The Cryosphere Discussions

The Cryosphere Discuss., referee comment RC2
https://doi.org/10.5194/tc-2021-82-RC2, 2021

Comment on tc-2021-82

Anonymous Referee #2

Referee comment on "Ground-penetrating radar imaging reveals glacier's drainage network in 3D" by Gregory Church et al., The Cryosphere Discuss., https://doi.org/10.5194/tc-2021-82-RC2, 2021

Review of "Ground-penetrating radar imaging reveals glacier's drainage network in 3D" by Gregory Church et al., May 2021

General Comments:

This paper presents the results of a high-resolution, 3D ground-penetrating radar (GPR) experiment conducted near the terminus of the Rhonegletscher in Switzerland. Approximately ~85 line km of GPR data were acquired with 25-MHz antennas along a series of parallel survey lines oriented perpendicular to glacier flow. A dense (2-m) line spacing was used in order to avoid spatial aliasing of reflection events in the cross-line direction. By examining the spatial distribution of reflection amplitudes in the processed 3D GPR data cube, the authors are able to clearly identify and map major englacial and subglacial channels, which allows them to importantly confirm that englacial conduits tend to flow around glacial overdeepenings rather than directly over them. Further, they identify a number of other high-amplitude zones near the glacier bed that may represent accumulations of subglacial water.

Overall, I found this paper to be of excellent quality and think that it represents a very interesting contribution to the existing literature. The amount of work to acquire these data (on foot!) is impressive, and the results strongly encourage the continued use of dense 3D GPR acquisitions in glacier hydrological studies. My suggested revisions (see below) are rather minor and mainly focus along the following three themes:

1) The authors should further acknowledge previous work involving dense 3D GPR acquisitions on glaciers and avoid statements suggesting that this is the first study of this kind. The study is excellent and the findings are extremely interesting, but it is not the first time that people have considered these kinds of data, even within the context of glacier hydrology.

2) The authors should reduce the conclusive nature of a number of statements in the manuscript concerning channel widths and heights, data resolution, and the presence of subglacial water. For me, many of these findings are not absolute and the corresponding uncertainty should be clearly expressed in the interpretation.

3) A more in-depth discussion of some aspects of the GPR data processing, as well as on resolution, should be provided.

Specific comments:

Line 6: Please delete "for the first time" and "unprecedented" from this sentence in the abstract. As much as the results presented in this paper are truly excellent and impressive, the wording suggests that such data have never been acquired before. Harper et al. (2010) use high-resolution, unaliased 3D GPR data to identify basal crevasses forming part of the subglacial drainage system of Bench Glacier, Alaska. More recently, Egli et al. (2021) identify the subglacial channel network on two Swiss glaciers from unaliased 3D GPR surveys. Hansen et al. (2020) also use 3D GPR to map the englacial and subglacial drainage system in a High-Arctic glacier, albeit in this latter case the survey lines were spaced quite far apart.

Lines 27-46: The introduction of the paper is quite good, but very short, and for me what is missing is a summary and acknowledgement of work where people have used similarly unaliased 3D GPR surveys to investigate glaciers. Papers to be mentioned specifically in this context include Harper et al. (2010), Murray and Booth (2010), Reinardy et al. (2019), and Egli et al. (2021). Of these, Harper et al. (2010) and Egli et al. (2021) specifically investigate the glacier drainage system.

Line 89, "Such a processing step...": This sentence is confusing. What do you mean by an amplitude imprint?

Line 90: Please provide details on how exactly the data were "interpolated and regularized". What do you mean by regularization?

Line 93: Please provide some further details on the Kirchhoff migration procedure. How did you choose the constant velocity of 0.167 m/ns, which corresponds to ice with essentially zero water content? And what aperture was used for the migration? I assume that no corrections for the radiation pattern of the antennas were included (?) Did you account for the effects of the glacier surface topography?

Line 95: More details on the Q compensation are needed. How significant was the dispersion in the data and why?

Line 95: The data were already once bandpass filtered. Now, after migration, you mention that they were bandpass filtered again. Please explain why exactly this second filtering is necessary.

Line 100, "The spatial extent...": This step is not at all clear and needs further details and explanation.

Line 110: You mention that a weak ice-bed reflection indicates that subglacial water is not present, but there could be other explanations. For example, the bed reflection may change amplitude as a result of variable success of the migration of the data. That is, assumptions in the migration (e.g., constant velocity no radiation patterns) along with the biased nature of the sampling (0.5 m in-line; 2 m cross-line) may cause amplitude artifacts along the bed. Also, I would think that, at a frequency of 25 MHz, you would need quite a thick layer of water at the bed to be seen (i.e., water may still be there, but in a thinner layer).

Line 122, "The entire drainage network was identified from the GPR data": I think this sentence needs to be revised to reflect the fact that only the parts of the drainage network within the resolution limits of the GPR data were identified. There may be many more smaller englacial and subglacial conduits that were simply not detected with the 25-MHz data because of its rather low resolution.

Line 123, "red in Fig. 4a": There is no red in Figure 4a.

Figure 4: Regions A,B,C,D should be labeled on both subplots (a) and (b). Also, it's not very clear how the amplitude plot in (a) was obtained. As I understand it, you extracted the outline of the glacier drainage network based on high reflection amplitudes observed in the data (blue lines in Figure 3). Then you went along this identified drainage network and calculated the RMS amplitude in a 2-m window centered around the drainage network (?) If this is the case, then why do we see only a thin yellow zone with high reflection amplitudes in (a)? Wasn't this entire drainage network region chosen because of high amplitudes in the data? You also mention that the high-amplitude (yellow) regions here correspond to water, but how do you know? Couldn't they correspond to air in the channel? Finally, the RMS amplitudes in the south are very low (near zero), suggesting that a conduit is not present. What is happening there?

Line 130: Observation "D" is not clear for me from Figure 4.

Lines 132-142: This paragraph attempts to use the GPR results in Figure 4a to assess the width and height of the identified channels, but for me the statements are far too conclusive given the resolution limitations and uncertainties in the data, and require some important assumptions. For example, in your assessment of the channel height, you appear to make use of the 1/4 wavelength vertical resolution criterion, which at 25 MHz and for water (velocity = 0.033 m/ns) is around 0.33 m. But this assumes that the channel is water-filled, which may not be the case. As the identified channels are extremely large, couldn't they be at least partly filled with air? In the case of an air-filled channel, the 1/4 wavelength value increases to 3 m meaning the channel height could be much greater. With regard to horizontal resolution, the GPR wavelength in ice will also have some effect. In perfectly migrated data, for example, the limit to horizontal resolution (if I remember correctly) is 1/2 wavelength, which for ice and 25 MHz is 0.84 m. But practically the value will be greater than this because of the limited migration aperture, lack of taking into account antenna radiation patterns, constant velocity assumption, etc. In short, I think some detailed discussion on resolution is needed in the manuscript, and statements should be written to reflect the substantial uncertainty as a result of limits to resolution.

Lines 148 and 150: The word "indicating" tells me that you are sure, whereas it seems that there is some uncertainty in this interpretation (i.e., other things could explain higher amplitudes in the bed reflection, as mentioned above). I would replace with "which may indicate".

Line 162, "A 3D migration effectively collapses...": The migration does indeed collapse the Fresnel zones and improve the resolution of the data, but I don't think it reduces it to the bin size (lateral resolution must still depend on wavelength, as noted above). We could not, for example, collect 25 MHz data with an extremely small bin size in all directions and have some limitless improvement in horizontal resolution.

Figure 5: How are you sure that none of the identified high-amplitude features are air-filled, which would also generate a strong bed reflection? Some explanation or justification is needed in the text.

Line 173, "This is the first time that a glacier's drainage network is imaged in 3D with GPR data": Given the existing literature, I think that this is over-selling things a bit and should be modified. Harper et al. (2010) and Egli et al. (2021) used similarly dense 3D acquisitions to image elements of the drainage system, whereas Hansen et al. (2020) used 3D data (albeit at a greater line spacing) to characterize the drainage network in 3D.

Lines 183-184: Again, the rather extreme width-to-height ratio was derived under the assumption of a water-filled channel, which must be justified or stated as an assumption.

Line 199: Replace "evidence" with "possible evidence" to reflect that it's not certain that it's subglacial water accumulation.

Line 207, "The high amplitude reflections along the basal interface (Fig 5a) represent water accumulations...": Again, this sentence conveys an absolute certainty, whereas it seems that there is some uncertainty.

Line 233, "We found the dimensions of the conduit were 60 times wider than its thickness...": See previous comments. This is assuming a water-filled channel which, given the channel size, may not be the case (?)

Line 237: Replaced "indicated" with "suggested".

Line 240 to end: For the reader, this paragraph suggests that this is the first application of high-resolution 3D GPR data to image glaciers, which is not the case. Please modify accordingly. For example: "3D GPR data have been adopted and have proven to be successful for imaging small-scale targets within the fields of archaeology and investigating shallow fault zones, and to a lesser extent in glaciological investigations. This study further confirms the feasibility and the opportunities that are offered by implementing 3D GPR to image glaciers and their hydraulic networks."

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