

Interactive comment on “The response of supraglacial debris to elevated, high frequency GPR: Volumetric scatter and interfacial dielectric contrasts interpreted from field and experimental studies” by Alexandra Giese et al.

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General Comments: A slight difficulty I had with the paper is it is a hybrid of a very technical GPR methods paper and a paper which applies those methods to mapping debris thickness across a glacier and then interprets them in terms of glacial processes.

We restructured the paper in response to this feedback; the most significant change was ensuring the main text of the manuscript was written for a glaciology readership and moving the technical details about GRP to the Supplementary Material for the

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interested reader.

- This is reflected in the title of the paper, which is not attractive and would not encourage many people to read it. - It is also reflected in the overall structure of the paper, where field data are analysed and presented, using information that is dependent on the results of the laboratory work, which is not presented until later. - And it is also reflected in the aim of the paper which is very brief (and then is followed by a summary of what was done) and stated on Page 3 lines 20-22: “Our aim was to find how a frequency relevant to remote radar systems (i.e. ≈ 1 GHz) performs in glacial debris. To this end, we compared the depth of volumetric backscatter from GPR data with ground truth measurements of debris thickness. We validate our indirect backscatter method with experimental studies”.

I would encourage the authors: (1) to think about the aims of the paper and to better articulate those following a relevant literature review;

We revised the Introduction section and carefully defined and articulated the scope and aims of the study. We feel that the literature review was sufficient and that there are simply limited references; we cite literature of GPR on debris covered glaciers and, additionally, related studies outside this niche (e.g. rounded “box-of-boulders experiment,” glacial till, debris covered glacier studies in the Antarctic dry valleys)

(2) to think whether the overall structure of the paper could be improved, perhaps putting the experimental lab work before the presentation of the field work, if the former is needed to interpret the latter;

We restructured the paper considerably from the initial submission to ensure that Methods, Results, and Discussion points were in their appropriate sections. Furthermore, we incorporated the reviewer’s observation that some of the arguments were based upon the results of the rock box experiment and presented before the experiment was described. We maintain that the field data are the most important data of our study and, therefore, keep the discussion of the rock box after that of the field data. How-

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ever, we revised the abstract and introduced significant modifications to the manuscript text to emphasize the role of the rock box experiments: to understand the data from Changri Nup Glacier.

(3) and then to come up with a better, less convoluted, more snappy, more engaging title for the paper.

We have renamed the paper, “Measuring supraglacial debris from elevated, high frequency GPR.”

A key element to the paper is the recognition that there is no obvious reflection from the ice at the base of a relatively thin debris layer. It is concluded (with apparent supporting evidence from the laboratory work) that this is not because of a lack of coupling between the radar and the surface but because the permittivity of the debris on Changri Nup Glacier is essentially the same as the underlying ice and so there is no dielectric contrast. This contrasts with the results from other (admittedly few) similar studies. I found the presentation of results, analysis, discussion and logic of the argument behind this point very difficult to follow as it seemed particularly labored and spread over many parts of the paper in different sections. Is it possible to present the results and the analysis in a much more focused and coherent way so that the reasons for a lack of reflection between debris and ice is more convincing?

Yes, and we have restructured and significantly reworked the new manuscript. Additionally, we expanded the “Absence of interface” section in the Discussion with more in-depth explanations. We also moved that section to be first in the discussion to feature it for readers.

Is it really nothing to do with the lack of coupling between radar and the debris? Is it to do with the radar frequencies used?

The rock box experiments showed that the coupling is sufficient; there is enough energy reaching the interface to be detected if it were detectable (i.e. that the energy is getting

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to the interface is evident from the strong reflection from the aluminum foil in the rock box). At the higher frequency we tested in the rock box, energy did not reach the interface through all clast sizes, but the rock box results clearly demonstrated that the 960 MHz system we used on Changri Nup could have detected an interface of sufficient dielectric contrast.

Is there really something special about the debris and ice on this glacier compared to glaciers studied in previous work?

It is difficult to say conclusively, but the main difference may have been liquid water. In the “Absence of interface” section, we discuss how the timing of our study differed from others’ studies, which may have detected an interface due to the presence of liquid water at the ice-debris interface during the melt season (the time of data collection).

Do the authors have any advice on what radar frequencies should be used in the future? Or whether different radar frequencies should be used in different settings?

Because we did not set out to test a range of frequencies, we feel that such advice is beyond the scope of this manuscript. The aim of our study was to investigate how GPR operating your 1 GHz performs in supraglacial debris. We investigated a bandwidth centered near 1 GHz for several reasons: first, lower frequencies may not resolve a complex interface between debris and glacier ice. Second, we knew from an initial, exploratory field season that average thickness was roughly only 30 cm. At a lower frequency and this thickness, we risked having interference between the surface and bottom reflection. While it is true that, at a lower frequency such as used by others, the scattering might be less and the power radiated stronger, we were interested in exploring a frequency that could be deployed over a range of debris thicknesses

Or whether the time of year and the presence / absence of water would have any bearing on the results?

This is now addressed in the updated “Absence of interface” section, which includes a

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[discussion of the season of data collection.](#)

I found the argument concerning the lack of reflection particularly difficult to follow partly because of the terminology regarding “dielectric” and “permittivity”. Could the authors ensure that these terms are being used correctly and consistently throughout the paper? For example: P1. L11 dielectric contrast P3 L14 relative dielectric permittivity P9 L1 dielectric constant P12 L3 irregular dielectric structure P14 L2 dielectric permittivity P17 L14 dielectric P17 L17 dielectric properties Are some of these actually the same thing?

[The updated “Absence of interface” section presents the arguments explaining the lack of reflection more clearly, logically, and comprehensively than in the original manuscript. Additionally, we now include definitions of dielectric and permittivity and state explicitly that they are used interchangeably in the manuscript.](#)

On P6 L1-2 it is stated that a 960 MHz antenna transmits a pulse with dominant wavelengths of $\lambda_{\text{air}} = 31$ cm in air and $\lambda_{\text{debris}} = 18$ cm in debris with a relative permittivity of 3. So it is assumed a priori that the debris on the glacier has a relative permittivity of 3 (is this the same as a dielectric constant?) and this is subsequently justified with reference to the artificial lab experiments.

[All instances of a priori assumptions based on the later rock box experiments have been removed and/or reordered in the rewrite of the manuscript.](#)

Detailed comments (line numbers refer to initially submitted manuscript, not the version prepared for TCD)

P1 L8-11. These two sentences do not quite seem logical to me and read like a circular argument/ tautology. Can you clarify precisely what the lab results show, and what this means in terms of the interpretation of field data?

[Yes. The new Abstract does clarify what the lab results showed and how they aided in the interpretation of field data: “The laboratory tests suggest that the ice-debris](#)

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interface return was missing in field data because of a weak dielectric contrast between solid ice and porous dry debris.”

P1 L18- 20. Something not right here. Debris covers 14-18% of glacier area in Himalaya. But then you say it’s even greater in the East at 25%. Is the 14-18% figure wrong? Or confined to the West and Central Himalaya?

The 14 – 18% figure is a regional average; the eastern part has a debris coverage greater than the average. This has been rephrased for clarity.

P2 L 4-5. This sentence seems to belong with sentences on lines 19-22 so suggest delete from here and move to below or vice versa.

The Introduction has been rewritten, and the stated aims and associated relevance are no longer separated.

P2 L5 say “be used to measure” instead of “indicate”?

The entire section has been rewritten, and the word “indicate” is no longer used in the context it was in the original manuscript.

P2 L6. What about other sources of debris on glaciers, e.g. what about extra debris from mass movements from valley sides / lateral moraines? And possibility, at least, of subglacial debris brought to surface by thrusting?

We changed the language to acknowledge other potential sources, by stating that debris is “predominantly rockfall from valley walls” and by adding additional references.

P2 L 33. Say 200 and 600 to be consistent with above.

Fixed.

P2 L33. Say “. . .Glacier, Nepal. . .”

Fixed.

P2 L35 – P3 L 6. This reads like results / discussion. Suggest move from here to later.

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Exception could be point about inability to drag antennas.

[This is no longer in the Introduction.](#)

Why is use of low frequencies "irrelevant"? Why is frequency relevant or not for areal coverage?

[We removed this link between frequency and area to avoid confusion. The thought behind this statement was that a lower frequency GPR system could not, practically, be run from a drone \(which would have vast areal coverage\).](#)

P3 L14-16. Something not right about this sentence. Also it presents results again. We need only a priori justifications for the methods. Or some reference to "preliminary data collection and analysis" or some such.

[We added the following sentence to our Introduction: "With the initial observation of no distinct, detected debris-ice boundary, we sought a technique to measure debris thickness from GPR data lacking an interface delineation."](#)

P3 L16. Should hypothesized be present tense?

[We use the past tense when discussing past actions or decisions; we use present tense for discussion of the data and processing. We would be happy to change this at the discretion of the editor.](#)

P3 L17. What do you mean by "favorable"? For what? Do you mean "high"?

[What we meant was a medium likely to produce backscatter in penetrating electromagnetic waves; however, this language has been replaced.](#)

P3 L18-19. This seems to be the key a priori reason for your approach. Is it the case that clasts are large at Changri Nup and dragging antenna is difficult, therefore you need a different approach involving use of backscatter information? I think you need a better articulation of the limitations of previous work, the differences between CN glacier cf. other glaciers studied, and therefore a better justification for your work

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culminating in a clear set of aims.

In the Introduction, we summarize the reasoning for our approach: We explore the middle ground: GPR of a high frequency that could potentially be deployed on an airborne platform. We collected ground based radar measurements but did not detect a debris interface. This differed from other studies, perhaps because of differences in debris lithology, porosity, or moisture content. Additionally, we clearly state our aim, which was to measure the thickness of Changri Nup's debris and, in doing so, explore how a 960 MHz system (i.e., a frequency relevant to remote radar systems, which operate near 1 GHz) performs in glacial debris. To this end, we compared the depth of volumetric backscatter from GPR data with manual ground truth measurements of debris thickness. We validate our indirect backscatter method with experimental studies and, thus, propose a methodology for determining debris thickness from GPR data that, for any number of reasons, do not show a clear debris bottom.

P4. Fig 1 etc. the term “cross” to refer to the transects running up and down glacier seems odd to me. I think of “cross glacier” and “cross transects” as going across a glacier and “along glacier” or “longitudinal transects” as going up and down glacier.

We have revised descriptions of the transects from “longitudinal” and “transverse” to “along-glacier” and “across-glacier.”

P5. Last sentence of Fig Heading. Is what is stated really obvious from the photos? Doesn't appear so to me.

No, not obvious. So we have added descriptions of each of the panels of the figure to the main text.

P6. L5. Consider “Although, as shown later, this raising caused...”

This sentence was rewritten to read: “Although neither elevation was sufficient to separate the direct coupling (DC) and the return from the debris surface. . .”

P7. L10. Why is N M 2017 referenced here?

The reference was for “sub-debris glacier surface topography is unknown (Nicholson and Mertes, 2017).” However, this has been removed from the rewrite.

P7. L14. “local” to what?

We now clarify the meaning as being local to the campus of Dartmouth College.

P7. L25. This sentence doesn’t make sense to me.

This sentence has been removed.

P7. L28. Suggest mention things here in text that are currently in the Fig Heading.

Details from the caption have been moved to the text.

Also, important to explain the “surface reflection” is debris surface not ice surface.

We specified that the “surface reflection” is the “debris surface reflection.”

P8 Fig 4 Caption. Change “Schematic” to “Annotated photograph”?

Fixed.

P9. Poor text quality in Fig 5. Y axis. In Fig caption suggest change sentence to something like: “In none of the stacked or uncompressed data profiles are the hyperbolic diffractions wide enough to be used to calculate the dielectric permittivity.”

The figure has been remade and its caption shortened. This sentence is now in the main text and reads: “in neither the uncompressed (Figure 5) nor stacked (Figures 6 and 7) data for any profile are there hyperbolic diffractions sufficiently wide to be interpreted accurately for dielectric permittivity (Arcone, 1996; Yilmaz, 1987).”

P 9. L6. Could delete the glacier name here.

Fixed.

Also, is this sentence correct? The profiles show an absence of 3 things? Seems odd. Wouldn't it be best to state what they do show?

For clarity, we have now enumerated what the profiles show.

P9 L9. Suggest replace “dramatically” with “much”.

We removed the word “dramatically.”

P9 L16 “raises”

See above response on verb tenses.

P11. L9. Delete apostrophe after ‘scatterers’.

This sentence was rewritten, and there is no longer the need for a possessive.

P12. Fig 8 Heading. Need consistency in referring to colours in key. Either refer to them all or none. Delete “climber’s left to climber’s right”. Suggest move penultimate sentence to higher up to discuss all the lines in the Fig. first.

We think it necessary to include “climber’s left to climber’s right” in the description of the transects because the glacier does not flow in a straight line and describing the direction as “West to East” does not apply on all transects. We reordered the caption to describe the lines and symbols in the figure first.

P13 Fig 9. Explain the reason for the gaps in the traces. Same with Figure B2 in Appendix. P13. Fig 10 Heading and Fig 6 Heading earlier.

The gaps are explained in the captions for Figure 6 (formerly 8) and B2, the only times they appear. Former Figure 6 has been moved to the Supplementary Material, and details have been moved from the caption to the text. Information from the former Figure 10’s caption has, similarly, been moved to the main text of the manuscript.

Need to better explain what “surface reflection” is. You have “surface reflection” but also “debris surface reflection”. Surface reflection is abbreviated SR and S inconsistently. Why is bottom reflection not defined in Fig 6?

We have revised this figure in the new version of the manuscript to accommodate these

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changes.

P14 L 1. “pine-board” ?

Here we are referring to both the pine boards and the pine shavings, so adding ‘board’ would alter that meaning.

P14. L2-4. How do these sentences follow on from the previous sentence? I don’t understand what the evidence for this is.

These sentences build the argument that it is reasonable not to see a reflection at the debris-ice interface. We have added references for the permittivity of ice.

P14 L10-12. What is the evidence for this? Refer to a Figure and describe / label the Figure?

We have moved the description of the antenna height to a more appropriate location in the Methods section. Raising the antenna insufficiently (inadvertently) to separate out the DC from the returns did enhance the chances of detecting a signal from the debris-ice interface because the antenna height produced a far field spherical wave, the curvature of which approximated a plane when intersecting the surface. This is not an observation from our results, as a reader may have concluded from the original manuscript, but rather a property and result of the antenna geometry.

P14 L13. “To estimate. . .”

Changed to “For locating. . .”

P14 L14-15. What does this mean? Are you just using the measurements to calibrate an equation to determine depth from radar data?

Yes, this is a nutshell version of the method, which is explained further and clarified in the revised manuscript.

P14 L 15. The procedure needs to be explained wrt Fig 11. P14 L17. Threshold τ

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needs explaining. You're referring to a threshold in the P14 L17-18. Confusion here. What is an iteration? If it's the number of times the "model" is run then it's run n-1 times right because you leave one out each time? P14 L19. “. . . assuring generation of quality statistics”. Poor English.

All 4 of the above comments have been addressed by a careful rewrite of this section.

P14 L 22. Can't Figs 11 and 12 be combined? Could use colors to show 20, 30, 40, etc

We have eliminated previous Figure 11 from the revised manuscript. We could indeed add colors on the curve to show percentages; though we think this might be more complicated for many readers, so we have kept the simplicity of the original figure 12.

P15 L5-6. Suggest “There is broad-scale agreement between the calculated and measured average depths (Table 3). An exact match is not expected because: . . .”

This is addressed by the language in the revised manuscript.

P16 L3. Delete “field measurements of solid block)” I assume?

We cite both Hubbard et al (1997) and our own field measurements for the claim that granite has a dielectric between 5 and 7. We switched the order of these citations to avoid confusion.

P16 L 5. Suggest “. . . shallow depths. This, together with point (a) above, emphasize. . .” P16 L11. Are you referring to debris grain size here? Small and uniform?

The above 2 comments are addressed by the rewritten language in the revised manuscript.

P17. L3. “would” not “should” to be consistent with L2.

Fixed.

P17 L20. “. . . lack to debris too thin, debris too thick, and high scatter” Poor English.

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Rewrite.

Rewritten.

P17 L21. “. . .but fail for thin layers”. What does this mean?

Eliminated from the revised manuscript.

P18 L56. No need for new paragraph here as you're discussing the same point.

P18 L30. These numbers here are different to those in Table 3.

Fixed.

Why only refer to the 3 cross glacier transects rather than the other 2 here?

We explained that lack of ground-truth points and the short length of these transects makes use of them more difficult.

P18 L31. It is really the case that these thicknesses “do not vary significantly”?

We have now put the variability in thickness with thresholds calculated locally into Table 3, showing how the change in threshold percent gives a change in depth. The changes in depth remain smaller than the uncertainty.

P20 L7. ...”dielectric permittivity across...”

This has been eliminated in the rewrite.

P21-32. Appendixes have got mixed up with the references. Might be useful to show location and look direction of all the photos on a Map (e.g. Fig 1).

The formatting (references mixed in with appendix figures) has been fixed. Since the photos are mainly intended to show the terrain (and debris-surface variability), we think a map is not necessary.

Interactive comment on The Cryosphere Discuss., <https://doi.org/10.5194/tc-2019-60>, 2019.

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