Author comments from Tom Jordan, University of Bristol.

We would like to thank both reviewers for their very thoughtful and constructive feedback, and welcome the opportunity to improve our manuscript. Below are our responses to both sets of reviewer comments, with our comments in blue text.

Anonymous Referee #1

The ms demonstrates a theoretical relationship between the signal abruptness (a relative measurement of the signal decay) of the radar bed echo and the self-affine properties of roughness, the latter being a proxy for the thermal state of the bed. Then, a comparison of the signal abruptness with a thermal state map of the GIS bedrock illustrates how the signal abruptness can be used to outline at first order thawed and frozen bed.

The ms provides a valuable effort to introduce self-affine descriptors to classify glaciers' bed properties from radar return. The ms is well-written, the theoretical part is clearly shaped, and the discussion provides interesting insights into the qualitative relationship between bed properties and roughness as seen by radar. I have mainly few questions/minor revisions and technical remarks that, I hope, would enhance the quality of the ms.

We now realise that a key message of our paper needs to be made explicit. We are not proposing that we have a new RES diagnostic for basal water/thawed beds (either in terms of the Hurst exponent or the waveform abruptness). Rather; we provide evidence that the previously used RES diagnostic in Oswald and Gogineni (2008, 2012) (specular reflections for basal water) does not, in general, hold. Specifically; their approach will fail to identify water in rougher regions of Greenland (high H, Low A). Additionally, many of the contiguous regions of higher A that they argued to be thawed (such as around the Camp Century Core); are likely to be frozen.

Ultimately, we demonstrate that abrupt waveforms (specular reflections) are best viewed as being under geometric/topographic control (quantitatively expressed through the Hurst exponent), rather than providing a specific RES diagnostic for water or the thermal state.

We have therefore revised the way that we present the frozen/thawed analysis in our paper. Key changes are:

(i)The abstract is now explicit about how our results impact upon basal water discrimination from RES, and the prior work of Oswald and Gogineni (2008, 2012)

(ii) The purpose of the frozen-thawed statistics (5.3) is now made clear throughout (i.e. testing the validity of Oswald and Gogineni (2008, 2012)).

(iii) Fig. 6 and Fig. 3 now have the frozen-thawed underlay removed (the underlay is now a subplot in Fig. 6). This enables us to better focus on the topographic control theme.

On a related note, we are now clearer about our use of the term thawed bed (meaning regions above pressure melting point, as in Macgregor et al. 2016.), and the fact that the RES sounding method in Oswald and Gogineni (2008, 2012) was supposed to discriminate wet beds/basal water.

We have therefore revised the title to:

Self-affine subglacial roughness: consequences for radar scattering and basal **water** discrimination in northern Greenland

1) What kind of signal processing should be avoided to optimize your technique? For example, the waveform abruptness is mainly made from incoherent signal scattered by the surface. Does this mean that any coherent processing (coherent pre-summing or Doppler focusing) will tend to reduce the abruptness and its spatial contrast?

As a nadir-facing sounder the scattering contribution to the waveform abruptness is mainly from coherent reflection (as opposed to side-looking SAR instruments which would be mainly diffuse scattering). Whether coherent processing acts to increases or decrease the abruptness value depends on the exact character and roughness of the surface. For example, consider the two cases below*:*

Case A: The specular/nadir component is assumed to be coherent and delayed (abruptness decreasing) echoes, whilst the diffuse/off-nadir component is assumed to be incoherent (e.g. Grima et al. 2014). In this scenario coherent processing (either pre-summing of Doppler focusing) would cause the specular component of the signal to increase with coherent gain but not the diffuse (incoherent) signal. Therefore the measured abruptness would decrease with gain.

Case B: The specular (nadir) and diffuse (off-nadir) components of the echo are coherent (and therefore both experience coherent gain) (e.g. Schroeder et al. 2013, Schroeder et al. 2015). In this scenario, for small SAR processing angles (coherent pre-summing) the waveform abruptness should be unaffected and for larger angles (exceeding the angle spanned by the specular component of the echo in the scattering function) then the measured abruptness will decrease with inclusion of coherent processing.

We have now added a summary of this to Sect. 3.3, where the waveform abruptness is introduced.

2) There is no mention of volume scattering in your ms while it is known to also contribute to the radar signal decay. What length scale for the heterogeneities of the volume scatterers would be needed to contribute to the abruptness? Could it explain some local mismatches between A and H on your maps? Is volume scattering a fair assumption in the context of bed and thawed glaciers' bed?

Both our study (and to the best of our knowledge all other similar RES works) ignore Mie/volume scattering. We suggest this to an appropriate assumption for two reasons:

(i) Ice-penetrating radar wavelengths, (~1-5 m in ice) are extremely long relative to ice surface remote sensing platforms (which we sense the reviewer may be more familiar with). Hypothetically, Mie/volume scattering would require a significant number of obstacles of the order of this metre length-scale (or slightly smaller given the higher dielectric values in the bed). However, this is physically implausible given the micro to millimetre scale of typical water pore radii (e.g. Nimno2014), or the millimetre scale of heterogeneities in ice regoliths (e.g. Aglyamov2017).

(ii) The radar signal in the bed often attenuates tremendously fast and echoes from any subsurface volume scatters (if hypothetically they did exist) would therefore not contribute significantly to the echo.

We have focused upon point (i) in the MS and have added the relevant references (see Sect. 4.1 when the radar scattering model is introduced).

3) How do you choose the location of the bed echo in the case of the green waveform (A=0.05) on Fig.4?

The position of the peak power was established by firstly using Level 2 Cresis picks, then applying a local re-tracker to centre over the peak power as show in Fig. 4. This has now been added to the text.

How do you compute Pagg? From fore and aft the chosen pick or just after it?

The integral considers fore and aft (since this better relates to the energy conservation arguments made later on), so we have now added this to the text. The calculation of P_agg was also described in more detail in our prior work in TC (Jordan et al. 2016), which we reference at the start of Sect 3.3.

Could you justify your choices and discuss putative bias arising from the specific case of this kind of waveform?

We think this is already alluded to in the text (in that our quality control filtering acts to filter out highly diffuse/messy waveforms). This would have the overall effect of slightly reducing our coverage in rougher regions, but is likely to be washed out by many of the other approximations we make in our paper: for example using a radially isotropic scattering model. We have therefore left the MS as is.

Specific Remarks

l.131: "proportional the rms deviation" should be "proportional to the rms deviation".

Changed as suggested.

l.162-3: For clarity, the origin of the profiles should be moved in the first part of the paragraph (when you introduce the figure) and added in Fig.1 caption.

Fig. 1 has now been substantially revised following the second reviewer’s comments (including referencing the profile locations to our coverage map, Fig. 3).

l.203-4: Could you briefly summarize the main signal processing applied to L1B data if any (any focusing or coherent pre-summing)?

This has now been explained in 3.1.

l.240: "is also is consitstent" should be "is also consistent".

Changed as suggested

l.270: How long is the range window across which you aggregate the power to get Pagg?

The range window is actually variable (and relates to our power decay threshold described in 3.1). This should hopefully already be clear.

l.302: "can then obtained" should be "can then be obtained".

Changed as suggested

l.507-8: Specify that this H-A apparent correlation stands in the context of frozen/thawed glaciers bed. Your study does not show this relationship stands in other environments, especially where volume scattering could be involved.

See our previous comments on volume scattering.

Discussion

Author Comments 2

Review of "Self-affine subglacial roughness: consequences for radar scattering and basal thaw discrimination in northern Greenland" (Jordan et al.,)

The paper applies statistical techniques widely used in planetary radar sounding measurements to radar soundings of a terrestrial ice sheet for the first time. The authors demonstrate that a series of parameters (roughness, abruptness etc.) are different depending upon whether the data are from thawed or frozen bed conditions.

General comments

The paper is very well-written and technically excellent. The analysis is clearly important and has been very carefully and thoroughly undertaken. Some readers could perceive the manuscript as having a slight shortfall in glaciological content. However, I am of the opinion that the analysis and findings of the manuscript are of sufficient significance to make the content appropriate for publication in TC. For example, importantly, and of direct relevance to glaciology, the manuscript demonstrates limitations associated with the approach of Oswald and Gogineni (2008,2012) for determining areas of thawed and frozen bed. However, I do recommend that the authors do consider approaches to make the manuscript more accessible to a general glaciological audience. A slightly more glaciological-facing paper should acquire a broader readership in the community. I have two suggestions for how to achieve this, neither of which should be too onerous:

1. Incorporate into the paper a figure with radargrams that provide examples of the different characteristics. Including the actual radargrams for the four examples of the Hurst exponent in figure could 1 achieve this. Figure 4 might also benefit from radargrams illustrating bed echo waveforms with different abruptness.

This is an excellent suggestion and Fig 1 (along-track bed elevation profiles) has been revised to include example radargrams. Underneath each radargram, each sub-figure bed-elevation profile now has a different aspect ratio which allows the reader to better visual surfaces with different H (in particular the persistence/anti-persistence of the elevation trends). The location of the profiles are now added to the coverage map (Fig. 3); which will enable readers to place profiles in the context of the Northern GrIS.

2. What about a focused case study of a particular glacier (or two) in NW Greenland to exemplify the authors' key points? There are few references throughout the paper to actual locations or sites in Greenland, even in the discussion (e.g. Camp Century, NorthGRIP), and a few more references to geographical locations may make this paper a little less 'abstract' and more broadly accessible.

This is again very helpful feedback and we have given the results and discussion an edit to make it more accessible to a geographical/glaciological audience.

Key changes include:

(i) Section 5.1 (the flight-track maps) now draws a comparison with Greenland bed topography. This comparison enables us to better place the RES-derived data (Hurst exponent, Waveform Abruptness, RMS deviation) in its geographical context. Specific locations have also been added to Fig, 6 and are referred back to in the discussion.

(ii) The uncertainty/sensitivity analysis (previously included in 5.1) has now been moved to its's own sub-section (5.4); thus improving the overall flow of the geographical results.

(iii) The discussion has been re-ordered, with more specific geographical locations and context included.

Specific comments

Intro – a very well-written intro, that sets the scene very effectively and concisely.

Section 3.2 – authors assume that all the level 2 data are consistent, but will have been picked by several different people. What confidence do the authors ascribe to the level 2 picks? Are there uncertainties associated with this data product that can be quantified?

The picking procedure is now described (in 3.1 rather than 3.2), outlining that we use the highest confidence picks from the Cresis data produce.

It is actually quite complex what uncertainty metric is relevant for our statistical analysis of along-track bed-elevation. For example, the presentation of Level 2 picks in Gogineni et al., 2001 and Bamber et al. 2013 subscribes an uncertainty ~ 10 m (based on cross-over analysis of flight-tracks). This, however, considers separate tracks, and is likely an overestimate for our along-track statistical application. Additionally, the manual picking preclude would introduce error auto-correlation (i.e. neighbouring points would likely have a similar bias). We therefore believe that the theoretical depth-range value (which we already quote) is the most useful number (even if it does not account for the picking procedure.)

Line 25 – are Seroussi and Schroeder references really the most appropriate here? I am sure that wet bed tends to = fast flow was determined by others long before 2013.

We have now added Weertman's and Nye's classic works on basal sliding.

Lines 130- 131 – Sentence needs rewording.

Changed to: `… and we focus upon this roughness parameter when integrating topographic-scale roughness with radar waveform data.'

Line 173 – some might suggest that reviewers could legitimately be referred to as 'asses', but the word I think you are looking for here is 'assess'.

Done.

Line 265 -"waveform corresponds to"? #

Done.

Line 305 – "model a decrease"?

Done.

Line 400 – smoothing? A google search suggests "smoothening" is predominantly something to do with the management of hair.

Done.

Line 528 – "(Gorman and Siegert 1999)"
Done.

Line 529 – "…depth at which a lake is electrically 'shallow' or 'deep'….."?

Sentence has been re-written.

Line 836 – "roughness"

Done.

Figure 6 – The colour scale in some parts of this figure (b and c) does not necessarily visualise the data as effectively as it might.

The colour scale has now been revised. We also have removed the frozen/thawed underlay (instead having it as a subplot), which improves the colour contrast between the flight-track data and the background.

Dr Neil Ross
Newcastle University
16th March 2017
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