Journal of Glaciology, Vol. 7, No. 49, 1968

FIELD MEASUREMENTS OF DIELECTRIC ABSORPTION IN ANTARCTIC ICE AND SNOW AT VERY HIGH FREQUENCIES

By M. E. R. WALFORD*

(British Antarctic Survey at the Scott Polar Research Institute, Cambridge, England)

ABSTRACT. Field measurements are presented of dielectric absorption in Antarctic snow and ice at frequencies of a few hundred megahertz. They are compared with measurements by other authors at very high frequencies. The dielectric absorption in ice at these frequencies is accounted for in terms of absorption bands both at radio frequencies and in the infra-red. Bands at radio frequencies are caused by a relaxation mechanism which depends upon the temperature and the impurity content of the ice. These two factors are therefore included in an account of the dielectric absorption in ice at very high frequencies.

RÉSUMÉ. *Mesures de l'absorption diélectrique de la glace et de la neige de l'Antarctique aux très hautes fréquences.* Des mesures de l'absorbtion diélectrique de la neige et de la glace de l'Antarctique, faites sur le terrain, sont présentées pour des fréquences de quelques centaines de mégahertz. Elles sont ensuite comparées avec les mesures d'autres auteurs, faites à de très hautes fréquences. L'absorption diélectrique de la glace à ces fréquences est exprimée en termes de bandes d'absorption, aussi bien dans les fréquences radio que dans les fréquences de l'infra-rouge. Les bandes de fréquences radio sont causées par un mécanisme de relaxation dépendant de la température, de la qualité et de la quantité des impuretés de la glace. Les facteurs susmentionnés sont donc inclus dans la prise en considération de l'absorption diélectrique de la glace aux trés hautes fréquences.

ZUSAMMENFASSUNG. *Feldbeobachtungen der dielektrische Absorption in antarktischem Eis und Schnee bei sehr hohen Frequenzen.* Feldmessungen der dielektrischen Absorption in Schnee und Eis der Antarktis bei Frequenzen von einigen hundert MHz werden dargestellt. Sie werden mit Messungen anderer Autoren bei sehr hohen Frequenzen verglichen. Die dielektrische Absorption in Eis bei diesen Frequenzen kann durch Absorptionsbanden sowohl im Bereich der Radiofrequenzen wie im Infrarot erklärt werden. Die Radiofrequenzbanden sind durch einen Relaxationsmechanismus verursacht, der von der Temperatur und dem Verunreinigungsgrad des Eises abhängt. Diese beiden Faktoren werden daher in die Darstellung mit einbezogen.

INTRODUCTION

Evans (1965) reviewed the dielectric properties of ice at temperatures from $-0.1°C$ to $-66°C$ and at frequencies from 10 Hz to 10^5 MHz. At frequencies up to a few hundred megahertz, dielectric absorption is due to a relaxation process with a single, temperature-dependent relaxation frequency. At higher frequencies the dominant influence is infra-red absorption, which shows no temperature dependence. In this paper we present new experimental data on dielectric absorption in ice, obtained from radio-echo studies at 30 to 440 MHz. These results, together with other published measurements in this band of frequencies are compared with the high frequency extreme of the relaxation spectrum and with the low frequency extreme of the infra-red spectrum. Satisfactory agreement is obtained if account is taken of both the temperature and the purity of the ice.

METHOD

At very high frequencies (V.H.F.) dielectric absorption in ice is so low that the usual bridge methods of measurement are rather difficult. Instead we have estimated the absorption by measuring the attenuation of radio signals propagating through the ice. From electromagnetic theory the attenuation of plane radio waves of frequency f is $90\,\epsilon'^{\frac{1}{2}} f \tan\delta$ decibels per kilometre path where the complex permittivity of ice is $\epsilon^* = \epsilon' - j\epsilon''$, the loss tangent is $\tan\delta = \epsilon''/\epsilon'$ and f is in MHz. Since $\epsilon'^{\frac{1}{2}}$ for ice is nearly constant at V.H.F. we take $f \tan\delta$ as a convenient measure of the dielectric absorption.

During 1963 the author carried out radio-echo-sounding experiments on the Brunt Ice Shelf, Antarctica (lat. 75° 31′ S., long. 26° 40′ W.) (Walford, unpublished). Soundings were

* Present address: Physics Department, College of Arts and Science, University of the West Indies, Bridgetown, Barbados.

mostly at 35 MHz but there are some results at 100 and at 440 MHz. Echo strengths from natural targets at the bottom of the ice shelf were measured using calibrated attenuators and from these measurements we estimate the mean dielectric absorption in the Brunt Ice Shelf. We must take account of other factors which may affect the signal strength of radio echoes. Estimates show that scattering and partial reflections within the ice do not contribute significantly to the signal attenuation but that the inverse square law, the directivity of the aerials and refraction into the snow do affect signal strengths. We may estimate these contributions to the total attenuation with sufficient precision, but an important factor which is rather uncertain is the nature of the radio-echo target at the bottom of the ice shelf. A radio-echo-sounding traverse across the Brunt Ice Shelf (Walford, unpublished) shows that at 35 MHz the ice–sea-water interface at the bottom of the ice shelf behaves like groups of targets approximately a hundred metres across. The groups are separated by horizontal distances of approximately one kilometre and between groups the echoes fade by at least 60 decibels. This is a remarkably large range; possibly heavy absorption of radio signals occurs only where salty or wet ice is present within the ice shelf and echoes are detected where the ice shelf contains only pure ice. We assume that the strongest radio echoes are reflected from non-absorbing targets about a hundred metres in diameter and we regard the resulting values of $f \tan \delta$ as defining the maximum dielectric absorption for pure ice, probably of inland origin (see Barclay, 1964).

Radio-echo sounding suffers from uncertainty in the path of propagation of the signals and in the nature of the echoing target. These uncertainties are avoided by the use of guided waves, and a separate series of values of $f \tan \delta$ has been obtained from measurements using twin-wire transmission lines (Walford, unpublished). The lines consist of two parallel copper wires 20 cm apart initially mounted horizontally 2 m above the snow. A balanced feeder at one end of the lines transmits radio waves which are reflected at the other end by a large metal plate. We use a small magnetic probe to plot the resulting standing-wave pattern. These preliminary experiments show that the power losses along the lines due to radiation and to ohmic resistance are small and may be neglected in the second part of the experiment. Then the lines are lowered to the snow surface and allowed to bury naturally in drift snow to a depth of about one metre. Standing-wave patterns are again plotted and from the standing-wave ratios we calculate the dielectric absorption in snow. Over forty experiments of this type were carried out at frequencies between 30 and 300 MHz in snow of measured temperature and density.

The accuracy of the transmission-line experiments is limited in practice by a troublesome effect arising with the transmission lines buried in snow. A few metres of the line must be led into the air to permit standing wave measurements, and a little power is therefore reflected at the air–snow interface. The standing-wave pattern is modified by an unknown amount and is found to be irregular in shape due to the irregular snow surface nearby. With the equipment available in the field no experimental arrangement was found to eliminate these effects,which reduce the accuracy of the experiments, but the unwanted reflections could probably be avoided by measuring the attenuation of radio signals with an impedance bridge connected across the lines and allowed to bury with them.

Results

Figure 1 shows values of $f \tan \delta$ calculated from the measured signal strengths of radio echoes through the ice shelf and from the experiments with buried transmission lines. The temperature profile through the ice shelf is not directly known but is assumed similar to that through the ice shelf at Maudheim. On this assumption we find that a suitable weighted mean for the Brunt Ice Shelf is -15°C. The temperature of the surface layers down to 2 m was measured during the transmission-line experiments and was found to vary from -18°C to -22°C at the depth of the lines and a mean value of -20°C is used in Figure 1. In each case the measurements on drift snow have been corrected by Weiner's formula (see Evans,

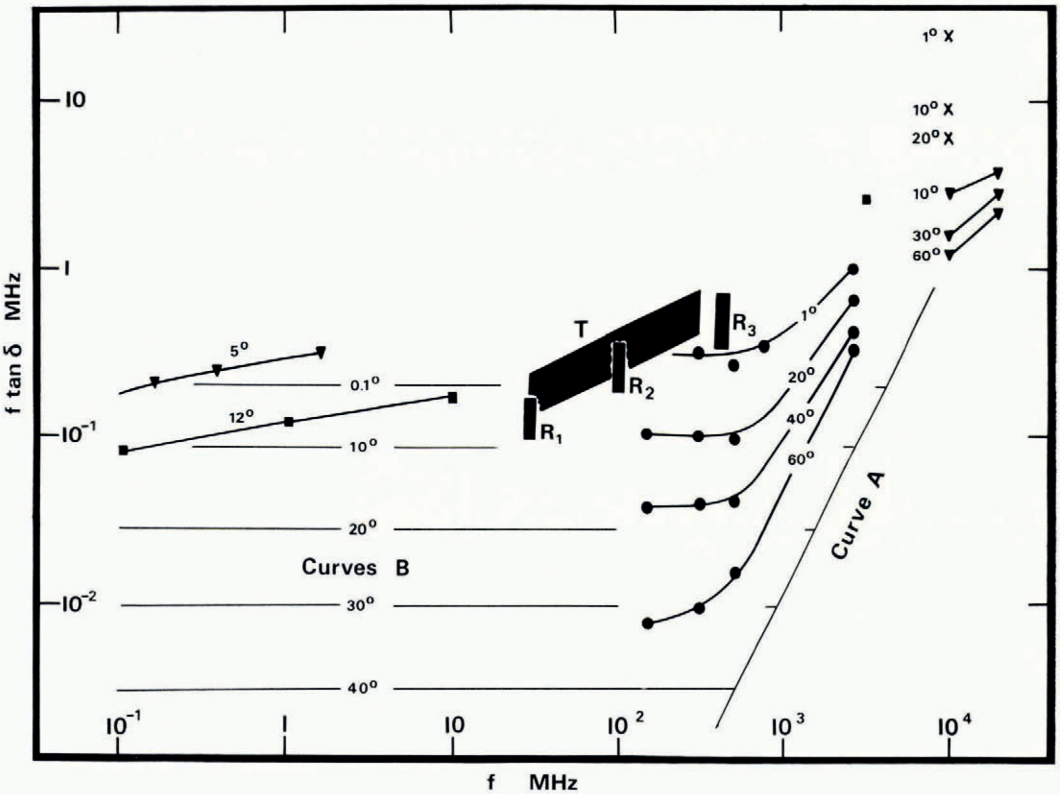

Fig. 1. f tan δ *of ice versus frequency. Ice temperatures are marked in degrees Celsius below zero. Curve* A*: Expected dielectric absorption due to resonance absorption at infra-red wavelengths (Cartwright and Errera, 1936). Curves* B*: Expected dielectric absorption due to relaxation absorption at lower radio-frequencies (Auty and Cole, 1952).*

● *Westphal (Ragle and others, 1964). Laboratory measurements at V.H.F. on ice from the Ward Hunt Ice Shelf, Ellesmere Island.*

▼ *Lamb (1946) and Lamb and Turney (1949). Laboratory measurements at V.H.F. on non-annealed ice made from distilled water.*

× *Cumming (1952). Laboratory measurements on ice made from distilled water, melt water or tap water.*

■ *Von Hippel (1954). Laboratory measurements on non-annealed ice made from conductivity water.*

T: Walford (unpublished). Field measurements by transmission line methods on snow of the Brunt Ice Shelf, Antarctica, corrected for the density of the snow. Mean snow temperature −20°C.

R_1, R_2, R_3: Walford (unpublished). Field measurements by radio echo sounding at 35, 100 and 440 MHz respectively through the Brunt Ice Shelf, Antarctica, corrected for the density of the snow. Weighted mean temperature of the ice shelf −15°C

1965; Walford, unpublished) so that they are equivalent to solid ice: the value of the Formzahl was assumed to be 2 and the magnitude of the correction was never greater than a factor of 2. Figure 1 includes other published measurements of dielectric absorption in ice at frequencies from 100 kHz to 10^4 MHz.

The new data are compared first with the low-frequency extreme of the infra-red absorption spectrum. Infra-red absorption in ice has been studied at wavelengths as long as 150 μm, equivalent to 2×10^7 MHz (Cartwright and Errera, 1936). Curve A in Figure 1 is extrapolated from these measurements using the equation $f \tan \delta = Af^2$ which is derived from elementary resonance theory (Bleaney and Bleaney, 1957). We obtain the constant A and hence absolute values of dielectric absorption from the measurements of Cartwright and Errera. The extrapolation is correct to within a factor of two provided no peaks occur in the infra-red absorption spectrum of ice at wavelengths greater than 150 μm. The experimental data in Figure 1

https://doi.org/10.3189/S0022143000020426 Published online by Cambridge University Press

becomes rather insensitive to temperature above a few hundred megahertz and appears to approach curve A asymptotically. The agreement is remarkably good bearing in mind that curve A is extrapolated over four decades of frequency. We conclude that above a few hundred megahertz dielectric absorption in ice is dominated by the infra-red spectrum and probably no peaks occur in this spectrum below 2×10^7 MHz.

We next compare the new experimental data in Figure 1 with the high-frequency extreme of the relaxation spectrum. The relaxation spectrum of pure polycrystalline ice is accurately described by Debye's theory for polar dielectrics with a single relaxation frequency f_r. Measurements by various authors are generally in good agreement with the Debye equation:

$$\epsilon - \epsilon_\infty = \frac{\epsilon_s - \epsilon_\infty}{1 + jf/f_r}.$$

The static value of the relative permittivity of ice ϵ_s increases smoothly from 92 to 124 as the temperature falls from 0 to $-66°$C and the high-frequency limiting value ϵ_∞ is 3.17. The relaxation frequency f_r varies with the absolute temperature T and is given in megahertz by the following equation (after Evans, 1965, p. 774)

$$\log f_r = 9.3 - \frac{2900}{T}.$$

An approximate form of the Debye equation useful for calculating dielectric absorption at the high-frequency extreme of the relaxation spectrum is

$$f \tan \delta = \left(\frac{\epsilon_s}{\epsilon_\infty} - 1\right) f_r.$$

This gives $f \tan \delta$ to within 5 per cent at frequencies greater than $25 f_r$ and it is used to plot the set of curves B in Figure 1. The curves agree qualitatively with the experimental data: between 0.1 and 100 MHz $f \tan \delta$ varies rapidly with temperature and rather little with frequency. Quantitative agreement however is less satisfactory and there are discrepancies of as much as a factor of ten. These discrepancies probably arise from the effects of ionic impurities upon the dielectric relaxation process in ice.

The Effect of Impurities

According to the Debye theory, at frequencies above $25 f_r$, dielectric absorption in ice is independent of frequency. Except for the effects of infra-red absorption bands, the data in Figure 1 generally support this hypothesis, and so $f \tan \delta$ is plotted as a function of the impurity content of the ice with temperature as the only parameter in Figure 2. Cook (1960), Westphal, and Kuroiwa (1954) explicitly state the nature and concentration of major impurities in their samples but the present author has estimated the impurity concentrations for the remaining data in Figure 2 from the original papers. The impurity content of the Brunt Ice Shelf is not directly known and the values in Figure 2 were assigned by comparison with the Maudheim ice shelf (Brocas and Delwiche, 1963; Walford, unpublished). The estimates of impurity concentrations are probably accurate only to a factor of three and no attempt has been made to take account of differences in chemical composition between various samples. Such differences may be rather small because four authors use samples of naturally occurring ice or snow, Cook (1960) uses ice of similar composition to natural sea ice and Auty and Cole (1952) use pure ice made from conductivity water.

Despite uncertainties it is clear from Figure 2 that dielectric absorption in ice generally increases with impurity content. Over most of the range of temperatures and concentrations the absorption increases linearly with the impurity content. The measurements at V.H.F. by Westphal (personal communication and in Ragle and others, 1964), Cook (1960) and the present author agree well with data extrapolated from measurements on the relaxation spectrum of ice by Auty and Cole (1952), Watt and Maxwell (1960) and Kuroiwa [1956].

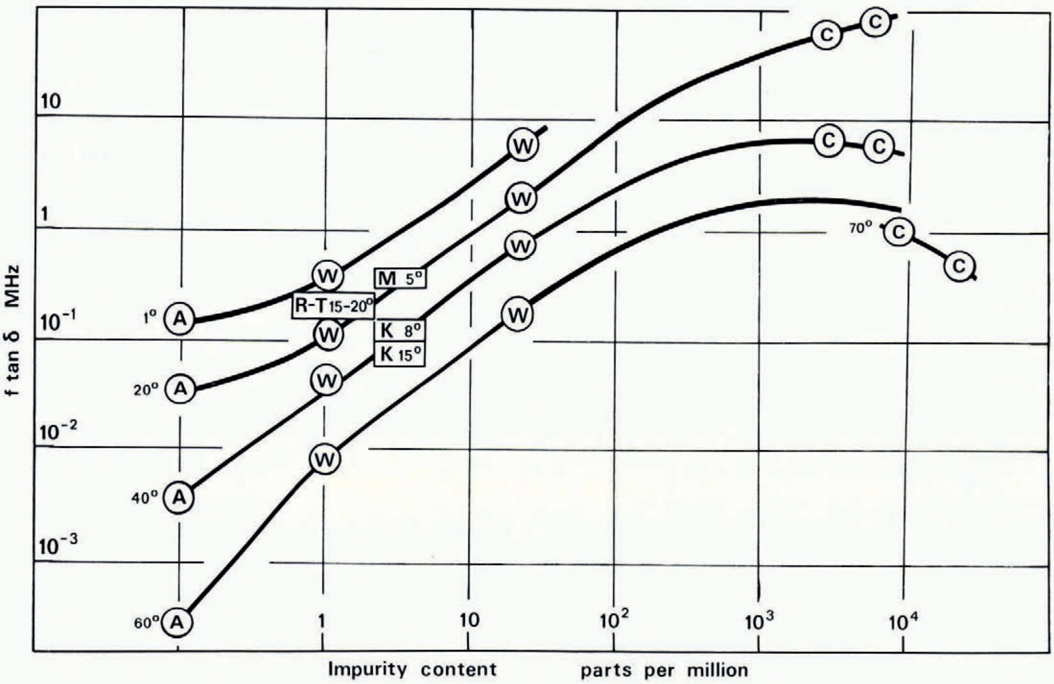

Fig. 2. f tan δ *versus impurity content of ice. The temperature of each sample is marked in degrees Celsius below zero and smooth curves are drawn through measurements at similar temperatures by different authors.*

A: Auty and Cole (1952). Laboratory measurements on relaxation spectrum of annealed ice made from conductivity water. High frequency limiting values of f tan δ *plotted against estimated impurity content.*

W: Westphal (Ragle and others, 1964). Laboratory measurements at V.H.F. on two types of ice from the Ward Hunt Ice Shelf, Ellesmere Island. f tan δ *plotted against measured impurity content.*

C: Cook (1960). Laboratory measurements at V.H.F. on artificial samples of salty ice of similar composition to natural sea ice. f tan δ *plotted against measured impurity content.*

K: Kuroiwa [1956]. Laboratory measurements on the relaxation spectrum of natural snow, density 0.6 g/cm³ collected at Sapporo, Japan. High-frequency limiting value of f tan δ *plotted against the measured impurity content.*

M: Watt and Maxwell (1960). Field measurements on the relaxation spectrum of ice, Athabasca Glacier, Canada. High frequency limiting values of f tan δ *plotted against the estimated impurity content.*

R–T: Walford (unpublished). Field measurements at V.H.F. by radio-echo and transmission-line techniques on the Brunt Ice Shelf, Antarctica. f tan δ *plotted against the impurity content characteristic of Antarctic shelf ice (Brocas and Delwiche, 1963). Temperature range −15 to −20°C*

Two laboratory studies have been made of the relaxation spectrum of ice as affected by temperature and impurity content. Brill and Camp studied ice doped with controlled amounts of ammonium fluoride (Brill, 1957; Brill and Camp, 1961; Camp, 1963) and Gränicher and others (1957) studied dielectric absorption and ice doped with hydrogen fluoride. They discuss their results using solid-state defect theory and account for dielectric absorption in terms of diffusion of charged defects through an ice crystal under an electric field (Gränicher and others, 1957; Gränicher, 1963; Jaccard, 1965). The two different laboratory studies use different doping chemicals but agree on the magnitude of the effects to within a factor of two. They show that as ice becomes more impure the static dielectric constant increases and the dielectric relaxation process takes place at higher frequencies, being now described by a spectrum of relaxation frequencies instead of a single one. If we attempt to compare the laboratory results with those in Figure 2 we find that satisfactory agreement is obtained for rather pure ice but that above a hundred parts per million of impurity discrepancies of a factor of ten occur. This is not surprising and may be due partly to the different chemical impurities present and partly to using the extrapolation equation $f \tan \delta = (\epsilon_s/\epsilon_\infty - 1) f_r$ which applies strictly only to ice with a single relaxation frequency.

Summary

Present measurements support the view (Evans, 1965) that dielectric absorbtion at V.H.F. is caused partly by infra-red absorption bands and partly by the radio-frequency relaxation process. Relaxation is dependent upon temperature and impurity content and future experiments should include measurement of the ionic impurity content of the ice. There are few measurements on the V.H.F. spectrum or on the relaxation spectrum of natural, undisturbed ice or snow. There are no systematic studies of the effect upon the V.H.F. dielectric absorption spectrum of controlled amounts of known ionic impurities.

The measurements presented in this paper were carried out at Halley Bay, Antarctica, in 1963 when the author was a member of the British Antarctic Survey. He thanks the personnel of the station for their interest and assistance in the field work. He is also very much indebted to Dr. G. de Q. Robin and Dr. S. Evans for supervision and encouragement during his post-graduate work at the Scott Polar Research Institute, Cambridge.

MS. received 16 June 1967 and in revised form 20 September 1967

REFERENCES

Auty, R. P., *and* Cole, R. H. 1952. Dielectric properties of ice and solid D_2O. *Journal of Chemical Physics*, Vol. 20, No. 8, p. 1309–14.

Barclay, L. W. 1964. Sledging and surveying. (*In* Brunt, *Sir* D., *ed. The Royal Society International Geophysical Year Antarctic Expedition. Halley Bay, Coats Land, Falkland Islands Dependencies, 1955–59.* Vol. 4. London, Royal Society, p. 329–38.)

Bleaney, B. I., *and* Bleaney, B. 1957. *Electricity and magnetism.* Oxford, Clarendon Press.

Brill, R. 1957. Structure of ice. *U.S. Snow, Ice and Permafrost Research Establishment. Report* 33.

Brill, R., *and* Camp, P. R. 1961. Properties of ice. *U.S. Cold Regions Research and Engineering Laboratory. Research Report* 68.

Brocas, J., *and* Delwiche, R. 1963. Cl, K and Na concentrations in Antarctic snow and ice. *Journal of Geophysical Research*, Vol. 68, No. 13, p. 3999–4000.

Camp, P. R. 1963. Properties of ice. Part II. *U.S. Cold Regions Research and Engineering Laboratory. Research Report* 114.

Cartwright, C. H., *and* Errera, J. 1936. Extreme infra-red dispersion of polar and non-polar liquids. *Proceedings of the Royal Society*, Ser. A, Vol. 154, No. 881, p. 138–57.

Cook, J. C. 1960. RF electrical properties of salty ice and frozen earth. *Journal of Geophysical Research*, Vol. 65, No. 6, p. 1767–71.

Cumming, W. A. 1952. The dielectric properties of ice and snow at 3.2 centimeters. *Journal of Applied Physics*, Vol. 23, No. 7, p. 768–73.

Evans, S. 1965. Dielectric properties of ice and snow—a review. *Journal of Glaciology*, Vol. 5, No. 42, p. 773–92.

Gränicher, H. 1963. Properties and lattice imperfections of ice crystals and the behaviour of H_2O–HF solid solutions. *Physik der kondensierten Materie*, Bd. 1, Ht. 1, p. 1–12.

Gränicher, H., *and others.* 1957. Dielectric relaxation and the electrical conductivity of ice crystals, by H. Gränicher, C. Jaccard, P. Scherrer and A. Steinemann. *Discussion of the Faraday Society*, No. 23, p. 50–62.

Jaccard, C. 1965. Mechanism of the electrical conductivity in ice. *Annals of the New York Academy of Sciences*, Vol. 125, No. 3, p. 390–400.

Kuroiwa, D. [1956.] The dielectric property of snow. *Union Géodésique et Géophysique Internationale. Association Internationale d'Hydrologie Scientifique. Assemblée générale de Rome, 1954*, Tom. 4, p. 52–63.

Lamb, J. 1946. Measurements of the dielectric properties of ice. *Transactions of the Faraday Society*, Vol. 42A, p. 238–44.

Lamb, J., *and* Turney, A. 1949. The dielectric properties of ice at 1.25 cm. wavelength. *Proceedings of the Physical Society*, Sect. B., Vol. 62, Pt. 4, p. 272–73.

Ragle, R. H., *and others.* 1964. Ice core studies of Ward Hunt Ice Shelf, 1960, by R. H. Ragle, R. G. Blair and L. E. Persson. *Journal of Glaciology*, Vol. 5, No. 37, p. 39–59.

Von Hippel, A. R., *ed.* 1954. *Dielectric materials and applications.* Cambridge, Mass., Technology Press of M.I.T.; New York, John Wiley and Sons, Inc.

Walford, M. E. R. 1964. Radio echo sounding through an ice shelf. *Nature*, Vol. 204, No. 4956, p. 317–19.

Walford, M. E. R. Unpublished. Radio echo sounding of polar ice masses. [Ph.D. thesis, University of Cambridge, 1967.]

Watt, A. D., *and* Maxwell, E. L. 1960. Measured electrical properties of snow and glacial ice. *Journal of Research of the National Bureau of Standards* (Washington, D.C.), Sect. D, Vol. 64, No. 4, p. 357–63.