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INVESTIGATION OF SUB-ICE BEDROCK CHARACTERISTICS BY RADIO-ECHO SOUNDING

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Abstract. Qualitative inspection of the results of the 1971/72 S.P.R.I.–N.S.F. Antarctic radio-echo sounding programme shows that it is possible to infer some characteristics of the lower face of the ice from the form of received echoes. We confirm the existence of lakes of liquid water beneath the east Antarctic ice by inspection of the top and bottom surface gradients of the ice, and suggest that basal melting occurs over a wide area in this region.

Quantitative studies in Devon Island indicate that small-scale irregularities in the bedrock are characterized by slopes of about 1 : 40, with some higher gradients present, possibly indicating the presence of morainal boulders. We deduce that a geological boundary was crossed between 25 and 40 km west of the base camp, the rock to the west of the boundary having lower permittivity, and higher surface slopes than that to the east.

The question of the usefulness of the spatial fading of the echo in deducing surface characteristics is briefly discussed. We conclude that measurements of the fading are indeed useful, especially in the case of echoes with short "tails".

Résumé. *Recherches sur les caractéristiques du lit rocheux sous-glacier par sondage radio-echo.* Un examen qualitatif des résultats de la campagne de sondage par radio-écho du SPRI–NSF dans l'Antarctique en 1971–72 montre qu'il est possible de supposer quelques unes des caractéristiques de la face inférieure de la glace à partir de la forme des échos reçus. Nous confirmons l'existence de lacs d'eau liquide sous la glace de l'Antarctique orientale par l'examen des pentes de surface de la glace au sommet et au fond, et nous suggerons que la fusion basale intervient sur une large étendue dans cette région.

Des études quantitatives dans le Devon Island indiquent que les irrégularités à petite échelle du lit rocheux sont caractérisées par des pentes d'environ 1/40 avec quelques pentes supérieures, pouvant indiquer la présence de blocs morainiques. Nous émettons l'hypothèse qu'une limite géologique court entre 25 et 40 km à l'ouest du camp de base, la roche à l'ouest de la limite ayant une permittivité inférieure et des pentes superficielles supérieures à celle de la roche à l'est.

On discute brièvement la question de l'utilité du "fading" spatial de l'écho pour déceler des caractéristiques de surface. Nous concluons que les mesures du "fading" sont vraiment utiles, spécialement dans le cas d'échos à courtes "queues".

Zusammenfassung. *Besonderheiten des Felsuntergrundes mittels Radar-Echolotung.* Eine qualitative Durchsicht der Ergebnisse des S.P.R.I.–N.S.F.-Radar-Echolotungsprogramms von 1971/72 in der Antarktis zeigt, dass es möglich ist, aus der Form der empfangenen Echos auf einige Eigenschaften der Unterseite des Eises zu schliessen. Die Existenz von Seen flüssigen Wassers unter dem ostantarktischen Eis wird auf Grund der Betrachtung der Gradienten der Oberfläche und der Unterseite des Eises bestätigt. Es lässt sich vermuten, dass in einem grossen Bereich dieses Gebietes das Eis am Untergrund schmilzt.

Quantitative Untersuchungen auf der Devon-Island deuten an, dass kleinräumige Unregelmässigkeiten des Untergrundes durch Neigungen von etwa 1 : 40 gekennzeichnet sind, wobei auch grössere Gradienten auftreten, die möglicherweise auf Moränenblöcke hinweisen. Es wird gefolgert, dass zwischen 25 und 40 km westlich des Basislagers eine geologische Trennfläche überquert wurde, wobei der Fels westlich der Grenzfläche geringere Durchlässigkeit und grössere Oberflächenneigungen als im Osten aufweist.

Es wird kurz die Frage der Brauchbarkeit des räumlichen Schwund des Echos für die Bestimmung der Oberflächeneigenschaften diskutiert. Dabei zeigt sich, dass Schwundmessungen tatsächlich nützlich sind, insbesondere im Falle von "kurzschwänzigen" Echos.

A section of S.P.R.I. radio-echo record is shown in Figure 1. It shows a depth profile for a 7 km length of path, at a depth of approximately 3 000 m. The echo from bedrock can be clearly distinguished as an almost continuous line close to the centre of the vertical range scale. Though the strength is steady, on the average, over the width of such a section, it is clear that it varies considerably over a distance of a few metres, or tens of metres. This phenomenon of "fading" has been recognized, and understood in principle, since the earliest experiments in radio-echo sounding. It arises from the interference between reflections from different facets of the rough reflecting surface. Though it was known that the appearance of the echoes would depend on the form of the bedrock surface, the variation was treated as a minor nuisance to trouble the depth sounder.

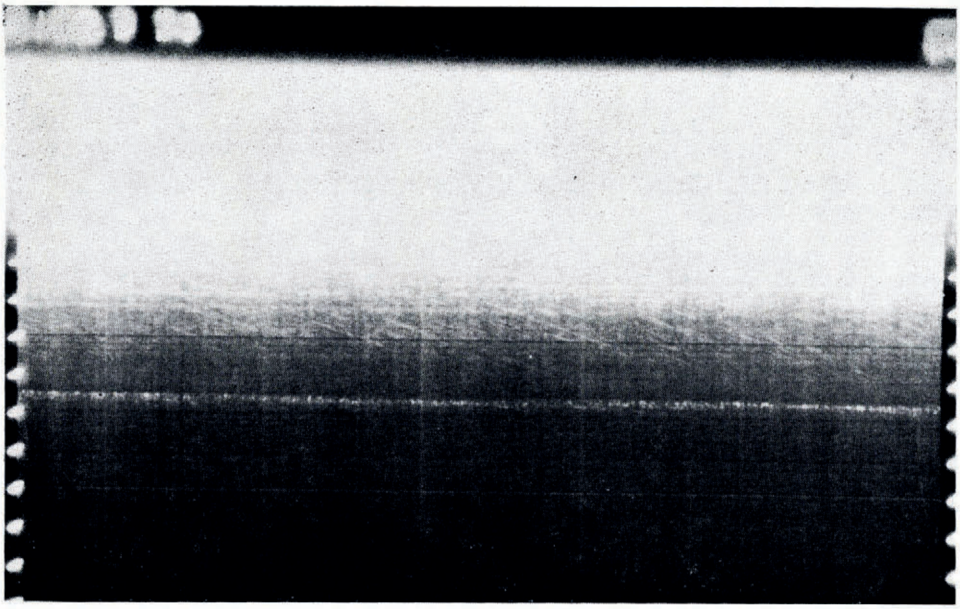

Fig. 1. A section of radio-echo record showing a normal fading bedrock echo.

However, it has been shown by Harrison (unpublished) and Berry (1973), among others, that the variations in the echo are related, through the echo sounder characteristics, to the statistical properties of the roughness of the bedrock surface. They showed that it is, in principle, possible to infer much about the surface from the behaviour of the radio echoes, and this paper describes the first attempts to make such inferences using S.P.R.I. echo-sounding technique.

Throughout the experiments, a radar with a carrier frequency of 60 MHz was used, giving a radio wavelength in ice of 2.8 m.

Preliminary work was carried out using the results of the 1971/72 S.P.R.I.–N.S.F. Antarctic radio-echo sounding programme. Though the primary purpose of the fieldwork was to record a simple depth profile of the ice, the photographic records are of such quality that some detailed aspects of the echoes may be observed, classified, and compared, area to area. Comparisons were essentially qualitative, since the records do not contain a quantitative measure of the received power, and a detailed statistical analysis was not possible. However, it was thought that significant differences between echoes should in some cases be detectable in a visual examination.

A qualitative measure of the echo strength could be obtained by examination of the exposed area of film corresponding to the bedrock echo. The degree of exposure is a function of the received power, and may be classified realistically into three classes; weak, medium, and strong. The results of a survey of the recorded echoes is mapped in Figure 2. The strength is highest in the cold, central regions of the ice sheet, as would be expected. The observed strengths are, however, somewhat higher than might be expected in particular in a region north of Vostok station, and somewhat outside the centre of outflow of ice, known as Dome "C".

The possible significance of this feature only became apparent in the light of the major finding of this work on the Antarctic results, that is, the discovery and identification of lakes of liquid water underlying the central region of the east Antarctic ice sheet (Oswald and Robin, 1973).

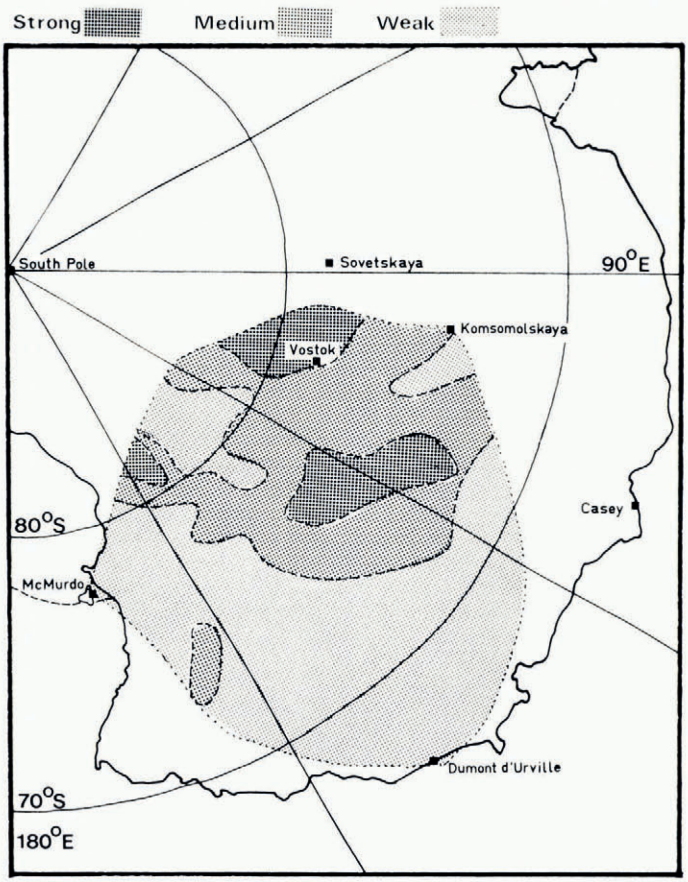

Fig. 2. A map of the qualitative classification of echo strengths observed in east Antarctica for the area of the 1971 survey.

The sites of the observed lakes can be seen, indicated by diamond dots in Figure 3, and an example of a lake echo trace is shown in Figure 4.

We can now confirm, from the radio-echo records, the identification of the lakes as consisting of water, by inspecting the surface slopes of the lakes and of the overlying ice.

We consider the equilibrium of a fluid of density ρ_l, underlying a mass of ice of density ρ_i. If the ice has a surface gradient of α, the condition for hydrostatic equilibrium in the fluid is that a gradient β exists in the ice–fluid interface such that:

$$(\alpha-\beta)\,\rho_i+\beta\rho_l = 0$$

or

$$\rho_l = \rho_i(1-\alpha/\beta)$$

In the majority of cases the surface slopes of the ice are so small that measurements are not possible. However, in two locations the surface slopes of 1 : (1 000$\pm$500) and 1 : (500$\pm$250) gave rise to gradients of -1 : (70$\pm$10) and -1 : (50$\pm$10) respectively in the interface.

Entering these figures in the above formula, we arrive at the following values for ρ_l using $\rho_i = 0.92$ Mg m^{-3}: $\rho_l = 0.99\pm0.04$ Mg m^{-3} or 1.01 ± 0.05 Mg m^{-3}.

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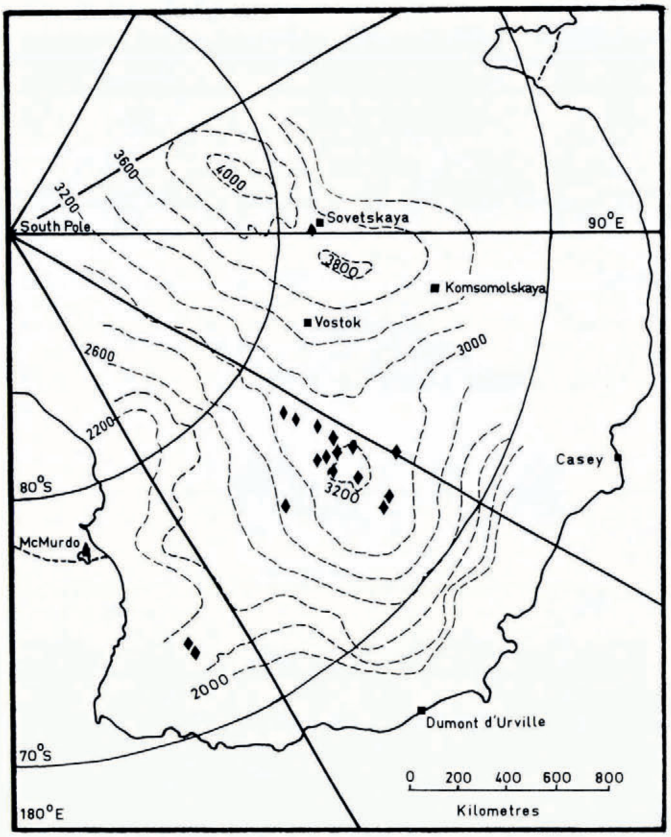

Fig. 3. The diamonds mark the positions of subglacial lakes in east Antarctica.

These results can be seen to be very close to the density of water and, as the alternative possibilities are few, we may take this as confirmation of our identification of the lakes.

Though the very long continuity of these echoes was limited to a small number of sites, the other anomalous characteristics, of high strength, long, though irregular fading lengths, and short echo "tails", occur frequently in the areas of high echo strength in Figure 2. An example of such an echo is shown in Figure 5.

Comparison with neighbouring bedrock echoes, and of the variation of strength, by region, with calculations based on temperature estimates, suggests an augmented reflection coefficient at the lower boundary of the ice.

The existence of the lakes establishes that some areas of the base of the ice sheet are at the pressure melting point. It seems unlikely that melting is confined to these specific localities where the topography is suitable for the formation of extensive lakes. We should expect it to occur over a much wider area, and the combination of the above echo characteristics suggests that water does indeed exist over the areas indicated.

The fact that high-angle reflections are not frequently seen in association with these echoes suggests that any channels are incised downwards into the rock, with relatively flat upper surfaces. This would agree with the form of a network of pools and "Nye channels", or possibly Weertman's (1972) "modified sheet". In this case the distinction between the two, with only very low flow rates involved, is probably small.

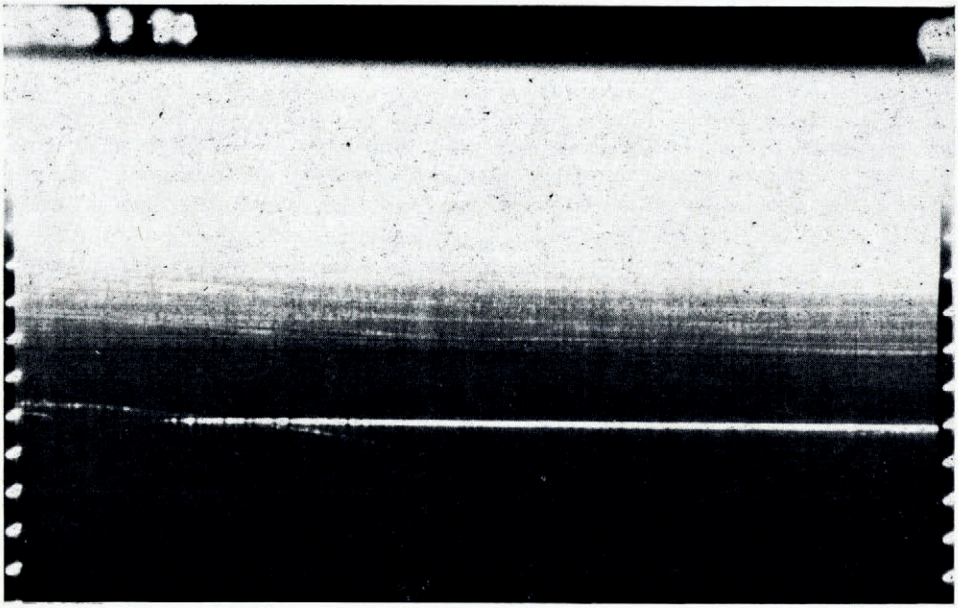

Fig. 4. A section showing the echo from a sub-ice lake.

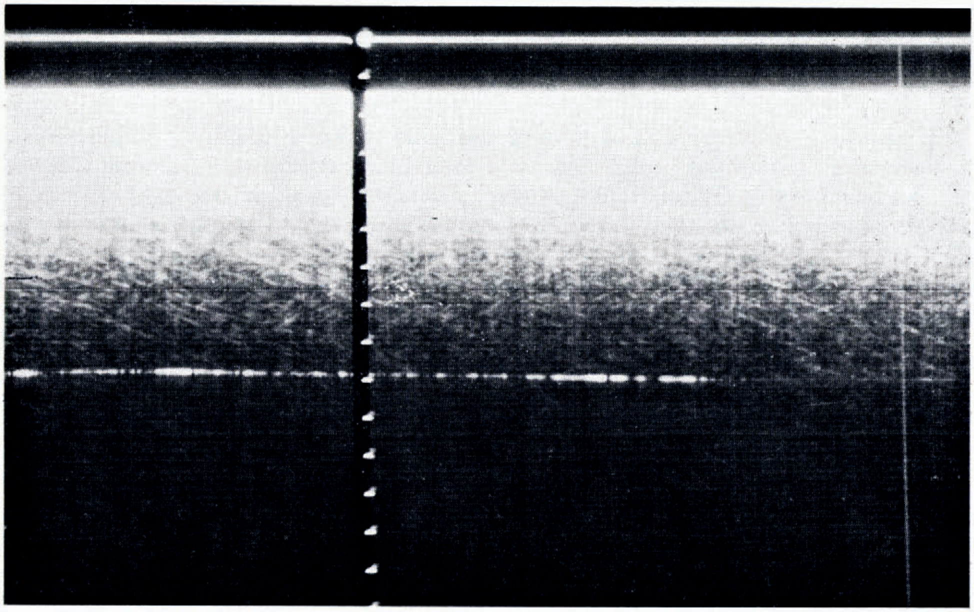

Fig. 5. The echo from a position where the ice is thought to be at the pressure-melting point, without the formation of a definite "lake".

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It has been possible, from the foregoing argument, to make some more or less tentative deductions concerning the nature of the base of the Antarctic ice sheet. However, if we wish to perform a more detailed analysis, and to be able to distinguish more subtle differences in the bottom surface than that between water and generalized rock, a quantitative measure of the instantaneous echo power is necessary.

The Devon Island expedition of 1973 presented an opportunity to make precise and detailed recordings of the echo waveform, as a pilot study for large-scale work in the Antarctic and elsewhere. The equipment already provided a display of the envelope of the received waveform, in the form of an "A-scope" trace. An 8 mm ciné camera was used to photograph this display at pre-determined intervals along the sounding track, giving a complete record of the signal envelope, accurate to ±1 dB over a range of about 60 dB. One such photograph can be seen in Figure 6.

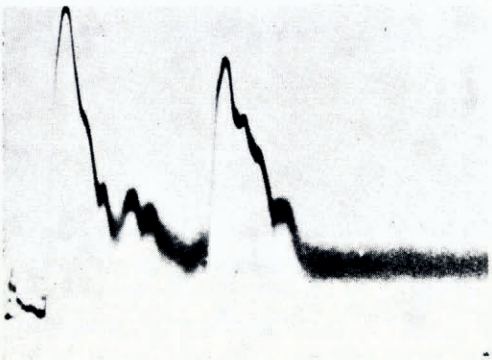

Fig. 6. An example of an "A-scope" trace. The horizontal axis covers about 800 m of ice depth: the vertical axis is a logarithmic scale of echo strength, with a range of some 60 dB. The trace is initiated at the left-hand end of the scale, and the peak near the centre represents the bottom echo.

The soundings in Devon Island covered the lines shown in Figure 7. These include a fairly dense net close to the camp, and three radiating traverses, two running towards the north, and one towards the west. We wished to obtain a statistical description of the small-scale bedrock roughness in these areas, and also to locate the geological boundary which is thought to pass beneath the ice in a north–south direction across the island.

A-scope recordings were made at 50 m intervals over almost the entire survey path. In addition, recordings were made at 1 m intervals over distances of several hundred metres at several widely spaced sites over the area of the survey. They are lettered in Figure 7. At each of these sites the ice thickness was effectively uniform, and varied from site to site between 400 and 800 m. The closely spaced records give an almost continuous record of the echo waveform, and the large number of them allows us to make a detailed statistical analysis.

A total of some 25 000 A-scope recordings were made. In order to reduce the stored data to manageable proportions for analysis, it is necessary to select the components of the echo which will most satisfactorily yield the required information. Harrison's general wave treatment has been used extensively in the reduction and analysis, since his terminology is closely linked with S.P.R.I. radio-echo practice. His assumptions are those of Kirchhoff diffraction theory, mainly concerning the amplitude and degree of "spikiness" of the reflecting surface roughness. The imposed restrictions are not important in the present case.

It seems reasonable to direct our inquiry initially towards the most accessible aspect of the received signal, namely the maximum observed level of power in the echo. If we can establish

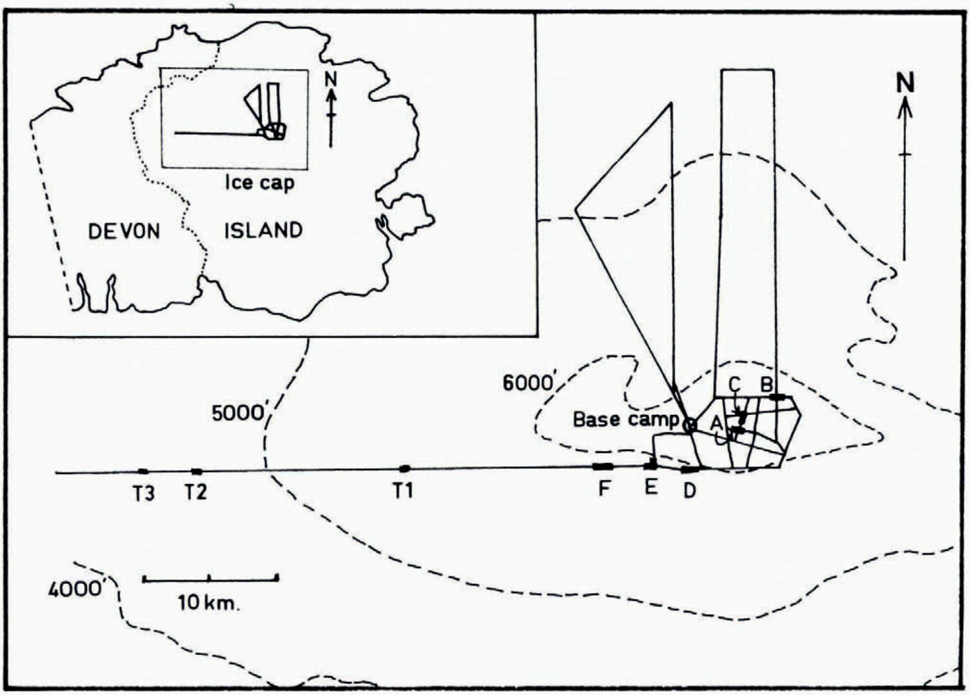

Fig. 7. The inset map shows the eastern end of Devon Island, the ice cap covering most of the area to the east of the dotted line. The positions of the survey lines, and of the nine sets of closely spaced strength measurements, can be seen at larger scale in the main part of the figure. Contours are in feet; 5000 ft = 1520 m.

that much of the information obtainable about the reflecting surface is represented in the behaviour of the maximum level, we shall have gone a long way towards reducing the complexity, and also the tedium, of the analysis.

The validity of the maximum level in this sense depends largely on the extent to which the rough reflecting surface scatters power away from the "specular reflection" ray paths.

We describe the roughness in terms of the parameters a, T, ϕ_0, and β, representing respectively the r.m.s. height of the deviations from smoothness, the horizontal autocorrelation length of the deviations, the phase change introduced by a in the reflection of the radio waves ($\phi_0 = 4\pi a/\lambda$), and the r.m.s. slope existing in the surface, ($\beta = 2a/T$).

In the case where both $\phi_0 > 1$, and $\beta > (p/z_0)^{\frac{1}{2}}$, (where p is the spatial half-length of the transmitted pulse, and z_0 is the distance from sounder to bedrock), the mean value of the received power will be reduced by a factor

$$-\frac{p}{z_0}\left(\frac{T}{2\phi_0}\,\frac{2\pi}{\lambda}\right)^2$$

below that expected from a smooth surface. Otherwise we may take this mean to be within at most 2 dB of the expected value.

We may obtain a rough estimate of β by observing the fall-off of received power with angle of reflection (as determined by the extension of the delay beyond that of the "first return").

For a surface with a Gaussian vertical distribution, the dependence of received power P_r on angle of reflection is given by Harrison as:

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$$\langle P_r \rangle = \frac{P_t A G (\pi/2)^{\frac{1}{2}} p}{16\pi^2 r_0^3 \cos^2\theta} \frac{k^2 T^2}{\phi_0^2} \exp\left[-\frac{(2k\sin\theta)^2 T^2}{4\phi_0^2}\right]$$

where θ is the inclination of the reflection to the vertical, P_t the transmitted power, G the antenna gain, $k = 2\pi/\lambda$ the wave number of the radiation, and r_0 the distance from transmitter to reflecting point.

Table I shows these estimates of β for the nine sets of data mentioned above. They are consistently somewhat less than the critical value $(p/z_0)^{\frac{1}{2}}$ for each set. The difference is small, however, and we should bear in mind the possibility of a small reduction in power. It will be possible later to check these estimates against those derived from the autocorrelation functions of the received power.

TABLE I. VALUES OF BEDROCK PARAMETERS FOR VARIOUS STATIONS ON THE DEVON ISLAND ICE CAP

			A	*B*	*C*	*D*	*E*	*F*	*T1*	*T2*	*T3*
	z_0	m	450	550	495	775	740	560	700	550	640
	$(p/z_0)^{\frac{1}{2}}$		0.23	0.20	0.22	0.17	0.18	0.20	0.18	0.20	0.19
*	β_1		0.17	0.16	0.16	0.14	0.15	0.18	0.17	0.19	0.16
*	τ_P	m	7	22	8	7	7	11	8	4	4
	$\lambda z_0^{\frac{1}{2}}/2^{\frac{3}{2}}\pi p^{\frac{1}{2}}$	m	1.1	1.3	1.2	1.5	1.4	1.3	1.4	1.3	1.4
*	β_2		0.04	0.01	0.04	0.04	0.04	0.03	0.04	0.07	0.07
*	T/ϕ_0	m rad^{-1}	10	31	11	10	10	16	11	6	6
*	v_P'		2.6	2.9	1.6	2.6	1.5	4.1	2.7	1.9	1.0
*	T	m	20	5	—	30	—	20	30	—	—
*	a	m	0.4	0.025	—	0.5	—	0.25	0.5	—	—
*	ϕ_0	rad	1.5	0.1	—	2.5	—	1.0	2.0	—	—

The quantities z_0, p, λ, refer to the ice depth, one-half the transmitted pulse length, and the radio wavelength in ice. In this case, $p = 23$ m, $\lambda = 2.8$ m. They define the various critical values, with which those quantities derived from the observations are to be compared.

The derived quantities are marked with asterisks.

β_1 is the estimate of the r.m.s. slope derived from the decrease of received power with angle of reflection.

τ_P is the observed autocorrelation length of the received power.

β_2 is the estimate of the r.m.s. slope derived from the observed autocorrelation length.

T is the autocorrelation length of the bedrock roughness.

ϕ_0 is the phase change introduced by reflection from a surface with r.m.s. vertical displacement a.

The angle $(p/z_0)^{\frac{1}{2}}$ defines the edge of the area illuminated for Harrison's "first return", when the centre of the pulse has just arrived at the surface.

The mean observed strengths are plotted against the depth of ice at each site in Figure 8. The strength is expressed in terms of the implied attenuation by absorption in ice, and by losses on reflection, after correction for that due to geometrical spreading of the wavefronts.

Seven of the points can be seen to lie close to a straight line. Their correlation coefficient is 0.97, and a linear regression analysis results in a line of gradient 4.8 dB/100 m. Remembering the two-way passage through the ice, this corresponds to absorption of 2.4 dB/100 m, averaged over ice between depths of 400 and 800 m. An assumption of uniform temperature (and therefore absorption) throughout the ice gives rise to an intercept at zero depth of $-(4.8 \pm 1.4)$ dB. This is the implied reflection coefficient at the bedrock surface. The numerical similarity of gradient and intercept is, of course, entirely fortuitous, and has no physical significance.

The isothermal assumption is, of course, a gross oversimplification. This figure for absorption implies, from Westphal's (Robin and others, 1969) figures, a mean absorption temperature of $-12°$ C for the ice between 400 and 800 m depth. The temperature near the surface is known to be about $-23°$ C in this area. We can arrive at an improved estimate of the absorption, though with less apparent precision, by using a mean absorption temperature of $-20°$ C between the surface and 400 m depth. This corresponds to absorption of 1.6 dB,

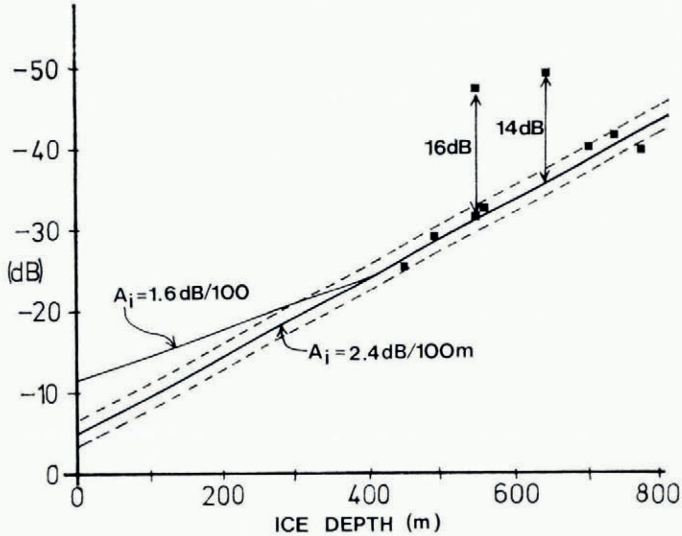

Fig. 8. Echo strength versus ice depth on the Devon Island ice cap. The power is expressed in terms of the total attenuation due to absorption in ice (A_i) and reflection losses at the bedrock. The dotted lines represent the standard error arising from the linear regression.

and gives a figure of −11 dB for the reflection coefficient. This is within the expected range of −10 to −20 dB, but is still somewhat higher than might be expected, since the bedrock in this area is thought to be granitic with a reflection coefficient of about −15 dB. However, the uncertainties in the temperature distribution, and in the dependence of absorption on temperature probably include a range of at least ±4 dB in the estimate.

Of the nine points plotted in Figure 8, we have so far mentioned only seven, which we grouped owing to their high degree of correlation. There are two further points which do not conform to this line, and which we are treating as separate. They represent the sets of measurements made at the outward end of the western traverse, and are separated from their expected positions on the regression line by some 15 dB. Some of the discrepancy may be accounted for in terms of absorption, when we remember that the surface of the ice will be somewhat warmer at the lower altitude of these sites than that at the higher eastern sites.

Equating the change in the ice temperature to that in the mean air temperature for the drop in altitude of 500 m, we may expect a temperature change of between 4 and 6° C. The corresponding rise in absorption should be between 0.4 and 0.7 dB/100 m, giving a total rise, for a two-way passage through 600 m of ice, of between 5 and 9 dB. We still have a discrepancy of between 6 and 10 dB, which can only be satisfactorily explained in terms of the reflection loss. The large uncertainty in the value of the reflection coefficient applies mainly to the absolute value. The relative values for the two areas are, we believe, different by 8±2 dB, which is highly significant in view of the standard error of estimate of ±1.4 dB derived from the seven eastern points.

We deduce that, in the course of the traverse to the west of the camp, the geological boundary mentioned above was crossed, and that the radio waves were being reflected from a different type of rock in the western area. We make no attempt to identify the types of rock involved, owing to the uncertainty in the absolute value of the reflection coefficient. The transition is, however, in the sense of a change from higher to lower permittivity when travelling from west to east.

It is difficult to see how the accuracy of the absolute values can be improved without extensive measurements of real temperature profiles and more detailed understanding of the phenomenon of absorption.

We next examine the extent of variation of the received power over short distances. We define the "normalized variance" of the instantaneous power at a fixed delay time as:

$$v_P' = \frac{\langle P \,.\, P\rangle - \langle P\rangle \,.\, \langle P\rangle}{\langle P\rangle \,.\, \langle P\rangle}$$

where the angular brackets denote the arithmetic mean.

The value of v_P' depends on that of ϕ_0 and of T. Bramley and Young (1967) have calculated v_P', for the first return, as a function of $1/T^2$ for various values of ϕ_0, and his results are shown in Figure 9. The value exceeds unity only under the conditions that $\phi_0 > 1$, and T is of the order of $(az_0)^{\frac{1}{2}}$. This refers to focusing of reflections near the receiver.

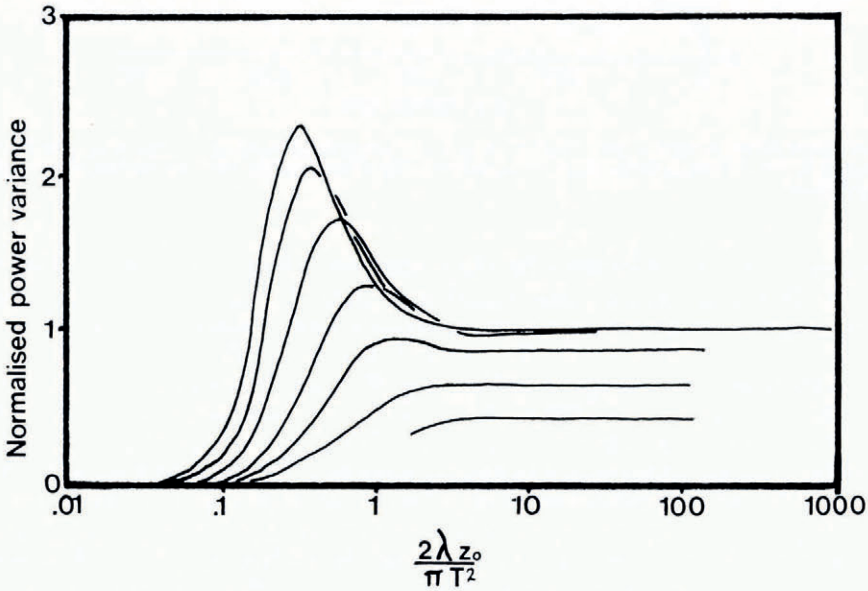

Fig. 9. The normalized variance of the received power, plotted as a function of $1/T^2$, for increasing values of ϕ_0 between 0.2 and 4.

We have calculated the normalized variances for the nine sets of closely-spaced observations, and the values are shown in Table I. They cover a range from close to unity up to about four, with four sets at about 2.5.

In all cases it would appear that $\phi_0 > 1$, and that in the cases of sets A, B, D, F and T1, the horizontal correlation length T is in the region of $(az_0)^{\frac{1}{2}}$.

The calculation of the variance has enabled us to place a lower limit on the vertical scale of the roughness, such that $a > 0.25$ m. We have an estimate for $T^2/2a$, which can give us values for T and a, when combined with values for the slopes, $2a/T$.

Our third independent direction of approach for deriving the bedrock characteristics is through examination of the horizontal autocorrelation functions of the received signals. Though Berry (1973) states categorically that the "spatial fading . . . is not a potential source of extra information about the form of the rough surface", Harrison deduces that in many cases the horizontal autocorrelation length of the echo power is proportional to that of the surface roughness. We resolve this conflict as follows: Berry speaks of the rate of fading as a function of arbitrary delay time, and states correctly that, in the case of very long-tailed echoes, it is uniquely defined by the delay considered. However, for short-tailed echoes with a pronounced maximum, delay times are not easy to measure accurately. The fading rate of particular features of the echo such as the maximum is a sensitive indicator of the angular spectrum of received power, which can then be related to that of the surface roughness. In S.P.R.I. experience, the condition for very long-tailed echoes is only frequently fulfilled in the case of reflections from heavily crevassed ice surfaces. It represents an extreme case, where

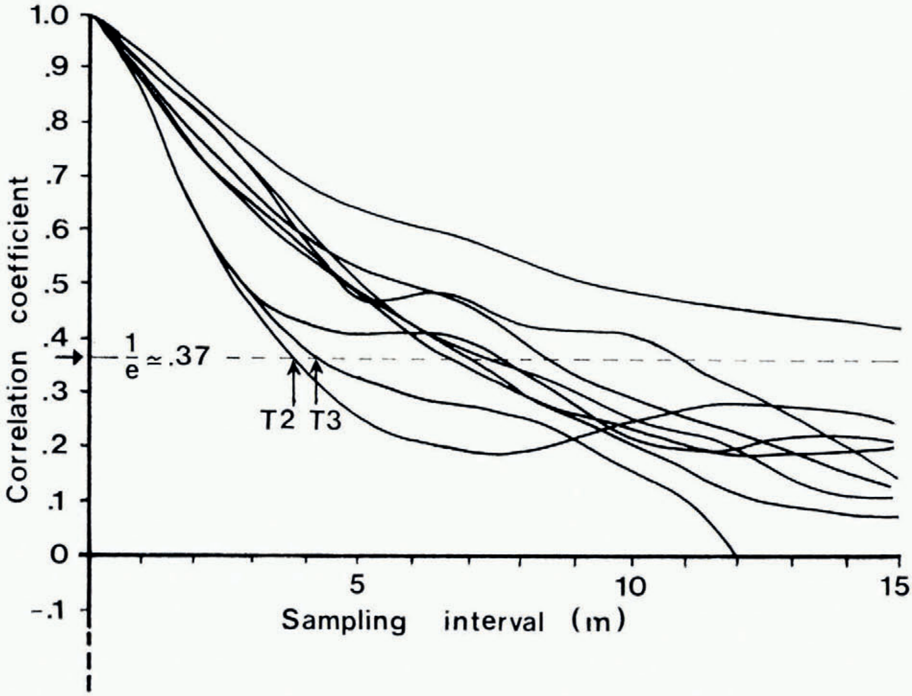

Fig. 10. Autocorrelation functions for nine sets of echo strength measurements at 1 m intervals.

the r.m.s. slope β considerably exceeds the angle $(p/z_0)^{\frac{1}{2}}$. Put in this context, Berry's statement can be seen to agree with Harrison's treatment of this case for the geometrically defined "first return".

The autocorrelation functions of received power have been calculated for the nine data sets, and are shown in Figure 10, up to a separation of 100 m. The "autocorrelation length" τ_P is defined as that separation of points for which the correlation coefficient falls below 1/e. Values of τ_P obtained from these calculated functions are shown in Table I, and can be seen uniformly to exceed the minimum values $\lambda z_0^{\frac{1}{2}}/2^{\frac{3}{2}}\pi p^{\frac{1}{2}}$ defined for the first return, and also shown in Table I. We may, as a result, be more confident of our previous measurement of the mean received power.

We may now derive a second estimate for T/ϕ_0, which we believe to be an improvement on that derived previously from the fall-off of power with angle. This estimate depends on a large number of measurements of the well-defined maximum level, rather than of the comparatively ill-defined position at which the power has fallen off by a fixed large factor (in that case 40 dB).

Harrison shows that, if $\phi_0 > 1$, and τ_P for the first return exceeds its minimum value, then

$$T/\phi_0 = \frac{\lambda}{2\pi\beta} = \tau_P 2^{\frac{1}{2}}.$$

These new values for T/ϕ_0 and β are given in Table I. The difference indicates that returns at angles between 25° and 40° to the vertical are of higher intensity than would be predicted by observation only of the first returns. We tentatively suggest that this is due either to the effect of refraction of power into the ice at about this angle, or to the presence of small morainal boulders at the base of the ice on an otherwise gently undulating surface.

The autocorrelation lengths for the two western sets of observations are shorter than for the other seven. This tends to support our previous suggestion that the western bedrock is of different type from that in the east.

Estimates of a and T are shown in Table I. Those derived for set B present an unresolved problem, in that a surface with such a small scale of vertical relief could not be expected to give rise to the observed value of variance, namely 2.9. However, the use of the condition for $v_P' \approx 1$ only gives an order-of-magnitude estimate for T, a and ϕ_0, and we are reminded not to place too much weight on the actual figures derived by this method.

Conclusions

From 1971/72 Antarctic depth-sounding records, we have shown that it is possible to infer some characteristics of the lower boundary of the ice from the form of the received echoes. We concluded that not only do isolated lakes of liquid water exist beneath the East Antarctic plateau, but that considerable areas of the base of the ice should be considered as being at the pressure melting point, with an underlying film of water.

More detailed studies in Devon Island give no such suggestion of the existence of water. The bedrock surface is thought to be, in general, gently undulating, containing slopes with an r.m.s. value of about 1 : 40. There is an indication of a small but significant proportion of slopes considerably greater than this value, possibly indicating the presence of small morainal boulders. We believe that a geological boundary was crossed between 25 and 40 km west of the base camp, in the course of an extended traverse in that direction. The rock changed from a type with comparatively high permittivity to a lower-permittivity type.

The analysis so far performed on the Devon Island results has by no means exhausted the information content of the records. However, we believe that these results demonstrate the applicability of the method, and that semi-automated processes of recording and analysis could yield similar information on a much larger scale.

Detailed analysis of the later returns in the signal are a potential source of much information, but would be impracticable on a large scale without automation.

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DISCUSSION

M. V. Berry: You have shown that spatial fading can give useful information about bedrock roughness when the bed is smooth (vertical roughness scale $<\lambda/10$). The echo in this case has a short tail. When the surface is rough and the echo incoherent, with a long tail, however, the fading depends only on geometrical factors related to the echo sounder, and nothing can be deduced about the bed roughness. Do you agree?

G. K. A. Oswald: No. We believe that the bedrock we have observed has roughness $>\lambda/10$ (from the extent of variation of the received power), and that in many cases, including the present, analysis of the autocorrelation of the echo power can yield information on the angular spectra of received power and therefore on that of the surface.

S. Evans: Oswald's important point is this: echoes which appear to be "long", in this connection, may not be long when the dynamic range of the A-scope record is taken into account. The range may be 60 dB, and the time taken for the echo to fall (say) 3 dB is short compared to the transmitted pulse-length, whereas the whole recorded echo tail is much longer than the transmitted pulse. This is a short or *coherent* echo in Berry's terminology.

Oswald: This is true, except for the equivalence indicated between *short* and *coherent* echoes. The coherence of the echo depends on the vertical scale of the roughness, whereas the length of the tail depends primarily upon the angles of slope of the rough surface. We believe that we are observing *short*, but almost completely *incoherent* echoes.