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Interactive comment on "Simulated Ka- and Ku-band radar altimeter scattering horizon on snow-covered Arctic sea ice" *by* Rasmus T. Tonboe et al.

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Interactive comment on "Simulated Ka- and Ku-band radar altimeter scattering horizon on snow-covered Arctic sea ice" by Rasmus T. Tonboe et al. General comments: The objective of this paper is to evaluate the capability of Ka/Ku bi-fréquency altimeters to measure the snow depth (SD) over sea-ice using a simulator. The authors tackle a particularly complex subject: what is the impact of the type of snow (salinity, density, temperature, grain size, etc.) on the performance of the measurements. The simulator is powered by measurements of terrain and its outputs are confronted with airborne measurements. This type of work is indispensable to improve the quality of the measurements of the sea ice thickness (SIT) by satellite, and to prepare for the the Copernicus project of the CRISTAL dual-frequency altimetry satellite, one of the first missions of which is to monitor the physics and dynamics of the sea ice. As such, this work and the data used must be disseminated and made public.

Reply: Thank you for your review and pointing out where the MS could be improved. Responding to your comments has definitely improved the MS.

Nevertheless, the results presented are in contradiction with several results already published and the arguments are not sufficiently convincing.

Reply: We don't think that our simulation results are in contradiction with already published results. Actually, our simulations are confirming that we have a re-tracker sensitivity to snow (the radar penetration correction, eq. 4). We also show that there is a difference in the mean Ka- and Ku-band scattering horizons (height estimations) which is confirming the results of earlier studies. However, this Ka- and Ku-band difference is only indirectly linked with snow depth: Ka-band extinction in the snow is larger than Ku-band extinction because of the scattering from the granular structure of the snow (snow grains scattering). Deeper snow has more scattering and maybe larger snow grains, and the snow grain size is very important. Snow salinity plays a role as well but these parameters are not directly linked with snow thickness.

Indeed, although this is not explicitly stated, this study seems to conclude that the Ku-frequency almost no penetrate the snow, no matter what are the snow caracteristics (see Figure 6). In fact, most of the paper focuses on the _differential_ of snow penetration between Ka and Ku.

Reply: We don't think that we conclude anything like that. However, we understand that section 6 and figure 6 (now fig. 7) were not clear and have rewritten this section and improved the figure with attention to comments from both reviewers.

Penetrations in the snow of each individual frequency is not analyzed.

Reply: We have rewritten section 6 with attention to your point.

However, the conclusions are largely based on the measurement of the ice freeboard (FB) by means of the Ku frequency alone, a measure which appears only in this section 6 without being justified beforehand. Figure 6 in the same section is therefore difficult to interpret. For example, it is not clear how the Ku nor the green differential curve have been obtained. For SD=0 we observe an ice freeboard of 0.2m and a Ku freeboard of 0m while it does not may have a problem of penetration in the absence of snow: these 2 measures should be equal. This section 6 is far from insignificant because it leads to surprising conclusions, repeated in conclusion, including in particular the fact that the measurement of the SIT is little impacted by the method of obtaining the snow depth. This assertion is in contradiction with equation (1) of equilibrium which shows that the snow depth is involved in the process for about 30% of the measurement of the SIT (the density of snow being about 1/3 of that of water and the values of FB and SD being of the same order of magnitude). Also the model implicitly assumes that the alitimeter is in LRM mode, while all Ku altimeters currently in flight are in SAR mode. The SAR mode has a much smaller footprint than the LRM mode. It is therefore less sensitive to surface roughness and especially one cannot make the hypothesis of a retracking at 50% of the waveform (in SAR mode the retracker is between 85% to 95%). This does not call into question the study presented because the comparison of Ka/Ku penetrations is a primordial subject that deserves to be studied whatever the the altimeter mode. But it is important to mention it. And with this perspective we would like to see more precisely what are the backscatter of each of these 2 individual frequencies according to the surfaces and interfaces considered (air/snow retrodiffusion, snow/ice and volume in snow).

Reply: The different altimeter processing centers are using different re-trackers (including one of them using the $\frac{1}{2}$ power re-tracker for CryoSat-2 data processing) and all processing centers are correcting for radar penetration in the snow meaning that the re-tracker is sensitive to snow. Otherwise they would not have to do that. Our model simulation experiments are confirming that the track-point is sensitive to snow in line with the practice of the different processing centers.

Finally, this multilayer model seems to consider only one layer for snow, whereas we generally consider at least 2 layers for snow over sea ice, with a hard and dense superciel layer and a deepest layer of very metamorphosed grains of consequent dimensions (of the order of centimeters). This point should also be discussed. I would therefore recommend to the authors to deepen the presentation of the measures carried out, and especially the model deployed and the conclusions that it brings on each of the frequencies, quite to reduce the part 6 on the results expected by altimetry.

Reply: We have detailed the discussion of justifying the one layer set-up vs. the multilayer set-up in the 5 detailed profiles in the text. We agree that the one layer set-up is a simplification compared to reality. However, it allows us to study the direct effect of snow depth on the track-point and on the Ka- and Ku-band track point difference. This would not be possible with a multilayer set-up and actually the simulations with the 5 multilayer profiles are largely confirming the simulations with the one-layer set-up.

Detailed comments: P1 L27: I do not agree with the following sentence: "... the impact of using a snow climatology versus the actual snow depth is relatively small on the measured freeboard" that must be more clearly demonstrated (see general comments and other comments bellow).

Reply: In the processing of radar altimeter data for deriving the radar freeboard (often assumed coincident with the snow ice interface) there are two corrections involving snow: 1) the buoyancy correction, eq. 1, 2) and the radar snow propagation correction, eq. 4. That's it. These two corrections almost cancel out and that is why the impact of snow is small in the processing.

P2 L45: "The radar scattering horizon or track point is conceptualized as the scattering surface depth detected by the radar re- tracker algorithm and the floe buoyancy" : this study should not depend on the buoyancy but only on the penetration.

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Discussion paper

Reply: We have to deal with both the radar penetration and the buoyancy at the same time because these two effects largely cancel out (fig. 7).

P2 L51: The following sentence is true only for the heuristic retrackers, not for the retrackers based on physical models: "The re-tracker algorithm can be tuned so that the radar scattering horizon coincides with the snow/sea ice interface."

Reply: Ok, we added that tuning is possible with the re-tracker that we are using. Bias correction is always possible with any re-tracker even though this is not removing the track point sensitivity to snow. All processing centers (using different re-trackers) are doing the same radar penetration correction (eq. 4) which means that the different re-trackers are all sensitive to snow. This sensitivity can be illustrated with a simple re-tracker and this is what we do here.

P2 L54: What do you mean by : "leading to preferential sampling of the thinner ice types " ?

Reply: We have rephrased this statement in the text because both reviewers had comments about the term "preferential sampling". Radar backscatter from thin ice is orders of magnitude larger, in areal fraction, than backscatter from thick ice and when both are present within the footprint. As such, the waveform is dominated by the thin ice backscatter disproportional to its areal fraction. This is preferential sampling. It is described in Tonboe et al. 2010 (reference list). Thin ice backscatter can be detected because of its specular backscatter but the disproportional sampling of the radar also happens with ice surface types within the footprint which are not easily detected. P2 L61: when speaking of "penetration correction" do you include the speed propagation reduction into the snow ? Reply: Yes, the speed of light in the snow is a function of its permittivity. It is included in the model. This is mentioned in connection with the description of equation 2.

P6 L142: You say that the "surface roughness is assumed to not influence the scattering horizon variability in our model simulations" while the surface as a strong impact on the altimetric waveforms. Does that mean that the model do not reflect the altimetric behavior? Please comment.

Reply: The model does include surface roughness as a parameter (F in Tab. 1) but it is constrained to one value in the simulations and therefore it does not influence the scattering horizon variability. We do not assume that roughness does not influence the scattering horizon variability, because it does, but not in these simulation experiments. That is also stated in the text.

P7 Fig 3: Please specify that depth=0.0 corresponds to the bottom, not to the surface! (if I dont mistake)

Reply: Thanks, good point, it has been included in the text.

P9 L206: You say that "The track point is found at half of the maximum waveform power point in time". It is a true mean for LRM altimetry but physical retrackers show that this value varies according to the roughness and the specularity of the surface. For SAR altimetry the mean value is much higher.

Reply: The justification of using this re-tracker threshold is given in the sentence that follows: " While different track point thresholds will shift the scattering horizon vertically (Ricker et al., 2014), the location of the scattering horizon does not change the modeled sensitivity to snow depth (Tonboe, 2017)." Using our model, we do not see that the different levels of the track-point changes the sensitivity to snow (Tonboe, 2017) and the roughness and "specularity" is constant in our simulations.

P9 L210: What do you mean by "the total backscatter is dominated by surface/interface scattering"? The interface is between the surfaces? Or it is another surface? Do you mean that the volum scattering is negligeable? In such a case it must be said/shown explicitely.

Reply: In the model we deal with two types of scattering: 1) surface scattering from the plane interfaces (air-snow, snow-ice and snow layering), and 2) volume scattering from the granular structure or particles in the snow. Yes, surface/interface scattering dominates and volume scattering is negligible as a backscatter source. However, vol. scattering contributes to extinction in the snow and therefore to the magnitude of the snow ice interface scattering. Volume scattering is described in lines 230-233 of the original version of the manuscript.

P9 L213: In the sentence "This assumption is believed to be more realistic than other sea ice surface scattering" please specify which other sea ice surface scattering you are thinking off.

Reply: Thanks, the geometric optics model is building on different assumptions than the flat-patch model that we are using, yet the two models have quite similar predictions (Fetterer et al. 1992). We have specified that in the revised version.

P10 L241: "the track point is computed as a point in time located midway between the noise floor and the maximum return signal power received by the radar." This is pertinent only for LRM altimetry.

Reply: This re-tracker is used for SAR altimeters as well.

P11 Table1: Only one layer for the snow. Is it realistic? Please comment.

Reply: Snow on sea ice can be layered and therefore we included the 5 snow profiles from the Canadian Arctic in addition to the one layer set-up in Tab. 1. In fig 7 you can see that the simulations of the layered profiles line up with the one-layer set-up especially for snow depths less than 20 cm. To answer your question: yes, it is realistic, the one layer set-up does give similar simulation results as seen in fig 7. This is also commented in the text discussing fig. 7.

P12 L297: Typo: "Ku- and Ku-"

Reply: Thanks.

P14 L338: "The snow climatology is used to 1) compensate for the effect of the snow cover on the ice floe buoyancy, and 2) to compute radar propagation in the snow." For point 2) I suppose that you mean "compute radar slow down speed propagation in the snow" ?

Reply: Thanks, yes, that is what is meant. It has been clarified in the text.

P15 L345: "We do not show the actual ice thickness, but it is proportional to the freeboard." As shown by your equation (1) the SIT depends also on the snow load. So please could you precise the SIT used in the Fig 6.

Reply: Yes, the thickness is written in the figure text as well. The ice is 2m thick.

P15 L352: "The green line in Figure 6 shows the combined effect of snow on the track point and the floe buoyancy." Which track point? Ka? Ku? Until this section 6 only the ka-ku difference has been considered.

Reply: It's the Ku-band track point. This is written in the figure text, and it has now been included it in the legend in the revised text.

P15 L357: "The effect of snow depth on the Ku- and Ka- track point is linear up to snow depths of âĹij 50 cm (Figure 6)." Fig 6 does not show the Ka measurement.

Reply: Thank you. We have now added both the Ka- and Ku-band track-points in figure 7 and described that in the text.

P15 L360: "The correction" for the track point is on average 0.35 times the snow depth". Which track point? Ka? Ku?

Reply: Thanks, it's Ku. . . it has now been specified.

P15 L368: typo "SYI"

Reply: It was not, but should have been defined earlier in the text at L312. SYI is second year ice... It has been defined in the text.

P16 Fig 6: "Red circles is the Ku-band radar track point as a function of snow depth and density" : The Ku FB has not been introduced beforhand, how do you obtain it? "The combined effect of both Ka- and Ku-band track point and buoyancy is the green line freeboard": how it is computed ? How do you get a nul Ku-FB for a ice-FB, without snow, of 20cm? Thus it is clearly not a problem of snow penetration!

Reply: The freeboard is 21cm when there is no snow (blue line). We realize that this is a busy figure and we have tried to make it clearer.

P17 L389: "the snow climatology results in a small impact on the derived sea ice thickness": this sentence is clearly in contradiction with equation (1). See general comments.

Reply: Equation 1 is describing the floe buoyancy and it is not including the correction for radar penetration in the snow. Adding the two together gives a small impact on the effect of snow.

P17 L393: "The small impact of the snow on the measured freeboard is the reason why the sea ice thickness can be derived using radar altimeters even without actual snow information." If the first part of this sentence could be true, the second one is clearly false. Even if we can not measure precisely the FB, the SD does have nevertheless a strong impact on the resulting SIT! It is easy to demonstrate using equation (1) and various SD datasets.

Reply: There is equation 1 and the radar penetration correction. Both are included in radar altimeter data processing and they largely cancel out. This is merely confirmed by our model simulations.

P17 L405: "Our simulations demonstrate that the direct Ka- and Ku-band track point difference sensitivity is about 0.033 times the snow": it is not (yet) a demonstration but still an assumption based on a model. Please mitigate.

Reply: We have changed the wording here from “demonstrate” to ”shown” It has been shown that there is a Ka- and Ku-band radar freeboard difference on SIT estimation from radar altimetry and that this can be linked with snow depth: e.g. Armitage and Ridout, 2015, Guerreiro et al., 2016, Lawrence et al., 2018 What we show is that this difference is not solely a function of snow depth, but rather both scattering and absorption processes leading to enhanced extinction in the snow. Snow salinity, snow grain size inhomogeniety are further linked with different ice types.

P18 L421: "This implies that the measured freeboard is nearly independent of snow depth." Using Ka? Ku? Both? Please be more precise or mitigate.

Reply: Yes, that is the point. We reformulated the sentence to explain better.

P18 L424: "the impact of actual snow depth is small in the sea ice thickness estimate": equ (1) shows that the SD may not be negligeable at all.

Reply: Again, considering both equation 1 and the radar penetration correction, these largely cancel out.

Please also note the supplement to this comment:
https://tc.copernicus.org/preprints/tc-2020-196/tc-2020-196-AC2-supplement.pdf

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