# The Complex Dielectric Constant of Snow at Microwave Frequencies

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*(Invited Paper)*

*Abstract*—**The complex dielectric constant of snow has been measured at microwave frequencies. New and old snow at different stages of metamorphosis have been studied. The results indicate that the complex dielectric constant is practically independent of the structure of snow. For dry snow, the dielectric constant is determined by the density. For wet snow, the imaginary part and the increase of the real part due to liquid water have the same volumetric wetness dependence. The frequency dependence of the complex dielectric constant of wet snow is the same as that of water.**

**A nomograph for determining the density and wetness of wet snow from its dielectric constant is given. A snow sensor for field measurement of the dielectric constant has been developed. It can be used for determining the density and the wetness of snow by a single measurement.**

## I. DIELECTRIC CONSTANT OF DRY SNOW

### *A. Real Part of the Dielectric Constant*

THE COMPLEX DIELECTRIC constant of dry snow $\epsilon_d$ has been measured at the Radio Laboratory of the Helsinki University of Technology by one of the authors [1] during the winter 1981–1982. The dependence of $\epsilon_d$ on temperature, density, and frequency were studied. The measurements were made using cylindrical cavity resonators operating on the $TE_{011}$ mode. Four different frequencies were used: 850 MHz, 1.9 GHz, 5.6 GHz, and 12.6 GHz. The cavity was filled with a snow sample and the shift in the resonance frequency and the quality factor were measured in order to find the real part and the imaginary part of the dielectric constant of the sample. In addition, the temperature, density, and the structure of the snow sample were determined.

The real part of the relative dielectric constant $\epsilon_d'$ was found to depend almost solely on the density. No difference was found between coarse old snow, aged snow, new fine-grained snow, undisturbed snow, and prepared snow. All measured points are shown in Fig. 1 along with a second-order polynomial fitted to the points

$$\epsilon_d' = 1 + 1.7\rho_d + 0.7\rho_d^2. \tag{1}$$

In (1), $\rho_d$ is the relative density of dry snow (compared to water). The results agree well with the curve obtained by applying the mixture theory of Taylor for randomly oriented disc-shaped particles [1], [3]. For very light new snow, the mixture theory for needles gives better values, and for very dense snow spherical particles give the best results. The mixture theory of Tinga *et al.* [4], which assumes spherical particles, gives too low values. For practical purposes, $\epsilon_d'$ can be approximated by a linear model

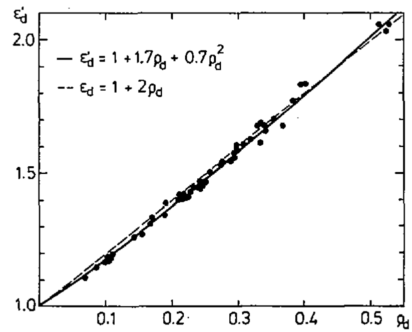


Fig. 1. Real part of the dielectric constant of dry snow as a function of the density of dry snow relative to water.

$$\epsilon_d' = 1 + 2\rho_d. \tag{2}$$

This formula gives slightly larger values for light snow and slightly lower values for dense snow. For densities over 0.5 g/cm$^3$, the error increases rapidly.

Ambach and Denoth [5] have also proposed a linear model

$$\epsilon_d' = 1 + 2.2\rho_d. \tag{3}$$

Equation (3) is based on experimental data for coarse old snow at low frequencies (MHz range).

Hallikainen, Ulaby, and Abdel-Razik [6] have obtained for dry snow in the 4–18 GHz range

$$\epsilon_d' = 1 + 1.91\rho_d. \tag{4}$$

It can be seen that the present model is in good agreement with earlier results.

### *B. Imaginary Part of the Dielectric Constant*

The density dependence of the imaginary part of the dielectric constant of dry snow was studied by measuring it around 2 GHz at a constant temperature. Fig. 2 shows $\epsilon_d''/\epsilon_i''$, where $\epsilon_i''$ is the imaginary part of the dielectric constant of pure ice. The best fit second-order polynominal including the point $\epsilon_d''/\epsilon_i'' = 1$ for $\rho_d = 0.917$ is

$$\frac{\epsilon_d''}{\epsilon_i''} = 0.52\rho_d + 0.62\rho_d^2. \tag{5}$$

The best fit can be obtained when $\epsilon_i''$ at 2 GHz and $-20°C$ is assumed to be $8 \cdot 10^{-4}$. Applying Taylor's mixture theory, the best fit in this case corresponds to randomly distributed needle-shaped particles.

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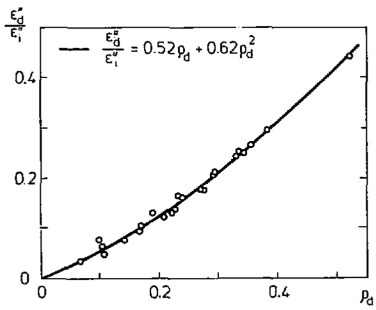


Fig. 2. Imaginary part of the dielectric constant of dry snow relative to that of pure ice as a function of the density of dry snow. The imaginary part used for pure ice is $\epsilon_i'' = 8 \cdot 10^{-4}$ at 2 GHz and $-20°$C.

The temperature dependence and the frequency dependence of the imaginary part of the dielectric constant of dry snow were studied by measuring the loss tangent $\tan\delta_d = \epsilon_d''/\epsilon_d'$ as a function of temperature at four different frequencies: 840 MHz, 1915 MHz, 5.62 GHz, and 12.6 GHz. The results are shown in Fig. 3.

An equation giving the best fit for all temperatures and frequencies is given by

$$\tan\,\delta_d = \frac{\epsilon_d''}{\epsilon_d'} = 1.59 \cdot 10^6 \, \frac{0.52\rho_d + 0.62\rho_d^2}{1 + 1.7\rho_d + 0.7\rho_d^2} \cdot (f^{-1} + 1.23 \cdot 10^{-14}\sqrt{f})e^{0.036T} \qquad (6)$$

where $T$ is the temperature of snow in degrees Celsius. The curves in Fig. 3 are calculated from (6). The dry snow model can be used to obtain the imaginary part of the dielectric constant of pure ice as a function of frequency by substituting $\rho_d = 0.917$ in (6). Fig. 4 shows the results at $-20°$C together with earlier results [7]. Present results indicate that $\epsilon_i''$ has a minimum close to 3 GHz. The scatter in the previous experimental data is substantial. Obviously, this is due to difficulties in measuring low losses at microwave frequencies.

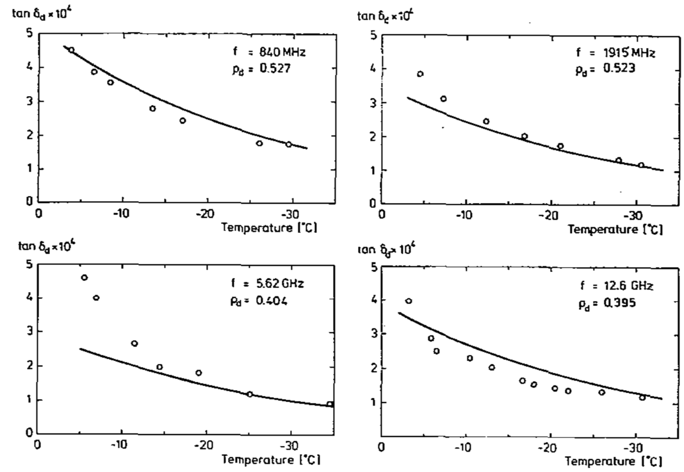


Fig. 3. Measured loss tangent of dry snow ($\tan\delta_d = \epsilon_d''/\epsilon_d'$) as a function of temperature at frequencies 840 MHz, 1915 MHz, 5.62 GHz, and 12.6 GHz. Curves are calculated from (6).

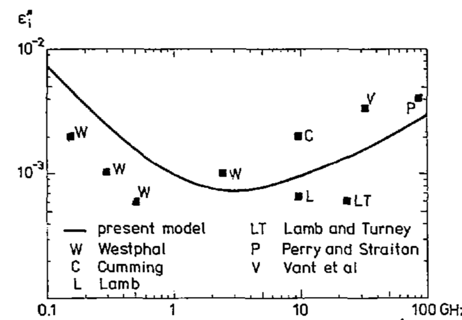


Fig. 4. Imaginary part of the dielectric constant of ice at $-20°$C as a function of frequency. The squares are $-20°$C data from [7]. The solid line is calculated using (6) with $\rho_d = 0.917$.

### C. Pollution Dependence of Losses

During the measurement program, an additional parameter that obviously has an effect on the dielectric behavior of snow was detected, namely, the acidity. It was found that samples from the same site but from different depths gave different values for $\epsilon_d''$ although there was no detectable difference in either the grain size or the temperature. When the acidity was measured, a considerable difference was found. Fig. 5 shows the results reduced to $\rho_d = 0.35$. The two points at the right represent samples of new fine-grained snow from the same site but from different depths. The data point at the left represents old coarse snow. It is possible that this value differs from the other two partly because of the different grain size. Grain size had, however, no effect on $\epsilon_d'$. The measurements on which (6) is based were made using coarse, old, clean (pH 6.5) snow. Assuming that the increase in the loss tangent is directly proportional to the concentration of free $H^+$-ions, the following model is obtained

$$\tan\,\delta_d = \tan\,\delta_0 + A10^{-\mathrm{pH}}. \qquad (7)$$

Here the value of constant $A$ must be determined empirically.

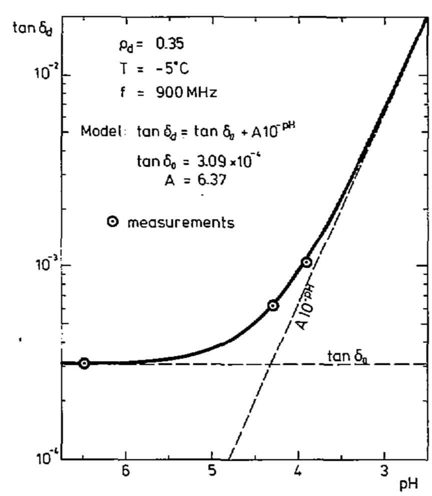


Fig. 5. Loss tangent of dry snow as a function of the pH value of snow.

It may depend, e.g., on temperature. Fig. 5 shows that $A$ = 6.37 provides a good fit to the experimental data. More measurements are needed to verify this hypothesis and to determine the value of constant $A$.

## II. DIELECTRIC CONSTANT OF WET SNOW

### *A. Previous Results for Wet Snow*

Wet snow is a mixture of ice particles, air, and liquid water. According to Colbeck [8], wet snow has two distinct regimes of liquid saturation, the pendular and funicular regimes. In the pendular regime, air is continuous throughout the pore space and the liquid occurs as isolated inclusions. This is the case at low wetnesses. In the funicular regime, the liquid is continuous throughout the snow and the air occurs in distinct bubbles trapped at narrow constrictions in the pores. This is the case at high wetnesses. There should be a sharp transition between the two regimes. In porous material with closely packed spheres this transition occurs at a liquid saturation of about 14 percent of the pore volume [8]. Colbeck has shown that by applying the Polder and van Santen mixing theory the best fit with the experimental results for the real part of the dielectric constant of wet snow $\epsilon_s'$ in the pendular regime can be achieved by assuming spheroidal water particles with an axial ratio of 3.5. He predicts that the dielectric constant of wet snow depends on its history as well as on its liquid content and porosity.

Ambach and Denoth [5] have found that for frequencies above 10 MHz and below 100 MHz the real part of the dielectric constant of wet snow is independent on frequency and does not depend on the grain size and, hence, on the stage of metamorphosis. Their equation for $\epsilon_s'$ is

$$\epsilon_s' = 1 + 2.2\rho_s + 21.3 W_v \tag{8}$$

which can be put in the form $\epsilon_s' = 1 + 2\rho_d + 23.5 W_v$. There, $\rho_s$ is the relative density of wet snow and $\rho_d$ that of snow when the liquid water is replaced by air. $W_v$ is the wetness by volume. Denoth [9] has found that when the mixture theory of Polder and van Santen is applied the optimized values of the depolarization factors for the water particles change abruptly when the wetness exceeds 5 to 7 percent by volume. The change can be attributed to the transition from the pendular to the funicular regime.

There are many experimental results from the measurements of the relative dielectric constant of wet snow [5]–[11]. Especially, the results concerning the imaginary part are contradictory. Some of the discrepancies are due to the difficulties in determining the liquid water content of snow and to the inhomogeneity of snow field. It is also possible that in some cases the dielectric characteristics of snow change when snow is disturbed.

### *B. Present Experimental Results*

Three sets of experimental results are used in the following. The first set of measurements was made by Hallikainen *et al.*, and the measurement procedure along with the first results are described in [6]. In this paper, their detailed results measured at 4 GHz in 1982 are used. The measurements were conducted in Kansas using undisturbed new wet snow in the Spring of 1982. The accuracy of the measurement is estimated to be $\pm 5$ percent for the real part and $\pm 10$ percent for the imaginary part. A cold calorimeter was used for determining the wetness of snow.

The second set of measurements was made by Denoth, Mätzler, Tiuri, *et al.* [10] at Stubai Alps in Austria in August 1982. In the measurements, the snow fork developed at the Helsinki University of Technology [12] was applied. When pushed into the snow it measures the complex dielectric constant. The measurement frequency varies between 0.5 and 1 GHz, depending on snow $\epsilon_s'$. The accuracy of the measurement is estimated to be $\pm 5$ percent for the real part and $\pm 10$ percent for the imaginary part. The measured snow was old and coarse. The measurements are described in detail in [10]. A calibrated snow wetness measuring system (a plate capacitor) developed by the University of Innsbruck was used to determine the wetness.

The third set of measurements was made by one of the authors (Sihvola) at Sodankylä in Finland in Spring 1983, using the same snow fork that was used at Stubai Alps. The snow was wet and old. The wetness was determined by a dilatometer developed at the Helsinki University [13].

In all sets of measurements the accuracy of snow wetness calibration can be assumed to be $\pm 0.01$ by volume.

The increase of the real part of the dielectric constant $\Delta\epsilon_s'$ caused by liquid water

$$\Delta\epsilon_s' = \epsilon_s' - \epsilon_d'$$

$$\Delta\epsilon_s' = \epsilon_s' - 1 - 1.7\rho_d - 0.7\rho_d^2 \tag{9}$$

is shown in Fig. 6 using the results from Kansas (USA) and in Fig. 7 using the results from Stubai Alps (AUT) and from Sodankylä (FIN). The imaginary part of the dielectric constant of wet snow $\epsilon_s''$ is shown correspondingly in Figs. 8 and 9 as a function of wetness. The curves are second-order polynomials fitted to the points. In Fig. 9, the data points measured in the 600–900-MHz range are transformed to 1 GHz assuming that the relative frequency dependence is the same as that of water (see Section III, equation (19)).

It can be seen from the figures that the increase in both the real and the imaginary part of the complex dielectric constant of snow seems to be dependent on the wetness in a similar way.

## III. FREQUENCY DEPENDENCE OF THE COMPLEX DIELECTRIC CONSTANT OF WET SNOW

In order to compare the results measured at different frequencies, the results can be reduced to 1 GHz by assuming that water dominates the behavior of $\Delta\epsilon_s'$ and $\epsilon_s''$. This assumption holds as soon as there is some liquid water in snow as can be seen by comparing the results in Figs. 3, 6, and 8.

The dielectric constant of pure water $\epsilon_w$ obeys the Debye equation (for example, [2]):

$$\epsilon_w = \epsilon_{w\infty} + \frac{\epsilon_{ws} - \epsilon_{w\infty}}{1 + j\omega\tau_w} = \epsilon_w' - j\epsilon_w'' \tag{10}$$

where the high-frequency permittivity can be taken to be $\epsilon_{w\infty}$ = 4.9. Because the temperature of liquid water in snow is quite near 0°C, the temperature-dependent terms in the

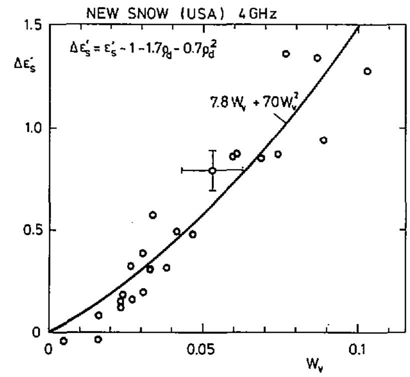


Fig. 6. Increase in the real part of the dielectric constant of new snow as a function of wetness at 4 GHz.

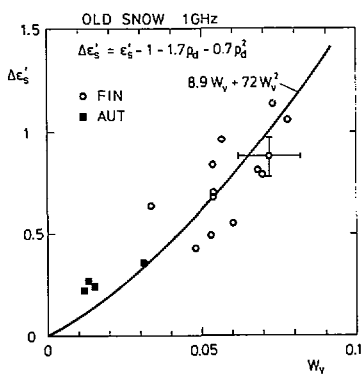


Fig. 7. Increase in the real part of the dielectric constant of old snow as a function of wetness at 1 GHz.

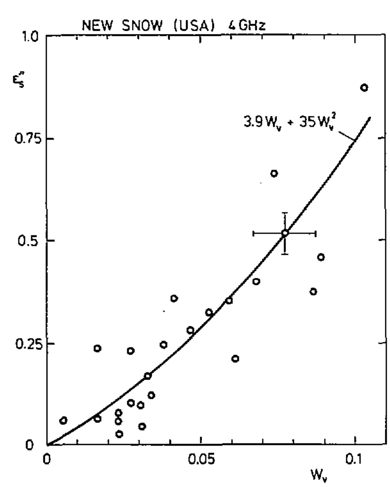


Fig. 8. Imaginary part of the dielectric constant of new snow as a function of wetness at 4 GHz.

formula have the following values: the static dielectric constant $\epsilon_{ws} \simeq 87.74$ and the relaxation time $\tau_w \simeq 18$ ps. This yields

$$\epsilon_w' = 4.9 + \frac{82.8}{1+(f/f_0)^2} \tag{11}$$

and

$$\epsilon_w'' = \frac{82.8(f/f_0)}{1+(f/f_0)^2} \tag{12}$$

where $f_0 \simeq 8.84$ GHz.

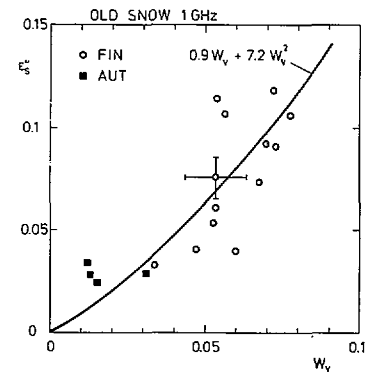


Fig. 9. Imaginary part of the dielectric constant of old snow as a function of wetness at 1 GHz. The data have been transformed to 1 GHz according to (19).

Because of the quadratic frequency term in the denominator, $\epsilon_w'$ is constant and $\epsilon_w''$ is directly proportional to frequency at low frequencies ($f \ll f_0$). However, the loss tangent of water $\tan\delta_w = \epsilon_w''/\epsilon_w'$ is directly proportional to frequency up to considerably higher frequencies than $\epsilon_w''$. From (11) and (12)

$$\tan\delta_w = \frac{82.8(f/f_0)}{87.7+4.9(f/f_0)^2}. \tag{13}$$

The Taylor expansion gives

$$\tan\delta_w \simeq 0.944(f/f_0) - 0.0527(f/f_0)^3 + \cdots. \tag{14}$$

This means that the inaccuracy in the linear approximation for the loss tangent is less than 1 percent below 3.8 GHz and less than 6 percent even at the relaxation frequency of water $f_0 = 8.84$ GHz ($= 1/2\pi\tau_w$).

From (11), (12), and (14), the following relations are obtained:

$$\epsilon_s''(f) = \frac{\dfrac{f}{f_0}}{1+\left(\dfrac{f}{f_0}\right)^2}\,\epsilon_s''(f_0) \qquad (f_0 = 8.84\ \text{GHz}) \tag{15}$$

$$\epsilon_s''(f) = 0.944\,\frac{f}{f_0}\,\Delta\epsilon_s' \qquad (500\ \text{MHz} < f < 4\ \text{GHz}). \tag{16}$$

Equation (16) assumes that the liquid water has an equal effect on the real and imaginary part of the dielectric constant. The following relations for $\epsilon_s$ between 1 and 4 GHz are obtained:

$$\Delta\epsilon_s'(1\ \text{GHz}) = 1.18\Delta\epsilon_s' \qquad (4\ \text{GHz}) \tag{17}$$

$$\epsilon_s''(1\ \text{GHz}) = 0.297\epsilon_s'' \qquad (4\ \text{GHz}) \tag{18}$$

$$\epsilon_s''(1\ \text{GHz}) = \frac{10^9}{f}\,\epsilon_s''(f) \qquad (500\ \text{MHz} < f < 1\ \text{GHz}). \tag{19}$$

## IV. DISCUSSION AND CONCLUSIONS

Equation (19) was used to reduce the results in Fig. 9 from the measurement frequency to 1 GHz. The results at 1 GHz are

$$\left.\begin{aligned}\Delta\epsilon_s' &= 8.9W_v + 72W_v^2\\ \epsilon_s'' &= 0.9W_v + 7.2W_v^2\end{aligned}\right\} \qquad (\text{AUT and FIN}). \tag{20}$$

If (17) and (18) are applied to the 4-GHz results, the following equations are obtained for wet snow at 1 GHz:

$$\left.\begin{aligned}\Delta\epsilon_s' &= 9.2W_v + 83W_v^2\\ \epsilon_s'' &= 1.2W_v + 10.4W_v^2\end{aligned}\right\}\quad \text{(USA)}. \tag{21}$$

Equation (16) gives for $\epsilon_s''$ when $\Delta\epsilon_s'$ is substituted

$$\begin{aligned}\epsilon_s'' &= 1.0W_v + 8.9W_v^2 \quad &\text{(USA)}\\ \epsilon_s'' &= 1.0W_v + 7.7W_v^2 \quad &\text{(AUT and FIN)}.\end{aligned} \tag{22}$$

Equations (22) agree with experimental curves in Figs. 8 and 9, considering the measurement accuracy. The new results show that for wet snow in the pendular regime, both the real part and the imaginary part of the complex dielectric constant seem to be almost independent of the structure of snow. They also are close to what can be expected when the water is assumed to dominate the dielectric behavior of wet snow.

Using (11) and (12) and taking the average of the results of (20), the following general equations for the dielectric constant of wet snow are obtained:

$$\begin{aligned}\Delta\epsilon_s' &= (0.10W_v + 0.80W_v^2)\epsilon_w'\\ \epsilon_s'' &= (0.10W_v + 0.80W_v^2)\epsilon_w''.\end{aligned} \tag{23}$$

If a mixture of water particles and air is considered, Taylor's mixture theory [3] gives too high values for randomly oriented needle-shaped water particles and too low values for spherical water particles. Equations (23) give values which are about halfway between those two. This was to be expected.

Equation (8) obtained by Ambach and Denoth [5] at 18 MHz for $\Delta\epsilon_s'$ gives the same coefficient for $\rho_d$ when $\rho_d$ is 0.57, but the coefficient for $W_v$ is much larger than the present value. This may be due to the type of snow and to a different measuring system (a multiplate condenser). It is unlikely that the low measuring frequency used by them causes the difference. Also, at higher frequencies, a larger coefficient has been derived, namely from the measurements of Sweeny and Colbeck at 6 GHz [14], [15]. The results obtained by Linlor at 4 GHz [11] for the imaginary part are close to the present results. However, his values for the real part are higher.

The present results indicate that the snow fork is a very promising instrument for determining the density and the wetness of wet snow by a single measurement. Fig. 10 shows the obtained nomograph for determining the volumetric wetness and the dry density of snow when $\epsilon_s'$ and $\epsilon_s''$ are measured using the snow fork. The nomograph is drawn using the following equations:

$$\begin{aligned}\epsilon_s' &= 1 + 1.7\rho_d + 0.7\rho_d^2 + 8.7W_v + 70W_v^2\\ \epsilon_s'' &= \frac{f}{10^9}(0.9W_v + 7.5W_v^2), \qquad f = 500 \cdots 1000 \text{ MHz}\\ \rho_s &= \rho_d + W_v.\end{aligned} \tag{24}$$

Corresponding relations between $\epsilon_s$, $W_v$, and $\rho_d$ for other frequency ranges can be derived using (11), (12), and (23). Assuming that the pendular regime in high-density snow corresponds to a water saturation of less than 14 percent of the pores as indicated by Colbeck [8], the corresponding border line is near $\epsilon_s' = 3$. When $\epsilon_s'$ exceeds 3, large deviations can be expected because part of the snow sample may be in the pendular and part in the funicular regime. Denoth [16] has studied the transition saturation for different types of snow. He has found that for old, coarse-grained snow, the transition water saturation is 7 $\cdots$ 12 percent. This means that the range of validity of Fig. 10 is restricted to about $\epsilon_s' \leqslant 2.6$ for this type of snow. In the funicular regime, the equations corresponding to (23) and (24) must be found by additional experiments.

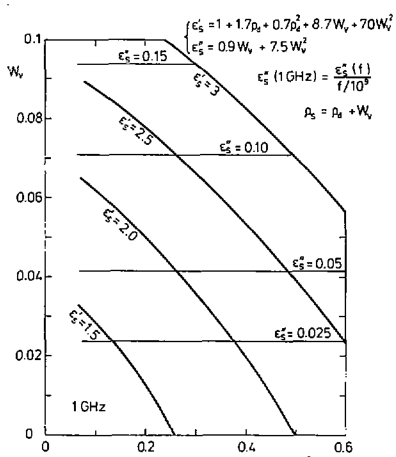


Fig. 10. Nomograph for determining the wetness and density of snow from its complex dielectric constant at 1 GHz.

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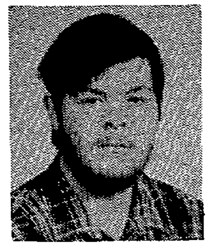

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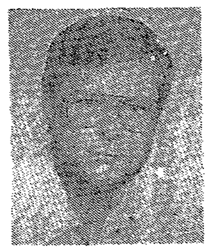

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