RADIO ECHO-SOUNDING ON THE BRUNT ICE SHELF AND IN COATS LAND, 1965

By J. T. BAILEY *and* S. EVANS*

FOREWORD

JEREMY THOMAS BAILEY joined the British Antarctic Survey on 1 September 1964 for the express purpose of continuing the research and development of radar ice-depth sounding. The equipment for this had been designed by Dr. S. Evans of the Scott Polar Research Institute and Bailey spent a year working with Evans, both in Cambridge and in Greenland. By the time he left for the Antarctic he was fully acquainted with the techniques.

On arrival at Halley Bay he took every opportunity to experiment during short local journeys and to prepare himself for the longer journeys to come. The first of these led over the Brunt Ice Shelf onto the inland ice sheet, and from it Bailey returned with valuable results.

It was in the course of the next major journey, this time to Tottanfjella, that he and his two companions, David Peter Wild and Dr. John Kershaw Wilson, lost their lives when their tractor fell into a crevasse. With them went all the records of that journey and some part of those previously obtained.

In the present paper Evans presents the results of Bailey's field work under their joint names. It is a small memorial to a man who could have gone far in his subject.

V. E. FUCHS

ABSTRACT. This paper presents the analysis of the records obtained on a journey from Halley Bay to a sub-station in Coats Land, 300 km. to the south, carrying radio-echo apparatus for sounding ice depth. There is some discussion of the practical problems arising when using this apparatus on light-weight oversnow vehicles. The main result is a profile showing the elevation of the top and bottom surfaces of the ice. The first part of the route, 60 km. in length, is along the seaward edge of the Brunt Ice Shelf where there are large variations in echo strength over distances of less than 1 km., suggesting variability in composition of the ice, at least near the bottom surface, and there is one unexplained section of several kilometres where there are regular and repetitive features on the bottom surface. The inland section of the profile shows a large part where the bedrock appears as a plain about 100 m. below sea-level. At the nearest point to the Theron Mountains the bedrock elevation is about sea-level —though there is a mountainous section rising to 500 m. farther north—and it is possible that ice drains south-westwards between the Theron Mountains and the Touchdown Hills into the Filchner Ice Shelf. An upper limit of -5°C can be set to the temperature at the ice/rock interface in this area.

THIS work was planned in 1964 to follow that of Walford (1964) at Halley Bay and to take advantage of any vehicle journeys which might be made onto the inland ice. No specific glaciological programme was arranged because, at that stage, our experience of continuous radio echo-sounding was limited to one journey in Greenland (Bailey, Evans and Robin, 1964). The possibilities in mind were the measurement of radio-wave velocity and attenuation under different conditions from those experienced in Greenland, the general topography under the inland ice as far as that was accessible, and the investigation of the very large variations in echo strength previously reported on the Brunt Ice Shelf.

Radio-wave attenuation in the inland ice will be discussed later, but there are no new field measurements of velocity of propagation. This is partly because the field work was not completed but also because emphasis was shifted from velocity measurements when it was concluded that no improvement on laboratory values was likely with the present field apparatus. Our knowledge of the topography of the land beneath the ice is given in an unbroken profile which extends from Halley Bay across the ice shelf and on to a sub-station about 300 km. to the south in Coats Land. This was the first use of continuous radio-echo recording of ice depth on an Antarctic journey though much previous work had been accomplished, notably by the U.S. Army Electronics Laboratory and by the University of Wisconsin. The

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use of VHF radio techniques for sounding ice depths has a history which extends over about 20 years but most progress has been made rather recently and all known activities during the years 1963 to 1966 inclusive have been sumarized in a progress report by Evans (1967).

Apparatus

The apparatus used in the work reported here is the SPRI radio echo-sounder Mark II and its parameters are discussed in a later paper by S. Evans and B. M. E. Smith. It is the same in principle as the Mark I apparatus used by Walford at Halley Bay but there are great practical differences including: the use of transistorized circuits, conventional linear time bases in the monitor and (separate) recorder displays, photographic recording, and the use of a balanced dipole aerial system. These last two are of particular consequence for the field operator and they will be discussed in more detail.

Walford's experience had underlined the importance of continuous recording but the disadvantages of using photographic film on field operations were not to be ignored. There is no certainty that the record is intact until it has been processed and, at best, this will only be possible at the end of a day's work. Some darkroom facilities can be dispensed with but the necessity for clean washing water and drying arrangements can prove difficult with long length[illegible] of 35 mm. film. On other operations (not reported here) film has been processed on board large vehicles in motion, but on this journey daylight developing tanks were not used and the records were processed some weeks later after the return to the base station.

That having been said, it is now clear that the use of photographic film gives a worthwhile increase in sensitivity, by time-integration of the output, and that the high resolution of transparent-base film is convenient both in storage space and in instruments aiding analysis. Ilford 5G91 film in cassettes holding 7·5 m. lengths was used and the recording camera may be loaded and unloaded in daylight. The film is later transferred, in the darkroom, to a Kodak spiral holder which is placed in the successive processing solutions in separate containers. Baumann Diafine (two-bath) developer was used since no strict temperature or time control is required and because there is a valuable "auto-dodging" effect whereby small areas of low exposure in a general region of barely detectable exposure (the shadows) receive the maximum enhancement of sensitivity, whereas in a general region of heavy exposure (the highlights) the sensitivity is depressed, so that small variations are detectable in both regions. More recent experience has shown that Kodak TRI-X is better in this respect and that the combination with Diafine has a speed rating of 2400 ASA; the advantage of this high value is that an almost sub-visual trace may be used on the cathode ray tube and thus the finest resolution is obtained on the screen. It is the spot size on the cathode ray tube screen which, at present, limits the resolution of the recorder. Processing is completed by a drier which uses a mains-driven fan and heater and which accepts the film in the same spiral processing spool.

The other change concerned the disposition of the aerials on the vehicles and this required some trials, which were conducted on the ice shelf about 4 km. south of the Halley Bay station in order to be free of interference from other radio apparatus. The aerial arrangement finall[illegible] adopted is illustrated in Figs. 1, 2 and 3. The transmitting aerial is on the Muskeg cab and a short cable leads directly to the transmitter inside. It is desirable to use bulkhead connectors or, failing that, an efficient connection between the coaxial outer conductor and the vehicle skin, at the point where the cable enters the cab. The receiving aerial is supported on a sledge 18 m. away and in line with the aerial on the Muskeg; in this way the signal which enters the receiver directly from the transmitting aerial is reduced by approximately 50 dB. Furthermore, the receiver gain is suppressed during transmission and (with this aerial arrangement) the gain will recover before an echo returns from the base of the ice shelf at a depth of approximately 140 m. It remains true that shallow depths are difficult to record with this apparatus at maximum gain and it is hoped that improvements in the receiver suppression will be made in the future. However, as far as the sensitivity is concerned there is no disadvantage in having a long length of coaxial cable on the input to the receiver apart from inconvenience and the problem of preventing damage at the tow-bar connections between sledges. This was aggravated by low temperatures which caused the PVC sheath, over the braided outer conductor, to split in many places. At the time there was no risk of liquid water percolating into the braid

Fig. 1. Muskeg tractor train showing the three-man cab carrying the transmitting aerial on a boom to one side, and the rearmost sledge carrying the receiving aerial and bicycle wheel odometer.

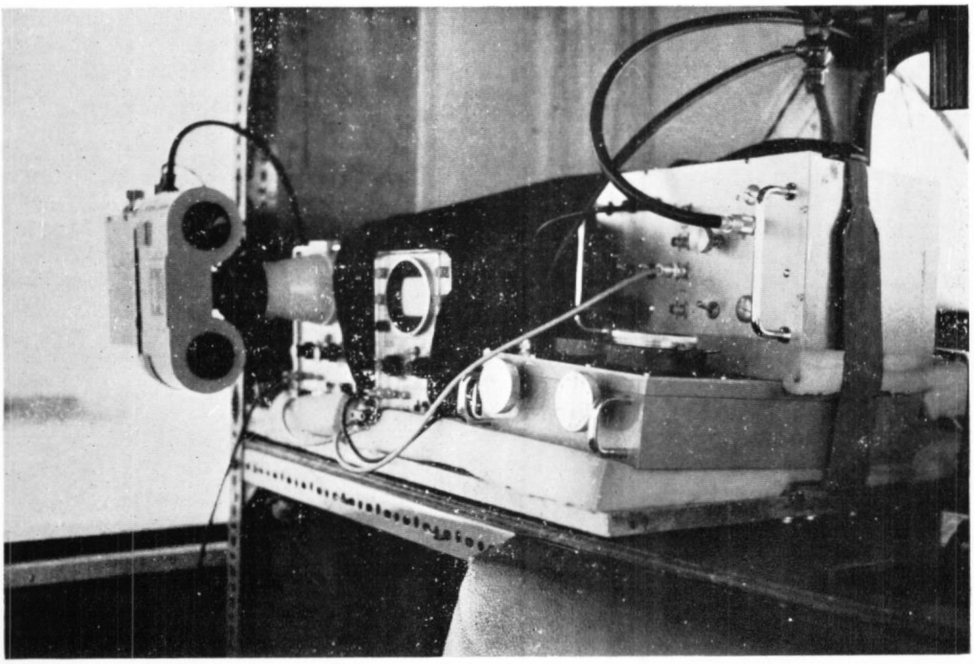

Fig. 2. Arrangement of the apparatus within the cab. On the left is the recording camera with oscilloscope. Next to it is the monitor oscilloscope with a black cloth for shielding strong outside illumination. On the right is the receiver with the attenuator controls to the front. The transmitter and aneroid altimeter are carried on the lid of the receiver.

and no precautions were taken. Coaxial cable type UR91,* which is double screened, was used. Type UR92, which has a special screen, is possibly better, and type UR67, which is more commonly available, may be satisfactory in most situations. To special order, it is possible to have a black high-density polythene sheath for improved protection at low temperatures rather than the standard PVC sheath. Polythene is invariably used for the dielectric between the conductors and it is generally reliable unless flexed rapidly.

It is necessary to establish that the transmitter pulse, which is used as the zero of the range scale, does not leak into the receiver case directly or into the aerial lead, but enters via the receiving aerial, as the echo does, and suffers the same delays in the cables and the receiver itself as the echo suffers. This was established by disconnecting the receiving aerial and substituting in its stead a matched resistive load on the end of the cable, causing the transmitter pulse to disappear at the receiver output. It is still necessary to allow for the time which it takes for the pulse to travel through the air from the transmitting aerial to the receiving aerial, but this point will be discussed later.

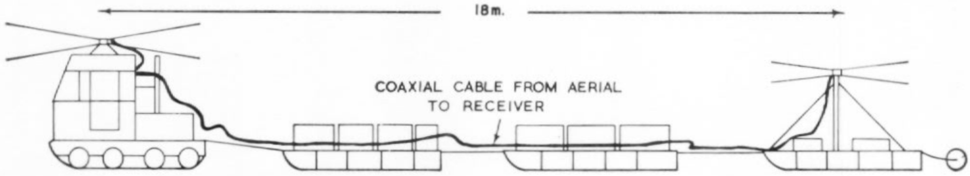

Fig. 3. Sketch of the tractor train showing the aerial arrangement.

OPERATIONS

The journey to "Coats station" was made during March and April 1965. The party departed from the Halley Bay station on 11 March, arrived at Depot 70 on 13 March and departed for "Coats station" on 14 March, arriving there on 16 March to relieve the I.Q.S.Y. wintering party. "Coats station" was abandoned on 18 March and, after a 2-day enforced stop *en route*, the party returned to Depot 70 on 22 March. They made a journey inland to Depot 140 starting on 26 March and returning on 30 March, after which the radio-echo record is incomplete. In addition, short journeys with the radio echo-sounder were made on the ice shelf to the south of the Halley Bay station earlier in March and in August. Apart from aerials, mentioned above, the complete radio-echo apparatus was installed within the three-man cab on the Muskeg and powered by the vehicle battery.

The routes, which had been flagged in previous years, are shown in relation to the coastline in Fig. 4. Distance travelled was measured by a bicycle wheel odometer for which there is no independent calibration over a known distance other than the astrofix at "Coats station". However, the odometer readings, the positions of trail markers, the magnetic heading, the aneroid altimeter and event marks on the radio-echo film are all directly correlated by the written log and are therefore internally consistent. Over short distances, interpolation on the film is particularly accurate since the film-transport mechanism was triggered by the odometer signal. Over long distances the calibration adopted is 2·00 m. per revolution; by comparison with known positions on the map (and by calculation from the wheel size), this possibly is too small by 2–4 per cent and this magnitude of error should be accepted.

Altitudes above sea-level are based entirely on a Casella 3 in. (7·5 cm.) aneroid altimeter read at 200 m. intervals on the outward and return journeys. The altitude of the snow surface at the Halley Bay station is taken to be 32 m. (MacDowall, 1964, p. 278) and the altitude of Depot 70 has been calculated using 5 days (27–31 March 1965) of simultaneous pressure readings there and at the Halley Bay station, the mean of the surface temperatures at the two stations, and the wind at 900 mbar from radio-sonde ascents. The mean value is 644 m. above sea-level and the standard deviation is ± 4 m., but the real uncertainty in altitude, due to the unknown temperature of the air column, is probably ± 20 m.

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* These are United Kingdom Ministry of Supply types made by several British manufacturers.

Altitudes on the journey from "Coats station" to Depot 70 have been calculated by assuming for simplicity a linear relation of -9 m./mbar. This is the gradient at 850 mbar in an air column at -13°C. No correction has been made for the horizontal pressure gradient since it is estimated to be less than 2 mbar (or less than 20 m.) from the synoptic charts compiled for sea-level and 700 mbar. The altitude derived thus for "Coats station" is 1,108 m. above sea-level and it should be noted that this is 50 m. lower than that derived from the outward journey. This difference cannot be accounted for in terms of likely temperature changes or

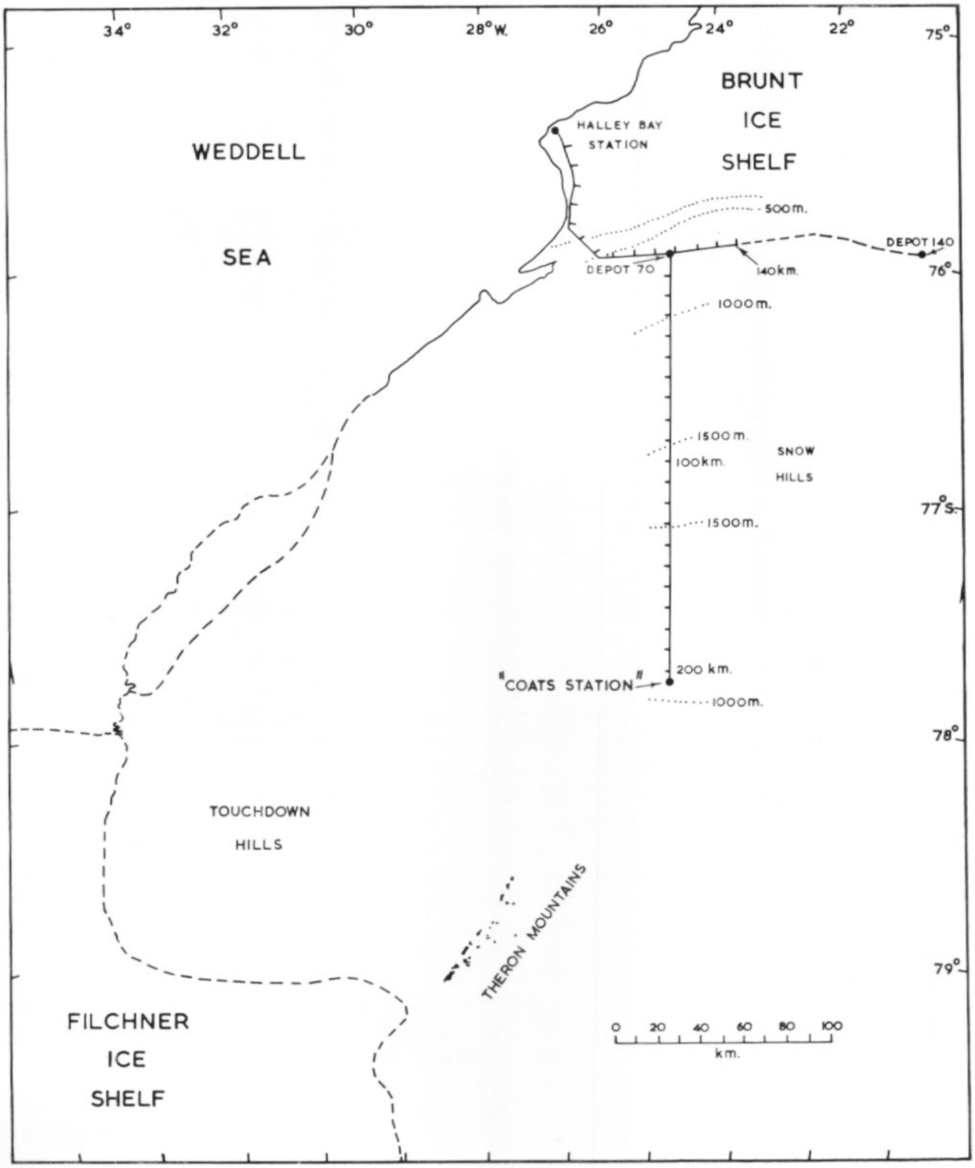

Fig. 4. Map showing the relationship of the route to the coastline (based on D.O.S. (Misc.) 415). The route is marked at 10 km. intervals so that it may be correlated with the profiles in Fig. 6. The 500, 1,000 and 1,500 m. contours are based on aneroid altitudes measured on this journey and on no other information.

changes in the synoptic situation. The return journey pressures are used because they are correlated with odometer readings, permitting interpolation along the whole route, whereas for the outward journey they are not. However, the large uncertainty in the absolute height of "Coats station" should be recognized.

SCALING OF RECORDS

A section of the record covering 90 km. of trail to the south of Depot 70 has been printed in Fig. 5 with a compressed horizontal scale. At this stage the apparatus did not contain any automatic range calibration marks and vertical sweep speed and the zero of range must be established independently. The wave form of a 2033 kHz. crystal oscillator was photographed at intervals; they occur in the gaps marked a, b, c and d in Fig. 5, and a scale of microseconds may be constructed to fit the film or a print of any magnification. In this analysis we have gone a stage further and assumed throughout a velocity of propagation of 169 m./μsec. This value applies to solid ice and the uncertainty in it and the corrections to be applied in lower-density firn are discussed in a later paper by G. de Q. Robin, S. Evans and J. T. Bailey in which it is concluded that, in accumulation areas, up to 10 m. should be added to the depth derived by assuming solid ice, to take account of the higher velocity of propagation in low-density firn near the surface. For the published density distribution in the ice shelf at Maudheim (Schytt, 1958, p. 121) a correction of +8 m. has been derived and a constant correction of this value has been made to all the depths quoted in this paper for both the ice shelf and the inland ice.

There are two more "zero errors". The instant when the transmitter pulse enters the receiver is masked by the instability which occurs due to the suppression of receiver gain, producing the initial white band (e in Fig. 5) followed by the dark band. The second white band occurs after the suppression is removed and it contains some overlapping echoes from nearby reflectors. At intervals (a, c and d in Fig. 5) the receiver suppression is removed and the input attenuators are adjusted so that the direct pulse from the transmitter is reduced to a strength similar to that of the echoes which are measured. It is important that time differences are measured between signals which are of similar strength, because very large signals travel through the receiver more rapidly than non-saturating signals; the effect seems to be larger than can be explained by the total rise time of the transmitted pulse. The leading edge of the attenuated transmitter pulse, in the absence of suppression, is the zero from which the echo-delay time is measured. It follows the upper edge of the suppression line (e in Fig. 5) by a time equivalent to 25 m. depth of ice.

Finally, allowance is made for the aerial separation of 18 m. Since it has been shown that the direct transmitter pulse enters via the receiving aerial, the time delay in the air path is 60 nsec. (equivalent to 5 m. ice depth) which should be added to the measured echo delay. The total effect of these three adjustments is that the ice depth is scaled from the upper edge of the suppression line assuming 169 m./μsec., and 12 m. is subtracted from the result obtained.

On the inland ice the record is unbroken except for weak returns in the deepest ice about 100 km. south of Depot 70. On the ice shelf there are very large variations in echo strength and sections of trail where no echo is detectable. The results of the whole journey are shown in a section through the ice at a 20 : 1 vertical exaggeration in Fig. 6. Following the route south from the Halley Bay station, there is a generally high section of ice shelf between flags F and B, and a generally low section (with few echoes) between flags B and 01. The place where the inland ice becomes afloat shows with more certainty in the surface slope (at 60 km.) than in the characteristics of the bottom echo. The crevassing extends from the 48 km. point on the ice shelf side to the 70 km. point on the inland side of the junction, the most severe crevassing being concentrated around 58 km. The morphology of the Brunt Ice Shelf and the adjacent inland ice has been described by Ardus (1965); he paid particular attention to the steep surface slope and the resultant fracturing at the boundary between the two.

From here to the east, the bedrock surface has the appearance of a plain 100 to 150 m. below sea-level, the deeper parts probably representing valleys which cut across the route. It has the same general appearance for 60 km. beyond the end of the profile which is plotted but the log books for this section were lost. To illustrate the order of magnitude of the effect on the rock levels produced by the weight of overlying ice, it has been assumed that the rock is now in

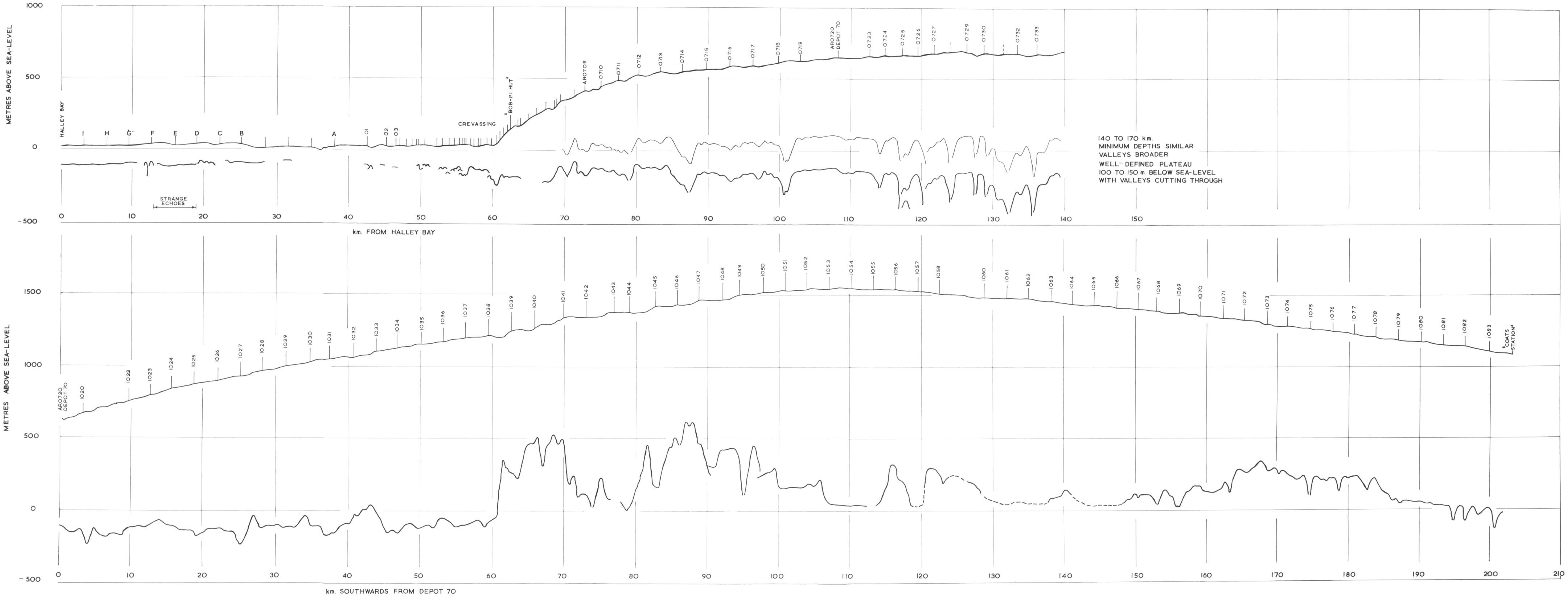

Fig. 6. Sections through the ice at a 20 : 1 vertical exaggeration. The upper profile refers to the route from the Halley Bay station, across the ice shelf, the "Bob-pi" ascent and the route to Tottanfjella as far as 140 km. from the station. The British Antarctic Survey route flags are marked on the surface profile and a scale in kilometres, based on the bicycle wheel odometer, is given below. The lower profile shows the route from Depot 70 to "Coats station", 203 km. to the south. Vertical scale: 5 cm. = 1,000 m.; horizontal scale: 5 cm. = 20 km.

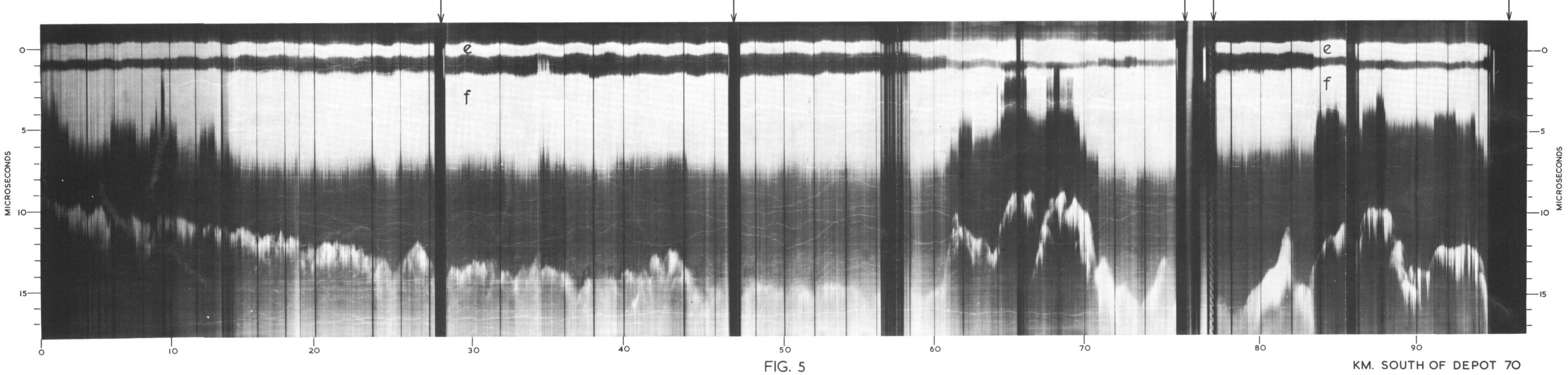

FIG. 5

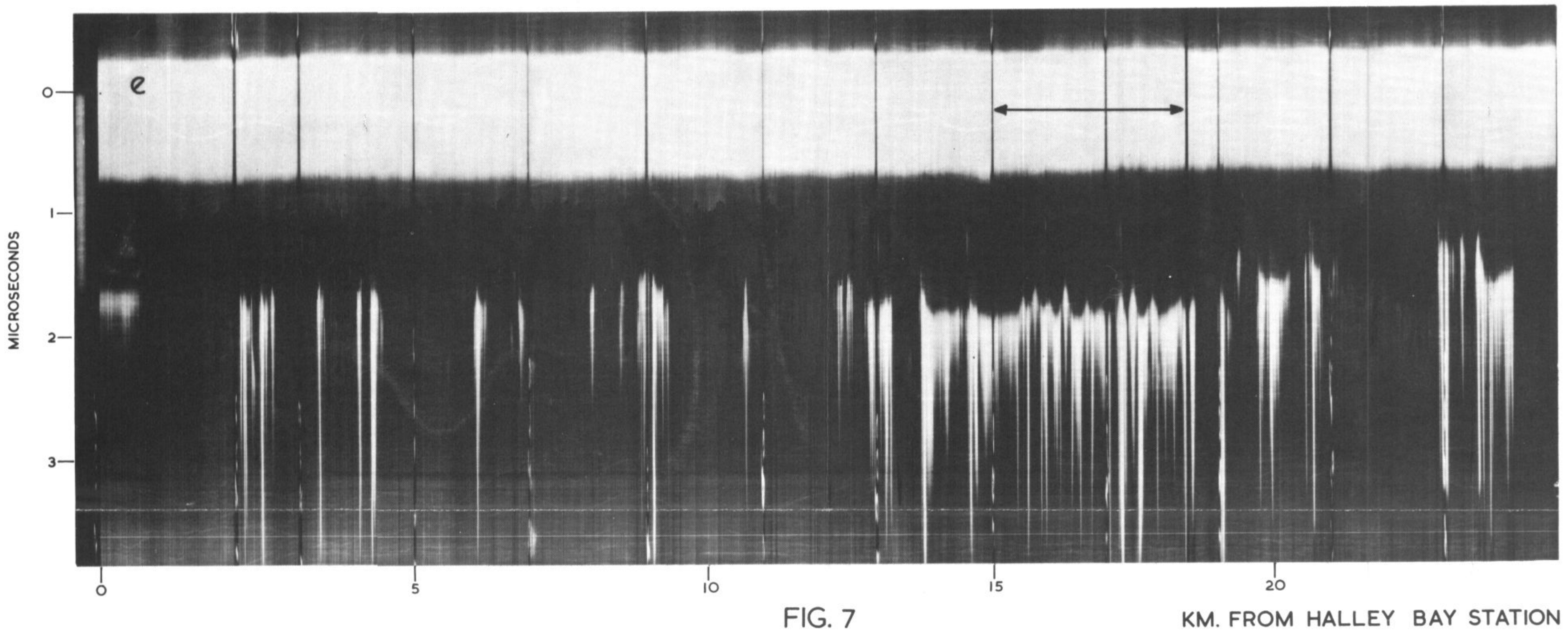

FIG. 7

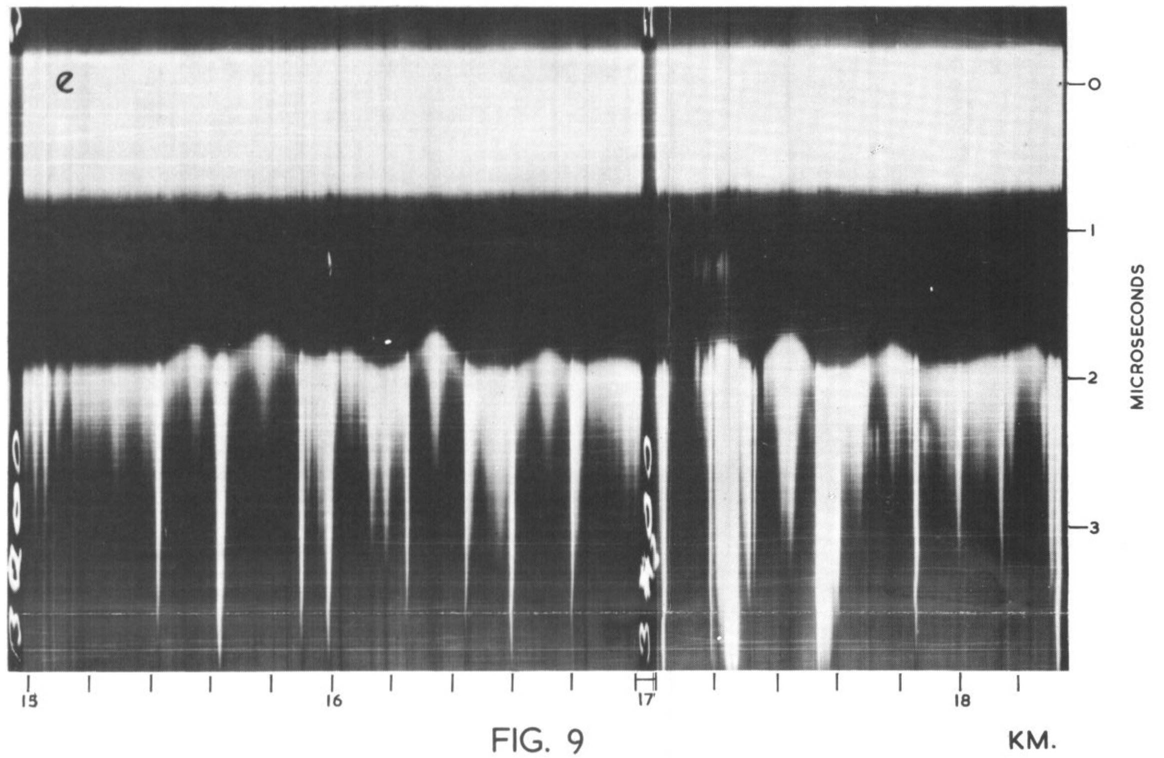

FIG. 9

Fig. 5. Original radio-echo record, compressed in horizontal scale, showing the route from Depot 70 for 90 km. southwards. Calibration marks occur in the gaps marked a, b, c and d, and the band e contains the zero of the vertical range scale. The band f contains echoes from partially reflecting layers within the snow but they are not satisfactorily recorded because of receiver instability immediately after the gain suppression is removed.

Fig. 7. Radio-echo record of the ice shelf from the Halley Bay station to flag B, 25 km. to the south. Notice the steady echo near the station, the strong echoes of limited horizontal extent over most of the route and the continuous echo from 15 to 19 km.

Fig. 9. Extended section of the record from 15 to 18 km. in Fig. 7 (flags F to D). The rounded humps, about 200 m. wide, rise 15 m. above the surrounding level.

isostatic equilibrium with the ice load over a radius of 20 km. and that the average density of the ice is 0·28 of the rocks immediately beneath. Then the thin line between 70 and 140 km. on the east—west profile through Depot 70, represents the elevations to which the rock surface would eventually rise after removal of the ice load. The plain would then be significantly above sea-level and it is possible to imagine that the narrow valleys could have been cut by glacier action.

To the south from Depot 70, in the lower profile, the existing rock is generally below sea-level up to the point where the mountains rise steeply to 500 m. elevation. In this section there is a clear correlation between the ice-surface slopes and the peaks in the bedrock, indicating ice flow along the profile. What is perhaps more important is that there are few surface slopes which are not correlated in this way with bottom features, indicating that the ice-flow direction is predominantly towards the north along the profile.

It is more surprising to find that there is identifiable correlation, though it is less strong, on the southern section near "Coats station", indicating a component of southward flow. Referring to Fig. 4, there is a suggestion that some ice drains between the Theron Mountains and the Touchdown Hills into the bay on the Filchner Ice Shelf. Approaching from the north, the bedrock surface at "Coats station" again falls to sea-level, and though there is considerable uncertainty in the elevation of "Coats station" it does not affect this general result.

FACTORS AFFECTING ECHO STRENGTH

The system performance, S, is defined as the ratio of the transmitter peak power to the minimum detectable power at the receiver input, usually expressed in decibels. There was no significant difference in this ratio between the visual monitor and the photographic recorder and, as estimates over a period of several months all lay in the range 140 to 145 dB., a constant value of 142 dB. will be used throughout. When this quantity is known, if the input attenuators on the receiver are used to reduce an echo signal to the noise level, then the echo strength is known directly. In practice, the echo returned from an irregular reflector fades through a range of 13 dB. as the observer moves, this being due to the sum of a number of random vectors. It is a property of the Rayleigh distribution so formed that 90 per cent of the observations lie above the median value minus 8 dB., and 10 per cent above the median plus 5 dB. The receiver attenuator setting, D, has been recorded at frequent intervals in the log and, since it is adjusted so that the output signal only occasionally falls to the noise level, it has been assumed that the median level is 10 dB. above the noise. Thus echo strength above the limit of detection, $E = (D + 10)$ dB.

The three factors making up the difference between S and E are discussed in a later paper by G. de Q. Robin, S. Evans and J. T. Bailey. R is the power reflexion coefficient at the ice/rock interface, estimated to be -14 dB. for common rocks but as low as -22 dB. for uncemented silica sands and approaching 0 dB. for an ice/water interface. The aerial gain, the effect of refraction at the air/ice interface and the inverse square law are grouped together in a geometrical factor, G. Using single dipole aerials without reflectors for both transmission and reception, assuming a plane reflector, and refraction through the snow surface at normal incidence, it has been found that at 35 MHz., $G = 0{\cdot}94/d^2$ or, in decibels $G = -20 \log_{10} d$, where d is the ice depth in metres.

The total attenuation of the signal due to absorption in the two-way transmission through the ice is represented by A. The measurements of Westphal are used (see Evans, 1965, p. 783) on ice-core samples taken from a tunnel in the ablation zone of the Greenland ice sheet. The attenuation varies from 5 dB./100 m. path (one way) at -1°C to 1 dB./100 m. path at -30°C, so that for depths greater than a few hundred metres the temperature distribution within the ice is a very significant factor in the echo strength. A useful, and fundamental, relation between the radio-wave absorption and the impurity content of ice has recently been given by Walford (1968), who collected results from many sources including his own measurements on two-wire transmission lines buried in the ice shelf at Halley Bay. His results strengthen our earlier view that, for the time being, the values given by Westphal are the most appropriate for polar ice sheets over the whole VHF band, but laboratory measurements on a wide range of samples would be desirable.

The power loss due to reflection at the top snow surface and from irregularities within the ice is expected to be negligible except in the presence of liquid water layers.

THE BRUNT ICE SHELF

Immediate vicinity of the Halley Bay station

On the ice shelf, echoes were obtained from the bottom only in limited areas as had been found earlier by Walford (1964). Since there are other glaciological data for the immediate vicinity of the Halley Bay station, it is fortunate that a strong echo was obtained at constant depth for a distance of 600 m. out from the station to the south (see Fig. 7, left-hand extremity). In this section the depth is 144 m. and the height of the surface above sea-level is 32 m. The relation between these two is in general agreement with the large collection of experimental values of height and depth given by Crary and others (1962, p. 62) for the Ross Ice Shelf, but a more exact analysis may be possible in the case of the Halley Bay station. The density distribution in the top 12 m. of the ice shelf at the Halley Bay station has been given by Ardus (1965) and the similarity to the distribution at Maudheim (Schytt, 1958, p. 121) is so close that for greater depths the Maudheim values, which are known down to a depth of 100 m. from core drillings, will be assumed. The area between the actual depth/density curve and the constant value of 0·917 g./cm.^{3} for solid ice has been integrated using a planimeter. The area represents the weight of ice which is missing due to the included air and it is equivalent to a missing column of solid ice of depth 18 m. Equating the pressure in the sea-water at the bottom of the ice shelf to the pressure due to the ice depth, and taking the specific gravity of sea-water at Halley Bay as 1·027, then the expected depth of water would be 113 m. and the height of the ice surface 31 m. above sea-level, which is in close agreement with the measured value.

There have been no satisfactory measurements of the ice depth at the Halley Bay station by the seismic technique but an independent radio measurement using ionospheric records from the station gave a reflection delay time of approximately 1·67 μsec. in the frequency range 1 to 6 MHz. (Evans, 1961; Piggott and Barclay, 1961), which should be compared with 1·60 to 1·64 μsec. at 35 MHz. found by us within 1 km. to the south of the station (the beginning of the record reproduced in Fig. 7), and 1·50 to 1·60 μsec. found by Walford within 1 km. to the north-east. In all cases, the same assumptions about the velocity are required to derive the ice depth.

Echo strengths

The receiver attenuator settings, D, have been plotted against ice thickness in Fig. 8 and all points less than 200 m. in thickness refer to the ice shelf. The top curve represents the geometrical factor, G, assuming total reflection at a plane surface. Thus this curve gives the level of the signal, in decibels above the noise power, for a perfect plane reflector with no absorption in the intervening medium. In the ice shelf the absorption, A, may be estimated with little uncertainty because the temperature distribution is sufficiently well known. The temperature of the snow surface has been taken as -18°C and a linear rise to -2°C at the bottom surface has been assumed in deriving the curve A1. It can be seen that, on the ice shelf, the maximum receiver attenuator settings plotted from the field log would reduce the echo strengths which have been predicted theoretically to about 10 dB. above the noise level and this is the level used when recording. Thus the strongest echoes observed can be accounted for only by supposing that there are some areas where the bottom of the ice behaves as a total plane reflector, and this conclusion is not much affected by the assumptions about the absorption because the total absorption is small.

There are other areas where the echoes are as much as 25 dB. weaker and there are areas where no echoes are detectable at all, implying at least 80 dB. more attenuation than has been calculated above. It can only be suggested that there is imperfect reflection, due to a diffuse boundary between the ice and sea-water, or orders of magnitude greater absorption than was measured in the ice sample used by Westphal. Thus both possibilities point to essentially the same phenomenon: the percolation of sea-water or the presence of saline ice formed from sea-water. It is suggested that the very lossy layer need be only a few metres thick. Then as the dielectric dissipation, tan δ, approaches unity, the losses increase steeply until only evanescent waves are possible. The critical condition is equivalent to an attenuation of the order of 5 dB./m. path or an effective electrical conductivity of 7×10^{-4} mhos/m., which is close to the d.c. conductivity of sea ice measured by Dichtel and Lundqvist (1951) at −7°C and an order of magnitude lower than that measured by Cook (1960) at 100 MHz. on artificial samples of salty ice. Thus a layer of this nature, as it increased in thickness or in salt content, would reduce the echo power by 20 or 30 dB. before it reached the critical condition beyond which oscillatory waves could not be supported, and this may account for the absence of echoes in the 0 to 50 dB. range in Fig. 8. Alternatively, the extreme contrast between the presence and absence of echoes must be attributed to distinctly different conditions between one part of the ice shelf and another (as suggested by Barclay (1964) and Walford (1964)). An objection to this view is the small scale of the phenomenon. It can be seen in Fig. 7 that patches of echoes over a distance of less than 1 km. are frequently separated from one another by distances of several kilometres. It appears from the experience of the University of Wisconsin group, using similar radio-echo apparatus on the Ross Ice Shelf (personal communication from C. R. Bentley), that the extremes of echo strength observed on the Brunt Ice Shelf are not found on all other ice shelves.

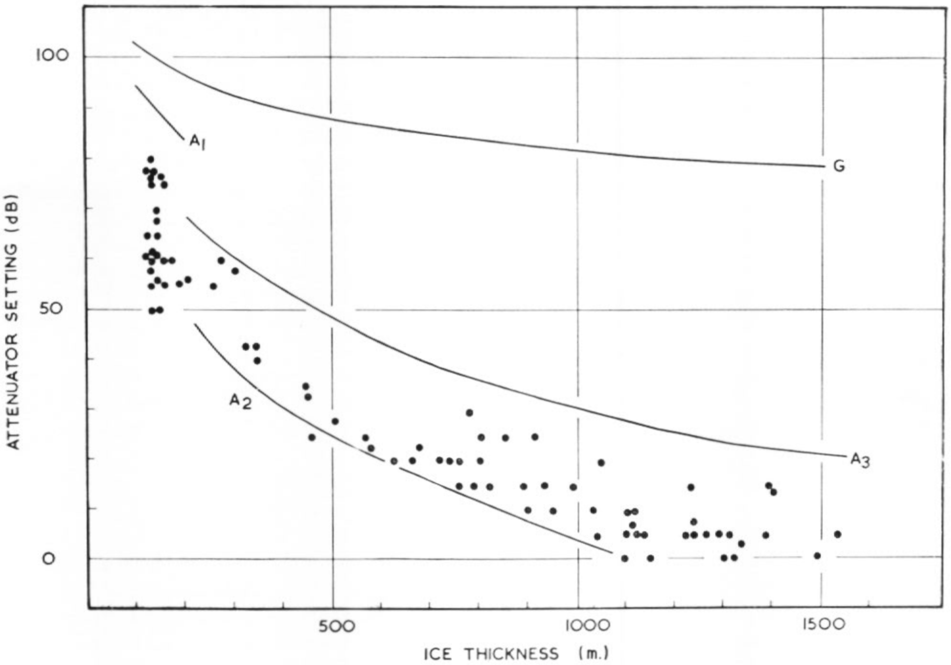

Fig. 8. Receiver attenuator settings (ordinates) versus ice thickness (abscissae). The echo power may be derived by assuming that, after attenuation, the mean signal is 10 dB. above receiver noise level. Ice thicknesses less than 200 m. all refer to the Brunt Ice Shelf and thicknesses greater than 200 m. refer to the land ice. The smooth curves represent the echo strength, in decibels over noise, on various assumptions about the attenuation on reflection, and by absorption in transmission through the ice.

Flags F to D

Unusual echoes, forming a striking pattern, were found on this section of the trail where the surface elevations are 35 to 45 m. above sea-level, higher than was found elsewhere on the ice shelf. The echoes were first noticed on 11 March and the area was re-visited on 19 and 25 August with the same results on each occasion, and thus there is no possibility that the effect is due to instrumental defects or fortuitous aerial positions. Furthermore, it was in the same area that Walford obtained his strongest and most continuous echoes. An example is shown in Fig. 9. The main features are, a strong echo (attenuator setting, $D = 75$ dB. throughout) with no fading, flat parts with a long trailing edge, humped parts with a much shorter trailing edge, and very long trailing edges at the junctions between the two. The mean depth of ice in the flat parts is 168 m. and at the top of the smooth humps the depth is less by 15 m. on the average. On the flat parts, the length of the trailing edge implies that reflections arise at angles from the normal up to 30°, on the humps of the order of 20°, and to account in this way for the very long echoes at the junction would require angles of 60° from the normal. The last angle, if not the others, seems most unlikely and some alternative mechanism should be suggested to account for the extended duration of the echo. A variety of models has been tried for the whole pattern of echo ranges but without great success. It is worthy of note, however, that a small isolated reflector, standing 15 m. above the general level, would give rise to a curved (hyperbolic) echo pattern whose width above the echo from the relatively flat background would be 150 m. This is rather less than the widths of curve observed but a raised line reflector rather than a point would widen the curve by an amount which depends on the angle at which the line is crossed. Finally, it should be pointed out that the surface elevations above sea-level are 10 m. higher than would be estimated from the density distribution discussed earlier for the vicinity of the Halley Bay station, and they are outside the scatter of empirical values for the Ross Ice Shelf given by Crary and others (1962). From hydrostatic considerations, variations in thickness of the order of 15 m. would not be expected to give rise to easily detected features on the ice-shelf surface. Robin (1958, p. 121) has described how a regular series of valleys and ridges of a few metres height and a few hundred metres wave-length form on an ice shelf in areas of diverging flow. Although this condition probably exists here and the scale and regularity of the wave pattern makes it an attractive model to invoke, it seems probable that the orientation of the wave crests would be approximately parallel to the route; furthermore, there is no clear idea of their effect on the bottom surface of the ice shelf.

INLAND SECTION

When the ice is aground, the echo appearance is generally different due to the large-scale roughness of the surface, which shows in the depth variations, and to the smaller-scale facets reflecting over a range of angles, which cause the echo power to fluctuate more rapidly than for a smooth reflecting surface. For example, in the section of record in Fig. 5 there are approximately 25 maxima in echo power per kilometre of trail. Thus the average fading scale is 40 m. and there is no significant change in this for the whole of the trail where the ice is grounded. It implies that reflection occurs at angles out to approximately 6° from the normal point.

It has already been noted that there is no obvious change in the echo at the place where the inland ice becomes afloat but this observation is complicated by heavy crevassing on both sides of the boundary, and further by the difficulty which was experienced in recording the short-range echo from the bottom of the ice shelf. It is particularly surprising that there is no change in average echo strength at the boundary, since the depth decreases suddenly from 320 m. at the "Bob-pi" hut to 160 m. on the ice shelf, at 3 km. distance. From a consideration of the mean absorption per metre, this implies a rise in the mean effective temperature in the ice of at least 10°C, and more than this if the reflection coefficient of the rock surface is less than for the floating ice shelf as one would expect.

What may be learnt about the temperatures in the inland ice from an analysis of echo strengths will now be considered in more detail. A regular record of the receiver attenuator settings was kept in the log and these have been plotted against ice thickness for the route from the ice shelf, via Depot 70, to the summit of the "Coats station" leg, 110 km. south of Depot 70. Assume, as suggested earlier, a constant reflection coefficient of -15 dB. for the ice/rock surface and that the median echo strength was 10 dB. above the noise after the input attenuators. Then, in Fig. 8, 25 dB. of the difference between the observed settings and the curve G have been accounted for, and the remainder of the difference must be due to absorption. Since there is no direct information about any of the ice temperatures, except at the Halley

Bay station (though the mean annual temperature of the surface might be inferred from an atmospheric lapse rate), this result has been illustrated by plotting the mean absorption against the surface elevation above sea-level (Fig. 10). It is not very satisfactory to relate this to an effective mean temperature because the result is over-weighted by the warmer areas where the absorption is high. Instead, it has been decided to calculate the expected echo strengths having adopted a particular model for the temperature distribution. Assume a constant value for the temperature gradient at the bottom of the ice due to the supply of geothermal heat; the value taken is 3°C/100 m. and this estimate includes an additional 20 per cent in the supply of heat due to the mechanical work dissipated in ice deformation. This far, the model is reasonable, but it will now be supposed that the same gradient is maintained throughout the thickness of the ice to the top surface. Although this is unlikely, it allows some limits to be set on the real distribution of temperature by comparing the attenuator settings with the echo strengths predicted on the model. The absorption has been integrated through the whole ice thickness and, allowing -15 dB. for the reflection coefficient, two results are shown in Fig. 8. Curve A2 is based on the assumption that the bottom is at 0°C, and clearly the receiver attenuator settings which have been plotted would reduce the predicted echo strengths to below the noise level. Curve A3 is based on a bottom temperature of -5°C, and it probably represents very roughly the actual echo strengths which were observed since the attenuator settings are from 0 to 20 dB. lower than this curve. Certainly it illustrates how a small change in temperature can produce an effect which is easily noticed with only rough measurements of echo strength. For ice thicknesses greater than 800 m. the temperatures at the snow surface are likely to be warmer than in the model, so that the absorption will be greater. Thus it is certain that at the bottom the absorption is less, and therefore the temperature is lower than

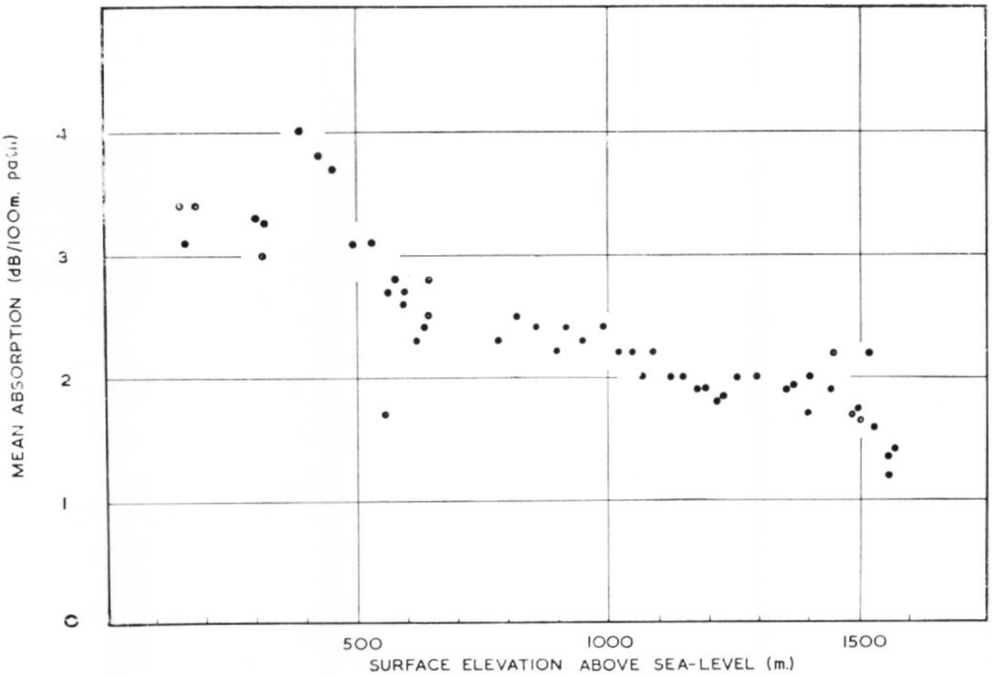

Fig. 10. Mean absorption (ordinates) in two-way transmission through the ice versus surface elevation above sea-level (abscissae). The mean annual temperature at sea-level is —18°C in this area.

−5°C. In the range from 200 to 700 m. thickness, all that can be said with certainty is that the temperature is below 0°C, probably about −5°C. More detailed treatment can be given to echo-strength measurements when the 10 m. temperature and the annual accumulation are known.

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