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Short-pulse radar investigations of freshwater ice sheets and brash ice

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Short-pulse radar profiles and waveform traces were recorded over natural, freshwater ice sheets and an artificially made, 1.6-m-diameter column of brash ice. The purpose was to study the feasibility of this type of radar to detect ice thickness, determine ice properties and distinguish ice forms. The radar utilized two antennas: one with a spectrum centered near 900 MHz and a second more powerful one near 700 MHz. Distinct top and bottom reflections from several ice sheets were produced by both antennas, but the value of dielectric permittivity calculated from the time delay of the reflections varied between sheets as one ice sheet was ready to candle and contained free water. The brash ice distorted

20. Abstract (cont'd)

signals and allowed no discernible bottom return. The lower frequency antenna also gave returns from the lake bottom (separated from the ice bottom by about 1 m of water), which could allow ice thickness to be determined indirectly. The report concludes that these antennas can be used to determine sheet ice thickness and to supply information to help in the detection of brash ice. The water content of an ice sheet may also be estimated if independent studies show a correlation between dielectric permittivity and free water content.

PREFACE

This report was prepared by Dr. Steven A. Arcone, Research Geophysicist, and Allan J. Delaney, Physical Science Technician, both of the Snow and Ice Branch, Research Division, and by Roscoe E. Perham, Mechanical Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by Civil Works Project CWIS 32284, *Ice Control Structures.*

This report was technically reviewed by Dr. Lindamae Peck and Dr. Kenneth Jezek of CRREL.

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Short-Pulse Radar Investigations of Freshwater Ice Sheets and Brash Ice

S.A. ARCONE, A.J. DELANEY AND R.E. PERHAM

INTRODUCTION

Short-pulse or ground-probing radar has been commercially available since about 1972. It generally operates in a frequency band centered around 100 MHz where a good tradeoff exists between propagation absorption losses attributable to free water and vertical resolution. It has been most successful in arctic surveying where frozen soil and water conditions often allow maximum signal penetration. Because data are most easily interpreted in terms of plane wave (i.e., raypath propagation) theory, radar is best applied to situations where even, extensive layering exists. Consequently, radar surveying of both freshwater and saline ice sheets has attracted much attention (see the review by Arcone [1985] for a list of references).

The most important obstacle to interpreting radar ice data is resolving a surface reflection from a bottom reflection. Until about 1981, commercially available antennas produced pulses of such long duration that only ice sheet thicknesses of more than about 0.7 m could be measured. By 1981, however, the GSSI company of Hudson, New Hampshire, introduced several new antennas operating at much higher frequencies, and therefore providing much shorter pulses. As will be shown later, the minimum detectable thickness of ice was reduced to about 0.2 m. In this report we discuss the use of these antennas for surveying freshwater ice sheets and brash ice.

The objective of these studies was to determine the feasibility of using short-pulse radar as a sheet ice thickness sensor, a brash ice detector and, possibly, thickness sensor, and an ice property (mainly water content) sensor. Several surveys were conducted over two lakes, in one of which we made a zone of brash ice. Both analog and digital recordings were made, the latter using temporal waveform stacking. We also attempted spatial averaging.

MATERIALS AND METHODS

The radar equipment consisted of two different control units and two different antennas. The use of a second control unit for some experiments was necessitated by obligations of the first unit, which had digital capability, to a second project. The first unit was a Xadar Electromagnetic Profiling System (Xadar Corp., Springfield, Virginia) mated with a GSSI Model 101C (900 MHz) antenna. The second unit was a GSSI Model 400 control unit mated with a GSSI Model 3102 (700 MHz) antenna, which radiated much more power. The basic operation of subsurface radar has been described by Morey (1974) and Annan and Davis (1976) among others and will only be briefly reviewed.

In subsurface radar, pulses (idealized in Fig. 1) are emitted at a repetition rate of 50 MHz. The received echoes are compiled into scans or periods during which all reflections received are recorded and displayed. A scan may last from 50 to 2000 ns, which is the range of the Xadar unit. The GSSI unit may readily display scans between 50 and 360 ns, or longer, with special modification.

The pulse waveform scans are often compiled into a graphic display as shown in Figure 1. Such a display of usually thousands of horizontally stacked scans calibrates signal intensity against darkness so that thin white lines represent zero amplitude. Since these white lines are also wavefronts of constant amplitude and sometimes phase, they allow the wavefront of a single pulse to be traced throughout a record.

Data interpretation is simplest when the ground consists of vertically stacked layers of homogeneous, nondispersive dielectric materials. In such an ideal case, the round trip time t of propagation through each layer is related to the thickness d of each layer by the simple formula

$$t = \frac{2d\sqrt{x}}{c} \quad (1)$$

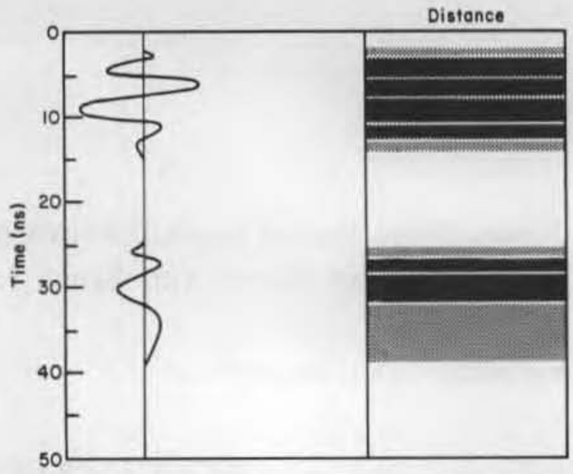


Figure 1. Idealized pulse returns and equivalent graphic display should these returns remain constant with distance.

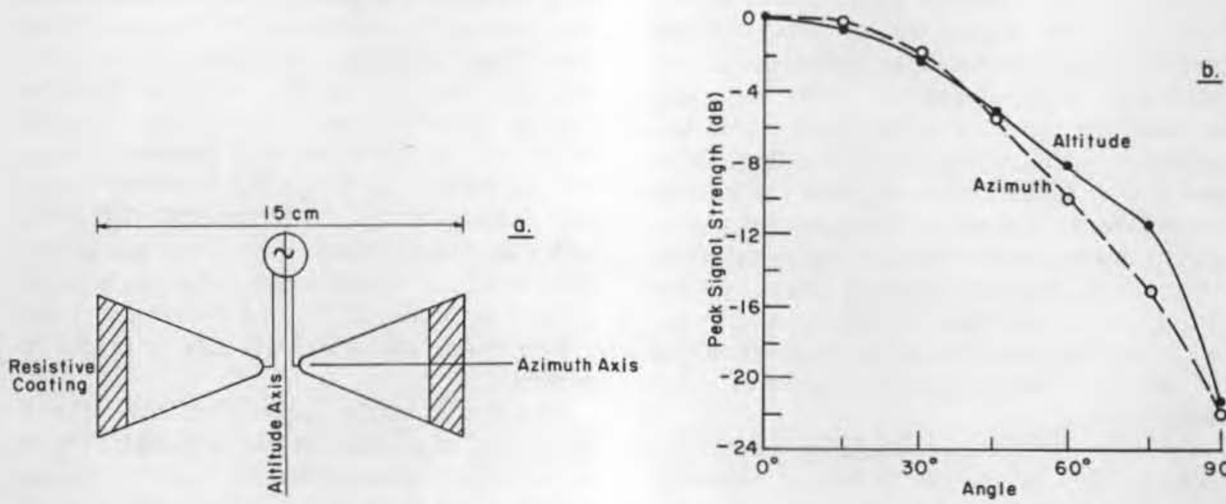


Figure 2. Schematic of the 101C (a), a resistivity loaded, broadband bowtie, UHF dipole, and the altitude and azimuth patterns (b) measured in air above a metal sheet. The pulse waveform is well maintained at 75° in both planes. The 3102 antenna is of similar design and must therefore have similar patterns.

where $\varkappa$ is the dielectric constant (square of the index of refraction) and c is 30 cm/ns, the speed of light in a vacuum. If the propagation medium is absorbing (either conductively or dielectrically) then it is also dispersive and will distort the pulse waveform. In some cases (e.g., wet silts and clays) penetration is limited to less than 1 m. For ice, $\varkappa = 3.2$ and for water at about 5 °C, $\varkappa \cong 85$. Below about 500 MHz water is not highly absorbing unless it is extremely conductive. In this case a measure of the depth of penetration is given by δ such that

$$\delta \cong 0.5\sqrt{\varrho/f}$$

where ϱ is the resistivity in ohm metres and f is frequency in megahertz. Over this depth 8.68 dB of signal strength is lost, or about 17.4 dB per round trip.

Both radar systems have about the same performance figure of 100–110 dB. Losses will occur because of absorption (i.e., δ), geometric spreading of energy (proportional to the inverse square of the distance propagated), and scattering or reflection. The antennas used are by necessity of very low gain and thus have a large beamwidth.

The 101C antenna (Fig. 2) has a 3-dB beamwidth of about 70° in free space. When the energy enters a dielectric medium, refraction will give some collimation. For example, when entering ice the 70° beam will narrow to 38°. The pulse shape emitted by the 101C is shown in Figure 3. The beamwidth and pulse shape of the 3102 are similar (by electromagnetic similarity), but could not be easily recorded with the GSSI analog control unit. These beamwidths are formed within 25 cm of the antennas when in air.

SITES AND SITE PREPARATION

Two sites were selected for this study. We conducted a preliminary study of waveform returns over bare ice at the first site. We used the second site for a more extensive study of both brash and sheet ice.

The first site was Lake Morey in Fairlee, Vermont, surveyed on 6 March 1985. The area chosen had a 40-cm ice cover that was covered with approximately 20 cm of fresh snow. The water beneath was over 6 m deep with an average ϱ = 90 Ω-m. The snow was cleared over a 6-m radius for some studies of just the ice cover, which was frozen solid.

The second site was Post Pond in Lyme, New Hampshire, surveyed on 14 and 20 March 1985. The nearshore area chosen had a 38- to 41-cm ice cover on 14 March, including some very porous snow ice for the top 5 to 8 cm. Below this was 5 cm of solid snow ice, underlain by 28 cm of clear ice in a candled state, i.e., long crystals with intercrystalline liquid water. The depth of the unfrozen water beneath varied from about 0.5–1.0 m, with an average ϱ = 330 Ω-m. A hole of about 1.6 m diameter was cut out, lined with a snow fence to about 1.2-m depth and filled with chunks of ice to simulate a brash ice cover.

The first tests on Post Pond were conducted on 14 March 1985. The depth of the brash ice column varied from 77 to 97 cm and total water depth was approximately 1.5 m. Most of the brash ice mass was in blocks that varied in size from 15 by 15 by 37 cm to 15 by 30 by 37 cm (approximately), but the mass included many fractional sizes also. The second tests were conducted on 20 March on this same, but rejuvenated, ice column. On 19 March the column had compacted and solidified to a depth of only 43 to 46 cm. Therefore, more ice was added on 20 March, which increased the brash zone depth to between 94 and 102 cm. In addition, the water level of the pond had slightly dropped, leaving a maximum ice plus water depth of about 1.3 m. On 20 March we used the 3102 antenna with the GSSI control unit.

RESULTS AND DISCUSSION

Antenna polarization was perpendicular to the profile traverse direction for all studies. In the 101C profile, the antenna was attached to a 5.8-m long "2×4-in." beam and hand carried along the traverse. In the 3102 surveys, the antenna was pulled along the surface or elevated by a specially rigged suspension cable.

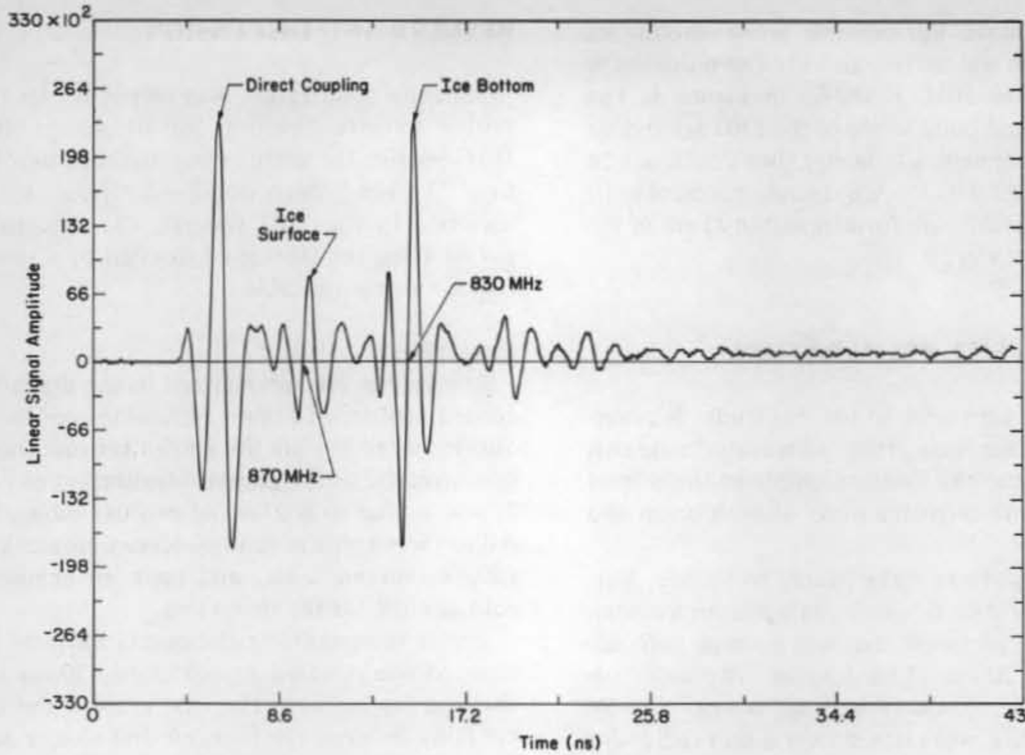
Lake Morey

The results are summarized in the digitally recorded profiles of Figure 3. Analog profiles were also recorded but are not shown because they are as uneventful as the graphic idealization of Figure 2, and similar to sections of profiles shown later. All of the waveform echo displays were stacked to reduce random noise, and have an exponential gain applied for the first 11 ns.

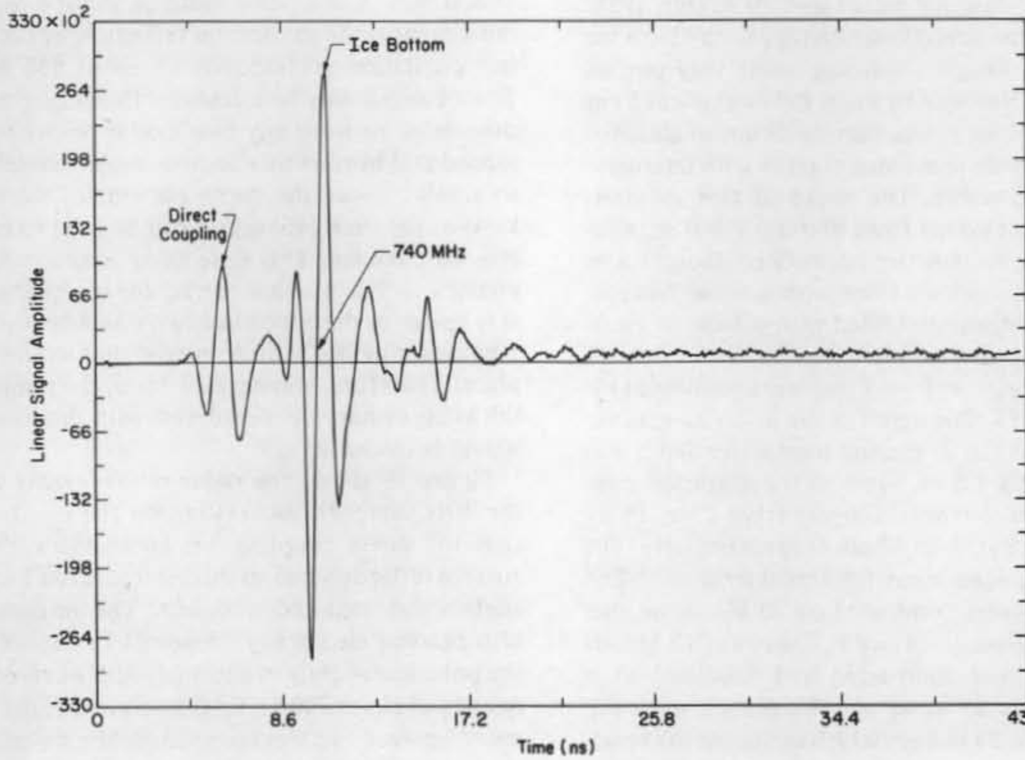
Figure 3a shows the radar events when the 101C antenna was elevated approximately 70 cm above the bare ice surface. The first event is the direct coupling between the transmit and receive antennas. The second event identified is the ice surface reflection, which is also the transmitted pulse waveform. It has an approximate center frequency of 870 MHz and a pulse width of about 4 ns. The third event is the ice bottom reflection whose central oscillation corresponds to about 830 MHz. The ice depth may be calculated by measuring the time delay between any two similar points on the second and third events because these wavelets are so similar. Since the depth (40 cm) of the ice is known, the time calibration can be used to calculate x of the ice. This time delay is about 4.8 ns giving $x = 3.2$, which is correct for freshwater ice. It is apparent that these last two wavelets could be 2 ns closer before serious interference would take place. Therefore, solving eq 1 for d, the minimum thickness of bare ice measurable with this antenna would be about 23 cm.

Figure 3b shows the radar return events when the 101C antenna was resting on the ice. In this case the direct coupling has combined with the surface reflection and so this reference has become slightly distorted and is inexact. The antenna has also become electrically "loaded" by the ice and the pulse has slightly broadened, with a center frequency of about 740 MHz. Consequently, the time delay between two similar points in the waveforms now varies from 4.6 to 5.0 ns, giving less accuracy than was obtained with the elevated antenna. The main advantage of surface emplacement is that more power is transmitted into the ice.

The 3-dB beamwidth measured in Figure 2 can



a. d = *40 cm, antenna height ≅ 70 cm.*



b. Antenna placed upon the ice sheet.

Figure 3. Antenna 101C return events from the Lake Morey ice sheet.

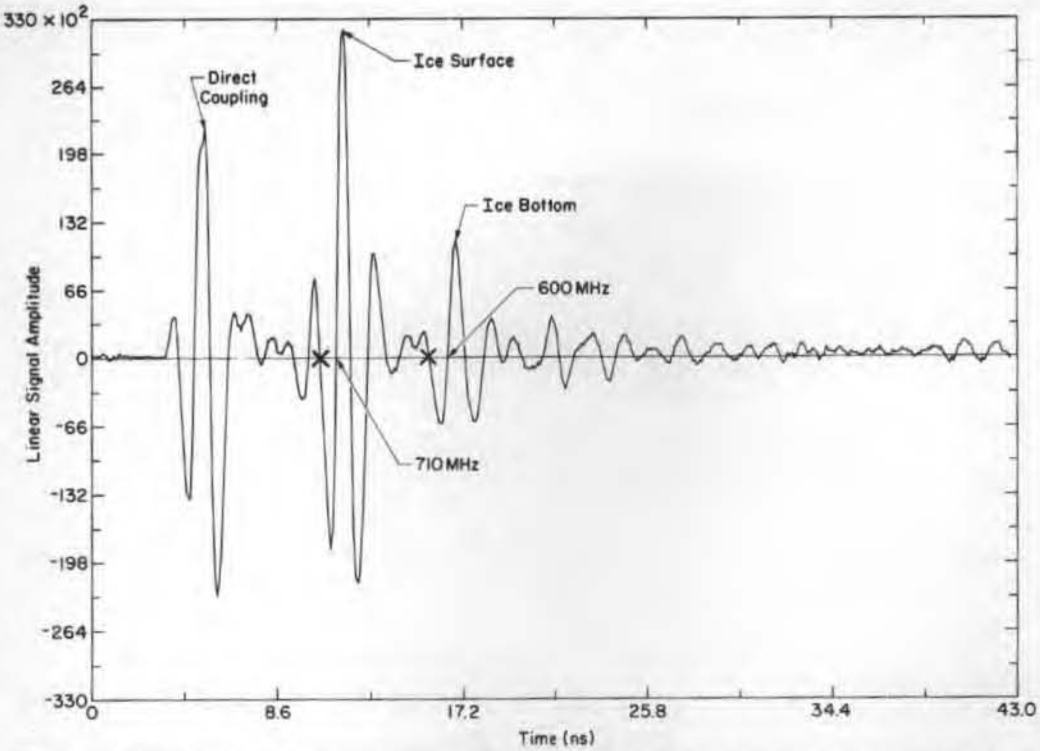


Figure 4. Antenna 101C return events from the Post Pond ice sheet on 14 March 1985. d = *38 cm, antenna height ≅ 1 m.*

be used to determine the approximate area of illumination of the ice beneath the raised antenna by employing Snell's Law. At a 70-cm height and a 70° beamwidth (BW), the diameter of the illuminated ice surface is about 100 cm plus the width of the antenna, or about 115 cm. In general, it is simply approximated by $2h\tan(BW/2)$ where h is the height of the antenna when greater than 1 m. The diameter D_{illum} of the illuminated portion of the bottom of the ice can be found from the formula

$$D_{\text{illum}} = 2h\tan\frac{BW}{2} + 2d\tan\left\{\sin^{-1}\left[\frac{\sin(BW/2)}{\sqrt{x}}\right]\right\} + \text{antenna width.} \quad (2)$$

In our case of $h = 70$ cm, $d = 40$ cm, $x = 3.2$ and $BW = 70°$; $D_{\text{illum}} = 140$ cm or about 1.5 m² of area.

Post Pond

Warm weather and rain had occurred by the time of the Post Pond study, and water was visibly draining from removed blocks of ice. The presence of free water is revealed by analysis of Figure 4, which shows the wavelets returned from the undisturbed ice sheet. The figure is to be compared with Figure 3a for Lake Morey. The wet and bubbly surface has lowered the center frequency of the surface reflection from 870 to about 710 MHz. The water within the ice sheet caused further dispersion and lowered the center frequency of the bottom reflection to 600 MHz. Calculating a value of x from similar points (marked with an x on the time axis) at the start of these waveforms gives 4.1, considerably higher than 3.2 for solid ice. To first order, this roughly corresponds to a volumetric water content of about 1%.

Figure 5 shows one of many varied returns obtained when the antenna was over the brash ice column. The surface reflection centers around 500 MHz and has become distorted with no identifiable bottom reflection present. Earlier work (Arcone 1981) has shown that even the most dispersive materials (e.g., water) cause serious distortion of these wavelets during transmission, but not upon reflection. The many facets of a rough ice surface, however, can scatter at many different frequencies (mostly UHF to microwave where wavelength is comparable to effective obstacle size), thus causing distortion. Therefore, distortion (or severe loss of higher frequency energy) may be a good indicator of brash ice.

Several attempts were made to improve the sig-

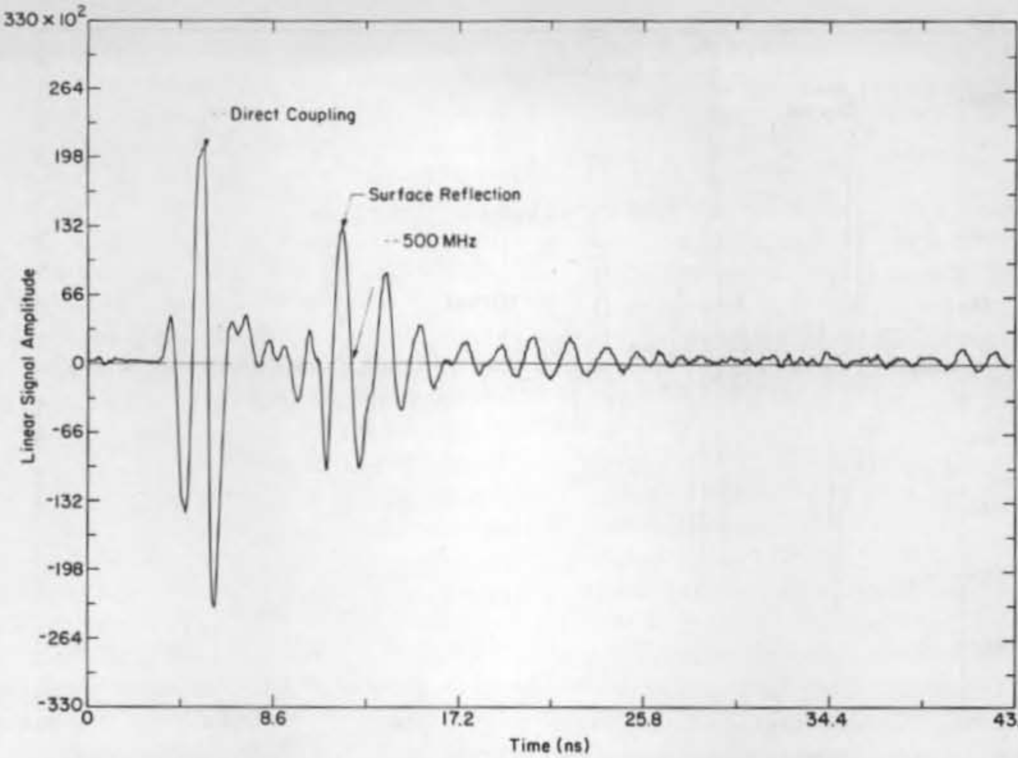


Figure 5. Antenna 101C return events above a circular column of artificial brash ice 1.6 m in diameter and 76–97 cm deep at Post Pond, 14 March 1985.

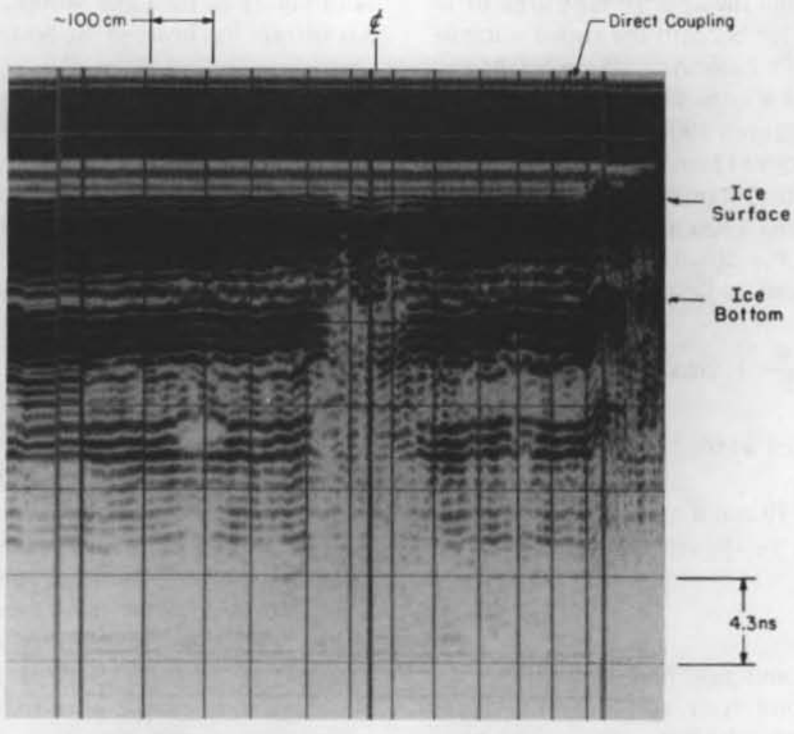


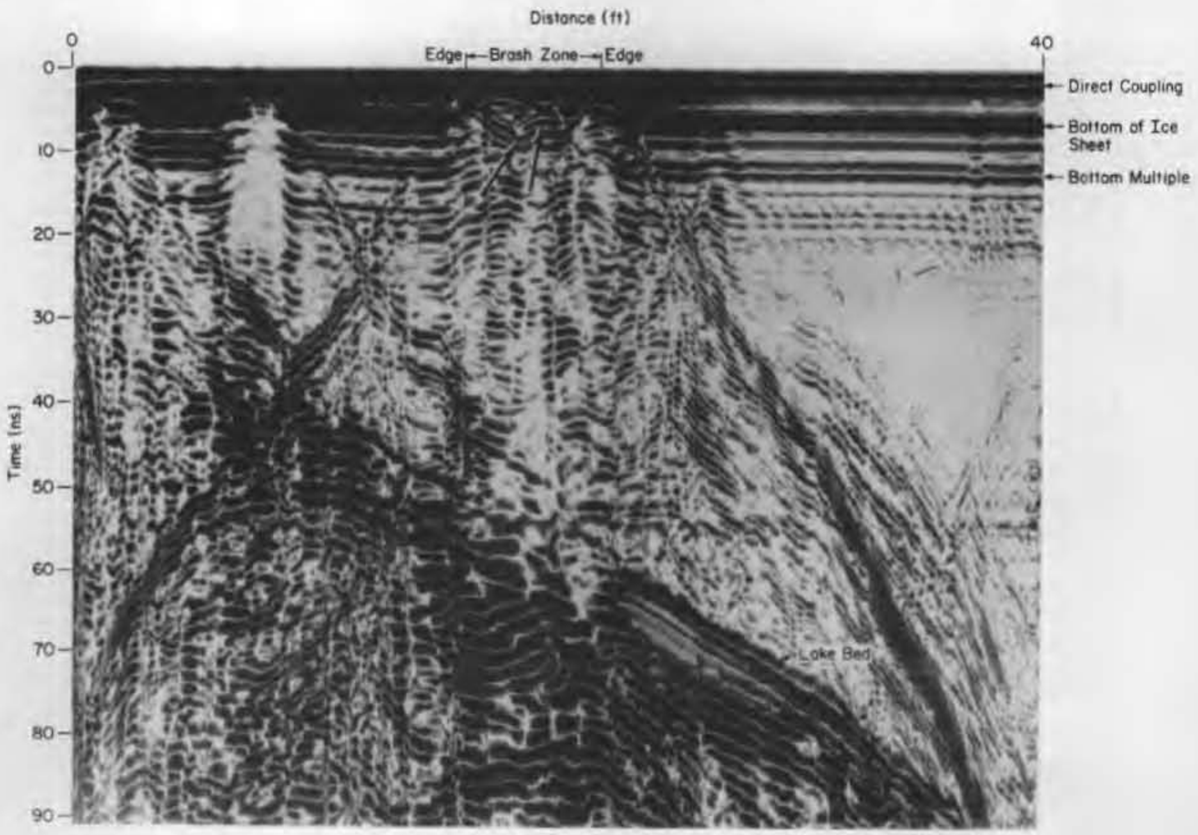
Figure 6. 101C profile over the artificial brash ice column, Post Pond, 14 March 1985. Antenna elevation ≅ 1 m. ℄ is the center of the brash ice.

nal quality by rotating the antenna while stacking, thus averaging the signal over many different polarizations. This did not bring out a bottom reflection, but did slightly improve the surface reflection.

Figure 6 shows a 101C analog profile over the brash ice zone. The first set of dark bands is the direct coupling, the second set is the ice surface, the third set the ice bottom and the much fainter fourth set a multiple bottom reflection. The brash ice column obscures the bottom reflection for a distance slighty less than 2 m, or about its actual diameter.

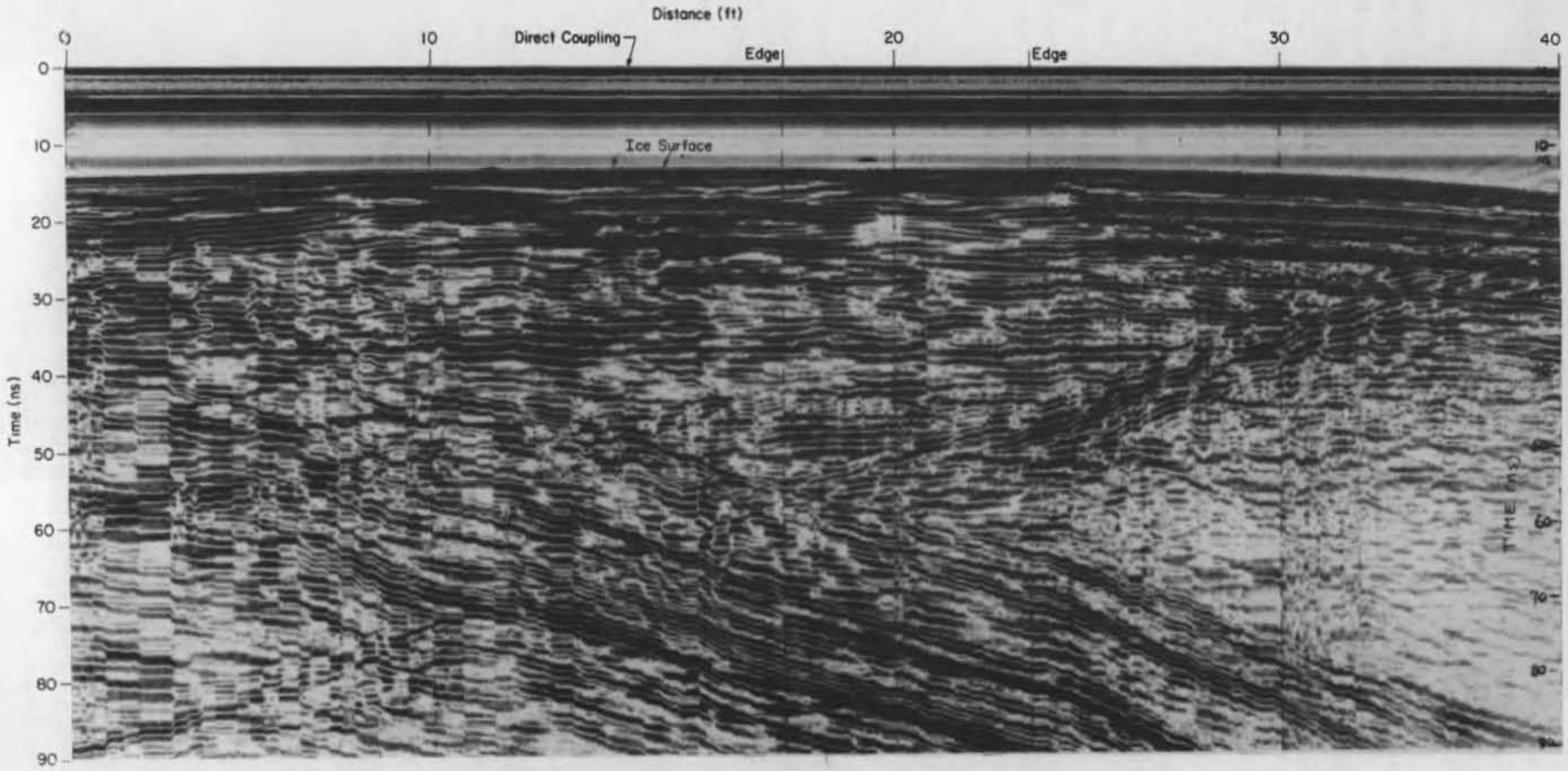
Figure 7 shows profiles taken on 20 March using the 3102 antenna. The profiles were recorded while we were moving away from the shoreline so that a water bottom return would be identifiable from its sloping reflection profile. Figure 7a was taken across the brash zone plus another 12 m of ice sheet surface with the antenna resting on the ice surface. The surface loaded the antenna and lowered its center frequency to about 500 MHz. As marked on the figure, the first horizontal bands are the direct coupling and the second bands are the ice bottom reflection. A heavy set of diagonal bands indicates that the lake bed and several subsurface reflections from beneath the lake bed can be seen. The bed reflections are partially obscured beneath the brash zone. The time scale indicates that the lake depth from the ice surface was about 1.2 m at the brash zone and about 1.5 m at one end of the survey on the right of the profile.

The most interesting features of Figure 7a are the returns caused by the brash zone. Between the markers indicated as "edge," two of the zero amplitude (thin white line) parts of the reflection from the bottom of the solid ice sheet can be followed almost continuously from edge to edge. These lines are marked by arrows. At the center of the zone, these wavefronts dip by an additional 3 ns. Assuming this reflection indicates the 55-cm-deep interface between the older, solidified brash ice and the newly added and wetter brash ice, the dielectric constant of the material above this re-



a. Antenna rests on the surface.

Figure 7. 3102 profile over the artificial brash ice column at Post Pond, 20 March 1985.



b. Antenna is elevated approximately 3 m above the surface.

Figure 7 (cont'd). 3102 profile over the artificial brash ice column at Post Pond, 20 March 1985.

flection is about 3.6, which is reasonable for wet, candled ice. In any case this indicates either a change of depth or a transition in electrical properties between the brash zone and the solid sheet.

The long diagonal reflections emanating from the edges of the brash zone are transverse electric waveguide modes (Arcone 1984) reflected back from the brash zone and propagating and dispersing within the ice sheet. In the absence of the guiding ice sheet, they would be diffraction hyperbolas. Their existence is evidence enough of the difference in electrical properties (both κ and ϱ) between the brash zone and the sheet ice. The slope and frequency of these events can be used to determine the dielectric constant of a layer and earlier work (Arcone 1984) has shown how to do this.

Figure 7b is over the same traverse as Figure 7a, only with the 3102 antenna elevated about 3 m above the ice surface. The time scale is the same as that of Figure 7a but because the antenna is elevated, the frequency is much higher (> 600 MHz) and the dark bands are narrower. The ice surface reflection is now separated from the direct coupling and because of the increased resolution, much more detail is revealed in the bottom sediments (the diagonal return sloping up to the right is artificial). The added elevation, however, now makes the brash zone much less visible because of the broad beamwidth. At a height of 3 m, the 3-dB diameter of the illuminated ice surface is about 4.4 m or about 2.8 m greater than the actual zone diameter.

CONCLUSIONS AND RECOMMENDATIONS

Short-pulse radar using the GSSI 3102 and 101C antennas was able to measure freshwater ice sheet thickness, to distinguish brash ice at close range (depending on roughness and lateral extent) and also, perhaps, to predict the free water content of a freshwater ice sheet by measuring its dielectric permittivity (κ). Detection of the bottom of a brash ice section is not deemed feasible because of waveform distortion and scattering losses. However, it may be possible to detect brash ice beneath a continuous ice sheet.

Detection of the bottom of the water body may be possible in up to 2 m of water (including the ice) with the 3102 antenna, providing that the water is not too conductive. At Post Pond the water was unusually resistive (330 Ω-m) giving a skin depth of about 26 cm (exact calculation) at 700 MHz. This gives a large 33-dB/m absorption loss or about 100 dB in 2 m (including a 50 cm ice sheet), leaving about 10 dB for geometric spreading, reflection and scattering losses. The total loss would be about the limit of detection for an unmodified GSSI system. More usually, the resistivity of water is much lower (especially when polluted) so that river or bottom returns may not be visible in over 1 m of unfrozen water.

If a snow cover exists on the ice, the radar echo from the bottom of the ice sheet will be additionally delayed, thus introducing an error in the ice thickness determination. Generally, late spring conditions are such that the snow has thawed and refrozen to give additional thickness to the ice. If the snow is cold and powdery, very little error will result and clear reflections from the ice surface and bottom will be seen.

We recommend that a higher power version of the 3102 antenna be used in an analog mode for remote sensing from a helicopter at an altitude of about 10 m. At this altitude the 3-dB illumination area of the ice surface will be about 150 m^2 (7 m radius) and the bottom surface illumination area will not be much different. A filter and shielding design should be undertaken to eliminate helicopter clutter and noise. Power frequency spectra should be computed after a survey to detect possible brash ice zones. Such a running computation may be within our capability at CRREL by 1986. Deconvolution of the radar signal does not seem necessary with the 3102 as the pulse is short enough to measure a minimum of about 25 cm of ice. If lesser thicknesses are desirable then deconvolution will be necessary.

It is also recommended that a controlled laboratory study be undertaken to establish the correlation between water content of the ice and dielectric permittivity for horizontal polarization at normal incidence. Such a study could establish a margin of error for thickness measurements performed when the ice is known to be at 0°C.

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