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Electromagnetic measurements of multi-year sea ice using impulse radar

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Electromagnetic measurements of multi-year sea ice using impulse radar

Austin Kovacs and Rexford M. Morey

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modified to include the effects of the gas pockets found in the multi-year sea ice. This three-phase mixture model was found to estimate the EM properties of the multi-year ice studied over the frequency band of interest. The latter values were determined by: 1) vertical sounding to a subsurface target of known depth, where the two-way travel time of the EM wavelet in the ice is measured; 2) cross-borehole transmission, where the transit time of the EM wavelet is measured through a known thickness of sea ice; and 3) a wide-angle or common-depth-point reflection method. Preliminary findings also indicate that a representative value for the apparent bulk dielectric constant of multi-year sea ice over $2\frac{1}{2}$ m thick is 3.5. This represents an effective EM wavelet velocity of 0.16 m/ns, which may be used to estimate multi-year sea ice thickness in cases where the ice bottom is detected in ice profile data.

PREFACE

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ELECTROMAGNETIC MEASUREMENTS OF MULTI-YEAR SEA ICE USING IMPULSE RADAR

Austin Kovacs and Rexford M. Morey

INTRODUCTION

The ability to remotely measure the thickness of sea ice first became a reality about ten years ago when impulse radar technology was shown to be capable of detecting an interface at the bottom of cold first-year sea ice. The remote estimation of first-year sea ice thickness has improved significantly in the last five years, both in terms of equipment and our understanding of the electromagnetic properties of the ice. It is now possible to remotely estimate the thickness of cold first-year sea ice 1 to 3 m thick using impulse radar operating in the 80- to 500-MHz frequency band. However, there are limits to this measurement capability and its accuracy. We now have reasonable evidence that the interface observed in the radar profile data at the bottom of first-year sea ice is located at a depth where the temperature is about -2.2°C (Morey et al. 1984). In cold first-year sea ice 1 to 2 m thick, this interface is about 5 cm above the ice/water interface.

The accuracy to which sea ice thickness can be determined is a function of our ability to estimate the effective velocity of the electromagnetic (EM) wavelet in the ice. This velocity is a function of the real effective bulk dielectric constant of the ice, which in turn is a function of its density and average bulk brine volume. The latter is controlled by ice growth processes and temperature. Since temperature and ice thickness change with time, the effective EM wavelet velocity also changes. Without prior knowledge of ice temperature it is, therefore, only possible to make reasonable estimates of the effective velocity at the time of the survey,

based upon the relative air temperature preceding the survey. For example, if cold first-year sea ice is to be profiled, a reasonable effective velocity to use for the EM wavelet in the ice is 0.14 m/ns. For ice experiencing higher air temperatures of -15 to -5°C , an effective velocity of 0.13 m/ns is reasonable, as may be inferred from Kovacs and Morey (1980). The penetration depth and propagation of electromagnetic energy in first-year sea ice is a very complex phenomenon which has recently been brought into perspective and modeled by Morey et al. (1984). However, little information existed on the propagation of EM energy at about 80 to 500 MHz in multi-year sea ice. Thus, our ability to estimate the thickness of multi-year sea ice using impulse radar EM wavelet travel time remained uncertain.

Several field studies have been made to profile multi-year sea ice, both from the ice surface and from the air. The results have not been satisfactory. In some cases the ice bottom was not detected but an interface well above the bottom was observed; in others no subsurface return was seen at all. Determination of the cause of these results was therefore in order. It was also considered important to devise the capability to model the properties of multi-year sea ice so as to determine the sensor performance specifications required to profile its thickness. This report presents the results of our efforts to profile multi-year sea ice thickness using impulse radar and to determine the relationship between its electromagnetic and physical properties.

SEA ICE THICKNESS INVESTIGATIONS

Most of the ridges and surrounding floe ice investigated in this study had passed through only one melt season and therefore were second-year ice formations. This is the predominant type of old ice found in the near-shore waters along the Alaskan Beaufort Sea coast. With this clarification, we henceforth refer to this ice as "multi-year." This is the terminology conventionally used by most Beaufort Sea ice investigators to describe not only this ice type but also true multi-year ice that has survived two or more melt seasons. This misusage is not surprising; both second- and multi-year ridges have a similar appearance. However, the former generally have steeper sail slopes, rougher surface relief, occasional voids within the sail, and moist or slushy areas in the keel due to incomplete freeze-back or solidification of the voids in the ice block structure. The moist areas were typically found 4 or more meters below sea level in the ridges studied.

Ridge cross sections were determined through elevation survey and drill hole measurements. The moist areas within the ridges were generally located by observing the composition of the ice cuttings removed during augering. Where ice cores were obtained, the bulk density, salinity, temperature, brine volume, air volume and porosity of the ice were determined, as was the brine-free ice density. Impulse radar ice thickness profiles were made along the surface elevation survey routes. One 265-m-long profile was made on a multi-year rubble field floe. Three other profiles 50 to 60 m long were run over multi-year ridges, and one 20-m-long profile was made on a thick multi-year floe. In addition, borehole transmission and common-depth-point reflection measurements were made.

The cross section of the first ridge studied, ridge 9, is shown in Figure 1. (Ridge numbers are not sequential.) This ridge was, and had the classic shape of, a true multi-year pressure ridge. Drill hole ice thickness measurements were made every 3 m along the survey line, and ice cores were obtained at the center of the ridge (Fig. 1). The physical properties of the ice, as determined from core analyses, are listed in Table 1. The tabulated ice density, liquid brine and gas (air) volumes were calculated from the measured temperature, salinity and bulk density data following the procedure of Cox and Weeks (1983). The ice density values shown are those for the ice with all the brine drained out. The average bulk brine volume v_{br} of the ice was found to be 10%. Using the equation given by Kovacs and Morey (1980),

$$v_m = 0.17 - 0.00068 v_{br} \quad (\text{m/ns}) \quad (1)$$

we calculated v_m , an effective velocity of the EM wavelet in the medium, to be 0.163 m/ns. And from

$$\epsilon_a = (c/v_m)^2 \quad (2)$$

where c = free space EM wavelet velocity, 0.3 m/ns, we determined ϵ_a , the apparent dielectric constant of the ice, to be 3.4. By rounding off the above velocity to 0.16 m/ns, and using the two-way travel time (t) scale for the profile record, a depth (D) scale was constructed from

$$d = (v_m t/2) \quad (\text{m}). \quad (3)$$

This scale appears along the left margin of each impulse radar profile.

Impulse radar profiles were run across ridge 9 using antennas with air-coupled center frequencies of about 80, 120 and 500 MHz (Fig. 2-4). The dashed line in each figure tracks the first zero crossing of the reflected EM wavelet. This crossing is conventionally used to represent the time to or depth of a subsurface interface. Superimposed on each record are the drill-hole-measured depths. The agreement between the measured and the radar depth in Figure 2 is very good except at stations 1 and 2. Here our interpretation of the radar data indicates the ice bottom is about 1 1/2 m below the drill hole depth. At this location the radar may be tracking a deeper interface off to the side of the survey line. This could occur because of beam spreading (the antennas have about a 90° beam angle) and the fact that the 80-MHz antenna is about 1 1/4 m wide and therefore "sees" a wider subsurface area than that probed by a drill hole.

The profile obtained with the 120-MHz antenna (Fig. 3) also shows reasonably good agreement between the drill-hole- and radar-determined ice depths. There is again a lack of agreement between the two ice depths at stations 1 and 2. The reason may be the same as that discussed above. However, in this case the antenna is about 1 m wide. The interesting feature in the 120-MHz antenna profile is an apparent second interface emerging above the ice bottom interface. This new interface is visible in the profile on the right side of the ridge. Its appearance is due in part to the higher resolution obtained with the 120-MHz antenna. Such results can make interpretation of the record difficult.

The internal layer resolution achieved with the

Figure 1. Cross section of ridge 9.

Figure 2. Radar profile of ridge 9 obtained with the 80-MHz antenna.

Table 1. Measured and calculated ice properties versus depth at station 8 on ridge 9.

Measured				Calculated					
Depth (m)	Bulk ice density (Mg/m ³)	Salinity (‰)	Temperature (°C)	Air volume (‰)	Brine volume (‰)	Porosity (‰)	Ice density (Mg/m ³)	Apparent dielectric constant (ϵ_a)	Attenuation (dB/m)
0.05	—	0.04	-14.4	—	—	—	—	—	—
0.15	—	0.01	-14.3	—	—	—	—	—	—
0.25	—	0.08	-14.3	—	—	—	—	—	—
0.35	0.830	0.24	-14.2	97.0	0.9	97.9	0.828	2.94	0.04
0.45	0.837	0.48	-14.2	88.9	1.9	90.8	0.834	3.00	0.14
0.55	0.845	0.38	-14.2	80.6	1.5	82.1	0.843	3.01	0.10
0.65	0.860	0.33	-14.2	64.2	1.3	65.5	0.858	3.05	0.08
0.75	0.853	0.41	-14.1	71.9	1.6	73.5	0.850	3.03	0.11
0.85	—	0.60	-14.1	—	—	—	—	—	—
0.95	0.850	0.70	-14.0	75.4	2.8	78.2	0.846	3.07	0.26
1.05	—	0.34	-14.0	—	—	—	—	—	—
1.15	0.834	0.55	-13.9	92.6	2.2	49.8	0.831	3.00	0.18
1.25	0.852	0.70	-13.8	72.5	2.8	75.3	0.848	3.07	0.26
1.35	0.853	0.95	-13.7	72.5	3.9	76.4	0.847	3.11	0.45
1.45	0.830	1.00	-13.5	97.8	4.0	101.8	0.824	3.05	0.47
1.55	0.858	0.80	-13.5	66.8	3.3	70.1	0.853	3.11	0.34
1.65	0.845	0.47	-13.3	80.7	1.9	82.6	0.842	3.02	0.14
1.75	—	0.65	-13.3	—	—	—	—	—	—
1.85	0.820	0.85	-13.2	108.4	3.4	111.8	0.815	3.00	0.37
1.95	0.796	1.40	-13.1	134.5	5.5	140.0	0.789	3.00	0.82
2.05	0.800	0.43	-13.0	129.2	1.7	130.9	0.798	2.88	0.12
2.15	0.822	0.33	-12.9	105.7	0.6	106.3	0.820	2.91	0.02
2.25	0.843	0.21	-12.7	82.7	0.9	83.6	0.841	2.98	0.04
2.35	0.804	0.29	-12.5	125.0	1.2	126.2	0.802	2.88	0.07
2.45	0.870	0.34	-12.4	53.3	1.5	54.8	0.868	3.09	0.10
2.55	0.830	0.18	-12.4	96.2	0.8	97.0	0.829	2.94	0.04
2.65	0.827	0.27	-12.2	99.8	1.2	101.0	0.826	2.95	0.07
2.75	0.820	0.29	-12.0	107.8	1.2	108.0	0.818	2.92	0.07
2.85	0.834	0.41	-12.0	92.1	1.8	93.9	0.832	2.99	0.14
2.95	0.835	0.37	-11.8	90.9	1.6	92.5	0.833	2.98	0.11
3.05	—	0.75	-11.8	—	—	—	—	—	—
3.35	0.852	1.58	-11.0	73.5	7.5	81.0	0.843	3.24	1.40
3.45	0.860	1.87	-10.9	65.7	9.0	74.7	0.849	3.33	1.89
3.55	0.858	1.20	-10.7	67.5	5.9	73.4	0.857	3.25	0.95
3.65	0.865	1.30	-10.4	60.0	6.5	66.5	0.857	3.25	1.12
3.75	0.855	1.64	-10.2	71.2	8.3	79.5	0.845	3.29	1.69
3.85	0.848	1.20	-10.0	78.4	6.1	84.5	0.841	3.19	1.03
3.95	—	2.81	-9.9	—	—	—	—	—	—
4.05	0.837	2.87	-9.8	91.7	14.7	106.4	0.821	3.50	4.30
4.15	0.822	1.30	-9.6	106.5	6.6	113.1	0.815	3.13	1.20
4.35	0.848	2.16	-9.0	79.3	11.9	91.2	0.836	3.42	3.11
4.45	0.852	2.16	-8.8	74.3	12.2	86.5	0.840	3.45	3.24
4.55	0.859	1.81	-8.6	77.1	10.4	87.5	0.839	3.36	2.52
4.65	0.832	1.75	-8.4	95.7	10.0	105.7	0.823	3.30	2.39
4.75	0.834	1.64	-8.2	93.6	9.6	103.2	0.825	3.28	2.24
4.85	—	1.70	-8.0	—	—	—	—	—	—
4.95	0.848	1.20	-7.7	78.5	7.5	86.0	0.841	3.25	1.46
5.05	0.873	2.30	-7.5	52.8	15.1	67.9	0.859	3.66	4.41
5.15	0.858	1.35	-7.1	67.5	9.2	76.7	0.850	3.35	1.97
5.25	0.850	1.99	-7.0	77.5	13.5	91.0	0.838	3.51	3.64
5.35	0.843	1.70	-6.8	84.5	11.8	96.3	0.833	3.41	2.92
5.45	0.865	2.46	-6.6	61.4	17.9	79.3	0.851	3.79	5.55
5.55	0.852	2.40	-6.4	75.2	17.7	92.9	0.839	3.74	5.39

Table 1 (cont'd).

Measured				Calculated					
Depth (m)	Bulk ice density (Mg/m ³)	Salinity (‰)	Temperature (°C)	Air volume (‰)	Brine volume (‰)	Porosity (‰)	Ice density (Mg/m ³)	Apparent dielectric constant (ϵ_a)	Attenuation (dB/m)
5.65	—	1.46	-6.2	—	—	—	—	—	—
5.85	0.870	1.35	-5.8	54.7	11.1	65.8	0.862	3.48	2.48
5.95	0.871	1.52	-5.5	54.2	13.1	67.3	0.862	3.58	3.14
6.05	0.860	1.87	-5.2	66.4	16.7	83.1	0.849	3.71	4.52
6.15	0.863	1.70	-5.0	63.0	15.8	78.8	0.853	3.68	4.11
6.25	0.876	1.40	-4.8	48.7	13.7	62.4	0.868	3.63	3.17
6.35	0.876	1.40	-4.6	48.8	14.2	63.0	0.867	3.65	3.30
6.45	0.876	1.30	-4.3	48.8	14.1	62.9	0.868	3.65	3.17
6.55	0.863	1.58	-4.1	63.1	17.6	80.7	0.854	3.77	4.39
6.65	0.891	2.22	-3.8	34.0	27.5	61.5	0.878	4.44	8.31
6.75	0.878	1.64	-3.6	47.2	21.2	68.4	0.868	4.01	5.48
6.85	0.878	1.52	-3.2	47.3	21.9	69.2	0.869	4.05	5.41
6.95	0.881	1.25	-3.1	43.5	18.6	62.1	0.873	3.88	4.12
7.05	0.881	1.52	-2.9	44.1	24.2	68.3	0.872	4.18	5.88
7.15	0.888	1.52	-2.6	36.9	27.2	64.1	0.879	4.37	6.58
7.25	0.883	2.05	-2.4	43.8	39.6	83.4	0.871	5.12	11.0
7.35	0.883	1.99	-2.2	43.9	42.1	86.0	0.871	5.25	11.1

500-MHz antenna is higher still, but, as shown in Figure 4, a bottom interface was barely detectable in the graphic record. This indicates that for the constant gain setting used, the 500-MHz antenna had reached its sounding depth limit. Increasing the gain might have improved the results, but probably not significantly. The higher resolution obtained with the 500-MHz antenna is apparent when the three records are compared. Clearly there is greater definition of the internal layers and features in the 500-MHz antenna profile record. It is also interesting that with the use of the 1/3-m-wide, 500-MHz antenna, a bottom interface was detected at stations 1 and 2 which is in close agreement with the drill-hole-measured ice depths. As with the 120-MHz antenna profile, the 500-MHz antenna profile indicates the existence of two "bottom" interfaces on the right side of the ridge keel. The higher interface may be the reflection from another interface off to the side.

All three records show that the radar-determined ice thickness is less than the drill-hole-measured ice thickness at station 8. This is also true for stations 1 through 9 on the 500-MHz record. Figure 1 indicates the presence of moist ice at the bottom of the keel. Sea ice with high brine content has been shown to be highly conductive. This can prevent, through absorption processes, the passage of EM energy in the frequency band at which our antennas operate (Morey et al. 1984). In addition,

at the "moist/dry ice" interface we can expect a good dielectric contrast, which would give rise to a boundary with a high reflection coefficient. For these reasons we believe that the bottom interface profiled is the top of the moist zone near the bottom of the ridge. This zone may be close, within centimeters, to the true ice bottom, as was found to be the case for cold first-year sea ice (Kovacs and Morey 1978, 1979, 1980, Morey et al. 1984). Or, as will be discussed later, the top of this zone may be located well above the ice/water interface. The depth of penetration into the moist zone is frequency-dependent, with an 80-MHz EM wavelet penetrating deeper than one at 500 MHz. This may be why the 500-MHz antenna profile of the left side of ridge 9 indicates thinner ice than the drilling measurements.

The cross section of ridge 5 is shown in Figure 5, and the radar ice thickness profile obtained with the 80-MHz antenna is given in Figure 6. The open circles in Figure 6 are the drill-hole-measured ice thicknesses. Here again the agreement between the indirect radar determination and the measured ice thickness is quite good.

This agreement did not hold for ridge 6, where the bottom of the keel was found to consist of moist, and in some places rather "wet," ice (Fig. 7). The radar profile of this ridge is shown in Figure 8. The open circles represent the drill-hole-measured ice thickness and the dashed line gives

Figure 3. Radar profile of ridge 9 obtained with the 120-MHz antenna.

Figure 4. Radar profile of ridge 9 obtained with the 500-MHz antenna.

Figure 5. Cross section of ridge 5.

Figure 6. Radar profile of ridge 5 obtained with the 80-MHz antenna.

Figure 7. Cross section of ridge 6.

Figure 8. Radar profile of ridge 6 obtained with the 80-MHz antenna.

Figure 9. View of multi-year rubble field.

the ice bottom as interpreted from the radar profile. There is reasonable agreement between the two measurements only at stations 3, 4 and 17 through 20. The black dots represent the relative depth to the moist zone as determined from the consistency of the cuttings removed during drilling. This method of determining the depth to the moist interface is not very accurate because the boundary is not necessarily a sharp one and the cuttings take time to appear at the surface. The depth at which the cuttings originated could only be estimated. Nevertheless, the data indicate that between stations 4 and 17 the interface profiled by the radar was not the ice bottom but the top of the moist zone. This also indicates that in this ridge there was a good dielectric contrast at the "dry" and "wet" ice boundary, which provided a good reflective interface. This is evident between stations 11 and 16 where the intensity (amplitude) of the reflected EM wavelet, as indicated by the darkness of the record, was quite high. If the interface was not well defined or was diffused, the EM wavelet energy could be absorbed with no reflection seen in the record.

The longest impulse radar profile was made on a multi-year rubble field (Fig. 9). The cross section and impulse radar profile record of this feature are shown in Figures 10 and 11, respectively. Stations are 10 ft (≈ 3 m) apart. This record is difficult to interpret because of variations in the intensity of the reflected EM energy and the "branching" of the "ice bottom" interface, for example at about station 47. There is also no apparent bottom interface between stations 65 and 83. Our field interpretation of the ice bottom location in the

graphic record is depicted by the bold dashed white line. The bifurcation (interface B) which occurs at about station 47 is puzzling. At about station 56 is the peak of ridge A (Fig. 10). It was reasonable to expect the keel under this 3-m-high ice feature to be over 9 m deep, that is, for the total ice thickness to exceed 12 m, based upon the sail-height-to-keel-depth ratio of about 1 to 3.3 found for multi-year ridges by Kovacs (1983). To verify that the chosen interface was the correct one, a drill hole ice thickness measurement was made at distance mark 171 m, as shown in Figures 10 and 11 (station 56). The agreement was surprisingly good. We believe that a depression existed under the survey line between stations 47 and 60, and that the lower interface (dotted line in Figure 11), which is the reflection from deeper ice off to the side, is more representative of the ice thickness in the area. Indeed, deeper ice in the keel would be required to maintain buoyancy equilibrium between ridge sail and keel. This points out a difficulty in interpreting the impulse radar record and shows that interpretation is of necessity sometimes subjective. It is also obvious that on this floe the apparent ice bottom in the impulse radar record frequently did not agree with the drill-hole-measured ice thickness. Between stations 1 and 8 and at station 44 the difference was about $2\frac{1}{2}$ m. This was particularly surprising at station 44, where a strong bottom reflection occurred.

A moist ice zone is shown in Figure 10 at about the 55 m distance along the profile. This ice zone either scattered or absorbed the EM wavelet energy and prevented the radar from "seeing" the ice bottom between stations 17 and 19, as shown

Figure 10. Cross section of multi-year rubble field.

Figure 11. Radar profile of rubble field floe obtained with the 80-MHz antenna.

in Figure 11. A high volume of conductive brine in the ice between stations 65 and 83 is also believed to have prevented the ice bottom from being seen in this area as well.

Between stations 51 and 52, there is a reflection from a target which appeared to be located 2¼ m below the ice surface. Six exploratory holes, about 5 m deep, were drilled at 1-m intervals along the survey line over the target. No anomalous ice conditions were encountered. This signature is apparently another artifact created by side reflections.

ELECTROMAGNETIC AND PHYSICAL PROPERTIES OF SEA ICE

Theoretical considerations

Propagation of electromagnetic energy in multi-year sea ice can be described by the complex propagation constant γ , which is defined as (Morey et al. 1984)

$$\gamma = \alpha + j\beta \quad (4)$$

where the attenuation constant α is defined as

$$\alpha = \omega \left(\frac{u' \epsilon_e}{2} \right)^{1/2} \left[\left(1 + \frac{\sigma_e^2}{\omega^2 \epsilon_e^2} \right)^{1/2} - 1 \right]^{1/2} \quad (5)$$

and the phase constant β is

$$\beta = \omega \left(\frac{u' \epsilon_e}{2} \right)^{1/2} \left[\left(1 + \frac{\sigma_e^2}{\omega^2 \epsilon_e^2} \right)^{1/2} + 1 \right]^{1/2} \quad (6)$$

where $\omega = 2\pi f$ = angular frequency

f = frequency

u' = real part of magnetic permeability = $u_0 (= 4\pi \times 10^{-7}$ henrys/m) $\times u_r'$

u_r' = real relative part of the magnetic permeability = 1 for sea ice

ϵ_e = effective dielectric constant $\approx \epsilon_0 (=$ free space dielectric constant $= 1/36\pi \times 10^{-9}$ farads/meter) $\times \epsilon_r'$

ϵ_r' = real relative dielectric constant

σ_e = effective conductivity (siemens/m)

$j = \sqrt{-1}$.

As the electromagnetic wavelet propagates through the ice with a phase velocity

$$v_m = \omega/\beta \quad (\text{m/ns}) \quad (7)$$

it suffers an exponential attenuation A of

$$A = 20\alpha \log e \quad (\text{dB/m}). \quad (8)$$

Various types of pulsed electromagnetic transmission measurements were made through multi-year sea ice to determine some of the properties of the ice. The principal quantity measured was transit time, either the one-way travel time between boreholes or the two-way travel time between the ice surface and a subsurface reflector. Also, the change in received signal amplitude was used to calculate the relative attenuation of the ice. For the cross-borehole transmission measurements, a transmitting antenna and a receiving antenna were lowered at equal depth increments into two vertical boreholes. The flight time and the relative signal attenuation of the EM wavelet which traveled through the ice between boreholes (distance L) were determined.

The EM wavelet velocity in the medium at each depth was calculated from

$$v_m = L/t \quad (\text{m/ns}). \quad (9)$$

An apparent dielectric constant ϵ_a was then calculated from eq 2 and the relative attenuation A from

$$A = 20 \log(V_2/V_1) \quad (\text{dB}) \quad (10)$$

where V_1 = received wavelet voltage level in air at the borehole separation distance

V_2 = received wavelet voltage level after wavelet pass through ice between boreholes.

For the wide-angle-reflection (common-depth-point-reflection) measurements a transmitting and a receiving antenna were moved incrementally in opposite directions on the surface of the ice away from a starting point. The antennas were moved an equal distance x from the starting point on each move. The two-way transit time of the EM wavelet to and from a subsurface reflector was used to calculate velocity of propagation from

$$v_m = \frac{x}{\sqrt{t_s^2 - t_d^2}} \quad (\text{m/ns}) \quad (11)$$

where t_s = travel time at x separation (ns)

t_d = two-way vertical travel time (ns).

Equation 2 was then used to calculate an apparent dielectric constant.

The dielectric constant and attenuation of the multi-year sea ice can be estimated from the temperature, salinity and density of the ice, and some knowledge of the ice structure. Sea ice is a mixture

composed primarily of "fresh" ice, liquid brine and gas (air). Using the known electromagnetic properties of the pure ice, brine and air and an appropriate mixing formula, the relative electromagnetic properties of the sea ice mixture can be calculated.

The relative dielectric constant ϵ_{ri} of the brine-free ice/air mixture was calculated from the following refractive mixing formula for very low-loss materials:

$$\epsilon_{ri} = (v_a \sqrt{\epsilon_{ra}} + v_i \sqrt{\epsilon_{ri}})^2 \quad (12)$$

where v_a = air volume fraction

v_i = ice volume fraction

ϵ_{ra} = relative dielectric constant of air = 1

ϵ_{ri} = relative dielectric constant of solid ice = 3.14.

The relative complex dielectric constant of brine, ϵ_b^* , was next calculated using the procedure of Morey et al. (1984). Then the real (ϵ'_{rm}) and imaginary (ϵ''_{rm}) parts of the relative complex dielectric constant of the air/ice/brine mixture were calculated from (Morey et al. 1984)

$$\epsilon_{rm}^* = \epsilon'_{rm} - j\epsilon''_{rm} = \epsilon_{ri} + \frac{v_b \epsilon_{ri} (\epsilon_b^* - \epsilon_{ri})}{n(1-v_b)(\epsilon_b^* - \epsilon_{ri}) + \epsilon_{ri}} \quad (13)$$

where v_b is brine volume and n is the depolarization factor. The depolarization factor is a function of the sea ice structure and the orientation of the radar electric field relative to that structure, as will be discussed later.

The real part of the complex dielectric constant (ϵ'_{rm}) was used in eq 5 and 6 as the effective dielectric constant (ϵ_e), whereas the effective conductivity (σ_e) was calculated from

$$\sigma_e = \sigma_{D.C.} + \omega \epsilon''_{rm} \epsilon_0 \quad \text{siemens/meter (S/m)}. \quad (14)$$

The D.C. conductivity $\sigma_{D.C.}$ of the unsaturated multi-year sea ice was calculated using a form of Archie's rule formulated for water-wet rocks (Sen et al. 1981, Lysne 1983, Morey et al. 1984) as

$$\sigma_{D.C.} = \sigma_b (S_w \phi)^m \quad (\text{S/m}) \quad (15)$$

where σ_b = brine conductivity (given in Morey et al. 1984)

S_w = volume fraction of the pore space occupied by the conductive brine

ϕ = porosity of the ice

m = a constant.

It should be noted that $S_w = v_b/\phi$; therefore, eq 15 reduces to $\sigma_{D.C.} = \sigma_b (v_b/\phi)^m$. Archie's rule is an empirical relationship and there is no satisfactory theoretical explanation for it. Numerous studies on clay-free sedimentary rocks and igneous rocks put the value of m anywhere between 1.3 and 4, depending upon consolidation, pore geometry and orientation, and where the water residues within the pore spaces.

Morey et al. (1984) found that for saturated first-year sea ice m varied between 1.55 and 1.75. In this study of multi-year sea ice various values of the depolarization factor and exponent m were used in eq 13 and 15. The values of m and n were chosen based on how well both the calculated average apparent dielectric constant and the attenuation agreed with the measured values.

The EM wavelet velocity of propagation (eq 7) and attenuation (eq 8) were calculated using ϵ_e and σ_e as derived above from the ice, brine and air volumes. This velocity was then used to calculate an apparent dielectric constant (eq 2), which was then compared with the measured ϵ_a value derived from the EM wavelet propagation distance and travel times as used in eq 9 and 2.

The above attenuation was used to calculate the relative total loss in the ice between the transmitting and receiving borehole antennas. The far-field signal power for transmission through a relatively homogeneous lossy dielectric, such as multi-year sea ice, follows the relation

$$\frac{P_R}{P_T} \propto \frac{\exp(-2\alpha L)}{L^2} \quad (16)$$

where P_T = transmitted power

P_R = received power

α = attenuation constant (eq 5) = $A/8.686$.

Solving for the power ratio in dB yields

$$10 \log \frac{P_R}{P_T} \propto -(AL + 20 \log L) \quad (\text{dB}) \quad (17)$$

Field measurements

To gain a better understanding of the EM propagation in multi-year sea ice, and the ice properties, ridge 9 was selected for further study. Two other features were also selected: a 22½-m-thick multi-year pressure ridge (Fig. 12) grounded in

Figure 12. Cross Island multi-year pressure ridge fragment. Arrows point to major brine drainage channels. Note that this portion of the ridge was formed by ice blocks which tended to lie one on top of another.

14.8 m of water west of Cross Island and a small multi-year floe north of Cottle Island. This latter floe was over 10 m thick at our study site.

The cross-borehole radar system was "calibrated" in water. The borehole antennas were placed in plastic tubes submerged in the water. The distance between the tubes was varied and the one-way transit time of the EM wavelet through the water was measured. A plot of transit time as a function of antenna separation is shown in Figure 13. The measured apparent dielectric constant was found to be 87.7. This is in excellent agreement with the static dielectric constant ϵ_{rs} of water at our test temperature of 0.25°C. For example, King and Smith (1981) show $\epsilon_{rs} = 88.2$ at 0°C. (It should be noted that the dielectric constant of water is constant from D.C. to about 10 GHz.) The measured D.C. conductivity of the water was 5.5×10^{-2} S/m and the center frequency of the frequency spectrum of the received wavelet was 104 MHz. Thus the calculated attenuation is 9.6 dB/m (eq 5 and 8). The total loss as a function of antenna separation, as calculated from eq 17, is plotted in Figure 14 along with the measured relative attenuation. Agreement is only good for far-field conditions, which are probably not met for antenna separations of less than about 1 m in water.

Boreholes were drilled in freshwater lake ice near Prudhoe Bay, Alaska. The transit times at three different antenna separations are plotted in

Figure 15. The data indicate an apparent dielectric constant of 2.97, which is reasonable for bubbly lake ice at a density of about 0.87 Mg/m³.

Ridge 9 site

As stated earlier, ice cores were obtained at the center of ridge 9. The physical properties of the core (Table 1) were used to calculate an apparent dielectric constant and attenuation at each sample depth. These values (listed in Table 1) were calculated using $n = 0.07$ and $m = 1.7$. The average apparent dielectric constant for the values listed in Table 1 is 3.40. This dielectric constant was made

Figure 13. EM wavelet travel time in water versus antenna separation distance.

Figure 14. Measured and calculated EM energy loss in water versus antenna separation distance.

Figure 15. EM wavelet travel time in lake ice versus antenna separation distance.

Figure 16. Calculated ϵ_a versus depth in ridge 9.

Figure 17. Calculated EM wavelet attenuation versus depth in ridge 9.

to agree with the calculated dielectric constant, as determined on page 2, through the use of the above values of m and n . The average attenuation is 2.70 dB/m. Figures 16 and 17 are plots of the apparent dielectric constant and attenuation, re-

spectively. Using the average of these values for the dielectric constant and attenuation in the radar range equation (Morey and Kovacs 1982), we calculated the maximum range at 100 MHz to be about 8.4 m. As Figures 2 and 3 indicate, a strong

Table 2. Measured and calculated ice properties versus depth for Cross Island multi-year ridge.

Depth (m)	Measured			Calculated				Apparent dielectric constant (ϵ_a)	Attenuation (Total loss @ 100 MHz) (dB)
	Bulk ice density (Mg/m ³)	Salinity (‰)	Temperature (°C)	Air volume (‰)	Brine volume (‰)	Porosity (‰)	Ice density (Mg/m ³)		
0.10	0.745	0.57	-10.5	190.0	2.6	192.6	0.7413	2.75	15.50
0.35	0.817	0.40	-11.0	111.0	1.8	112.8	0.8150	2.94	14.86
0.45	0.784	0.14	-11.1	145.8	0.6	146.4	0.7840	2.80	14.27
0.65	0.824	0.24	-11.4	102.6	1.0	103.6	0.8235	2.94	14.38
0.75	0.822	0.40	-11.6	105.6	1.7	107.3	0.8200	2.95	14.79
0.85	0.854	0.63	-11.8	70.8	2.7	73.5	0.8510	3.08	15.48
0.95	0.840	0.57	-11.9	85.2	2.5	87.7	0.8379	3.03	15.33
1.05	0.864	0.65	-12.1	59.4	2.9	62.3	0.8615	3.12	15.62
1.15	0.870	0.70	-12.3	53.0	3.1	56.1	0.8670	3.15	15.78
1.25	0.888	1.13	-12.5	35.4	5.1	40.5	0.8815	3.27	17.76
1.55	0.886	1.94	-13.0	37.6	8.5	46.1	0.8765	3.40	22.26
1.85	0.876	2.36	-13.5	48.6	10.0	58.6	0.8650	3.43	24.61
2.05	0.844	1.34	-13.8	82.3	5.1	87.4	0.8390	3.14	17.68
2.15	0.899	1.47	-14.0	23.3	6.1	29.4	0.8920	3.35	18.73
2.50	0.854	2.64	-14.2	72.9	10.4	83.3	0.8423	3.37	25.12
2.65	0.830	2.35	-14.3	99.4	8.7	108.1	0.8197	3.22	22.46
2.80	0.876	2.82	-14.3	49.5	10.3	59.8	0.8640	3.44	24.81
2.95	0.812	2.74	-14.3	119.5	10.9	130.3	0.7983	3.24	26.19
3.05	0.810	2.60	-14.2	120.3	10.5	130.8	0.7982	3.22	25.47
3.25	0.816	2.15	-14.2	114.1	8.2	122.3	0.8070	3.16	21.70
3.40	0.897	2.36	-14.0	26.4	12.3	38.7	0.8834	3.59	28.33
3.50	0.815	2.41	-13.9	115.4	9.5	124.9	0.8042	3.21	23.84
3.60	0.837	2.30	-13.8	91.4	10.2	101.6	0.8253	3.30	25.01
3.75	0.808	1.49	-13.6	122.4	5.8	128.2	0.8010	3.05	18.59
3.85	0.783	1.80	-13.4	149.7	7.4	157.1	0.7740	3.02	20.88
4.00	0.839	1.99	-13.2	89.3	8.0	97.2	0.8295	3.23	21.65
4.10	0.861	1.99	-13.1	64.4	8.1	72.6	0.8522	3.30	21.75
4.20	0.769	1.52	-12.9	165.1	5.9	171.1	0.7617	3.93	18.90
4.30	0.761	1.89	-12.7	173.7	7.1	180.8	0.7526	2.95	20.58
4.40	0.751	1.85	-12.5	184.1	7.0	191.1	0.7430	2.92	20.53
4.50	0.774	1.48	-12.2	160.4	8.5	168.9	0.7633	3.03	22.97
4.60	0.851	1.55	-12.0	75.2	6.7	81.8	0.8435	3.22	19.91
4.75	0.883	1.68	-11.6	40.0	8.5	48.5	0.8740	3.39	22.67
4.85	0.857	1.74	-11.4	69.2	11.5	80.7	0.8448	3.43	28.28
4.95	0.854	1.32	-11.2	72.7	9.9	82.6	0.8430	3.28	25.47
5.05	0.860	1.59	-11.0	65.7	7.6	73.3	0.8510	3.28	21.44
5.15	0.873	1.35	-10.8	52.0	10.3	62.3	0.8610	3.43	26.09
5.25	0.859	1.61	-10.6	66.8	9.6	76.4	0.8483	3.35	24.96
5.35	0.798	1.78	-10.3	133.4	8.2	141.6	0.7885	3.10	22.82
5.45	0.805	1.11	-10.1	124.8	5.8	130.6	0.7990	3.04	19.05
5.55	0.766	1.50	- 9.9	166.5	5.7	172.2	0.7603	2.92	19.03
5.65	0.836	1.24	- 9.7	91.7	6.4	98.1	0.8280	3.26	20.02
5.75	0.790	1.44	- 9.5	140.6	7.1	147.7	0.7825	3.04	21.14
5.85	0.794	1.21	- 9.2	136.1	6.2	142.3	0.7875	2.02	19.76
6.00	0.845	2.17	- 9.0	82.8	12.2	95.0	0.8311	3.41	30.78
6.10	0.857	2.62	- 8.8	69.5	13.3	82.8	0.8423	3.50	33.12
6.20	0.859	1.98	- 8.6	66.6	10.0	76.6	0.8481	3.37	26.24
6.30	0.851	1.68	- 8.4	75.5	9.7	85.2	0.8398	3.33	25.68
6.40	0.859	2.59	- 8.2	67.1	15.0	82.1	0.8431	3.59	37.25
6.50	0.852	2.49	- 8.0	74.4	15.4	89.8	0.8358	3.59	38.12
6.60	0.857	2.66	- 7.8	70.2	17.6	87.8	0.8378	3.71	43.43
6.80	0.877	3.04	- 7.4	48.3	20.2	68.5	0.8548	3.92	49.60
6.90	0.866	3.50	- 7.2	60.1	22.9	83.0	0.8417	4.04	56.58
7.05	0.865	4.01	- 7.0	62.6	26.7	89.3	0.8356	4.27	67.19
7.15	0.874	4.26	- 6.8	53.4	30.3	83.7	0.8410	4.57	77.39
7.25	0.906	3.46	- 6.7	18.4	26.1	44.5	0.8770	4.38	63.88
7.35	0.904	3.68	- 6.5	21.1	28.4	49.5	0.8725	4.53	70.25
7.45	0.890	3.62	- 6.4	35.3	27.9	63.2	0.8602	4.44	68.72
7.55	0.912	3.79	- 6.2	11.9	30.7	42.6	0.8785	4.72	75.35

Figure 18. Relative brine volume versus depth in Cross Island pressure ridge.

Figure 19. Relative air volume and total ice porosity versus depth in Cross Island pressure ridge.

radar reflection at this borehole station came from a depth of about 7.2 m, well within the calculated range of the radar.

The depolarization factor is a measure of both the shape and the orientation of the brine channel inclusions with respect to the external electric field. For three idealized cases, the depolarization factor is 0 for needles, $\frac{1}{3}$ for spheres, and 1 for plates (Morey et al. 1984). The influence of n and m on the dielectric constant and attenuation is greatest for higher brine volumes, which are near the bottom of the ice. The implication of the particular values of n and m which give the most reasonable dielectric constant and attenuation in comparison with the radar measurements is that there is an anisotropic brine-ice structure near the bottom of the multi-year ice, which may or may not be the physical case.

Cross Island site

Two boreholes were drilled 5.1 m apart in the grounded multi-year pressure ridge near Cross Island. Continuous ice cores were taken from each borehole and cut into sections approximately 0.1 m long. At a depth of 7.55 m drilling was stopped because brine had infiltrated into the hole. Ice temperature, air volume, brine volume, porosity and the bulk and brine-free ice density data are listed in Table 2, along with the calculated apparent dielectric constant and attenuation. The physical data (listed in Table 2) are the average for the ice obtained at the same depth in both boreholes. The brine volume, air volume and porosity, and bulk and brine-free ice density are shown in Figures 18, 19 and 20 respectively. The brine volume increases gradually to a depth of about $1\frac{1}{2}$ m and then averages about 8‰ down to sea level. From

Figure 20. Relative bulk and brine-free ice density versus depth in Cross Island pressure ridge.

Figure 21. Example of EM wavelet received in borehole transmission study.

Figure 22. Measured and calculated ϵ_a values versus depth in Cross Island pressure ridge.

Figure 23. Measured and calculated (smoothed) ϵ_a values versus depth in Cross Island pressure ridge. The bold line is a least-square fit to the data. The light line represents a perfect one-to-one fit.

Table 3. Apparent dielectric constant, relative attenuation and center frequency of EM wavelet spectra determined versus depth from borehole transmission measurements at Cross Island multi-year floe.

Depth (m)	Apparent dielectric constant (ϵ_a)	Relative attenuation (dB)	Center frequency of EM wavelet spectra (MHz)
0.6	2.84	15.0	118
1.1	3.20	14.1	113
1.6	3.33	22.2	110
2.1	3.41	24.2	106
2.6	3.26	29.9	89
3.1	3.24	27.6	108
3.6	3.21	22.2	112
4.1	3.16	20.3	111
4.6	3.13	19.2	111
5.1	3.12	20.0	111
5.6	3.30	18.4	110
6.1	3.50	20.2	110
6.6	3.79	27.1	111

this horizon the brine volume continues to increase rapidly with depth. The effect of the brine volume and weight is also reflected in Figures 19 and 20. In the former, the difference between the air volume and the total porosity is the amount of brine present in the voids. In Figure 20, the density difference shown is of course simply due to the weight of the brine. From an electromagnetic perspective, Figure 18 is instructive, for it indicates that the conductivity of the ice below sea level will be increasing rapidly and will become more lossy as the liquid brine content increases.

Cross-borehole transmission measurements were made in 0.5-m increments down the holes. Figure 21 is an example of the received EM wavelet. The time-of-flight data were used to calculate a measured apparent dielectric constant. Voltage amplitude data were used to calculate the relative EM wavelet attenuation. Table 3 lists these results along with the center frequency of the received EM wavelet frequency spectrum.

The measured and calculated apparent dielectric constants of the ice as a function of depth are shown in Figure 22. Here again, a depolarization factor of 0.07 and an $m = 1.7$ allowed for the calculation of an apparent dielectric constant which matches best the measured values. The average apparent dielectric constant is 3.37, and the average attenuation, based on the effective conductivity, is 2.98 dB/m. As explained above, the ϵ'_{rm} values and effective conductivity were used to calculate an apparent dielectric constant, using eq 6, 7 and 2.

Since the borehole antennas have a finite length of about 1 m, the time-of-flight and attenuation measurements are made through a finite volume of ice between the boreholes. In order to compare the calculated apparent dielectric constant and attenuation, as listed in 10-cm increments in Table 2, with the cross-borehole measurements, a fourth-order least-squares polynomial curve was fitted to the calculated ϵ_a data (Fig. 23).

A depolarization factor of about 0.07 implies that on average the brine inclusions and residual drainage structure are vertical cylinders. This seems reasonable since the brine in first-year sea ice migrates downward as the ice is transformed into multi-year sea ice. Evidence of the residual structure in the form of "vertical" brine-drainage channels was clearly visible where the ridge had split apart, as may be seen in Figure 12. A plot of the calculated versus the measured value of ϵ_a is shown in Figure 24. The data are shown correlated with a linear least-squares fit, dark line, which is somewhat skewed from a perfect one-to-one fit, as depicted by the light line.

The total calculated attenuation (eq 17) at 100 MHz and the relative measured attenuation are plotted in Figure 25 as a function of borehole depth for $n = 0.07$ and $m = 1.7$. A polynomial curve was fitted to the calculated data as shown in Figure 26. The agreement between this curve and the measured relative attenuation is fairly good. The implication of the dielectric constant and attenuation results is that the dielectric mixing form-

Figure 24. Comparison of the measured and calculated (smoothed) ϵ_a values for Cross Island pressure ridge.

Figure 26. Measured and calculated (smoothed) EM wavelet attenuation versus depth in Cross Island pressure ridge.

Figure 25. Measured and calculated EM wavelet attenuation versus depth in the Cross Island pressure ridge.

ula (eq 13) is a good mixture model for determining the complex dielectric constant of multi-year sea ice.

A radar sounding profile was made on the ice surface along a survey line passing through the two borehole locations. There was no discernible reflection at a depth of about 6.2 m, where the brine volume of the ice was found to increase rapidly with depth (Fig. 18). There also was no bottom reflection seen in the profile data. An elevation survey indicated that sea level was about 6.2 m below the ice surface (Fig. 18). Using the average values for the dielectric constant and attenuation in the multi-year pressure ridge, and using the radar range equation given in Morey and Kovacs (1982), we calculated the maximum radar range at 100 MHz to be about 5.3 m. Thus the present radar equipment will not profile the bottom of this pressure ridge, which was measured by drilling to be about 22 m thick, or to detect the high brine volume interface, which was located below the 6-m depth.

Cottle Island site

A radar sounding profile was made on a multi-year sea ice floe near Cottle Island (Fig. 27). Bore-

Table 4. Average measured and calculated ice properties versus depth for combined Cottle Island multi-year floe stations 10, 13 and 17.

Depth (m)	Measured			Calculated					Attenuation (Total loss @ 100 MHz) (dB/m)
	Bulk ice density (Mg/m ³)	Salinity (‰)	Temperature (°C)	Air volume (‰)	Brine volume (‰)	Porosity (‰)	Ice density (Mg/m ³)	Apparent dielectric constant (ϵ_a)	
0.05	0.806	0.30	-6.0	121.6	2.2	123.8	0.804	2.95	13.4
0.15	0.823	0.21	-6.8	103.4	1.4	104.8	0.822	2.97	12.8
0.25	0.840	0.15	-7.9	85.4	1.0	86.4	0.839	3.00	12.5
0.35	0.863	0.10	-8.3	60.1	0.6	60.7	0.862	3.04	12.2
0.45	0.846	0.13	-8.6	78.5	0.7	79.2	0.846	3.00	12.3
0.55	0.844	0.04	-8.8	80.7	0.2	80.9	0.844	2.97	12.1
0.65	0.834	0.01	-9.0	91.9	0.1	92.0	0.834	2.93	12.1
0.75	0.810	0.06	-9.2	119.0	0.3	119.3	0.808	2.86	12.1
0.85	0.809	0.30	-9.3	119.0	1.6	120.6	0.808	2.94	13.0
0.95	0.752	0.32	-9.4	180.4	0.3	180.7	0.752	2.71	12.1
1.00	0.757	0.53	-9.4	175.4	0.6	176.0	0.757	2.74	12.2
1.10	0.838	0.20	-9.5	88.3	1.0	89.3	0.836	2.99	12.5
1.20	0.830	0.21	-9.5	97.2	1.0	98.2	0.828	2.96	12.5
1.30	0.840	0.51	-9.5	85.4	2.7	88.1	0.837	3.08	14.0
1.40	0.836	1.69	-9.6	91.3	8.8	100.1	0.826	3.41	24.0
1.50	0.839	2.58	-9.6	88.6	13.5	102.1	0.825	3.73	34.5
1.60	0.867	2.99	-9.6	60.0	17.7	77.7	0.847	4.15	44.7
1.65	0.855	3.14	-9.6	72.7	16.7	89.4	0.836	4.02	42.3
1.75	0.893	3.13	-9.5	30.8	17.4	48.2	0.874	4.23	43.8
1.85	0.896	2.82	-9.4	27.2	15.8	43.0	0.878	4.10	39.7
1.95	0.900	3.87	-9.4	24.7	22.2	46.9	0.876	4.69	56.4
2.05	0.912	3.32	-9.3	11.0	19.3	30.3	0.890	4.46	48.6
2.15	0.916	3.45	-9.2	6.8	20.3	27.1	0.893	4.57	51.3
2.25	0.914	3.25	-9.2	8.4	19.2	27.6	0.892	4.46	48.4
2.35	0.909	2.50	-9.0	13.3	14.7	28.0	0.892	4.07	37.1
2.45	0.914	3.04	-8.9	8.3	18.3	26.6	0.894	4.39	46.3
2.55	0.912	3.15	-8.8	12.0	21.8	33.8	0.888	4.71	55.6
2.65	0.906	2.99	-8.6	17.4	18.2	35.6	0.885	4.34	46.4
2.75	0.914	3.63	-8.4	9.0	22.8	31.8	0.889	4.82	58.8
2.85	0.907	3.45	-8.3	16.1	21.9	38.0	0.884	4.71	56.4
2.95	0.912	3.73	-8.1	11.6	24.7	36.3	0.885	5.00	63.6
3.05	0.911	3.15	-8.0	11.4	20.8	32.2	0.889	4.61	52.8
3.15	0.914	2.98	-7.7	8.7	20.1	28.8	0.892	4.54	50.5
3.25	0.905	2.80	-7.5	17.7	19.2	36.9	0.884	4.42	48.0
3.35	0.908	3.80	-7.3	15.4	27.3	42.7	0.879	5.24	69.2

Figure 27. Radar profile of Cottle Island multi-year ice floe obtained with the 500-MHz antenna.

holes were cored at stations 10, 13 and 17. Cross-borehole transmission measurements were made between stations 13 and 17, a 4-m separation. Wide-angle reflection measurements were made over stations 10 and 15. The properties of the ice as determined by averaging the core data for the three holes are listed in Table 4, along with the calculated apparent dielectric constant and attenuation. The brine volume, air volume and ice porosity, and bulk and brine-free ice density determinations as a function of depth are shown graphically in Figures 28, 29 and 30 respectively. The brine volume of the ice above sea level is shown to be consistently below 5‰ (Fig. 28). Below sea level, there is an abrupt increase in brine volume to over 15‰ followed by a gradually increasing trend. Again this implies that the ice below sea level will have a high conductivity and cause high

Figure 28. Relative brine volume versus depth in Cottle Island ice floe.

Figure 29. Relative air volume and total ice porosity versus depth in Cottle Island ice floe.

Figure 30. Relative bulk and brine-free ice density versus depth in Cottle Island ice floe.

Figure 31. Measured and calculated ϵ_a values versus depth in Cottle Island ice floe.

attenuation of an EM wavelet in the frequency range of interest. The plots of air volume and total porosity (Fig. 29) show that the two are for all intents and purposes the same down to sea level, i.e. there is very little brine in the ice. However, below sea level the two curves diverge as a result of increased brine volume. The density curves in Figure 30 also show a divergence due to the weight of the

brine. In short, there is rapid increase in ice density to about 0.88 Mg/m^3 at $\frac{1}{2} \text{ m}$ below sea level, below which the density remains relatively constant.

The apparent measured dielectric constant and relative attenuation at each borehole depth are listed in Table 5. A plot of the measured and calculated apparent dielectric constant as a function

Table 5. Apparent dielectric constant and relative attenuation as determined versus depth from borehole transmission measurements at Cottle Island multi-year floe.

Depth (m)	Apparent dielectric constant (ϵ_a)	Relative attenuation (dB)
0.6	3.01	12.0
0.85	3.11	14.7
1.10	3.22	22.7
1.35	3.47	34.0
1.60	3.90	39.9
1.85	4.49	42.3
2.10	4.86	46.1

Figure 32. Measured and calculated EM wavelet attenuation versus depth in Cottle Island ice floe.

Figure 33. Measured and calculated (smoothed) ϵ_a values versus depth in Cottle Island ice floe.

of depth is shown in Figure 31. The measured ϵ_a data appeared to fit the calculated ϵ_a data best when $n = 0.05$ and $m = 1.6$, implying, on average, a somewhat more vertical cylinder-like brine channel structure than that at the Cross Island site. Figure 32 is a plot of the measured and calculated total attenuation as a function of depth. The received radar EM wavelets below 2.1 m were too low in voltage to analyze. A fourth order polynomial curve was fitted to the calculated apparent dielectric constant and total attenuation data versus depth as shown in Figures 33 and 34 respectively.

Figure 34. Measured and calculated (smoothed) EM wavelet attenuation versus depth in Cottle Island ice floe.

As can be seen, the "smoothed" calculated versus measured values follow similar trends. Figure 35 is a plot of the measured apparent dielectric constant as a function of the "smoothed" calculated apparent dielectric constant. Again there is reasonable agreement between the mixing model "smoothed" calculated values and the measured results. The consistent offset in the measured ϵ_a values versus a perfect one-to-one fit, as illustrated in Figure 35, could be due to a small timing error of about 0.5 ns or 2%.

Radar sounding profiles were taken using three

Figure 35. Comparison of measured and calculated (smoothed) ϵ_a values for Cottle Island ice floe. The bold line is a least-square fit to the data. The light line represents a perfect one-to-one fit.

Figure 36. Radar profile of Cottle Island floe obtained with the 300-MHz antenna. Time scale is 15 ns between scan lines.

Figure 37. Radar profile of Cottle Island floe obtained with the 120-MHz antenna. Time scale is 15 ns between scan lines.

different antennas with air-coupled transmission center frequencies of about 500 MHz, 300 MHz, and 120 MHz. The profiles are shown in Figures 27, 36 and 37. The figures show a marked decrease in subsurface target resolution with decreasing antenna center frequency. Using the calculated dielectric constant and attenuation data, the approx-

imate maximum radar ranges as calculated for each center frequency are about 1.9 m, 2.2 m and 2.9 m respectively. The radar profiles indicate this deeper target detection trend by the fact that deeper reflectors were observed in the 120-MHz profile data.

Wide angle reflection profiles were taken over

Figure 38. EM wavelet travel time versus antenna separation distance as constructed from the common point reflection data.

stations 10 and 15 with the 500-MHz antennas. At each antenna separation the two antennas were tilted vertical to record a direct EM wavelet air wave time of flight between the antennas. These flight time data were used for timing calibration. The t^2, x^2 plot from the measured time-of-flight data in air and in the ice as a function of antenna separation is shown in Figure 38. At station 10 the apparent bulk dielectric constant was determined to be 2.87 and the calculated depth to the reflector 1.03 m. These values agree with the radar profile two-way flight time and the drilled depth to the subsurface "bright spot" (Fig. 27), which was found to be a "firn" layer about 2 cm thick at a depth of 1 m. From the latter measurements we calculated a bulk ϵ_s of 2.92.

For the ice at station 15, the common-depth-point reflection data (Fig. 38) gave an apparent dielectric constant of 2.94 compared to an average value from Table 4 of 2.98 to the depth of 1.4 m. There is a major change in brine volume at a depth of about 1.4 m (Fig. 28). The weak reflector between stations 12 and 18 in Figure 27 at a depth of about 1.4 m is the boundary between relatively "dry," brine-free ice and relatively wet, brine-"soaked" ice. Sea level at station 15 was 1.4 m below the ice surface, as determined by elevation survey. The radar sounding system could not profile the bottom of this ice floe because of its high brine content, probably associated with seawater infiltration due to the incomplete solidification of the block structure.

CONCLUSIONS

The dielectric mixing formula used by the authors for first-year sea ice (a two-phase model) appears to model the electromagnetic properties of multi-year sea ice when the large volume of air pockets found in this type of ice is accounted for. The method presented in this study for including the effects of air pockets in a three-phase mixing model of multi-year sea ice seems appropriate. Brine volume was found to dominate the loss mechanism in first-year sea ice, and this study indicates that the same is true for multi-year sea ice. The relative thickness of the multi-year ice studied could not always be profiled by the impulse radar system used because of the electromagnetic attenuation which resulted from the high conductivity liquid content of the ice. The high liquid volume was probably associated with seawater infiltration into porous ice.

Five methods were used to determine the apparent dielectric constant: 1) a determination based upon the bulk brine volume of the ice, 2) a calculation based on the relative volumes of air, ice and brine and an assumed depolarization factor, 3) a cross-borehole transmission method, wherein the EM wavelet transit time is measured through a known thickness of sea ice, 4) a wide-angle reflection method, and 5) by EM wavelet transit time to the ice bottom and the drill-hole-measured ice thickness. The first four methods were found to give comparable results. The fifth method would

also give similar results provided the subsurface interface seen in the radar record was indeed the ice bottom. Measured borehole attenuation values were found to follow the same trend as the calculated total attenuation, although the correlation was not as good as that for the calculated versus measured apparent dielectric constant values.

From the preliminary results of this study it would appear that for determining the thickness of multi-year sea over 2½ m thick ice using impulse radar operating in the megahertz frequency band, an effective velocity for the EM wavelet of 0.16 m/ns is reasonable when the wavelet is indeed reflected from the bottom of the ice. The problem is determining whether the reflected EM wavelet came from the bottom of the ice or from some interface located well above the ice bottom. This problem remains. When the reflection is from an interface other than the ice bottom, the EM wavelet velocity given above may no longer apply. A higher velocity probably will, because of the lower density ice with lower liquid content typically found in the upper portion of multi-year sea ice pressure ridges. Depending upon the ice properties, the effective velocity could be as high as about 0.18 m/ns.

It is also important to note that for multi-year and especially two-year-old sea ice less than 2½ m thick, the effective EM velocity of 0.16 m/ns may not be reasonable. The thinner ice may well have a bulk brine volume similar to that of first-year sea ice (Kovacs et al. 1973). In this case, the effective EM velocity could be as low as 0.12 m/ns, as can be inferred from Kovacs and Morey (1980).

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