Response to reviews of "Brief Communication: An empirical relation between center frequency and measured thickness for radar sounding of temperate glaciers"

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We thank the editor and both reviewers for their thorough and constructive comments on this manuscript, especially given that these reviews were conducted amid the ongoing pandemic and associated workplace challenges. Below is our response to the reviewers' comments on the original manuscript submitted to The Cryosphere Discussions in January 2021. We have edited the manuscript in response and made a few other minor cosmetic changes, all with changes tracked. We've added an additional co-author, John Paden, who has provided further insight into suitable frequencies for radar sounders based on his experience.

Separately, after the discussion period closed, we received valuable external feedback from Laurent Mingo (Blue Systems Integration) on the potential ambiguity in our interpretation of the definition of center frequency. Briefly, he noted that the wavelength transmitted into the surrounding medium by a given physical antenna will be the same regardless of whether that medium is air or ice. However, the *frequency* of the resulting radio wave will differ depending on the medium's radio-wave velocity. Because the radio-wave velocity in ice is slower than that of air, the effective frequency of a given physical antenna is lower for a ground-based survey than an airborne one. In general, we expect that the reported frequency is for air, which is the case for airborne systems, commercial GPRs and likely to be the case for some (if not clearly all) custom-build ground-based systems. However, which frequency is reported in the literature is not always clear, so we have opted to clarify our assumption for ground-based surveys. This clarification does not materially alter our conclusions, but we have adjusted several statements to reflect this improved understanding.

Material comments are in blue and italicized, and our response in black follows each comment. For reviewer #1, some comments are grouped/reorganized to avoid repetition.

Response to reviewer #1 (M. Grab)

> *The relation between the central frequency of impulse radars and the penetration depth of the radar waves into glacier ice is complex, because it depends on various factors given by the nature of the glaciers such as water content in the ice, roughness of the glacier bed, or size and spatial density of crevasses, and on instrument parameters like the height of instrument employment above the ice or the transmitter power. Due to this complexity, no simple formula is known up to date for evaluating the central frequency required to investigate a glacier with a certain ice thickness.*
>
> *In recent years, a database has been compiled by Welty et al. (2020), containing an unprecedented number of ice thickness data from all over the world obtained from radar campaigns. In their study, MacGregor et al. made use of these data and established a simple log-linear relationship, that indicates the maximum ice thicknesses that can be surveyed with a given frequency. According to the authors and also to my knowledge, this is the first time, such an investigation has been done based on such a comprehensive amount of data.*

We thank the reviewer for their very positive comments. We are particularly glad that their perspective on the purpose of the manuscript is well aligned with what we hoped to achieve, i.e., not the last word on relating radar center frequency and ice thickness, but a useful step in connecting the two by relating a lot of recently aggregated information.

General Comment:

The study is well written and concise, therefore well-suited for a 'brief communication' in The Cryosphere journal. I agree with the authors (line 109) that a more complex relationship is not justified under consideration of the potential biases listed on lines 93-103.

I recommend the authors add a few sentences at the end of the article, where they summarize how they interpret their empirical relationship between sounding depth and frequency and how they would like to see it be used in practice (See also my minor comment about lines 118-120.

Lines 118-120: "For most temperate regions (10/13), a modern ≤ 100-MHz radar sounder could plausibly sound the maximum ice thicknesses of 95% of their glaciers (< 500 m; Fig. 2). For Alaska, Iceland and the Southern Andes, a lower-frequency (≤ 30 MHz) radar sounder remains necessary,..."

This is the only section in the article, in which you give a hint how the empirical relationship you established could be used in practice. I would very much like to see a concluding remark at the end of the article, where you explain how you interpret your empirical relationship.

I don't agree that it is plausible that sounders with up to 100 MHz could sound the maximum thickness of this high amount of 95% of the glaciers in a region with glaciers of no more than 500 m ice thickness. I would rather say it is the maximum we can expect under perfect (and therefore unrealistic) circumstances.

Within the critical frequency range >10 MHz, the envelope is supported by only a few data points (mainly those with GlaThiDa ID's 507, 508, 2040, 2149, Fig. A). According to the discussions on Lines 110-113, the authors interpret the instrument performance for such points to be at their limit, whereas for other points, instruments either underperformed or where "unusually challenged by temperate ice". According to my experience in glacier thickness surveying, this challenge could occur on numerous glaciers. Therefore, it is not realistic that with a 100 MHz instrument the maximum ice thickness of 95% of the glaciers with ice thicknesses ≤ 500 m can be detected.

If I would be in the position to design an instrument for surveying a large region with glaciers ≤ 500 m thick, I would, based on Figure 1a, choose a frequency of certainly no more than 50 MHz.

We agree with the reviewer that the originally submitted manuscript was insufficiently clear in how this envelope could be interpreted. We've now added a new paragraph to the Discussion and Conclusions that clarifies our recommendations in terms of frequency given different survey scenarios. We've further reorganized some of the statements in this section to better distinguish the nature of this envelope and how we think it ought to be applied. We've replaced the term "plausible" with "possible", given the reviewer's dislike for it and because the former's definition can have negative connotations. Within the Figure 2 caption and in the text, we now clarify that this is meant to indicate a survey under ideal conditions.

Minor Comments:
Line 18: "Newer airborne radar sounders generally outperform older, ground-based ones at comparable frequencies":

This finding cannot be deduced from the results presented in this manuscript. See comments about lines 87-88 below.

Lines 87-88: "Especially at higher frequencies (≥ 20 MHz), newer radar sounders (2000–onward) outperform older ones, which favored lower frequencies (≤ 10 MHz).":

This cannot be deduced from the data shown in Figure 1a. There are only two data points acquired before 2000 at frequencies ≥ 20 MHz: the two with GlaThiDa id's 334 and 2100 (see Fig A). The data point with id 334 is showing an ice thickness which is larger than all the thicknesses from newer campaigns at the same frequency and for temperate ice. Also in comparison with newer measurements at other frequencies the measured ice thickness of point 334 seems to be larger than average. The other data point with id 2100 shows a lower thickness of only around 120 meters but is even closer to the envelope. Either not all the data is shown (are there some symbols hidden by others in Fig 1a?) that leads to the conclusion that newer campaigns outperform older ones or this conclusion is wrong.

All the available data is shown. The reviewer is correct that these statements concerning newer systems outperforming older ones is not always accurate, but we maintain that it is generally true within a broad frequency range (25–100 MHz), which we now specify. We included qualifiers to that statement previously (e.g., "tend to outperform"), but admit that these statements were insufficiently nuanced and did not capture the evolution well, leading to the confusion that the reviewer identified. We've reformulated both the abstract and this paragraph to better represent the observed patterns as follows.

Abstract sentence in question now reads:
"Between 25–100 MHz, newer airborne radar sounders generally outperform older, ground-based ones, so radar-sounder success is also influenced by system design and processing methods."

Paragraph in question now reads:
"Most radar-sounding surveys of temperate glaciers before 2000 (55 of 63) deployed systems with frequencies below 20 MHz, while about half (138 of 258) of modern surveys (2000–onward) used higher frequencies (≥ 20 MHz). At very low frequencies (< 3 MHz) and at higher ones (> 20 MHz), it is these modern radar sounders that sound unusually large ice thicknesses compared to older surveys at nearby frequencies. However, between 3–20 MHz ground-based surveys are predominant and sound the thickest ice. Between 25–100 MHz, newer airborne systems tend to outperform ground-based systems at comparable frequencies, and helicopter-borne systems tend to outperform fixed-wing systems (e.g., 100 MHz), presumably due to the former's slower platform speed and potentially lower altitude above ground level (Fig. 1b). Higher frequencies (≥ 60 MHz) can sound much thicker polythermal or polar ice than has been achieved for temperate glaciers, but this relative performance advantage for colder ice is reduced significantly below ~30 MHz, which may be due to lower antenna gains and increased environmental interference."

Line 82: Caption of Figure 1-a: Only after studying Figure 1-b it becomes clear that grey symbols are data from cold glaciers. I suggest to add a comment in the caption.

We've slightly deepened the color of these symbols to emphasize that they are blue and have added mention of their nature to both the legend to address this issue. We've also reworded the caption to flow better and capture this nuance.

Lines 94-96: "2. While the situation is changing with the advent of globally modeled glacier thicknesses (e.g., Farinotti et al., 2019), radar-sounding surveys have historically not always known beforehand where ice thickness is predicted to be greatest, nor its expected value"

The reader can only guess how this leads to the "likely negative bias" to which you refer to on line 99. Please provide further explanations. Do you mean that ice thickness models provide information for planning radar surveys? If the glacier exhibits larger ice thicknesses than expected and researchers accidently use a radar system with too low penetration depth, their instruments perform at the limit and we would not expect a negative bias. Alternatively, researchers might acquire data while choosing a too short acquisition time window (for example described in Ruthishauser et al. 2016). In this case, indeed, the instrument would underperform which would result in a negative bias.

We agree with the reviewer's assessment that this bias was not so clear, so we've reworded this bias. Our focus was on simply missing the maximum thickness if there's no good prediction of where it is beforehand, but the reviewer also identified other system selection and survey design considerations that would also induce this effect.

We've reworded this sentence to:
"Most radar-sounding surveys have rarely known beforehand where ice thickness is predicted to be greatest or its expected value there, so for a given glacier this location may not have been surveyed or a suitable radar sounder may not have been selected. (this situation has ameliorated recently with the advent of globally modeled glacier thicknesses, e.g., Farinotti et al., 2019)".

Line 122: Some of the histograms are difficult to read because lines are overprinted trough other histograms and because some colours are hard to differentiate. I suggest to display them separately with vertical offset and maybe in 2 or 3 columns.

Agreed. We've changed Figure 2 to be two panels now, with one panel representing the first six presumed temperate regions in sequential order of RGI region number and the second showing the remaining seven.

Line 157-159: "Multiple (≥ 3) antenna elements in a plane perpendicular to the platform's direction of travel are essential to resolving cross-track ambiguity in the direction of arrival of coherently recorded reflections,...": Additionally, it can be beneficial to use orthogonal pairs of antennas when the target glaciers are valley glaciers, as we have presented in our study by Langhammer et al. (2019).

Agreed, and thanks for drawing our attention to this highly relevant study, of which we were previously unaware. We've now added mention of this study and its orthogonal antenna strategy in the final paragraph: "Langhammer et al. (2019) recently demonstrated that two orthogonal pairs of helicopter-towed 25-MHz antennas can better sound temperate glaciers because the pseudo-scalar sum of the antenna response is less sensitive to unfavorable bed geometry."

Response to reviewer #2 (anonymous)

General comments: The manuscript is very well written, and the results are presented concise and clearly. In my opinion, the study makes a significant contribution to the radioglaciology community as it systematically analyzes, -and confirms, the previously assumed relationship between frequency and ice thickness over temperate glaciers. Furthermore, I think that this study provides *useful insights when planning future radar sounding surveys. Overall, I think that the study is well-suited for a 'brief communication' in The Cryosphere, and only have a few recommendations/suggestions.*

We thank the reviewer for their clear and constructive review. Their summary demonstrates that what they gleaned from our study is exactly what we'd hoped to convey.

Minor comments:

L35-36: The following sentence structure is somewhat difficult to understand, maybe change to "... keep the signal-to-noise ratio high between the ice-bed reflection (signal) and the cavity induced volume scattering arising from the cavities (noise) high."

We agree and have simplified the last part of this sentence to: "between the ice–bed reflection (signal) and any cavity-induced volume scattering (noise)."

L95-96: "... radar-sounding surveys have historically not always known beforehand where ice thickness is predicted to be greatest, ..." The sampling bias resulting from this statement is not clear, I suggest clarifying this sentence.

Reviewer #1 had a similar comment on this particular bias. To clarify the nature of this sampling bias, we've changed this sentence to: "Most radar-sounding surveys have rarely known beforehand where ice thickness is predicted to be greatest or its expected value there, so for a given glacier this location may not have been surveyed or a suitable radar sounder may not have been selected. (this situation has ameliorated recently with the advent of globally modeled glacier thicknesses, e.g., Farinotti et al., 2019)"

L98-99: "Some glaciers we assume are temperate -... - are not.' This sentence reads as the authors know which glaciers were incorrectly assumed as temperate. I suggest changing the last part of the sentence to 'are maybe not."

Agreed and adjusted the final part of this sentence to "may not be temperate".

Figure 2: The figure is quite busy, and it is difficult to identify the ice thickness distribution for some survey regions. If possible, I suggest splitting the figure into a few separate panels, each including a few regions.

Reviewer #1 had a similar comment, so we've now broken out Figure 2 into two panels as per both reviewers' suggestions.