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A comparative study of instruments for measuring the liquid water content of snow

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Different dielectric sensors for measuring the liquid water content of snow are compared and described in detail. The instruments make use of the significant difference in the dielectric properties of ice and liquid water at radio frequencies; they are operated with frequencies ranging from 1 MHz up to 1.3 GHz. Plate condensers in connection with ac bridges are used as sensors in the frequency range up to 100 MHz whereas open resonators are used in the GHz regime. Test measurements with the different sensors on homogeneous samples like dry sand and mixed and prepared snow showed the same results for the dielectric constant: the discrepancies are less than 1%. In the natural, inhomogeneous snow cover, the special properties of the different sensors appear. Snow wetness is calculated from the measured dielectric constant and the snow density using the model of Polder and van Santen. The comparative field measurements were made with Alpine snow in the Stubai Alps in Austria.

I. INTRODUCTION

Measurement of snow wetness is a delicate task because of the rapid snow metamorphism at and near the melting point. Any disturbance of snow may change its structure, texture, and wetness rapidly. Therefore, snow measuring techniques have to be rapid and preferably nondestructive. The most promising physical property to be used for the determination of the liquid water content in snow is the dielectric constant at radio- and microwave frequencies.[1,2] The relationship between snow porosity, wetness, texture, and dielectric constant is well understood.[3–7]

To a first-order approximation, neglecting the effects of snow texture and liquid water distribution, the real part of the relative dielectric constant ϵ' of wet snow is a linear function of density ρ ($0.1 < \rho < 0.5$ g/cm^3) and a quadratic function of volumetric liquid water content W ($0\% < W \lesssim 8\%$)[8]:

$$\epsilon' = 1 + a\rho + bW + cW^2, \tag{1}$$

where a, b, and c are quasiconstants, i.e., nearly independent of snow type and texture over a wide frequency range from 10 MHz to 1 GHz. From measurements of ϵ' using wet alpine snow in the frequency range 10–100 MHz, the constants $a = 2.2$, $b = 0.187$, and $c = 0.005$ are obtained. The dependence of the density-reduced relative dielectric constant $e = \epsilon' - 1 - 2.2\rho = 0.187W + 0.005W^2$ on the liquid water content W is shown in Fig. 1, where W was determined using a freezing calorimeter with an accuracy of ± 0.5 vol %.[9]

Instruments for measuring the dielectric constant or snow wetness can be destructive. Depending on the operating frequency of the instruments, two essentially different sensors have been developed. At frequencies below 100 MHz, plate condensers were used for measuring the average liquid water content in a volume of snow of approximately 1000 cm^3 and flat condensers were used in a stripline arrangement for measurements in thin layers of up to a few centimeters. At higher frequencies, especially in the GHz region, the need for very accurate configurations of the electric field favors closed systems such as waveguides or waveguide resonators. However, these sensors are, in general, impractical for field measurements. A careful analysis of electric fields in various open geometries shows that there exists a number of potential sensors which should be applicable in snow. A disadvantage of such open structures is the lack of exact solutions to Maxwell's equations, since no exact relation between the measurable signals and the dielectric constant of the material under test may be formed from theory. However, approximations may still be sufficiently accurate, especially for the real part of the dielectric constant. For sensors with unambiguous signals it is possible to test the approximation using materials with known dielectric constants.

Recent efforts in constructing moisture meters using various plate condensers and flat condensers in stripline arrangements have been undertaken at the laboratory in Inns-

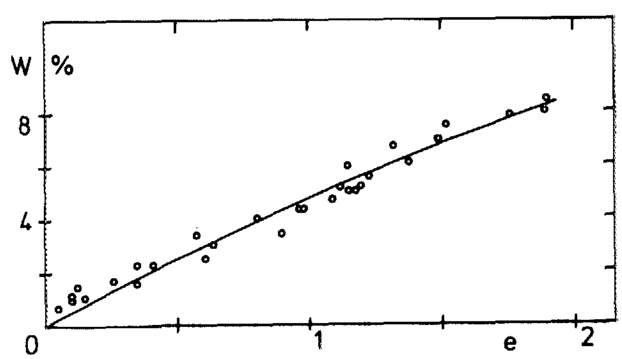

FIG. 1. Relation between liquid water content W and the density-reduced dielectric constant $e = \epsilon' - 1 - 2.2\rho$ (at 10 MHz). The water content W was measured with a freezing calorimeter.

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bruck; open dielectric sensors, mainly open resonators, for measuring the liquid water content of snow have been developed recently at the laboratories in Helsinki and Bern. A variety of instruments with different operating frequencies and different sensors is now available. The best of these sensors were compared and tested with wet old snow and glacier firn during an international workshop in August 1982 in the Stubai Alps in Austria [Test field: Schaufelferner, 3100-m above sea level (a.s.l.)]. The relatively coarse grains of up to 2 mm of this Alpine snow were a challenge for the small and handy open sensors. This paper describes the comparison of the various instruments and reports the results of this joint field study.

II. THE INSTRUMENTS[10]

In the field measurements, a total of 6 different instruments and sensors were compared: a quarter-wavelength coaxial resonator and a "saw" resonator from the Swiss group, a "fork" resonator from the Finnish group, and three systems (a twin-T bridge, a Wien–Robinson bridge and two-port measurements with a network analyzer, all using air-gap condensers as dielectric sensors) from the Austrian group. In addition, the average liquid water content of snow in a volume of $13 \times 13 \times 10\ \text{cm}^3$ was measured by an absolutely calibrated dielectric moisture meter [probe G1; cf. Fig. 8(a)] with an operating frequency of 3.55 MHz. It uses a resonance circuit in the sensor electronics (Q meter).

Apart from the dielectric sensors to be described below, the snow was characterized by its density, grain size, and grain shape. The mean grain size and the mean grain shape (mean shape factor) are derived from photographs of the snow samples under the test.[11] One of these photographs representing coarse-grained old 1982 snow is shown in Fig. 9. Snow density was determined by weighing; in addition, in some cases snow liquid water content was measured directly using a freezing calorimeter with an accuracy of ± 0.5 vol %.

A. The snow probes of the University of Berne

1. Quarter-wavelength coaxial resonator for measurements of the surface layer

The Swiss group selected a coaxial resonator shown in Fig. 2 as the primary sensor. It was described by Aebischer and Mätzler[12] as a surface sensor for ground truth support for microwave remote sensing. Because of the grain structure of snow, a pure surface sensor is not reliable in determining the snow wetness. Therefore, the sensor is allowed to slightly penetrate into the snow surface. This mechanical penetration depth D can be changed by moving the circular ground plate. In addition to positioning the sensor on the snow surface, this plate acts as a reflector and decreases the radiative losses of the resonator ($Q \sim 140$). For $D = 2$ mm, the measurement is nearly nondestructive, and the frequency range of 950–1400 MHz covers all resonance frequencies corresponding to the possible values of dielectric constants of snow ($1 < \epsilon' < 5$). Coupling of electromagnetic energy to and from the resonator is achieved by inductive loops well protected at the closed end. For the operation of the sensor in the field, a portable and battery-driven electronic device, including a voltage-controlled oscillator and a frequency counter, is used. A block diagram of the sensor electronics is shown in Fig. 3.

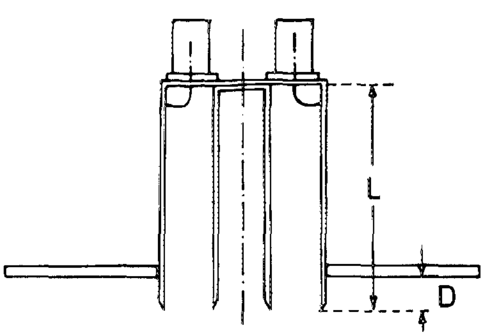

FIG. 2. Cross-sectional view, along the axis, of the coaxial resonator. The shape of the conductors at the open front end of the resonator is designed to assure proper entering of the snow into the space between the two conductors when they are inserted into the snow cover.

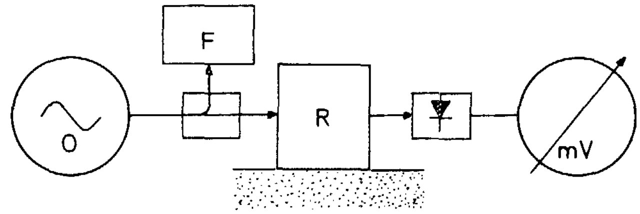

FIG. 3. A block diagram of the coaxial sensor electronics. O: oscillator, F: frequency counter; R: resonator.

To perform a measurement, the sensor is put on the snow surface and its resonant frequency f is measured. The transcendental equation, quickly solvable on a pocket calculator, relates the measured frequency f to the desired dielectric constant ϵ':

$$\frac{\cot \beta_2 D_{\text{eff}}}{\beta_2} \cong \frac{\tan[\beta_1(L - D)]}{\beta_1}, \tag{2}$$

with $\beta_2 = (\omega/c)\sqrt{\epsilon'}$, $\beta_1 = \omega/c$, $\omega = 2\pi f$ the resonance frequency, c velocity of light, L the length of the resonator, and $D_{\text{eff}} = D + 4.8$ mm is the electrical penetration depth. The accuracy in ϵ' is 2%, and the resulting absolute accuracy in the determination of snow wetness W is 0.5 vol %.

2. Saw resonator

A secondary sensor developed by the Swiss group is a degenerated parallel-wire resonator consisting of a saw blade and a reflecting metal plate as shown in Fig. 4. It uses the same sensor electronics as the coaxial resonator. The parallel-wire line consists of the real saw blade and of its mirror image. When this sensor is inserted in the snow or ice with the metal plate lying on the flat surface, the test material is

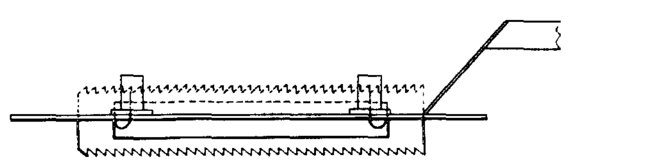

FIG. 4. Longitudinal section of the saw resonator. Dashed lines indicate the imaginary mirror image of the saw blade.

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mirrored also. Then the relationship between resonance frequency f and dielectric constant is given by the simple formula

$$\epsilon' = (f_0/f)^2,$$

where f_0 is the free-space resonance frequency.

The resonator can be operated at a half wavelength corresponding to $f_0 = 1192$ MHz and at a full wavelength, corresponding to $f_0 = 2360$ MHz. It is especially suited for hard materials such as crusty snow and ice. The sensor was used to support some of the measurements made with the primary surface instrument (λ /4 coaxial resonator).

B. The snow probe of the Helsinki University of Technology

The snow probe used by the Helsinki University of Technology[13] consists of a "fork resonator" that can be pushed into snow or any other porous, granular, or liquid material. The resonator is a parallel-wire transmission-line resonator that is open circuited at the one end and short circuited at the other one, according to Fig. 5. High-frequency power is fed in and out through rigid coaxial cables and coupling loops. The cables are coated and supported by a glass fiber pipe which forms a solid stock. The coupling loops are protected by epoxy plastic. The wires are made of stainless steel and they are sharpened at the end, which makes the structure easy to push into snow even through a crust. However, the wires are thin enough that the measurement does not deform snow and change the density considerably.

The real part of the dielectric constant is determined by the resonant frequency when the probe is inserted totally in snow:

$$\epsilon' = (f_0/f)^2,$$

where f_0 is the free-space resonant frequency. Dielectric losses ϵ'' can be calculated from the broadening of the resonance curve when the resonator is in snow.

The probe is also suitable for measuring solid materials and bodies that have a flat surface. The probe is placed on the surface and the material makes its dielectric effect on half of the fields of the resonator. The measured dielectric constant ϵ' is then the mean value of snow ϵ_s' and air:

$$\epsilon' = \frac{\epsilon_s' + 1}{2}.$$

The whole measuring system consists of the probe and a control unit which automatically measures the characteristic quantities of the resonance curve. A block diagram of the measuring system is shown in Fig. 6. Voltage controlled oscillator and electronics are needed for automatic measure-

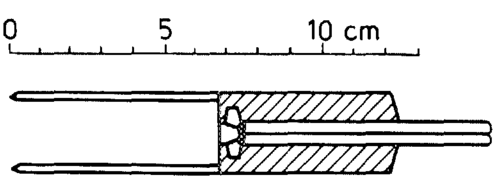

FIG. 5. Snow probe developed by the Radio Laboratory of the Helsinki University of Technology.

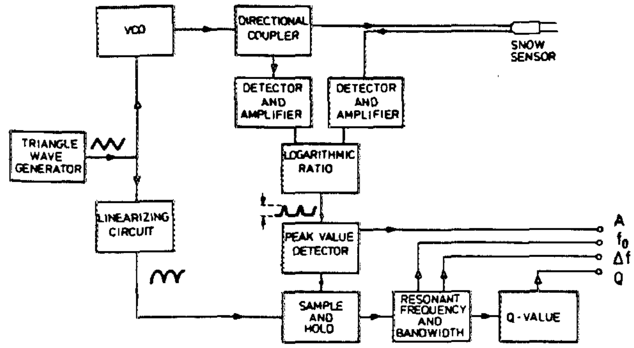

FIG. 6. A block diagram of the sensor electronics for automatical measurement of the resonant frequency and the Q factor.

ment of the resonant frequency and the 3-dB bandwidth. These values can be recorded on tape in the field using a lightweight instrumentation recorder.

C. The snow probes of the University of Innsbruck

The different snow probes developed by the University of Innsbruck use air-gap condensers as dielectric sensors and, according to the relatively low operating frequencies ($f < 100$ MHz), alternating current bridges in the sensor electronics. The condensers consist of 7 stainless-steel plates, 10×13 cm^2, 1.5 mm in thickness, and a spacing of 2.1 cm. Block diagrams of the sensor electronics of the different probes are shown in Figs. 7(a) and 7(b).

Figure 7(a) shows the sensor electronics of the probe G2, based on a Twin-T bridge. This system has been optimized for 4 operating frequencies of 1, 5, 9.3, and 13.6 MHz, respectively.[9] After completed tuning, both the relative dielectric constant ϵ' and the loss factor ϵ'' can be determined separately. The quantity of interest ϵ' follows from the simple formula:

$$\epsilon' = 1 + \alpha \Delta c,$$

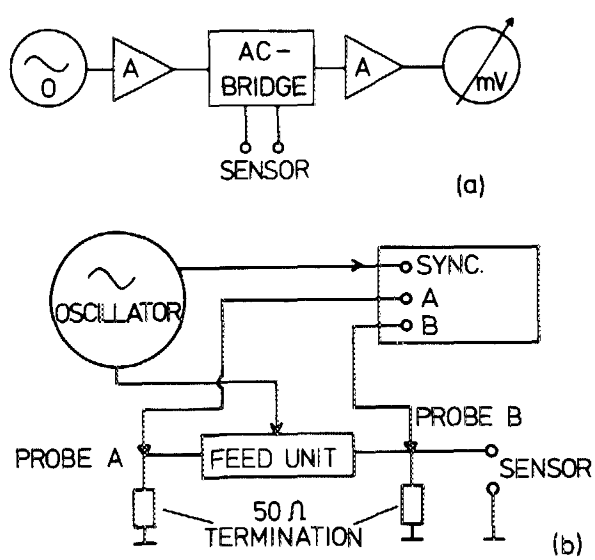

FIG. 7. (a) A block diagram of the sensor electronics of the snow probe $G2$ (Twin-T bridge) and G3 (Wien–Robinson bridge). O: oscillator; A: amplifier; mV: voltmeter. (b) A block diagram of the sensor electronics of the snow probe G4 based on a 50-Ω microwave bridge.

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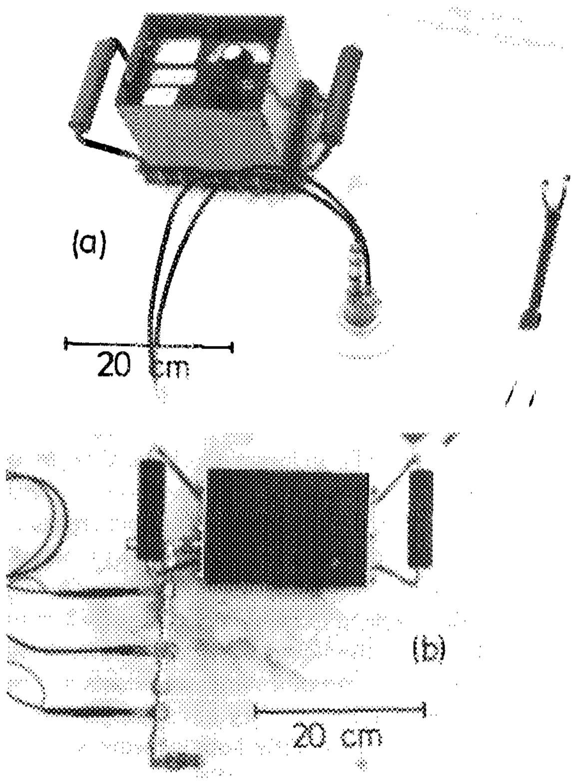

FIG. 8. (a) Coaxial and fork resonators are shown together with G1, the absolutely calibrated snow moisture meter. (b) Microwave bridge (feed unit and voltage probes) and the plate condenser.

where Δc means the difference in capacity of the sensor with and without snow.

The block diagram of the sensor electronics of the probe G3, based on a Wien–Robinson bridge, is also shown in Fig. 7(a). This system has been developed for measuring the complex dielectric constant of snow in the frequency range of 80 Hz–2 MHz. The real part of the dielectric constant can easily be calculated from

$$\epsilon' = 1 + \beta s - \gamma.$$

β and γ are parameters of the sensor and the bridge, and s is the measured quantity when tuning is completed.

The measurements of ϵ' at higher frequencies ($f \gg 1$ MHz) were made by means of two-port measurements using a 50-Ω microwave bridge and a network analyzer (measuring unit G4). A block diagram of the sensor electronics is given in Fig. 7(b). The built-in Microprocessor allows the measurement of the impedance of the snow-filled condenser directly.

Figure 8(a) shows the coaxial resonator and the "fork" resonator together with the absolutely calibrated moisture meter G1; Fig. 8(b) shows the measuring system G4: the air-gap condenser, the microwave bridge, and the voltage probes.

III. TEST OF THE DIELECTRIC ACCURACY WITH DRY SAND

A less delicate material than wet snow was first used to test the accuracy of some of the sensors enabling the decoupling of potential errors in determining the dielectric constant from disturbances produced in the snow. For this purpose, a fine-grained, homogeneous material with similar dielectric properties to snow in the high-frequency regime is required. We used fine-grained sand whose only moisture content was that due to capillary condensation under ambient conditions of humidity and temperature. Over a period of many days the dielectric constant remained constant within $\pm 2\%$. All sensors which were tested with the same sand are listed in Table I. The deviation of ϵ' of the sensors above 5 MHz does not exceed 1% from the mean value 2.91. On the low-frequency side, however, the instruments show a slightly larger uncertainty; the relatively large error of the measurement with G1 is due to an observed small air gap in the condenser which may not have been corrected completely. Also, at frequencies below 5 MHz, a slight increase in both the dielectric constant ϵ' and the losses ϵ'' is observed, which may be caused by interfacial polarization effects at lower frequencies. Above 10 MHz the dielectric constant ϵ' is frequency independent up to more than 1 GHz, and according to Njoku[14] remains constant throughout the cm-wavelength region.

TABLE I. Compilation of dielectric data ϵ' and ϵ'' for sand measured with the different sensors.

Sensor	f(MHz)	ϵ'	ϵ''
coax $\lambda/4$	1075	2.91	0.08
	1147	2.87 ± 0.03	0.079 ± 0.002
saw	1381	2.92	...
	700	2.90	...
fork	670	2.90	0.19
G1	3.55	3.01 ± 0.06	
G2	1.0	3.05 ± 0.04	0.76 ± 0.15
	5.0	2.94 ± 0.05	0.36 ± 0.03
	9.3	2.90 ± 0.06	0.30 ± 0.05
	13.6	2.96 ± 0.03	0.20 ± 0.05

IV. COMPARATIVE MEASUREMENTS IN WET ALPINE SNOW

Comparative measurements were carried out at the Schaufelferner–Daunferner in the Stubai Alps near Innsbruck in August 1982. The tests were made in the natural snow cover, with mean snow grain size varying from 0.5 to 1 mm on the surface and up to 2–3 mm in 3-year-old firn found in a depth of approximately 3 m.

When the first measurements were compared the result seemed to be disappointing. Discrepancies of up to 10%

TABLE II. Results of measurements of ϵ' of vertical inhomogeneous snow. Test A: measurement on the surface. Test B: measurement on a new surface 6 cm deeper.

Sensor	Test A	Test B
coax	3.04 ± 0.07	2.62 ± 0.02
fork	2.53 ± 0.01	2.41 ± 0.01
G1	2.81 ± 0.05	2.58 ± 0.03
density (g/cm^3)	0.56	0.56
W (%)	3.1 ± 0.4	1.5
W_{cal} (%)	3.65 ± 0.7	...

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TABLE III. Comparative measurements of ϵ' on nearly homogeneous snow. Test C: old 1982 snow; Test D: very coarse-grained 1979 firn; Test E: mixed and prepared sample of wet surface snow. Snow density, mean grain size d, and liquid water content are also given.

Sensor	Test C old 1982 snow	Test D 1979 snow	Test E prepared snow
coax	2.34 ± 0.08	2.29 ± 0.05	3.29 ± 0.03
saw	...	2.29 ± 0.03	...
fork	2.34 ± 0.12	2.36 ± 0.02	3.32 ± 0.03
G1	2.35 ± 0.04	2.35 ± 0.05	3.28 ± 0.04
G3	...	2.37 ± 0.04	...
G4	...	...	3.39 ± 0.05
density (g/cm^3)	0.51 ± 0.005	0.54 ± 0.01	0.58 ± 0.01
d (mm)	1.2	1.5	0.7
W (%)	1.35 ± 0.21	1.18 ± 0.17	5.1 ± 0.5
W_{cal} (%)	...	...	5.75 ± 0.70

between the mean values of the fork and coaxial resonators were observed; furthermore, the individual measurements with the sensors had a tendency to anticorrelate rather than to correlate. A strong vertical and a slight horizontal inhomogeneity of the dielectric constant of the natural snow cover was responsible for this observed behavior.

When comparing the measurements of the different sensors, it has to be remembered that the saw sensor and coaxial resonator sense only a thin layer—approximately 1 cm in depth—at and parallel to the test surface, whereas the fork resonator averages over a cylindrical volume that is orthogonal to the surface layer, and whose center of sensitivity is 6 cm below the surface. The plate condensers, however, average over a depth of 11 cm (including the fringing field) and a surface area of approximately 13×13 cm^2.

A second set of measurements was made to confirm the above interpretation. After removing the eroded top layer of snow, a flat surface was prepared and a set of measurements, Test A, was made. Then the top snow layer was again removed for the preparation of a "new" surface approximately 6 cm deeper and a second set of measurements, Test B, was made. The results of these measurements are given in Table II.

Both ϵ' and the observed standard deviation decrease with depth and the comparable measurements between coax (Test B) and fork resonator (Test A) show similar dielectric constants. As has to be expected, the measurement with G1 gives more or less the mean of ϵ' of the two other sensors.

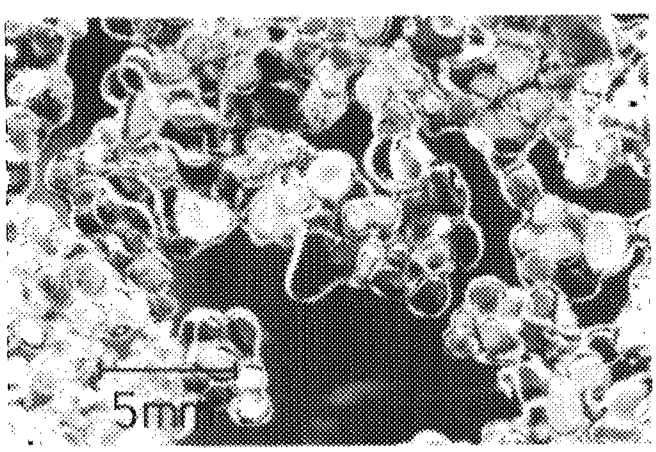

FIG. 9. Photograph of wet snow from the place of test C.

The small variability of ϵ' in larger depth encouraged us to take measurements in deeper holes in the snow where a uniform 0 °C temperature can be expected and where solar irradiation is strongly reduced. Two holes were prepared, one in moderately coarse (~ 1 mm) old 1982 snow (Test C) and one in a 3-m-deep hole in old and very coarse (~ 2 mm) 1979 firn (Test D). Since the liquid water content in these deep test holes was low, the set of test measurements had to be completed by measurements on very wet snow. The only way to obtain a wet and sufficiently homogeneous sample was by collecting and mixing a sample of surface snow (Test E). Table III summarizes these measurements on nearly homogeneous snow. Snow parameters like density, grain size, and liquid water content are also given. A photograph of the old 1982 snow of Test C is shown in Fig. 9.

Although the observed variability of ϵ' is not negligible in the coarse-grained snow of test D, the mean values found by the different instruments coincide within 1% for Test C and for Test E, except the measurement with G4. A slight discrepancy appears for the 1979 hole, where the surface sensors—coaxial and saw resonator—show lower dielectric constants than the volume sensors. This difference can be explained by the fact that mechanically the surface is defined by the top part of the grains, while the jump of the dielectric constant from air to snow is somewhat smeared out over a

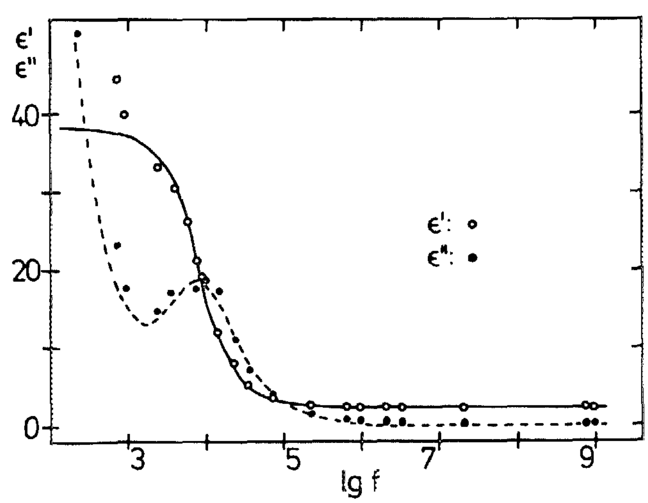

FIG. 10. Frequency dependence of the dielectric constant ϵ' and the loss factor ϵ'' for the snow of test D. Data points are shown together with model calculations.

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TABLE IV. Liquid water content (in % by volume) as seen by the different sensors, interpreted by Eq. (1) (G1 is an absolutely calibrated moisture meter).

Test	Sensor				G1	Freezing calorim	Remarks
	Coax	Saw	Fork	Plate			
A	3.9 ± 0.3	...	1.5 ± 0.1	...	3.1 ± 0.4	3.65 ± 0.70	inhomogeneous
B	2.0 ± 0.1	...	0.9 ± 0.1	...	1.5 ± 0.5	...	inhomogeneous
C	1.1 ± 0.3	...	1.1 ± 0.5	...	1.35 ± 0.21	...	
D	0.6 ± 0.3	0.6 ± 0.2	0.9 ± 0.1	1.0 ± 0.2	1.18 ± 0.17	...	
E	4.8 ± 0.2	...	4.9 ± 0.2	5.2 ± 0.3	5.1 ± 0.5	5.75 ± 0.70	

distance comparable with the grain size. This effect is extreme for the large 1979 grains (Test D).

V. SNOW MOISTURE MEASUREMENTS AND INTERPRETATION OF DIELECTRIC DATA

Systematic studies[4–6] of various mixing theories used for the interpretation of the dielectric constant of a heterogeneous material have shown that the model of Polder and van Santen is especially suited for application to wet snow. This model accounts for the snow texture and the geometry of the water inclusions by shape factors, while the snow grains are described as ellipsoids. Following Chaloupka,[15] irregularly-shaped particles can be described as a superposition of an infinite number of differently-shaped ellipsoids. Therefore, the model of Polder and van Santen can easily be modified for application to irregularly-shaped snow grains or to snow showing a large variability in shape factors. Figure 10 shows the frequency dependence of the dielectric constant and loss factor of snow from Test D together with model calculations. The shape factors of the ice grains were derived from a set of photographs; they varied from $g = 0.2$ to $g = 0.25$.

The liquid water content of 1.06% was measured with the absolutely calibrated moisture meter G1. Except at very low frequencies ($f < 1$ kHz) where additional polarization effects may occur, the model calculations agree well with the measurement. As can be seen from Fig. 10, ϵ' is frequency independent from a few MHz up to more than 1 GHz. In this frequency band, snow wetness can be calculated from ϵ' and snow density; the influence of snow metamorphism on liquid distribution, however, has to be considered.[6]

Table IV gives a compilation of calculated and measured snow wetness data for the tests A–E. Tests A and B confirm the vertical inhomogeneity of the snow layers. The other calculated and measured snow wetness data compare favorably. The uncertainties were calculated from the observed variabilities of the individual measurements. As has to be expected, snow wetness measured with G1 or the freezing calorimeter is more or less the average of the values derived from the surface-sensitive coaxial or saw sensors and the fork sensor.

VI. CONCLUSION

Test measurements with the different sensors on homogeneous samples like sand or prepared and mixed snow show the same results for the dielectric constant. In particular, the real part ϵ' was found to be frequency independent from 10 MHz up to 1.3 GHz. The measurements with sand showed that the discrepancies between the different sensors are less than 1% of ϵ'.

In the natural snow cover, however, where considerable local differences in snow texture, liquid water content, and also liquid distribution may occur, the special properties of the different sensors appear: The coaxial and saw sensors are surface sensitive (approximately 1-cm penetration depth), the fork sensor measures in a small cylindrical volume (approximately 6 cm in length) where surface effects can easily be excluded. With these sensors operating at frequencies of approximately 1 GHz, nearly nondestructive measurements of the dielectric properties of snow are possible. The result with the plate condenser, however, is the complex dielectric constant, averaged over a surface area of approximately 13×13 cm^2 and a depth of approximately 10 cm; the measurement with this sensor is destructive and restricted to operating frequencies below 100 MHz. Snow wetness can be calculated from the measured dielectric constant using the powerful model of Polder and van Santen; snow density or porosity has to be measured separately. In this respect dielectric snow wetness measurements with all these sensors are still destructive.

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