Comment on “Brief communication: An empirical relation between center frequency and measured thickness for radar sounding of temperate glaciers” by Joseph A. MacGregor et al.

Review by Melchior Grab
February 18, 2021

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 data base 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.

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.

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.

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.

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.

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.

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.

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.

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).

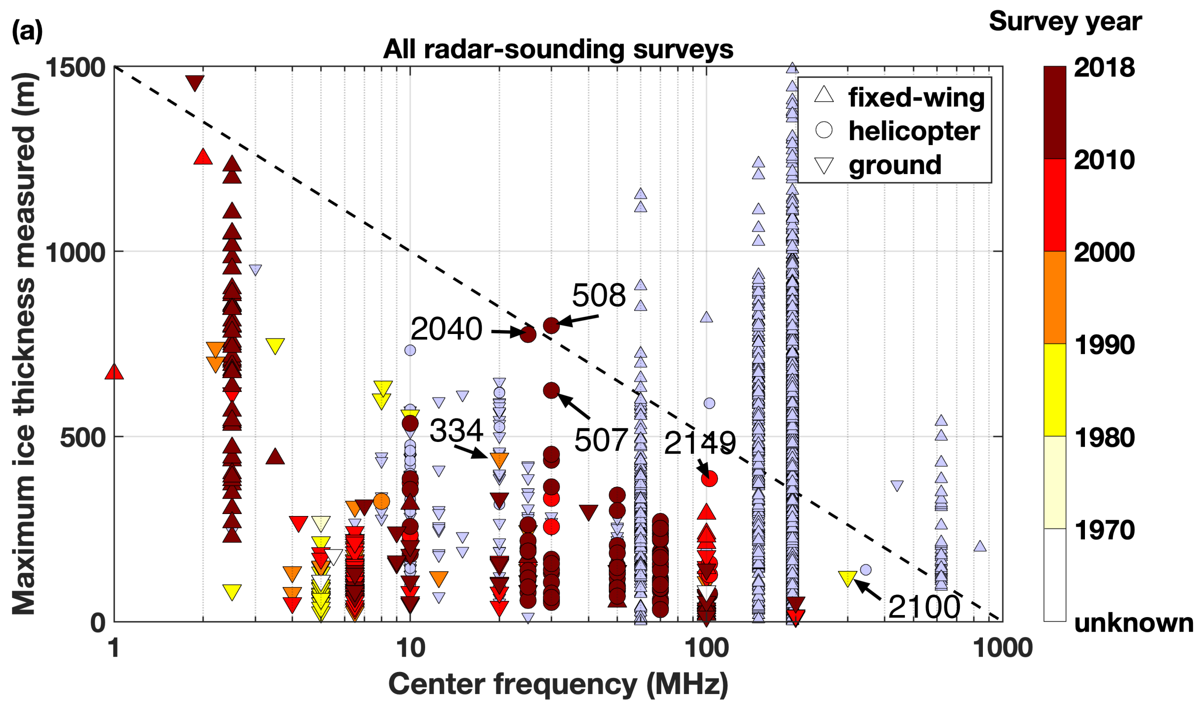

Figure A: Identical with Figure 1a by MacGregor et al. Black numbers indicate GlaThiDa ID's of points referred to in the reviewing comments.

References:

Langhammer et al. (2019): "Glacier bed surveying with helicopter-borne dual-polarization ground-penetrating radar." Journal of Glaciology 65.249, 123-135.

Rutishauser et al. (2016). "Helicopter-borne ground-penetrating radar investigations on temperate alpine glaciers: A comparison of different systems and their abilities for bedrock mappingHelicopter GPR on temperate glaciers." Geophysics 81.1, WA119-WA129.

Welty, Ethan, et al. (2020): "Worldwide version-controlled database of glacier thickness observations." Earth System Science Data 12.4, 3039-3055.