Ground Penetrating Radar Surveys for Detailed Glaciological Investigations in the Polar and Himalayan Regions

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Non-invasive imaging of land through ice sheets has provided huge steps forward in the mapping and understanding of these features since the 1980s. Historically, airborne Radio-Echo Sounding (RES) has been undertaken over cold dry polar ice sheets, which are virtually transparent to radiowaves, and depths of investigation of up to 5 km are not unknown. Since then, developments in radar equipment and analytical techniques have enabled the derivation of other significant information about the structure, composition, layering and dynamics of these major ice masses and related physical processes. The first use of impulse radar (Ground Penetrating Radar; GPR) for glaciological purposes was in the early 1970s. Since the mid-1990s, there has been huge growth in the use of commercial GPR systems in particular over temperate glaciers, which are at their pressure melting point. RES systems were first deployed from large aircraft in Polar Regions. GPR systems were originally used in ground-based investigations of temperate glaciers and have been used with increasing benefit in similar ways in Polar Regions. However, GPR systems are now being mounted onto helicopters for

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use in rugged mountain environments, such as in the European Alps and the Indian Himalaya. By examining the radar characteristics of key glaciological features in both Polar and Himalayan regions it is possible to design optimal radar surveys for a variety of glaciological applications. Such surveys, such as may be undertaken in the Indian Himalaya, can produce information that is key to climate change monitoring, measuring glacier volume fluxes, enhanced mass balance estimations, and that forms a high-quality baseline against which changes over time can be measured.

Keywords: Chhota Shigri Glacier, crevasses, Ground Penetrating Radar, Radargram, Rutford Ice Stream, sub-glacial landform

INTRODUCTION

The investigation of Polar ice sheets using radio-waves (Radio-Echo Sounding – RES) from aircraft began in earnest in the early 1960s and led to major steps forward in the mapping of such features, with the discovery of whole mountain ranges buried beneath the ice. Analysis of reflections within the ice itself provides important information about the structure and dynamics of the ice sheets. The use of large aircraft has been critical to cover large areas of otherwise inaccessible terrain quickly and efficiently.

The advent of commercial Ground Penetrating Radar (GPR) systems since the mid-1990s with operating frequencies in the range 50-700 MHz, has enabled ground-based glaciological investigations to image through smaller temperate glaciers as well as Polar glaciers. The majority of these systems do not have the power to operate from aircraft and by having to be deployed on the ground, field expeditions can only investigate small areas of glaciers where access is possible. However, the development of GPR antennae in the last few years that can be used from aircraft as air-launch systems has brought the benefits of commercial GPR systems to airborne deployments. This now enables fast ground coverage with rapid data acquisition by using highly manoeuvrable helicopters, which have the operational flexibility to access valley glaciers at low flying heights. Consequently, a whole new range of glaciological investigations is now possible.

Summaries of GPR and other geophysical techniques have been provided by Hubbard and Glasser (2005), Jol (2009), and Reynolds (2011); and of geophysical exploration and remote sensing by Reynolds (2012). The use of RES of Polar ice sheets has been reviewed by Bogorodsky et al. (1985), developments including

GPR for glaciological applications have been discussed in detail by Allen (2008), Arcone (2009), and in a dedicated issue of the Annals of Glaciology, 50(51) in 2009, for example.

The objectives of this article are twofold: firstly, to introduce the principles of RES and of GPR in glaciological applications in the Polar and Himalayan regions; and secondly, to identify prospective glaciological applications of airborne GPR in the Indian Himalaya.

RADIO ECHO SOUNDING

Both RES and GPR use the principle of measuring the time it takes for a pulse of radio-waves to travel from a transmitter to and into the ground or glacier and be reflected back to a receiver as depicted schematically in Figure 1. The speed with which radio-waves travel through air is that of the speed of light (300 mm/ns), but radiowaves slow down when passing through materials with a dielectric constant

![](image-url)

Fig 1. Schematic illustration of the principle of Radio-Echo Sounding (adapted from Allen, 2008).
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greater than one. Polar ice in particular is virtually transparent to radio-waves and as long as the transmitter is designed appropriately and the system has sufficient power, then radio-waves are able to penetrate through the thickest Polar ice sheets.

As the aircraft flies along a designated route, the radar system is triggered at fast repetition rates and at each point a two-way travel time trace is produced. A radargram comprises adjacent and subsequent traces as the aircraft travels over the ground and represents a time-picture of the sub-surface as shown in Figure 1. The radio-wave velocity through ice \(V_I\) is generally around 167 mm/ns, and by using this velocity measurements of the two-way travel time can be converted to depth below the surface by using the expression \(d = \frac{V_I t}{2}\) where \(d\) is the depth, and \(t\) is the two-way travel time.

GROUND PENETRATING RADAR (GPR)

As with RES, GPR comprises of a signal control unit and transmitter and receiver antennae, which may be mounted inside a single module to form a monostatic antenna unit or as two separate (bistatic) antennae a fixed distance apart. For ground-based surveys the antennae can be deployed by being towed behind a vehicle (e.g. snowmobile) or hand-carried. The British Antarctic Survey has developed a low-frequency ground-based GPR system, which was used to acquire data over the Rutford Ice Stream in West Antarctica, as part of a series of closely-spaced transects; an example radargram is shown in Figure 2. The base reflector was interpreted on each radargram and used to generate a 3D interface that indicates the sub-glacial landform (King et al., 2008).

Not only can commercial GPR systems be used over solid ground but they can also be used from rubber dinghies over fresh water such as lakes. A 100 MHz system was used at Tsho Rolpa, Rolwaling Himal, Nepal, and profiles acquired over shallow glacial lakes. An example radargram (Figure 3) shows the base of the lake and coarse bouldery supra-glacial moraine overlying stagnant glacier ice. It is thought that preferential melting associated with a former crevasse has led to the accelerated lowering of the glacier surface and the submergence of the surface beneath the lake water.

There is a wide range of commercial GPR systems now available with a comprehensive selection of antennae with different centre-frequencies. Most are specifically designed to be used in contact with the ground. However, there have been significant developments in recent years to be able to deploy air-launch antennae from aerial platforms (fixed-wing aircraft and helicopters). This now permits the use of GPR systems from aircraft.
HELIÇOPTER DEPLOYMENT

One manufacturer of airborne GPR systems is Radarteam, Sweden, who produces antennae with centre-frequencies at 65 MHz, 83 MHz, 106 MHz, and 334 MHz, all of which can be used from airborne platforms, such as shown in Figure 4. These antennae have been used extensively for glaciological applications especially in Scandinavia and Europe and have started to be used in the Indian Himalaya. The specially-designed antennae are mounted beneath the fuselage of the aircraft partly for logistical reasons but also to help shield the antennae from the rotor blades reflecting radar energy, which would cause reflection flicker. In all cases thus far, only one set of antennae have been used at a time although it is possible to use up to four sets of antennae in a multi-channel data acquisition system. Navigation data are provided either from the aircraft's GPS or via a dedicated Inertial Monitoring Unit that can position the aircraft and measure its flying aspect (pitch and yaw) very accurately (to within 5 cm following post-processing). It is also possible to deploy other sensors simultaneously with multi-channel GPR antennae, such as LiDAR and ortho-photographic equipment. Details of these sensors lie outside the scope of this article.

Whereas RES is undertaken predominantly from fixed-wing aircraft (e.g. Hercules C-130, de Haviland Twin Otter/Dash 7), helicopters afford a much more manoeuvrable platform in the constricted flying space associated with high-altitude mountain ranges such as the Himalaya.

Fig 4. (a) Single GPR high centre-frequency (334 MHz) monostatic antennae module mounted beneath a helicopter for airborne radar acquisition over glaciers in Switzerland. (b) Helicopter-mounted bistatic low centre-frequency (65 MHz) antennae used for monitoring volcanoes. (Photos courtesy: Radarteam, Sweden).

PROSPECTIVE GLACIOLOGICAL APPLICATIONS IN THE HIMALAYA

A helicopter-mounted GPR survey of glaciers in the Indian Himalaya can be conducted in the context of other, independent, data such as can be obtained from remote sensing imagery (optical and synthetic aperture radar). Details of these methods lie outside the scope of this article. However, there are two key applications for which helicopter-deployed GPR can be used very effectively, namely, glacier mapping and glacier hydrology and these will be discussed in turn.

Glacier mapping

The essence of mapping glaciers is to define the areal extent, surface elevation, thickness and volume of each glacier at a given date in time. This serves as key baseline information against which subsequent surveys can be compared in order to determine any changes and potential rates of change as a function of time. It also complements the mapping of Indian glaciers that has already been undertaken (Raina and Srivastava, 2008), which lists details of 9,575 individual glaciers. However, very few glaciers have had the benefit of very detailed investigations, either airborne or ground-based. Consequently, the scope for helicopter-borne multi-sensor glaciological investigations is considerable.

Five aspects of glacier mapping have been identified, each of which will be addressed briefly in turn:
1. Glacier surface morphology
2. Structural glaciology
3. Glacier thickness
4. Glacier volumes
5. Snow and firn detail.

Glacier surface morphology: The first task is to define the areal extent of each glacier within an individual glacier system but this may not be as simple as it first appears. Firstly each glacier might comprise a number of glacier tributaries that feed into the main glacier tongue and parts of the glaciers may be debris-covered. Each needs to be defined as each might behave differently to climatic forcing and ambient mass balance conditions. Therefore, to understand each glacier surveyed, it is essential to define the components of each glacier system. It is assumed for the sake of this discussion that access to high-resolution optical remote sensing imagery is available to provide the spatial context of each glacier surveyed.

The first task is to map the lateral extent of the glacier system using the GPR in conjunction with surface imaging data (e.g. remote sensing imagery). Digital Elevation Models (DEM) can be obtained from stereo satellite images, aerial photographs and/or LiDAR data. To aid this mapping, it is important to use
information about the glacier surface landforms to identify key morphological indicators of the boundaries of the constituent glaciers, such as medial and lateral moraines, flow lines, debris trains, etc. The glacial morphology (Benn and Evans, 1998, pp. 15-25) helps to define the components within each glacier system (see also Hubbard and Glasser, 2005, Chapter 9).

The remote sensing imagery provides the local context to help define catchment boundaries and gross morphology while the helicopter-borne instrumentation provides the very-high resolution information from which the detail can be extracted. Where there is snow cover that conceals some diagnostic features, the GPR radargrams can be interpreted to help identify key features (medial moraines, crevasses, etc.) (Reynolds, 2000).

**Structural glaciology:** One aspect of the mapping of glacier systems that is predominantly overlooked and hence under-utilised is the analysis of the structures within the glacier system. These relate to the overall composition of the glacier system, with its various tributary glaciers and sub-units, and their inter-relationships. As part of the mapping of each glacier the individual flow units need to be defined (Reynolds and Hambrey, 1988). This can be done using the remote sensing and ortho-photography by observing the surface morphology but also by using the GPR data to identify key internal features such as the interface between the snow/firn layers and the underlying glacier ice, and the base of the glacier as well as more vertically orientated features such as inter-flow-unit shear zones, and medial moraine boundaries. Furthermore, details from the surface crevasse fields are important in compiling the overall 3D structure of a glacier system.

The only known example of a structural glaciological study in a commercial project was that undertaken at Trakarding Glacier, in Rolwaling Himal, central Nepal (RGSL, 1999). The primary sources of information were vertical and oblique hand-held photographs taken from a specifically-chartered helicopter (Fig 5). The results were used to help assess the glacial hazards downstream from the main glacier but within a large body of debris-covered stagnant glacier ice in which pre-existing structures were being reactivated by thermokarst processes (Richardson and Reynolds, 2000a).

The structural glaciological analysis is useful to determine the individual flow units (e.g. Figure 6a) and to help determine surface and internal structures that would affect the glacier hydrology and flow behaviour (Figure 6b) (RGSL, 1999). By knowing more about the constituent flow units within a glacier system it is possible to make better correlations with changes with time to the affects of climate change. The traditional over-simplistic determination of ice front positional change is often misleading and inaccurate as different parts of a glacier system can respond in different ways to aspects of the same climatic signal.

The reason that Trakarding Glacier ice front is so irregular (Figure 6) is that it comprises a complex structure arising from at least three different constituent flow units, each of which is behaving differently dynamically, as influenced by the

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Fig 5. Collated vertical aerial photographs (top) taken from a helicopter over the northern edge of part of Trakarding Glacier, Rolwaling, Nepal, with the structural glaciological analysis interpretation (below). (RGSL, 1999).

Fig 6. Structural glaciological results for the snout of Trakarding Glacier as viewed from (a) the south and (b) the north. Letters A, B and C denote individual flow units in Trakarding Glacier, which flows from right to left in (a); P denotes a supra-glacial pond. A boulder (circled) can be identified in both images. Numbers 1 and 2 denote open and closed crevasses, respectively in (b). (RGSL, 1999).
individual accumulation zone characteristics (shape, aspect, constrictions, slope, etc.).

While the surface morphology and DEM can be determined using LiDAR and ortho-photography (if available), details of the internal structure can be obtained using the GPR data (Arcone, 2009; Reynolds, 2000, 2006; Hambrey et al., 2008). The first pass analysis would be to determine the interfaces between the firm and the glacier and the base of the glacier. However, subject to data quality it might be possible to obtain information about the basal units within the glacier and the nature of the glacier sole (debris bands, debris, water, structures, etc.). In addition, where radar profiles cross a glacier key vertical structures, such as medial moraines and flow unit boundaries, can also be investigated and imaged.

Glacier thickness: The only way to determine glacier thickness non-intrusively is by using geophysical methods such as GPR. At its most basic, each antennae pair would produce a radargram along each profile flown. Each radargram can be processed and interpreted separately with each being the focus of different depth ranges and vertical resolutions as a function of their respective frequency bandwidths.

Prior to any interpretation and generation of outputs it is essential that the radar data are suitably processed to produce the most interpretable data sets. The use of migration techniques, for example, can assist in clarifying basal reflections (Welch et al., 1998). However, any radar investigation of glaciers should take into account the fundamental electrical and dielectric properties of ice (Reynolds and Paren, 1980, 1984) and the geometrical constraints of laterally-restricted valley glaciers (Azam et al., 2012).

Whereas Polar ice masses are virtually transparent to radio-waves, as soon as there is free water present, absorption and attenuation of radio energy can occur due to the large dielectric constant of water (81) compared with glacier ice (3.2) and air (1). Consequently, GPR surveys of temperate or polythermal glaciers can be adversely affected by the presence of water, which has for many years restricted the application of GPR investigations of temperate glaciers.

Binder et al. (2009) have given an example of the use of a 20 MHz GPR system to map the base of a temperate glacier in the Eastern Alps in Austria. They were able to produce a map showing interpolated bedrock elevations merged with surface DEM data, thus demonstrating the use of GPR data combined with surface DEM information, from which a glacier volume was estimated.

Azam et al. (2012) have described the use of a very-low frequency (4.2 MHz) ground-based GPR system to acquire five profiles over the Chhota Shigri Glacier in Himachal Pradesh. They successfully imaged the base of the glacier through up to 300 m of temperate ice. Such low-frequency antennae form dipoles about 20 m long, which preclude their use from a helicopter.

In contrast, an example radargram with a low-frequency (65 MHz) bistatic antennae pair acquired from a helicopter platform over a glacier near the Matterhorn in Switzerland is shown in Fig 7. The reflection at about 12 m is the glacier surface. The white arrow indicates a near-surface feature (like an inverted 'V'), which could be from a crevasse or a supra-glacial water conduit. The yellow arrows point to the reflection that is interpreted to be from the base of the glacier. The zone encircled in red shows different reflection characteristics to elsewhere that probably indicates variations in water content within the glacier.

Snow and firm detail: High frequency radar data are used to determine information about snow and firm overlying each glacier (Hubbard and Glasser, 2005, chapter 6, Ice radar). Such information would be useful to compare with ground-based investigations on these glaciers where snow pits can be excavated for direct sampling of the snow for mass balance studies (Hubbard and Glasser, 2005, chapter 7, Glacier mass balance and motion). A detailed case history on the use of both helicopter-borne and ground-based GPR for snow depth measurements has been provided by Marchand et al. (2003). Negi et al. (2008) presented a case history undertaken in the Indian Himalaya where high-frequency (334 MHz) GPR data were used to estimate snow depth and to determine the detectability of buried objects using helicopter-borne GPR. They used the same system as that shown in Figure 4a.
A further example of the integration of GPR surveys and DEM data has been provided by Macheret et al. (2009) where both 20 MHz RES and 200 MHz GPR systems were used over the temperate Bowles Plateau ice cap on Livingston Island, Antarctic. An extract from one of their 200 MHz radargrams is given in Figure 8, which shows detail of stratigraphy within the firn layer and the firn/ice boundary. Although the radiowave velocity varies in snow and ice as a function of the snow density, a radiowave velocity of 190 mm/ns was used to convert the two-way travel time data to a depth-domain image, as shown in Figure 8.

Glacier volumes: From the preceding sections it has been demonstrated that it should be possible to extract geo-referenced interfaces for the base of the firn and the base of each glacier surveyed. Examples have already been provided above of the measurement of ice thicknesses using GPR. To further exemplify the style of information that can be generated from these integrated investigations, a panel of three maps of ice thickness, ice surface and glacier bedrock from Bowles Plateau ice cap in the Antarctic Peninsula is shown in Figure 9. The radar profiles were widely spaced and covered only a portion of the glacier area as the investigation was ground-based. Safety consideration precluded accessing the glacier margins. Each radargram was treated as a separate entity and the results manually extracted.

While the acquisition of five profiles over the Chhota Shigri Glacier by Azam et al. (2012) is a tremendous physical achievement at the altitudes and conditions there, the ground-based investigation remains spatially under-sampled by the widely-separated discrete profiles. Although the survey undertaken by Macheret et al. (2009) also used widely spaced profiles (>0.5 km), their profile layout permitted them to undertake a limited amount of interpolation between lines to produce the maps shown in Figure 9. However, a helicopter-borne GPR survey would enable profile lines to be acquired as close as every 25 m, for example, and thus permit an order of magnitude finer spatial sampling, as well as being able to investigate those areas of the glacier inaccessible on the ground. The close proximity of adjacent profiles improves the quality of inter-line interpolation and the spatial resolution of the data acquired. It also means that the amount of data available is massively increased relative to the examples given above. It also lends itself to treating 2D radargrams in a 3D interpretation environment, such as is used in the oil industry for seismic data. GPR data can be processed in the same way as seismic data as both are full waveform datasets.

Where existing ground-based GPR transects have been collected successfully, such as by Azam et al. (2012) over Chhota Shigri Glacier in Himachal Pradesh, they can be used to help calibrate any helicopter-borne GPR transects should they be acquired over this glacier.

By having a DEM for the firn/glacier surface and the derived interfaces for the base of firn and base of each glacier from the GPR data all within a geo-referenced 3D volume, it is possible then to generate volumes of snow/firn and of glacier ice. If such information is regenerated in subsequent years from repeat surveys, then the variations spatially and temporally can be determined. This would produce the
most accurate determination of changes in stored water equivalent for a glacier system ever produced.

Glacier hydrology
One of the critical unknowns in many parts of the Himalaya is the distribution of thermal regimes within the glaciers. Some are probably cold-based, others are temperate but there are also many that are likely to be polythermal. GPR can be used to differentiate different thermal regimes in glaciers (see King et al., 2008). Where the water is located within these glaciers is extremely important, especially when considering the glaciers as part of water resource estimation and management. There are a variety of techniques by which the presence of water can be detected and mapped.

Stored supra-glacial water volume: The main methods of determining stored supra-glacial water volumes are satellite-based high-resolution Synthetic Aperture Radar (SAR) and GPR. The former uses its radar capacity to probe the snow pack to identify characteristic signals associated with water. As the SAR technique maps the snow/glacier surface its reflection characteristics can be used to determine the presence of water and provide an indication as to the distribution of the stored water.

Supra-glacial water masses: The GPR technique is affected by the presence of water by virtue that the radiowave velocity through water is significantly slower in water than in either air or ice (33 mm/ns, 300 mm/ns and 167 mm/ns, respectively). Furthermore, localised water bodies, such as ponds and particularly supra-glacial streams, can provide characteristic radar anomalies on radagrams, as a result of the marked velocity contrasts between water and ice. Where water is present in an inter-granular form, it can lead to characteristic radar reflection textures on radagrams (see Figure 7, within the red ellipse).

En-glacial and sub-glacial water masses: Where water is present in en-glacial conduits, these can be identified on radagrams both by characteristic diffractions but also by the velocity anomalies caused by the presence of water and in some cases also by the air in partially-filled en-glacial channels and conduits.

Where water is present at the base of a glacier, its presence can be identified both by singular reflections and by the velocity contrast associated with the water. However, water at the base of a glacier can be difficult to identify unequivocally as it may also be present with complex debris bands that can also produce prominent reflections. The task then is to differentiate between the causes of such anomalous reflections.

Glacier mass balance: The highest frequency GPR dataset can be used to map the detail within the snow pack overlying the glacier. This information can be used to generate snow volumes. When coupled with ground-based measurements of snow density and localised water equivalent, detailed mass balance determinations can be made as for example at Chhota Shigri Glacier, Himachal Pradesh (see Waggon et al., 2007; Azam et al., 2012).

CONCLUSIONS
Airborne RES continues to be a major method in the investigation of Polar ice masses. So too, ground-based GPR surveys have demonstrated their usefulness and effectiveness over both Polar and temperate glaciers. It is clear that technological developments in commercial GPR systems now offers the opportunity of upsampling helicopter-borne surveys of glaciers in the Indian Himalaya using multi-sensor systems with multi-channel GPR acquisition and data processing techniques.

Such GPR surveys can produce information that is key to climate change monitoring, measuring glacier volume fluxes, enhanced mass balance estimations and water resource estimates, and that forms a high-quality baseline against which changes over time can be measured.

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