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Brief Communication: Bed mapping of southern Greenland outlet glaciers using helicopter-borne ground penetrating radar (AIRETH)

Ilaria Santin[1,2], Huw Horgan[1,2,3], Raphael Moser[1,2], Nanna Bjørnholt Karlsson[4], Faezeh Maghami Nick[5], Andreas Vieli[6], Anja Rutishauser[4], Hansruedi Maurer[7], and Daniel Farinotti[1,2]

[1]Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zürich, Zürich, Switzerland
[2]Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Sion, Switzerland
[3]Antarctic Research Centre, Victoria University of Wellington, Wellington, New Zealand
[4]Geological Survey of Denmark and Greenland, Copenhagen, Denmark
[5]Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands
[6]Department of Geography, University of Zürich, Zürich, Switzerland
[7]Institute of Geophysics, ETH Zürich, Zürich, Switzerland

Correspondence: Ilaria Santin (santin@vaw.baug.ethz.ch)

Abstract. We present the first southern Greenland deployment of the redesigned Airborne Ice Radar of ETH Zurich (AIRETH). We surveyed 348 km of flight lines over three outlet glaciers and identified bed reflections along 102 km (29%). The 25 MHz configuration achieved an effective penetration depth of about 300 m and a maximum inferred ice thickness of about 340 m, while bed detectability decreased over thicker and/or heavily crevassed ice. These results define the current depth limitation of our system and show that terrain-following helicopter surveys can provide targeted constraints that complement existing datasets in complex topography.

1 Introduction

The Greenland Ice Sheet is currently losing mass at a rate of ∼200 Gt yr^{-1} (IMBIE Team, 2020). This loss reflects the combined effects of surface mass balance and dynamic discharge, with the latter controlled by ice flow speed and ice thickness, particularly across fast-flowing outlet glaciers at the ice-sheet margin (King et al., 2020). While ice velocities can be mapped from remote sensing observations (Moon et al., 2012), ice thickness remains harder to constrain because of the scarcity of direct measurements.

Ground-penetrating radar (GPR) are effective and established methods for mapping ice thickness (Schroeder et al., 2020). In Greenland, extensive airborne depth-sounding campaigns were conducted in the frame of NASA's Operation IceBridge (OIB) (Studinger et al., 2010). Using the Multichannel Coherent Radar Depth Sounder (MCoRDS), a high-power, multichannel depth-sounding radar operated from aircraft, OIB achieved deep bed detection at regional scale (Paden et al., 2010). These radar data underpin Greenland ice-thickness and bed-elevation products such as BedMachine (BM), a dataset that combines airborne and ground-based radar thickness measurements (OIB) with surface elevation and ocean bathymetry through a mass-conservation inversion, complemented by interpolation and hydrostatic-equilibrium estimates (Morlighem et al., 2017).

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However, southern Greenland still contains gaps in radar-derived thickness coverage, particularly along the coastline and within deep, narrow outlet-glacier corridors (Mouginot et al., 2014). Narrow outlet glaciers can fall between the widely spaced OIB flight lines and, even where crossed, may include segments without reliable bed picks (Fig. 1a, black and grey lines). In addition, rough topography and the water content of temperate ice can increase scattering and attenuation, reducing bed detectability, especially for higher-frequency systems (MacGregor et al., 2016).

Here, we report the first deployment of the redesigned, helicopter-borne AIRETH radar system in southern Greenland. We focus on quantifying bed-detection performance in this challenging setting and on assessing how AIRETH bed picks complement the existing OIB and BM ice-thickness products, particularly in complex fjord terrain and near ice-marginal lakes. Our campaign targeted three outlet glaciers on the ice-sheet margin around Narsarsuaq (Figure 1a): Qooqqup Sermia, Eqalorutsit Kangilliit Sermiat, and Sermilik Bræ. These sites span marine and lake-terminating glaciers in tidewater settings in high-relief terrain, where terrain-following helicopter surveys are advantageous to access the narrow tributaries and ice-marginal lake sectors. In addition, the basal geometry of such sites provides key boundary conditions for both fjord-glacier interactions and lake-related processes (Carrivick et al., 2022). We first summarize the survey and processing workflow, then show representative GPR sections and bed-detection success rate, and finally compare AIRETH bed elevations with OIB and BM to illustrate where helicopter-borne GPR adds new constraints.

2 Methods

2.1 AIRETH system

AIRETH (Figure 1b–c) is a dual-polarization, helicopter-borne GPR system designed for glaciological surveys that has been used extensively in the European Alps (Langhammer et al., 2019; Grab et al., 2021). Our Greenland campaign was conceived as a first deployment under polar conditions and as the first description of the current, redesigned AIRETH configuration. It aimed to assess whether AIRETH can provide measurements in polythermal, fast-flowing and crevassed outlet-glacier terrain.

AIRETH comprises a lightweight modular airframe carrying two commercial PulseEkko radar systems (Sensors & Software). At the core of the system are two orthogonal bistatic dipole antenna pairs operating at central frequencies of 25, 50, or 100 MHz. The radar hardware is controlled by a central unit (SPIDAR pulseEkko Pro NIC-500P) and complemented by an integrated positioning and attitude system composed of (i) four GNSS antennas mounted at the frame corners, (ii) a central inertial measurement unit, and (iii) a laser altimeter providing ground-clearance information (Figure 1c). System status and acquisition are monitored in real time from the helicopter cockpit.

Compared to earlier AIRETH configurations (Langhammer et al., 2019), the system has been substantially redesigned to improve robustness and data quality: the original wooden carrier frame was replaced by fibreglass-reinforced plastic beams, reducing total weight by about 60% (now at ∼115 kg); the positioning system was integrated to retrieve platform position and orientation during flight; and cable routing was optimized to reduce electromagnetic noise in the GPR signal. Together, these changes yield a self-contained, modular platform with improved signal quality and reduced operational constraints. A detailed hardware description of the current AIRETH configuration is provided in Supplementary Figure S1.

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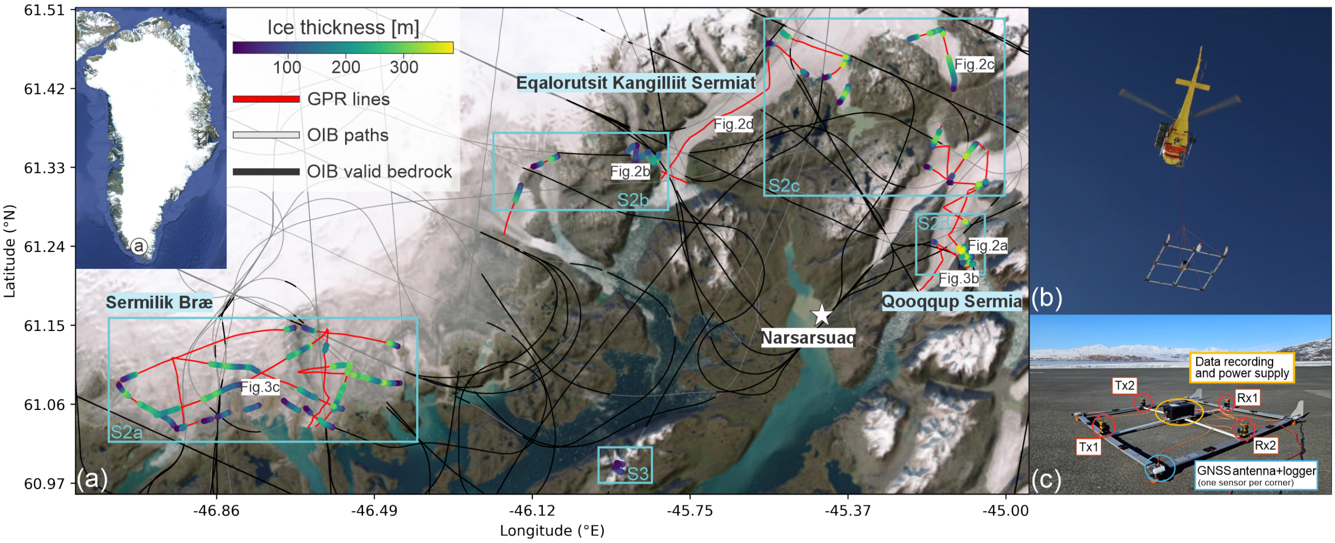

Figure 1. (a) Overview of ice thickness data availability in the Narsarsuaq region of Southern Greenland. Red lines: helicopter-borne AIRETH GPR profiles. Grey lines: OIB flight paths; Black segments: OIB samples with valid bed picks. Colored dots along AIRETH lines show ice thickness where the bedrock was interpreted. The investigated outlet glaciers Sermilik Bræ, Eqalorutsit Kangilliit Sermiat, and Qooqqup Sermia are labeled. Light-blue squares refer to Supplementary Figures S2 and S3. The white star points to the location of Narsarsuaq settlement and airport. Basemap: Esri WorldImagery. (b) AIRETH during acquisition with the carrier frame suspended as a sling-load. (c) AIRETH system layout: quad-loop GPR antenna array (two orthogonal Tx–Rx pairs), GNSS antenna + logger, and data-recording/power unit mounted on the carrier frame.

2.2 GPR data acquisition and processing

The surveys took place in March 2025, deploying AIRETH in the 25 MHz configuration to maximize the penetration depth. Data were acquired at a target altitude of about 30 m above ground, with typical speeds of $\sim$35 km h^{-1} on across-glacier profiles and $\sim$55 km h^{-1} on longitudinal profiles. The few intersections of profiles with clear bed returns were used to assess continuity and internal consistency across individual survey lines. Overall, the collected dataset comprises 348 km of survey lines, encompassing at least one longitudinal profile and several cross profiles for each glacier. The Matlab based GPRglaz package (Grab et al., 2018) was used for data processing. It included two main steps: processing of the positioning system and processing of the GPR data. GNSS, IMU and laser-altimeter data were quality-controlled and combined to obtain platform positions, which were projected onto the glacier surface and synchronized with the GPR traces via GNSS timestamps.

The GPR data were processed following a standard radar processing workflow to improve signal–to–noise ratio and enable clear interpretation. Processing aims to extract the glacier bed reflections and includes the following steps: i) time zero correction based on the arrival of the direct wave, ii) removal of the ringing noise from helicopter using singular value decomposition filtering, iii) Butterworth bandpass filtering (10-75 MHz), iv) trace binning at a spatial sampling rate of 1 m for

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regular sampling, v) surface reflection picking based on the laser altimetry, vi) merging the dual-polarization data channels, vii) time-to-depth conversion by data migration (Kirchhoff and Reverse time migration algorithms), assuming constant radar wave velocities of 0.30 m ns^{-1} and 0.168 m ns^{-1}, for air and ice, respectively. The signal associated with the basal reflection was manually picked in the Petrel software environment (Schlumberger) and the ice thickness was computed as the difference between the elevation of the glacier surface and the elevation of the basal reflections.

2.3 Comparison with existing bedrock estimates

In order to place our results into the context of existing information, we compare them with two available ice thickness and bed elevation constraints: NASA's OIB radar soundings and the BM mass-conservation inversion product (Morlighem et al., 2017). We use point-wise comparisons at collocated locations to assess the local consistency between AIRETH and existing constraints.

For the comparison with OIB, we used the Level-2 radar product of (Paden et al., 2010). We converted the reported one-way surface and bottom ranges to elevations following Paden et al. (2010). Since both datasets are referenced to the WGS-84 ellipsoid, no surface correction is required. For each AIRETH bed pick, we matched OIB soundings (along-track spacing 15 m) within a 10 m horizontal radius and, where multiple valid soundings existed, averaged their bed elevations. Unmatched points were discarded. We excluded a small set of extreme outliers with clearly inconsistent matches, i.e. Δbed = $\mathrm{bed}_{\mathrm{GPR}} - \mathrm{bed}_{\mathrm{OIB}}$ > 600 m.

For BM comparison, we used BM v5 (NSIDC IDBMG4) from the NSIDC DAAC (Morlighem et al., 2022). We sampled its gridded bed, surface, thickness, and source index at each AIRETH bed-pick location. Within our study region, only 5.5% of BM grid cells are reported as directly constrained by thickness measurements; the remaining 94.5% rely on mass-conservation inversion and interpolation.

3 Results and discussion

3.1 AIRETH survey and basal detection in southern Greenland

Bed reflections were identified along about 29% (102 km out of 348 km) of the AIRETH flight lines, with most bed picks obtained in the Sermilik Bræ and Qooqqup Sermia areas (Figure 1a). The spatial distribution of the bed returns is biased towards shallower glacier margins, whereas bed picks are mainly absent in the thicker, central glacier sections. This pattern is consistent with a limited effective penetration depth of about 300 m, as bed returns tend to disappear towards glacier central sectors after being observed along the margins, and only 5% of bed picks indicate ice thicknesses greater than 300 m. At locations without interpretable bed returns, BM indicates thickness higher than 300 m in about 32% of cases, predominantly along the longer longitudinal profiles. The ice thickness retrieved from GPR data is up to 340 m, with a mean value of 230 m. For glacier-scale context and to facilitate identification where bedrock was interpreted, Supplementary Figures S2 and S3 provide zoom-in maps for the glaciers highlighted in Figure 1a.

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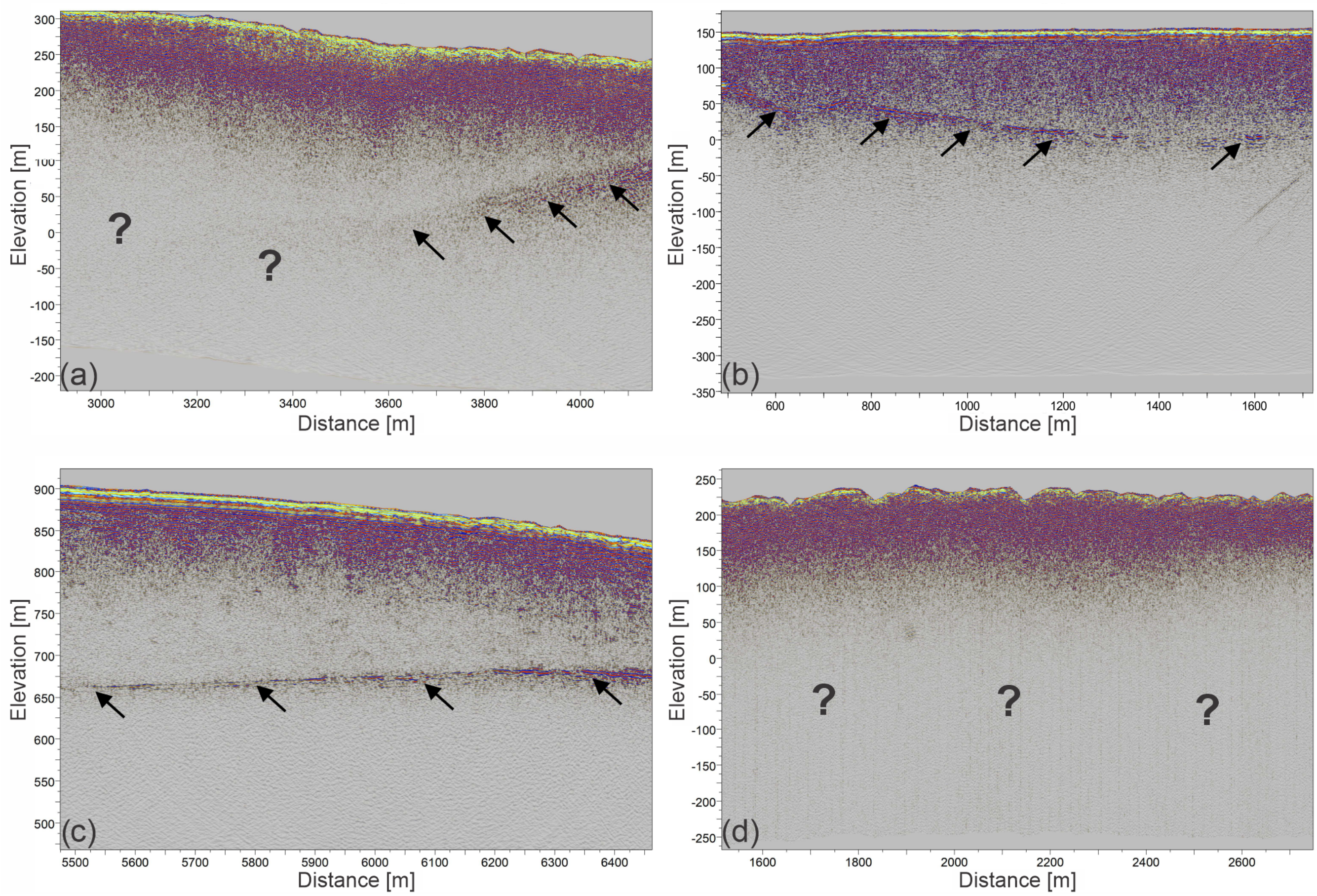

Figure 2. (a–d) Examples of 25 MHz radar sections. Black arrows mark the interpreted bed, while question marks highlight sectors with no reliable basal return. For profiles location, see Figure 1a.

Across most profiles, the bed signal is not observed as a continuous, high-amplitude reflector. Instead, the basal return commonly manifests as a transition from low-amplitude, texture-like clutter to a zone of persistently higher backscatter. We therefore picked the bed at the onset of higher backscatter, guided by lateral continuity (black arrows in Figure 2a), which in places fades below detectability. In a few sectors (cf. Figure 2b–c), the bed forms a continuous, high-amplitude horizon. Longitudinal lines are frequently uninterpretable over deeply crevassed and thicker ice, where the 25 MHz antenna lacked penetration and coherent basal returns (Figure 2d). By contrast, cross-glacier profiles are more reliable, benefitting from tie points at rock outcrops along the margins. Internal englacial reflectors are generally absent in the 25 MHz data. An exception is Narsaq Bræ (Supplementary Figure S3; location in Figure 1a), where profiles show a distinct internal scattering zone that could be consistent with a cold–temperate transition within the glacier (Supplementary Figure S3b).

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3.2 Comparison to OIB and BM estimates

To assess consistency with existing estimates and place AIRETH picks (referred to as "GPR" here below) into context, we compare bed elevations at crossings with OIB and at collocated points with BM. At the intersections of OIB and GPR, bed elevations mostly follow the 1:1 line (red dots in Figure 3a). The median bed difference is about +7 m, which is comparable to our point-wise GPR bed-elevation uncertainty (13 and 22 m for depths of 100 and 400 m, respectively; see Appendix A2). A subset of points departs from this pattern, with OIB indicating bed elevations up to about 390 m lower than AIRETH at a few crossings in the Qooqqup Sermia sector. On the contrary, OIB generally yields higher bed elevations than GPR around Sermilik Bræ.

Comparison between GPR and BM bed points shows a broad scatter around the 1:1 line (Figure 3a; blue dots). Many points lie below the line, meaning that AIRETH tends to indicate a lower bed than BM. A non-negligible number of AIRETH points are higher than the BM estimate, though. The spread increases with depth and includes spatially coherent clusters deviating in both directions. Overall, the bed difference $\Delta\text{bed} = \text{bed}_{\text{GPR}} - \text{bed}_{\text{BM}}$ has a median of -126 m (mean -92 m). A representative profile (Figure 3b) illustrates a case where BM is more than 300 m deeper than our interpretation at the deepest point, despite a broadly similar bed shape.

The surface offset $\Delta\text{s} = \text{surf}_{\text{GPR}} - \text{surf}_{\text{BM}}$ has a median of -4.9 m, a mean of -2.5 m, and a standard deviation of 21 m, i.e. a few tens of meters at most. These offsets are thus much smaller than the bed differences reported in Appendix A2, meaning that surface-elevation differences are not the dominant source of the AIRETH–BM mismatch. Rather than attempting a detailed attribution of these discrepancies, we simply note that bedrock elevations from different products can differ by up to a few hundred meters locally, even where surface elevations agree within a few meters.

3.3 AIRETH as a complement to existing datasets

The comparisons above highlight that helicopter-borne GPR can complement existing products by filling gaps between flight lines, and by targeting complex marginal terrain and narrow outlet-glacier corridors, at least within the penetration range of the current 25 MHz setup. In our study area, AIRETH and existing products show broadly consistent bed elevations at many locations, although local mismatches of up to a few hundred meters occur. At the same time, the BM source index indicates that only a small fraction of the BM grid cells are directly constrained by thickness measurements, meaning that local differences should be interpreted with care. In the Sermilik Bræ sector, BM is directly constrained by radar-derived ice-thickness measurements only along a few flight segments (black lines in Figure1a); elsewhere it relies on the inversion between tracks without such data. Similarly, in the northern part of the survey, near Eqalorutsit Kangilliit Sermiat, AIRETH provides additional bed measurements along outlet-glacier trunks where OIB lines are sparse. More generally, we argue that helicopter-borne GPR can supply targeted thickness measurements where outlet glaciers are otherwise unconstrained, particularly in shallower ice. Similarly, such surveys could be applied elsewhere to densify bed observations in regions with sparse or no radar coverage.

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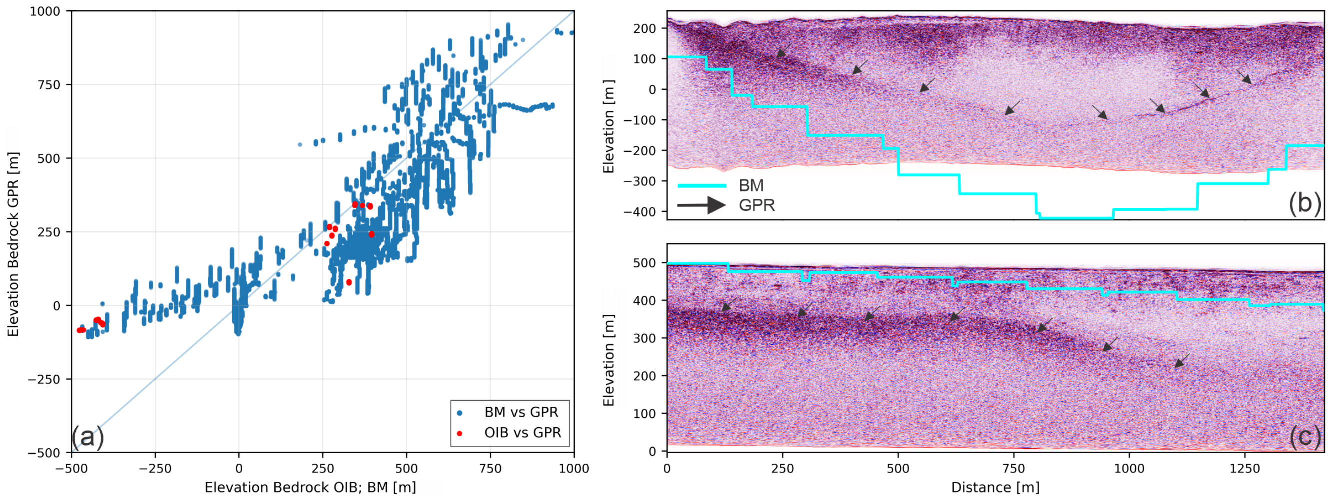

Figure 3. (a) Scatterplot of AIRETH-derived bedrock elevations compared to BM (blue) and OIB (red). The pale diagonal represents the 1:1 line. (b, c) Representative GPR profiles showing the mismatch between the bed identified in AIRETH profiles (black arrows) and BM (light blue line). For profile location, see Figure 3a.

Our surveys help to quantify bed-detection performance and practical limitations of the current AIRETH setup. Using a 25 MHz center frequency, bed reflections are generally retrieved up to depths in the order of 300 m (only ∼5% of picks are deeper), whereas attenuation and scattering increasingly obscure the bed in thicker, crevassed ice, particularly along longitudinal profiles. A lower-frequency configuration (e.g. 12.5 MHz) could extend this depth range, at the expense of spatial resolution. Although higher transmit power could also improve penetration, it is not freely adjustable due to hardware constraints and radio-frequency/aviation regulations. On the positive side, the helicopter platform permits slow flight speeds and tight manoeuvring, enabling dense stacking and targeted coverage in complex glacier geometry. AIRETH can thus be valuable in filling gaps in existing ice thickness products despite its current depth limitation.

4 Conclusions

Our AIRETH survey in southern Greenland shows that a 25 MHz helicopter-borne GPR can recover the ice thickness along about 29 % of the flown profiles (102 km out of 348 km), despite temperate ice conditions. Retrieved thickness values range from a few tens of meters up to about 340 m, with a mean of 230 m. Relative to existing datasets, these new bed picks provide direct thickness constraints in under-sampled outlet-glacier corridors and can therefore support refinement of gridded ice-thickness products in such areas. The survey also constrains the practical operating range of the current AIRETH configuration. At 25 MHz, bed reflections are typically retrieved up to depths of ∼300 m, with only about 5% of picks in thicker ice. This provides a first estimate of the usable depth window. Future deployments will explore a lower-frequency setup (12.5 MHz) to extend penetration depth, acknowledging the associated trade-off in spatial resolution while retaining the flexibility of the

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helicopter-borne platform. Targeted surveys of this type could support selective mapping of ice thickness in other polar regions, and contribute to the goals of the UN Decade of Action for the Cryosphere Sciences (2025-2034).

Data availability. Basal reflection picks are available at https://doi.org/10.3929/ethz-c-000794464. The corresponding AIRETH radar data will be available through the ETH Research Collection soon.

Author contributions. Conceptualization: DF, NBK, FMN, AV, AR, HM. Survey planning: IS, RM, DF. Data acquisition: RM, DF. Data processing: IS, RM. Data interpretation: IS with contributions from HH, HM. Manuscript writing: IS with contributions from all co-authors.

Competing interests. Two co-authors - NBK and DF - are members of the editorial board of The Cryosphere.

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Appendix A: Estimation of GPR uncertainties

Since interpretable basal reflections were sparse in our dataset, no interpolation was performed between profiles. Uncertainties therefore refer to pointwise bed elevations and include contributions from vertical referencing, the assumed radar-wave velocity in ice, and bed interpretability.

For the vertical referencing, we determine a crossing-point surface mismatch of $\mathrm{err}_z \approx 6\,\mathrm{m}$, estimated as the standard deviation of surface-elevation differences at line intersections. This metric captures uncertainties in georeferencing, surface roughness, small horizontal mismatches over sloping terrain, and slight differences in frame tilt between different flight directions.

In the absence of site-specific constraints for the radar-wave velocity in ice, we use $v = 0.168 \pm 0.008\,\mathrm{m\,ns^{-1}}$ (Grab et al., 2021). If ice is significantly wetter than assumed, effective velocities may be lower than 0.168 $\mathrm{m\,ns^{-1}}$, which would systematically reduce thickness, and thus bed depth, estimates in direct proportion to v. For instance, using $v = 0.160$ $\mathrm{m\,ns^{-1}}$ would decrease thickness by $\sim$5%. The velocity-related uncertainty $\mathrm{err}_v(h)$ scales linearly with depth h as

$$\mathrm{err}_v(h) = \frac{0.008}{0.168}\,h \approx 0.047\,h\,. \tag{A1}$$

To account for diffuse or ambiguous basal returns, we adopt a conservative picking uncertainty of $\mathrm{err}_p = 10\,\mathrm{m}$, informed by the "ambiguous bed" class in Grab et al. (2021) and rounded to reflect our common bed appearance. Assuming independent uncertainties and combining these terms in quadrature, the pointwise bed-elevation uncertainty $\mathrm{err}_{\mathrm{bed}}(h)$ is

$$\mathrm{err}_{\mathrm{bed}}(h) = \sqrt{\mathrm{err}_z^2 + \mathrm{err}_v(h)^2 + \mathrm{err}_p^2}. \tag{A2}$$

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Based on Equation A2, $\mathrm{err}_{\mathrm{bed}}(h)$ is ∼13 m, 15 m, 18 m and 22 m for depths of $h = 100$ m, 200 m, 300 m and 400 m, respectively. Equation A2 should be interpreted as a lower bound for intervals with ambiguous basal returns, where diffuse or multi-peaked reflections can increase the picked horizon beyond err_p.

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