MEASUREMENT OF SNOWPACK WETNESS

By

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Introduction

The water-equivalent of snowpacks represents an important resource, since water supplies and hydroelectric power obtained from them are in great demand. Effective management of water resources requires adequate knowledge of the snowpack extent, depth, density, and wetness, on a timely basis. The field methods in current use have proved to be of great value in providing information to permit forecasting of the amount of water runoff; however, instrumentation is seriously lacking regarding snowpack melting time which involves "ripening" and wetness of the snow.

This paper considers three electrical methods for measuring wetness (i.e., water content) of snow, for which preliminary descriptions have been given by Linlor and Smith (1974) and by Linlor et al. (1974):

a. Change in capacitance of a sample before and after freezing,

b. Dielectric loss (or "quality factor") of a sample in a high-frequency field,

c. Attenuation of a microwave beam in transmission through snow.

Various systems are already available for wetness determinations, such as calorimeters, centrifuges, etc. Although each method has its proponents, none has been uniformly accepted. Methods in current use require sampling and are difficult to automate. Of the three proposed electrical methods, two also require sampling, but the microwave system can be operated entirely automatically in remote installations, utilizing satellite telemetry (or other transmission methods) for data gathering. The microwave system can be combined with the density-profiling instrument described by Smith et al. (1972), so that density and wetness are measured simultaneously over essentially the same path. Such measurements would serve to determine snowpack properties without physically affecting the snowpack. With both density and free-water profiles available, interpretations can be made regarding the condition of the snowpack on a time-progressive basis. Combined with meteorological information, the density and wetness information increases the reliability of predictions regarding the melting time and water discharge rates from snowpacks.

The capacitance of a given test unit is proportional to the net dielectric constant of the medium between the electrodes. For dry snow - a mixture of air and ice - the factors that affect the net dielectric constant include (a) the individual dielectric constants of the air and the ice, (b) the relative proportions of each, (c) the temperature, (d) the oscillation frequency at which the measurements are made, and (e) the "form factor" (also called "formzahl"), which depends on the shapes and orientations of the individual crystals of snow.

For wet snow, the situation is more complicated, even though the temperature is not a variable, being essentially $0^{\circ}C$. The dielectric constant of pure water at $0^{\circ}C$ is 87.7, but when the water is in contact with snow crystals, intramolecular forces can affect the dipole moment of the water molecules. Nevertheless, the dielectric constant of snow is greatly increased by the presence of liquid-phase water, and this fact has been the basis for previous methods of determining snow wetness by Gerdel (1954) and Ambach and Denoth (1972).

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The relative dielectric constant k^* has real and imaginary components k' and k'', the latter also being known as the "loss factor." The ratio k'/k'' is known as the "quality factor" or Q.

$$k^* = k' + jk'' \tag{1}$$

$$Q = k'/k'' \tag{2}$$

Change in Capacitance upon Freezing

The change in capacitance of a sample before and after freezing is directly related to the amount of moisture initially present. Since the effects of form factor and density are present in both measurements, in the subtraction process the net contribution vanishes. The mathematical relation is obtained as follows: Let C_0 represent the capacitance of the empty unit (only air being present), C_1 represent the capacitance of the unit having wet snow, and C_2 the capacitance of the unit after freezing.

$$C_1/C_0 - C_2/C_0 = AW \tag{3}$$

where A is a proportionality factor, and W is the volume percent of liquid-phase water (i.e., 100 times the grams of water per cm^3). The value of A must be determined by calibration tests.

Several methods for calibrating the snow samples are under consideration. One is based on calorimetric procedures: for this an insulated container is necessary, preferably with a double-wall, one of which is maintained at 0° C by a water-and-ice bath. With the dry snow sample and the rest of the apparatus at 0° C, the initial capacitance is measured; then a known quantity of heat is given to the snow sample (by electric heating, or other method of precision heat addition). After equilibrium has again been reached, the final capacitance is measured. The change in capacitance is due to the water produced by the known amount of heat added.

A more elegant method of calibration could be based on the use of heavy water (D_2O) or other known isotopes in a refrigerated room. With a large volume of snow at a temperature slightly below freezing, about -0.1° C, a known amount of heavy water would be sprayed so that the upper portion of the snow would become saturated. After suitable time intervals, samples from various layers of the snow would be selected, and capacitance values measured before and after freezing. These changes in dielectric constant would then be related to the heavy water present in each sample, using a mass spectrometer or other nuclear abundance instrument to obtain the relative amount of heavy water and water (i.e., grams D_2O/grams H_2O). The homogeneity of the D_2O distribution may be similarly evaluated by dividing the snow sample from the test unit into small portions and measuring them separately on the nuclear instrument.

The effect of wetness on the dielectric constant of snow represents the basic information desired. However, it is difficult to prepare a snow sample having known amount of wetness unless elaborate calibration procedures are used. The development of electrical methods for the measurement of liquid-phase water in snow is expedited by employing a host medium whose properties can be controlled and are reproducible. Substances such as foam polyurethane, sand, etc. appear to be similar to snow in water retention, and thus can provide information that should serve as a guide, in regard to the dependence of the dielectric constant on frequency and wetness. No melting or freezing considerations are involved, and a refrigerated environment is not necessary. Weight of the sample before and after adding water yields the value W for the known volume. The question naturally arises whether the "binding" of water molecules to alternative materials resembles the case of snow, but for preliminary experiments this uncertainty is offset by the convenience, reproducibility, and ease in achieving desired amounts of wetness. The results can be expected to serve as a guide to the behavior of wet snow.

Pieces of foam polyurethane 12 in. x 12 in. x 1 in. (30.5 cm × 30.5 cm × 2.54cm) having a density of 0.018 gm/cm^3, and a dielectric constant (dry state) of 1.05 in the MHz range were selected. To add water to a specimen, the material was first saturated by squeezing it under water to expel air, then permitting it to expand, filling the pores with water. Next the specimen was placed on an inclined plane and squeezed to a pre-determined thickness (e.g., 0.62 cm, 0.31 cm, etc.) using a heavy roller on spacers. From the volume of the specimen and the increase in weight produced by the water, we obtained the volume percent wetness. For three specimens tested the wetness values were 11.3, 9.9 and 10.3 volume percent, giving an average of 10.5. Subsequent rolling-out of the water produced wetness values of 4.87, 3.83, and 4.18, for an average of 4.29 volume percent.

Specimens with known wetness were placed between the plates of a capacitor for measurement of the capacitance C and quality factor Q at a range of frequencies. Results are given in Fig. 1, showing the real part of the dielectric constant (k') plotted versus frequency. The straight-line relationship was obtained by fitting to individual plots (not shown). The standard deviation for the three specimens averaged about ±10 percent of the value of k'.

Equation (3) shows that the proportionality factor A is frequency-dependent, decreasing as the frequency is increased. The value of k' at 9.3 GHz is also shown in Fig. 1 for comparison, obtained by microwave techniques to be described later. It was concluded that for foam polyurethane the increase in the real part of the dielectric constant is proportional to the amount of wetness, for the range of 0 to 10 percent by volume, within a standard deviation of about ±10 percent, this being applied individually to the wetness and to the value of k'.

Figure 2 shows the values of k' versus frequency for wetness values of 4.3 and 10.5 percent. This, together with the data presented in Fig. 1, permits the design of calibration experiments for snow.

Quality-Factor Dependence on Wetness and Frequency

The dependence of the quality-factor Q on wetness for snow is shown in Fig. 3. The intrinsic Q of the snow capacitor is obtained as follows. For the Q-meter and associated coaxial leads, let the initial readings be designated as C_1 and Q_1, where C_1 includes the lead capacitance plus the dial-indicated capacitance. Next with the snow capacitor connected to the Q-meter, let the readings be designated as C_2 and Q_2; C_1 minus C_2 represents the capacitance of the snow capacitor.

The intrinsic quality-factor of the snow unit is:

$$Q_s = \frac{Q_1 Q_2 (C_1 - C_2)}{C_1 (Q_1 - Q_2)} \qquad (4)$$

The use of comparison host substances, such as foam polyurethane, for obtaining the dependence of Q on wetness and frequency is not a straightforward matter. The losses that occur are dependent on the ionic conductivity of the water, impurities in the host material, as well as binding effects of the water to the host substance.

Figure 2 shows the frequency dependence of the intrinsic Q of foam polyurethane samples at two wetness values (4.3 and 10.5 volume percent). This should be considered to be preliminary information. The relation of Q to wetness should be investigated more thoroughly before attempting to draw final conclusions. It is possible that pure wet snow cannot be approximated by wet substances having normal amounts of ionic conductivity, in the frequency ranges of interest. This does not, however, rule out the applicability of Q measurements for determining wetness of snow.

Microwave Beam Attenuation

Microwave techniques can be used in remotely operated, data-gathering systems either to obtain *in situ* profiles of snowpack free-water content or to obtain the average wetness of layer combinations. The measurement is based on the attenuation produced by liquid-phase water when present in snow.

The system proposed is based on "free-wave" propagation between sources and receivers. A theoretical description has been given by Linlor, Meier, and Smith (1974); in its simplest form the system consists of a source that can be moved vertically in a dielectric tube, and a receiver about a meter away, also arranged so that it can be moved vertically in its dielectric tube. Thus a horizontal beam would scan the snowpack when the source and receiver are moved vertically in synchronism. The arrangement would resemble physically and in principle the snowpack density profile system of Smith, Halverson, and Jones (1972), which is based on attenuation of a gamma-ray beam from a radioactive source. It may be possible to combine the two systems so that a density profile and a wetness profile are obtained simultaneously over essentially the same path.

A microwave system with a single source and receiver may encounter such difficulties as variable reflection at the source/snow interface when time-progressive changes in density and wetness alter the effective dielectric constant. Additional difficulties may result from power variations, receiver sensitivity drift, and similar effects. A possible solution to some of these problems is the use of two or more receivers, spaced at different distances from the common source. Receivers spaced at logarithmic intervals may provide dynamic range flexibility; the selection of the actual receiver spacings would depend on the wavelength and the wetness. The proposed microwave system may take a variety of forms, depending on the characteristics desired. Selected frequencies in the range of 10^9 to 10^{10} Hz can be used, or swept frequencies could be used with broad-band antennas. A crucial question is the amount of attenuation produced in the microwave region by wetness ranging up to about 10 percent by volume.

To obtain data on samples having known wetness, transmitters were constructed, each having two receivers, operating at 1.83, 2.73, 5.00 and 8.00 GHz. These units were tested in an anechoic chamber, yielding the values given in Table 1. In this table, the received power levels are relative to an arbitrary level; at -60 dB the receivers reached the noise level. Thus at the distance of 100 cm between source and receiver, the dynamic range was about 30 dB or greater for all frequencies.

TABLE 1. - RELATIVE POWER AT RECEIVERS

Frequency in gigahertz	Relative power at receivers, in decibels	
	Distance, 50 centimeters	Distance, 100 centimeters
1.83	-17.1	-23.4
2.73	-21.4	-26.3
5.00	-23.5	-30.7
8.00	-24.8	-30.5

To measure the effect of wetness, transmission tests were performed on samples of foam polyurethane, prepared as described previously. At a selected frequency, transmission levels were measured through interposed layers of foam polyurethane, each having approximately the same wetness. For foam polyurethane having an average wetness of 8.5 volume percent, the transmission test results are given in Fig. 4. At 5.00 and 8.00 GHz the data points fall reasonably well on the straight lines that are expected for exponential attenuation. At 1.83 and 2.73 GHz the data points exhibit oscillations with regard to the exponential attenuation lines. Such oscillations are expected on the basis of theory, produced by interference effects at the front and back surfaces of the foam polyurethane stack. Refinement of the experimental technique to remove the interference effects is possible, but adequate information can be obtained from the straight lines that are fitted to the data points.

Tests were run at 8.00 GHz for other values of wetness, with results given in Table 2. If the absorption coefficient is proportional to the wetness, then the absorption per unit of electrical length (equal to the physical length multiplied by the square root of the dielectric constant) divided by the volume percent wetness should be a constant for a selected frequency. Our measured values for the absorption in dB divided by the electrical length in cm and volume percent wetness are: 0.125, 0.127, 0.114, and 0.118 for the respective volume percent wetness values of 4.8, 8.5, 10.5, and 12.0. These four absorptivities have an average value of 0.121 and a standard deviation of ± 0.006.

To obtain the electrical length, a measurement of the dielectric constant k' is necessary. This was done by measuring the phase shift produced by the wet foam polyurethane. The signal from a microwave source operating at 9.3 GHz was divided into two legs, one of which had transmitting and receiving apertures; the other (comparison) leg had a calibrated phase shifting unit and a variable attenuator. The signal in the comparison leg was adjusted in phase and amplitude so as to essentially cancel the signal from the other leg; i.e., a phase difference of 180 degrees was obtained. As each layer of the wet foam polyurethane was inserted into the transmitter-receiver leg, the change in phase and attenuation in the comparison leg, necessary to preserve the 180-degree relationship, was measured. The phase shift is a measure of the electrical length of the inserted foam polyurethane layers, and because the physical length is known, the dielectric constant k' can be calculated.

TABLE 2.- ABSORPTIVITY DEPENDENCE ON FREQUENCY

Frequency in GHz	Wetness in Vol. %	Dielectric Constant k'	dB/cm	dB/cm % $\sqrt{k'}$
1.83	8.5	1.78	0.101	0.0089
2.73	8.5	1.78	0.276	0.0243
5.00	8.5	1.78	0.587	0.0517
8.00	8.5	1.78	1.444	0.1272
8.00	4.8	1.45	0.722	0.1248
8.00	10.5	2.01	1.693	0.1139
8.00	12.0	2.32	2.150	0.1176

Results are shown in Fig. 5 for the dielectric constant as a function of wetness in volume percent, for a frequency of 9.3 GHz. Six samples were tested at a variety of wetness values; the straight lines were fitted to the data points.

The data given in Table 2 have been plotted in Fig. 6, showing the attenuation per unit electrical lenght and per unit volume percent wetness, for the four frequencies. A theoretical curve for pure water, based on data published by Peter Ray (1972), is also shown, for which the abscissa is given at the top of the page.

Microwave Beam Measurements in Snow

Preliminary tests using microwave equipment were made at the Central Sierra Snow Laboratory (CSSL), Soda Springs, California. On January 29, 1975 the snow was about 65 cm deep and was below freezing, so it could be characterized as being dry. Two receiver distances were employed with each of the four transmitters: 223 cm and 798 cm. No measurable absorption was observed at any of the four frequencies. Some "ducting" effects on the transmitted signal were noted, as well as the expected multi-path interference effects.

Another set of measurements was taken at CSSL during the week of March 17, 1975. The snow was about 250 cm deep. Multi-path interference effects were noted; however, between the snow depth levels of 125 cm to 175 cm a wet layer was evident. If the assumption is made that the wet snow is similar to wet foam polyurethane in absorption characteristics, this snow layer had an average wetness of about one percent by volume. For the average snow density of about 0.35 gm/cm^3, this is equivalent to about 3 percent wetness by weight.

The microwave wetness-measuring system can be calibrated by taking a measurement profile, then sampling the snowpack by other techniques described earlier in this paper. A functional calibration method is also under consideration. This would consist of correlating the wetness measurements with the measured runoff data during the ripening and saturated-melting episodes.

Although our experience with *in situ* measurements of snow with microwave systems is in the initial stages, the results are very encouraging. The planned program for the immediate future includes (a) tests of snowpacks under the condition of active melting, (b) comparison of attenuation of microwave beams with dielectric constant measurements and with quality-factor of snow samples, and (c) comparison of electrical measurements with density-profiling gage data. Subsequently the program will include calibration of the various systems, as described in this paper. As soon as possible the systems will be coordinated with measurements involving passive microwave systems.

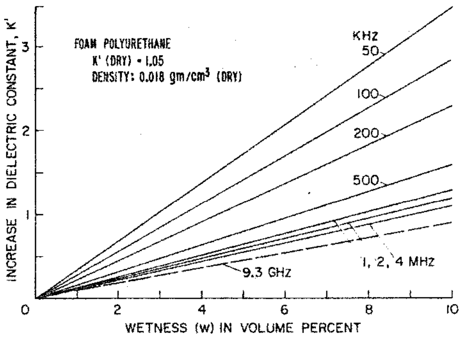

FIG. 1.- DEPENDENCE OF DIELECTRIC CONSTANT ON WETNESS

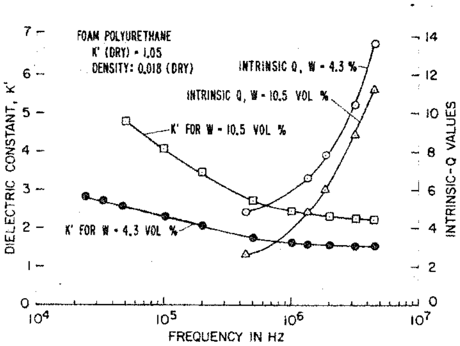

FIG. 2.- DEPENDENCE OF DIELECTRIC CONSTANT ON FREQUENCY

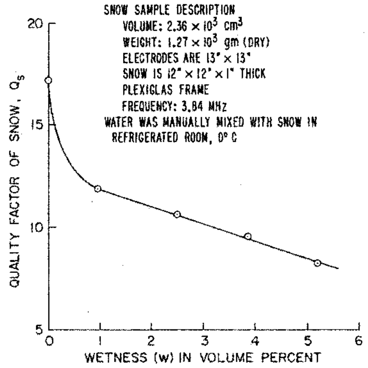

FIG. 3.- QUALITY FACTOR OF SNOW CAPACITOR VERSUS WETNESS

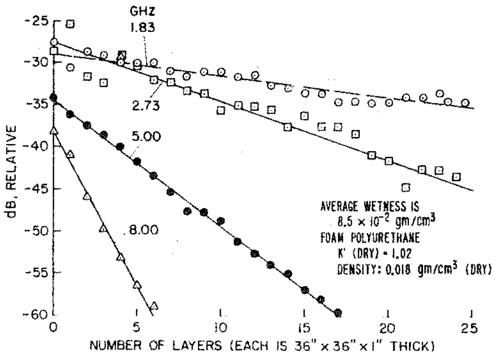

FIG. 4.- MICROWAVE BEAM INTENSITY VERSUS THICKNESS OF WET FOAM POLYURETHANE

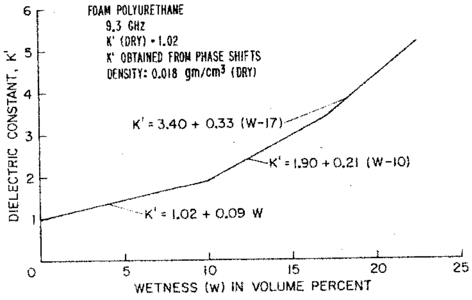

FIG. 5.- PHASE SHIFT PRODUCED BY WETNESS

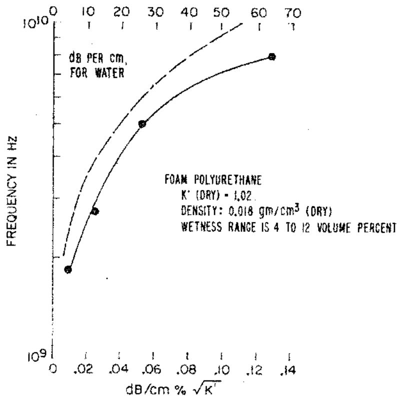

FIG. 6.- ABSORPTIVITY VERSUS FREQUENCY FOR WET FOAM POLYURETHANE

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