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## ***Interactive comment on “About uncertainties in sea ice thickness retrieval from satellite radar altimetry: results from the ESA-CCI Sea Ice ECV Project Round Robin Exercise” by S. Kern et al.***

### **Anonymous Referee #3**

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The authors present uncertainty analysis of satellite altimetry data of a combined time series of ERS-1/2 and ENVISat freeboard data in the Arctic. They use airborne, moored and submarine validation data to validate measurements and/or parameterizations of freeboard, snow-depth and densities of sea ice and snow. Their main findings are summarized in a list of 4 recommendations, which focus on the correct choices for snow depth and sea ice density.

The paper is well motivated and I fully agree with the authors that a validation of pulse-limited radar altimetry is a pending issue, as well as a consistent conversion of (either ice or snow) freeboard into thickness over the range of existing and future altimetry missions. I am however not fully convinced that the methodology and chosen datasets

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do the job. My main concerns can be summarized in three categories:

### 1) Pulse-limited radar altimetry

The authors focus too little on the potential biases freeboard from radar altimeters may have, especially the low resolution pulse-limited systems. The influence of physical snow properties and surface roughness on the radar range retrieval is not yet sorted out even for higher resolution data (CryoSat-2). Part of this problem is visible in the CryoVEx validation data the authors use here, where the difference of ASIRAS and ALS freeboard appears negligible. It seems therefore premature to use radar freeboard from ERS-1/2 and ENVISat without a bias analysis and contribute differences of satellite and validation data to assumptions of snow depth and ice density. Recently submitted studies of Kurtz et al. and Ricker et al. (in TCD) have shown how large the impact of radar waveform interpretation on freeboard retrievals can be.

### 2) Sea-ice thickness validation data

The authors use airborne altimetry datasets as validation data for sea-ice thickness. In the manuscript is this partly done in a confusing way (please see my detailed comments below). But since the authors acknowledge that the conversion of freeboard to thickness is yet containing significant uncertainties, even high resolution altimetry data cannot be used as a reference for sea-ice thickness, but only freeboard. If the satellite and airborne freeboard is converted into thickness in a consistent way, there is no gain in comparing more than freeboard (except visualizing the impact of freeboard differences in units of thickness). An independent validation of sea-ice thickness requires datasets which either directly measure sea-ice thickness (EM induction) or are much less affected by the uncertainties of densities and snow depth (e.g. ULS draft data used in this study).

### 3) Choice of datasets

It is my guess that the choice of data package in this paper was chosen at the beginning

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of the ESA CCI project. To my knowledge, the authors use only subsets of the airborne campaigns and especially the lack of comparisons against ICESat freeboard map is a missed opportunity in terms of consistency between missions. Even a comparison of CryoSat-2 and ENVISat would be possible in in early 2011. Other data sets (e.g. sea-ice thickness from EM-induction) are very briefly mentioned in the introduction but never used again.

Summarizing, the authors do not provide a convincing case for their recommendations. Mainly because the validation of the ERS-1/2 and ENVISat data lacks radar altimetry specific biases and the choice of validation data sets is limited. The sensitivity study for radar freeboard to thickness conversion and the comparison of snow-depth products does not produce novel insights than earlier publications from Giles, Kurtz, Kwok and others (all cited in the study). I also feel that often the comparison of satellite and validation data is not explained well enough.

But I definitely see the need and importance to extend the time series of Arctic freeboard data with the early pulse-limited data and I would strongly recommend that the authors focus their study on an estimation of freeboard bias and uncertainty of the pulse-limited radar systems and how they relate to other missions that complement (ICESat-1) or extend the time series (CryoSat-2). The consistent conversion to ice thickness would be only the next step after the sensor specific biases between different missions are approximated.

Minor points:

The title includes the term “Round Robin Exercise”. Have the different approaches been taken out independently by the different co-authors? A short explanation would be valuable.

The Discussion section is long and mixed with “Results”. Also, the Summary & Recommendation section should be only a Summary, with the Recommendations following anyway.

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Detailed comments:

P1520 L03 ff Please define “precise”. One of the main points of this study is that freeboard to thickness conversion has not been always done in a consistent way and depends on the choices of densities and snow depth.

P1521 L09 Sea Ice CCI Algorithm Theoretical Basis Document? Link or citation?

P1521 L10 Do the authors take the slower wave propagation speed of the radar waves in the snow layer into account?

P1521 L20 Is the grid optimized for RA/RA-2 data?

P1522 L03 ff Why is the area in Figure 1 limited to the Beaufort Sea and Canadian archipelago? It might be outside the region of available validation data, but interesting to see whether RA/RA-2 based freeboard shows basin-scale gradients.

P1522 L09 ff It is very questionable that W99 is valid in this region. I think it is stated later in the text, but it would be good to mention it already here

P1523 L01 ff The RA grid cell size is latitude dependent, the AMSRE and OIB data is a constant radius of 100 km. Can this introduce a bias?

P1523 L10 There are more and more studies that raises the question how radar data has to be interpreted to yield ice freeboard (see Willatt 2011, Kurtz in TCD or Ricker in TCD).

P1523 L13 The statement that ASIRAS measures ice freeboard is contradicting to statements later in the text

P1523 L20 How do the authors derive the ALS error of 10 to 15 cm. This range seems to be a rather high and only justified in regions which very few leads (which the Fram Strait data used here is typically not).

P1524 L18 Figure 2 caption: Change mooring to moorings

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P1525 L07 ff An additional assumption must also be made that pulse-limited radar altimetry yields a radar freeboard that is not biased by surface roughness. And with the different backscatter signatures of open water, level and deformed ice, this is not very likely. Higher resolution data may be less affected or differently biased, like oblique laser scanner data over open water. Therefore one important objective should also be the investigation of potential biases of space-borne radar altimeter data.

P1526 L8 Does “standard” mean no distinction between MYI and FYI?

P1526 L15 This statement is somewhat vague. What does control the dependence and which sensor is more/less affected by which factor? In the beginning of the next section it is stated that snow depth is crucial for all altimeter data

P1528 L21 Correct, but one could even state it more clearly that W99 is invalid in the CA completely unconstrained by observations. But what are the prospect of getting ice thickness retrievals inside the CA with RA/RA-2 anyway (closed ice cover, land contamination)?

P1529 L05 ff Add: Based on laboratory experiments (Beaven et al., 1995)

P1529 L13 I still don't see how the uncertainty of the ALS can be that high. How many leads were in the data as tie points for the sea surface correction? Could the difference not only be part of the sampling bias?

P1529 L17 Is there a missing curve in Figure 6? I see the red OIB freeboard and the OIB and W99 snow depth but not the blue RA-2 data

P1530 L01 ff I miss an explanation how the data was collocated. I am sure there was not always a good temporal and spatial match between the individual orbits and the submarine data.

P1530 L22 The authors state that the mooring is mostly in multi-year sea ice but in Table 4 the average draft (~1.6m) is more typical for first-year sea ice. Is there any explanation why the ice was untypically thin for multi-year ice?

P1531 L06 ff What is the reasoning of using airborne altimetry datasets as reference for sea-ice thickness when the main objective of the study is to determine how to get sea-ice thickness out of altimetry datasets? Sea-ice thickness from OIB is a product of observations (freeboard, snow depth) but not an observation itself.

P1532 L05 Is this the result of a completely wrong snow depth assumption or could it be that the number of data points for the comparison is insufficient to stick out of the noise level?

P1533 L08 0.02 cm as a mean (?) difference sounds unbelievable good. What is the standard deviation?

P1534 L03 ff Please use consistent naming for the realizations (Numbering not included in the legend or caption of Figure 8)

P1534 L13 “any snow depth” means a statistically chosen value?

P1534 L17 Figure 8 gives the impression to me that none of the realization is able to capture the trend of ULS sea-ice draft in any year. Often, the entire range of realization is necessary to explain the winter cycle. Also if A3 (one fixed ice density) and A1 + A4 (both ice type dependent densities) “agree equally well”, does this not mean that the ice-type dependent ice density is overruled by the choice of snow?

P1535 L27 Was not the RA-2 sampled on  $2^\circ \times 0.5^\circ$  grid and the validation data on a 100 km sphere?

P1536 L01 This is a bold assumption, given the mix of surface types in the large footprint. It is questionable the deformed ice and level contribute equally to the backscatter signal and this has to be proven.

P1536 L03 I do not understand. Does this study not use the OIB freeboard and snow depth data and can produce the thickness with consistent assumptions? Or is this the Round-Robin part of the exercise?

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P1536 L013 ff Here I am lost. Why do the authors reverse-engineer the sea-ice densities with (obviously) different snow densities than the provider of the ice thickness data?

P1536 L25 ff The reason is that Ku-Band radar data may be influenced by density contrast in the snow or volume scattering in general and that the final word of the “correct” interpretation of SAR altimetry waveforms is not yet spoken. The data of ASIRAS is a very good example why Ku-band radar data should be taken with a grain of salt. It must therefore be the first step to understand the bias and uncertainties of radar freeboard before the conversion into thickness.

P1538 L18 ff (ii) What are the uncertainty factors in the airborne campaign? How do these uncertainties relate to those in the satellite data?

P1540 L11 ff I downright disagree: The validation of sea-ice thickness retrievals from altimetry needs independent and non-altimetry validation data. There might be consistency between different freeboard data sets but that does not mean the thickness of both datasets is correct.

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Interactive comment on The Cryosphere Discuss., 8, 1517, 2014.

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