GPR investigations of glaciers and sea ice in the Scandinavian Arctic

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Abstract

Recent GPR studies of ice have been carried out on glaciers in Svalbard, Norway and Sweden, and also on saline ice in the Baltic Sea, Greenland Sea, and Arctic Ocean. We have used Malå Geoscience and GSSI radar systems with antenna centre frequencies of between 50 and 500 MHz. Long time windows are necessary for receiving echoes from glaciers several hundreds of metres in depth. The 50 MHz Malå antennas clearly detected a bedrock return from glaciers where the ice was close to 0 °C up to depths of about 300 m. The data from these soundings on polythermal glaciers has been unexpectedly informative of the internal structure of glaciers, mapping features such as the boundary between water saturated ice at 0 °C, and colder ice containing no water bodies. The sub-glacial drainage systems of glaciers have been investigated and the potential exists for mapping large internal hydrological features. On the moderately saline ice of the Baltic Sea in the Gulf of Bothnia, helicopter and ground based surveys have been used in conjunction with other geophysical techniques to investigate ice dynamics and forces over a period of 2 weeks. The radar seems to penetrate easily the 1–2 m thick ice normally present in the Baltic, but is much less useful over ice ridges where ice floes collide. In the Arctic Ocean where water salinity is much higher, but the ice is thicker and older and sometimes quite well drained of brine, we have had mixed success.

Keywords: Glacier, Sea Ice, Arctic, Baltic Sea

1 Introduction

In contrast to most materials, cold ice is relatively transparent to radar waves, and in glaciology 'deep' penetrating radars have been used since the 1950s to map the bedrock beneath glaciers and ice sheets – to depths as great as several kilometres (e.g. Bogorodsky et al. 1985). These radars were specially designed for glaciology and often required skilled use and expert maintenance. However a new generation of reliable factory-made ground penetrating radars (GPR) have been used for glaciology work. These radar's do not have the capability to penetrate very deep. They have also been used to study internal features of glacial flow (Murray et al. 1997). In this connection, interest in the radar properties of the uppermost firn and ice layers is restricted to determining their radar velocity, which affects the depth calculation.

However, there are other reasons to be interested in the near-surface layers. Shallow or ground-penetrating radar (GPR) has been used to determine accumulation rates by finding datable reflecting horizons in Antarctic firn (Forster et al. 1991), and on temperate glaciers (Holmlund and Richardson 1995, Kohler et al. 1997). In addition, the dielectric properties of near-surface snow, firn and ice are important for interpreting SAR satellite images (Rott et al. 1993), particularly with the emergence of SAR techniques as an important glaciological tool for monitoring ice sheet elevations and flow patterns.

The penetration of radar waves in sea ice is extremely limited because of the absorption of the radar signal by the salty water present in sea ice. However in the low salinity sea ice of the Baltic Sea we expected that we may have more success, or at least be able to observe any snow ice formed on top of the sea ice. This would compliment other techniques of determining sea ice thickness such as low frequency EM sounding or manual drilling.

2 Case studies

1.1 Polythermal Glaciers on Svalbard

Spitsbergen glaciers are traditionally classified as the sub-polar or polythermal type in respect to their thermal structure (Schytt 1969, Baranowski 1977). They have a thick layer of cold ice (with temperatures below the pressure melting point) in their superimposed ice accumulation and ablation zones, underlain by temperate ice at the pressure melting point. In the firn accumulation zone the whole thickness of the ice is temperate with only the winter cold wave lowering the temperature of the near surface firn below freezing. The large difference in dielectric properties of ice and water make radar sounding a useful tool in discriminating ice containing water and ice that is dry – i.e. cold ice. Although the radar reflection in the ice may not correspond precisely with the pressure melting point in the glacier, due to the relative size of the water bodies and radar wavelength (e.g. Ødegård et al.

1997), or to the possibility of water bodies existing in cold ice. The general scheme of sub-polar glacier structure has been confirmed by airborne radar sounding (RES) by Soviet (Macheret and Zhuravlev 1982) and British-Norwegian groups (Dowdeswell et al. 1984). The majority of glaciers in Svalbard were overflown by one or other of the groups. Ground based radar soundings have provided a more detailed and complex picture of the thermal structure of some of these glaciers, (e.g. Holmlund and Eriksson 1989, Hagen and Saetrang 1991, Bjornsson et al. 1996, Ødegård et al. 1997), in some cases cold ice dominates and only the glacier sole is at the pressure melting point.

1.2 Hansbreen

Approximately 100 km of radar data were collected on Hansbreen in co-operation with the Polish Polar Base in Hornsund in May 1997. A typical section of 50 MHz RAMAC GPR data from Hansbreen is shown in Figure 1. Data were collected as 2048 samples in a time window of 5.303 ms, stacked twice on collection at a resolution of 1 scan per meter controlled by a sledge wheel. The radar was pulled 4 m behind a snowmobile, with data collected on a Husky PC. The internal RAMAC batteries were supplemented by an external lead acid accumulator giving enough power for full days of measurement. No problems were noted even in air

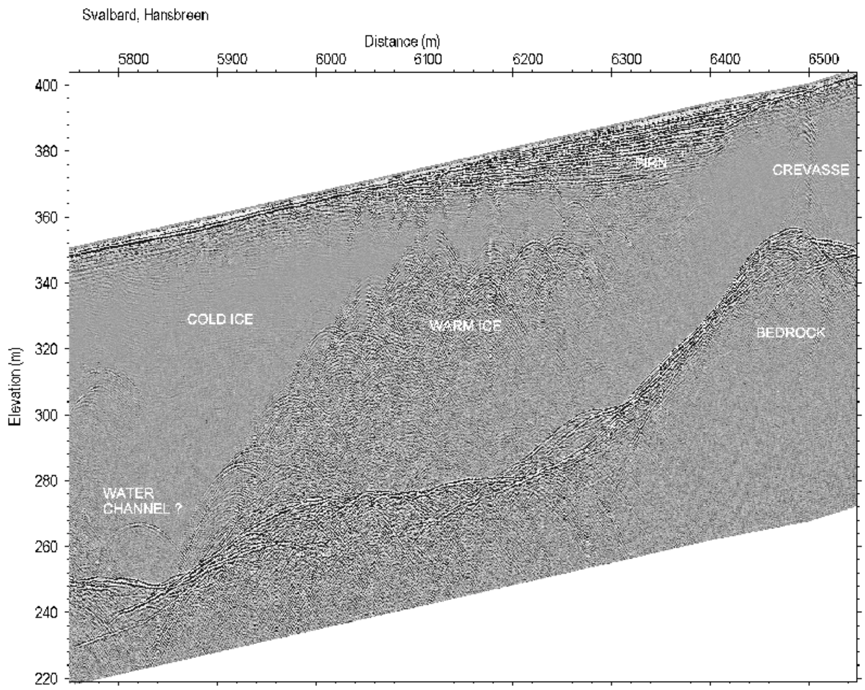

Figure 1. Elevation corrected topography of part of Hansbreen with RAMAC 50 MHz antennas.

temperatures as low as –30 °C. The character of reflections is typical of firn between about 6000–6500 m, warm ice associated with much scattering and cold ice with down dipping foliations between 5750 m to the intersection with the warm ice at 6050 m can be seen. A large hyperbolic reflection at 5800 m at 85 m depth is probably a water channel or pocket. A series of sharp hyperbolic reflections near the surface at 6500 m is probably caused by crevasses associated with the bedrock high and change in surface slope.

2.3 Brøggerbreen melt-water tunnel

Brøggerbreen is a small polythermal glacier in northern Svalbard. In the ablation zone near to the front of the glacier there is a large surface moulin about 5 m in diameter that is one of the main drainage features of the glacier. In May 1997 we profiled the glacier around the tunnel and mapped the moulin as it turned from the vertical and crossed the glacier to the close to the side margin. A series of reflections can be seen that corre-

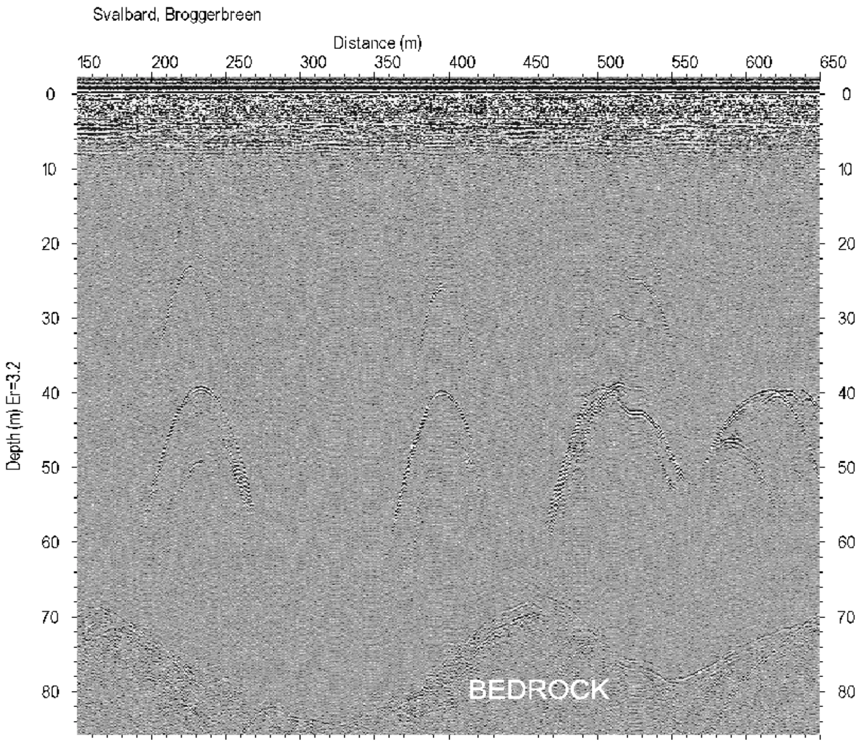

Figure 2.The melt water feature on Brøggerbreen, the path of the radar was a spiral and shows the same feature at increasing distances from the surface moulin measured with RAMAC 200 MHz antennas.

spond to the tunnel as we drove in a complex roughly spiral route from near to the surface moulin to further away. Positions were independently measured by differential GPS and will be processed to reveal the three dimensional path of the melt channel. data were collected using RAMAC 200 MHz antennas collecting 1024 samples in a 848 ns time window collecting 5 traces s^{-1}. It is clear that large meltwater hydrological systems of glacier can be mapped with the GPR.

2.4 Snow depth on Storglacierien

Storglacierien is a small polythermal glacier in northern Sweden. It has been extensively investigated for the past 50 years, and is regularly studied and measured for mass balance records. We investigated the usefulness of the RAMAC GPR in profiling the near surface snow at 400 MHz to determine if the radar could be used for winter snow thickness measurements in April 1996 (Figure 3). We used a time window of 250 ns with 512 samples and a trace taken every 0.1 m. There is clear evidence of laying visible and it is possible to assign summer surfaces to particular years when comparing the radar data to traditional mass balance techniques such as manual probing to feel the icy summer surface, or by drilling cores and digging pits. Similar work on Hardangerjokullen (Kohler et al. 1997) also showed the potential of radar to determine snow thick-

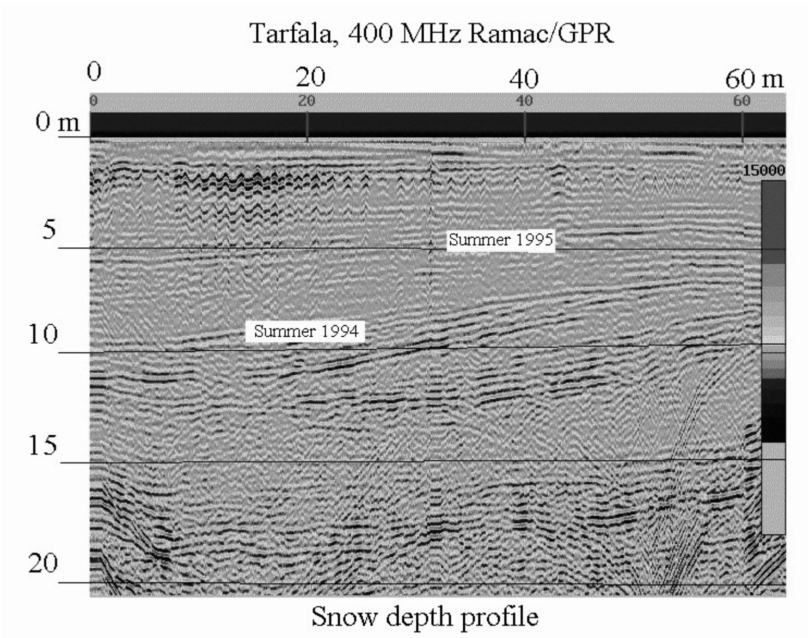

Figure 3. Snow thickness estimates found by identifying summer ice surfaces with the RAMAC 400 MHz antennas using a wave velocity of 220 m μs^{-1}.

ness, but it is extremely important to have adequate radar velocity data from profiles of snow density to constrain radar travel times to depths with good accuracy. This constraint means that radar surveys for snow thickness measurements can provide a complimentary method to be used in addition to more traditional techniques, it cannot replace it on its own. The modelling of radar reflections from the upper 10 m of Kongsvegen glacier in Svalbard has been attempted (Moore et al., in press), using dielectric data obtained from ice cores along radar profiles. Modelling does not show very good fits to radar data, which can be most easily interpreted by real variations in ice properties over the metre scale distances sampled by the wide angle GPR radar beams when compared with the 10 cm scale variations seen from a single ice core drilled in the beam area.

2.5 Baltic Sea Ice

The Bay of Bothnia is located at 63–66°N, 20–26°E. Its surface area is 37,000 km^2 and the mean depths vary between 43 m and 147 m. The water has a very low salinity, in general in the central basin the surface water salinity is 3.5 ppt. Sea ice occurs annually in the bay of Bothnia for 5–7 months and every winter the bay becomes totally ice covered. Maximum ice thickness in the coastal fast ice zone is 50–120 cm. In February 1997, as part of the EU funded ICESTATE project a large field program ZIP97 was carried out in the northern Bay of Bothnia (Haapala and Leppäranta 1997). Radar sounding was done on the ice using all terrain vehicles pulling a sledge, and also from a helicopter. The objective was to study the potential of the GPR systems to determine sea ice thickness from an airborne platform with two different radar systems: the RAMAC GPR with 200 MHz antennas and the GSSI SIR8 with 200 and 500 MHz antennas.

The large experiment allowed comparisons of radar derived thickness measurements to be compared with ground based drillings along an 8 km calibration line from the shore to the edge of the fast ice zone. The calibration line was measured three times with different antenna configurations. On the basis of the data from the calibration line, it was decided that the 500 MHz antennas gave the best data to use on the drift ice. Helicopter flights were made over a set of drifting buoys in the drift ice with the SIR 8 500 MHz antennas, and partially with the other antenna systems. Flight altitudes varied from 6 to 8 m and speed was 13–30 ms^{-1} depending on wind direction. The GSSI 200 MHz data were taken at 512 samples in a 400 ns time window at 25.6 scans s^{-1}, the 500 MHz data were taken over a 160 ns time window at 51.2 scans s^{-1}

Clutter from constant reflections from the helicopter was established for each profile by flying to 100 m altitude at which height no reflections from the ground were collected, allowing subtraction of the constant background.

In general the flat ice gave clear continuous reflections (Figure 4), but where ice floes had drifted to form ridges up to 10 m in height composed

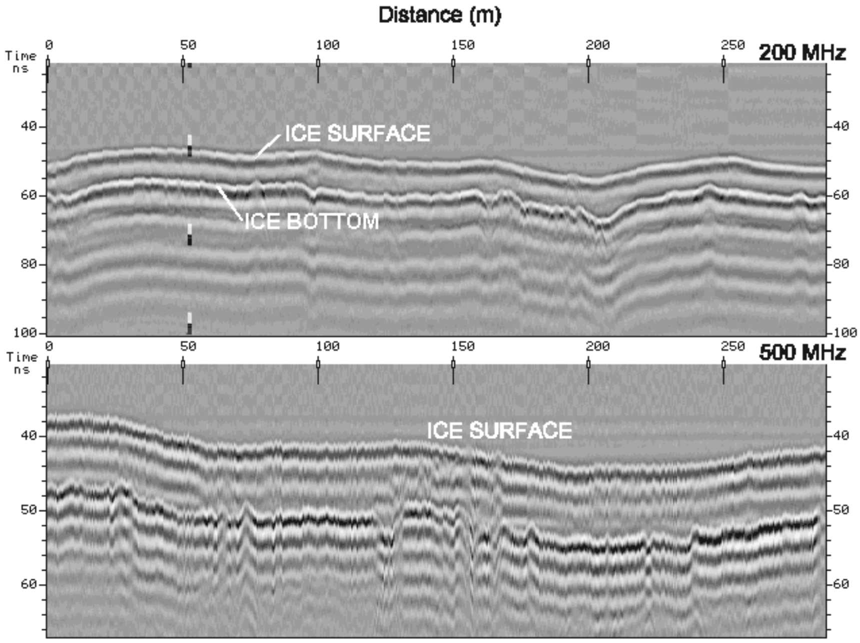

Figure 4. Helicopter-borne radar profiles over fast ice in the Baltic Sea, Gulf of Bothnia with GSSI SIR 8 200 MHz and 500 MHz antennas. The ice thickness is about 60 -70 cm assuming a velocity of 160 m μs^{-1}.

of a mass of loosely bonded ice blocks, the scattering from the blocks caused no real penetration of the ridges. One significant problem for interpretation is that in some places layers of ice are folded over each other leaving some cm of water between them. The water causes much attenuation of the radar signal and much scattering from the stacked ice floe surfaces also occurs, so it is possible that sometimes internal reflections from within the ice pack are interpreted as being the floe bottom. However in general comparison with the calibrations from drilling suggest that the radar gives rather good quality thickness data for relatively undisturbed parts of the Baltic sea ice cover.

3 Conclusion

Modern GPR radars provide excellent detail in resolution because of their monopulse nature. The low conductivity and low water content of cold glaciers allows penetration depths sufficient to reach bedrock for many glaciers with 50 MHz antennas. The digital acquisition of data also allows much processing and removal of clutter so allowing subtle features such as the sea ice bottom reflection to be extracted from the larger signals coming from the helicopter carrying the radar. GPR is especially suited to the polythermal or cold high polar glaciers where penetration is considerably better than in temperate wet glaciers as we have found from radar surveys of Gornerglacier in the Swiss Alps. The contrast in dielectric impedance between warm wet ice and cold ice causes reflections that are very easy to see and provides extremely valuable data in glaciological studies of the hydrology and structural evolution of glaciers.

Acknowledgements

We thank the Thule Institute for financial support for the radar and for AP salary, the CEC MAST III contract MAS3-CT95-0006 supported the sea ice work, Finnish Academy grant 51854 and the TMR Programme of the CEC through the Ny Ålesund LSF supported the Svalbard work.

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