1.31)
260  Eds=E1-.02*Mv-.015-.073*Mv"1.31/(1+A1^-2)
261  Neweds=E1-.25*SQRT(Mv-.25*(A1*Mv"1.8/(1+A1^-2)
262  Newpds=1.214*(1.474-1.428*(1-Neweds))^-1/(2)
263  Newpw=Mv/100+Newpds
264  Pds=1.214*(1.474-1.428*(1-Eds))^-1/(2)
265  Pws=Mv/100+Pds
266  GCLEAR
267  VIEWPOINT 10,120,25.75
268  FRAME
269  WINDOW 1,5,0,1.1*Max
270  FOR I=1 TO N
271    PLOT I,B(I)
MOVE X,Bmax
LABEL "x"
MOVE Khalf,Half
LABEL "x"
MOVE Khalf2,Half
LABEL "x"
PRINT "Center Freq. = ":,FO
PRINT "Q = ":,Q
PRINT "Dielectric Constant":,El,"-j",El1
PRINT "mv = ":,Mv
PRINT "Wet snow density = ":,Pws,"Bmax = ",Bmax
PRINT "OR (revised) density = ":,NewPws
MOVE 0,-Bmax
IF Cal_flag=1 THEN GOTO Jump3
IF F_flag=1 THEN
  INPUT "Store this data (Y/N)?",Ans$1
  IF (Ans$1="Y" OR Ans$1="y") THEN
    CLEAR SCREEN
    GCLEAR
    OUTPUT @Path1;FNP$(Dumm+1)@TIME$(TIMEDATE)
    OUTPUT @Path1;FNP$(Dumm+2)@"Comment: "@Comment$
    OUTPUT @Path1;FNP$(Dumm+3)@"Res. Freq.: "@VAL$(FO)
    OUTPUT @Path1;FNP$(Dumm+4)@"Q: "@VAL$(Q)
    OUTPUT @Path1;FNP$(Dumm+5)@"Dielectric const.: "@VAL$(El1)$
       "- j"@VAL$(E11)$
    OUTPUT @Path1;FNP$(Dumm+6)@"mv : "@VAL$(Mv)
    OUTPUT @Path1;FNP$(Dumm+7)@"Wet density: "@VAL$(Pws)$
       "(REvised)"@VAL$(NewPws)
    OUTPUT @Path1;FNP$(Dumm+8)@"DET_MAX: "@VAL$(Det_max)$
       and B_max = "@VAL$(Bmax)
    OUTPUT @Path1;FNP$(Dumm+9)@"Stars$
    Dumm=Dumm+9
  END IF
  END IF
Jump3:
SUBEND
!
!
SUB Quit
COM /Flag/ Qflag,Cal_flag
Qflag=1
GCLEAR
SUBEND
!
!
SUB Calibrate
COM /Avg$ /Fs,Gs,Fs,Ge,Caltype
COM /Cal_vlvs/ Mslope,B,cepe,F,air
COM /Flag/ Qflag,Cal_flag
COM /File_info/ F_flag,Stars$,F_name$,@Path1,Dumm
PRINT "May read in most recent cal parameters or re-calibrate."
INPUT "Do you wish you read in old values (y/n)?",Ans$
IF (Ans$1="y" OR Ans$1="y") THEN
ASSIGN @Path_2 TO "CALVALS"
ENTER @Path_2;Mslope,B_cept,F_air
ASSIGN @Path_2 TO *
PRINT "New values of mslope, b_cept, and f_air are:
PRINT Mslope,B_cept,F_air
END IF
OFF KEY
ON KEY 1 LABEL "HEPTANE",3 CALL Sugar
ON KEY 2 LABEL "AIR",3 CALL Air
ON KEY 3 LABEL "ESCAPE",3 CALL Quit
ON KEY 4 LABEL "COMPUTE",3 CALL Compute
WHILE Qflag<>1
END WHILE
! RESET QFLAG.
Qflag=0
IF F_flag=1 THEN
INPUT "Store cal data to file (Y/N)?",Answ$ IF (Answ$="Y" OR Answ$="y") THEN
OUTPUT @Path1;FNFr$(Dumm+1)@TIME$(TIMEDATE)
OUTPUT @Path1;FNFr$(Dumm+2)@"HEPTANE: "+VAL$(Fe)" ,"VAL$(Qe)
OUTPUT @Path1;FNFr$(Dumm+3)@"air: "+VAL$(Fa)" ,"VAL$(Qa)
OUTPUT @Path1;FNFr$(Dumm+4)@"BW = "VAL$(Mslope)" x f + "VAL$(B_cept)
OUTPUT @Path1;FNFr$(Dumm+5)&Stars$
Dumm=Dumm+5
END IF
END IF
SUBEND
!
!
SUB Compute
COM /Avgs/ Fs,Qs,Fa,Qa,Caltype
COM /Cal_vals/ Mslope,B_cept,F_air
Bw=Fs*1000*(1/Qa-8.00E-5/1.925)
Bwa=Fa*1000/Qa
Mslope=(Bwa-Bw)/(Fa-Fa)
F_air=Fa
B_cept=Mslope-Fs
!
! STORE CAL VALUES IN FILE FOR RETRIEVAL.
PURGE "CALVALS"
CREATE BDAT "CALVALS",1
ASSIGN @Path_2 TO "CALVALS"
OUTPUT @Path_2;Mslope,B_cept,F_air
ASSIGN @Path_2 TO *
ASSIGN @Path_2 TO "CALVALS"
!
CLEAR SCREEN
GCLEAR
PRINT "Bw = ";Mslope;" x f + ";B_cept
SUBEND
!
!
SUB Cal_main
377  COM /Avgs/ Fs,Qs,Fa,Qa,Caltype
378  COM /Cal_arrays/ F(10),Q2(10),N
379  COM /Flag/ Qflag,Cal_flag
380  N=0
381  Fsum=0
382  Qsum=0
383  OFF KEY
384  ON KEY 1 LABEL "GETDATA",5 CALL GetData
385  ON KEY 2 LABEL "DONE",5 CALL Quit
386  WHILE Qflag<1
387  END WHILE
388  IF N=0 THEN GOTO Jump
389  FOR I=1 TO N
390    Fsum=Fsum+F(I)
391    Qsum=Qsum+Q2(I)
392  NEXT I
393  IF Caltype=1 THEN
394    Fs=Fsum/N
395    Qs=Qsum/N
396  ELSE
397    Fa=Fsum/N
398    Qa=Qsum/N
399  END IF
400  Jump:  !
401  Qflag=0
402SUBEND
403  !
404  !
405SUB GetData
406  COM /Cal_arrays/ F(*),Q2(*),N
407  COM /Results/ E1,E11,F0,Q,Nw,Pws
408  COM /Flag/ Qflag,Cal_flag
409  Cal_flag=1
410  N=N+1
411  PRINT "Insert snow sensor and hit continue."
412  PAUSE
413  CALL Takedata
414  Cal_flag=0
415  INPUT "Use this one in calibration (Y/N)?",Ans$        
416  IF (Ans$<>"Y" AND Ans$<>"y") THEN
417    N=N-1
418  ELSE
419    F(N)=F0
420    Q2(N)=Q
421  END IF
422  CLEAR SCREEN
423  GCLEAR
424  PRINT "VALUES SO FAR...
425  FOR I=1 TO N
426    PRINT "F = ": F(I), "Q = ": Q2(I)
427  NEXT I
428SUBEND
429  !
430  !
431SUB Sugar
COM /Avgs/ Fs,Qs,Fa,Qa,Caltype
Caltype=1
CALL Cal_main
SUBEND
!
!
SUB Air
COM /Avgs/ Fs,Qs,Fa,Qa,Caltype
Caltype=2
CALL Cal_main
SUBEND
!
!
SUB Start_freq
COM /Values/ Fstart,PwrL,Det_max
CLEAR SCREEN
GCLEAR
PRINT "PRESENLY, STARTING FREQ. IS "';Fstart;' GHz."
INPUT "ENTER DESIRED STARTING FREQ. IN GHz:"';Fstart
SUBEND
!
!
SUB Pwr_lvl
COM /Values/ Fstart,PwrL,Det_max
CLEAR SCREEN
GCLEAR
PRINT "PRESENLY, POWER LEVEL IS "';PwrL;' dBm."
PRINT "ALLOWED RANGE IS 0 TO 15 dBm."
INPUT "ENTER DESIRED POWER LEVEL:"';PwrL
SUBEND
!
!
SUB Create_file
DIM String$[200]
COM /File_info/ F_flag,Stars$;F_name$,@Path1,Dumm
!
GCLEAR
CLEAR SCREEN
Str1$=DATE$(TIMEDATE)
Str2$=TIME$(TIMEDATE)
F_name$=Str1$[1,2]"$";Str2$[4,5]"$";Str2$[1,2]"$";Str2$[4,6]
PRINT "Default filename is "';F_name$'
INPUT "Use this name (Y/N)?"';Answ$
IF (Answ$="N" OR Answ$="n") THEN
    INPUT "Enter filename of choice (max. 10):"';F_name$
END IF
CREATE ASCII F_name$,100
ASSIGN @Path1 TO F_name$
PRINT "FILE "';F_name$';" CREATED."
INPUT "Add a comment to top of file (Y/N)?"';Answ$
IF (Answ$="Y" OR Answ$="y") THEN
    LINPUT "Type in message now:"';String$
    OUTPUT @Path1;FNP$(Dumm+1)&"Comment: ";String$
    OUTPUT @Path1;FNP$(Dumm+2)&Stars$
    Dumm=Dumm+2
END IF
String3$=" "
F_flag=1
SUBEND
!
!
SUB Close_file
COM /File_info/ F_flag,Stars$,F_name$,@Path1,Dumm
ASSIGN @Path1 TO *
F_flag=0
GCLEAR
CLEAR SCREEN
PRINT "File ",F_name$," closed."
SUBEND
!
!
DEF FNPr$(Dumm)
String$=" "
String$=VAL$(Dumm)&"," 
RETURN String$
FNEND
!
!
SUB Cal_line
COM /Line_loss/ Pstep,Pfrac,Pflag
COM /Values/ Fstart,Pwrl,Det_max
Pstep=0.
Pflag=1
PRINT "CONNECT TRANSMIT & RECEIVE CABLES TOGETHER W/O PROBE"
! SET POWER LEVEL TO -5 DBM
Dum=Pwrl
Pwrl=-5
PRINT "THEN PRESS CONTINUE"
PAUSE
CALL Takedata
Dum2=1-Pfrac
Dbs=-10*LOG(Dum2)
Pstep=.01*Dbs
!Pstep=INT(Pstep/.006)*.006
PRINT "pstep",Pstep
Pflag=0
Pwrl=Dum
PRINT "SYSTEM IS NOW CALIBRATED FOR LINE ATT." SUBEND
!
!
SUB Rate
COM /Samp_rate/ Srate$[2]
INPUT "Select sampling mode (1=med, 2=fast):",Dum
SELECT Dum
CASE 1
Srate$="S1"
CASE 2
Srate$="S2"
CASE ELSE
BEEP
C-10
PRINT "Invalid Choice"
GOTO Choose2
END SELECT
SUBEND