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Discussions

Interactive comment on "Simulation of the satellite radar altimeter sea ice thickness retrieval uncertainty" *by* R. T. Tonboe et al.

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This paper deals in a novel way with the issue of radar penetration into snow covered sea ice and the effects of hydrostatic equilibrium on the retrieval of sea ice thickness from satellite radar altimeter measurements of sea ice freeboard. There are issues related to the relevance of the results to existing and upcoming satellite radar missions and the models and field data used. The paper is unclear regarding some important aspects of the analysis performed, the validity of the models employed, and the significance of the results need to be put in context against the objectives and methodologies currently employed to obtain space-borne data on ice thickness from radar altimeters. The paper needs significant modification before it can be made acceptable for publication in Cryosphere. In particular the following 'Major Issues' must be addressed before

the paper can be accepted:

Major Issues: P519: The authors state that : "The forward model uses a set of snow and ice microphysical parameters for each layer : temperature, layer thickness, density, correlation length (a measure of the snow grain size or the ice inclusion size), interface roughness, salinity, and snow wetness to compute the eïn?A? ective scattering surface." Are all of these available for all of the campaigns or just the Antarctic? If the former then the values should be tabulated for all campaigns, if the latter then does the waveform modeling rely only on data from the Antarctic, in which case the results of this study may not be applicable to Arctic ice. The equations relating the permittivity to each of the physical parameters listed in tables 2-5 should be provided.

Reply: Equation 1 is the mixing formulae used for computing the snow and ice permittivity using input values from the reference table 2 and tables 3, 4, and 5. This study applies in particular to the period and region defined by the CryoSat mission aims (winter, Arctic, mostly thick multiyear ice) and also to a case outside the CryoSat mission aims in the Weddell Sea. The sensitivity study in sections 4.2, 4.3, and 4.4 with a homogeneous unlayered snow-pack may be simplistic, however, the setup enables us to identify the errors sources separately and it applies specifically to Arctic conditions in winter. The Antarctic cases can be regarded as worst case. This has been clarified in the discussion. However, Christian Haas has collected snow pit data from Alert (in the Arctic), not used in this paper, with nearly as diverse snow packs as the Antarctic cases.

P520 Equn. 2: This equation from Fetterer et al. originates from a paper by Ulander and Carlstrom (UC referenced by Fetterer paper) which states that the model is based on the assumption that the reflection originates from a small area fraction (the fraction used in this paper is 0.5%) of scatterers (or 'patches') a few metres across with an rms height less than one tenth of a wavelength (i.e. a few mm). Fetterer further sates that this equation describes that this equation may be used when the the 'patches are sufficiently large to generate a narrow peaked echo waveforms in a space-borne altimeter. This poses two problems: (i) If the authors consider the model for the surface geometry described above as as a reasonable representation for snow covered first or multi-year sea ice sea ice and if so they should provide evidence for this as anyone with field experience in the Arctic would almost certainly disagree (In fact the intention of both Fetterer and UC was to use this model to represent scattering from a small fraction of leads and new ice within the ice pack); (ii) Reflections from ice floes (as opposed to thin ice or open water) do not in fact generate narrow peaked waveforms in space-borne radar altimeter data but instead produce diffuse waveforms as shown in a number of papers (Fetterer, Fig 7-20b; Laxon, IJRS, 1994, Peacock and Laxon, JGR, 2004, etc.). The authors must explain why this model may also be suitable for 'diffuse' altimeter waveforms.

Reply to (i) above: The error due to penetration in the snow and ice and the error due to preferential sampling are treated separately. The error due to penetration is simulated in sections 4.2 to 4.4 using the reference profile in table 2 and realistic snow depths and snow densities from measurements in the Arctic. The radar altimeter backscatter is dominated by scattering from plane smooth surfaces and in fact we assume that the conditions are spatially homogeneous within the footprint in sections 4.2, 4.3 and 4.4. Clearly the surface scattering function in equation 2 is valid for such an ice floe and we are able to identify the errors due to penetration separately from the error due to preferential sampling. The error due to spatial heterogeneity and preferential sampling is further investigated in sections 4.5 and 4.6 using a different approach. Nevertheless, in addition to the new ice leads, smooth meter size "facets" are in fact present on natural sea ice, for example refrozen melt ponds on multiyear ice provide larger areas of very smooth, level ice.

Reply to (ii) above: The primary reason for natural waveforms from first- and multiyear ice to be diffuse is the large spatial heterogeneity and the scattering from various layers within the snow and ice. The scattering from various layers within the snow and ice is exemplified with three profiles from the Weddell Sea shown in tables 3, 4, and 5. As

explained above we investigate the error sources separately and the profile conditions are homogeneous within the footprint. These spatially homogeneous conditions are within the valid range of our model.

P525:L27: The authors use a value of 25dB for the backscatter co-efficient over new ice. However Fetterer et al show a backscatter range of 25-40dB over new ice (i.e. an upper range up to 30 times higher). At the upper range the new ice reflection would dominate the return echo and indeed this is the principle used in freeboard retrieval (e.g. Laxon, et al.). Indeed the processing of satellite radar altimeter data rejects any returns which appear to originate from more than one surface within the footprint (Peacock and Laxon, JGR, 2004).

Reply: In the first 8 lines on page 530 we describe that the detection of new-ice is possible because of its high backscatter intensity. The problem is the sampling of ridges and other low backscatter parts of the ice cover where a significant part of the ice volume is found. We believe that the backscatter values taken from Fetterer et al. (1992) are realistic for the four surface types.

P529 L8-10: The authors conclude that on the basis of their study that radar penetration is as important an error as factors affecting buoyancy. However this conclusion is based on analysis using field data gathered outside of the normal season (October - March) when space-borne altimeter estimates are normally used because it is known that penetration uncertainties start to become a problem during spring and summer that these data are discarded(e.g. Laxon et al, 2003; Giles et al., 2008). Evidence from both field (Conner et al, 2008) and modelling (Makynen, TGRS, 2009) indicates that during the winter period (relevant to the CryoSat mission aims) that reflection occurs at the snow-ice interface. This conclusion is therefore valid only for periods outside the normal observing period, or for the Antarctic.

Reply: Our investigation is not restricted by the CryoSat mission aims. The reservations for using radar altimeter data for ice thickness retrieval are clearly well documented. That is not the aim of this paper. We are identifying the error sources for eventually to be able to assign error bars to the retrieved ice thickness. Whether the size of these error bars is acceptable or not is up to the users to decide. We show in section 4.2, 4.3, and 4.4 that even when the primary scattering horizon is the snow/ice interface and there is no significant extinction in the snow, which is a winter situation within the CryoSat mission aims, it is still important to correct for BOTH the snow cover effects on buoyancy and for the effective scattering surface. This is not yet general practise in sea ice radar altimeter processing. In addition, during winter, there is the error due to preferential sampling described in sections 4.5 and 4.6. Our study provides evidence that during the summer measurements are indeed harder to do.

Minor Issues Abstract/P515: The authors should clarify that the objective that the objective of the CryoSat mission is to provide data on changes in thickness measured in the Arctic over the winter period. They should also clarify that previous studies on ice thickness change have made measurements in winter (October-March) and that the results presented in this paper are relevant to spring measurements in the Arctic and to measurements in the Antarctic.

Reply: The errors due to penetration and preferential sampling are relevant throughout the winter. However, we have specified that CryoSat is primarily designed for winter as suggested by the reviewer.

P151L16-19: The authors do not discuss the implications that the ice floe might be in hydrostatic equilibrium on a local scale in sections 4.5 and 4.6.

Reply: It is assumed in sections 4.5 and 4.6 that all the 4 surface types are in hydrostatic equilibrium. Since this could be misunderstood we have now stated this explicitly on page 525 and 526.

P516 L1-4: The authors should make reference to papers by Giles et al., RSE, 2007 and Conner et al., RSE, 2008 which suggest penetration to the ice/snow interface in airborne under-flights of space-borne altimeters and discuss the implications of those

results for the analysis in this paper.

Reply: In Giles et al. (2007) it is assumed that the scattering is from the snow ice interface. "For radar altimetry; 1) Uncertainty in the location of the radar scattering surface in the snow/ice system. Laxon et al. (2003) assume that the radar reflects from the snow/ice interface. This assumption is based on laboratory measurements by Beaven et al. (1995). However, there are no direct observations to confirm this assumption." (Giles et al., 2007). Giles et al do not really show how deep the penetration is, only that there is some penetration. They say that the different height measurements give snow thickness, but they do not provide any prove that their assumed snow thicknesses are actually true. Connor et al (2008) compares airborne laser altimetry with satellite radar altimeter estimates of sea ice freeboard and shows that difference compares with snow depth climatology along most of the transect. The same snow depth climatology that Connor (and Giles et al., 2007) uses is also used as input to the model in our section 4.4. Neither reference above explores the effective scattering surface further but both refer to a laboratory experiment described in Beaven et al. (1995). Beaven finds that most of the scattering at nadir from a snow covered frozen pond occurs at the snow ice interface. How the radar altimeter elevation measurement is affected by the snow cover on the ice is not investigated in Beaven et al. The fact that the snow ice interface is the primary scattering horizon for a relatively thin unlayed snow cover on ice as demonstrated by Beaven can be reproduced by our model.

Section 2: It is not clear how the measurements from the different campaigns are combined to produce table 2.

Reply: Table 2 is not a compilation, it is a reference profile. The snow depth shown in figure 4, and snow density in figure 6 is then varied separately according to the measured values from the different datasets. Each of the datasets is presented separately and for the snow density datasets we use two different snow depths. The simulated range variability from the three different datasets is quite similar.

The physical parameters from each field experiment (or set of experiments (e.g. Sever) should be tabulated separately. Reply: The physical parameters from each dataset: snow depth and snow density, are shown separately in figure 4 and 6 respectively.

P524 L7-9: Section 4.5 does not discuss the effects of surface roughness on backscatter.

Reply: The first lines in section 4.5 state: "High backscatter from limited smooth areas within the footprint can dominate the total altimeter backscatter coefficient as well the height of the effective scattering surface because the backscatter is nonlinear function of the surface roughness (Fetterer et al.,1992)." We have further elaborated on this in line 24, page 525.

P527 L12: The authors discuss the potential effects of melt-ponds on the altimeter return. Whilst this may be interesting it has no relevance to retrieval of ice freeboard during winter when meltponds are absent.

Reply: The melt ponds are not absent they are refrozen during winter this is also the terminology used in the reference: Onstott, (1992) on that page. Page 527, line 15 states that the melt ponds are refrozen. Since this could be misunderstood we have also added 'refrozen' in front of 'melt pond' in line 13 on page 527.

P528: The authors should make reference to Giles et al 2008 whose results suggest variable penetration over Antarctic sea ice.

Reply: Giles, K.A., Laxon, S.W. & Worby, A.P. (2008) Antarctic sea ice elevation from satellite radar altimetry. Geophysical Research Letters, 35, L03503, doi:10.1029/2007GL031572 state that the effective scattering surface is likely between the snow surface and the snow/ice interface for Antarctic sea ice but radar altimetry anyway provide useful information about the ice thickness. This is similar to our simulations of the three profiles from the Weddell Sea: penetration is not to the snow/ice interface nevertheless the three different profiles belonging to three different thickness

categories are distinguishable. We have included this reference.

P531 L18-20: The authors should make reference to the work of the CryoSat Cal/Val team and the CryoSat Calibration and Validation document. The authors should also make reference to the need for in-situ experiments needed to test radar penetration issues directly.

Reply: Recommendations including these two suggestions have been added to the conclusions.

Interactive comment on The Cryosphere Discuss., 3, 513, 2009.