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TDR Probes for Measuring Dielectric Permittivity of Glacial Ice Cores: Design and Performance

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Abstract

The dielectric properties of glaciers and ice caps, measured in field or airborne surveys using ice-penetrating radar, are of considerable interest. Permittivity contrasts in polar ice caps indicate ice stratigraphy and age, whereas those in temperate glaciers may reflect changes in unfrozen water content, which is an important control on glacier mechanics. Conventionally, measuring the dielectric permittivity of ice cores in the laboratory has been carried out using capacitive measurement systems [1]. However, such systems have an effective frequency of up to 300 kHz; the effective frequency of the TDR method (typically 500 – 1000 MHz) is much closer to those used in radar surveys (20 – 200 MHz).

Here, TDR probes have been developed for measuring the dielectric properties of ice cores from a temperate glacier in Switzerland. TDR probes cannot be inserted in glacial ice, and ice has a relatively low dielectric permittivity (~3), so we designed several flat probes with 'press-on' electrodes. The short two-way travel time compared with the signal rise time also meant that conventional trace picking methods, such as the tangent method [2], yielded significant errors. Alternative approaches were investigated, including use of traces from probes shorted at each end [3], use of voltage thresholds [4,5], and use of the apexes of the first derivative of the trace [6]. The most effective probe had a serpentine design to maximize the signal travel time; using the apexes of the first derivative proved the most effective trace picking method.

The dielectric permittivity of the ice cores was primarily dependent on air content. Most cores had dielectric permittivities of around 3.2, which correspond with literature values for air-free ice [7]. Ice cores from accumulation areas of the glacier which had not been deeply buried showed lower dielectric permittivity values owing to significant air content. The effects of unfrozen water present within the intercrystalline vein system on dielectric permittivity were too small to detect, because of its relatively low volumetric fraction. TDR has the potential to replace capacitive profiling as the standard technique for characterization of the dielectric properties of ice cores; however, use of a short rise-time signal generator with dense trace sampling would improve the accuracy of the measurement considerably.

Key words: Glaciers, ice, flat probes, water content, trace picking

Introduction

Field-based radar-echo sounding (RES) techniques have been used extensively to charactrise glaciers and ice caps, both in polar and temperate glaciers. In polar ice sheets, radar surveys typically identify ice stratification by detecting contrasts in dielectric permittivity of sequential ice layers [1]. In temperate glaciers, radar surveys have been interpreted to provide estimates of unfrozen water content [8, 9, 10, 11], which is expected to have a very strong influence on the velocity of electromagnetic (radar) waves in ice, because of the high dielectric constant (relative dielectric permittivity) of liquid water (~80) in comparison with ice (~3). Liquid water is known to be present in glacial ice in both vein systems at triple junctions between ice crystals [12], see Figure 1, and in larger scale features such as fissures and englacial conduits [10]. Characterisation of the amount of liquid water present in glacial ice is important because this has a very strong influence on glacier mechanical properties, which in turn determine how ice masses will respond to climate change. However, estimates of water content based on RES techniques are often of the order of several volumetric percent - much higher than unfrozen water contents measured in glacial ice cores. This may be because the unfrozen water is present in macroscopic inclusions (for example fracture systems) which are not included in ice cores, or because the cryophysical relationships typically used to determined unfrozen water contents of ice from radar wave velocities such as the Looyenga mixing rule [13], are incorrect (the Looyenga mixing rule predicts that 2% unfrozen water should increase the net dielectric constant by about 0.4 units). To investigate this, we developed press-on Time Domain Reflectometry (TDR) waveguides specifically for measuring the dielectric permittivity of cores taken from the Glacier de Tsanfleuron, Switzerland. Ice cores extracted from this glacier have been extensively characterized using SEM techniques [14], and the laboratory characterization work reported in this paper forms a part of a further study, which also consists of extensive radar surveys and numerical modeling of glacier movement. Experiments were conducted using several TDR waveguide designs on eight ice cores at temperatures between -2°C and -25°C.

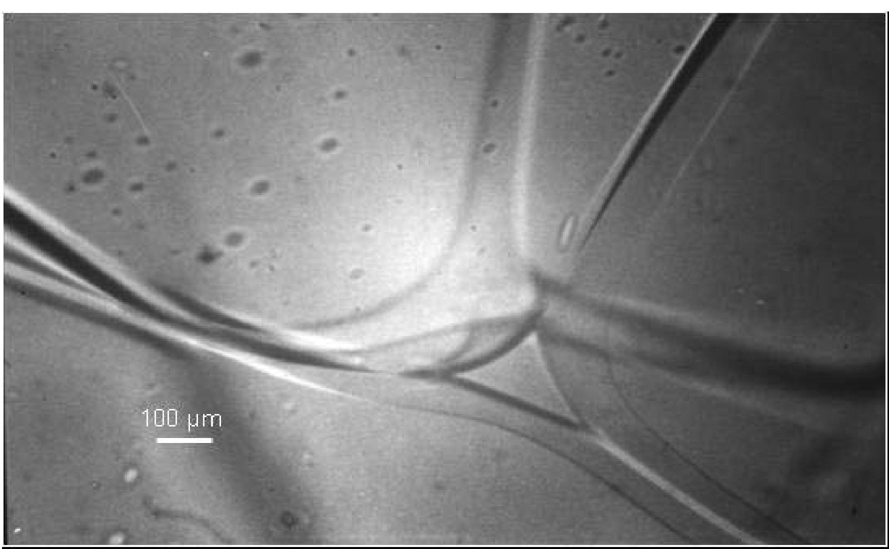


Figure 1. Example of a node (junction between ice crystals) in ice in thin section. Liquid water may exist at this junction of grain boundaries. View is down an interconnecting vein (Mader, personal communication, 2005).

Methodology

TDR was originally developed for characterizing soil water content. Soil water contents are typically several percent to several tens of percent, resulting in dielectric constants at MHz to GHZ frequencies that vary between perhaps 6 and 30, depending on the soil type and environmental conditions. In contrast, ice typically exhibits relatively low dielectric permittivity, typically around 3 to 4 dielectric units depending on density (i.e. air content), unfrozen water content, and chemical composition. Furthermore, TDR probes cannot be inserted into glacial ice. To address these issues we developed several 'press-on' waveguides designs, for use with ice cores (Figure 2). The two most successful probes designs are shown in Figure 3.

Probes were constructed by attaching brass waveguides to neoprene backing material using 'Evo-Stik' Impact adhesive. The neoprene backing material was itself mounted on solid PVC blocks to provide rigidity. The probe with wide electrodes (probe 1) was included to maximize the sampling volume as some ice cores had relatively large crystal sizes (≈5mm). The serpentine probe design (probe 2) was intended to provide the maximum possible probe length (44cm) and signal two-way travel time on the relatively short lengths (≈20 cm) of ice core available. Standard 50 ohm impedance co-axial cable was used to attach the waveguides to a Campbell Scientific TDR100 unit. This unit has a time response of 275 picoseconds with a timing resolution of 12.2 picoseconds.

Probes were calibrated using materials of known dielectric constant: calcite (K = 9.1), quartz (K = 4.5) and air (K = 1). Solids were selected in preference to liquids as they are more representative of the measurement medium (ice). Use of liquids as calibrants would have eliminated the air gaps around the edges of the electrodes where they stand slightly proud of the backing material, and so would not have been representative of measurement conditions. Calibrating using solids was undertaken by recording traces with the probes in contact with a smooth saw cut surface, under a 2kg load to ensure contact. Five measurements were taken with probes being repositioned between measurements, in order to assess repeatability.

Measurements on ice cores were taken on saw-cut surfaces in the University of Wales, Aberystwyth cold room facility. This facility has temperature control to +/- 1°C; core dielectric permittivity was measured at -25°C, -20°C, -15°C. -10°C, -8°C, -6°C, -4°C and -2°C. Three measurements were taken at each temperature with the probes being re-positioned between measurements in different orientations in order to assess repeatability; a 2kg weight was applied to maximize contact with the ice core. Probe start and end points were identified using several techniques in order to identify the best approach for ice core TDR data. Approaches used included the 'sloped tangents' method [2], using the WinTDR software supplied by the University of Utah, defining pre-determined threshold reflection coefficients corresponding to the start and the end of the probe [4,5], comparing traces with those taken with the probes shorted at the top and bottom [3], and using the peak first derivative of the reflection co-efficient [6]. The peak first derivative approach proved to be the most reliable because it was least sensitive to minor variations in trace shape. It also produced the dielectric constant values that were most consistent with values expected for glacial ice.

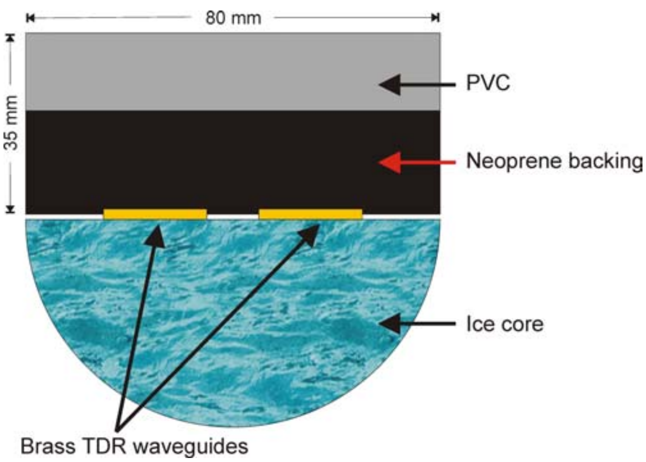


Fig. 2: Idealised usage of a TDR probe on a (half) ice-core.

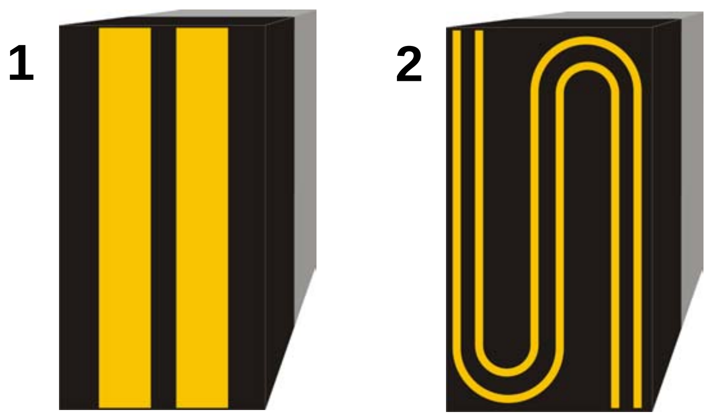


Fig. 3: TDR probe designs. Waveguides are brass and are glued to neoprene (20 mm thick), backed by PVC (15 mm thick). Each probe unit is 80 × 150 × 35 mm. Probe 1 – waveguides are 20 mm thick and 150 mm long. Probe 2 – waveguides are 3 mm thick and 440 mm long.

Calibration data

As the waveguides are mounted on backing materials, the measured dielectric constant will depend partially on the dielectric properties of the backing material and partially on the dielectric properties of the measurement medium. The measured relative dielectric constant K_{meas} will be given by,

$$K_{meas} = K_{med}\,(1-w) + K_{backing}.w \qquad (1)$$

where w is a weighting factor between 0 and 1, determining the relative contribution of the backing materials (dielectric constant $K_{backing}$), and the medium in front of the probe assembly (K_{med}). The weighting factor w for TDR probes attached to a backing material is independent of the dielectric constant of the measurement medium, provided that the backing material has uniform dielectric properties. The purpose of calibration is thus to determine both $K_{backing}$ and w using materials with known dielectric constants.

Figure 4 shows a plot of the relative dielectric constants of the calibration materials against the relative dielectric constants measured by the waveguide assemblies. Using the peak first derivative trace picking method, the calibrated values of w and $K_{backing}$ are 0.325 and 7.59 for probe 1 and 0.673 and 2.87 for probe 2 respectively. The published value for the dielectric constant of neoprene is in the range 6 – 9 [15], which suggests that the rearward sensed volume of probe 1 is mainly within the neoprene backing. The relatively low value for $K_{backing}$ for probe 2 is likely to have arisen because the electrodes pass close to the edges of the backing material, so part of the rearward sensed volume is occupied by air. This makes probe 2 (serpentine probe) somewhat less sensitive to the dielectric constant of the test material than probe 1 (the more conventional straight probe). However, as will be seen later this disadvantage of the probe 2 design is more than offset by the increase accuracy in the signal travel time measurement provided by its relatively long electrodes.

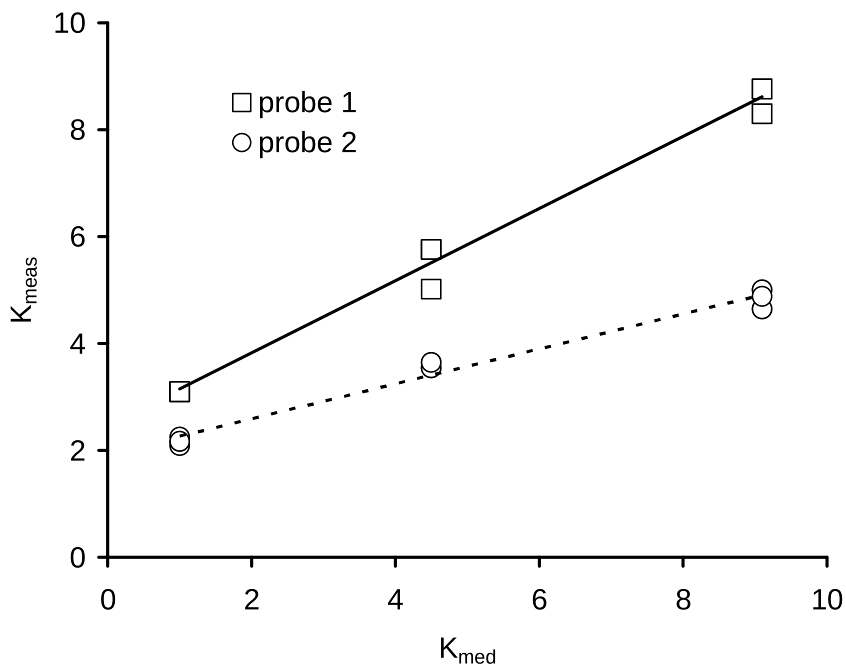
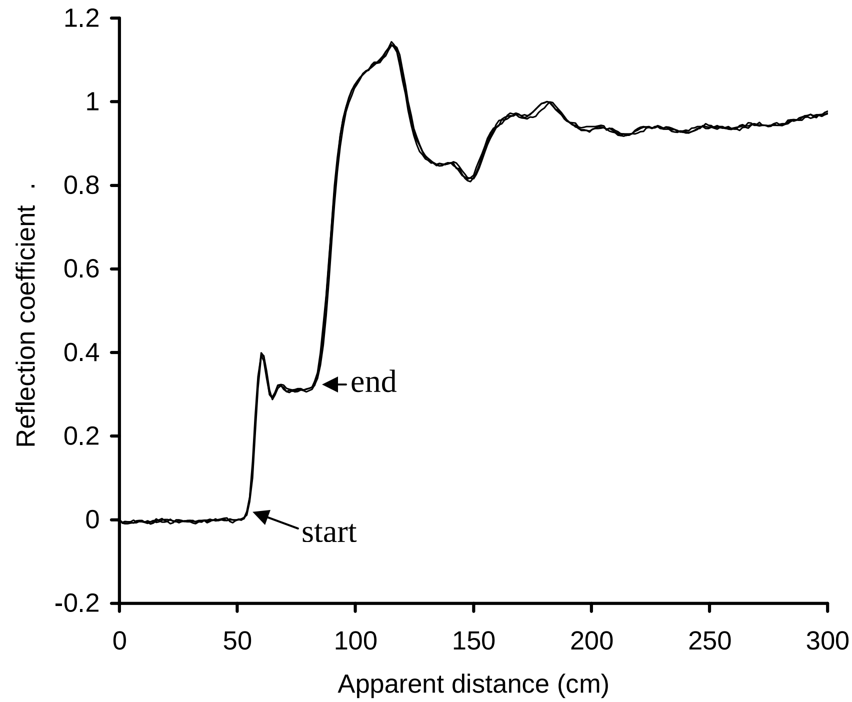


Fig 4. Calibration data. Calibration materials are air (K=1), quartz (K = 4.5) and calcite (K=9.1).

Ice Core Data

Example TDR traces recorded on selected ice cores are shown in Figure 5. The real probe length of probe 1 is 15 cm while that of probe 2 (serpentine electrodes) is 44cm. The wiggles in the trace for probe 2 at apparent distance of 25 and 50cm from the probe start represent the first and second bends in the waveguides. The graphs show successive measurements with the probe repositioned on the core between readings; as the three traces only diverge during multiple reflection events the repeatability of derived apparent probe lengths is potentially very good.



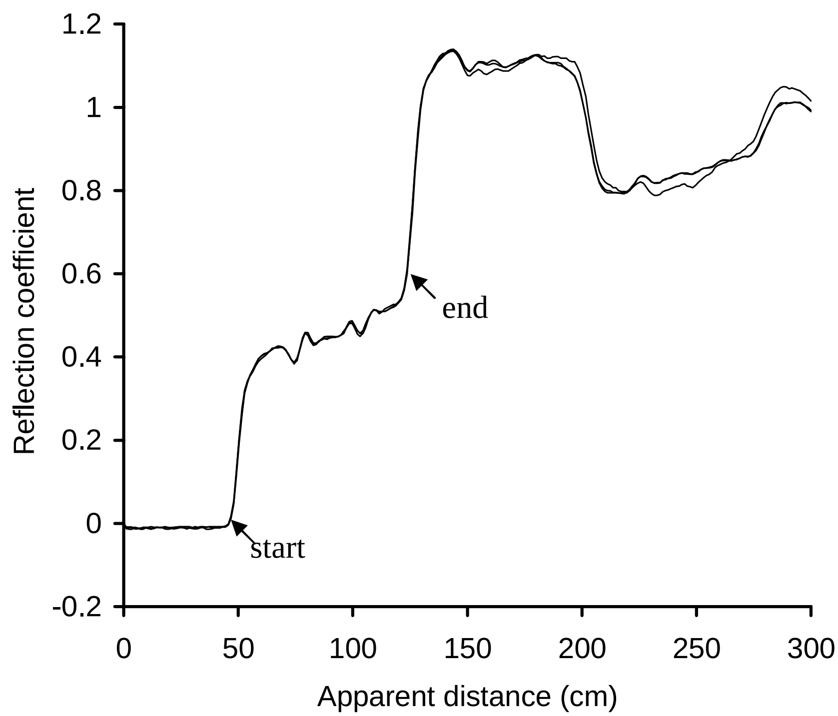


Fig. 5. Examples of TDR traces for core 1 at -25°C derived using a) probe 1, actual length 15cm, and b) probe 2, actual length 44cm.

Trace picking

A variety of methods have been developed for the identification of the start and end of the probe, and hence the apparent probe length, from TDR traces. Identification of these points is not straightforward because the TDR pulse generator has a finite rise time, and furthermore, dispersion in the cable and probe tend to cause flattening of the voltage step. In our data, because ice which has a relatively low dielectric permittivity compared with wet soil, errors introduced by the trace picking method are significant. Therefore, several methods were tested to identify that which gave the most consistent and repeatable data.

We tried the following methods for identification of the start and end of the TDR probes in the trace i) conventional method using 'sloped tangents' ii) comparing the trace with traces collected with the probe shorted at the top and bottom ends iii) using pre-determined reflection co-efficient values, referred to as 'voltage thresholding' iv) identification of the apexes of the first derivative of the trace corresponding to the start and the end of the probe. The conventional approach using sloped tangents proved unsatisfactory owing to the very steep nature of the voltage steps; essentially similar traces picked using this method produced substantially varying dielectric constants. The probe shorting approach required identification of the points where traces from the shorted probes deviated from the unshorted trace. Unfortunately this proved to be a non-trivial problem; rather than a sudden, sharp deviation, shorted traces gradually diverged from unshorted traces (see Figure 6). Hence, use of this approach required a threshold deviation from the unshorted trace to be defined, making it impossible to determine absolute values for dielectric constants.

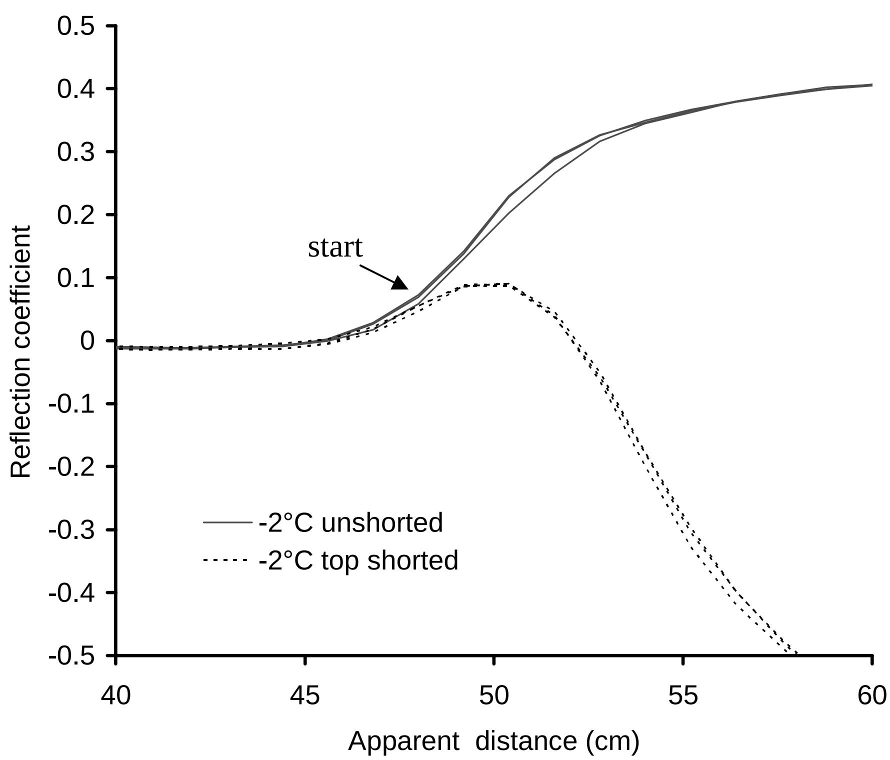


Fig. 6. Comparison of traces from start of probe 2 in shorted and unshorted condition (ice core 1 at -2°C).

Definition of voltage thresholds corresponding to the start of the upwards ‘kicks’ in the trace corresponding to the start and end of the probe produced repeatable results. However, the dielectric constants determined using this method represent those corresponding to the maximum passable frequency present within the TDR step pulse [6]. In contrast, those determined using the maximum first derivative approach correspond to the frequency at which most of the power of the signal occurs (David Robinson, pers. comm., 2005), typically 700 – 1000 MHz, which is closer to radar frequencies. Furthermore, the maximum first derivative approach produced a very high degree of repeatability in apparent probe length (see Figure 7), and does not require the selection of threshold voltages, so involves less subjectivity than the thresholding approach. Therefore, all of the values reported below were determined by this trace picking method.

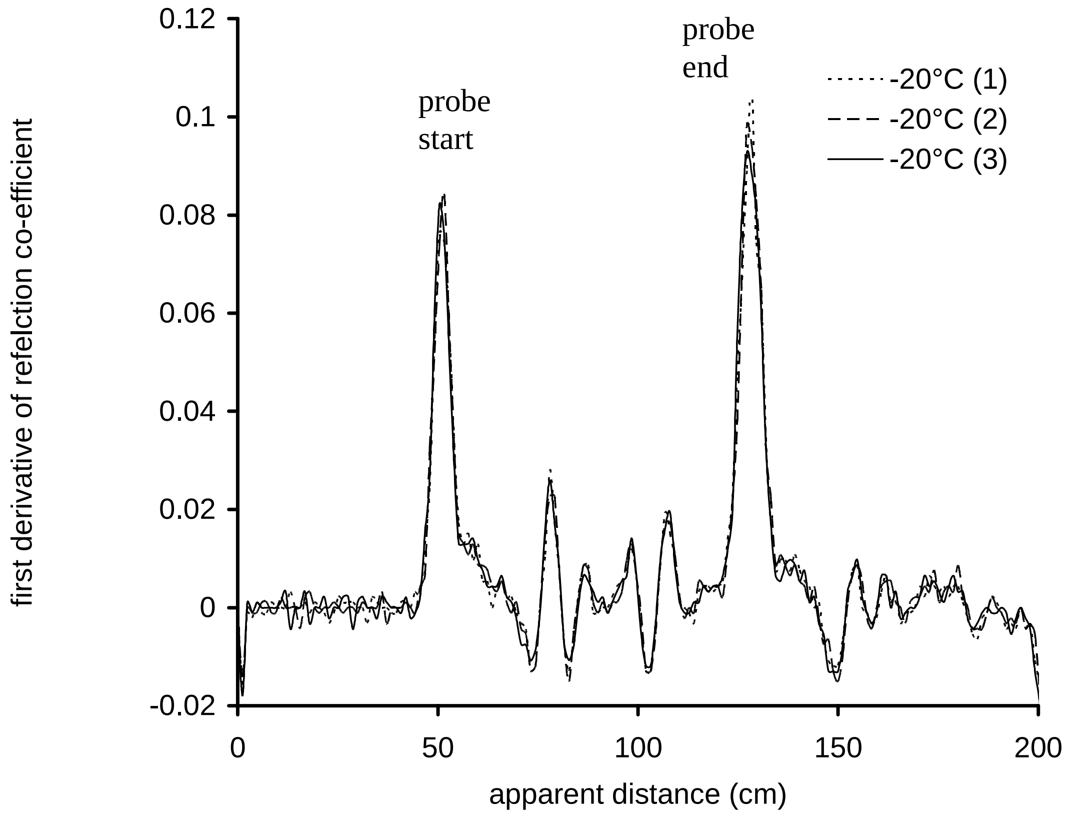


Fig. 7. Identification of probe start and end using apex of first derivative of reflection co-efficient. Three repeat readings on core 1 using probe 2 are shown; TDR probe repositioned on the ice core between readings.

Dielectric constant values

Measurement errors, estimated from the degree of scatter between repeat readings, were significantly larger for probe 1 than probe 2 (this is a consequence of the greater length of probe 2 which increases the accuracy of the travel time determination), hence only data from probe 2 are reported. Plots of dielectric constant values for four of the ice cores against the measurement temperature are shown in Figure 8. The data show no consistent trend with temperature; hence, data for all temperatures can be averaged to reduce the effects of random errors arising from trace picking and changes in the condition of the core surfaces between datasets. Average dielectric constant values for each core along with standard deviations are presented in Table 1. Dielectric constant values for all cores except cores 5 and 9 are within ±0.2 dielectric units of the air- and unfrozen water- free glacier ice value of 3.2. Core 5, dielectric constant around 2.5, is visually 'firn' like – i.e. it is compacted snow from the upper few metres in the accumulation area. Core 9, dielectric constant around 2.9, is also from a relatively shallow level (3m depth) from an area of the glacier which was an accumulation zone when the core was extracted in 1997. Hence the relatively low dielectric permittivity of these cores can be attributed to significant air content. Air contents for these cores of 10-20% are indicated using the Looyenga mixing rule [13], assuming no liquid water.

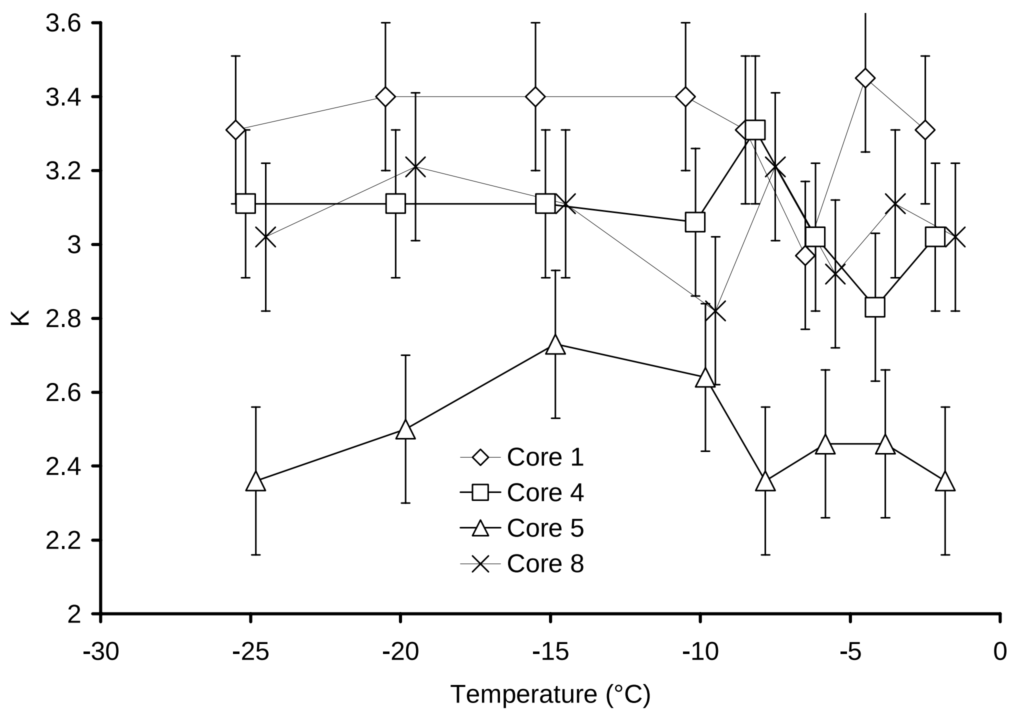


Fig. 8. Dielectric constant versus temperature for selected ice cores determined using probe 2. Traces picked using apex of first derivative. Data points corresponding to each measurement temperature are offset by up to 0.5°C on the temperature axis for reasons of clarity.

Table 1. Dielectric constant values from maximum first derivative, averages for all temperatures, probe 2.

core no.	**1**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
core name	96-5_V71	96-5_V128	96-5_V200	97-1_A10	97-1_A86	97-1_A88	97-2_B9	97-2_B10
depth (m)	20.67	37.91	42.83	4.04	35.54	36.36	3.21	3.58
Avge. K	3.32	3.20	3.07	2.49	3.13	3.21	3.05	2.86
SD	0.15	0.21	0.14	0.13	0.16	0.22	0.14	0.21

Summary and Conclusions

The permittivity of glacial ice is of considerable interest because of the development of radar characterization of both polar and temperate glaciers. Conventionally, dielectric constants of ice cores have been measured using capacitive probes, but the operating frequency of these probes falls well below typical frequencies used in radar surveys. TDR represents a better approach for characterization of ice-core dielectric properties. Here, press-on TDR probes have been developed for measuring the dielectric permittivity of glacial ice cores extracted from a Swiss glacier.

Two probe designs were tested extensively: one conventional straight electrode probe, with wide, flat electrodes to increase the sampling volume, and one serpentine probe design aimed at maximizing the signal travel time given the limited size of the ice cores. Both probes were calibrated using air and solids of known dielectric permittivity. While the straight electrode probe proved more sensitive to the dielectric permittivity of the measurement medium, the serpentine design has a much better signal to noise ratio and produced more repeatable data. The conventional approach to trace picking (i.e. sloped tangent method) proved unsatisfactory owing to the relatively low dielectric permittivity of the measurement medium. Various other approaches were tried, and the most satisfactory method was found to be use of the apex of the first derivative of the trace to identify both the start and end of the electrodes, as described by reference [6]. This method was not sensitive to minor variations in trace position, and produced the least scatter between repeat readings for our data (note that use of this method to identify the start of the electrodes may not be appropriate in cases where a complex probe head or balun is present). The accuracy of the resulting dielectric constant values is around ±0.2 dielectric units based on the degree of variation seen between datasets collected at various measurement temperatures. Accuracy could potentially be improved by use of a shorter rise time TDR signal generator with higher temporal resolution sampling, and by re-cutting or smoothing ice core surfaces immediately before the TDR probes are applied.

The results of the study suggest that the presence of air within glacial ice is a significant factor influencing radar velocity. Air may be present in ice at shallower levels within glaciers, which was never fully compacted. The potential presence of air within the ice needs to be taken into account in the interpretation of RES surveys on glaciers. Although unfrozen water will inevitably have been present at crystal boundaries within the ice cores, varying the temperature and hence the amount of liquid water present did not have a measurable effect on the dielectric permittivity over the range of temperature investigated. This result suggests that the amount of water present at grain boundaries even at the highest temperature (-2°C) was < 1%; hence the percentage level water contents interpreted from field surveys of glaciers probably arise from either the presence of macroscopic water bodies within glaciers (i.e. water filled fissures or conduits) or indicate ‘well-rotted’ ice at the pressure melting point.

Acknowledgements

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Biography

Jared West gained his first degree in Natural Sciences from the University of Cambridge in 1988, and was awarded a PhD by the University of Leeds in 1992. Since then he has worked at the University of Leeds in various roles, and is currently a Senior Lecturer in Hydrogeology.

David Rippin gained his first degree in Geography and Geology from the University of Birmingham in 1996; and was awarded a PhD by the University of Cambridge in 2001. He subsequently worked as a Post-doctoral Research Assistant at the University of Bristol, and then at the University of Leeds. Recently, he took up a position as an Academic Fellow at the University of Hull.

Tavi Murray gained her first degree in Physics and Computer Science from the University of Aberystwyth in 1987, and was awarded a PhD by the University of Cambridge in 1990. She subsequently held various positions at the University of Leeds and was awarded a Chair position in 2004. She is currently Professor of Glaciology at the University of Wales, Swansea.