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Review article
Surface geophysics

Studying cold regions with ground-penetrating radar: a review

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Abstract. Ground-Penetrating Radar (GPR) provides high-resolution, non-invasive insights into the subsurface, making it an essential tool for assessing climate change impacts and managing infrastructure in Arctic and sub-Arctic environments. This review examines GPR applications in mapping and characterizing cold-region features to enhance our understanding of the Critical Zone at high latitudes. Specifically, we focus on permafrost, including its active layer and embedded ice structures, as well as glaciers and front moraine, ice sheets, and snow cover. Furthermore, driven by advancements in miniaturization and energy efficiency, we extend our review to GPR-based subsurface exploration on the Moon and Mars, where environmental conditions and frozen geomorphological structures share similarities with terrestrial cold regions. Finally, we highlight the interconnection between hardware and software advancements and the expanding applications of GPR in cryospheric research.

Keywords. Ground-penetrating radar, Permafrost, Active layer, Glacier, Snow cover, Infrastructures, Planetary exploration.

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1. Introduction

Hypothesized since the Third Assessment report of the Intergovernmental Panel on Climate Change (Houghton et al., 1990), it is now observed that the thermal anomaly related to climate change is more pronounced at high latitudes than in the rest of the globe. This gave birth to the terms “Arctic thermal anomaly” and “Arctic amplification” which are now widely used in the literature (Previdi et al., 2021; Serreze et al., 2009). As warming trends are projected to accelerate by the end of the century (Pörtner et al., 2019), with varying magnitudes depending on the selected scenario (e.g., RCP 2.6, RCP 4.6), the fragile thermodynamic equilibrium of near-surface cold regions will be significantly affected. These changes will impact water resources and vegetation (M. T. Jorgenson, Romanovsky, et al., 2010), consequently altering key biogeochemical cycles, such as the nitrogen and carbon cycles (Petrone et al., 2007).

The effects of climate warming will be evident in various cold-region features, including permafrost and its active layer, which undergoes seasonal freeze-thaw cycles, as well as ice wedges, pingos, glaciers and their associated moraines, and snow cover. These impacts may manifest as a deepening of the active layer or through more dramatic geomorphological changes such as landslides, thermokarst formation (Zhirkov et al., 2023), and retrogressive thaw slumps (Costard et al., 2021). Examining these observable consequences in cold-region environments can, in turn, serve as a valuable proxy for quantifying the spatial and temporal extent of climate change impacts.

Near-surface geophysical methods provide a non-destructive means of investigating the subsurface over large areas in diverse contexts, contributing to

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their widespread adoption. In cold-region studies, electromagnetic (EM) wave-based methods, particularly radar, have been employed since the 1950s (A. P. Annan, 2001). Over time, radar technology has advanced from early pulse-based systems to impulse radar and continuous-wave emissions.

As technology has evolved and applications have broadened, the terminology for these radar systems has also diversified, encompassing terms such as “deep-looking radar”, “ice-penetrating radar”, “ice radar”, “ice-sounding radar”, “snow radar”, “impulse radar”, “(phase-sensitive) and (autonomous-phase-sensitive) radio echo sounder” and both “real” and “synthetic aperture radar.” The classification of these terms in the context of cryospheric research has been addressed by Schlegel, Kulessa, et al. (2022). In this paper, we focus on Ground-Penetrating Radar (GPR), including both impulse and continuous-wave systems, while excluding radio echo sounders. For a more detailed discussion of the latter, we refer readers to the review by Schroeder et al. (2020).

The GPR literature already includes review studies focused on cold region applications (e.g., Woodward and Burke, 2007; Arcone, 2009). Here, we provide an up-to-date review of cold-regions GPR research that goes beyond the previous review papers on the topic, covering a quite large panel of different applications. Following a brief overview of the physical principles of GPR, we categorize studies based on cold-region features, beginning with permafrost and active-layer investigations, followed by glacier and ice sheet studies, snowpack assessments, and infrastructure analyses. We then extend the discussion to recent extraterrestrial subsurface explorations. The final section highlights past, present, and future technological breakthroughs that have established and will continue to establish GPR as an indispensable tool for cold-region research.

2. GPR principles 101

A substantial body of literature explores GPR applications, technical advancements, and algorithmic developments, with numerous examples across various contexts (e.g. Slob et al., 2010; Jol, 2009; Forte and Pipan, 2017; Neal, 2004; Knight, 2001; A. P. Annan, 2003). Readers of French-language texts may refer to PhD manuscripts (Tillard, 1991; Leparoux, 1997; Saintenoy, 1998; Aboudourib, 2020; Brighi, 2024).

GPR is a geophysical technique based on the propagation of EM waves and is therefore sensitive to the dielectric permittivity (which influences EM wave velocity), electrical resistivity (which affects wave attenuation), and magnetic susceptibility of the medium through which the wave travels. The system operates with a transmitting antenna (Tx) that emits EM waves at frequencies ranging from 1 MHz to 4.5 GHz into the ground. These waves interact with subsurface structures, undergoing diffraction and reflection before being recorded by the receiving antenna (Rx). The transmitted frequency can be either fixed (with a certain bandwidth around the center frequency) or modulated, depending on the specific application. The recorded signals are then analysed in terms of time and amplitude to infer subsurface properties.

Different geometries of acquisition between Tx and Rx can be set up, using a fixed offset between them (giving mono-offset profiles), or varying ones (to obtain multi-offset profiles), with antennas both at the surface (reflection profiles) or in boreholes (transmission profiles). For reflection profiles, the antennas can be either on-ground or off-ground. Fixed pair of antenna can be used for monitoring EM property changes such as those implied during water infiltration (Saintenoy, Schneider, et al., 2008; Léger, Saintenoy and Coquet, 2014; Léger, Saintenoy, Coquet, et al., 2020), freezing-thawing cycles (Léger, Saintenoy, Serhir, et al., 2023), or snow layer transformation (Griessinger et al., 2018).

The EM wave velocity propagating in the different geological media ranges from 0.3 m/ns in air to approximately 0.03 m/ns in fresh water. This order of magnitude difference explains the success of this method for hydrological applications (see e.g. the review from Klotzsche, Jonard, et al., 2018). The aforementioned value intervals permit the calculation of the wavelengths of a GPR EM wave, which range from 6 mm in water at the upper frequency limit (disregarding dispersion effects) to 300 m in air at the lower limit. Different velocity analysis are applied depending of the GPR data, the most common method being the analysis of diffraction hyperbolas on mono-offset profiles (Ristic et al., 2009; Dou et al., 2016; R. Liu et al., 2023) allowing to convert time to distance through Kirchoff or Stolt migrations (Moran et al., 2000; Stolt and Weglein, 1985).

In its most common applications in cold regions, frequencies range from 2 MHz to 2 GHz for the detection of targets buried in media with velocities ranging from 0.05 to approximately 0.2 m/ns (the range of velocity is very much depending on if water is present in the pores of the sounded medium and its temperature). In these instances, the wavelength range is reduced to 0.1–100 m and the corresponding Fresnel zone, being roughly proportional to the quarter of the wavelength, gives the resolution. These rough calculations illustrate the range of heterogeneities typically investigated by GPR measurements in cold regions ranging from centimetric to multi-decametric scales. This is well illustrated by two studies within the edges of this range: Arcone (2009) carried GPR profiles in Antarctica with 3-MHz system and retrieved migrated profiles with a 2000 m depth of penetration. On the other side of the range, very thin layers (e.g. a 1 mm layer of ice within a thick layer of snow) were resolved through EM reflection amplitude enhancements (Widess, 1973) and exploited by Brandt, Langley, Giannopoulos, et al. (2009) to evaluate heterogeneities in firn (ice that is intermediate between snow and glacial ice).

Governed by the physics of EM waves, the penetration depth of a given radar system is primarily determined by the intrinsic attenuation properties of the medium it traverses. Signal loss is influenced by electrical resistivity, dielectric and magnetic relaxation processes, and the presence of multiple scatterers. For instance, high signal attenuation occurs in the presence of mineralized liquid water or/and clay particles within the thawed active layer, as well as in materials with small scatterers such as rock deposits in moraines or gas bubbles in ice. However, beyond scattering losses, EM wave attenuation is significantly lower in ice and frozen sediments compared to unfrozen materials. This reduction in attenuation makes such environments ideal for detecting signals from interfaces with minimal reflection coefficients, as demonstrated in various contexts in the following sections.

3. Applications in cold regions

3.1. *Permafrost and intra-permafrost structure studies*

Cold regions, characterized by mean annual temperatures close to or well below zero, present continuous, discontinuous, or sporadic permafrost associated with a seasonally thawing active layer, as well as distinct frozen features such as ice wedges. Additionally, these regions host large thawed features, including taliks and thermokarsts. All these features were the subjects of numerous geophysical studies (e.g. Hauck, 2013). Among them, we will focus on those using GPR.

The active layer, which annually thaws and freezes, is the object of great attention as its properties (thickness, temperature and liquid/solid water content) and their time and space variations are proxies for the permafrost thermal state and integrity, the near surface hydrodynamic (covering the water availability and as such, the plant–soil-micro and macro-organisms interactions with atmospheric boundary conditions), and the potentiality of CO_2 and CH_4 releases (Torn et al., 2025). In this case, the information brought by GPR for quantifying the active layer physical state concern mainly its thickness (Nakano and Sakai, 2008; Cao et al., 2017; Chen et al., 2016) and stratigraphy (Gusmeroli et al., 2015), as well as its solid/liquid water and soil and gas relative proportions (Gacitúa et al., 2012; Wollschläger et al., 2010; Westermann et al., 2010).

Due to its high heat capacity relative to most sediments and its low thermal conductivity, liquid water significantly influences permafrost thermal degradation and, consequently, active layer thickness. This effect has been investigated in various contexts (Bradford et al., 2005; Brosten et al., 2009; Léger, Saintenoy, Grenier, et al., 2023; Terry et al., 2020; Krutskikh et al., 2023), particularly in relation to water bodies such as streams and rivers. These studies aim to identify the key factors driving permafrost degradation, with the goal of improving predictions and mitigation strategies.

In Siberian permafrost studies, GPR profiles, combined with Unmanned Aerial Vehicle (UAV) data and electrical resistivity tomography (ERT) (Léger, Saintenoy, Grenier, et al., 2023), have been used to infer the thermal state of permafrost near a small river in Yakutia (Eastern Siberia). This analysis highlighted the complex interactions between solar orientation, vegetation type, river dynamics, and subsurface massive ice bodies, all of which influence active layer thickness and river-induced thermal effects on permafrost.

For larger water bodies, towed floating GPR systems have been employed, as demonstrated by Bradford et al. (2005), who obtained a clear, continuous image of the permafrost boundary both beneath and adjacent to a stream. Additionally, a more advanced approach integrating UAV and remote sensing techniques was conducted by Krutskikh et al. (2023) to study Palsa Mire features. Detailed vegetation mapping was correlated with GPR-derived permafrost table depth, enabling a more precise geomorphological interpretation and delineation of lateral permafrost degradation.

Since GPR data are typically collected and visualized as 2D transects, the representation of complex 3D geological structures can be misleading. To address this limitation, several studies have employed 3D mapping techniques by meshing multiple 2D GPR surveys (Brosten et al., 2009; Terry et al., 2020). Brosten et al. (2009) demonstrated the application of 3D GPR to map seasonal thaw thickness in different Arctic stream environments, showing that maximum thaw depth is influenced by subsurface lithology and distinct thermal processes. Similarly, Terry et al. (2020) combined GPR with nuclear magnetic resonance (NMR) and temperature sensing to identify a perennial suprapermafrost groundwater flow system beneath an Arctic aufeis field—large accumulations of ice common to Arctic river floodplains—supporting an extensive lateral talik.

Beyond permafrost studies, GPR has been widely used to investigate large, non-horizontal ice structures such as pingos, ice-wedge polygons, and massive ice bodies from glacial relics (Yoshikawa et al., 2006; Brandt, Langley, Kohler, et al., 2007; Ross et al., 2005). In Northern Alaska, near Fairbanks, GPR demonstrated sufficient resolution to delineate the internal structure and boundaries of a pingo using a low-frequency (<80 MHz) system (Yoshikawa et al., 2006). The choice of GPR over other geophysical methods was primarily driven by its portability, ease of use, and deep penetration capability for ice characterization. A more detailed mapping of the internal structure of two open-system pingos in Svalbard was conducted by Ross et al. (2005), who used GPR signal contrasts to infer variations in ice chemistry, as well as alternating layers of shale and ice, reflecting the pingos' formation within weak Jurassic shales. Similarly, GPR has been employed to image the internal structure of a relic glacier in Svalbard at varying resolutions (Brandt, Langley, Kohler, et al., 2007). The study compared results from different commercial GPR systems using antennas ranging from 200 to 800 MHz to effectively map the extent of buried ice and sediments.

Ice wedges, often forming polygonal networks, are iconic permafrost features in the Arctic and have been extensively studied as indicators of permafrost degradation (M. T. Jorgenson, Kanevskiy, et al., 2022; Liljedahl et al., 2016; Grant et al., 2017). GPR has proven to be a valuable tool for detecting and refining the geometry and spatial distribution of ice-wedge networks (Watanabe et al., 2013; Léger, Dafflon, Soom, et al., 2017; Harris et al., 2025). However, their detection is not always straightforward, and the combined use of GPR with ERT can improve characterization, as demonstrated by Léger, Dafflon, Soom, et al. (2017). The integration of two-dimensional and three-dimensional GPR surveys, along with ground thermal monitoring and acceleration measurements, has provided deeper insights into the factors influencing ice- and soil-wedge formation under present climatic conditions in the Kapp Linné region, Svalbard (Watanabe et al., 2013).

To conclude the discussion on GPR applications in permafrost studies, it is essential to address high-mountain permafrost. Over the past two decades, permafrost and other cryosols have attracted increasing interest, driven by expanding urbanization in mountainous regions (Ehrlich et al., 2021) and the accelerating impacts of climate change. This issue has direct societal relevance, as it affects slope stability (Magnin et al., 2023) and can trigger extreme events such as massive rock avalanches and large-scale solifluction flows—exemplified by the catastrophic event in India's Himalayan Uttarakhand state in 2021 (Verma et al., 2022). Despite the challenges posed by the accessibility of high-altitude permafrost sites, GPR has been successfully tested in conjunction with seismic refraction tomography and ERT to constrain subsurface models for estimating ice and water content. A notable example is the study by Steiner et al. (2021) in the Austrian Alps, where these geophysical techniques were integrated to improve the characterization of permafrost distribution and dynamics.

3.2. *Glacier and ice sheet investigations*

Glaciers and ice sheets are among the most suitable targets for GPR, as signal propagation is facilitated by the high electrical resistivity of ice, which can be considered a near-lossless medium. As opposed to permafrost, no dispersive active layer is above the ice body leading to excellent depths of penetration. However, this advantage is mitigated in the presence of sea ice or trapped brine, which can cause significant signal attenuation (Blindow, 1994). When saline inclusions are absent, GPR has been widely used to measure ice thickness (Cook, 1960; Evans, 1963; Arcone, 1996; Saintenoy, Friedt, et al., 2013), map internal stratigraphy (Arcone, Spikes, et al., 2004), and assess basal conditions (Saintenoy, Friedt, et al., 2013), such as the presence of subglacial water (Hart et al., 2015). These studies have taken on increasing urgency in light of the ongoing decline in glacier volume due to climate warming (Shannon et al., 2019), which contributes directly to rising sea levels.

Since the 1960s, Radio Echo Sounding has proven to be a powerful tool for obtaining extensive ice thickness measurements, particularly through aerial surveys (Cook, 1960; Evans, 1963). GPR measurements followed later, with significant advancements in the 1990s (Arcone, 1996). In 2001, a research team participated in a study of a small glacier in the tropical Andes, initially employing refraction seismic data before conducting a 50 MHz PulseEkko survey, which provided higher spatial resolution in thickness estimation than seismic methods (Ramírez et al., 2001). In Europe, extensive GPR surveys were conducted on the Austre Lovenbreen glacier (Svalbard), leading to the derivation of a digital elevation model of the underlying bedrock (Saintenoy, Friedt, et al., 2013). Additionally, all available ice thickness measurements across the Svalbard archipelago were integrated into a regional study to estimate total ice volume and its loss to sea (Fürst et al., 2018). Such large-scale studies are crucial for improving projections of future glacier mass loss and its impact on sea levels. A fundamental challenge in glacier volume estimation is accurately defining the glacier's contours. This issue has been addressed by multiple research groups employing GPR to delineate glacier extents and improve volume calculations (Santin et al., 2023; Bernard, Friedt, Saintenoy, et al., 2014; Bernard, Friedt, Prokop, et al., 2024).

The geometry reconstruction of the Irenebreen glacier (Svalbard) (Karušs et al., 2022) highlights the importance of multi-offset GPR measurements, as developed by A. D. Booth et al. (2008) and Murray, A. Booth, et al. (2007). These techniques are particularly valuable for distinguishing between solid and liquid water within a glacier (Barrett et al., 2007) and for constraining its thermal state (see also the thermal state assessments by Woodward, Murray, et al., 2003; Schannwell et al., 2014). The challenge of differentiating liquid and solid ice has been extensively studied, notably on the Tête Rousse glacier (France). There, GPR, combined with Nuclear Magnetic Resonance (NMR) data, was employed to characterize and monitor an internal water-filled cavity. This monitoring was crucial in guiding the controlled drainage of water to mitigate the risk of catastrophic flooding in the downstream valley (Garambois et al., 2016).

In a more invasive approach, borehole GPR has been used in conjunction with surface measurements to precisely characterize englacial water distribution, as demonstrated by Murray, Stuart, et al. (2000). Additionally, variations in radar amplitude have been exploited to infer water content within the basal substrate beneath the Rutford Ice Stream in Antarctica (Schlegel, Murray, et al., 2022). These variations in basal layer properties play a crucial role in ice flow modeling, further emphasizing the importance of geophysical techniques in glaciological research.

Moraine areas are more challenging for GPR survey as they are composed by rocks from several sizes, sediments and/or large blocks, inducing dispersion and multiple diffraction phenomena (Lønne and Lauritsen, 1996). These observed diffractions can actually help to understand the process of glacial thrusting or proglacial shear, as done for the first time by Lønne and Lauritsen (ibid.) to relatively date the occurrence of the glacial deformation and where it was mainly applied. The ability to discriminate between sediment and ice within glacial environments was further demonstrated by Murray and A. D. Booth (2010), who reconstructed 3D englacial sediment structures at the front of the surging Kongsvegen Glacier (Svalbard). Similarly, Midgley et al. (2013) used multiple 100-MHz GPR profiles to infer the internal structure of the moraine in front of the Austre Lovenbreen Glacier (Svalbard). Through common-midpoint velocity analysis, they identified differences in subsurface composition, revealing that the outer moraine contains a significant volume of buried ice, whereas the frontal zone moraine is more sediment-rich. These variations were linked to past glacier surging activity, as evidenced by a surface bulge. Their findings highlight the role of moraine structures as archives of paleoglaciological information from the Neoglacial period.

Rock glaciers have gained significant attention as key indicators for assessing the impacts of climate change on mountain permafrost. Under specific topographic conditions, their destabilization can lead to surface velocities of up to 10 m per year (Marcer et al., 2021). GPR has proven to be an effective tool for investigating rock glaciers. For instance, Buchelt et al. (2024) conducted a study on the Tellers Davains rock glacier in the central Swiss Alps using a PulseEkko 50 MHz system, achieving a penetration depth of approximately 15 m in the most resistive sections along a 1-km-long profile. A broader comparative study by Meng et al. (2023) examined four rock glaciers across Alaska, Wyoming, and Colorado. Using a 25 MHz antenna, they achieved a penetration depth of 50 m, enabling them to infer volumetric ice fractions. Their analysis linked these ice fractions to past ice accumulation and subsurface ice preservation processes. Notably, they highlighted the relevance of their findings for planetary exploration, particularly in the context of Mars, where numerous debris-covered glaciers suggest subsurface ice reservoirs.

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). Kim et al. (2010) tested a 100 MHz GPR, antenna under an helicopter, and Rückamp and Blindow (2012) used the BGR-P30-System developed at the University of Munster as a fast and efficient tool for mapping heavily crevassed coastal areas. In the continuity of these aerial data acquisition mode, some drone-based GPR are now available for glacier studies (e.g. Ruols et al., 2023).

3.3. *Snowpack analysis*

At the other end of the resolution spectrum, GPR was also applied to snowpack studies to measure snow-depth, -density, and -layer stratigraphy, aiming, in fine, to study seasonal snow accumulation (A. P. Annan, 2001), and monitoring water resources in snow-dominated hydrological regime regions (Griessinger et al., 2018; Yildiz et al., 2021; McCormack and Vaa, 2019; Vergnano et al., 2022; Valence et al., 2022).

Similar to mountaineous permafrost, collecting data on snow stratigraphy within potential avalanche zones, assessing stability, and aiding in avalanche forecasting require access to snow cover in remote and challenging mountainous terrains. This was one of the first motivations for UAV-mounted studies (McCormack and Vaa, 2019; Vergnano et al., 2022).

Heterogeneity in firn (ice that is at an intermediate stage between snow and glacial ice) can be assessed with GPR. More precisely, its response to seasonal percolation, with validation using cores and numerical modeling is the subject of Brandt, Langley, Giannopoulos, et al. (2009). However ground-based GPR applications necessitate direct contact with the snow surface, which alters its properties and renders subsequent surveys less representative of natural conditions. UAV GPR is a very promising method for precise snow hydrology studies (Valence et al., 2022).

Griessinger et al. (2018) use a system of four pairs of antenna in a way that they could acquire repeated profiles in the Swiss Alps in winter seasons. Their results open the way of new data sets acquisitions to validate snow melt models or to complement lidar-based snow surveys. The potential of combining Uncrewed Aerial Vehicle (UAV) photogrammetry with GPR to map snow water equivalent at large scales is again shown in Yildiz et al. (2021). UAV photogrammetry provides high-resolution, spatially continuous snow depth measurements at the basin scale. GPR complements this by enabling non-destructive snow investigations, allowing snow density to be estimated from radar velocities derived using photogrammetric snow depths and GPR two-way travel times at the snow-ground interface.

The development of upward-looking GPR to study snow cover properties has been done by Heilig et al. (2009) and Schmid et al. (2014). The integration of Water Content Reflectometry (WCR) and upward-looking GPR (1500 MHz) was tested in the Western Italian Alps from November to April (Godio et al., 2018) and showed to provide high accuracy in monitoring average snow density values. Furthermore, the combined use of upward GPR, water content probes, and conventional snow depth observations enables a detailed analysis of snow deposition, settlement phases, densification processes, and the melting and freezing phases.

3.4. *Infrastructure characterisation and monitoring*

As cold regions through the arctic anomaly is subject to stronger amplitude warming, the human infrastructures face a large panel of disturbances, such as frost heave and thawing permafrost leading to house instability, road damages and all the landslide and terrain movement consequences (Lamoureux et al., 2015; W. B. Yu et al., 2014; O. Tregubov et al., 2020; O. D. Tregubov and Uyagansky, 2024).

GPR was used to monitor roadbed conditions (Oldenborger et al., 2015; Fortier et al., 2011), airport airfield (Jørgensen and Andreasen, 2007), pipeline stability (Y. Wang et al., 2016; Oswell, 2011), and bridge pile foundations (You et al., 2017). It can detect voids or changes in soil moisture that could lead to structural failures. It is also a tool to monitor the thermal effects on the surrounding material when trying to insulate the pipes with thermosyphons (Y. Wang et al., 2016) or evaluate cooling measures effectiveness for highway maintenance when built over permafrost (Stephani et al., 2014; Huang et al., 2024).

3.5. *Subsurface investigations on the moon and mars*

Looking for water traces in the shallow subsurface of Mars as well as understanding the internal structure of the Moon to get indices of its history, have been exciting topics for many years (Schroeder et al., 2020). At first several orbiters equipped with radar systems have been sent around the Moon (Porcello et al., 1974; Peeples et al., 1978; Ono et al., 2010) and around Mars (Seu et al., 2007; Picardi, Plaut, et al., 2005). They were followed by in-situ GPR mounted on uncrewed rovers (Li, J. Liu, et al., 2015; Hamran, Paige, Amundsen, et al., 2020; L. Zou et al., 2024) to obtain higher resolution data that can be cross-validated with data from the orbiters.

Chang'E-3(CE-3) was the first GPR deployed on the Moon surface onboard a rover in December 2013 (Li, J. Liu, et al., 2015). A 114-m long profile was acquired and first interpretations allowed to distinguish regoliths, paleo-regolith and ejecta layer (Su et al., 2014; Fa et al., 2015). However Li, Xing, et al. (2017) alerted for signal artefacts due to the metallic rover, that were wrongly interpreted as coming from deep reflectors. This study illustrates the importance of testing the data acquisition and interpretation on Earth with similar systems as those sent to space (Soldovieri et al., 2009). In-situ Moon GPR investigations went on with Chang'E-4 that landed on the other side of the moon in 2019 (Jia et al., 2018). These missions provided high-resolution imaging of the lunar subsurface, revealing its layered structure and key properties like regolith thickness and composition, significantly advancing our understanding of lunar geology (Lai et al., 2019).

For Mars subsurface exploration, two orbiting GPRs revealed key insights into Mars' subsurface before in situ measurements (Picardi, Biccari, et al., 2004; Mouginot et al., 2012). The Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS), part of the Mars Express mission, operated from July 2005 with a frequency range of 1.3–5.5 MHz (Picardi, Biccari, et al., 2004). Its data were interpreted in terms of maps of dielectric constant distributions, suggesting a Late Hesperian ocean in the Utopia Planitia region (Mouginot et al., 2012). SHAllow RADar (SHARAD), with higher resolution (higher frequency range of 15–25 MHz), on-board the Mars Reconnaissance Orbiter, has been working since 2006. SHARAD has revealed the internal structure, composition, and history of Mars' polar caps, showed that mid-latitude glacial landforms are ice-rich debris-covered glaciers, and has provided first constraints on the interior composition and stratigraphy of volcanic and sedimentary layers (Putzig et al., 2024).

Meanwhile, Perseverance is a rover that landed on Mars in February 2021 inside the Jezero 45-km diameter crater (Bell et al., 2021). This rover is equipped with a monostatic frequency modulated continuous wave radar, acronym RIMFAX, that operates in the frequency range 150 MHz to 1.2 GHz. A detailed instrument description is in Hamran, Paige, Amundsen, et al. (2020). An interpretation of the first 3-km long radargram recorded with RIMFAX is presented in Hamran, Paige, Allwood, et al. (2022). It reveals dipping reflectors with cross beddings that could be explained either by magmatic or sedimentary layering. Casademont et al. (2023) present the statistical distribution of the EM velocity retrieved from 150 hyperbolas observed along the radargram at different arrival times. Each velocity value is the average from the surface down to the diffracted point creating the studied hyperbola. It varies from 0.07 up to

0.21 m/ns. Assuming a dry, non-magnetic and low-loss medium, the velocity is converted to relative dielectric permittivity with values varying from 2 to 20. In Eide et al. (2023) the radar attenuation, estimated from the returned signal power itself, is quite constant all along the studied profile. Both quantities, dielectric permittivity and attenuation rate, can not help to clearly identify the lithology of the different layers, which interfaces give radar reflections.

In May 2021, four months after Perseverance, the Tianwen-1 mission (Y. Zou et al., 2021) deployed successfully the Zhurong rover to explore an area south of the Utopia Planitia with onboard the Rover Penetrating Radar (RoPer). This device works at two different frequency ranges, the first being with higher frequency range (450–2150 MHz) than the other one (15–95 MHz). The high frequency system is recording full polarimetric data. It is the first tool with this possibility to work on another planet surface (it is worth noting that a French team (Ciarletti et al., 2017) has been working for years for a full-polarimetric GPR system mounted on a rover, the Water Ice Subsurface Deposit Observation on Mars (WISDOM)). The data were acquired with distance steps of either 25 cm or 50 cm. The first 1100 m of the profile acquired with the lower-frequency range has been interpreted as multi-layered media of different granulometric sequences analysing signal from diffractors as deep as 80 m (Li, Zheng, et al., 2022). With the higher frequency range system, L. Zou et al. (2024) present a processing strategy to estimate surface relative permittivity using HH and VV channels, based on the induced field rotation effect, which occurs when orthogonal EM waves propagate into an uneven surface with incident angles. A rough surface model was produced by employing colour images captured by the Navigation and Topography Camera (MSCam) located on the Zhurong Rover. As with the RIMFAX data, a velocity analysis has been carried on several hyperbolas using the high frequency data by R. Liu et al. (2023). More interpretation of the high frequency data have been carried on by Sun et al. (2025).

4. Key innovations in the last 3 decades and yet to come

Over the last thirty years, significant advancements in GPR technologies have facilitated its application in cold regions. These developments encompass a broad spectrum of innovations, ranging from data acquisition techniques to open-source software and hardware. In the following section, we will highlight several key advancements, firstly in hardware and subsequently in software, and their implications. More insights in the technology future can be found in the review of Schroeder (2022).

4.1. *Hardware evolution*

Recent progress in 3D field acquisition have been a game changer. In the 1990s, antenna had to be linked via coaxial cables to the control unit, which were of such substantial size that the use of a wheelbarrow was necessary for mobility (see photographs of the GSSI SIR-10 control unit (GSSI, 2025)). The use of optical fibers and the control unit miniaturisation marked a first improvement for impulse GPR field acquisition. Furthermore, recent advancements in technology enable the stacking of thousands of signal traces, significantly enhancing data quality by reducing noise (e.g. the ultra receiver described in P. Annan and Diamanti, 2018).

Contemporary, multi-antenna systems, equipped with up to 12 pairs of antennas, in conjunction with RTK GPS positioning, are a giant leap in comparison with the pioneering “wheelbarrow GPR” systems. These modern multi-antenna systems facilitate the coverage of extensive surface areas, reaching up to one hectare within a span of half a day. At present, the primary applications of these systems are in the domain of archaeological prospection (Trinks et al., 2010), in flat terrains as the bulky nature of this equipment currently limits its deployment in remote or topographically challenging environments.

As was outlined in the preceding sections of this document, the investigation of permafrost and analogous frozen features has given rise to considerable challenges with regard to accessibility. The primary solution to the problem of inaccessibility in remote regions has been the utilisation of helicopters (Kim et al., 2010; Rückamp and Blindow, 2012). This acquisition mode is susceptible to directional artifacts arising from the orientation of dipole antennas relative to undulating subsurface interfaces. To address this limitation, a dual-polarization GPR system was developed at ETH Zurich and has been successfully deployed to image several Alpine glaciers (Langhammer et al., 2019; Grab et al., 2021).

Another way has been indicated by the Moon and Mars exploration with the developments in uncrewed equipments (Li, J. Liu, et al., 2015; Hamran, Paige, Amundsen, et al., 2020; L. Zou et al., 2024; Arcone, Lever, et al., 2016; Ravnås et al., 2023). The scope of GPR applications has been expanded through the utilisation of satellites and rovers, and it is anticipated that this scope will continue to expand in the future with the augmentation of UAV payload capacity. GPR systems mounted on uncrewed rovers have been deployed for planetary exploration (Li, J. Liu, et al., 2015; Hamran, Paige, Amundsen, et al., 2020; Li, Zheng, et al., 2022) but also for terrestrial investigations in Antarctica (Arcone, Lever, et al., 2016). Drone-borne GPR has been explored for applications such as landmine detection (Šipoš and Gleich, 2020), soil moisture mapping (Wu et al., 2019) and alpine glacier surveying (Ruols et al., 2023). It was also tested for lake bathymetry map (Bandini et al., 2023), which inspires the feasibility of integrating GPR with uncrewed water surface systems for lake or riverbed investigations such as the one used with marine seismic equipment by Ravnås et al. (2023).

Aerial imaging technologies, including high-resolution topographic mapping and vegetation analysis such as greenness maps, support GPR surveys by identifying optimal survey locations and providing contextual data that helps the interpretation of GPR results (Helfricht et al., 2014; Krutskikh et al., 2023; Léger, Saintenoy, Grenier, et al., 2023). Furthermore, advancement in low-energy soil sensors, including those measuring soil water content and temperature, are encouraging in situ measurements used to constrain information from the field (Léger, Dafflon, Robert, et al., 2019). A particularly promising category is embedded passive sensors activated by surface GPR signal, as described in Friedt et al. (2018). This innovation paves the way for long-term in situ sensing and monitoring of various environmental parameters, such as gas and water chemistry.

The advent of open-source solutions has had a democratising effect on access to advanced GPR technologies. Open hardware initiatives in geophysics (e.g. Clement et al., 2020) have introduced innovative and cost-effective approaches to GPR development. For instance, a home-made GPR built from off-the-shelf components was successfully tested under cold chamber conditions (Léger, Saintenoy, Serhir, et al., 2023). This device was developed for the purpose of autonomous, long-term monitoring as a standalone automated apparatus, combining an antenna and a vector network analyser, both of which driven by a single-board computer with embarked filtering processes. All of this was aiming to enhance thermo-hydrodynamic characterisation of the active layer in remote regions while minimising impact on the study area. Standalone automatic devices are particularly relevant given the growing concerns over travel-related carbon emissions, restrictions imposed during global pandemics, and practical challenges such as transporting expensive and sensitive equipment across international borders.

4.2. *Software evolution*

Numerical modeling tools, such as GprMax (Warren et al., 2016), have significantly advanced the interpretation of GPR data, particularly in the heterogeneous environments characteristic of cold regions. These tools enable researchers, teachers and students, to simulate GPR responses and compare them with real data, incorporating increasingly detailed models, such as the presence of vegetation on the surface (Giannakis et al., 2015). Moreover, this software allows for the modeling of antenna behavior and the integration of a stochastic distribution of electromagnetic properties within materials using a fractal approach and sub griding the mesh to model for example the antennas (Wei et al., 2017).

The integration of multiple geophysical methods for characterizing cold-region features has proven valuable in refining data interpretation (Benjumea et al., 2003; Pavoni, Boaga, Wagner, et al., 2023; Pavoni, Boaga, Carrera, et al., 2023; Steiner et al., 2021; Garambois et al., 2016). Techniques such as refraction seismic, ERT, and EM induction provide complementary information to GPR, aiding in the estimation of ice properties and bedrock characteristics (Benjumea et al., 2003). An other example of multiple method integration is the investigation of a small glacier in the Italian Alps with GPR and frequency-domain EM measurements (Pavoni, Boaga, Carrera, et al., 2023). Most data processing software is specialized for a single geophysical method, making the interpretation of multi-method datasets challenging. Effective analysis requires software capable of integrating and processing diverse geophysical datasets.

Over the past decade, there has been a significant rise in open-source scientific computing tools, widely accessible through platforms such as the Python programming language and Jupyter Notebook environments. Notable examples include open-source GPR data processing tools (Plattner, 2020; Ralston and Hargrave, 2012). Collaborative efforts to integrate GPR data with other open-source geophysical platforms, such as PyGIMLi (Rücker et al., 2017), have facilitated multi-method interpretations and fostered interdisciplinary research, as demonstrated in Pavoni, Boaga, Wagner, et al. (2023).

The geophysical community, and GPR data processing in particular, has greatly benefited from the rapid advancements in Artificial Intelligence (AI) (S. Yu and Ma, 2021). Early applications focused on automatic hyperbola detection for reflector positioning in zero-offset profiles (Maas and Schmalzl, 2013). More recently, convolutional neural networks, combined with the You Only Look Once (YOLO) algorithm, have been employed to automatically extract signals for utility detection in urban environments and road prospecting (H. Liu et al., 2023). A decade earlier, full-waveform inversion (FWI) represented a major breakthrough in GPR processing, successfully applied to crosshole data (Ernst et al., 2007; Klotzsche, Vereecken, et al., 2019) and surface recordings (Lambot et al., 2009; Lavoué et al., 2014). Recent advancements have introduced frequency-dependent FWI techniques capable of handling dispersive media, improving conductivity reconstruction in highly attenuating, high-permittivity environments (Qin, Bohlen and Allroggen, 2023), with successful application on multi-offset surface GPR data (Qin, Bohlen, Allroggen, et al., 2024). The integration of AI with FWI now enables real-time GPR data interpretation, facilitating rapid decision-making in the field. For example, Xue et al. (2024) developed a deep learning-guided network that incorporates geological and geophysical knowledge to translate zero-offset GPR data into dielectric permittivity and electrical resistivity profiles in real time. This approach was successfully applied to GPR data collected above a pollutant spill, demonstrating its potential for environmental monitoring and subsurface characterization.

Real-time acquisition, visualization, and interpretation are particularly advantageous for applications in cold regions, enabling adaptive survey planning in response to field conditions. This capability is especially valuable in remote areas, where it can enhance operational efficiency and significantly reduce logistical costs.

5. Conclusion

In this brief review, we have provided a non-exhaustive overview of GPR studies focused on characterizing cold-region features, including permafrost and its active layer, pingos and other large ice bodies, glaciers and their associated moraines, as well as subsurface investigations on extraterrestrial bodies such as the Moon and Mars. We emphasized the strong connection between technological advancements and progress in GPR measurements and data processing, driven by hardware miniaturization and increasingly efficient algorithms. We believe that the seamless integration enabled by these hardware and software breakthroughs paves the way for research teams to develop customized, low-cost, energy-efficient, and lightweight (semi-) automated GPR systems tailored to their specific needs. Such devices can be deployed in the field for long-term, continuous monitoring, facilitating the observation of complex environmental phenomena in harsh and remote regions. Furthermore, we foresee opportunities for participatory science, fostering new collaborations between researchers and local communities who are directly affected by the ongoing impacts of climate change. This synergy can enhance data collection while empowering communities to actively contribute to scientific research and environmental monitoring.

Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

Dedication

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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