40 YEARS OF SNOW PHYSICS AT THE UNIVERSITY OF INNSBRUCK, AUSTRIA: AN OVERVIEW OF BASIC STUDIES; DEVELOPMENT OF INSTRUMENTS AND RESULTS

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ABSTRACT: Starting 1968, basic investigations have been performed of snow electromagnetic parameters – such as dielectric and magnetic functions – and of hydraulic quantities controlling the water flow through a snow cover – such as hydraulic conductivity, permeability and irreducible water saturation. The effect of snow texture and structure properties such as bulk density, porosity, mean grain size and grain size distribution, grain shape, the stage of metamorphism, and last but not least, the liquid water content and its spacial distribution were of special interest. Other topics of special interest were the detection of the geometrical structure of the water component in wet snow, its variation with water saturation and the development of techniques for snow and soil wetness measurements. Differences and similarities between maritime and alpine snow covers have been studied, and long-term measurements have been done to monitor the development of liquid water distribution and the formation of melt water waves in a snow cover. Results of a 40 year research periode are reported.

Keywords: Snow physics, electromagnetic properties, hydraulic properties, snow texture

1. INTRODUCTION

In this short review results of a 40-year research period are summarized: basic studies of snow electromagnetic properties have been started in 1968, eight years later, 1976, the research has been extended to the investigation of snow hydraulic properties. 1994 the studies have been focused on the electromagnetic properties of alpine soils and the snow - soil interface, and eight years later, 2002, comparative measurements have been started to investigate similarities and differences in water distribution of alpine and maritime snow covers.

One main topic of all these research programs was to study the effect of snow geometric structure parameters on water drainage and percolation and on the electromagnetic response of a natural snow cover with different stages of metamorphism and water content. Snow geometric structure parameters are density, porosity and size & shape of the ice grains. Controlling parameters of water drainage are the hydraulic conductivity, permeability, and the irreducible water saturation; and the electromagnetic response is characterized by the dielectric and magnetic permeability functions. The measurements have been carried out at two locations in the Stubai Alps, Tirol, Austria: in the glacier region of Schaufelferner and Daunferner at a mean height of 3000 m a.s.l., and Kühtai, at a mean height of 2200 m a.s.l., and at the Seegrube/Hafelekar near Innsbruck at heights between 1900 and 2300 m a.s.l. For the study of maritime snow covers (Jarosch and Denoth, 2005) the area around Akureyri in Iceland (county of Eyjafjarðarsýsla) was chosen as a representative for the maritime climate because of the closeness to the sea and yet a topography which matches excellently to the mountainous topography of Tirol.

2. INSTRUMENTATION

Wide band measurements ranging from a few Hertz up to the microwave K-band of snow dielectric and magnetic permeability functions have been done with a set of two network-analyzers, ZPV (Rohde & Schwarz) and HP8510A (Hewlett Packard), respectively, together with a set of different sensors, designed for field application. Both parallel plate and coplanar flat plate condensors have

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been used up to measurement frequencies of 40 MHz. In the range of 100 MHz to 2 GHz electromagnetic parameters have been derived from the driving-point impedance of monopole antennas (Denoth, 1997). A free-space technique has been applied in the microwave L- to K- bands (Denoth, 1989, 1997), whereby electromagnetic parameters of a snow sample have been deduced from an analysis of the magnitude and phase of the reflection and transmission coefficients of the smoothed air/snow interfaces.

Water drainage and short and long-term percolation studies have been done with repacked more or less homogeneous snow filled in aluminium columns of 0.25 x 0.25 m² cross section and different lengths of 1.40, 1.80 m, or 2 m, respectively. At the top of the snow columns a computer controlled sprinkler-system irrigated water and, optionally, fluorescent dye tracers. The water in- and outflow has been recorded continuously using capacitive level meters and dye tracer probes have been taken by an automatic tracer sampler (Wilhelm et al, 1992). Dye tracer concentration has been measured by a fluorometer (Gilson, type Spectra/Glo). In order to minimize snow texture changes during long-term experiments the columns have carefully been thermally insulated.

Water input rates have been chosen to simulate those produced naturally by radiation-induced melting or light rain fall. At three different levels within the snow columns water content has been recorded continuously using µP-controlled dielectric snow wetness meters (Denoth, 1994). Snow density, mean grain size and grain shape has been measured at the beginning and the end of the individual measurement series.

A typical experimental setup used for the measurement of snow electromagnetic parameters is shown in Fig.1. The networkanalyzer ZPV is shown together with the monopol antenna as dielectric probe.

A typical experimental setup used for the measurement of snow hydrological parameters is shown in Fig.2. The capacitive level meter to record water outflow is shown together with the automatic tracer sampler unit.

3. EXPERIMENTAL RESULTS

From this 40 year field research program a few experimental results of special interest are selected: Basic measurements of the incremental dielectric permittivity E and its dependence on water content (W) are shown in Fig.3 for two frequencies of 20 MHz and 8 GHz, respectively. E reflects the contribution of the water component to the total dielectric function. And Fig.4 shows a detail of a a long-term measurement of water percolation; data points are shown together with a model calculation according to Darcy’s gravity flow theory. The only parameter to be fitted is n, the “hydraulic” exponent, which relates the water flux u to the effective water saturation, S*:

$$u = K\,S^{*n};\; S^{*} = (S - Si) / (1 - Si)$$

Si the irreducible water saturation, and K the hydraulic conductivity (Denoth and Seidenbusch, 1978).

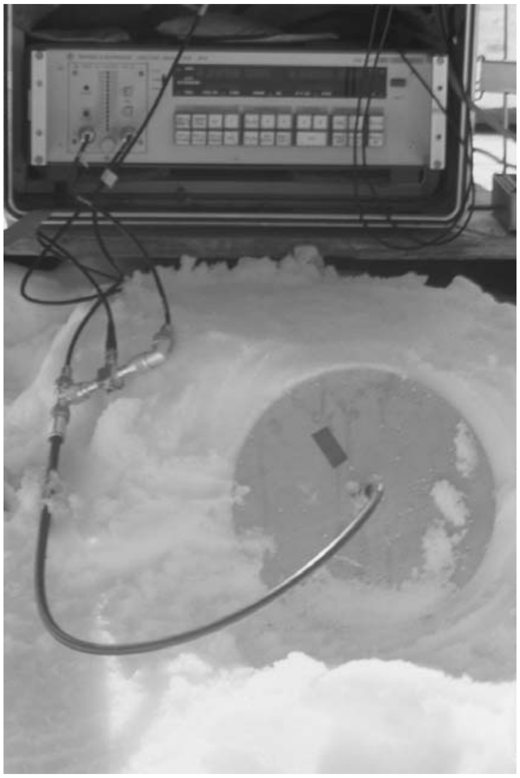

Fig.1. The networkanalyzer ZPV and the monopol antenna as dielectric probe.

Experimentally derived relations between the geometric structure parameters of the constituents of wet snow [the solid ice matrix and the liquid water body] – and snow characteristic quantities as dielectric (ε) and magnetic (µ) permeabilities, S and Si, the total and irreducible water saturation, and the hydraulic

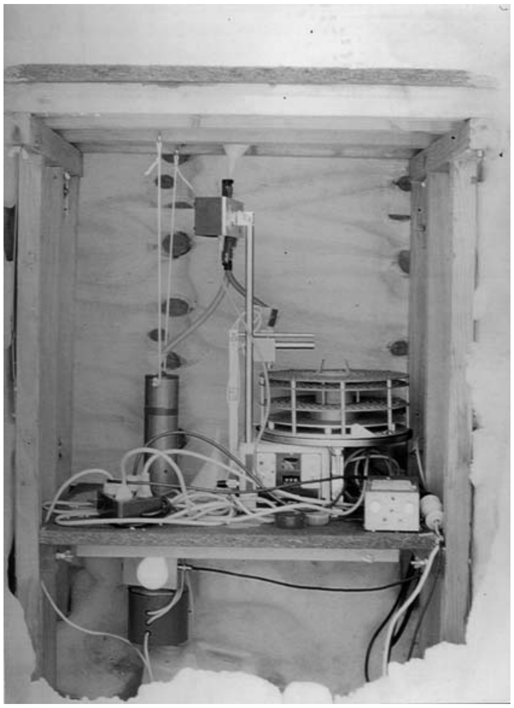

Fig.2 Capacitive level meter (left) and tracer sampler unit.

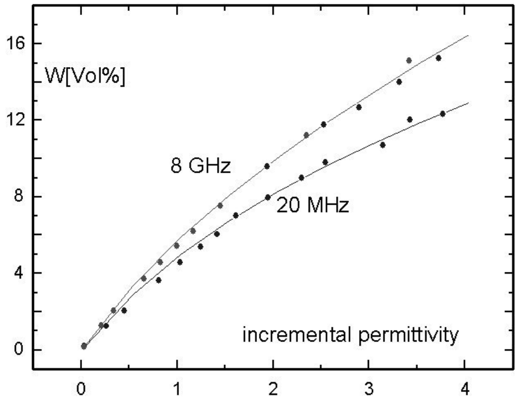

Fig.3. Dependence on water content W of the incremental permittivity for 2 selected frequencies of 20 MHz and 8 GHz.

exponent n are shown in the Figures 5 to 8. The solid ice matrix is characterized by its mean grain size, d, and grain shape, gi; the water body by water saturation, S, and "shape" of the water inclusions, gw. Grain shape gi has been derived from a photographical analysis of snow samples (Denoth, 1982a), and gw is defined as the effective electric depolarization factor of the water body, which solely depends on geometry (Denoth, 1982b).

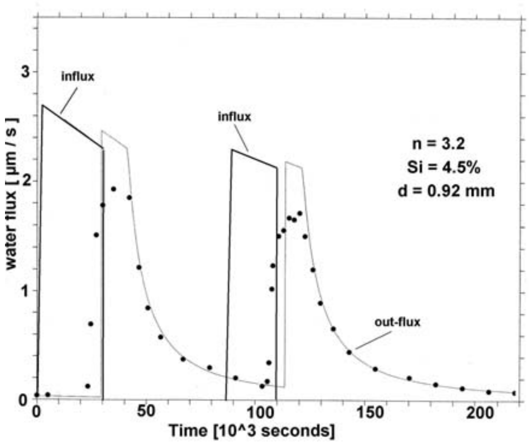

Fig. 4. Detail of a long-term water percolation measurement. Water influx, data points for water out-flux are shown together with a model calculation.

Fig. 5 shows the static (or extremely low frequency) dielectric permittivity as dependend on the ice grain shape and porosity; solid lines represent calculations according to the multiphase mixture model of Polder & van Santen (Sihvola, 1999). Open symbols represent data points of snow samples with ice shape factors less than 0.1, and solid circles represent samples with shape factors in the range 0.23 ≤ gi ≤ 0,30. It results a strong dependence of the static permittivity on porosity Φ and grain shape gi. So, the low-frequency limit of the dielectric function may be used as a textural index.

Fig. 6 shows the dependence on water saturation S of both the shape factor of the liquid water inclusions, gw (represented by solid circles), and the magnetic loss factor µ" (represented by open circles). As µ" depends strongly on frequency and grain size, data shown have been selected for a measurement frequency of 14 GHz and are normalized to 1mm grain size. S is the water content W normalized to the snow pore volume, S = W/Φ. Three main saturation regimes with different values of gw can be observed, and are marked in the figure by arrows: a pendular zone characterized by isolated water bodies, with

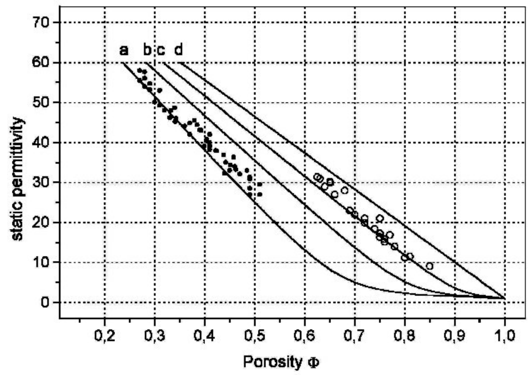

Fig. 5. Dependence of the static dielectric constant of dry snow on porosity Φ and grain shape. Solid circles represent old firn type snow, open symbols represent new snow. The solid lines show model calculations for 4 values of gi: 1/3 (a), 0.2(b), 0.1(c), and 0(d).

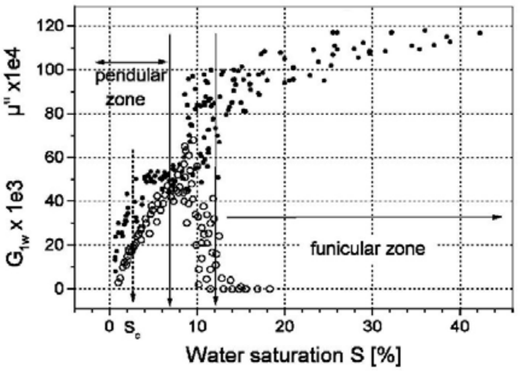

Fig. 6. Dependence of the shape factor gw and the magnetic loss factor µ“ on water saturation S. Different saturation regimes are marked by arrows.

gw < ~0,05, a transitional zone and a funicular zone characterized by merged water bodies, with gw > 0,08. Within the pendular zone, a sub-zone may be formed which is characterized by increasing magnetic losses µ“ with saturation, due to an induced diamagnetism caused by toroidal water structures. In addition, within the pendular zone a second sub-zone is formed at saturations S less than a critical saturation Sc ~ 3%. This sub zone is characterized by a strongly decreasing shape factor gw, gw → 0.

In this zone 0 < S < Sc the quantity of ice grains interconnected by capillary bridges decreases gradually; for S > Sc the quantity of larger fluid clusters increases. The critical water saturation, Sc, where confluence of water menisci begins, depends on the shape of the ice grains (Denoth, 1982a). Sc varies from Sc ~ 8% for newly fallen snow which has not undergone significant metamorphosis to Sc ~ 3% for old firn type snow with well rounded ice grains.
Surprisingly - or not? - in recent studies of the mechanical stability of moist/wet sand walls built-up of spherical grains, and analyzing water distribution by X-ray techniques, similar structures of water inclusions and similar / identical transition zones between different arrangements of water bodies have been found (Blossey, 2008).

The effect of grain shape gi on the limiting water saturation Si (irreducible saturation) derived from long-term water drainage and/or percolation experiments is shown in Fig.7. Data points are given together with a polynomial data fit (solid line). It is remarkable, that Si, the irreducible water saturation derived from drainage / percolation experiments excellently compares to the critical saturation Sc derived from electromagnetic measurements: Sc and Si may be identical.

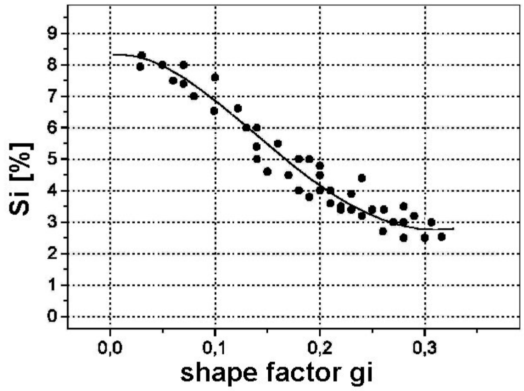

Fig. 7. Effect of ice grain shape gi on the irreducible water saturation Si. The solid line represents a polynomial data fit.

From a recently done re-investigation of water percolation data a weak correlation of the hydraulic exponent n with the mean grain size has been deduced. This is shown as a preliminary result in Fig. 8 together with a 2^{nd} order polynomial fit. The relative large scatter in the data indicates, however, that additional snow textures parameters (may be grain shape) influence n.

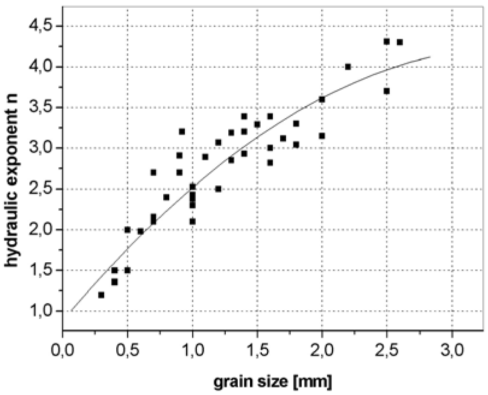

Fig. 8. Dependence of the hydraulic exponent n on mean grain size. The solid line represents a 2^{nd} order polynomial fit.

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