Journal of Glaciology, Vol. 30, No. 104, 1984.

RADIO ECHO-SOUNDING OF SPITSBERGEN GLACIERS: PROBLEMS IN THE INTERPRETATION OF LAYER AND BOTTOM RETURNS

By J. A. Dowdeswell, D. J. Drewry,
(Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, England)

O. Liestøl *and* O. Orheim
(Norsk Polarinstitutt, P.O. Box 158, 1330 Oslo Lufthavn, Norway)

Abstract. Airborne radio echo-sounding of Spitsbergen glaciers during 1980 used 60 MHz SPRI Mk IV equipment. On several glaciers results showed unambiguous bottom returns at depths 2–3 times those reported in previous Soviet echo-sounding at 440 and 620 MHz. Comparison of 60 MHz records and independent gravity-surveyed ice thickness for two glaciers agreed to within 10%, whereas Soviet ice thicknesses were only 30–60% of gravity depths. Soviet bed echoes often coincided closely with an internal reflecting horizon recorded by the SPRI Mk IV system, and it is shown that Soviet U.H.F. equipment failed to penetrate to the true glacier bed on a number of ice masses (e.g. Finsterwalderbreen, Kongsvegen, Negribreen). This was probably due to increased absorption and scattering at higher radio frequencies, related to the inhomogeneous nature of Spitsbergen glaciers, which are often at or near the pressure-melting point. Both 60 MHz and U.H.F. equipment seldom recorded bed echoes in ice-cap accumulation areas (e.g. Isachsenfonna), where firn soaking during summer and 10 m temperatures of zero degrees have been observed. An isolated internal reflecting horizon was recorded on many glaciers. It is unlikely to be a moraine layer, but may be related to ice with a water content of 1–2% observed at a similar depth (115 m) in a drill core from Fridtjovbreen.

Résumé. *Sondages par écho radio sur les glaciers du Spitsbergen: problèmes pour l'interprétation des réflexions sur des niveaux intermédiaires et sur le fond.* Des sondages par écho radio aériens sur les glaciers du Spitsberg en 1980 ont utilisés un équipement 60 MHz SPRI Mk IV. Sur de nombreux glaciers les résultats ont montré sans ambiguïté des échos sur le fond à des profondeurs de 2 à 3 fois celles trouvées par de précédents sondages soviétiques sur 440 et 620 MHz. La comparison des résultats des sondages à 60 MHz et de contrôle indépendants de l'épaisseur de la glace par gravimétrie sur deux glaciers ont concordé à 10% près tandis que les profondeurs de glace soviétique étaient seulement de 30 à 60% des profondeurs données par la gravimétrie. Les échos du "lit rocheux" selon les soviétiques coïncidaient souvent exactement avec un horizon interne de réflexion également enregistré par l'appareil SPRI Mk IV, et on montre que l'équipement U.H.F. soviétique n'a pas réussi a pénétrer jusqu'au véritable lit rocheux du glacier grand nombre d'appareils glaciaires (par exemple Finsterwalderbreen, Kongsvegen, Negribreen). Ceci était probablement dû à une plus forte absorption et à une plus grande dispersion aux hautes fréquencies radio, au regard à la nature inhomogène des glaciers du Spitsberg qui sont souvent proche ou juste au point de fusion correspondant à la pression. L'appareil à 60 MHz comme le U.H.F. ont rarement enregistré des échos sur le lit dans les zones d'accumulation de calotte glaciaire (comme l'Isachsenfonna) où des névés fondants pendant l'été et des températures à 10 m de 0°C ont été observés. Un horizon de réflexion interne isolé a été enregistré sur beaucoup de glaciers. Il est peu probable qu'il s'agisse d'un niveau morainique mais il peut y avoir de la glace contenant 1 a 2% d'eau comme observé à une profondeur de cet ordre (115 m) dans un forage au Fridtjovbreen.

Zusammenfassung. *Radar-Tiefenmessung über Gletschern Spitzbergens: Probleme der Deutung von Schicht- und Bodenechos.* Radar-Tiefenmessungen über Gletschern Spitzbergens im Jahre 1980 benutzten eine 60 MHz-SPRI-Mk IV-Ausrüstung. Bei einigen Gletschern traten in den Ergebnissen eindeutige Bodenechos aus Tiefen auf, die 2- bis 3-mal so gross waren als die bei früheren russischen Messungen mit 440 und 620 MHz. Der Vergleich zwischen 60 MHz-Aufzeichnungen und unabhängigen Schwerkraftbestimmungen der Eisdicke ergab bei zwei Gletschern eine Übereinstimmung von 10%, während die russischen Eisdicken nur auf 30–60% mit den Schwerkraftwerten übereinstimmten. Die russischen Bodenechos passten oft sehr gut zu einem inneren Reflexionshorizont, der vom SPRI-Mk IV-System aufgezeichnet wurde, und es lässt sich zeigen, dass die russische U.H.F.-Ausrüstung bei einer Reihe von Eismassen (z.B. Finsterwalderbreen, Kongsvegen, Negribreen) nicht bis zum wirklichen Gletscherbett durchdrangen. Der Grund hierfür war vermutlich die erhöhte Absorption und Streuung bie höheren Radiofrequenzen, hervorgerufen durch die inhomogene Natur der Gletscher Spitzbergens, die sich oft auf dem oder nahe am Druckschmelzpunkt befinden. Sowohl die 60 MHz- wie die U.H.F.-Ausrüstung zeichneten nur selten Bodenechos im Akkumulationsgebiet der Eiskappen (z.B. Isachsenfonna) auf, wo während des Sommers eine Durchtränkung des Firns und Null-Grad-Temperaturen in 10 m Tiefe beobachtet wurden. Ein isolierter, innerer Reflexionshorizont wurde bei vielen Gletschern festgestellt. Es dürfte sich dabei kaum um eine Moränenschicht handeln, doch könnte eine Verbindung zu Eis mit einem Wassergehalt von 1–2% vorliegen, das in ähnlichen Tiefen (115 m) in einem Bohrkern des Fridtjovbreen beobachtet wurde.

INTRODUCTION

Temperature measurements on several Spitsbergen glaciers indicate that they are of "sub-polar" thermal regime, with accumulation-zone ice at or near the pressure-melting point and ablation-area ice somewhat colder (e.g. Sverdrup, 1935; Schytt, 1964; Baranowski, 1975). "Sub-polar" and "temperate" glacier ice is both less homogeneous and more lossy to electromagnetic energy than colder Antarctic and Greenland ice masses. At these higher temperatures both scattering and absorption of radio waves increase relative to colder ice, making radio echo-sounding of glacier thickness problematic (Smith and Evans, 1972; Goodman, 1975; Watts and England, 1976).

A primary aim of radio echo-sounding has always been to record an unambiguous bed echo (Smith and Evans, 1972). However, analysis of airborne echo-sounding data collected in Spitsbergen during 1980 showed bottom returns from certain glaciers at depths 2-3 times those reported in previous echo-sounding studies (Macheret, 1980; Macheret and Zhuravlev, 1982). This paper reports the results of airborne radio echo-sounding in Spitsbergen at a frequency of 60 MHz, and suggests that certain echoes assumed by previous workers to be from the ice-bed interface are in fact returns from an internal reflecting horizon. Reasons for the failure of Soviet 440 and 620 MHz systems to penetrate to the true bed of a number of Spitsbergen glaciers are discussed, along with possible explanations of observed internal reflecting layers.

RADIO ECHO-SOUNDING EQUIPMENT AND METHODS

Radio echo-sounding of Spitsbergen glaciers during April and May 1980 used a Scott Polar Research Institute (SPRI) Mk IV sounder mounted in a Bell 206 helicopter (Drewry and others, 1980). The sounder operated at a centre frequency of 60 MHz with a pulse length of 350 ns, and had a system performance of 140 dB (excluding antenna gain). This was somewhat below its previous specifications in Antarctica due to the use of 20 dB attenuation, which reduced problems of receiver saturation at the low altitudes flown. A list of system parameters for the SPRI Mk IV equipment is given in Table I, which also includes information on the 440 and 620 MHz systems used for Soviet radio echo-sounding in Spitsbergen (Kotlyakov and others, 1982). Navigation was by visual sightings on known points. Along-track fixing on larger valley glaciers was about 1 km in error at worst, and across-

TABLE I. PARAMETERS OF SPRI AND SOVIET RADIO ECHO-SOUNDING EQUIPMENT USED IN SVALBARD

System parameter	*Radio echo-sounding equipment* SPRI MkIV	RV-10,-17	RLS-620
Transmitter power (W)	300	7	820
Carrier frequency (MHz)	60	440	620
Pulse length (ns)	350	500	100-1000
Receiver bandwidth (MHz)	15	6	15
System performance* (dB)	160	130	146
Antenna type	single 1/2 wave dipole	two 1/2 wave dipoles	16 element triple square grid
1/2 power beamwidth (°)	100	100	18
Forward gain (dB)	2	2	19.5

*System performance excludes antenna gain and a 20dB attenuation used throughout Spitsbergen operations.

track deviations from the glacier centre-line were normally less than 0.5 km.

During 1980, radio echo-sounding results were recorded as range or "Z" profiles (Fig.1). No quantitative echo-strength measurements were made. Helicopter terrain clearance, ice surface, internal reflector, and bed echoes were digitized, and ice thickness was calculated using a velocity of radio waves in ice of 168 mμ s^{-1}. The ice surface elevations used in constructing glacier profiles were obtained from existing Norsk Polarinstitutt 1:100 000 scale maps of Svalbard. The Spitsbergen glaciers discussed in this paper are located in Figure 2. More detailed discussion of echo-sounding equipment, navigation, and reduction of data collected in 1980 may be found in Dowdeswell and others (in press).

RESULTS OF AIRBORNE RADIO ECHO-SOUNDING

Identifiable bed echoes were recorded for only 50% of the 740 track kilometres flown during 1980, illustrating the general difficulty of sounding ice at or near its melting point. However, in this paper discussion concentrates on those Spitsbergen glaciers where discrepancies have been observed between our own and Soviet ice thickness measurements. Results from some 31 further glaciers in Spitsbergen will be reported elsewhere (Dowdeswell and others, in press).

A range or "Z" profile from Negribreen is shown in Figure 1. Ice-surface and bed echoes are visible, together with an internal reflection varying between depths of 80 and 190 m beneath the surface. Bottom echoes are distinguished from layer echoes by position (i.e. the deepest reflector), and because they are usually stronger than internal echoes (e.g. Fig.1). Digitized and calibrated profiles from seven Spitsbergen glaciers are shown in Figures 3, 4, and 5. These range in size from valley glaciers such as Finsterwalderbreen (12 km long) to relatively large ice-cap outlet glaciers, for example Negribreen (35 km long). All glaciers except Austre Grønfjordbreen exhibit an internal reflecting horizon. Maximum recorded ice thicknesses for these seven glaciers are 430 m on Negribreen and 400 m for Kongsvegen.

Data obtained using other geophysical methods of ice thickness measurement are included in Figure 4, and Soviet radio echo-sounding results are presented in Figures 3, 4, and 5.

COMPARISON WITH EXISTING ICE THICKNESS DATA

Gravity and bore-hole measurements

Gravity surveys (Husebye and others, [1965]; Oelsner, 1966), yielding ice depths averaged over an area equivalent to ice thickness, are compared with glacier thicknesses measured from radio echo returns (Fig.4). For both Finsterwalderbreen and Kongsvegen, ice depths derived from gravity surveys and from 60 MHz radio echo-sounding rarely deviate by more than 25 m or 10% of glacier thickness. Drewry (1975)

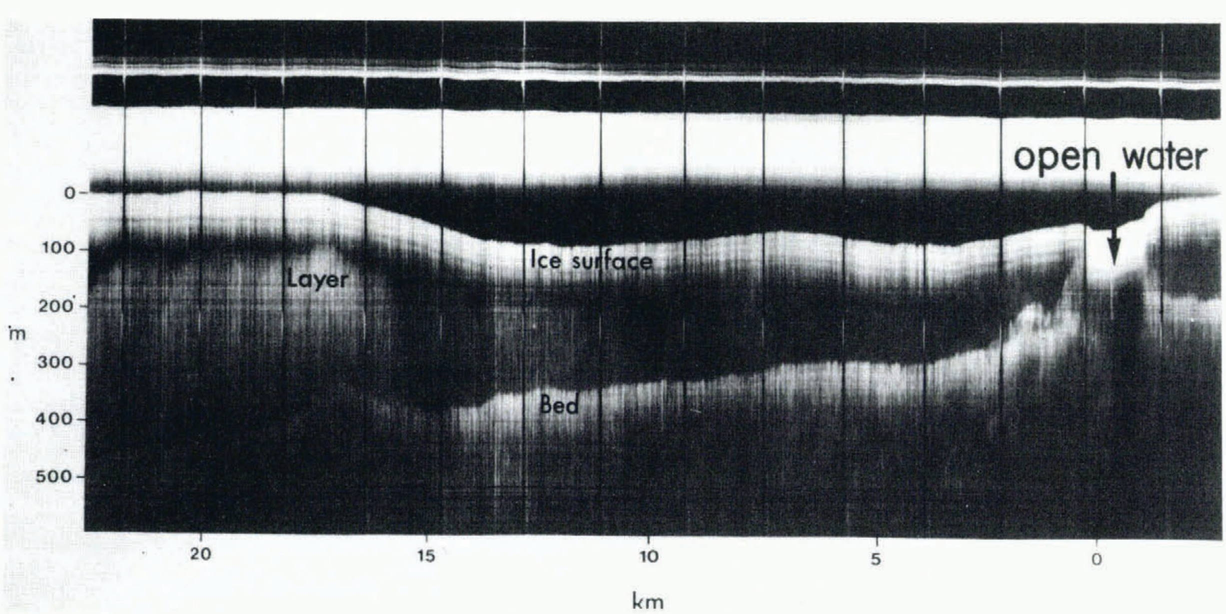

Fig.1. Radio echo-sounding range or "Z" profile of Negribreen from SPRI Mk IV 60 MHz equipment.

https://doi.org/10.3189/S0022143000008431 Published online by Cambridge University Press

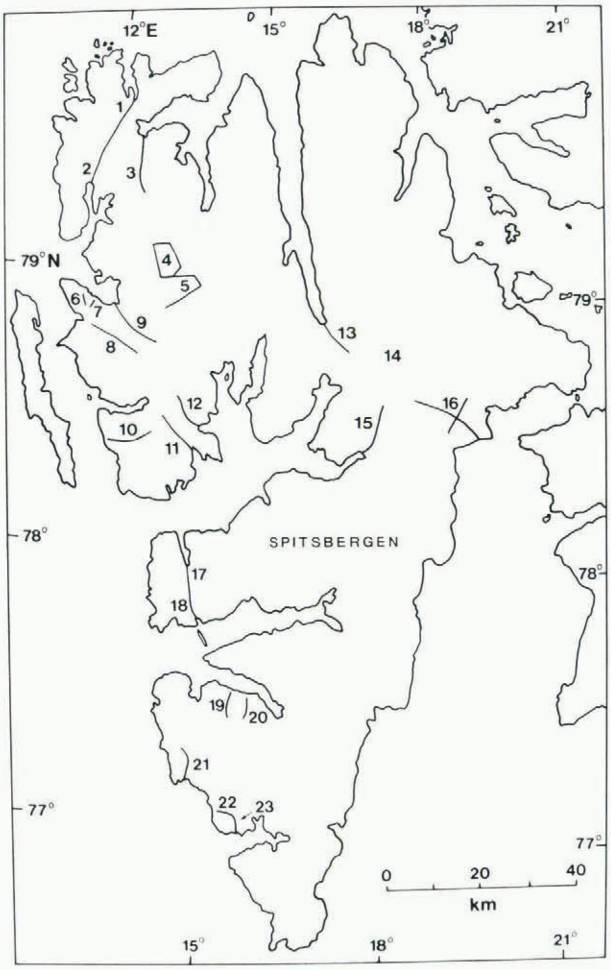

Fig.2. Map of Spitsbergen showing the location of glaciers and ice caps mentioned in the text. Airborne radio echo-sounding flight lines are indicated. 1-Raudfjordbreen, 2-Lilliehøøkbreen, 3-Monacobreen, 4-Isachsenfonna, 5-Holtedahlfonna, 6-Austre Brøggerbreen, 7-Midre Lovenbreen, 8-Uversbreen, 9-Kongsvegen, 10-Eidembreen, 11-Borebreen, 12-Wahlenbergbreen, 13-Mittag-Lefflerbreen, 14-Lomonosovfonna, 15-Tunabreen, 16-Negribreen, 17-Austre Grønfjordbreen, 18-Fridtjovbreen, 19-Finsterwalderbreen, 20-Penckbreen, 21-Vestre Torellbreen, 22-Werenskioldbreen, 23-Hansbreen.

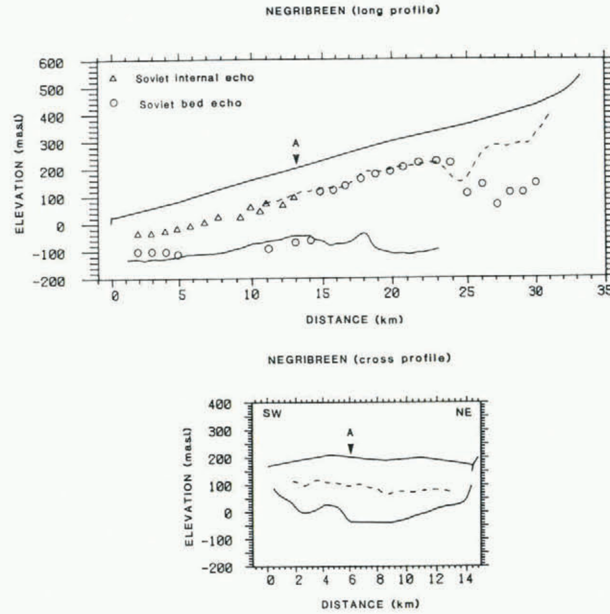

Fig.3. Reduced radio echo-sounding record of Negribreen, showing SPRI Mk IV 60 MHz surface and bottom echoes (solid lines) and an internal reflector (dashed line). The results of Soviet echo-sounding are also included. Soviet ice-thickness data were measured from continuous or intermittent profiles at 1 km intervals. The point A represents the crossing point between long- and cross-profiles of Negribreen.

has noted that in certain areas of the Antarctic differences between ice thicknesses derived from gravity and radio echo-sounding could be as much as 15-20%.

Thermal drilling on the ice divide between Austre Grønfjordbreen and Fridtjovbreen reached the glacier bed at 211 m (Zagorodnov and Zotikov, 1981), whereas echo-sounding with the SPRI Mk IV system in the vicinity of the drill hole recorded bed returns at 205 m (Fig.4). A second bore hole did not reach the glacier bed.

The limited, but independent, information available from other geophysical methods of ice thickness measurement therefore agrees with the results of 60 MHz echo-sounding to within 10% or better on Finsterwalderbreen, Kongsvegen, and Fridtjovbreen (Fig.4).

Evidence from Soviet radio echo-sounding

Soviet radio echo-sounding in Spitsbergen began in 1974, and ice thickness data for a relatively large number of glaciers have since been published (Macheret, 1976, 1981; Macheret and Zhuravlev, 1980, 1982; Macheret and others, 1980). Bed and layer echoes recorded by Soviet radio echo-sounding systems (Table I) are plotted in Figures 3, 4, and 5. All these glaciers, except Austre Grønfjordbreen and Fridtjovbreen, show significant discrepancies in ice thickness relative to the data collected in 1980. In every case the Soviet work *underestimates* glacier depth (Figs 3, 4, and 5). For example, Penckbreen is a maximum of 140 m thick according to Soviet data, but up to 240 m deep from our evidence (Fig.5). Further, ice thickness measurements by Macheret (1981) are only 30-60% of those from independent gravity surveys of Finsterwalderbreen and Kongsvegen.

Figures 3, 4, and 5 also show the correspondence between Soviet echoes assumed to represent the ice-bed interface and the internal reflecting horizons recorded by the SPRI 60 MHz system. More than 60% of Soviet bed echoes coincide closely with these internal echoes. However, on Fridtjovbreen and the lower part of Negribreen an internal echo is explicitly identified as such by Macheret and Zhuravlev (1982). It is almost exclusively in areas where a layer echo is recognized in Soviet work that SPRI Mk IV and Soviet systems record bed echoes at similar depths (Figs 3 and 4).

Further, several relatively large ice masses sounded by Macheret and co-workers, but not investigated during 1980, may also be subject to the mis-identification of bottom echoes, for two reasons. First, these glaciers appear thin (90-200 m deep) relative to their length (15-30 km). Second, internal echoes are not reported from them. Preliminary results of SPRI Mk IV 60 MHz radio echo-sounding during April and May 1983 confirm that the thickness of several more Spitsbergen glaciers has been underestimated considerably in Soviet work. These glaciers include Borebreen, Eidembreen, Lilliehøøkbreen, Monacobreen, Raudfjordbreen, Tunabreen, Uversbreen, and Wahlenbergbreen (Fig.2).

The presence of apparent depressions or rapid changes in bedrock elevation on certain glaciers was also inferred from Soviet radio echo-sounding records (Macheret, 1981). According to Macheret's data for

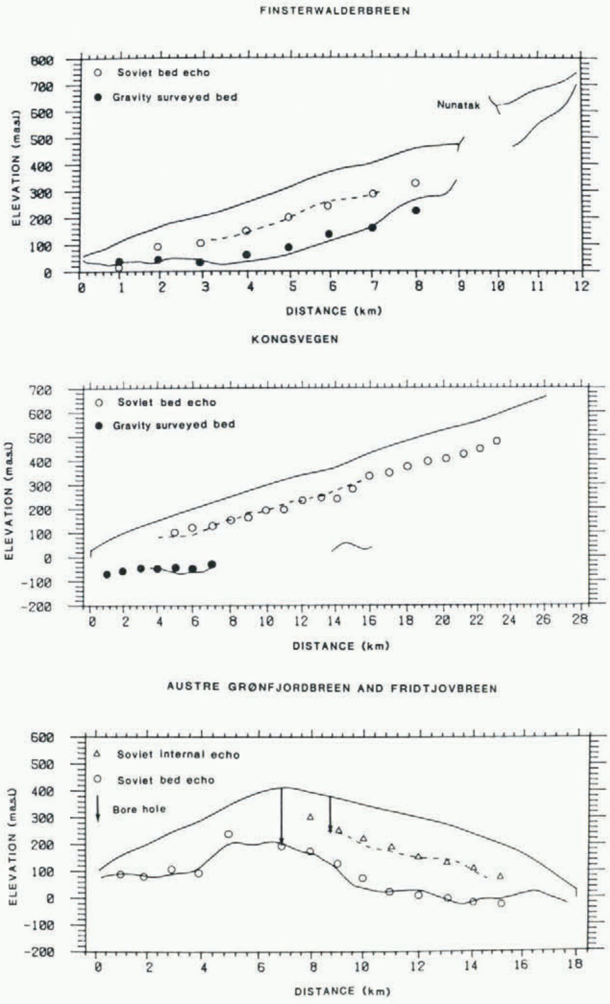

Fig.4. Reduced radio echo-sounding records for three glaciers where independent depth surveys have taken place. Gravity surveys are available for Finsterwalderbreen (Husebye and others, 1965) and Kongsvegen (Oelsner, 1966). Bore holes have been drilled on the divide between Austre Grønfjordbreen and Fridtjovbreen (Zagorodnov and Zotikov, 1981). Austre Grønfjordbreen is to the left of the ice divide. Soviet radio echo-sounding results are also shown.

Negribreen, bed elevation rises by over 200 m between 14 and 15 km up-glacier (Fig.3). However, the Soviet bed echo between 15 and 25 km from the glacier terminus closely follows an internal echo from the SPRI Mk IV system (Fig.3). It is suggested that the real bottom echo disappears from the Soviet record at approximately 14 km from the glacier terminus, and from there up-glacier an internal echo at a higher elevation was misinterpreted as the bed. Further, such rapid changes in bed elevation are improbable on glaciological grounds, since the glacier surface profiles do not reflect this presumed change. Similar problems may account for apparently rapid changes in bed elevation in the Kronebreen-Holtedahlfonna region and on Mittag-Lefflerbreen (Macheret, 1981).

Finally, it should be noted that close agreement (± 15%) exists between Soviet data and results from the 1980 season for several glaciers. Comparative profiles for Austre Grønfjordbreen and Fridtjovbreen are shown in Figure 4. Further examples are Austre Brøggerbreen, Midre Lovenbreen, Vestre Torellbreen and Werenskioldbreen.

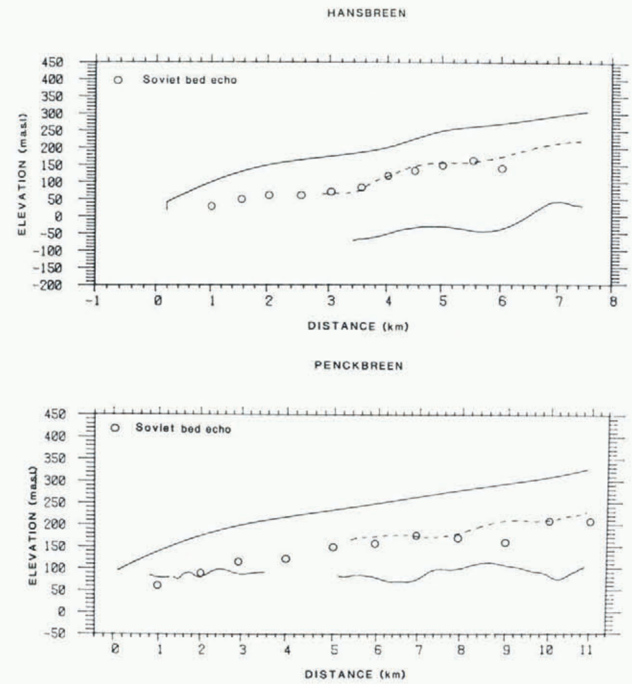

Fig.5. Comparison of SPRI Mk IV and Soviet radio echo-sounding data for Hansbreen and Penckbreen.

RADIO ECHO-SOUNDING OF SPITSBERGEN SUB-POLAR GLACIERS AT 60, 440, AND 620 MHz

The deepest ice sounded successfully by 620 MHz equipment was 540 m (Macheret, 1981), whereas the 440 MHz sounder had a maximum penetration of between only 150 and 250 m (Macheret, 1981; Macheret and Zhuravlev, 1982). The contrast in penetration between the two Soviet systems is due to the higher system performance and antenna gain of the 620 MHz equipment (Table I). The SPRI Mk IV sounder recorded a maximum ice thickness of 530 m on Holtedahlfonna during 1980.

The use of Soviet 440 MHz equipment to sound Svalbard glaciers more than 150-250 m thick could clearly lead to the misinterpretation of layer echoes as basal, since the true bed would be too deep to be recorded. This may explain the discrepancies between our own and Soviet sounding of Finsterwalderbreen and Kongsvegen (Fig.4), which were both sounded at 440 MHz during 1974 (Macheret, 1976).

The reasons for discrepancies between the results of 60 and 620 MHz sounding are less obvious because the two systems penetrate to approximately similar maximum depths. However, although the Soviet equipment has a higher system performance and antenna gain than the SPRI Mk IV (Table I) a layer echo, rather than the true bed, was generally recorded during 620 MHz sounding of Negribreen, Hansbreen, and Penckbreen (Figs 3 and 5).

Smith and Evans (1972) showed that absorption and scattering by surface melt water, soaked firn, ice layers and ice lenses increases with radio frequency. Their three-layer model was used to calculate signal attenuation resulting from such inhomogeneities for a glacier 250 m thick at -2°C. For example, the presence of a surface water layer 5 mm thick results in two-way signal attenuation of about 1.5 and 15 dB at 60 and 620 MHz respectively. Davis and others (1973), using 440 MHz equipment, observed a 10 dB weakening of returned signals during daytime sounding of an east Greenland glacier in the melt season. Model results also showed that attenuation by soaked firn and ice layers increased with radio frequency (Smith and Evans, 1972). Liestøl and others (1980) have described supraglacial lakes on several Spitsbergen glaciers during summer, and on Lomonosovfonna a soaked firn layer up to 2 m thick has been noted (Kotlyakov and others, 1980). Ice layers and lenses have also been observed during snow stratigraphic studies in Svalbard. For example, Ahlmann (1935) reported more than ten discrete ice layers of between a few millimetres and 0.5 m in thickness in several 5 m snow-pits on Isachsenfonna.

The 1980 echo-sounding with SPRI Mk IV 60 MHz radar therefore had two advantages over the Soviet 620 MHz system. It was conducted at a lower radio frequency, and flying took place before the start of the melt season, reducing the effects of absorption and scattering by inhomogeneities within and on the surface of Spitsbergen glaciers. Soviet sounding generally took place during the melt season.

PROBLEMS IN RADIO ECHO-SOUNDING OF GLACIER ACCUMULATION AREAS

Both SPRI Mk IV and Soviet echo-sounding equipment recorded bed echo returns only intermittently. In particular, Macheret (1981) reported the disappearance of 440 and 620 MHz signals in glacier accumulation areas and near ice divides on thicker glaciers. Bed echoes were only seldom recorded in similar areas during sounding at 60 MHz. For example, bottom echoes were noted for less than 20% of a 109 km fight over Isachsenfonna and Holtedahlfonna. Bottom returns also disappear in the accumulation areas of Negribreen and Kongsvegen (Figs 1, 3 and 4).

Measured 10 m temperatures on a number of Spitsbergen glaciers suggest that firn and ice in accumulation areas are often close to the pressure-melting point (e.g. Sverdrup, 1935; Baranowski, 1975). The high temperatures, along with liquid water and inhomogeneities associated with melting and refreezing, may partly account for the lack of success of both our own and Soviet equipment in sounding the accumulation zones of thicker glaciers.

Smith and Evans (1972) also showed that bottom returns can be obscured by the diffuse return from a multitude of scatterers. The masking of bottom-echo returns may be occurring preferentially in glacier accumulation areas if ice lenses and water inclusions (Watts and England, 1976) are more numerous in firn and ice at its melting point.

Scattering may also result from heavy surface crevassing, a phenomenon well known from Antarctic radio echo-sounding. Many Spitsbergen glaciers, especially those that surge, have large crevassed areas which may spread considerable distances up-glacier.

INTERNAL REFLECTING HORIZONS IN SPITSBERGEN GLACIERS

Internal reflections from depths of 70-180 m were reported by Macheret and Zhuravlev (1980). Reflecting horizons were recorded at between 70 and 190 m by SPRI Mk IV equipment, with about 70% of observations falling between 90 and 110 m depth (Figs 1, 3, 4, and 5). These layers are different from multiples of the ice surface echo. Only single isolated layer echoes were observed on any glacier, although it is not known whether a reflection corresponds to a single discontinuity in the ice or is integrated over the pulse length or wavelength of the radar (Harrison, 1973). The multiple layer echoes observed in the Antarctic and Greenland ice sheets have not been reported from radio echo-sounding studies of Spitsbergen glaciers. Further, comparison between spring and summer sounding by our own and Soviet systems indicates that these isolated layers are relatively constant in location, in contrast to the rapidly changing pattern of intraglacial reflectors interpreted as expressions of internal hydrological changes by Goodman (1973).

Internal reflectors could result from the presence of impurities (such as moraine or ash layers and chemical precipitates), fluctuations in ice density, bubble content, geometry and crystal axis orientation, the presence of brine, or changes in water content and temperature with depth.

Reflection coefficients cannot be used to estimate the possible causes of layer echoes because quantitative echo-strength measurements were not made in 1980. However, from visual inspection, bottom-echo returns were usually stronger than layer signals (Fig.1). This, along with the lack of an obvious debris source in many areas, indicates that the internal reflector is probably not a moraine layer. Ice cores from Fridtjovbreen (Fig.4) did not reveal any moraine layers, but transparent and impure ice was noted at depths of 50-85 m, 102-106 m, and 145-149 m (Zagorodnov and Zotikov, 1981). Macheret and Zhuravlev (1982) also reported preliminary ice-core data suggesting that ice with a water content of 1-2% was present at depths greater than 115 m, which coincided with the height of the internal reflecting horizon in this area of the glacier. The layer echo might therefore be associated with ice at the pressure-melting point. However, more ice-core drilling, together with data on radio echo signal strengths and reflection coefficient calculations, is needed to provide additional evidence concerning the interpretation of these layer echoes.

CONCLUSIONS

The results of radio echo-sounding of certain Spitsbergen glaciers at 60 MHz show that previous investigations using 440 and 620 MHz radar systems (Macheret, 1981; Macheret and Zhuravlev, 1982) have underestimated ice thickness by two to three times. An unambiguous bed echo, with significant lateral continuity, has been identified consistently from 60 MHz records at greater depths. This conclusion is confirmed by: (1) the agreement (± 10%) between 60 MHz-derived ice thicknesses and independent gravity surveys on two glaciers, in contrast to Soviet ice depths which are only 30-60% of gravity thicknesses; (2) the strong correlation between echoes interpreted as bottom returns by Macheret and co-workers and echoes from an internal reflector in our own study; (3) the unusual glacier morphology required by Soviet results (i.e. very thin glaciers relative to length, and sudden bed depressions unrelated to ice surface topography). Where a layer echo was explicitly recognized as such by Macheret and co-workers there is good agreement with our ice thickness estimates. Preliminary analysis of 60 MHz sounding conducted during the spring of 1983 shows that Soviet results underestimate the thickness of several more Spitsbergen glaciers. Such errors imply that Macheret and Zhuravlev's (1982) calculation of the ice and water resources of Svalbard is inaccurate.

The lack of penetration by Soviet echo-sounding equipment has probably resulted from the higher frequency of their radar systems, given the relatively high temperatures and surface and internal inhomogeneity of Spitsbergen glaciers. Both absorption and scattering increase with radio frequency, and the use of 440 and 620 MHz equipment, together with the presence of melt water during summer sounding, may explain the lack of penetration relative to investigations using 60 MHz radar. This finding implies that lower-frequency (V.H.F.) equipment has certain advantages over U.H.F. radars in sounding relatively thick ice at or near its melting point, although resolution remains poorer at lower frequencies.

Interpretation of the internal layers reported in this study and Soviet work remains equivocal. Further ice-core drilling, along with detailed echo strength measurements, should lead to a better understanding of the internal structure of Spitsbergen glaciers.

ACKNOWLEDGEMENTS

This research is part of a continuing cooperative glaciological research programme in Svalbard involving the Scott Polar Research Institute, Cambridge, and Norsk Polarinstitutt, Oslo. We wish to thank Store Norsk Spitsbergen Kullkompani for assistance in Longyearbyen and with field operations. Dr C.S. Neal prepared the radar equipment and took part in field work. SPRI funding was provided by United Kingdom Natural Environment Research Council (NERC) Grant GR3/4463 to Dr D.J. Drewry. J.A. Dowdeswell acknowledges support from a NERC Studentship.

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MS. received 24 May 1983 and in revised form 1 August 1983