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Critical Literature Review

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Measuring snow accumulation using ground-penetrating radar(GPR)

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Abstract

Ground-penetrating radar (GPR) is a non invasive geophysical method that uses radar pulses to image the subsurface. GPR can be used in a variety of media, including rock, soil, ice, fresh water, pavements and structures. In polar ice sheets, snow accumulation is transported by ice flow to outlet ice streams and glaciers and/or ice shelves. Time scales for this transport can vary up to 105 years depending on the physical processes operating within the ice sheets. Therefore understanding of the internal physical processes, internal structure and flow regime is of great importance for understanding past, present, and future changes of the ice sheet. Radar is an established geophysical technique that has been and continues to be applied to investigate a variety of ice mass properties. This review presents the evolution of the technique from its early inception to the modern currently used Ground penetrating Radar (GPR) systems in the application of primarily measuring snow accumulation in Polar Regions.

Abstract

Ground-penetrating radar (GPR) is a non invasive geophysical method that uses radar pulses to image the subsurface. GPR can be used in a variety of media, including rock, soil, ice, fresh water, pavements and structures. In polar ice sheets, snow accumulation is transported by ice flow to outlet ice streams and glaciers and/or ice shelves. Time scales for this transport can vary up to 105 years depending on the physical processes operating within the ice sheets. Therefore understanding of the internal physical processes, internal structure and flow regime is of great importance for understanding past, present, and future changes of the ice sheet. Radar is an established geophysical technique that has been and continues to be applied to investigate a variety of ice mass properties. This review presents the evolution of the technique from its early inception to the modern currently used Ground penetrating Radar (GPR) systems in the application of primarily measuring snow accumulation in Polar Regions.

Introduction

Radio-echo sounding(RES), or Radar (*ra*dio *de*tection *a*nd *r*anging),is based on the transmission and detection of electromagnetic waves at frequencies of between 1 and 1000MHz (Plewes and Hubbard 2001). Ground-penetrating radar (GPR) is a technique that uses radar pulses to image the shallow subsurface of the earth. This non destructive method uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum, and detects the reflected signals from subsurface structures (Daniels 2000). It can be used in a variety of surfaces and can detect objects, changes in material, and voids and cracks. The elapsed time between when the energy is transmitted, reflected from buried materials or sediment and soil changes in the ground, and received back at the surface is then measured (**Figure 1.**). The depth range of GPR is limited by the electrical conductivity of the ground the transmitted centre frequency and the radiated power. As the conductivity increases the penetration depth decreases(Daniels 2000). The relative transparency of ice to radar waves means that considerable depths may be sounded to provide valuable information on ice thickness, internal structures the nature of ice-bed interface and hydrology.

Radar signal propagation in ice is essentially controlled by two electrical properties (1) relative electrical permittivity; and (2) electrical conductivity(Plewes and Hubbard 2001) Permittivity is essentially the capacity of ice to store an electrical charge, effectively impeding the flow of an applied electrical current. Permittivity in ice can be enhanced by the presence of free water and impurities, such as acids and salts(Fujita, Matsuoka et al. 2000). Similarly sensitivities can occur due to material properties such as crystal orientation, temperature and pressure (Boned, Lagourette et al. 1979).Electrical conductivity (EC) describes the ability of a material to conduct an applied electrical current. Principally EC of ice is controlled by the ices impurity content primarily derived from sea salt or volcanic aerosol deposits.

The method is relatively new, the history of which is intertwined with the diverse applications of the technique.

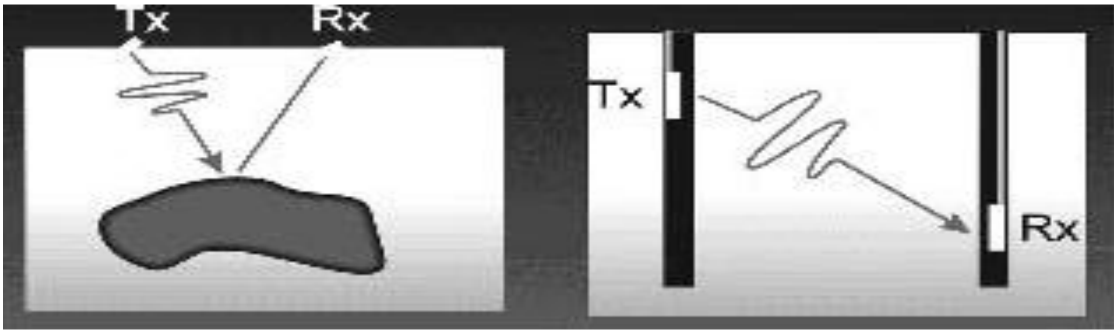

Figure 1. Ground penetrating radar uses radio waves to probe the subsurface of dielectric materials. Two modes of measurement are common. In the first, detection of reflected or scattered energy is used. In the second signal, variation after transmission through the material is used to probe a structure. *Source*: Modified from Annan (2001)

History

The following is a necessary albeit very brief overview of evolution of radar use. Noteworthy is that some of the earliest use of the methods were applied in the field of glaciology to determine ice thickness.

In the early 1950's the first reported attempt at measuring subsurface features with radio wave signals was reported. El Said attempted to use the interference between direct air transmitted signals and signals reflected from the water table to image the water table depth (Said 1956). The next reported observation of radio frequency sounding of geological materials came about when the USAF reported altimeter errors when attempting to land aircraft on the Greenland ice sheet (Waite and Schmidt 1961)This was the first time that repeatable indications of penetration into the subsurface through a naturally occurring material were reported. This spawned the era of researchers focused on developing radio echo sounding in ice(Annan 2002). The majority of activity, and significantly in respect to this review, during this interval involved radio echo sounding in ice. Groups, such as the Scott Polar Research Institute at Cambridge, (Bailey, Evans et al. 1964)and the Geophysical and Polar Research Centre at the University of Wisconsin (Bentley 1964; Walford 1964)

During the 1970's the ice radio echo sounding activity continued. In addition, applications in other favourable geologic materials started to be explored such as in coal mines since coal can be a low loss dielectric material in some instances. Similarly (Holser, Brown et al. 1972; Olhoeft 1974; Unterberger 1978) initiated evaluations in underground salt deposits for similar reasons. This period was also the start of lunar science mission planning for the Apollo program. Several experiments were devised to examine the lunar subsurface which was believed to have electrical character similar to that of ice. Key discoveries during this time was the greater understanding of wave fields about antennas on the ground surface and modified antenna directivity (Annan 2002). As time progressed a better understanding of electrical properties of geologic materials at radio frequencies started to become available.

By the 1980's knowledge increased, through the work of Olhoeft (1975, 1987), of the electrical character of natural occurring geological materials and the relationship between electrical conductivity and dielectric polarisation of these materials. Increasing availability of computers and technology allowed the greatest growth of applications and probably also the increased knowledge of geology. The Geological Survey of Canada explored its application to gain a better understanding of permafrost terrain in the Arctic for engineering pipelines. Interest in the tool and method was gaining momentum at this time(Annan 2002) . A whole series of ever improving GPR measurements and work enabled increased understanding of the effect of scattering on radio echo sounding in temperate glaciers (Watts and England 1976). Archaeological applications began to be explored as well as the ongoing work on permafrost by the Geological survey of Canada on the Alaska pipeline routes.

By the 1990's GPR had really advanced to the point where it had come into its own and many groups worldwide were interested for a variety of applications. Geophysical and engineering communities, archaeology (Goodman 1994)) environmental (Brewster and Annan 1994) and many other areas expanded. By 2000 numerical modelling of full 3D problems became possible. The ability to manage large volumes of information and manipulate them became routine. As a result the acquisition of data on grids to make maps and 3D visualisations became simplified and practical (Annan 2002). The commercial market and demand resulted in a variety of user friendly systems becoming available on the market. The research area strengthened with many groups formed at a number of universities which pushed development, expertise and advancement of GPR frontiers.

Now in 2012 GPR is on a very solid footing with the advent of new technology, instrumentation, field procedures, the routine application of the radar method is becoming economically viable and the method continues in popularity.

Cryospheric Applications of GPR

Glacial polar mass balance records contain important records of climatic change and such should give an accurate prediction of future change (Palli, Kohler et al. 2002). A depositional process of snow accumulation creates stratigraphic layers within the subsurface. Melting and refreezing of snow at the end of summer results in relatively dense layers of snow and/or hoar frost that appear in GPR data as reflection horizons (**Figure 3**). These layers are shaped by spatial variation in accumulation, surface slopes, and wind-induced snow deposition and erosion.

Since the first surface-based radar soundings of ice in 1964 (Walford 1964), glaciological applications of GPR have included measurements of glacier or ice sheet thickness(**Figure 2**), basal conditions, liquid water content (Arcone 1996) and internal structure (Moore, Pälli et al. 1999) including crevasse and buried debris detection for the purposes of construction (Arcone, Delaney et al. 2000). The clear and important merit of this remote-sensing technique is that a wide area can be investigated using such platforms as airplanes and ground-based vehicles. Internal structures can be detected from internal radio echo layering. In this category, GPR surveys have been successfully conducted to identify layering as an indicator of constant-time-horizons (or isochrones). These reflection horizons are used for correlating between disparate ice cores in order to better calibrate their time-depth relationships(Eisen, Wilhelms et al. 2003). Reflections of radio waves from within the ice are caused by sudden changes in complex dielectric properties of ice layers comprising polar ice sheets(Fujita, Matsuoka et al. 2000). Internal reflection horizons have also been used to infer glacial dynamics (Vaughan, Corr et al. 1999) and, more relevant to the current study, patterns of snow accumulation over time and space. Other cryospheric applications of GPR include mapping of permafrost extent and depth as well as measurements of snow depth and snow water equivalent (SWE) in alpine mountain catchments.

Because the transparency of pure ice to radar waves penetration and the dielectric contrasts between that ice and water or rock allow ice radar to be used to investigate a variety of physical properties, many of which are summarised by Plewes and Hubbard(2001). These studies can generally be classified in terms of the interpretation of reflected radio waves(generally ice surface radio-echo sounding) and the interpretation of direct radar waves (borehole based transmission radar)(Hubbard and Glasser 2005). While GPR presents huge advantages to the currently available point measuring methods in monitoring ice there are still some difficulties which present some challenges to the method which will be briefly outlined below.

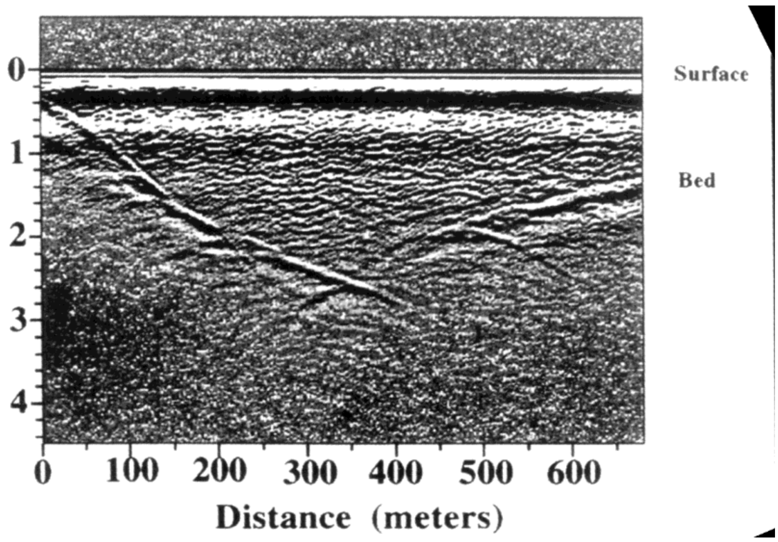

Figure 3: Radar cross section showing glacier bed. *Source* Fountain and Jacobel (1997)

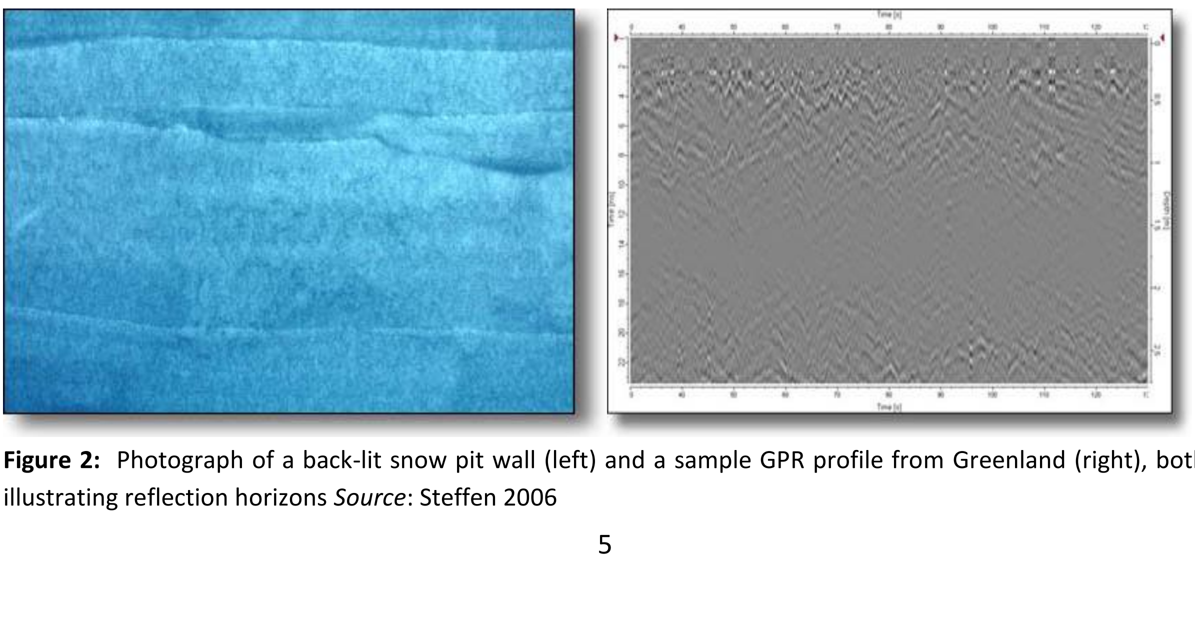

Figure 2: Photograph of a back-lit snow pit wall (left) and a sample GPR profile from Greenland (right), both illustrating reflection horizons *Source*: Steffen 2006

In practise, a great deal of signal strength loss occurs as a result of scattering, which is the general term used to describe a variety of energy loss processes including reflection, refraction and diffraction. Certainly much of the appeal of ice radar is about desirable scatter which is produced by the wave reflections from the target of interest. Unwanted scatter is also termed clutter or noise. Scattering losses are a function of the number, size and type of scattering bodies in the ice(Hubbard and Glasser 2005).

Antenna ringing

Horizontal banding in the resulting radar-gram is caused by "ringing" of the radar signal (negative and positive perturbations of signal strength) that results from interference due to radar waves that flow directly from the transmitting antenna and couple with the signal received at the receiving antenna during data acquisition.

Near-field effect

GPR does not collect good data near the surface down to a depth of about 1.5 times the centre wavelength(Goodman 1994)while the signal first penetrates the surface from the air above it and is still in the process of coupling with the subsurface medium.

Interpretations

Because dielectric discontinuities can be due to a variety of factors, the interpretation of GPR data can sometimes be challenging, in cryospheric applications as well as in others. Reflection horizons in glacial sub surfaces can be due to accumulation layers, sporadic ice lenses from refrozen melt water, layers of melt water, relatively dense snow resulting from past weather events, crevasses, debris, dust layers, etc. At lower resolutions, also, the reflections that are apparent in the radar gram are a combined effect of dielectric properties within the subsurface since individual layers cannot be resolved, making the data interpretation all the more complex. For these reasons, it is important to include *in situ* observations (e.g. snow pit stratigraphy, historical AWS measurements, manual probes, firn/ice cores, etc.) along with a GPR survey to help identify features and interpret the resulting radar gram.(Plewes and Hubbard 2001)

Echoes

There is often evidence of multiple reflections (i.e. echoes) from a single reflection horizon in the resulting radar-gram when part of the return signal continually bounces between the surface boundary and the reflection horizon. With each subsequent "bounce," however, the signal dissipates in energy so that subsequent echoes become increasingly faint in the resulting GPR data. The brightest return in the radar gram, therefore, can be interpreted as the first reflection and the true source of the reflector in the subsurface(Plewes and Hubbard 2001).

Conclusion

Understanding of the internal physical processes, internal structure and flow regime is of great importance for understanding past, present, and future changes of the ice sheet. To investigate physical processes operating within the ice sheet and internal structure, ice drilling, ice core analysis, and subsequent borehole logging are direct methods which can provide the most detailed internal information. In summary, almost all of the aforementioned GPR publications on using GPR for cryospheric applications report high spatial variability in snow accumulation over both short and regional scales due to either surface and/or basal topography and the wind patterns that surface topography controls, even on surfaces with very gradual slopes. The majority of authors therefore recommend caution in the interpretation of point measurements when used to represent average accumulation over a surrounding area. Ground-penetrating radar (GPR) has become firmly established in the last decade or so as an important tool for high-resolution shallow subsurface investigation, principally in environmental geology, archaeology and forensics, and engineering, infrastructure and continues to grow in popularity.

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