Journal of Glaciology, Vol. 15, No. 73, 1975

RADIO-ECHO SOUNDING: GLACIOLOGICAL INTERPRETATIONS AND APPLICATIONS

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Abstract. After a brief review of factors relevant to the propagation of radio waves in ice, problems of profiling the upper and bedrock surfaces of ice sheets are considered. These include deconvolution of echo traces and accurate navigation. Results already available not only provide knowledge of sub-ice geomorphology, but also confirm our general ideas on interaction of temperature and flow in large ice sheets. Difficulties encountered in the study of temperate glaciers appear to be due to irregular dielectric properties of the ice mass, which in turn suggest an irregular distribution of water. In the future, application of radio-echo methods should lead to more detailed knowledge of accumulation and ablation over ice masses, improve our understanding of temperatures at great depths in polar ice sheets, and give data on ice movement from central areas of ice sheets.

Résumé. *Sondages par radio-écho: interpretation glaciologique des applications.* Après une brève revue des facteurs qui règlent la propagation des ondes radio dans la glace, les problèmes de détermination des profils supérieurs et basals des calottes glaciaires sont abordés. Ils comprennent l'identification des échos reçus et la précision de la navigation. Les résultats déjà obtenus non seulement permettent de connaître la géomorphologie sous-glaciaire, mais confirment également nos idées générales sur l'interaction température–écoulement dans les grandes calottes glaciaires. Les difficultés rencontrées dans l'étude des glaciers tempérés apparaissent comme dues à l'irrégularité des propriétés diélectriques de la masse glaciaire, laquelle suggère en retour une distribution irrégulière de l'eau. Dans l'avenir, l'application de la méthode des sondages par radio-écho devrait conduire à une connaissance plus précise de l'accumulation et de l'ablation dans les appareils glaciaires, à une meilleure compréhension des profils de température aux grandes profondeurs dans les calottes, et à des données sur le mouvement de la glace depuis les zones centrales des indlandsis.

Zusammenfassung. *Radar-Echolotung: Glaziologische Interpretationen und Anwendungen.* Nach einer kurzen Betrachtung der für die Ausbreitung von Radarwellen in Eis bedeutsamen Tatsachen werden Probleme der Aufnahme von Oberflächen- und Untergrundsprofilen von Eisschilden betrachtet. Dazu gehören die Entzerrung von Echospuren und die genaue Navigation. Bisher vorliegende Ergebnisse vermitteln nicht nur die Kenntnis der subglazialen Geländeform sondern bestätigen auch die allgemeinen Vorstellungen vom Zusammenhang zwischen Temperatur und Fliessbewegung in grossen Eisschilden. Schwierigkeiten bei der Untersuchung temperierter Gletscher scheinen auf unregelmässige dielektrische Eigenschaften der Eismasse zurückzuführen zu sein, die wiederum eine unregelmässige Verteilung von Wasser vermuten lassen. Zukünftige Anwendung der Radar-Echomethoden sollten zu einer genaueren Kenntnis der Akkumulation und Ablation über Eismassen führen, das Verständnis der Temperaturen in grossen Tiefen polarer Eisdecken fördern und Daten über die Eisbewegung aus Zentralgebieten von Eisschilden liefern.

Introduction

Glaciologists no longer ask "Is it possible?" when referring to radio-echo sounding of polar ice sheets and glaciers. They ask questions such as, "Why is radio-echo sounding not being used very much on temperate glaciers?", and "Will it be possible to make radio-echo soundings of the ice sheets of Greenland and Antarctica from satellites in polar orbit?". Coupled with this general interest is the more specialist interest of the people closely concerned in the development of these methods. They are concerned with interpreting and explaining the observations that have already been made in terms of the properties of ice and ice sheets, in understanding why it is difficult to obtain soundings for certain regions, and in developing new and improved equipment to overcome these difficulties.

As our understanding improves, new applications of radio-echo techniques are opening up. We have a tool for glaciologists which is equivalent to X-rays for the medical profession and the physicists. By the radio-echo method we can plot bedrock beneath a glacier and record internal reflecting horizons within the ice mass. But apart from successes, the difficulties of the technique can also aid our understanding of glaciers. Absorption of radio waves in ice may be a nuisance in terms of obtaining soundings to maximum depths, but as our knowledge of the processes of absorption improves, we are likely to understand much more about the glaciers themselves. Absorption is so dependent on ice temperature that we already have a tool which tells us that our ideas on temperature distribution in polar ice sheets are at least semi-quantitatively correct over wide areas. When dealing with reflections from bedrock and from within the ice mass, we have limits to the resolution of detail imposed by the wavelengths used. However, we know that bottom reflections come mainly from surfaces that appear rough rather than smooth at the wavelengths we use, although there are significant exceptions. We are gradually coming to understand the cause of internal reflections, a feature that was not anticipated when the technique was first proposed, but which is going to provide a great deal of useful knowledge. Even in the case of temperate glaciers, our efforts to explain the difficulty of making observations by radio-echo methods are throwing fresh light on the irregular pattern of dielectric properties of temperate ice. We find that this is probably due to an irregular distribution of free water in the ice mass. There is indeed much more to radio sounding of glaciers than was thought of initially, not only by Waite when he first appreciated and tried out soundings with the radio altimeter SCR 718, but also by Evans and the group at the Scott Polar Research Institute who set themselves the task of designing the optimum radio-echo sounding system for glaciologists.

In reviewing developments in this field, Gudmandsen is covering equipment and systems, while this review approaches the subject more from the point of view of the glaciologist. We will not attempt to cover all the detailed field work that has been carried out in the Arctic and Antarctic. But before approaching the main theme—interpretation and application of echo sounding—we will need to discuss some of the processes involved in the radio-echo method and certain problems, such as navigation, which are essential for the proper application of the technique.

Processes

Propagation of radio waves through ice masses is controlled by their refraction, absorption, and reflection. We start by considering refraction—or, in other words, the factors governing the velocity of radio waves in ice masses.

(i) *Velocity*

We need to know the velocity of radio waves in ice and firn in order to interpret echo times as ice depths, and to plot radio ray paths or wave fronts in relation to the geometry of propagation and reflection. The problems are similar to those of seismic shooting, although studies of radio-wave propagation are at an earlier stage of development. One obtains a reasonable approximation to the group as well as the phase velocity V of radio waves in ice and firn from $V = c/\epsilon^{\frac{1}{2}}$ where c is the velocity of electromagnetic waves in space, and ϵ the permittivity of polycrystalline ice. Using mean figures of ϵ from laboratory studies, we find $V = 169$ m/μs, which agrees reasonably well with field studies such as those of Robin and others (1969), Clough and Bentley (1970), and Robin (1975).

Analyses of seismic velocity measurements reported by Bentley (1975) use the relationships between velocity and temperature, density, and crystal fabric (especially crystal orientation) so that seismic waves can be used to study these parameters in large ice sheets. Such studies have not yet been made in relation to radio waves, mainly because of the difficulty o making sufficiently precise measurements of permittivity in the laboratory, or of velocity in the field. Nevertheless we are approaching the stage when useful studies may become possible, especially as bore-hole techniques are developed (Robin, 1975).

The major contrast between radio and seismic wave propagation arises in regard to density variations of ice and firn. As waves move from firn into ice of increasing density, seismic wave velocities increase (Robin, 1958; Crary and others, 1962), whereas radio-wave velocities decrease. This is of major importance in applying the two techniques. With low density firn near the surface of a polar ice sheet, there is a "defocusing" effect, which refracts energy away from the vertical with seismic waves (Fig. 1a), but towards the vertical with radio waves (Fig. 1b). The result is a tendency for ducting of seismic energy in layers near the surface with consequent effects on noise generation after an explosion (Robin, 1958; Bentley. 1964). This ray pattern readily permits studies of the variation of seismic wave velocity as a function of depth, since the depth of penetration of the first waves to arrive at any seismometer increases as the separation between shot point and seismometer is increased. One cannot use this simple technique with radio waves, as rays are refracted in the opposite direction. With radio waves, not only is such ducting absent, but, for the normal radio antennae in air, refraction within ice and firn bends a limiting ray downwards by 56°, so that the area of

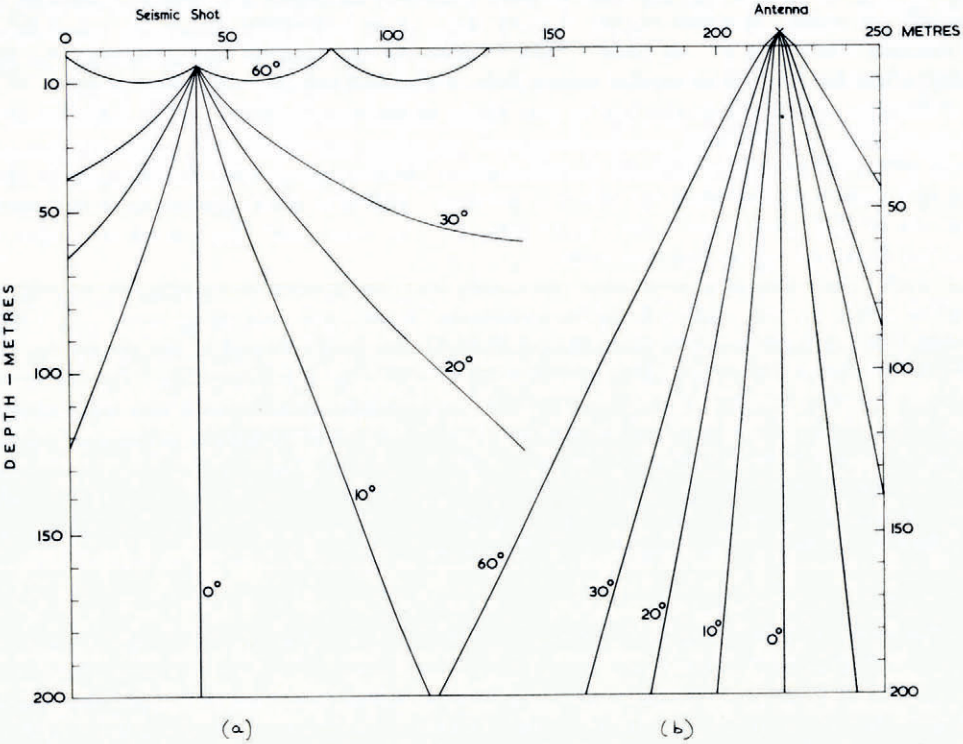

Fig. 1. Ray paths of energy radiated into a polar ice sheet with a typical density profile for a mean temperature around −20° C. Ray paths that start downwards at 0°, 10°, 20°, 30° and 60° are shown for
(a) a seismic explosion at 5 m depth, and
(b) radiation of electromagnetic waves from an antenna 5 m above the surface.

bedrock illuminated is limited to an approximately vertical cone of half-angle 34°. Furthermore, bottom slopes beneath an ice sheet of greater than 34° to the horizontal will not produce any specularly reflected energy that returns to the surface, although a weaker return of scattered energy within the cone illuminated may be present. The contrast between the two systems is shown diagrammatically in Figure 1. We should now consider the factors affecting velocity in more detail.

Velocity: density. While the change in refractive index with density is close to linear, the detailed changes depend on the crystal fabric or "Formzahl" (Evans, 1965; Robin, 1975). Refraction studies with seismic waves have proved very useful in producing depth–density relationships deduced from velocity–depth curves. Development of similar techniques with radio waves is unlikely, first because the decrease of radio wave velocity with depth in an ice sheet produces refraction which seriously impedes data collection, and second because it is difficult to make accurate velocity determinations. The proportionate variation of velocity with density is about half that of seismic waves.

Velocity: temperature. The fractional change of velocity with temperature of radio waves shown in Robin (1975, fig. 4) is about one third that of the variation of seismic wave velocities with temperature. Although some correction is desirable when making soundings of ice depth, such a correction has not been applied in practice as the absolute value of the velocity is not known with sufficient precision.

Velocity: crystal structure and ice fabric. With seismic studies, the preferred orientation of ice crystals at great depths increases the vertical velocities by about 4% over the velocity for an isotropic ice mass. Bentley (1972) showed that mean velocities previously used in depth calculations were 2 to 3% in error. Furthermore, he has applied this knowledge to deduce mean properties and tilt of crystal *c*-axes from analysis of seismic refraction data.

Although anisotropy in the ice mass is likely to have some effect on the velocity of radio waves, precise experimental measurements of the effect are not known to the reviewer. Use of the bore-hole system of velocity determination (Robin, 1975) may provide a field method that will show whether such an effect is present. Different investigators have assumed the variation in the velocity of radio waves between the *c*-axis and the normal direction to be from less than one up to four per cent.

Velocity: water content of ice masses. Attention was first drawn to the extreme limits of this problem when it was observed by Swithinbank (1968) that soundings were still obtained through extensive pools of water on the ice shelf of George VI Sound in the Antarctic. Smith and Evans (1972) discuss the effect of water on the velocity of propagation. For water of low conductivity, the velocity of radio waves in water is approximately one fifth that in ice. In general, the water layers in question are less than one metre in depth, so errors introduced by the presence of water are not serious. However, it is possible that with water-soaked firn and snow of temperate glaciers, the total water content could be greater and introduce significant errors. It may be worth using this effect in such cases as a means of determining changes of the effective water content of glaciers with seasons.

(ii) *Reflection*

Echoes recorded from basal or internal surfaces within the ice mass can show the characteristics of specular reflection from a smooth surface, of scattering from a rough surface, or a combination of these two effects (Robin and others, 1969). The theory for specular reflection is simple, the echo being of steady amplitude, of the same duration as the transmitted pulse, and usually a little stronger than the return from a rough scattering surface.

The theory for a rough scattering surface outlined by Robin and others (1969) has been further developed by Berry (1972) and Harrison (unpublished), while Oswald (1975) has collected and analysed field evidence as a test of theory. If one assumes that the reflection coefficient at any point on a rough scattering surface is constant, then one can derive statistical information on the roughness of the surface from the way in which the echo strength varies as one moves over the upper surface of an ice sheet. A detailed discussion is given by Oswald (1975). For this review we should mention that theory and observation indicate that an echo from a rough surface varies in amplitude by ± 10 dB about a mean, as one moves over the ice sheet. Oswald's results show that both the horizontal correlation distance and the reflection coefficient vary with location: they therefore have some potential for distinguishing between different types of bedrock surface and thus may indicate changes of bottom geology. An extreme case is the identification of lakes beneath the thick ice of east Antarctica (Oswald and Robin, 1973). A study is also being made by C. S. Neal of the characteristics of echoes from the base of ice shelves. As with inland ice, while the echoes from beneath ice shelves sometimes show the characteristics of specular reflection, the most frequent type shows the deep fading normally attributed to a rough surface. Whether this is due to a genuinely rough surface, to changes of reflection coefficient, or to changes of internal absorption within the ice mass, or to any combination of these, remains to be determined.

(iii) *Absorption*

A remarkable aspect of our early studies of radio-echo strengths was the success of our predictions of echo strengths at widely varying localities. The predictions were made from temperature–depth profiles of the ice mass calculated along the lines suggested in Robin (1955) and on laboratory measurements of the loss factor, tan δ, of samples of ice from north-west Greenland made by Westphal (see Robin and others, 1969). The success of these estimates implied not only that our estimates of temperature–depth profiles gave reasonable approximations to actual conditions, in itself a worth-while result, but also that Westphal's measurements on ice from north-west Greenland gave results that were representative for the ice at all locations on the ice sheets of Greenland and Antarctica. This latter conclusion is surprising, bearing in mind that the chemical impurity content in coastal regions of an ice sheet may be an order of magnitude greater than that of central regions. Paren and Walker (1971) suggested the concept of a solubility limit within the main crystal lattice structure of polar ice, with excess impurities being concentrated at the grain boundaries. However, more recent results (Fitzgerald and Paren, 1975) suggest that this may not provide the explanation. Further studies are needed to explain this feature, but in the meantime we will continue to estimate absorption on the basis of Westphal's results. There is clearly some variation present, but the mean absorption throughout the ice mass of the east Antarctic plateau is still about 80% of that predicted. Although this topic will be dealt with by Gudmandsen in this symposium, it has also to be considered as a factor in interpretation of radio-echo results.

The preceding remarks apply to cold polar glaciers. When we deal with temperate glaciers or other cases where water is present in the ice mass, such as brine-soaked firn layers of an ice shelf or of sea ice, we must take account of the electrical conductivity of the water. With sea-water, or a brine layer in an ice shelf, effective penetration at the frequencies used for radio-echo sounding is limited to a few centimetres. However, for water melted from snow, or rain water of high purity, the absorption is similar to ice, but absorption rises rapidly as the impurity content increases. In the case of temperate glaciers, apparent absorption may also be caused by numerous reflexions from dielectric discontinuities in the glacier, caused by ice lenses or an irregular water distribution within the ice mass.

Profiling of ice depths and related problems

Undoubtedly the most obvious and dramatic use of radio-echo sounding of ice sheets is its application to continuous profiling of the bedrock surface of Antarctica and Greenland. In marine science, major features such as trenches in mid-oceanic ridges were not identified until effective methods of continuous sounding of the ocean floor were introduced. Furthermore, the systematic alignment of magnetic anomalies was not appreciated until precise methods of navigation of ships were developed. These features, along with systematic information from seismology and other fields, brought together sufficient data to stimulate the concepts of plate tectonics.

Many lessons may be learned from marine science, as the interpretations and logistic problems of radio-echo sounding are similar, although not identical. The ability to sound ice depths from aircraft means that we can make continuous soundings at ten or twenty times the speed of ship-borne studies. On the other hand, precise aircraft navigation is more difficult than ship navigation, although introduction of inertial navigation for radio-echo flights over Antarctica in 1971–72 helped greatly. With aircraft, however, there is the additional requirement that the height of the aircraft above sea-level must be known, as well as latitude and longitude at any instant. The overall operation is therefore very complex and requires a high degree of co-ordination between the aircraft operators and radio-echo group. The most extensive sounding programme to date has been that of the Scott Polar Research Institute/National Science Foundation over Antarctica in long-range aircraft of the U.S. Navy. This started with a trial season in December 1967 in a C131 J Super Constellation aircraft, and has continued in C130 Hercules aircraft in 1969–70 and 1971–72. It is now clear that effective sounding over 90% or more of the Antarctic ice sheet should be possible with the present technology, and a similar result appears likely from Danish/U.S. flights over Greenland.

We will discuss first the basic methods of identifying and recording echoes from the bottom of the ice and then certain problems that are essential for large-scale sounding of ice sheets.

Interpreting the echo signal

Radio-echo soundings of ice thickness can be made from surface vehicles or from aircraft. In earlier years, several groups measured depths by oscilloscope A-scope displays, but all groups now use the continuous film recording of an intensity-modulated oscilloscope display developed in the Scott Polar Research Institute (Robin and others, 1969; Evans and Smith, 1969). In the following discussion, unless otherwise stated we deal with this system. Photographic recording of oscilloscope A type of display also continues to be important for accurate recording of echo strengths and other applications.

When sounding polar ice from aircraft, separate echoes from the upper and lower surfaces of the ice sheet are usually obtained without difficulty. The upper surface is normally very strong and shows little fading, whereas the strength of the lower surface usually varies rapidly as the observer moves. However, this fading is so rapid that the bedrock echo is virtually continuous, provided that it is strong enough to be recorded.

Misidentification of echoes. Owing to the continuity of bedrock echoes, few mistakes in their interpretation are likely, although very occasionally an internal echo has been mistaken for an echo from bedrock. In general, the reliability of interpretation is such that radio-echo records provide a standard against which earlier seismic and gravity depth estimates may be tested for gross errors (Drewry, 1975).

Deconvolution. Since the record on a radio-echo film shows the range to the nearest ice–rock interface, and not the vertical depth of ice, the film record does not present a true vertical profile of the bedrock surface. The same problem exists in marine sounding, but analysis is more complicated with radio-echo sounding from aircraft owing to considerable refraction at the air–ice interface. Harrison (1970) has shown how to deal with the problem by use of computers, and his programme has also been used by Drewry (unpublished). Macheret and Luchininov (1973) have used similar methods in surface radio-echo sounding of mountain glaciers. When dealing with bottom slopes of less than, say, 1 in 20, application of Harrison's deconvolution methods is of minor importance, but for greater slopes it is essential and its use should be more widespread. In developing automatic methods for analysis of radio-echo records, we aim to incorporate a programme for deconvolution of bottom echoes on a regular basis. It may be that the understanding and experience of methods of deconvolution gained with radio-echo sounding could help interpretation of seismic reflection shooting material (Harrison, 1970, fig. 13 and 14).

Temperate glaciers

Although glaciers of the more temperate regions of the Earth constitute only two or three per cent of the ice masses on Earth, they are of considerable economic importance. Introduction of more rapid methods of sounding these glaciers, such as an effective system of radio-echo sounding, would be of great importance. Consequently, several groups have tried to develop such systems and to understand the background physics. In the Scott Polar Research Institute, Smith and Evans (1972) analysed the problems of absorption and scattering by water inclusions and ice lenses. Their work included trials in Norway and Switzerland, the latter being continued by Davis (unpublished), who has analysed the results available in order to make as extensive deductions as possible on the size and nature of the irregular dielectric properties of temperate glacier ice. Goodman (1970) has put considerable effort into production of an efficient system for sounding temperate glaciers in Canada, using a higher frequency (620 MHz) than the Cambridge group's trials (35, 60, 150 and 480 MHz). In the U.S.S.R., work has been carried out on sounding of mountain glaciers, as reported by Zotikov and others in a paper submitted to this symposium (see p. 471).

In general, results for temperate ice indicate that the absorption at lower frequencies is not much above 5 dB per 100 m, the value indicated by Westphal's laboratory studies on polar ice. Unlike the relatively clear echoes from polar glaciers, irregular but quite strong echo returns (or clutter) are recorded from throughout the ice mass of temperate glaciers. In some cases, especially with thinner ice, the bottom echo has been recorded clearly, but frequently it is lost in the continuous return of clutter (Fig. 2). This takes place because, owing to the relatively long wavelengths used, radio energy is radiated through a wide angle so that oblique clutter echoes from within the ice continue beyond the arrival of the bottom echo, which follows a path normal to the ice–rock interface. Sukhanov and his colleagues (1973) have developed operational and statistical methods for identifying the bottom echo, which shows continuity of properties against a background of irregular clutter echoes. This work appears to have been successful, but is not widely appreciated in other countries.

Another way of overcoming the problem is to use a narrow pencil beam with little energy radiated in side lobes. To do this, one must use shorter wavelengths and larger antennae systems to obtain the directivity. However, absorption rises at shorter wavelengths, due to higher dielectric losses and increased loss by scattering, so a compromise solution at an optimum frequency appears to be the answer. It seems likely that Goodman's choice of 620 MHz is at about the optimum balance between directivity obtainable with antennae and

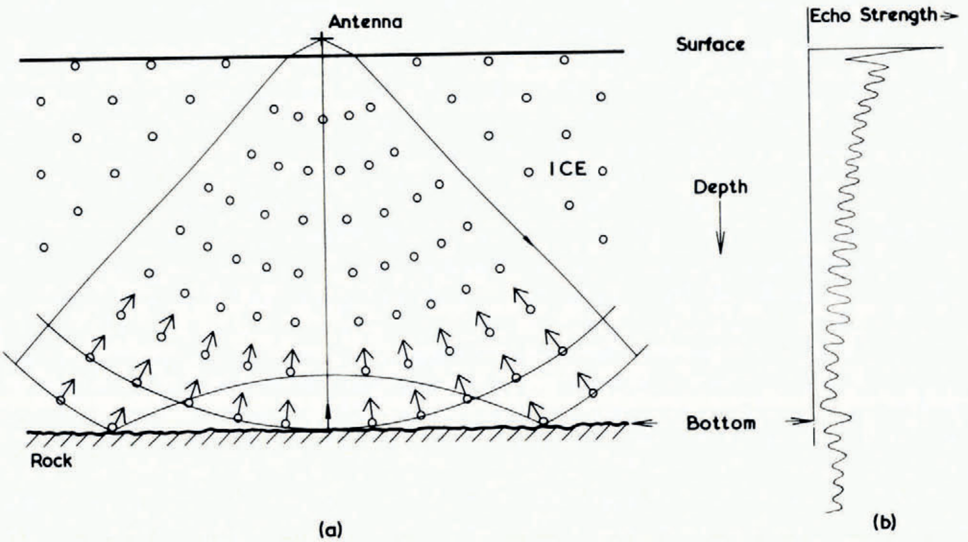

Fig. 2. Effect of random distribution of scattering centres in a temperate glacier (a), on the energy received and displayed on an A-scope trace (b).

https://doi.org/10.3189/S0022143000034262 Published online by Cambridge University Press

the rising absorption with frequency. It is clear that all groups concerned have obtained some results, but that results have not been obtained with the consistency and clarity of those on polar glaciers.

The key to interpretation of results from temperate glaciers appears to lie in the irregular distribution of water within the glacier. In the analysis by Davis, and from the methods of Sukhanov and his colleagues, it appears that the scale of irregularities, even at depths approaching bedrock, is of the order of one metre. Strangway and others (1974) find the dimensions of dielectric scatterers on Athabasca Glacier to be less than 35 m and probably due to crevasses.

Sub-polar glaciers

We should mention sub-polar glaciers as a separate class—especially the case of glaciers with much of the ice mass at only −1° to −2° C. This appears to be the situation in north-west Greenland between 800 and 1 000 m elevation (Robin and others, 1969) and on the ice piedmonts around the Antarctic Peninsula (Swithinbank, 1968) and on King George Island (Govorukha and others, 1974). Successful soundings in these regions to depths of 200 to 600 m suggest that, although dielectric absorption is high, the problem of clutter from irregularities of the dielectric rapidly disappears as the temperature drops a degree or so below melting point and so eliminates most of the free water within the ice mass—even though melt water is present at the ice–rock interface.

This observation prompts the suggestion that soundings of certain glaciers and ice caps in locations such as Nordaustlandet could be satisfactory, and it may explain the success of some soundings of high Alpine glaciers in the Soviet Union.

Aircraft navigation

The earliest trial flights of radio-echo sounding of glaciers in 1966 paid little attention to navigation. Over Ellesmere Island the pilot flew by eye along a course estimated as the centre line of valley glaciers. Longer-range flights by U.S. scientists over Greenland in 1966 involved bigger errors owing to lack of landmarks. Swithinbank's first flights around the Antarctic Peninsula in January 1967 attempted better navigation, including flying between well-located peaks, while the first S.P.R.I.–N.S.F. long-range flights over Antarctica were equipped with SFIM photographic flight recorders which by means of galvanometer traces, showed aircraft heading, indicated air-speed, static air pressure, and air temperature. It was a lengthy procedure to process these data for the 94 h of flying in 1967, and because of variable winds at lower altitudes, the results were frequently no better than the rapid position fixes in flight. Good fixes were however obtained when within sight of the mountains from use of trimetregon air photographs. The net result of the 1967 flights was that about 90% of time spent on data reduction was spent on navigational data and only 10% on radio-echo analysis.

In 1969–70 it was decided to continue the same recording systems, but to accept the navigator's position calculations made during the flight. Since some 330 h of radio-echo flying was carried out, this was essential. Furthermore, the flying was done at greater altitudes where the winds are less variable. The improvement in the navigational data was considerable, as could be seen from the consistency of ice depth figures between different flights, while the time spent reducing and checking navigational data dropped to about 30 to 40% of the time spent on the reduction of all data.

The aircraft was fitted with inertial navigation (Litton 51 C) for the 1971–72 season, when 160 h of flying was carried out. Not only did this reduce time spent on evaluating navigation data to perhaps 10% of the total analysis time, but the resultant data were an order of magnitude better than could have been obtained on long-range flights over the Antarctic plateau. With inertial navigation, flight lines were planned to cover a 100 km square net over the plateau of east Antarctica. Position errors are unlikely to exceed 6 km during these flights, and the mean error will be less than half this figure. This is confirmed by comparison of ice depths at the crossing points of flight lines over the Antarctic plateau, where the greatest difference between soundings at some 91 crossing points was 117 m and the mean difference was 30 m (Drewry, 1975). Without inertial navigation it would not have been possible to fly a systematic square network, because flight lines would have had to converge on the few available navigational control points on the ice sheet as often as possible—say every three hours.

Navigation is mentioned at some length as it forms an essential basis to the study of polar ice sheets from aircraft. In well-mapped areas with frequent nunataks visible, conventional methods, including air photography, may supply the necessary data, but when no control points are visible, as on ice sheets, use of an accurate, sophisticated method of navigation is as necessary for studying ice sheets as is the equivalent system for marine studies.

Surface profiling and the problem of aircraft altitude

If one is to map bedrock beneath a large ice sheet in terms of elevation above or below sea-level on the basis of ice thickness, one must start by knowing the surface elevation. This is not known with much precision for the large ice sheets of Greenland and Antarctica. The problem of determining surface altitudes of the ice sheet along radio-echo flight lines from a knowledge of the aircraft altitude and its height above the snow surface is similar in complexity to the problem of navigation. Considerable time and effort is required to produce satisfactory surface maps of the ice sheet, but the techniques are not very different from surveying techniques and will not be discussed at length in this review.

Geomorphology

Once the true bedrock profiles have been determined, the problem of their interpretation lies largely in the fields of glacial geology, geomorphology, and crustal geophysics. Discussions of the wider significance of seismic and gravity studies of Antarctica have been presented by Woollard (1967), Bentley (1964), and Kapitsa (1968). Drewry (unpublished) has looked at wider problems in relation to the data from radio-echo sounding. He has shown that sub-ice relief of east Antarctica, classified in terms of the amplitude of relief in vertical and horizontal dimensions, appears to fall into different zones which probably reflect different geological provinces. However, our interpretations of sub-ice geology are limited by lack of comparable geophysical information along flight lines, especially of geomagnetic records, while gravity and seismic information would help also to make reliable assessment of the sub-ice geology more practicable. On a smaller scale, Drewry (1971) has studied faulting and landforms around the Transantarctic Mountains. His interpretation of the presence of large glaciated valleys trending inland is of considerable importance to the history of Antarctic glaciation. It implies a long period during which wet-based glaciers were actively eroding the mountain region before the main continental ice mass was formed.

Airborne profiling by Kozlov and Fedorov (1968) between long. 35° and 56° E., lat. 67° and 75° S. has shown that the sub-ice morphology is similar to that of the coastal mountains of this region, and that the sub-ice trench below sea-level suggested by I.G.Y. results does not exist. Similar subglacial relief was found during airborne soundings around Lambert Glacier by an Australian group (Morgan and Budd, 1975) and also further east by the South African traverse groups (Schaefer, 1972, 1973; van Zyl, 1973). Around the Antarctic Peninsula, airborne soundings have shown a rough topography beneath the ice plateau (Swithinbank, 1969; Smith, 1972).

Surface accumulation, ablation, and ice movement

We will now consider, from the glaciological point of view, the parameters that are needed to understand the mechanism and history of polar ice sheets. We can then assess how useful radio-echo techniques may be in helping us to collect these data. The basic elements we need to study are the rates of accumulation and ablation of ice sheets and ice shelves, their thickness, and the distribution of temperature and velocity of movement throughout the ice masses.

(i) *Accumulation*

Annual layering in snow and ice may range from 2 or 3 cm of ice in central Antarctica to 60 cm or more on polar ice sheets and several times that amount on temperate glaciers. Direct, discrete reflections from individual annual layers should soon be possible with the latest pulse techniques, using a 1 ns pulse (Vickers and Rose, 1972). More general studies of mean thicknesses of multiple layers could be made with a swept-frequency system.

If it becomes possible to identify a prominent internally reflecting layer with an event of known data, such as a volcanic eruption, this horizon could then give information over wide areas on the mean accumulation rate. It would, of course, be necessary to correct for vertical strain over the period in question. On a more practical level, if internally reflecting horizons can be confirmed as former deposition surfaces, as has been shown in north-west Greenland for one layer at about 400 m depth (Robin and others, 1969) then one should be able to interpolate mean accumulation rates between controlling sites, where adequate information is available. Already the indications from the continuity of such echoes are that the slow variation of mean accumulation rates with position on the ice sheet which are apparent from widely-spaced stake and stratigraphic measurements is verified in more detail by the continuity of internal reflections that tend to parallel the top and bottom surfaces of the ice sheet.

One further example of indirect evidence of low accumulation rates in the vicinity of Dome "C" of the S.P.R.I.–N.S.F. flights over the Antarctic plateau comes from the presence of lakes beneath 3 000 m of ice in this vicinity (Oswald and Robin, 1973). The steady state theory of temperature distribution (Robin, 1955) indicates that for bedrock to be at the melting point in this area where surface temperatures approach $-50°$ C, the surface accumulation must be about 3 cm a^{-1}, rather than the estimate of about 7 cm a^{-1} that one obtains by interpolating on the map prepared by Bull (1971). Subsequent measurements by Lorius (private communication) approaching Dome "C" give a figure of 5 cm a^{-1}, which, as later digital calculations by Jenssen indicate, may fit basal melting where the ice thickness is increasing along a flow line. Thus prediction was roughly in line with the later direct evidence.

The ultimate instrumental system for determining annual layer thicknesses within the ice sheets may be an instrument similar to the ionospheric sounder which sweeps through a wide range of frequencies of, say 50 to 500 MHz. Then by studying the fading pattern against depth, one should in principle be able to determine the dominant layer thickness at any depth in a manner similar to the interpretation of the earlier ionospheric soundings at Halley Bay (Evans, 1961). The technicalities, costs, and complexities of interpretation may, however, mean that the development of such methods is a distant prospect.

(ii) *Ablation*

Certain of the comments on the possible determination of accumulation rates by radio-echo methods can apply to the study of ablation due to melting at the top or bottom surfaces of ice sheets or ice shelves. This is possible if internal layering can be observed in ablation areas of ice sheets. Then, if a particular horizon can be followed over a wide area, one can, after making corrections for vertical strain, determine how much ice has melted off the surface as a function of distance from the equilibrium line. Then, if one knows the velocity of movement, one can convert this into an ablation rate. The method appears particularly attractive for determination of the bottom melting beneath ice shelves, especially the Ross Ice Shelf, where considerable knowledge of the ice movement has been, and is being, acquired. Unfortunately, efforts to record suitable internal layering of ice shelves by radio-echo sounding have not been successful so far, but the value of these observations is such that efforts should continue.

(iii) *Temperature*

Ice temperature is the parameter that has been a central consideration in the development of radio-echo sounding, since the large variation of dielectric absorption with temperature would make the method of echo sounding impracticable on polar ice sheets if a large fraction of the ice column were at the melting point. It was shown by Robin and others (1969) that the bottom echo strength recorded at Camp Century, Greenland, was such that no substantial thickness of ice near bedrock could be at the melting point, although the accuracy of theory and observation did not enable one to be sure whether the ice–rock contact was frozen or at the melting point.

Several observers (Bailey and Evans, 1968; Bogorodskiy and others, 1970[b]) have used a useful though crude parameter, the mean absorption temperature. This is determined by dividing the observed absorption by the path length through ice (twice the depth), and converting this figure from Westphal's curve to a temperature. Owing to the non-linear relationship between absorption and temperature, the answer is not close to the true mean temperature, but it is useful in discussing radio-echo sounding performance. In general, the mean absorption temperature will be appreciably—and possibly substantially—warmer than the true mean temperature of the ice.

It appears likely that once a better understanding of the processes causing internal reflections of radio waves in polar ice sheets has been gained, it may be possible to make quantitative estimates of temperature and absorption gradients at depths below 2 000 m in polar ice sheets. This arises from work of Paren and Robin (in preparation) showing that the main reflection process at greater depth is due to changes of dielectric loss (i.e. tan δ) between different layers, so that the reflection coefficient itself is very temperature-dependent. This applies only below 1 500 to 2 000 m at the site studied. At depths of less than 1 500 m, the reflections appear to be due to density or similar variations, and although absorption still plays a part in determining the recorded echo strength of internal reflections, it may prove difficult to isolate the absorption losses from the other factors so as to produce satisfactory estimates of temperature. Nevertheless, as our understanding of the physical processes causing internal reflections improves, it appears likely that we may be able to gather much more detailed information on temperature distribution within ice masses than is given by the mean absorption temperatures. In turn this information may let us draw indirect conclusions on accumulation rates at the surface along lines indicated previously. The potential accuracy will not however be great enough to replace the precise temperature measurements in bore holes that are necessary when relating present-day temperature profiles to the past surface temperatures.

We should not conclude this section without pointing out again that the whole progress of radio-echo sounding has been dependent on our understanding of temperature distribution within polar ice sheets. The successful development of radio-echo sounding methods in itself provided confirmation of our theoretical models of temperature distribution before more direct evidence was given by results from deep drilling at Camp Century in Greenland and "Byrd" station in Antarctica.

We need more detailed studies of the variation of absorption with location in the future if we are to confirm the representative nature of a temperature–depth profile for the surrounding region. Clearly, there is no evidence at present which would favour the suggestion that convection occurs in polar ice sheets as proposed by Hughes (1971). If convection within the ice sheet did occur, we would expect the resultant temperature pattern to produce rapid variations of absorption with location, and this would result in rapid changes in the depth from which internal reflections are recorded. In addition, the continuity and parallel nature of such reflecting surfaces would be broken by the existence of convection. Evidence of the lack of convection in an ice sheet, in spite of the existence of favourable conditions pointed out by Hughes, should be of interest to those concerned with the possibility of convection in the Earth's mantle.

Reflecting horizons within the ice mass

We have already drawn attention to the significance of the continuity of internal reflections. Their continuity over long distances in Greenland and the presence of strong echoes from internal layering at centres of outflow in Antarctica both favour the idea that these horizons are depositional features. If these main internally reflecting horizons can be confirmed as relics of earlier surfaces of the ice sheet, as discussed earlier, then we have an important parameter displayed on our radio-echo records that can be related to past accumulation and ice movement. The position of past surfaces, or "isochrons" as they have been called, have been calculated and are shown in the computer prints of Budd and others (1971).

Polarization

Evidence of polarization of radio echoes in polar ice sheets has been produced by Bogorodskiy and others (1970[a]) and by Jiracek and Bentley (1971). Since transmitted pulses are usually polarized at the source, the problem in making observations is to study the processes of depolarization. There are two significant factors: the effect of anisotropy within the ice mass, and the process of reflection. The problems will be discussed elsewhere in this symposium and readers should refer to Bentley (1975) and p. 442.

Ice movement

If radio-echo fading patterns of bedrock echoes are fixed in space, then these patterns may be used as a fixed reference frame against which one can determine ice movement. If the fading patterns are due entirely to the irregularities of the bedrock surface and are not affected by inhomogeneities that move with the ice mass, such as moving morainal material or dielectric variations in the main ice mass, then it is reasonable to expect them to form a suitable reference frame. The time scale involved in developing and testing this concept will serve to illustrate the time gap between producing an idea and applying it.

The concept of using the fading pattern was first suggested by the reviewer at a colloquium in the Scott Polar Research Institute in 1969, but the initial conclusion was that the frequency dependence of the fading pattern would require a high degree of stability of radio frequency and band-width in the equipment. In view of other commitments for the research group, the idea was not pressed until J. F. Nye raised the matter in a personal discussion in February 1971, when he pointed out that frequency stability requirements were not as stringent as had been thought and could readily be met. It was agreed that Nye's group in Bristol should pursue this line of work.

Short field trials of the method were then made in the 1971–72 season, using the conventional radio-echo equipment (SPRI Mark II) on Fleming Glacier, Antarctic Peninsula. In spite of some operational difficulties, the first results on this glacier (Walford, 1972) showed an ice movement of 38 ± 3 cm d^{-1} (radio echo) compared with an ice movement of 46 ± 5 cm d^{-1}

(theodolite). Further work by Doake (British Antarctic Survey) on the same glacier, which is probably sliding at its base, and on Devon Island where the basal ice is about −18° C, is being evaluated and should help to show if the reference frame in either case can be considered as fixed in space (see p. 89).

Following these initial trials, equipment designed for the specific purpose of determining the ice movement from fading patterns is being built at Bristol. This will not only determine horizontal movement, but will aim to determine any small changes in ice thickness with time, by measuring any vertical displacement in relation to the fading pattern. Technical difficulties of the latter are considerable, so no preliminary assessment with conventional radio-echo gear is practicable. The principles of operation are given by Nye and others (1972). It is hoped that field trials will be commenced during the coming year.

It is already clear that an accuracy of position-fixing in the horizontal frame in relation to the fading pattern is possible to better than 10 cm—at least an order of accuracy greater than appears possible from satellite fixing methods. Thus the system may give effective measurements of movement in a fraction of the time necessary for satellite methods, which is an important operational consideration. When experience of the method has been gained, it might prove possible to use fading echoes from internal layers to determine the relative horizontal and even vertical movement between the surface and these layers, and hence determine the velocity and strain pattern throughout the ice masses.

Conclusion

I believe that this review has drawn attention to the wide range of glaciological problems on which light can be thrown by radio-echo techniques. However, if we are to take advantage of these opportunities, there must be very close cooperation between the designers of radio-echo systems and the glaciologists who use these systems. Requirements for the future range from the development of light-weight systems which can be readily managed by the glaciologists to the development of complex and powerful systems employing new techniques which will enable us to look at aspects of glaciology that cannot be tackled by any other means.

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DISCUSSION

H. LISTER: The higher intensity of the reflected energy shown by Dr Robin as achieved from an aerial near the surface is encouraging to those of us who are glad of a reason for walking over the glacier rather than just flying over it. However I can be wrong in this because of generator power since the input energy to the transmitter aerial seemed high. What was that input for say a favoured frequency of 50 or 60 MHz?

G. DE Q. ROBIN: There are certainly advantages in working on the surface. The transmitter input can vary widely; in one set we have used, the peak power input is 150 W.

J. CLOUGH: The refraction effect or refraction gain is the same whether the antenna is on the surface or several wavelengths above the surface.

ROBIN: When the antenna is actually on the surface, or within a small fraction of a wavelength, I would expect some effects on antenna impedance—otherwise I agree.

T. HUGHES (written comment—not presented orally at the symposium): Your comments on the inability of radio-echo flights to detect evidence for thermal convection in the Antarctic ice sheet cannot yet constitute a conclusive case against convection in ice sheets for three reasons: First, convective instability is probably marginal in ice less than 3 km thick and the great bulk of radio-echo flight-lines are over ice not exceeding this thickness. Second, where flight space lines do cross ice where convection is predicted (ice over 3 km thick), the radio-echo data only suggest that convection is not in the form of the Bénard cells or rolls typically observed in fluids. This is not surprising, because fluid viscosity is much less sensitive to temperature than the effective viscosity of crystalline solids. For this reason, convection in crystalline solids such as the Earth's mantle or the Antarctic ice sheet will consist of narrow ascending pipes or curtains, between which the cold material sinks *en masse*. In the Earth's mantle, convecting pipes are believed to form hot spots on the Earth's crust and convecting curtains are identified as crustal rifts. These hot spots and rifts are typically in the range of 100 km to 300 km wide, compared to a mantle thickness of 3 000 km and an average distance between hot spots and rifts of at least 6 000 km. Scaling these dimensions to the Antarctic ice sheet, convecting pipes or curtains would be only 100 m to 300 m wide in ice 3 km thick, and would be at least 6 km apart. They would be vertical hot wedges in the ice with temperature effects similar to the sea-ice filled cracks on the underside of the Ross Ice Shelf which Clough (1975) detected from radio-echo signals generated at the top surface of the ice shelf. I understand that you were much less successful in getting internal reflections from radio-echo signals generated from airplanes flying over the Ross Ice Shelf, but did get bottom reflections from these cracks. I would therefore suggest that aerial radio-echo signals from flights over the ice sheet will also be unlikely to detect narrow convecting pipes or plumes as internal reflections, but only as bottom reflections. However these bottom reflections would be indistinguishable from those resulting from bed roughness and other causes. Third, convecting pipes or curtains may not reach more than half-way to the surface of the ice sheet (i.e. to the "nose" of the density–depth curve). It is presently difficult to obtain internal reflections from the lower half of the ice sheet. In summary, surface radio-echo profiling should be more effective than airborne profiling in detecting convecting pipes or curtains, and technological refinements in radio-echo equipment would also be helpful.