Environment Canada Environnement Canada

Radio Depth-Sounding on Meighen and Barnes Ice Caps, Arctic Canada

Stephen J. Jones

SCIENTIFIC SERIES NO. 25

INLAND WATERS DIRECTORATE,
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Abstract

Depth measurements are given for Meighen Ice Cap and Barnes Ice Cap which were obtained by using a 35 MHz S.P.R.I. radio echo sounder. By comparison with a known borehole depth on Meighen, the velocity of the radio waves in the ice was 178 ± 2 m μs^{-1}. The minimum depth that could be sounded was 90 m. On Barnes Ice Cap, the velocity was measured by a wide angle reflection technique as 168 ± 2 m μs^{-1} and continuous photographic recording of the depth was obtained. Estimates of absorption in the ice from attenuator settings of the echo sounder were significantly greater than previously published values.

Radio Depth-Sounding on Meighen and Barnes Ice Caps, Arctic Canada

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INTRODUCTION

In April 1970, a Scott Polar Research Institute (S.P.R.I.) MK II 35 MHz radio echo sounder was used to obtain depth and velocity measurements on Meighen Ice Cap, Meighen Island (lat. 80° N, long. 99° W) and Barnes Ice Cap, Baffin Island (lat. 70° N, long. 72° W). At the same time Dr. W.S.B. Paterson and Dr. R.M. Koerner of the Polar Continental Shelf Project, Department of Energy, Mines and Resources, were using a 440 MHz radar altimeter in order to compare the two units in operation on Meighen Island. Also, a calibration of the echo sounders, or a measure of the velocity of the radio waves, could be obtained from the known depth of a borehole on Meighen Ice Cap. On Barnes Ice Cap, the 35 MHz unit only was used, which gave good bottom reflections over most of the "South Dome" area. In particular three profiles were obtained along lines of stakes forming a trilateration network which is to be used for strain-rate measurements. The velocity of the radio waves was also measured on Barnes by a wide angle reflection technique.

APPARATUS

The electronics of the Scott Polar Research Institute MK II radio echo sounder has been described by Evans and Smith (1969) and its operation in Greenland by Robin, Evans and Bailey (1969). The concern was to measure small depths of the order of 100 m on Meighen Ice Cap using over-snow vehicles rather than aircraft. The major problem, therefore, was to resolve the reflected pulse from the tail end of the transmitted pulse which was always picked up by the receiver. Independent transmitting and receiving antennae were separated by about 50 m in order to minimize the saturation effect of the transmitted pulse but, even so, this pulse was always at least 1 μs long. It was not possible to suppress the receiver during the transmission without also suppressing the reflected pulse. The antennae were of the half-wave dipole type with a coaxial 'trombone' balun. Two oscilloscopes were connected to the receiver output; one of them gave a conventional "A-modulated" output display for monitoring purposes, the second gave a "Z-modulated" output in which the spot is blacked out in the absence of a signal. The video signal from the receiver modulates the brightness of the spot. The photographic film in the recorder is driven slowly at right angles to the linear time base sweep on the cathode-ray tube so that a single strong echo, constant in range, will produce a single straight line down the length of the film. A second line is produced by the signal which arrives directly from the transmitter at the beginning of the sweep.

The most satisfactory arrangement of the equipment is shown in Figure 1. A twin track skidoo pulled a hut mounted on a Nansen sled, inside which sat the operator with the receiving equipment (Figure 2). The hut was made of plywood, insulated with expanded polystyrene, and held together with Dexion angle iron. It was covered with a tarpaulin to keep out light which would make viewing of the oscilloscope trace difficult. The receiving antenna was mounted on the side of the hut. Towed behind the first sled, at a distance of about 50 m, was another Nansen sled on which was mounted the transmitting equipment. The transmitting antenna was about 0.3 m from the ice surface and the receiving antenna was about 1.5 m from the ice.

The 440 MHz system, used by Paterson and Koerner, is an SCR-718 radar altimeter and has been described by Weber and Andrieux (1970). The only addition to their apparatus was the incorporation of a storage oscilloscope and camera to give a continuous photographic record as well as spot readings. The major disadvantage of this addition was that the oscilloscope consumed so much power that it could only be used for about one hour before the batteries were drained.

RESULTS

General Results

As mentioned previously the major problem was to resolve any reflected pulse from the tail end of the direct transmitted pulse which was at least 1 μs in length. On both Meighen and Barnes Ice Caps the transmitter and receiver had to be separated by at least 50 m in order to reduce the intensity of the direct transmitted pulse. Even with this separation it was impossible to obtain a photographic record of the depth on Meighen Ice Cap where depths were less than about 100 m, although spot measurements could be made. This was because the "Z-modulated" oscilloscope

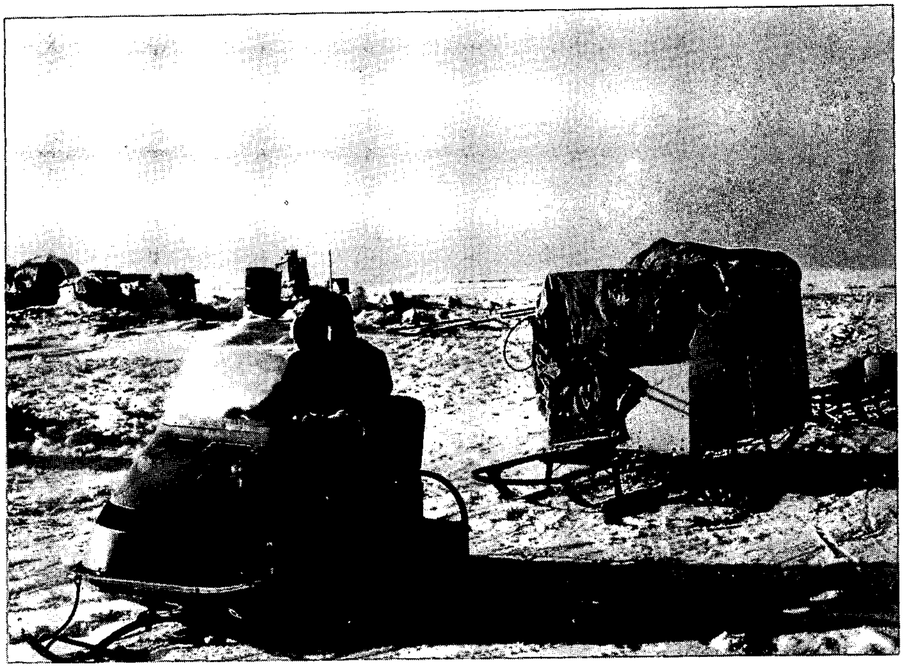

Figure 1. A skidoo pulling Nansen sleds with the hut for the receiving equipment mounted on the first sled and the transmitting equipment on the second.

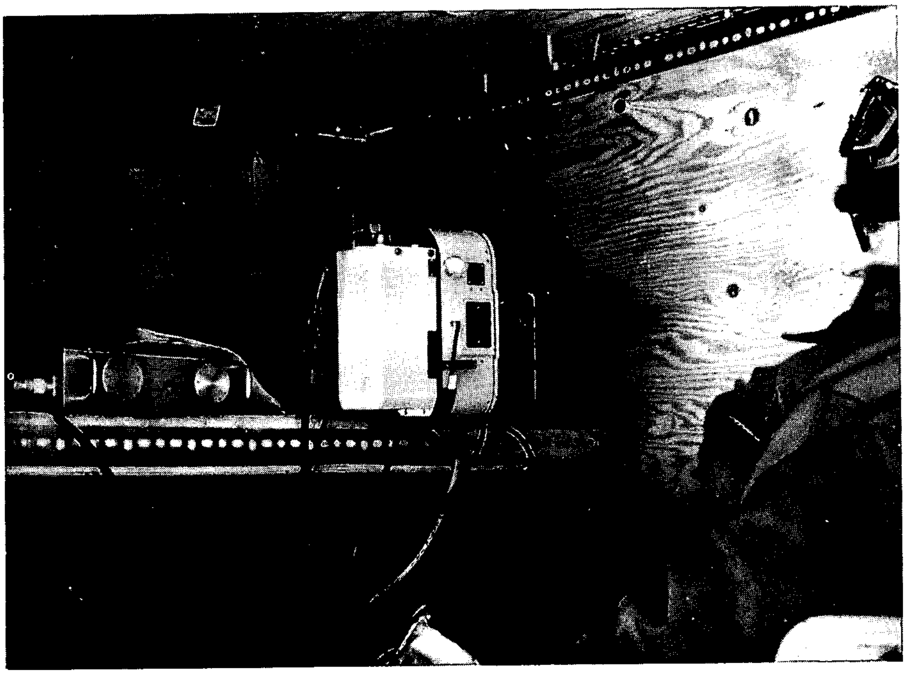

Figure 2. The arrangement of the receiving equipment inside the hut.

required a stronger signal to trigger it than the normal "A-modulated" oscilloscope; to make the reflection strong enough for the Z-modulated oscilloscope the receiver attenuation was reduced thus allowing more of the transmitted pulse through and obliterating any reflected pulse. Spot measurements were possible with a A-modulated oscilloscope, and by continuous observation of the trace the bottom reflection could be picked out from the background quite easily. On Barnes Ice Cap, where depths were greater (300 m) a photographic record was obtained.

Depth Measurements

All depth results were calculated using the equation:

$$4d^2 = [V_i(t + x/V_a)]^2 - x^2$$

where d is the depth of ice, x is the transmitter to receiver distance, V_i is the velocity of the radio waves in ice, V_a is the velocity of the radio waves in air and t is the measured time difference between the arrival of the direct transmitted pulse and the reflected pulse. The distance, x, was held constant for a particular experimental 'run' but could be altered between 'runs'.

V_a is assumed to be 300 $m\mu s^{-1}$, and V_i is assumed to be 169 m μs^{-1}. This corresponds to a relative permittivity of 3.17 and is the value preferred by Robin and others (1969, p. 459). The time difference could be measured to ± 0.1 μs.

Results from Meighen Ice Cap

The depth of the ice at the borehole is known to be 121 m and the temperature varies from −17.5°C at a depth of 10 m to −15.9°C at the base (Paterson, 1968). By comparing our measured values of t obtained at the borehole, for various known x, we have deduced a value for V_i and this is shown in Table 1. The mean and standard deviation (of 5 measurements) is 178 ± 2 m μs^{-1}, with the error in a single reading being about ± 14 m μs^{-1} due largely to the accuracy with which the oscilloscope could be read. This result corresponds to a relative permittivity, ϵ, of 2.85 ± 0.05, significantly lower than that used by Robin and others (1969) or measured in the laboratory on pure ice (Paren, unpublished). The fact that there was difficulty in resolving the reflected pulse from the transmitted pulse cannot explain the high velocity; if anything, a lower velocity corresponding to a wider separation of transmitted and received signals would have been more readily observed. Paren (unpublished) has calculated the expected ice density variation of dielectric constant of an ice matrix containing random spherical air bubbles. His calculation gives $\epsilon = 2.85$ at a density $\rho = 0.80$ Mg m^{-2} increasing linearly to $\epsilon = 3.2$ at $\rho = 0.92$ Mg m^{-2}. A probable figure for the mean density of the bubbly ice of Meighen Ice Cap is 0.88 Mg m^{-2} which is not low enough to account for the dielectric constant we obtained.

Table 1. Determination of V_i by comparison with a known borehole depth of 121 m.

x m	t μs	V_i m μs^{-1}	Mean V_i
20	1.3	177	
86	1.1	185	
20	1.3	177	178 ± 2
70	1.2	176	
70	1.2	176	

The remaining depth measurements, calculated with V_i = 169 m μs^{-1}, obtained on Meighen Ice Cap are shown in Table 2. Column 4 gives the depths obtained with the 35 MHz system while column 5 gives the results obtained with the 440 MHz radar altimeter. The location of the stakes is shown by Paterson (1969, Fig. 2, p. 343). At 3 of the 8 stakes, where both systems gave readings, agreement between columns 4 and 5 is good and at the remaining 5 the 440 MHz unit gave values of up to about 10 m deeper than the 35 MHz unit. It is unusual that the 440 MHz unit should always give greater depths than the 35 MHz. From laboratory dielectric studies on ice, there is no evidence that the dielectric constant varies between these frequencies. If the discrepancy is significant, and it should be remembered that the amount of data is limited, it probably reflects a systematic error in one or other of the echo sounders.

Table 2. Depth measurements obtained on Meighen Ice Cap.

Location Stake Number	Transmitter Receiver Separation x m	Time Between Pulses t μs	Calculated Depth d m 35 MHz		Calculated Depth d m 440 MHz
35	–		<90		65
34	20	1.1	98	101	113
	20	1.1	98		
	70	1.0	97		
	86	1.1	109		
32	70	1.1	106		113
Camp	86	1.0	99	107	121
	70	1.2	115		
27	70	1.1	106		117
29	70		<90		94
25	70	1.1	106		108
24	70	1.0	97		98
21	70	1.1	106		107
20	70	1.0	97		102

The minimum depth that could be measured with the S.P.R.I. system was about 90 m. As mentioned earlier, this limit is governed by the width of the transmitted pulse. Thinner ice has been sounded with this equipment mounted in an aircraft (Hattersley-Smith, Fuzesy and Evans, 1969). In such a case it is possible to suppress the receiver during transmission and still to see the pulses reflected from the top and bottom surfaces. The 440 MHz SCR-718 radar altimeter had the advantage that it could be used to slightly thinner depths, ≈ 60 m minimum.

Results from Barnes Ice Cap

Velocity Measurements

The velocity of the 35 MHz radio waves in the ice was measured by a wide-angle reflection technique, as used by Jiracek and Bentley (1966), Jiracek (1967), Robin and others (1969) p. 462, Clough and Bentley (1970). From equation (1) it follows that for constant d and V_i if $(t + x/V_a)^2$ is plotted against x^2, a straight line of slope $(1/V_i)^2$ and intercept, at $x = 0$, of $(2d/V_i)^2$ is obtained. If d is not constant a correction factor $\pm 4 \times d \sin \Theta$, where Θ is the mean slope of the bed, can be added to each x^2 value. The correction is positive if d increases with increasing x. This is an important term when the ice is relatively thin as in the present case (410 m). Sin Θ was 0.025 and this made a difference of 7 m μs^{-1} to the calculated value of V_i. The result obtained is shown in Figure 3 in which the crosses are the measured t values (squared) and the filled circles are the $(t + x/V_a)^2$ values. From this figure it can been seen that although the t^2 values vary little with x^2, except for very small x, the plot of $(t + x/V_a)^2$ against x^2 is a straight line. From the slope of the line a least squares analysis gives $V_i = 168 \pm 2$ m μs^{-1} and an intercept of 25.5 μs^2. This value of V_i corresponds to a relative permittivity of 3.1 ± 0.1, in excellent agreement with other laboratory and field measurements on pure ice (Paren, 1970, Fig. 5.3). This agreement is however probably fortuitious for three reasons. First, the t values measured in the field were only accurate to ± 3%. This error was due largely to the fact that the transmitted pulse through the air was used both to trigger the oscilloscope and as a reference from which to measure t. Hence, part of the leading edge of this pulse was missing and so it was necessary to extrapolate it back to the zero line in order to measure t. It would be an advantage to trigger the oscilloscope ahead of the arrival of the transmitted pulse as was normally done when determining depths, but this requires a number of additional long cables which were not available at the time of this work. Second, there are two "correction factors", neither of them negligible, which affect the resulting velocity. The term x/V_a which is added to all the t values is of the same order of magnitude as t and varies far more than t as a function of x. However, any error in x/V_a should be negligible since x was measured with a steel tape to within ± 5 cm. It was

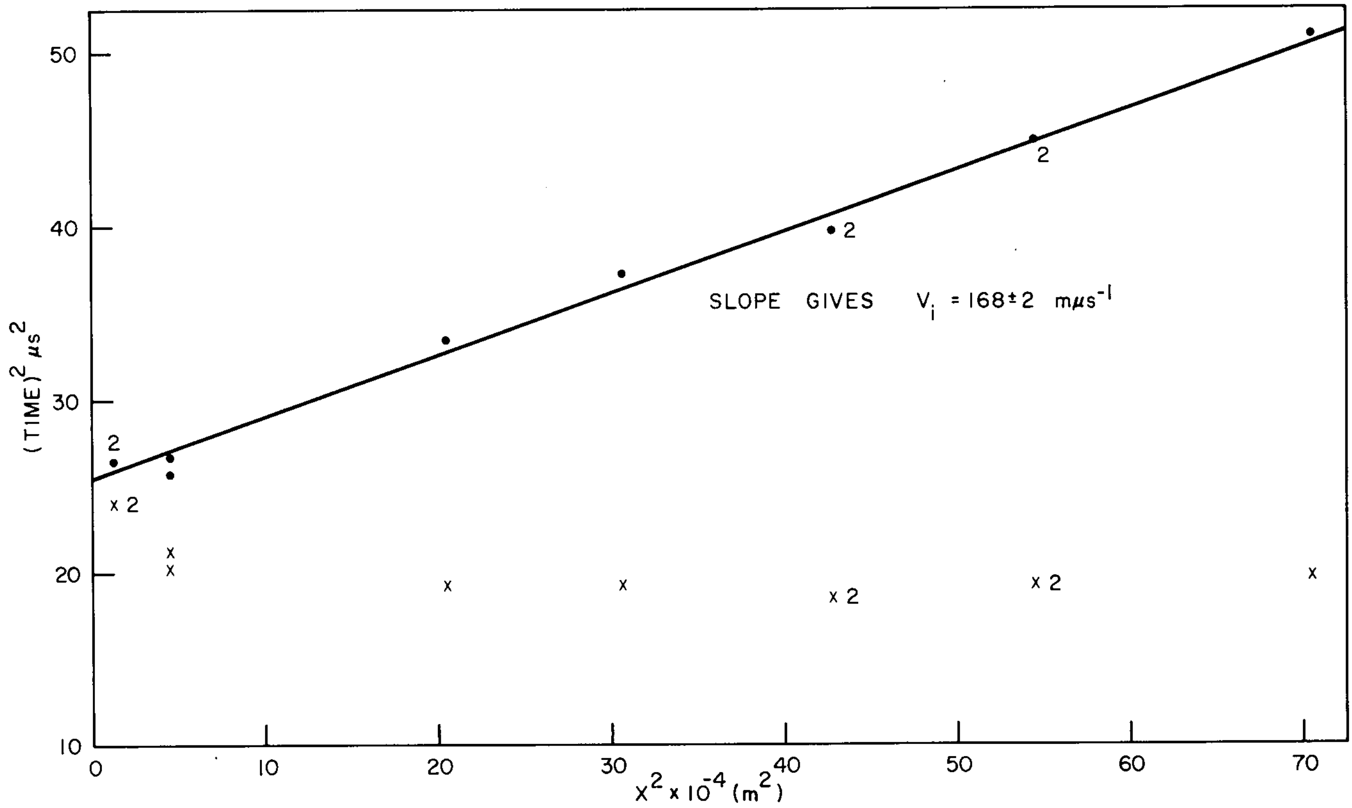

Figure 3. Wide-angle reflection velocity determination on Barnes Ice Cap. The crosses are the measured t^2 values and the filled circles are the $(t + x/V_a)^2$ values. The number 2 indicates two identical data points.

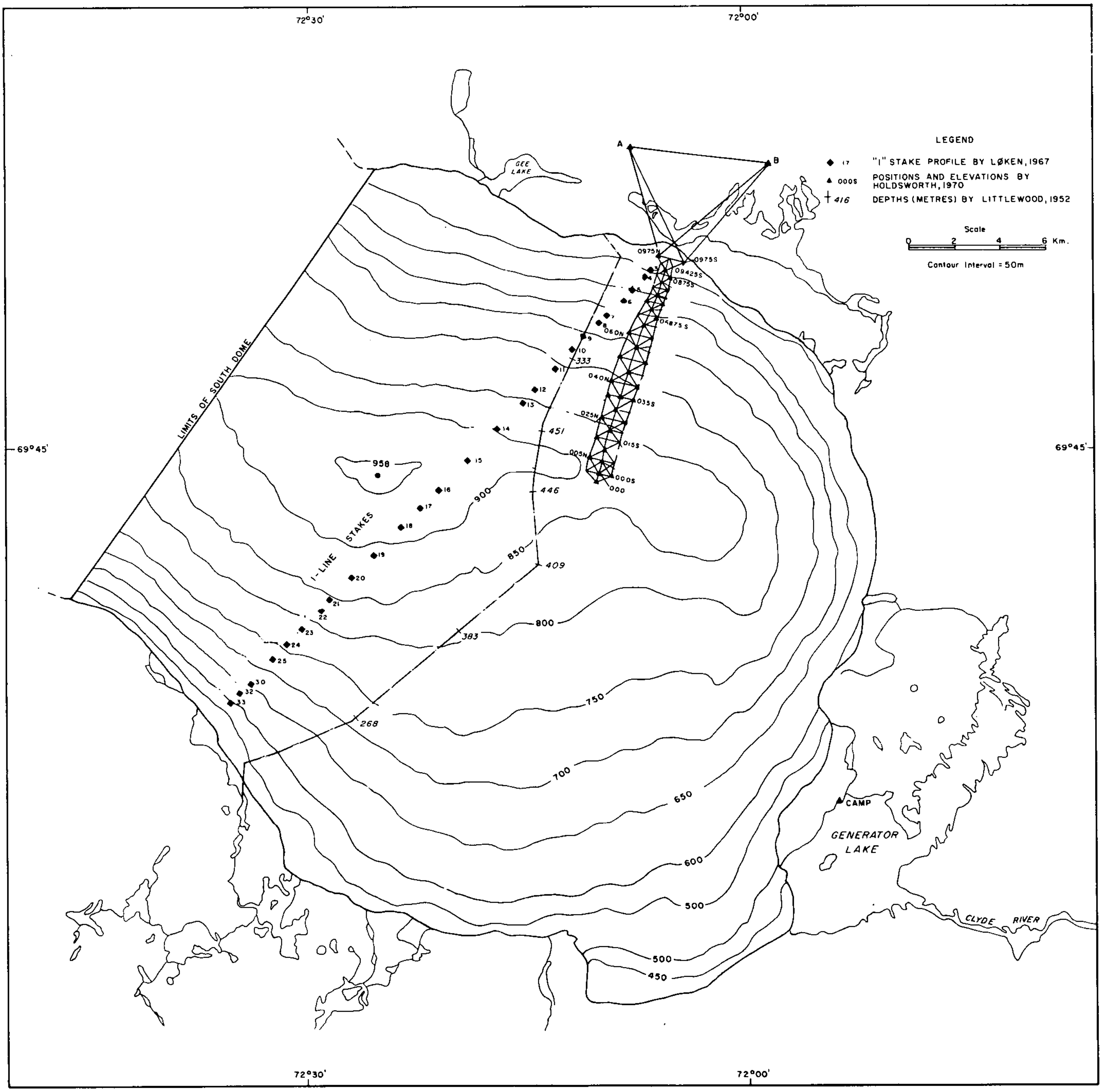

Figure 4. The location of the trilateration network of stakes, the I-line and part of Littlewood's (1952) gravity traverse on the "South Dome" of the Barnes Ice Cap. Ice depths obtained by Littlewood are shown at a number of points.

assumed that V_a is constant at 300 m μs^{-1}. The second correction factor is the term 4xd sin Θ which was added to each value of x^2 to take account of the increase in depth of the ice of about 20 m between x = 0 and x = 800 m. Neglect of this factor would have reduced V_i by about 7 m μs^{-1}. Ideally this experiment should be done under conditions where the top and bottom surfaces of the ice are parallel; this factor could then be neglected. Third, refraction at the snow surface and within the upper layers of the ice cap is neglected. This is probably justified for the Barnes Ice Cap because the snow was only 1.7 m thick before ice was reached (Holdsworth, unpublished data; Baird, 1952).

Clough and Bentley (1970) have also measured the velocity of radio waves in the Barnes Ice Cap by the wide

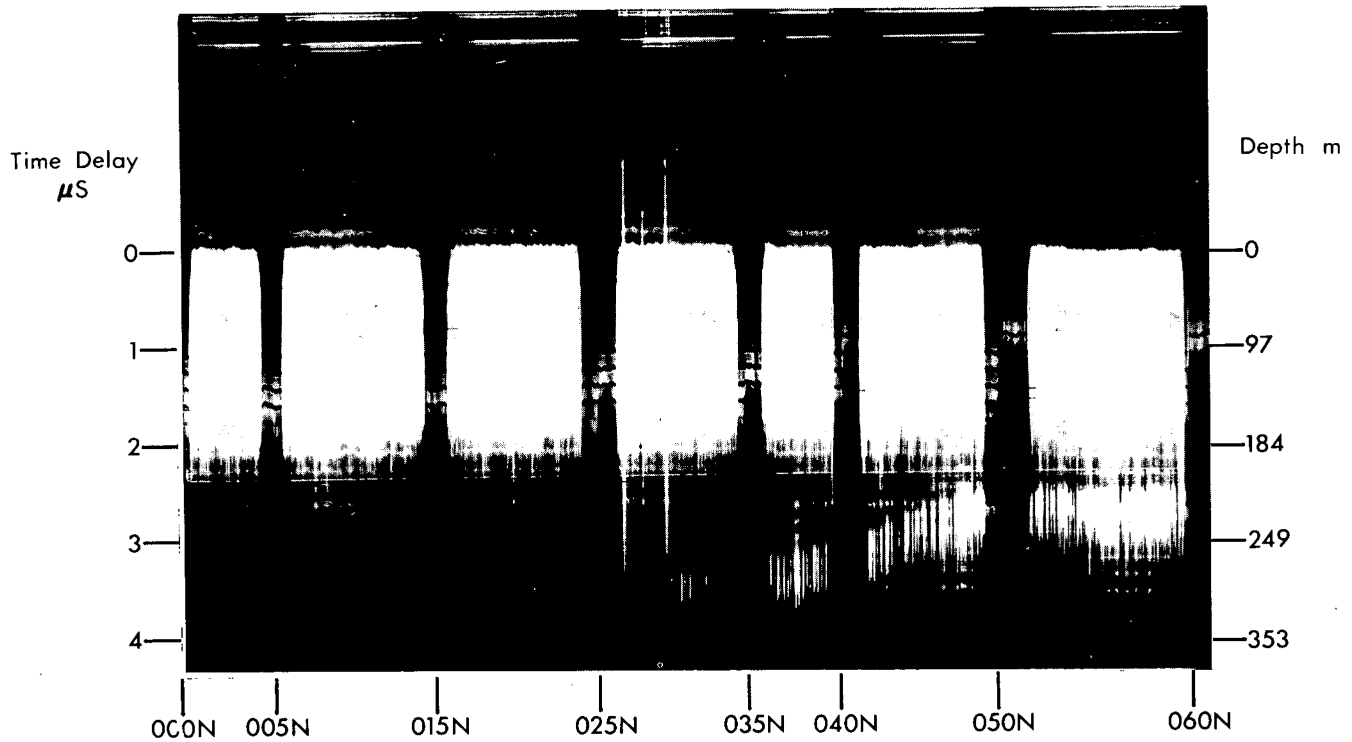

Figure 5.(a) Continuous photographic record of depth measurements along the north line of the trilateration network.

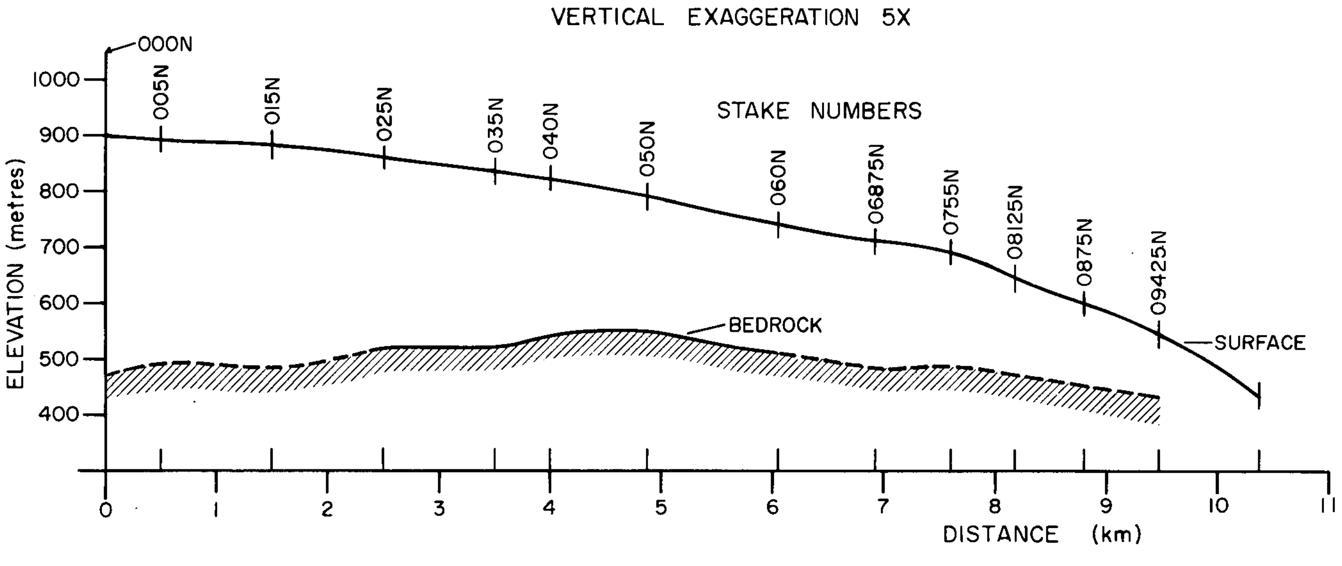

Figure 5.(b) Surface and bottom profile along north line of trilateration network: the surface profile was determined by surveying, the bottom profile from the radio echo sounding. A dotted line for the bottom profile indicates that spot measurements only were available.

angle reflection technique and obtained a result of 171.4 ± 0.8 m μs^{-1}. The intercept of their $t^2 - x^2$ plot corresponds to a depth of 260 m. They do not mention what corrections, if any, were made to their data for non-parallel top and bottom surfaces. The slight disagreement between their value and the present one of 168 ± 2 m μs^{-1} is considered insignificant and probably arises because a least squares standard deviation of the slope of the $t^2 - x^2$ plot gives an exaggerated impression of the accuracy of the experiment by ignoring any systematic errors.

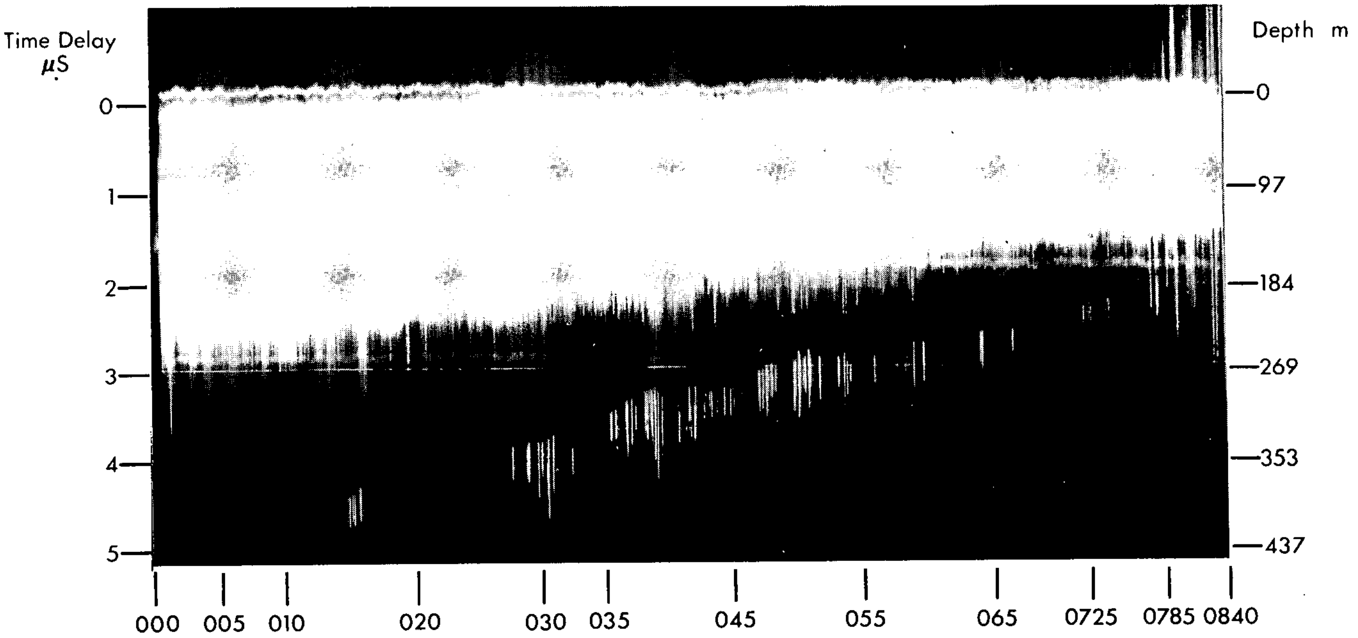

Figure 6.(a) Continuous photographic record of depth measurements along centre line of trilateration network.

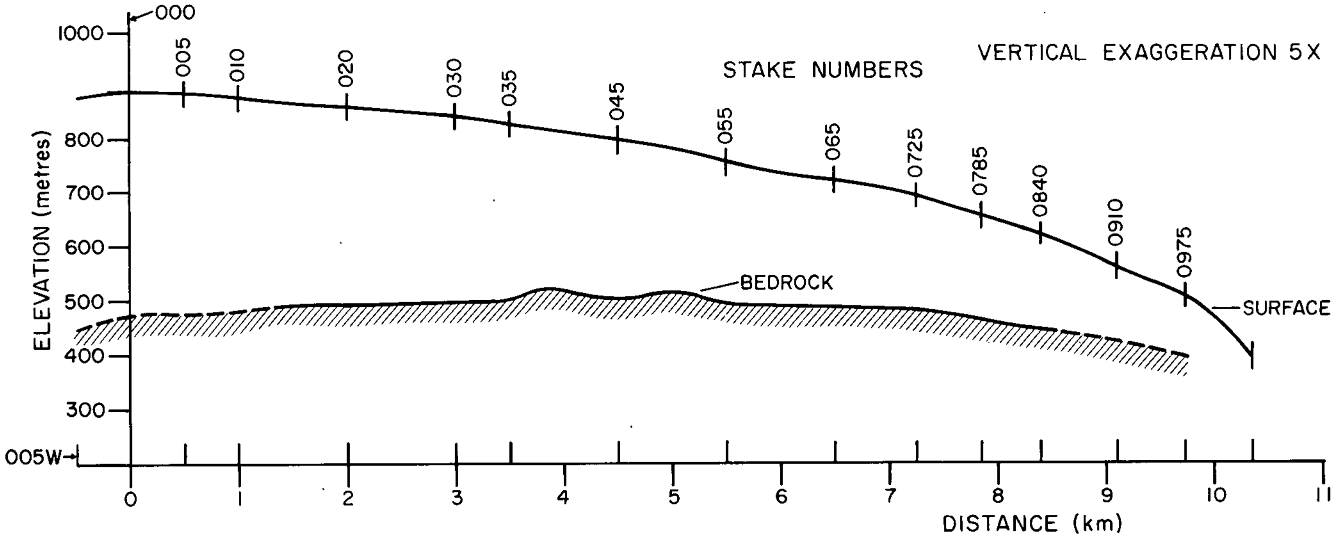

Figure 6.(b) Surface and bottom profile along centre line of trilateration network: the surface profile was determined by surveying, the bottom profile from the radio echo sounding. A dotted line for the bottom profile indicates that spot measurements only were available for the depth.

Depth Measurements

Measurements of ice depths were made along a trilateration network of stakes which had been drilled into the ice cap by Dr. G. Holdsworth, Glaciology Division, Inland Waters Directorate, for the purpose of making strain-rate measurements. The three parallel lines of stakes forming the network are referred to as the north, central and south lines respectively. Stake 000 is the origin of the central line and stake 0840 (for example) is 8.4 km from 000 on the central line. The location of the network on the "South Dome" of the Barnes Ice Cap is shown in Figure 4. The location of the I-line stakes is also shown in Figure 4, together with part of the gravity traverse made by

Littlewood (1952). Spot measurements were made at each stake and a photographic record was also obtained between the stakes. Figure 5b shows surface and bottom profiles along the north line of stakes; the spot readings are used together with values taken from the photographic record obtained by measurement of the film under a microscope. Where only spot readings are available, a dotted line shows the bottom profile. Figure 5a shows the radio echo sounding photographic record corresponding to Figure 5b. Figure 6 shows the profile down the centre line of stakes and Figure 7 the south line. In each case the surface profile was determined by surveying techniques (Holdsworth, unpublished data) and the results made available to the author.

Table 3. Depth measurements obtained at the stakes of the trilateration network.

Location	Surface Elevation (metres)	Depth (metres)
0975 N	513	
0975 S	512	
0975	509	115
09425 S	541	
09425 N	540	115
0910	567	141
0875 S	606	141
0875 N	592	149
0840	622	164
08125 N	640	
08125 S	647	167
0785	661	196
0755 N	677	201
0755 S	682	201
0725	693	211
06875 S	714	235
06875 N	705	235
065	724	243
060 N	736	241
060 S	746	255
055 S	760	263
050 N	785	239
050 S	780	285
045	796	292
040 S	813	330
040 N	815	278
035	829	320
035 N	828	310
035 S	828	330
030	841	334
025 S	852	334
025 N	853	343
020	863	369
015 S	873	402
015 N	872	395
010	881	391
005 N	888	404
005	888	414
005 S	888	413
000	893	417
000 N	893	429
000 S	893	429
005 W	887	438
S – 10	948	–
S – 2	951	454
S – 1	951	463
S – 3	942	429
S – 4	942	446
S – 5	940	454
S – 6	945	463
S – 9	949	–
S – 8	948	–
S – 7	941	–

Depth measurements were also obtained along the I-line of stakes shown in Figure 4 and these are shown in Figure 8. A continuous record was only obtained between stakes I 1-I 18. Spot measurements were obtained between I 18-I 32, again shown by a dotted line in Figure 8c. The surface profile was determined by temperature-corrected altimetry. Depth measurements along the I-line agree in general with those of Clough and Løken (1968). However, in detail there are disagreements and this is thought to be because Clough and Løken (1968) had only spot measurements every 0.25 to 1.0 km. Comparison with Littlewood's gravity measurements gave agreement to within 10% of the depth.

Table 4. Depth measurements obtained at the stakes of the I-line profile.

Location	Surface Elevation (metres)	Depth (metres)
I-1	527	132
I-3	592	154
4	620	172
5	659	202
6	684	224
7	718	243
8	735	260
9	760	260
10	789	283
11	817	310
11.5		
12	837	340
12.5		
13	857	356
13.5		
14	886	385
14.5		
15	912	364
16	920	410
17	916	407
18	908	388
19	896	404
20	872	387
21	846	337
22	816	350
23	785	323
24	758	281
25	728	256
30	649	212
32	620	193
I-33	591	

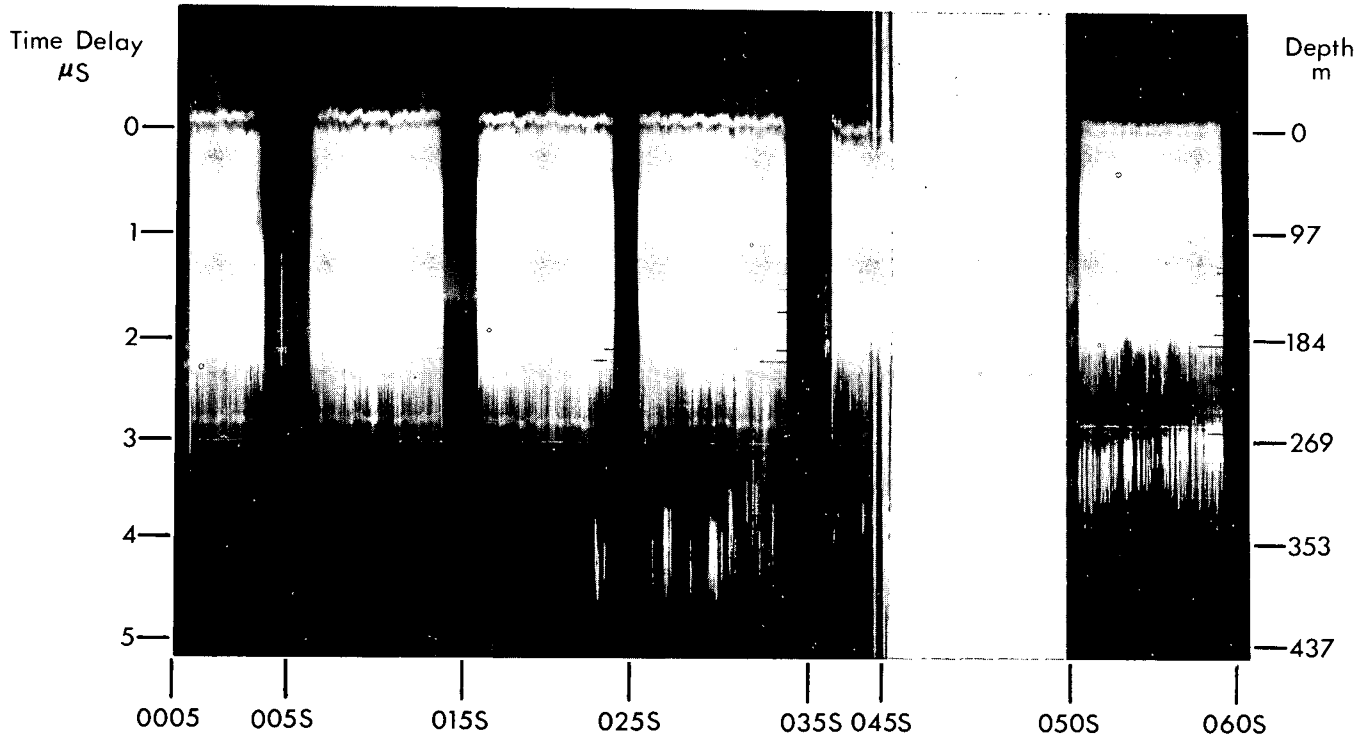

Figure 7.(a) Continuous photographic record of depth measurements along south line of trilateration network.

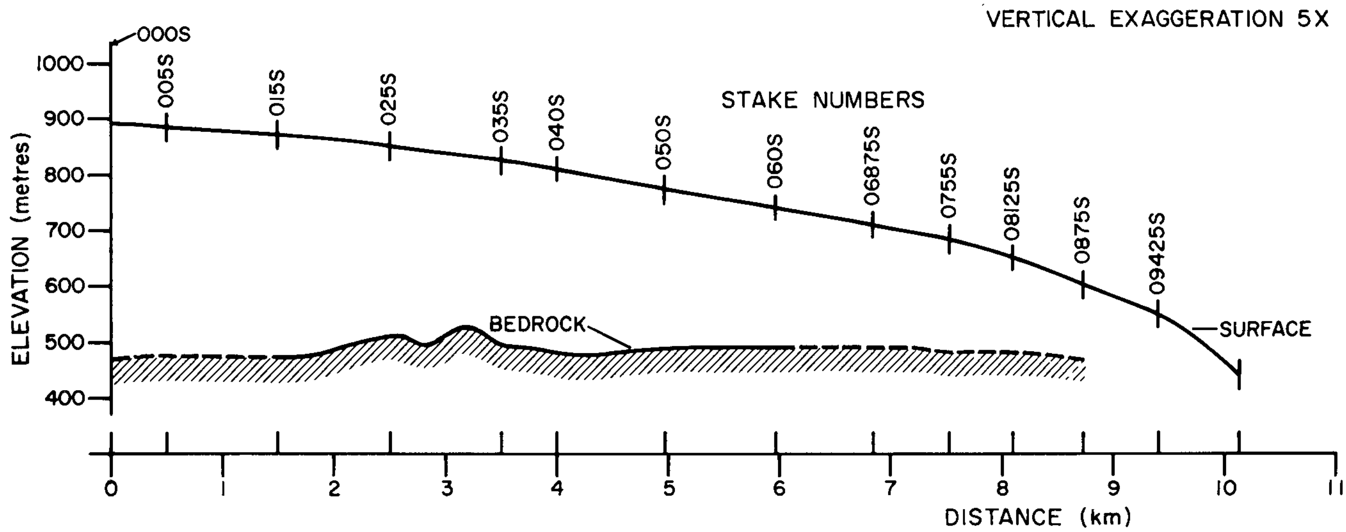

Figure 7.(b) Surface and bottom profile along south line of trilateration network: the surface profile was determined by surveying, the bottom profile from the radio echo sounding. A dotted line for the bottom profile indicates that spot measurements only were available for the depth.

This is considered to be good because Littlewood (1952) had no way of estimating the variation of the regional gravity field due to the subsurface geology. Tables 3 and 4 list the depth values obtained at each stake (Fig. 4).

Absorption Estimated from Echo Strengths

Following Robin and others (1969, p. 476) we have plotted the attenuator setting of the receiver against ice thickness as shown in Figure 9. Each point represents an individual measurement and the values at small depths have been corrected to allow for the fact that the path length in the ice is $(x^2 + 4d^2)^{1/2}$ rather than 2d. We have also added 10 dB to the setting recorded in the log to give the setting at which the echo would be lost in the noise. It is assumed that the equipment performance and the reflection coefficient at the bottom surface were constant throughout. The full line drawn on Figure 9 represents an absorption loss of 5 dB/100 m path length (50 m depth) while the dotted line shows the effect of adding to this the loss by spreading due to an inverse cube law (Robin, Evans and Bailey, 1969, equation 5, p. 448).

The value of about 5 dB/100 m is expected for ice at 0°C from both laboratory and other field data. Auty and Cole (1952) studied the relaxation spectrum of pure ice and their results, extrapolated, were 3.5 dB/100 m at 0°C; Robin, Evans and Bailey (1969, p. 476), [corrected in Smith and Evans (1972) p. 135, footnote] quote a value of 5.7 dB/100 m derived from Westphal's measurements; Robin, Evans and Bailey (1969) found 4.5 dB/100 m for

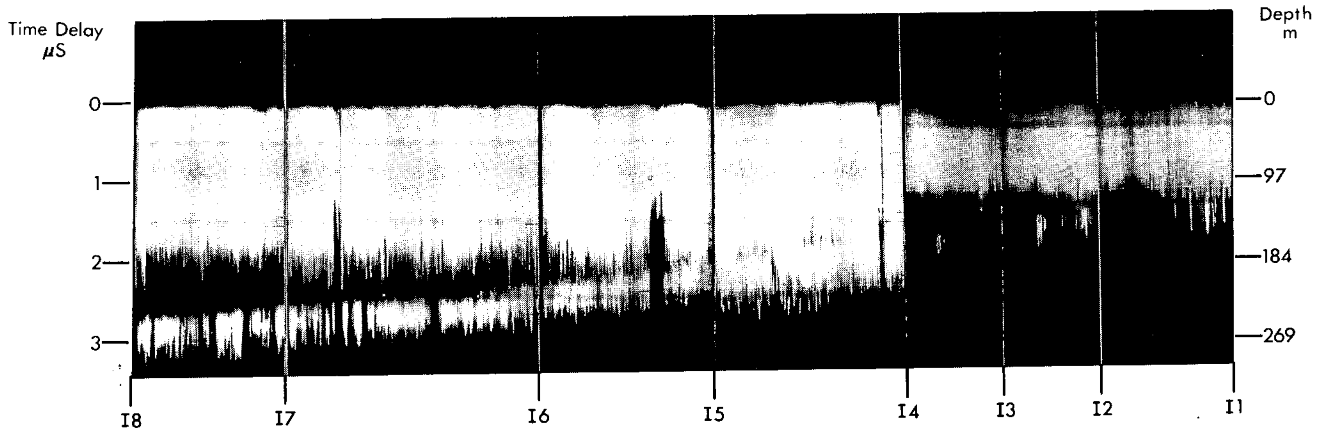

Figure 8.(a) Continuous photographic record of depth measurements along the I-line of stakes from I 1 to I 8.

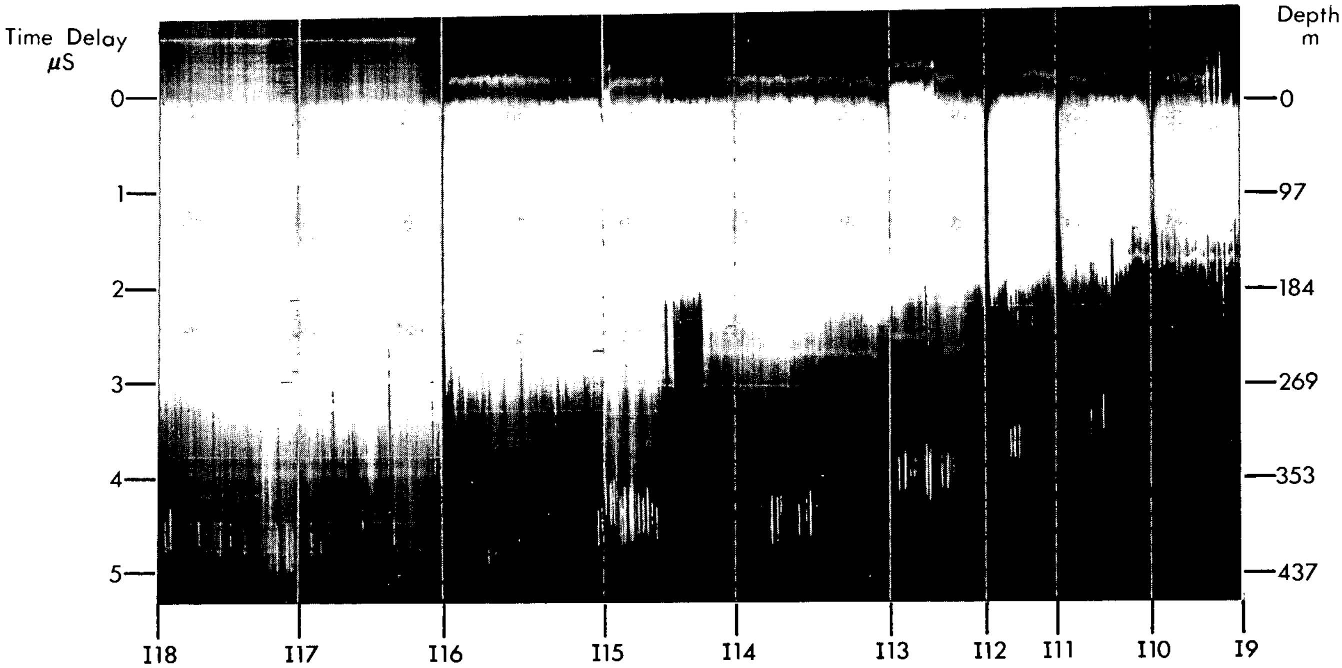

Figure 8.(b) Continuous photographic record of depth measurements along the I-line of stakes from I 9 to I 18.

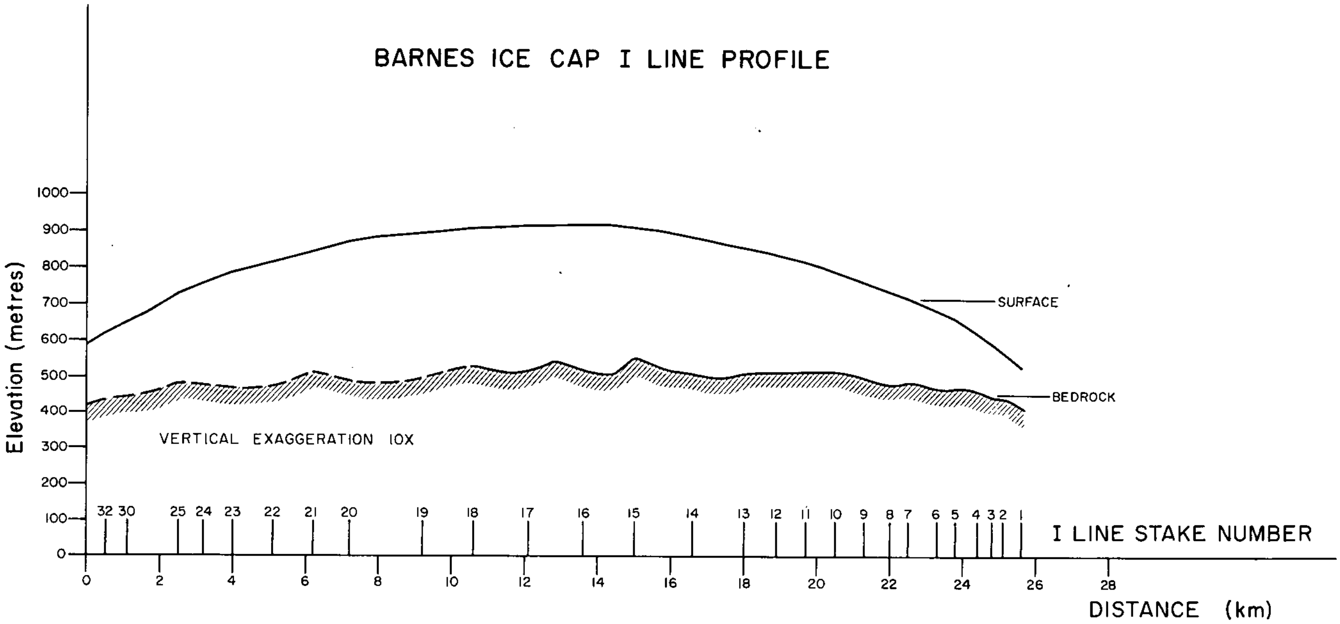

Figure 8.(c) Surface and bottom profile along the I-line: the surface profile was determined by temperature-corrected altimetry, the bottom profile from the radio echo sounding. A dotted line for the bottom profile indicates that spot measurements only were available for the depth.

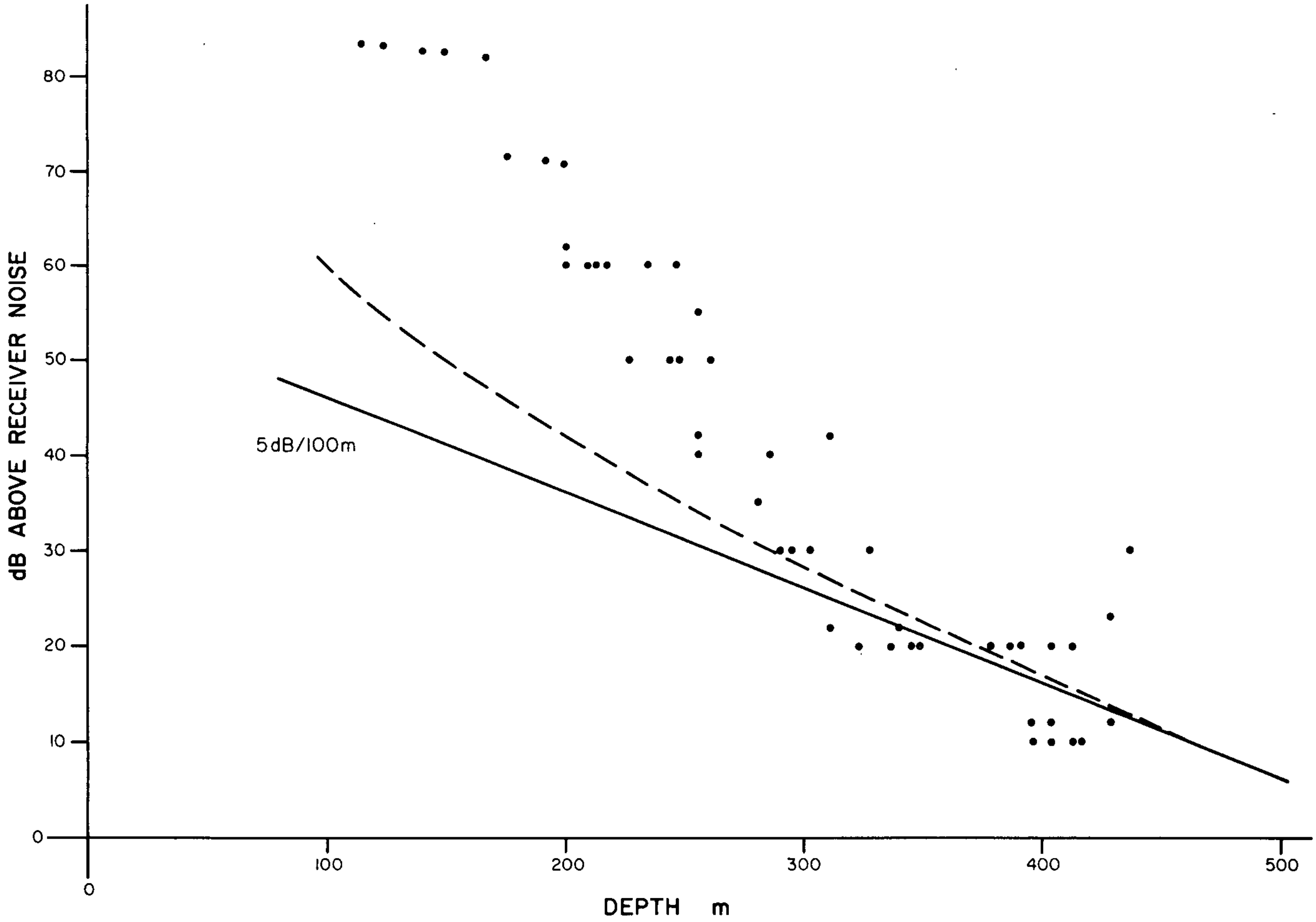

Figure 9. Echo strength measurements compared to calculation. The gradient of the solid line is 5 dB/100 m and the dotted line shows the effect of adding to this the loss due to spreading according to an inverse cube law.

ice below 1000 m surface elevation in Greenland, and Smith (in press) found 4.5 dB/100 m on the Fuchs Piedmont, Adelaide Island, Antarctica.

Referring to Figure 9 it can be seen that the values do not agree with this value of absorption of 5 dB/100 m, except for depths greater than 300 m. For all depths less than this there was observed significantly more absorption than 5 dB/100 m. This greater value implies that either one (or both) of the two assumptions mentioned earlier are not valid, or that there is some additional absorbing mechanism in the ice. Smith and Evans (1972) have recently discussed absorption and scattering by water inclusions and ice lenses in temperate glaciers but water inclusions are hardly relevant to the Barnes Ice Cap, where it is not likely that the *bulk* of the ice is at the pressure melting point. Ward and Orvig (1953) quote 3 m temperatures on the "South Dome" of about −14°C and the 20 m temperature at stake 000 of the trilateration network was −8°C (Holdsworth, 1973). There was no evidence of any internal reflection that would indicate a scattering phenomenon.

SUMMARY

The velocity of 35 MHz electromagnetic waves in the Meighen Ice Cap was determined by comparison with a known borehole depth as 178 ± 2 m μs^{-1}, somewhat higher than the value of 169 m μs^{-1} expected from dielectric measurements on ice. On Barnes Ice Cap a velocity of 168 ± 2 m μs^{-1} was determined by a wide angle reflection technique. Spot measurements of depths on Meighen were obtained at a number of places, and agreement between two radio echo sounders operating at different frequencies (35 MHz and 440 MHz) was obtained. On Barnes, a continuous photographic record of depths was obtained along three lines of a strain-rate network and along the I-line. In general, the depth values agreed with previous radio-echo sounding depths and with gravity measurements obtained 20 years earlier. Absorption of the radio waves in the ice, estimated from the strength of the bottom echo, was greater than that obtained by other workers both in the laboratory and in the field.

ACKNOWLEDGMENTS

I am particularly indebted to Mr. G.A. Barnett, Glaciology Division, who built the hut, drove the skidoo, and provided valuable technical assistance throughout. The Polar Continental Shelf Project, Department of Energy, Mines and Resources provided logistic support on Meighen Island. The cooperation and encouragement of Dr. G. Holdsworth, Glaciology Division, was important and I am grateful for permission to use his unpublished data. Dr. R.H. Goodman, Glaciology Division, and Dr. W.S.B. Paterson and Dr. R.H. Koerner, Department of Energy, Mines and Resources, provided valuable advice and assistance. I am also indebted to the Scott Polar Research Institute, Cambridge, England, for allowing the use of their equipment to produce Figures 5a, 6a, 7a, 8a and 8b.

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