

Response to reviewer comments by Adriano Ribolini

Thank you for the careful reading of our manuscript and for the detailed comments. We have addressed all comments point by point below.

- The paper is essentially based on Ground-Penetrating Radar, and how this type of data can validate or reject model-based glacier thickness assessments. For this reason, I believe more attention should be paid to describing the individual steps of GPR data processing, data interpretation, and data visualization. It is unclear to me why data migration was not applied once the radar wave propagation velocity was determined.

The radar profiles do not appear to have been interpreted unambiguously; the areas indicated as characterized by strong scattering appear similar to others interpreted differently.

Some signals are not interpreted, despite being frequent in the two images presented.

Response: Thank you for the comment. We must note that the bed reflection was weak in many profiles, and in some cases bed detection was only possible by identifying changes in the overall character of the GPR signal scattering rather than a distinct reflection. Initially we tried to apply migration, however it had the adverse effect of further attenuating the weak bed signal, making the bed impossible to trace.

We acknowledge that the dataset is challenging to interpret. For this reason, bed picks were made only in sections where a reflection was traceable, and we deliberately avoided picking in sections where no reliable signal could be identified. Englacial reflections visible within the ice column were not interpreted, as their detailed analysis falls outside the scope of this study, although most are consistent with hyperbolic diffraction arms from point scatterers within the ice.

- The issue of propagation velocity is a delicate one, as is well known. However, interpreting radar images by emphasizing the existence of areas with different water content ("characterized by strong scattering signals") implies a non-constant propagation velocity of EM waves, whatever the value assumed. It could be useful to use a velocity model, even with values derived from the literature.

Response: We agree that EM velocity in a temperate glacier is likely spatially variable, and likely exhibits 3D characteristics. However, without CMP measurements or clear hyperbolic diffractions (neither of which were available in this survey) it is not possible to determine spatially variable velocity values. We note that our chosen value of 0.168 m/ns is consistent with GPR studies on temperate Alpine glaciers, for example Church et al. (2020) used 0.1689 m/ns for Rhonegletscher and Rutishauser et al. (2016) applied the same for Swiss Alpine glaciers. Using a single well-supported velocity value is standard practice in glaciological GPR studies and provides transparency about the assumptions made. To show the magnitude of this assumption quantitatively, we used an extreme temperate ice value of 0.156 m/ns (Murray et al., 2000), representing a highly water-saturated glacier, that showed that in a worst-case scenario there would be a 7% systematic overestimation of GPR-derived ice thickness (~5.7 m on our mean thickness of ~81 m), confirming that the velocity assumption has no significant effect on our conclusions.

- The (admitted) uncertainties in choosing a constant velocity value, the possible lateral/vertical velocity variations, and the (in my opinion) unclear interpretation of zones of the radar profiles could undermine the validation of glacier thickness based on modelling.

Response: We acknowledge that the dataset presents interpretational challenges, as discussed in our previous responses. However, the differences between modelled and GPR-derived ice thickness are substantial - reported model biases of 40–60 m far exceed any plausible GPR uncertainty. Furthermore, as quantified above, using a lower temperate ice velocity would reduce GPR-derived thickness, which would increase rather than decrease the apparent model bias. The conclusions of this study are therefore robust regardless of the specific velocity assumption made.

- finally, I believe the GPR methodological part should be enhanced, and the interpretation improved, also in light of additional processing steps.

Response: Thank you for the suggestion. The main GPR processing steps are already described in the manuscript: bandpass filtering (Ormsby filter, 20–70 MHz), manually adjusted time-dependent signal gain function, topographical correction using the DSM, and bed reflection picking at approximately 10 m intervals. We will add the time sampling parameter (range per sample: 2500 ps) which was inadvertently omitted.

Comments in the .pdf file:

P4. please provide (in brackets) according to which EM velocity, and how this velocity was assumed a priori

Response: We used $\epsilon=3.2$. We will add this information to the manuscript.

P5. Please explain what you actually picked. A travel time (ns) picked every 10 m is not fully clear to me. Perhaps it is a travel-time depth converted?

Response: We picked two-way travel times of the basal reflection from each GPR profile. These travel times were subsequently converted to ice thickness values using the assumed EM velocity of 0.168 m/ns. The ~10 m spacing refers to the horizontal distance between individual picks along each profile, not a depth interval. We will clarify this in the revised manuscript.

P5. do you mean internal to the glacier? can the existence of scattering points led to point-sourced hyperbola diffractions? Is it possible that the absence of hyperbolas is related to the low central frequency of the antenna?

Response: Yes, we are referring to scattering points internal to the glacier, most likely water inclusions. Point sources in general produce hyperbolic diffractions, but this is not always the case. The visibility of hyperbolas depends on the size of the scattering object relative to the wavelength, the antenna frequency, and the contrast in dielectric properties. The low central frequency of our 38 MHz antenna results in a wavelength of ~4.4 m in ice (calculated as $v/f = 0.168 \text{ m/ns} / 38 \text{ MHz}$). The commonly cited rule of thumb requires scattering objects to be at least $\lambda/3 \approx 1.5 \text{ m}$ in size to produce detectable hyperbolas, though published values vary and this threshold is not always met in practice even when larger scatterers are present. In practice, from our experience working with GPR antennas across a wide frequency range (38 MHz to 2 GHz) in various environments, the theoretical conditions for hyperbola formation are not always reliably met in field settings.

P5. Did you also consider other values from more modern publications?

Response: We selected the most widely used and well-supported value for glacier ice (0.168 m/ns), which is also consistent with direct measurements from temperate Alpine glaciers as discussed in our previous responses. We do not consider a more recently published value to be any more accurate for this specific glacier, because without direct velocity measurements, any value selected from the literature carries the same fundamental uncertainty. The sensitivity of our results to this choice is already quantified in the manuscript, where using the extreme temperate ice value of 0.156 m/ns yields a worst-case 7% systematic overestimation, confirming that the velocity assumption does not affect the conclusions of this study.

P5. The data processing section seems a bit limited to me. The GPR data and their interpretation are crucial to this paper, and data processing would have deserved a little more space. For example, the signal gain function is not described, and a power spectrum justifying the bandwidth selection is not shown. Why was migration not attempted?

Response: Thank you for the comment. Regarding the signal gain function, we applied a manually adjusted time-dependent gain function based on the classical assumption of exponential EM wave attenuation with depth. Manual gain adjustment is a standard and widely used approach in GPR data processing, particularly when the primary goal is to identify and trace specific reflections rather than preserve amplitude fidelity.

Regarding the power spectrum and bandwidth selection, the Ormsby bandpass filter parameters (20–70 MHz) were centred on the nominal antenna frequency of 38 MHz. In the low-frequency range applicable here, dielectric permittivity shows weak frequency dependence, which significantly constrains the meaningful spectral range available for filtering. Bandpass filter selection at low antenna frequencies is therefore relatively straightforward, and a power spectrum figure is not standard practice in glaciological GPR publications, at least we are not aware of any published glacier GPR study that includes such a figure.

Regarding migration, this is addressed in our response above.

P6. If you are referring to vertical resolution, could you explain why it's not $\lambda/4$? Or do you mean $\pm\lambda/2$?

Response: The $\lambda/4$ criterion refers to the theoretical vertical resolution limit under ideal conditions, where the minimum separation between two distinct reflectors can be distinguished. As noted by Navarro and Eisen (2009), in practice this may worsen to $\lambda/2$, which represents a conservative estimate of picking uncertainty for a single reflection. The figure below illustrates this distinction: at $\lambda/4$ separation the two reflectors are just barely resolvable, while at $\lambda/2$ they are relatively clearly separated, demonstrating that $\lambda/2$ represents a realistic upper bound on the uncertainty in identifying the true peak position of a weak reflection. Given the weak and noisy bed reflection in our data, where the wavelet peak cannot always be unambiguously identified, we consider $\pm\lambda/2$ the appropriate and conservative choice, fully

consistent with Navarro and Eisen (2009).

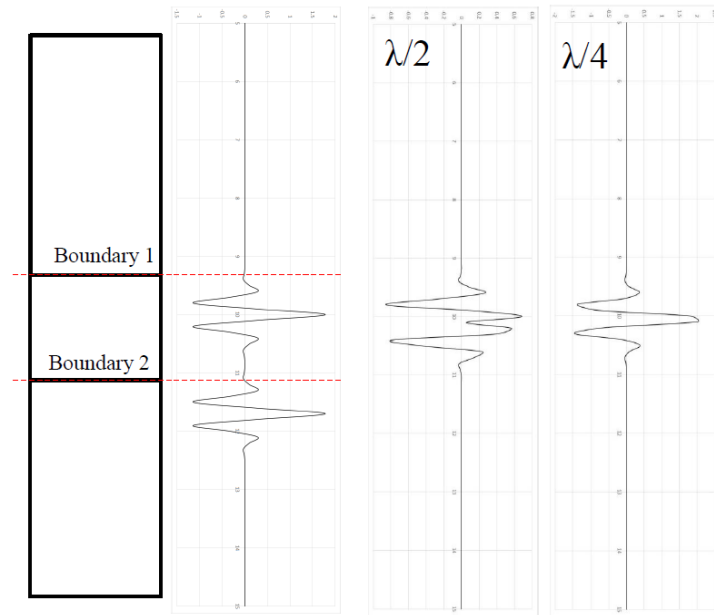


Figure: Schematic illustration of vertical resolution concepts showing two boundaries separated by $\lambda/2$ (left) and $\lambda/4$ (right). It is our own simulation for illustrative purposes.

P6. I think the problem could be a little more complicated. If you've identified parts of the glacier as potentially water-rich, this means that the velocity can vary vertically and laterally. So assuming a constant velocity, and evaluating a bias while also considering another constant velocity, I'm not sure can lead to a very refined evaluation of the picking error. However, I also believe that in the end, the percentage deviation shouldn't be relevant for the purposes of the paper. And besides, without CMP surveys and diffraction hyperbolas, there aren't many other alternatives.

Response: We agree that a spatially variable velocity would complicate the uncertainty assessment, and that a precise evaluation is not possible without CMP surveys or clear hyperbolic diffractions - as you already note in the comment. The ~10% worst-case uncertainty cited in the manuscript represents the combined effect of the velocity assumption (~7%, derived from using the extreme temperate ice value of 0.156 m/ns) and the picking uncertainty (~3%), assuming both act in the same direction simultaneously. In practice these uncertainties are unlikely to fully combine, and the true uncertainty is likely lower. We agree with your conclusion that given the available data, there are no better alternatives for velocity determination, and add that regardless of the precise uncertainty estimate, the reported model biases far exceed any plausible GPR uncertainty.

P7. In the radar profiles in Fig. 2, two sets of regularly oblique reflections intersecting at approximately 90° are observed (particularly evident in Fig.2 b, I tried to mark on the figure). I would like to ask whether these could correspond to ice layering, or to hyperbola arms that locally interfere positively, or to noise that could be eliminated with FK filtering.

Response: Thank you for this observation. The marked oblique reflections visible in Fig. 2b, we interpret as arms of hyperbolic diffractions from point scatterers within the ice. FK filtering could theoretically suppress some of these features but given that the bed reflection is already at the noise level, applying FK filtering risked further attenuating the weak bed signal and was therefore not attempted.

In Fig. 2b, the area indicated as characterized by strong signal scattering doesn't seem very different from many other parts of the profile.

Response: We agree - the scattering characteristics in the indicated area are not clearly distinct from other parts of the profile. We will remove this arrow from the figure in the revised manuscript as it is misleading. In this case we meant signal scattering that is visible basically everywhere in radar images and created by temperate ice.

It might be useful to apply a constant velocity migration.

Response: As we explained to the comments before, migration was attempted during data processing. However, in profiles where the bed reflection was already at or near the noise level, migration did not improve bed visibility and in some cases made bed tracing more difficult. We therefore proceeded without migration for those profiles.

P7. Is this the only possible interpretation? I would be more cautious.

Response: Of course, there is also possibility that there are debris incorporated into the ice, but in this case and many other cases in temperate alpine glaciers, also glaciers in Iceland, Alaska etc., it is commonly interpreted as an indication of temperate ice with water inclusions. If there are some scattered debris inclusions, they would produce the similar signal characteristics locally, larger debris bands however would create planar reflections what was not in this case. Reflections from possible debris bands, for example, we encountered in Greenland (Lamsters et al., 2024) with clearly notable planar expression. We do not see any convincing signals that could be attributed exclusively to debris bands in this case due to high water content and scattering created by that primary.

P7. Could you mark the reflection generated by this surface on the GPR profile?

Response: Yes, we will mark it with arrows.

It is not clear to me: if there is a piezometric surface, does this mean that everything below it is saturated? If so, why does the signal scattering due to water content only occur in a limited portion of the subsurface?

Response: Thank you for the comment, yes, that theoretically means that the ice below contains voids filled with water. All water inclusions below generate radar signal scattering characteristic for temperate glaciers, especially Alpine ones as described by Murray et al. (2000), Lamsters et al. (2020b), and we are going to add more references and details in the updated version of the manuscript such as “and demonstrated by a combination of GPR measurements and borehole data by Jania et al. (1996). Also, Bradford and Harper (2005) found a similar distinct boundary (upper low-water content/lower high-water content layer) in temperate glacier in Alaska, which specifically coincided with the average piezometric surface measured in boreholes. Therefore, the lack of EM wave scattering suggests that the transparent upper ice is not a cold ice but reflects the boundary between high and low water content within temperate ice due to the absence of water that could trigger such scattering.”

We would like not to go in more details as more extended discussion of this issue is already present in literature and also in our previous study from Iceland (Lamsters et al., 2020b).

Signal scattering we are referring to does not occur in the limited portion of subsurface but practically everywhere, as mentioned before, except the very topmost part of some radar

images. More intense scattering of vertically stacked hyperbolae in some profiles is referred as crevasses and/or supraglacial streams.

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