

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.

Anonymous Referee #2

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The response of supraglacial debris to elevated, high frequency GPR: Volumetric scatter and interfacial dielectric contrasts interpreted from field and experimental studies

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Review for The Cryosphere

This is a novel and timely piece of work developing techniques for quantifying debris thickness on debris-covered glaciers from high frequency GPR using the characteristics of volume scattering of radar returns where a distinct reflection from a debris-ice

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boundary is absent. As the authors state, there is a growing interest in mapping debris cover from space, from the air and from the ground because of its impact on the energy balance and melt processes. The paper develops methods for analysing relatively high frequency radar data collected from just above the debris layer (so without direct contact with the surface) over a glacier in the Nepal Himalaya (960 MHz) and over an artificial laboratory debris layer covering pine board (960 MHz and 2.6 GHz) in terms of the attenuation of volume backscatter, and using this to calculate debris thickness. Errors are discussed.

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. 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: to think about the aims of the paper and to better articulate those following a relevant literature review; 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; and then to come up with a better, less convoluted, more snappy, more engaging title for the paper.

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 sup-

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porting 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? 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? Is there really something special about the debris and ice on this glacier compared to glaciers studied in previous work? 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? Or whether the time of year and the presence / absence of water would have any bearing on the results? 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? On P6 L1-2 it is stated that a 960 MHz antenna transmits a pulse with dominant wavelengths of ~ 31 cm in air and ~ 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.

Detailed comments 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

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results show, and what this means in terms of the interpretation of field data? 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? 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. P2 L5 say "be used to measure" instead of "indicate"? 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? P2 L 33. Say 200 and 600 to be consistent with above. P2 L33. Say "...Glacier, Nepal..." P2 L35 – P3 L 6. This reads like results / discussion. Suggest move from here to later. Exception could be point about inability to drag antennas. Why is use of low frequencies "irrelevant"? Why is frequency relevant or not for 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. P3 L16. Should hypothesized be present tense? P3 L17. What do you mean by "favorable"? For what? Do you mean "high"? 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 culminating in a clear set of aims. 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. P5. Last sentence of Fig Heading. Is what is stated really obvious from the photos? Doesn't appear so to me. P6. L5. Consider "Although, as shown later, this raising caused..." P7. L10. Why is N & M 2017 referenced here? P7. L14. "local" to what? P7. L25. This sentence doesn't make sense to me. P7. L28. Suggest mention things here in text that are currently in the

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Fig Heading. Also, important to explain the “surface reflection” is debris surface not ice surface. P8 Fig 4 Caption. Change “Schematic” to “Annotated photograph”? 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.” P 9. L6. Could delete the glacier name here. 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? P9 L9. Suggest replace “dramatically” with “much”. P9 L16 “raises” P11. L9. Delete apostrophe after ‘scatterers’. 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. 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. 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? P14 L 1. “pine-board” ? P14. L2-4. How do these sentences follow on from the previous sentence? I don't understand what the evidence for this is. P14 L10-12. What is the evidence for this? Refer to a Figure and describe / label the Figure? P14 L13. “To estimate. . .” P14 L14-15. What does this mean? Are you just using the measurements to calibrate an equation to determine depth from radar data? P14 L 15. The procedure needs to be explained wrt Fig 11. P14 L17. Threshold τ needs explaining. You're referring to a threshold in the % of an area under a curve right? 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. P14 L 22. Can't Figs 11 and 12 be combined? Could use colors to show 20, 30, 40, etc % of area under curve, then show a line for 38%. 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: . . .” P16 L3. Delete “field measurements of solid block”) I assume? 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? P17. L3. "would" not "should" to be consistent with L2. P17 L20. ". . .lack to debris too thin, debris too thick, and high scatter" Poor English. Rewrite. P17 L21. ". . .but fail for thin layers". What does this mean? P18 L5&6. 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. Why only refer to the 3 cross glacier transects rather than the other 2 here? P18 L31. It is really the case that these thicknesses "do not vary significantly"? P20 L7. ". . ."dielectric permittivity across. . ." 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).

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