A NEW TECHNIQUE FOR DIELECTRIC LOGGING OF ANTARCTIC ICE CORES

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Résumé - Un système a été construit pour obtenir rapidement le profil diélectrique des carottes de glace au fur et à mesure de l'extraction. Cet équipement a permis d'obtenir des résultats sur les premiers 38m d'un forage à 133 m à Dolleman Island Antartique. Les résultats montrent que la méthode utilisée permet d'accéder aux paramètres habituellement obtenus par les techniques conventionnelles. Des analyses chimiques et isotopiques de la carotte sont nécessaires avant d'établir des corrélations entre le comportement diélectrique de la glace polaire et les autres paramètres.

Abstract - A system has been developed for rapid dielectric profiling of ice cores at the time of drilling. Data from the top 38 metres of a 133 m core from Dolleman Island, Antarctic Peninsula, show that this method is capable of providing detailed dielectric parameters comparable to those obtained by conventional techniques. Chemical and isotopic analysis of the core is needed before establishing correlations between the dielectric behaviour and other parameters.

1. INTRODUCTION

Radio echo sounding has revolutionized studies of the third dimension in ice sheets. The technique provides continuous profiles of ice thickness and roughness of the bedrock, and in addition, stratigraphic detail within the ice. Some internal echoes have been tentatively correlated with the dates of volcanic eruptions [1] and changes in ice acidity due to volcanic activity have been detected in ice cores from high-field direct current measurement [2,3]. Admittance variations at echo sounding frequencies (VHF) could be due to the same processes that lead to high scratch conductivity at direct current or to variations in the dielectric absorption in the kHz region. The present studies seek to explore these possibilities by profiling ice cores in the range 20 Hz to 300 kHz at the time of drilling, and to investigate whether annual cycles are apparent.

A 133 metre ice core was drilled at an elevation of 400 metres near the summit of Dolleman Island (70°37'S, 60°44'W) in the Antarctic Peninsula in the summer of 1985-86. Earlier studies had shown that shallow cores from the site preserved a clear seasonal cycle, undisturbed by snow melt. The intention of the drilling was to develop a record of climate and volcanism over a period of several hundred years. The top 38 metres of the core were logged in the field for their dielectric behaviour. Pit and shallow core studies showed that the meltwater conductivity of the ice followed an annual cycle with values ranging from 5 to 10 μS cm^{-1} at 0°C.

2. INSTRUMENTATION FOR PROFILING ICE CORE

The system is based on a Wayne Kerr 6425 Multi Bridge and Hewlett Packard HP85B Microprocessor [Figure 1]. It enables a one-metre length of core to be studied at 5 cm intervals at 42 frequencies between 20 Hz and 300 kHz in thirty minutes, making in situ study practical. Accuracy in capacitance and conductance is around 0.5% over most of the measurement range.

The electrode assembly contains twenty 'LO' electrodes each consisting of curved segments of palladium-coated brass 5 cm in width [Figure 2]. Together they span a 1 m length of core. Guard plates, also curved and 25 cm long, are fitted at

each end of the 1 m section. The side guards are flat plates of anodized aluminium and run the whole 1.5 m length of the electrode assembly. The 'HI' electrode is similar to the 'LO' electrode except that the curved section is not split into 5 cm lengths: all curved sections have the same radius of curvature as the ice core. The size and shape of the electrodes were derived from experiments on ice cores. The choice was a compromise between having a suitable impedance for accurate operation of the bridge, and the need for sufficient resolution in the profile to detect annual cycles in an accumulation regime of 0.6 metres of water a year. The 108° arc for each electrode was again a compromise. A greater angle of arc would have given a larger admittance but this would have been dominated by the ice near the edges of the plate - a region likely to be the most contaminated in any drilling operations. The electrodes are enclosed in an aluminium case to prevent electromagnetic interference. Usually two adjacent electrodes are connected to the bridge and the remaining electrodes earthed. The sequence of measurements is controlled by an electronic switching circuit and a complete set of capacitance and conductance measurements for each electrode combination along a core is stored by the HP85B on magnetic cartridge.
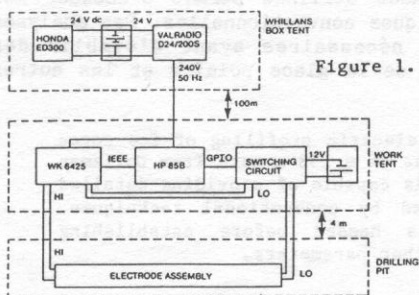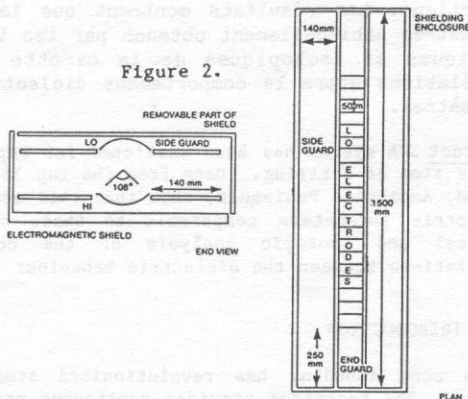

Figure 1.

Figure 2.

Figure 1.   Schematic diagram of the dielectric profiling equipment.

Figure 2.   Construction of the electrode assembly.

3.   RESULTS

The electrode assembly was housed in the 3 m deep drilling pit. After recovery, weighing and stratigraphic analysis, the core was put in a polythene sleeve, and allowed to reach the pit temperature of −9 ± 1°C. Temperature fluctuations during dielectric measurement of a core section were less than 0.1°C. Figure 3 shows capacitance and conductance values for the first eight lengths of retrieved ice core, measured whilst the cores were sealed within their protective polythene. Three frequencies have been selected in Figure 3: 60 Hz and 75 kHz are typical of the static and high frequency end of the dominant dispersion in polar ice, whilst 12 kHz is close to its relaxation frequency. In order to test the repeatability of the system, the first core section, 0.65 m long, was measured on three occasions. After the first measurement it was left untouched for over an hour and remeasured. Subsequently it was removed and repositioned within the electrode assembly. The three records match well.

The horizontal scale in Figure 3 represents the separate data sets. If two electrodes are used at a time, there are a possible 19 data sets for the 1-metre long electrode assembly. Not all of these are measuring areas of ice core (since not all ice cores are 1 metre long), so data from the gaps were removed before plotting the diagram. Large variations of capacitance and conductance were found.

This variability extended to the whole 38 m of ice core. With 720 individual data sets a statistical analysis could be performed on all the data recorded. Using the measured air capacitance of 1.1 pF for each electrode pair (which is close to the theoretical expectation) Figure 4 shows mean values and standard

deviations for ε" the imaginary component of permittivity; σ conductivity; and ε"/ω (ω is the angular frequency) against ε' the real component of permittivity. The diagrams demonstrate that the ice experiences a major relaxation process in the frequency range investigated.
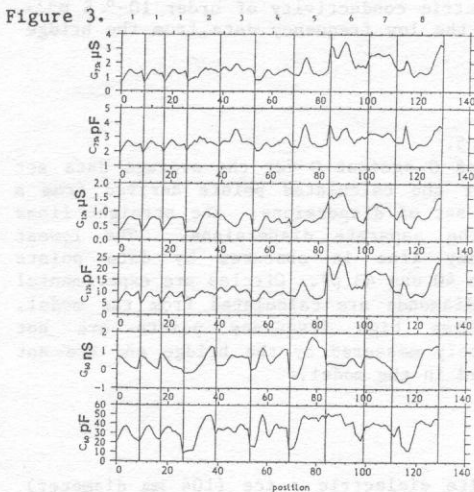
Figure 3.

Figure 4.

Figure 3. Capacitance and conductance values at 60 Hz, 12 kHz and 75 kHz for the top 6.6 m of the core. The first 3 sections numbered 1 are the same piece of ice. The ends of each section are shown with a vertical line. Each data set is represented by one position on the x axis.
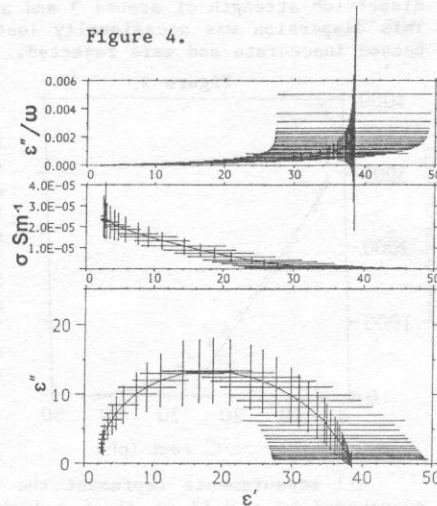
Figure 4. Graphs of ε"/ω, σ and ε" against ε' of the average data set from the top 38 m of core. The bars represent ± 1 standard deviation from the mean.

An analysis of the dielectric spectrum has followed closely the techniques used by Gross et al. [4] and earlier by D.B. Knoll in reference [5]. It is based on the plots of conductance G, against capacitance C. The ice dispersion is assumed to be described by a high frequency permittivity ε_∞ and a series of overlapping simple Debye spectra, each characterised by a dispersion strength $\Delta\varepsilon$ and relaxation time τ. The G-C diagram should then show a set of straight lines bent by the effects of adjacent spectra. The analysis program corrects each portion of the plot for the effects of its neighbours until a set of consistent relaxation parameters emerges. To start the program, a set of initial 'break points' is given to delimit the frequency range of each dispersion. Once a set of relaxation parameters has been calculated, the agreement is compared between the measured dielectric data and those derived from the model. If the agreement is unsatisfactory a different set of 'break points' is generated, and this process continues until the fitting is acceptable. The next data set (the adjacent core) is analysed with these break points for its initial fitting.

Figure 5 shows the average G-C diagram for the 38 metre core. Experimental values and the values computed from the derived dielectric parameters are shown together with the three straight lines which individually contribute to the observed curvature of the model's G-C dependence. Three dispersions adequately describe the behaviour at -9°C of firn in the density range 0.415 Mg m^{-3} to 0.758 Mg m^{-3} surrounded by polythene.

The highest frequency dispersion has a relaxation frequency of 15 kHz, a dispersion strength of 25 and a dielectric conductivity of 2.5 x 10^{-5} S m^{-1}. This corresponds closely with values reported previously in the Literature for the major relaxation process in polar ice [6]. The second dispersion has a relaxation frequency of 2.5 kHz, a dispersion strength of 12 and a dielectric conductivity of 2 x 10^{-6} S m^{-1}. There may be a correspondence with an "intermediate" dispersion

found by Gross et al. [7] and von Hippel et al. [8]. The dielectric conductivity of this dispersion is very close to typical values of d.c. resistivity found by a four-electrode resistivity survey of Dolleman Island and elsewhere in polar regions [9]. The low frequency dispersion has a relaxation frequency of around 100 Hz, a dispersion strength of around 3 and a dielectric conductivity of order 10^{-8} S m^{-1}. This dispersion was occasionally lost when the low frequency data from the bridge became inaccurate and were rejected.
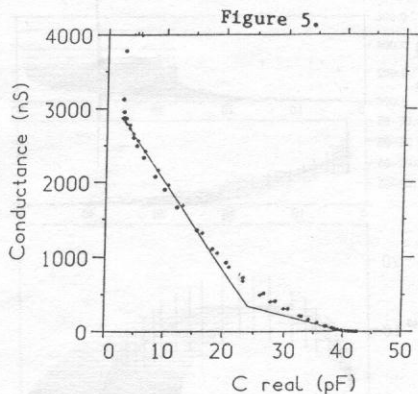

Figure 5.

Figure 5.
Graph of G against C for the average data set and for the calculated points derived from a fitted set of dispersions. The straight lines show the separate dispersions. The lowest frequency line is obscured by data points between 40 and 43 pF. Circles are experimental data; diamonds are calculated from the model. The three high frequency points are not accurately measured by the bridge and are not included in the model.

All measurements represent the composite dielectric : ice (104 mm diameter) surrounded by a 0.13 mm thick polythene sleeve. The polythene sleeve acts as a blocking layer and the true ice core parameters are in principle accessible [10]. However their derivation, particularly at low frequencies, is sensitive to the choice of the low frequency intercept on the C axis. The parameters of the highest frequency dispersion are the least affected by this complication — and are also, fortunately, the most important values in the study.

The major problems involved in the individual analysis of the 720 data sets were

1)   The derivation of ice-core parameters from an ice core-polythene capacitor.
2)   The choice of the dielectric model to which the experimental data were compared.
3)   The criterion used to judge the fit of experimental data to that of a dielectric model.

These are discussed in turn.

1) No attempt has been made to remove the effect of the polythene blocking capacitance from the results. The low frequency capacitance varies from around 20 pF to 80 pF. This suggests that variations occur in the blocking layer capacitance, probably due to an irregular ice core surface/polythene contact. Nevertheless the variations between sections of the ice core over the whole frequency range are greater than can be explained by this alone.

2)   The individual data sets have been fitted to the same model as selected for the average of the 38 m of core, i.e. three Debye dispersions seem adequate for the ice-polythene system at $-9°C$.

3)   This problem has been addressed before for the composite ice-insulator dielectric [10]. We see every advantage in following a similar procedure, that is to minimize

$$\sum_i \left| (C'_{ic} - C'_{im})^2 + (G_{ic} - G_{im})^2 / \omega_i^2 \right|$$

where there are i frequency points, c represents calculated model values, and m represents measured values. A fit was deemed acceptable when the experimental data

fitted the model to a r.m.s. error of less than 1.5% of the low frequency limiting capacitance value. This was generally easily achieved; however, a few data sets failed to fit satisfactorily, and these will be reinvestigated.

4.   DISCUSSION

The 720 samples increase by an order of magnitude the number of ice-core samples examined for dielectric behaviour. Although at a fixed temperature, they have the advantage of being measured at the time of drilling before possible contamination and 'ageing' by atmospheric gases could occur [3]. By being measured within polythene, the virgin state of the ice core is preserved for subsequent chemical analysis. The effect of transport on the cores will be re-examined at a later date.
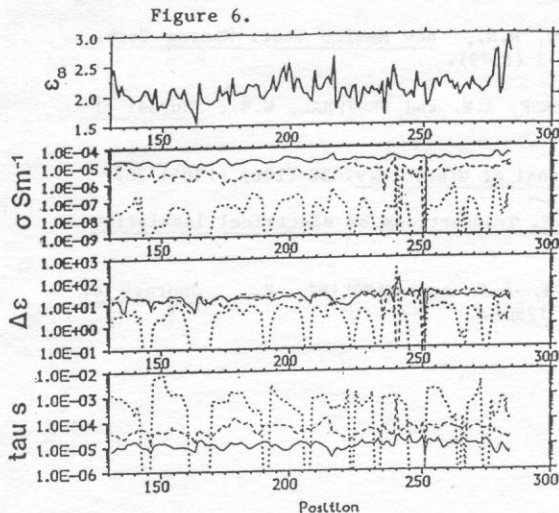
Figure 6.

Figure 6.
Plot of ice core parameters derived for 154 data sets between 6.6 m and 15.3 m down the core. Each data set represents one position on the x-axis. The dotted lines represent the low frequency dispersion, the dashed lines the second dispersion and the continuous lines the dominant dispersion. Where the low frequency dispersion disappears the dotted line runs along the bottom of each plot.

Figure 6 shows the large variation in dielectric parameters along an 8.7 m section of the core. The extent of the variations are in most cases less extreme than have been found when high-frequency dielectric data from cores from different polar sites are intercompared [6]. There is no obvious periodicity present. Peaks in high frequency conductivity occur at minima of the relaxation time of the dominant dispersion, but they appear to show no correlation with the dielectric conductivity of the second dispersion. In blocking layer configurations this conductivity has been taken to approximate to the true d.c. conductivity of the material. Until the effect of the varying electrode-polythene-ice contact is accounted for, a rigorous comparison of the dielectric and d.c. contributions to the conductivity of ice cannot be made. Despite this drawback, the dielectric relaxation time (in the kHz range) emerges as the primary control on the high frequency conductivity of polar ice.

An interesting feature in Figure 6 is the behaviour at data set 215. The relaxation frequencies of the two highest dispersions separate and there is a peak in the high frequency dielectric conductivity. Chemical and isotope analysis should be able to confirm whether this is related to the 1974/75 peak in non-marine sulphate observed at two sites in the Antarctic Peninsula: James Ross Island [11] and Gomez Nunatak [R. Mulvaney, personal communication]. A detailed chronology of the ice core is required to interpret dielectric events from earlier times.

5.   ACKNOWLEDGEMENT

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COMMENTS

G.W. GROSS

I was interested in that you also observed a steep rise in the slope of the $\varepsilon''\omega$ vs. ε' curve at the high-frequency end. We have also observed this phenomena regularly in laboratory-grown ice measured between blocking electrodes. We interpret this as a Wagner-Sillars effect (caused by surface roughness at the polyethylene-ice contact). Do your values of σ, $\Delta\varepsilon$, and τ represent bulk ice values or those of the Maxwell-Wagner layered capacitor ?

Answer :

The data for the three highest frequency points (150 kHz, 200 kHz, 300 kHz) are not accurately measurable with our system. The capacitance values given by the bridge are physically invalid and are therfore rejected from the analysis program.
The data in Figure 6 represent the Maxwell-Wagner layered capacitor. The dominant dispersion is the highest frequency dispersion that we modelled and the derived parameters will be the least affected by the presence of the polythene.