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Perspectives in Ground-Penetrating Radar at high latitudes: from occasional imaging to automated continuous monitoring

Introduction

Northern high latitude regions, well known for their near to far below zero mean annual temperatures, present numerous glaciers and/or permafrost areas. These bodies have been investigated as soon as the end of the XVIIIth century, using pictures for glacier volume annual variation, or soil movement due to permafrost evolution. They are even more under investigation since the estimated warming in the last decades compared to pre-industrial situation is twice as high in Arctic and Subarctic than in the rest of the globe (Allen *et al.*, 2019). Using temperature and precipitation scenarios from global climate models (e.g. RCP 1.9 or RCP 8.5) until 2100, projections show large decrease in global mass-balance of glaciers (Bliss *et al.*, 2014) and permafrost (Lawrence and Slater, 2005). In addition to the mean temperature increase, the likelihood of extreme temperature events is rising, with notable instances such as the very high temperatures observed in July 2020 in Verkhoiansk (Siberia), as well as the increase in wildfire occurrences and burn severity in Boreal regions (Hu *et al.*, 2015). These disturbances in temperature at different times and scales lead to changes in various compartments, notably vegetation, soil water content, atmosphere humidity implying severe permafrost degradations, expected to have high impact on global climate because of soil carbon release to the atmosphere (Schaefer *et al.*, 2014). Accurate global warming predictions cannot be achieved without taking into account permafrost greenhouse gases release, implying the need for investigating the permafrost areas at different spatial and temporal scales. This duality in the temporal and spatial scales requires the use of different methods, integrating different volumes/surfaces and having the capacity to be used on site or remote.

The first studies, mainly photographic based, led to the development of powerful remote sensing methods, to gather surface information over large areas, integrating various phenomena over large periods of time. For example, Nitze *et al.* (2018) estimate permafrost degradations from 1999 to 2014 in Arctic and Subarctic by quantifying lake coverage, wildfire burn scars and retrogressive thaw slumps through Landsat surface reflectance data. Similarly, the advances in remote sensing during the last decades led to centimetric altitude monitoring, allowing global scale glacier evolution estimations from satellite images (e.g. Hugonnet *et al.* (2021)). However tracking climate impact involving complex processes requires smaller scale studies. Different on-site methods have been deployed over the last decades to study glacier dynamics: since the 1960s, Ground-Penetrating Radar (GPR) has proven to be a powerful tool to get extensive ice thickness information (Cook, 1960; Evans, 1963; Arcone, 1996). Access difficulty pushed for the development of airborne GPR, introducing a mid-scale between on-ground and satellite measurements Rutishauser *et al.* (2016), with pioneering explorations on the King George Island ice cover, Antarctica (Kim *et al.*, 2010; Rückamp and Blindow, 2012).

On the other hand, the study of the thickness of the permafrost's active layer needs to take into account various intrinsic factors affecting the dynamics of its evolution: lithology of the soil, water content, soil structure, vegetation coverage, surface water, and snow timing and coverage (Dafflon *et al.*, 2017). For example, ice-wedge polygons observed in Alaskan tundra have been extensively studied Grant *et al.* (2017) to illustrate the relation between precipitation and active layer through microtopography. Among different geophysical methods employed for permafrost characterization (Kneisel *et al.*, 2008), GPR has been employed many times (Arcone *et al.*, 1998; Léger *et al.*, 2017). However these GPR characterization were and are still mostly performed during field campaigns which can be sparse in time, expensive and human resource demanding, and can be limited by the difficulty to access areas. The purpose of this short paper is to present two approaches for northern latitudes features imaging during field mission and discuss the benefits brought by hardware and software improvements to develop the field of long-term monitoring. The main objective of this paper is to highlight the new paradigm that the internet of things brought to the field of surface GPR characterization of high latitude environment.

Occasional imaging examples

The Austre Lovenbreen glacier in 2010

In April 2010, a three week expedition was conducted to acquire an extensive GPR data set over the Austre Lovenbreen temperate glacier in Svalbard (Norway) (Saintenoy *et al.*, 2013). Data were acquired using an old generation Malå equipment, with 50 and 100 MHz antenna 1. The antennas were pulled manually, and a second operator was needed to carry the control unit, loaded with heavy lead batteries and a rugged mobile computer. Due to perfect weather conditions, the acquired large amount of data lead to the bedrock 3D reconstructed surface. It would benefit from more data impossible to get in the three week expedition using the old fashion equipment. Radargrams pointed out some warm ice area. The monitoring of the evolution of its extension would be crucial with perennial means.

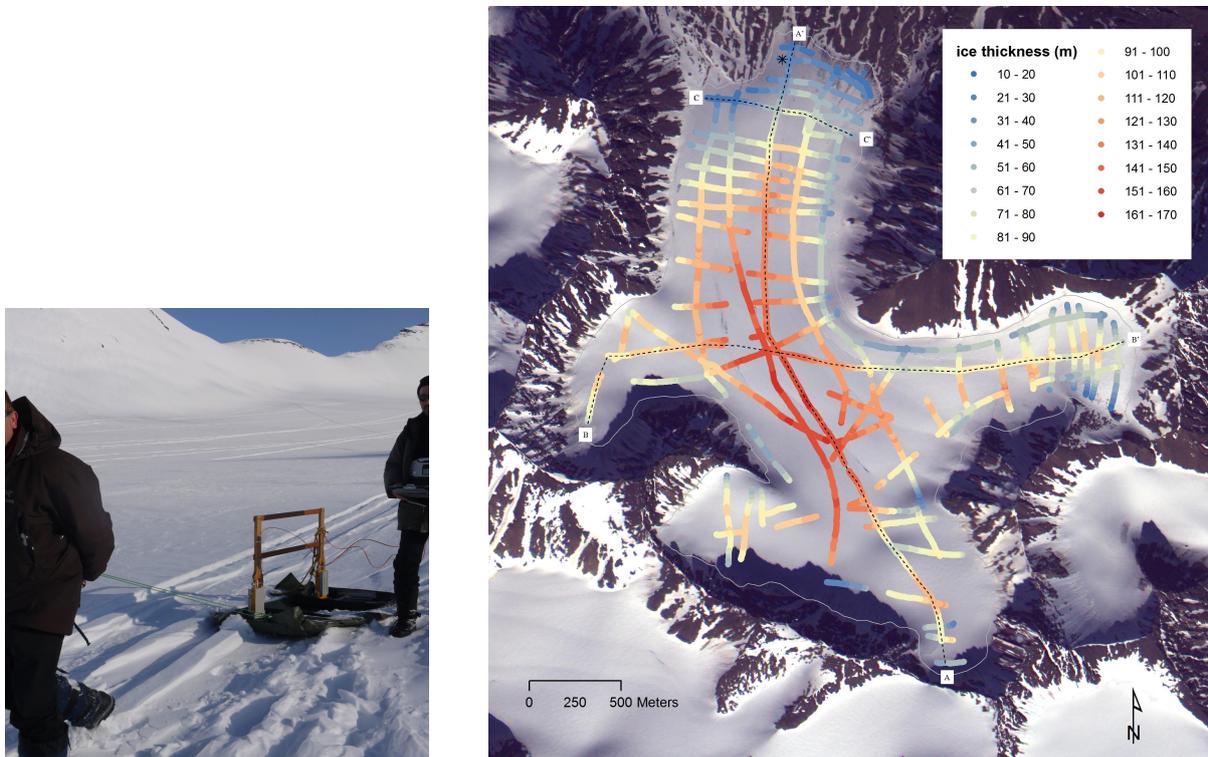


Figure 1 Right: Ice thickness map (from Saintenoy *et al.* (2013)) derived from GPR data set acquired with an old generation GPR system (left).

Active layer and river interaction in Eastern Siberia

For the last decade, the LSCE and GEOPS laboratories in collaboration with the Melnikov Permafrost Institute are engaged in the study of a river transect in continuous permafrost in Central Yakutia (Siberia) for the assessment and quantification of thermo-hydro processes within the active layer. The processes play a key role in the intrinsic evolution of water catchments. In this region of deep continuous permafrost, where water catchments undergo strong evolutions, we focus on a small river joining two thermokarstic lakes, using in situ sensors for measuring temperature at different depths and making direct probe measurements during end summer campaigns. In September 2017, we conducted a geophysical campaign to compare GPR data with temperature sensors, active layer depth from probes and electrical resistivity tomography data. These measurements gave cm-scale variations in the active layer depth depending on the orientation of the river bank and highlighted the influence of the river on the active layer depth and permafrost (Saintenoy *et al.*, 2020). The water, by its calorific capacity plays a strong thermal role by affecting the dynamic of the frozen layer (heat exchange) and the setting of the active layer. Therefore, tracking precisely the flow movement within the active/frozen layer dynamic is a key objective. Up to now a distributed temperature and water content sensor network provides punctual

monitoring and the geophysical data are acquired every once in a while depending on pandemic restrictions. There is a need for geophysical tools that could be installed for in-place monitoring of cumulative information: active layer depth, depth of supra-permafrost aquifer during the thawing or the freezing of the subsurface.

Open hardware and open-source software opening new way to GPR innovations

The two case studies presented above highlight an emerging trend for field-scale surveys in the Arctic and SubArctic area, evolving from heavy-weight expedition-based occasional measurements to automated continuous sensors. This evolution is prompted by the need for monitoring water movements while freezing and thawing processes in the active layer. It is also motivated by increasing concerns about travel-related carbon emission, by traveling limitations during worldwide pandemic situation, and even by down-to-earth difficulties such as carrying expensive and sensitive equipment across customs. This trend is enabled by rapid technological advances. With the development of the “Internet of things” (Ashton, 2009) and “makers’ movements” (Dougherty, 2012), the development of general purpose, open, inexpensive, nimble, and low-powered single-board computers coupled with the availability of a large variety of sensors led to a massive decrease in cost, energy and weight for deploying all types of sensors on the field; see for example (Léger *et al.*, 2019). Meanwhile, data processing – a posteriori, on the field, if not on board (edge computing) – has been greatly facilitated by the emergence in the last decades of a massive ecosystem of open-source software for scientific computation, widely accessible e.g. through the popular Python language.

GPR is no exception: it has gone a long way from its earlier requirements for heavy weight batteries, bulky antennae, loose connectors, and fragile optical cables; available software now cover both GPR numerical modeling (Warren *et al.*, 2016) and data processing (Plattner, 2020). These advances prompted us to develop a standalone automated device combining antennae and a Vector Network Analyser, all driven by a single-board computer, with embarked filtering and cm-precision location using RTK-GPS; this to better constrain the thermo-hydrodynamic of the active layer and diminish our impact on the studied area.

We believe that the ease of integration brought by these hardware and software breakthrough opens the door for rapid development by research teams of such bespoke low cost/energy/weight (semi-)automated devices tailored to their specific needs. Thanks to their features, such devices can then be left on the field, enabling long term continuous monitoring and sensing of complicated phenomena in arch-environment. We further envision opportunities for participative science, creating new collaborations for the benefit of both researchers on the field and the local population involved in first place in those massive climate changes.

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