**Author Responses (ARs) to each reviewer comment are in Bold.**

# Interactive comment on “Estimating snow depth over Arctic sea ice from calibrated dual-frequency radar freeboards” by Isobel Lawrence et al.

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Review for "Estimating snow depth over arctic sea ice from calibrated dual-frequency radar freeboards" by Lawrence et al.

General comments:

The study "Estimating snow depth over arctic sea ice from calibrated dual-frequency radar freeboards " by Lawrence et al. uses a combination of altimeters operating at different frequencies (Ku and Ka bands) and flying over the Arctic at the same period (2013-2016) in order to estimate snow depth at the top of sea ice.

Based on previous studies, the authors consider that the main return of the Ka-band radar signal arises from an upper part of the snowpack and that the main return of the Ku-band radar signal originates from a lower part of the snow pack. Using this difference of penetration depth into the snowpack, they estimate snow depth at the top of sea ice by calculating the difference of freeboard height between SARAL/AltiKa (Ka-band) and CryoSat-2 (Ku-band). Before processing the freeboard difference, the authors correct freeboard biases related to radar penetration/surface state. To correct these biases, they fit their Ka and Ku freeboard measurements using laser and radar measurements from the Operation Ice Bridge (OIB) 2013-2016 campaigns. To validate their "Dual-altimeter Snow Depth" estimates, the authors use "independent" snow depth measurements from the Operation Ice Bridge airborne campaigns. Further, they show that the methodology derived with CryoSat-2 and AltiKa can be reproduced using Envisat (Ku-band) and ICESat (Laser).

The paper focuses on a very relevant topic as snow depth is one of the most important sources of uncertainties when converting ice freeboard to ice thickness. Hence, measuring snow depth at pan-arctic scale with a good temporal resolution could strongly help to improve current sea ice thickness estimates. In addition, snow depth is a key thermodynamics parameter as it isolates sea ice from the cold atmosphere in winter and reflects an important amount of solar radiations in summer. Being able to measure snow depth at large scale could therefore truly help to improve our understanding of sea ice growth and melt processes.

In my opinion, the approach of using a combination of altimeter measurements to estimate snow depth deserves publication. However, I have some major remarks that must be addressed before the paper can be published:

1) While the authors considers that the Ka and Ku radar signals do not penetrate identically into the snowpack, it is not clearly stated where the main returns arise from. The authors quote Armitage and Ridout (2015) and Guerreiro et al. (2016), which draw different conclusions, but they don’t clearly give their thoughts. This precision is crucial as one needs to know if the freeboard fit they perform with OIB is used to correct footprint effects or/and penetration effects.

***Author Response (AR)*: The idea of correcting for both biases due to footprint effects / surface state and physical penetration at once is adopted in order to avoid quantifying the actual penetration of each satellite. Based on radiative transfer theory we assume in general that Ku will penetrate further into the snowpack than Ka but we make no assumptions about how far either is penetrating. The final section of the introduction (lines 3-15 page 4) has been re-written to clarify this.**

The authors say "Freeboard estimates from CryoSat-2 (Ku-band) and AltiKa (Ka-band) are calibrated against data from NASA's Operation IceBridge (OIB) to align AltiKa to the snow surface and CryoSat-2 to the ice snow interface*".* Considering this sentence, I assume that they consider (as in Armitage and Ridout (2015)) that Ku does not fully penetrate the snowpack while Ka does penetrate it a little bit, right?

***AR*: We assume that Ku penetrates further into the snow pack than Ka, and therefore choose to correct CryoSat-2 to the ice/snow interface and Ka to the snow surface. We make no assumptions about how far into the snow each is penetrating since we do not think the effects of snow penetration can be separated from biases due to footprint size and surface effects.**

If yes, this raises an important question that should be answered more clearly: why the penetration of the Ka and Ku-bands would change from one area to another (Figure 1 and 2 show that the corrections are not constant)?

***AR*: Figures 1 and 2 do not demonstrate that the snow penetration varies but rather that the combined effects of snow penetration and footprint/surface biases vary from one area to another. Again, the idea with this methodology is that nowhere do we separate the influence of the two. Ideas for why the combined effects of snow penetration and footprint/surface biases ($\Delta f$) varies from one area to another are given in the analysis of figures 1 and 2 (lines 18-25 page 8 and line 32 page 8 onwards).**

Also, this assumption seems to not take into account the results shown in Kurtz et al. (2014) and Guerreiro et al. (2017), why?

***AR*: Kurtz et al. (2014) and Guerreiro et al. (2017) demonstrate the importance for elevation retrieval of surface properties and footprint size respectively. Due to these findings, we do not attribute the deviation of retrieved freeboards from snow and ice freeboard respectively as being due to snow penetration differences but a combination of penetration differences and biases due to sampling area. A reference to the findings of Kurtz et al. (2014), not included in the original manuscript, is now included in section 2.3 (lines 16 – 19 page 6), while references to the findings of Guerreiro et al. (2017) are given in lines 27-31 page 3, lines 6-9 page 4, and lines 12-14 page 5.**

2) The "error calculation section" (4.2) deserves some improvements. First of all, the authors calculate the uncertainty from an error propagation using a quadratic formula with variables that are clearly not independent. The variables covariance should be taken into account to avoid this issue.

***AR*: We agree that covariance is required and have updated the formula and discussion in this section to account for this.**

3) Also, they consider that AltiKa and CryoSat-2 have a similar standard deviation on sea surface estimate and they come to the conclusion that, since AltiKa coverage is better than CryoSat-2, AltiKa freeboard error is smaller than that of CryoSat-2. In my opinion, this cannot be true even with the better coverage of AltiKa in the studied region. To derive appropriate

errors, the authors should calculate the standard deviation on sea surface for each satellite mission before injecting it in equation (6).

***AR*: Following your suggestion, we now calculate the error on the sea-level interpolation for AltiKa and CryoSat-2 independently. The methodology for this is outlined in section 3.2.**

Finally, I am not sure what the authors mean by "correlation coefficient" in section 5.1. According to the values in Table 2, I am guessing that they calculate the fit regression line slope. I think it would be preferable to provide a Pearson coefficient R, which is a more common parameter.

***AR*: We have replaced the correlation coefficient with the Pearson coefficient as suggested.**

4) I acknowledge that contemporary large-scale snow depth measurements are extremely rare and that using the same dataset for calibration and validation is one of the only existing options. Having said that, I would suggest to modify the plan of section 5.1 by not considering the year 2016 as a particular one (Figure 6). At the end of the day, Figure 6 (2016) and Figure 7 (2013-2014-2015) are almost identical: you remove observation from the considered year to evaluate your DuST snow depth. Thus, it does not require two figures nor two comments/conclusions.

***AR*: We have combined evaluations for each year into a single figure and conclusion section as suggested.**

Minor comments:

Page 1 L 4-6: "Freeboard estimates . . . ice/snow interface". Does it mean that Ka/Ku don't stop at the air-snow/snow ice interface?

***AR*: We make no assumption about where Ka/Ku penetrate to, only that Ku penetrates further than Ka and therefore we 'raise' Ka to the snow surface and 'push' Ku to the ice/snow interface. We feel this is now adequately explained in the introduction and does not require a clarification in the abstract.**

L 23: As you mention Envisat above, you should also quote Giles et al. (2008).

***AR*: We have included Giles et al. (2008)**

Page 2: L15-18: This is arguable. For LRM altimeters, the uncertainty related to free-board height is at least as large as the one related to snow depth.

**AR: We no longer reference the results of Giles et al. (2007) in this section and now state that "For both the radar and laser case, snow depth is one of the dominant sources of sea ice thickness uncertainty". Please refer to page 1, lines 21 onwards.**

Page 3: L 31: To be more precise, Guerreiro et al. (2017) suggest that the Ka-band signal stops within the first few centimetres and that the Ku-band signal can stop before the snow-ice interface in case of large snow grains.

***AR*: We have added this clarification (lines 9 to 18, page 3)**

L33: This is not exact: The first study that showed AltiKa freeboard measurements was the one by Maheshwari et al. (2015).

***AR*: We have removed this claim.**

Page 4:

L13: Here and elsewhere, can you mention which footprint you talk about (beam-limited or pulse-limited).

***AR*: We have specified which footprint we are referring to in the manuscript.**

L15: So here, you choose to follow the conclusion given in Armitage and Ridout (2015), which is that the Ka and Ku signals stop within the snow pack, right? If yes, could you state it more clearly? Also, considering the literature you quoted (or not) (Kurtz et al., 2014; Maheshwari et al., 2015; Guerreiro et al., 2016; Schwegman et al., 2015), could you please explain this choice. This is indeed a major point as your entire study is based on this assumption.

***AR*: In response to your major criticism number (1), we feel we have now addressed this point. Lines 3 onwards, page 4, have been re-written accordingly.**

L29: Not exact: see my previous comments.

***AR*: We have removed this claim.**

Page 6:

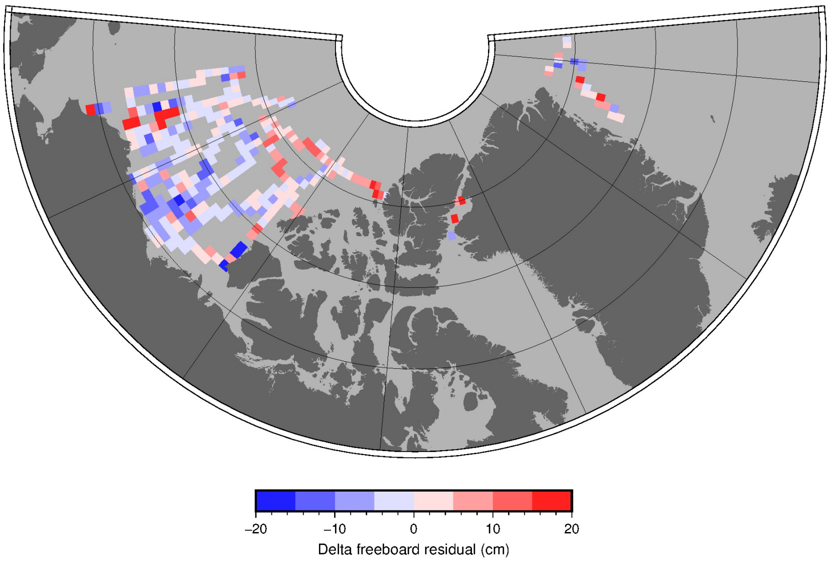
L3: In Armitage and Ridout (2015), I believe that the authors follow another condition related to the Leading Edge Width (see supplementary material). Could you check on that please?

***AR*: In the AltiKa processing, the Leading Edge Width (LEW) is a criterion for identifying 'valid' waveforms but it applies equally to leads and floes: both must have a LEW less than 2 range bins else they are discarded (Armitage and Ridout, 2015, supplementary). LEW therefore is not used to discriminate leads from floes, which is the focus of our discussion in this section. Having said this, the backscatter coefficient Sigma0 is used to identify leads for AltiKa, and for CS-2 the Stack Standard Deviation (SSD) is used to differentiate leads from floes. Details of this have been added (page 5 lines 21 - 23)**

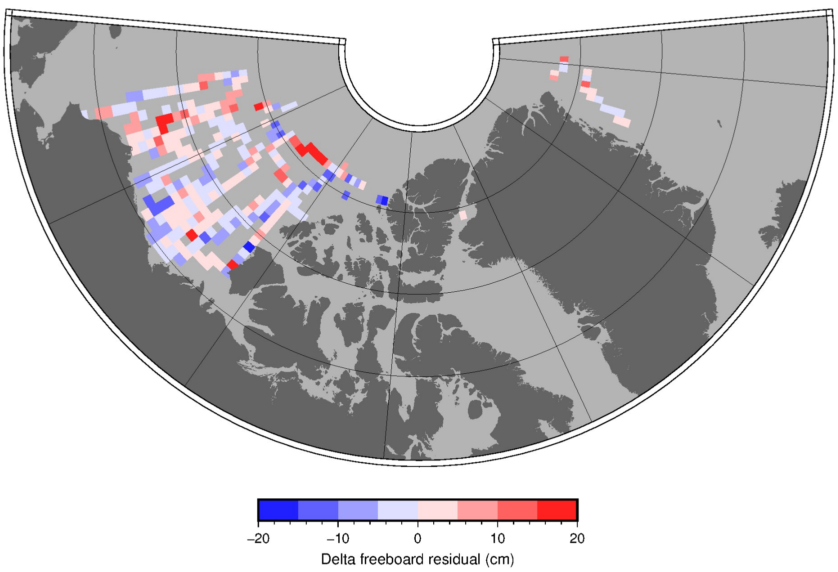
L26-31: To me, this way to proceed raises an important question: As you mention it above, the altimeter range can be biased by waveform hooking due to the proximity of specular reflections. Thus, if you calibrate your freeboards in a particular region (the one overflown by OIB for example), the calibration will likely depend on the density of Off-Nadir reflections found in this region. Consequently, the derived calibration might not work in regions where the density of Off-Nadir reflections is different. To check if your calibration is region-dependent or not, a simple test can be operated: you can plot the residuals of Figures 1 and 2 on a map and check if you observe regional patterns or not. This figure could be provided in the supplementary material.

**AR: Thank you for this suggestion; this is something we originally considered but did not include since there was no evident regional dependence to the linear regression residuals. We have included the plots below for reference. The calibrations themselves, i.e. the extent to which satellite freeboard deviates from the snow or ice freeboard is of course region dependent and this is why we choose pulse peakiness as a means to characterize the surface. Our methodology assumes that surface properties including density of leads are sufficiently accounted for with the pulse peakiness criteria (low peakiness regions correspond to thicker multi-year ice where less leads are present; conversely we would expect highly peaky regions to be lead-dense) to extend the calibration beyond the region sampled by IceBridge.**

AK delta freeboard calibration residuals map




CS2 delta freeboard calibration residuals map



Page 7:

L16-19: How do you evaluate the spatial and temporal resolution?

***AR*: The spatial and temporal resolution that give the most number of grid cells with a minimum of 50 OIB and satellite points in each. This has been clarified in the manuscript (page 8 lines 7-8).**

L28-30: Could you give the correlation coefficient (Pearson's)?

***AR*: This is now provided.**

Page 9:

L2-4: As you consider that the bias you fit is due to penetration effects, then yes, a fs > 0 would imply that the Ku-band signal penetrates through sea ice. However, if one considers that this bias is also due to surface properties (roughness for example), positive fs values would simply suggest that the empirical retracking you use is not adapted to sea ice surfaces. This was clearly demonstrated in the study by Kurtz et al. (2014). Could you provide with a more detailed comment by integrating this other aspect?

***AR:* This is a good point, thank you for this suggestion. The results of Kurtz et al (2014) are now discussed in section 2.3 (lines 16 – 19 page 6). Lines 1-4 page 9 have been updated to include this consideration.**

Page 11:

L-15-16: As you do not clearly mention why you need to calibrate AltiKa and CryoSat-2 freeboards (penetration depth? surface properties?, . . .), this conclusion is hard to understand. Why would your calibration be different from on region to another? Because of snow properties? Lead density? Surface diffusivity? You need to give more details in order to provide a more convincing conclusion.

***AR: This sentence has been removed and this is now discussed on page 13, lines 8-12. We hope that the clarifications made previously* (lines 3-15 page 4) *will now make this discussion coherent.***

L29-31: Same remark as above.

Page 12:

L3: Shouldn't the title be "Uncertainty calculation"? An error should be relative to a "truth measurement". . .

***AR:* Section title changed accordingly.**

Eq 6: As fAk and fAk are clearly not independent (see Figure 1), you must take into account their covariance to calculate the uncertainty.

***AR:* We now consider variable covariance in our uncertainty calculation.**

Page 14:

L1-2: Why do you apply the same standard variation value as for CryoSat-2 (4 cm)? As far as I know AltiKa sea level standard deviation is much larger than that of CryoSat-2. I would recommend to re-calculate a standard deviation for the two datasets here in order to make sure you have the right values.

***AR:*** **We now calculate CryoSat-2 and AltiKa freeboard uncertainty independently (section 4.2)**

Page 15: Figure 6: I am quite surprised about the r value you provide (0.73) considering the figure you show. How do you calculate this coefficient? It seems to me that you provide with the fit regression line slope. Am I right? If yes, I think it would be preferable to provide a Pearson coefficient R, which is more common parameter.

***AR:*** **This is now provided.**

Page 16:

Table 2: Same remark as above.

Section 5.1: I don't understand why you consider 2016 as a particular year. As suggested by Table 2, the comparison for 2016 is almost identical as for the other years (except that you don't use 2016 to calibrate your DuST snow depth for the 2013-2015 periods). In my opinion you should not make any distinction between 2013-2015 and 2016 and re-write this section as such.

***AR:*** **We have combined evaluations for each year into a single figure and conclusion section as suggested.**

L22: There is no link between the footprint size and the bandwidth. Also, you can have a similar footprint with 2 different frequencies depending on the antenna size.

***AR:*** **Lines 16-17 page 18 updated accordingly.**

Page 17:

L1: "Onto a" is written twice

***AR:*** **corrected**

L3-5: This description should be moved into the figure caption.

***AR:*** **corrected**

L10: What does 30+ mean? Can you provide with a range of values instead?

***AR:*** **corrected**

Page 18:

L19: Considering that you did not use validation data to validate your results, I would not use "demonstrated" here...

***AR:*** **We have changed this to 'tested'**

**Author Responses (ARs) to each reviewer comment are in Bold.**

The paper "Estimating snow depth over Arctic sea ice from calibrated dual-frequency radar freeboards" by Lawrence et al. deals with estimating snow depth by combining satellite-based measurements of snow and ice freeboard. The method requires prior calibration with independent freeboard measurements. Here, CryoSat-2 and AltiKa satellite freeboard measurements are calibrated with airborne Operation IceBridge (OIB) measurements.

The latter raises one of my main concerns: The method, as presented here, relies on having reliable independent freeboard data, which at the moment is only provided by OIB data. However, there is disagreement within the science community on how to interpret the OIB radar measurements, i.e. different retrieval algorithms differ in the way air-snow and snow-ice interfaces are detected and localized. A recent paper by Kwok et al. (2017) showed that this caused OIB snow depths as retrieved from different groups to differ on average by up to 7 cm (for first-year ice) and 12 cm (for multi-year ice) for the 2013-2015 data (see Fig. 7 & 8 in Kwok et al., 2017), which is used in the paper presented here. The variability of snow depths is also quite different (so it is not just a constant bias between the different products). Though this problem is briefly mentioned in the paper presented here, this is only done rather late (on p. 14, l. 14), which does not represent how severe this issue is for the proposed method of retrieving snow depth. I think that this should be mentioned and discussed far earlier and with more emphasis because it has major implications on the usability and accuracy of the proposed retrieval method! Ideally, the authors would perform their comparison not only for OIB quicklook data, but also for (at least) one of the other OIB-based freeboard retrieval data sets to estimate how much this can influence the results.

**Author Response (AR): You have raised an important point which was not addressed adequately in the first submission of the paper. In the latest draft, we discuss the results of the Kwok et al. (2017) inter-comparison paper early on in section 2.4 (page 7 lines 15-23) when first introducing Operation IceBridge (OIB), and acknowledge that the variability of OIB Snow Radar data from different groups presents a limitation to our methodology. Following the results of the Kwok et al. (2017) study we now employ instead NASA JPL snow depths in our methodology. This data set shows best agreement with ERA-interim and the Warren climatology for the years 2013-2015 (Fig. 9, Kwok et al. (2017)). Regardless of the discrepancy between different OIB Snow Radar datasets, our methodology offers a means to extrapolate the OIB snow depth dataset (whichever is chosen or deemed "best") to the wider Arctic, both spatially and temporally. Our DuST product would benefit from the development of a next-generation Snow Radar data set, combining the best qualities of each existing processing algorithm, as is advocated by Kwok et al. (2017). This is discussed in section 3.2 (page 13 line 14 to page 14 line 6). The use of an optimised OIB Snow Radar dataset could improve our snow depth estimates but would not alter the methodology, which we feel therefore deserves publication.**

A further concern is that the study of Guerreiro et al. (2016) also uses CryoSat-2 and AltiKa freeboard measurements to retrieve snow depth. Instead of calibrating these Ku and Ka-band measurements with independent data (as done here), they theoretically analyze the penetration depths of both radar altimeters in snow and use snow density estimates to modify the Ku-band radar signal's velocity through the snow. In their study, they compare their retrieved snow depths with OIB snow depths for the same years as in the study presented here (2013-2015). They seem to have somewhat lower RMSDs (4.1...5.4 cm) as compared to the results presented here (4.9...6.7 cm), although their results are independent of OIB measurements, while the results here are not. Why are these results not compared here? Is there any advantage of using the method presented here as compared to the one used in Guerreiro et al. (2016)? This comparison and discussion is missing here!

**AR: We now include a discussion of the Guerreiro et al. (2016) approach and outline why our methodology is different and has its own advantages (page 7 lines 1-13). We have aimed in this paper to outline a methodology that can be applied in future when AltiKa is no longer operational, and demonstrate the methodology applied to Envisat and ICESat in order to show that it could also be applied to CS-2 and ICESat-2 when ICESat-2 is launched. The method of Guerreiro et al. (2016) relies on the ability to reprocess CS-2 data to produce pseudo LRM CS-2 data in order to achieve a footprint similar to AltiKa. By doing so, the authors can then assume that the remaining elevation difference found between AltiKa and pLRM CS-2 is the result of snow penetration difference alone and thus snow depth can be found as the difference between the two. This methodology could not be applied to, for example, CS-2 and ICESat-2 because neither dataset can be processed such as to make the effective footprints the same.**

I found it confusing that the authors first declare that radar altimetry penetrates through to the snow-ice-interface, while laser altimetry does not (p. 2). AltiKa is presented as a radar altimeter (thus suggesting that it penetrates through the snow), but it is later compared with OIB's ATM laser freeboard (section 3.5). From what I understood, Guerreiro et al. (2016) conclude that the radar signal from AltiKa does not penetrate the snow, while Armitage and Ridout (2015) concluded that the AltiKa signal is scattered from roughly the midpoint of the snow layer. This discrepancy is not even mentioned here. What do your results suggest? Please comment/discuss/specify.

**AR: Please re-refer to the introduction since it has been restructured in line with your subsequent criticism. Following an overview of the Guerreiro et al. (2016) and Armitage and Ridout (2015) studies, we have added a paragraph (page 4, lines 3 - 22) to clarify our position on AltiKa and CS2 snow penetration.**

Another issue is that I think the structure of the paper could be improved:

a) In an "Introduction" I would mainly expect to read about the importance of the presented study, how it fits into the context of already existing studies and what is the new contribution of the presented study. Instead, we here get a general introduction on the importance of snow (ok) and we are presented the equations used to convert ice/ snow freeboard to snow depth (more appropriate for the "Data and Methods" section?). This is followed by a chapter that lists existing snow depth products, where I would prefer to read more about the differences to the presented study and the implications these have instead of a list of methods.

**AR: On your advice, we have changed the structure of the paper. The introduction no longer contains any equations but is rather an overview of: the importance of snow, the current methods to retrieve it, their limitations, and our proposed methodology and a justification for its necessity.**

b) The "Results" section contains a lot of what I would consider discussion (or speculation as some of the statements on p. 11 are not based on citations), while the "Discussion" section on p. 14, l. 20 starts with showing more results...

**AR: We have now combined Results and discussion into one section.**

Otherwise, the manuscript is, in general, well written and I was able to follow the method.

Specific comments:

p. 1, l. 3: "*...can be applied to any coincident freeboard measurements*" -> to any coincident snow and ice freeboard measurements? (would be clearer)

**AR: The methodology can be applied to any coincident satellite freeboards they do not have to measure the snow and ice freeboards (indeed we suggest that AltiKa and CS-2 do not measure snow and ice freeboard but rather that we do not know where in the snowpack their signal originates).**

p. 1, l. 19: "*...snow depth estimates could be usefully assimilated...*" -> "usefully" is a vague (and strange) expression here...

**AR: This has been removed. See page 1 lines 18-20.**

p. 1, l. 23-24: "*The implications ... is*" -> The implications ... are

**AR: removed**

p. 2, l. 4: Eq. (1) -> Is this formula from Beaven et al., 1995?

**AR: This section of the introduction including this formula has been removed**

p. 2, l. 27-28: " *The granular nature of snow acts to scatter and dissipate microwave energy radiating from the Earth's surface, reducing the surface brightness temperature.*" -> This statement is only true for part of the frequency spectrum of microwaves! Not true for low microwave frequencies.

**AR: This statement has been removed. See page 2 line 19 onwards.**

p. 2, l. 30: "*for a given frequency*" -> Too vague, I'd prefer to see the frequency (range) that you mean here.

**AR: This section has been condensed. See page 2 line 19 onwards.**

p. 3, l. 30-31: "*AltiKa was designated with a maximum penetration depth of 0, i.e. no penetration, and CS-2 a maximum penetration of 1, i.e. full snow penetration...*" -> What does this mean? Is it possible to retrieve snow depth using this method? Could you compare these with your method?

**AR: This statement has been clarified (see page 3, lines 14-19). We now discuss their methodology and its limitations further on page 6 (lines 34 onwards).**

p. 4, l. 8-14: You write about the issues raised by different satellite footprint sizes, please also give the CS-2 footprint size here to make the comparison easier.

**AR: This has been included (page 3, line 30)**

p. 4, l. 28: "*retrieves surface elevations up to 81.5◦*" -> a) Please add "latitude" (to avoid confusion with "geometrical elevations", which can also be given in degrees). b) I think this should be mentioned earlier in the manuscript because it constitutes a major limitation for polar applications of AltiKa.

**AR: "latitude" has been included (page 4, line 27). This is now also mentioned earlier on page 3, (line 11).**

p. 6: References for statements in l. 10-15 ?

**AR: Added (page 6, line 16)**

p. 6, l. 20: "*It*" -> it + "*this criteria*" -> this criterion

**AR: Corrected (page 6, line 23)**

p. 6, l. 21: Is "*snagging*" a word generally used for this? (just asking)

**AR: Yes. Not sure when the term was coined but it appears as early as 1992 in "F. M. Fetterer, M. R. Drinkwater, K. C. Jezek, S. W. C. Laxon, R. G. Onstott, and L.M. H. Ulander, "Sea Ice Altimetry," in Microwave Remote Sensing of Sea Ice. Washington, DC, USA: AGU, 1992, ch. 7"**

p. 6, l. 22: "*To overcome these problems,...* " -> refers to which problems? the off-nadir ranging of leads or also roughness?

**AR: This has been changed to "To overcome the CS-2/AltiKa freeboard bias" (page 6, line 26)**

p. 6, l.26: "*... we instead adopt an approach...*" -> Did you come up with this approach? Or did you take up an existing approach? (If yes, which one?/Reference?)

**AR: We came up with this approach. We have changed this to "we here introduce an approach" accordingly (page 6 line 31)**

p. 6, l. 30-31: "*the appeal of this methodology is its applicability to any freeboard data sets*"

Why would this (i.e. applying to any freeboard data sets) not be possible for the method described in Guerreiro et al. (2016), for example? Wouldn't both have to be re-evaluated for their performance with different freeboard measurements anyways?

**AR: The method of Guerreiro et al. (2016) relies on the ability to reprocess CS-2 data to produce pseudo LRM CS-2 data in order to achieve a footprint similar to AltiKa. By doing so, the authors then make the assumption that the remaining elevation difference found between AltiKa and pLRM CS-2 is the result of snow penetration difference alone and thus snow depth can be found as the difference between the two. This methodology could not be applied to, for example, CS-2 and ICESat-2 because neither dataset can be processed such as to make the effective footprints the same. This is explained in section 2.3, page 7 line 5 onwards.**

p. 6, l. 31: "*By calibrating satellite freeboards with an independent data set, biases are systematically corrected for*" -> I think this statement is too "optimistic"/general. Whether or not biases are systematically corrected for depends to a large extent on the quality, accuracy, and temporal + spatial resolution of the independent data. Not to mention that the bias is not the only thing to worry about...

**AR: This sentence has been removed**

p. 7, l. 7: "*snow depth, retrieved with the Kansas Snow Radar to within 5 cm accuracy* " -> Here (and also already in the introduction) it should be mentioned that different snow depth retrieval algorithms give very different snow depths! (Kwok et al., 2017)

**AR: This is now discussed in this section (see page 7 lines 15-23)**

p. 12, l. 5: Asterisk too high?

**AR: Asterisk has been removed. (Page 14 line 9)**

p. 14, l. 22: "*Spring*" -> spring

**AR: corrected**

p. 16, l. 3-5: Did you use 2016 OIB data for calibration when comparing with the 2013, 2014 and 2015 OIB data? If not, why not?

**AR: yes we did. This has been clarified (page 17, line 11)**

p. 16, l. 14-15: remove parentheses around "*Kwok et al., 2017*"

**AR: corrected**

p. 17, l. 1: "*onto a onto a*"

**AR: corrected**

p. 17, 9-10: "*Snow depth agrees with expected spatial distribution and magnitude"* -> Compared to what? How do you know? Or do you mean just with regard to the statement that follows (on thicker snow over multi-year and thinner snow over first-year ice)?

**AR: With regard to the statement that follows. This has been clarified (page 18, line 28 onwards)**

Fig. 18, l. 8: " *...this evaluation does demonstrate the ability to up-scale OIB snow depths to the wider-Arctic* " -> Do you mean ability as in "we do not get nonphysical snow depth values" or how is the ability for this demonstrated here without comparing the snow depths to independent data?

**AR: we mean that the scatter plots suggest the ability to use the calibration functions to predict OIB snow depths for an unsampled year and region. This has been clarified (page 19, line 13)**

Fig. 1 & 2: For the sake of completeness, it would be good to mention what the dashed grey line is (the zero line I guess).

**AR: included**

Fig. 3: Why are the snow depths smoothed? Is there a physical reason for this? The spatial variability contains information too (about real variability or about the "consistency" of the method, for example), why not show this?

**AR: Snow depth maps are now shown unsmoothed.**

Fig. 6: It is very hard to see the OIB measurements on top of the snow depth map. Maybe zooming into the campaign area would be useful? L. 3 of caption: "*each grid cells*" -> each grid cell"

**AR: Maps are no longer included and scatter plots for all years have been combined into a single plot.**

Fig 6 & 7: In none of the scatter plots there is snow depth values <0cm or >60cm, why would you show the data for a range of -20 to 80cm? This raises the question whether this was made to make the regression look "better"... and also creates unused white space that could be used for information instead.

**AR: Plots now scaled from 0-60 cm**

# Estimating snow depth over Arctic sea ice from calibrated dual-frequency radar freeboards

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**Abstract.**

Snow depth on sea ice remains one of the largest uncertainties in sea ice thickness retrievals from satellite altimetry. Here we outline an approach for deriving snow ~~thickness~~ depth that can be applied to any coincident freeboard measurements after calibration with independent observations of snow and ice freeboard. Freeboard estimates from CryoSat-2 (Ku-band) and AltiKa (Ka-band) are calibrated against data from NASA's Operation IceBridge (OIB) to align AltiKa to the snow surface and CryoSat-2 to the ice/snow interface. Snow depth is found as the difference between the two calibrated freeboards, with a correction added for the slower speed of light propagation through snow. We perform an initial evaluation of our derived snow depth product against OIB snow depth data by excluding successive years of OIB data from the analysis. We find a root-mean-square deviation of ~~4.9, 6.5, 6.7 and 7.6~~ 7.7, 5.3, 5.9 and 6.7 cm between our snow thickness product and OIB data from the springs of 2013, 2014, 2015 and 2016 respectively. We further demonstrate the applicability of the method to ICESat and Envisat, offering promising potential for the application to CryoSat-2 and ICESat-2, when ICESat-2 is launched in 2018.

## 1 Introduction

The addition of snow on sea ice, given its optical and thermal properties, generates several effects on the climate of the polar regions. Owing to its large air content, snow has a thermal conductivity ten times less than that of ice (Maykut and Untersteiner, 1971). During the winter freeze-up, it forms an insulating layer that reduces heat flow from the ocean to the atmosphere and slows the rate at which seawater freezes to the bottom of the ice, dampening further ice growth (Sturm et al., 2002).

Snow has an optical albedo in the range of 0.7-0.85, compared to 0.6-0.65 for melting white ice (Grenfell et al., 1977). At the onset of the melt season, short-wave solar radiation is reflected from the surface, limiting ice melt. These properties make snow on sea ice important in energy budget considerations and the inclusion of accurate Arctic snow depth estimates ~~could be usefully assimilated to improve~~ would improve current weather and sea ice forecasting (Stroeve et al., 2018).

As well as its climatic importance, snow depth plays a key role in the retrieval of sea ice thickness from satellite altimetry. Over the past two decades both radar (e.g. ERS-2, Envisat, CryoSat-2) and laser (e.g. ICESat) altimeters have enabled sea ice thickness to be ~~measured from space(Laxon et al., 2003, 2013; Kwok and Cunningham, 2008). The implications of uncertain snow depth is different for each measurement approach. For the radar~~ retrieved from space, first by measuring the sea ice freeboard (the portion of the ice floe above the water), and then converting this to thickness by assuming that the floe is in hydrostatic equilibrium with the surrounding ocean (Laxon et al., 2003; Giles et al., 2008; Laxon et al., 2013; Kwok and Cunningham, 200 For both the radar and laser case, snow depth ~~plays a two-stage role: First, under the assumption that the radar pulse penetrates through the snow to the ice /snow interface (Beaven et al., 1995), a correction to account for the slower speed of light propagation through the snow pack is required in order to convert radar freeboard to ice freeboard. This correction is given by :~~

$$f_i = f_r + h_s\left(\frac{c}{c_s} - 1\right)$$

is one of the dominant sources of sea ice thickness uncertainty (Giles et al., 2007; Ricker et al., 2014; Tilling et al., 2017; Zygmuntowska et

~~where $f_i$ is the ice freeboard, $f_r$ is the radar freeboard measured by the radar altimeter, $h_s$ is the snow depth and $c$ and $c_s$ are the speed of light in a vacuum and in snow, respectively~~

In-situ measurements of snow depth and density for the 37-year span from 1954-1991 provided the first comprehensive Arctic snow climatology. The data set, compiled and published by Warren et al. (1999) comprises of measurements gathered at Soviet drifting stations across the central Arctic. Stations were located over multi-year ice, which at the time of data collection spanned an area of some 7 x $10^6$ km$^2$. Recent studies have demonstrated that the Arctic is undergoing a transition from multi-year to first-year ice (Comiso, 2012) and the inaccuracy of the Warren climatology over seasonal ice has been emphasised by a number of studies (Kurtz and Farrell, 2011; Kurtz et al., 2013; Webster et al., 2014; Kern et al., 2015).

~~Secondly, the added weight of a snow cover alters the buoyancy of the sea ice floe, therefore snow thicknessis required to convert sea ice freeboard to thickness $t_i$. Assuming hydrostatic equilibrium, sea ice thickness is given by:~~

$$t_i = \frac{\rho_s}{\rho_w - \rho_i} h_s + \frac{\rho_w}{\rho_w - \rho_i} f_i$$

~~where $\rho_s$~~Despite only representing historical conditions, the Warren climatology remains the choice source of Arctic-wide snow depth estimates used in the processing of contemporary sea ice thickness, ~~$\rho_w$, and $\rho_i$ are the densities of snow, water and ice respectively.~~i.e. from CryoSat-2 (hereafter CS-2, a Ku-band radar satellite altimeter operational since 2010). In order to address the change to a more seasonal ice regime, Warren snow depths are halved over first-year ice regions to accommodate the lesser accumulation they experience (Ricker et al., 2014; Guerreiro et al., 2017; Tilling et al., 2017; Kurtz et al., 2014). Although this modification generates temporal and spatial variability of snow depths due to the changing multi-year ice fraction, trends in precipitation and accumulation are not accounted for, rendering time series analyses of snow depths impossible by this method.

~~For laser altimetry e. g. Kwok et al. (2004, 2007), where it is assumed that the laser does not penetrate the snow and thus the return echo comes from the air/snow interface (Zwally et al., 2002), the freeboard $f_l$ represents the height of combined ice plus snow layers above sea level and the hydrostatic equation becomes:~~

$$t_i = \frac{\rho_s - \rho_w}{\rho_w - \rho_i} h_s + \frac{\rho_w}{\rho_w - \rho_i} f_l$$

~~Giles et al. (2007) used typical values and their uncertainties for quantities in Eqs. (??) and (??) to perform an error sensitivity analysis on retrieved sea ice thickness. They found that snow depth uncertainty represents the dominant error contribution for both the radar and laser case; 48% and 88% of the total error respectively. Their typical snow depth uncertainty of 0.11 contributed a 0.32 error on sea ice thickness from radar altimetry, and 0.7 error on sea ice thickness from laser altimetry.~~

Only satellite-derived snow depth estimates can offer the spatio-temporal resolution required for time series analysis and accurate monthly sea ice thickness derivation, but retrieving snow depth from space has proven challenging and is an ongoing effort for the sea ice community. ~~This paper addresses this critical data gap by demonstrating an approach for deriving snow thickness that can be applied to any coincident freeboard measurements after calibration with an independent observation of snow and ice freeboard. Before outlining the proposed method and introducing our Dual-altimeter Snow Thickness (DuST) product, we first review the most successful existing approaches for retrieving snow depth from satellites, and discuss their limitations.~~

## 2 ~~Existing satellite snow depth products~~

~~Existing methods to retrieve snow depth from satellites~~ Existing methods have historically relied on using relationships between passive microwave brightness temperatures and snow thickness. ~~The granular nature of snow acts to scatter and dissipate microwave energy radiating from the Earth's surface, reducing the surface brightness temperature. Markus and Cavalieri (1998) developed the first snow-depth-on-sea ice algorithm on the basis of two features of this snow scattering: 1) The linear reduction in brightness temperatures with increasing snow depth for a given frequency, and 2) higher attenuation at higher frequencies.~~ Using data over Antarctic sea ice from the Defense Meteorological Satellite Program (DMSP) special sensor microwave/imager (SSM/I), ~~they~~ Markus and Cavalieri (1998) compared the spectral gradient ratio of the 19 and 37 GHz vertical polarization channels with in-situ snow depth data in order to express snow depth as a function of brightness temperature. The algorithm was later developed for application to Arctic sea ice using data from the Advanced Microwave Scanning Radiometer-EOS (AMSR-E), but due to the inability to distinguish signatures from snow and multi-year ice, the available AMSR-E data product is limited to seasonal ice only (Comiso et al., 2003; Markus and Cavalieri, 2012). Furthermore, subsequent studies have demonstrated the sensitivity of the retrieved snow depth to snowpack conditions and surface roughness (Stroeve et al., 2005; Powell et al., 2006).

~~In another study using passive microwave, Maaß et al. (2013)~~

Maaß et al. (2013) utilised a frequency of 1.4 GHz (L-band), measured by the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) satellite to retrieve snow depth. Although snow is transparent to L-band frequencies, i.e. the large wavelengths are not attenuated by the snow, their model-based study found brightness temperatures from the ice increased at L-band frequencies when a snow layer was present due to its insulating properties and the dependence of ice emissivity on temperature.

Using a radiative transfer model, they tested the impact of 0-70 cm varying snow thickness on L-band brightness temperatures for a number of scenarios (in which ice temperature, thickness, salinity, and snow density varied within a realistic range).

The snow depth which produced a brightness temperature most comparable (smallest root mean square deviation and best correlation coefficient) to SMOS brightness temperature was then compared with snow thickness from Operation IceBridge in order to asses which scenario performed best. Snow depths produced by this scenario correlated well (root-mean-square deviation = 5.5 cm) up to model-generated depths of 35 cm, but overestimated snow depth thereafter, owing to the desensitisation of brightness temperatures when snow depth increases above 35 cm. Furthermore, this approach requires that the values for the input parameters (ice temperature, thickness, salinity, and snow density) are assumed valid everywhere. In reality, these parameters vary in space and time and the authors express the need to develop the methodology further to allow regional and temporal variability of model input parameters. At time of publication of this study, no SMOS snow depth product has been made publicly available.

A ~~new~~ recent approach to snow depth retrieval from satellites was offered by ~~Guerreiro et al. (2016)~~Guerreiro et al. (2016), who demonstrated the potential to estimate snow ~~depth~~ thickness by comparing retrievals from coincident satellite radar altimeters operating at different frequencies. Snow depth over Arctic sea ice (up to 81.5° North) was retrieved by differencing elevation retrievals from AltiKa (Ka-band radar satellite altimeter, 2013-present) and ~~CryoSat-2 (~~CS-2~~) (Ku-band radar satellite altimeter, 2010-present)~~. To investigate the penetration properties of the two radar altimeters, the authors simulated penetration depth as a function of snow grain size, under different temperature and density conditions, derived from the equation for the extinction coefficient of the radar signal. Based on these model simulations ~~and using existing field campaign data to characterise average snow grain sizes, AltiKa was designated with a maximum penetration depth of 0, i.e. no penetration, and~~ the authors suggested that the Ka-band signal stops within the first few centimetres of the snow and that the Ku-band signal can be reflected before the snow-ice interface in case of large snow grains. In the following analysis to retrieve snow depth however, this grain-size dependence of signal penetration is essentially neglected and it is assumed that AltiKa does not penetrate the snow at all whilst CS-2 ~~a maximum penetration of 1, i.e. full snow penetration, across the Arctic basin.~~ penetrates it fully, allowing snow depth to be calculated simply as the difference between the two.

~~In contrast to this, Armitage and Ridout (2015) derived AltiKa freeboard for the first time and investigated the spatial variability of AltiKa and~~ A previous study by Armitage and Ridout (2015) also compared retrievals from AltiKa and CS-2~~penetration~~; they found a basin-mean freeboard difference of 4.4 cm in October 2013 increasing to 6.9 cm in March 2014, with AltiKa consistently higher across the basin and season. By comparing the freeboards retrieved from each satellite with ~~an independent measurement of~~ ice freeboard from NASA's Operation IceBridge (OIB), radar penetration at a local grid-scale level was quantified. Under the assumption that multi-year ice and first-year ice characterise snow and ice packs with distinctive penetrative properties, an average value for radar penetration factor was found for each satellite over each ice type. Though limited to the spring due to the availability of OIB data and therefore not necessarily representative of penetration properties throughout the year, the study highlights the importance of accounting for regional differences in penetration depth.

~~Guerreiro et al. (2017)~~ Guerreiro et al. (2017) compared freeboards from Envisat, a Ku-band pulse-limited altimeter, with those from the CS-2 SAR system. Since both altimeters operate at the same frequency, they are expected to penetrate to the same depth and therefore retrieve comparable freeboards. The study found Envisat was biased low compared with CS-2, attributed to differences in footprint size (0.3×1.7 km for CS-2 vs. 2-10 km diameter for Envisat) and the effect of ~~the retracker on SAR and~~

using an empirical retracker on Envisat's pulse-limited waveforms (discussed in Sect. 2.3). ~~Schwegmann et al. (2016)~~ Schwegmann et al. (2 a similar Envisat / CS-2 freeboard comparison over Antarctic sea ice and ~~similarly~~ also found a bias on Envisat's freeboard attributed to its larger footprint.

These results suggest that the freeboard difference between AltiKa and CS-2 ~~in Armitage and Ridout (2015) may not be a result of penetration differences alone, but subject to biases due~~ found in Armitage and Ridout (2015) may not have been solely the result of a difference in physical snow penetration, but due also to differences in sampling area and processing ~~techniques~~technique. AltiKa has a smaller pulse-limited footprint than that of Envisat (1.4 km compared with 2-10 km); nevertheless we would expect the impact of its different footprint with respect to CS-2 to introduce a bias like that seen in the Envisat data. This is discussed fully in Sect. 2.3.

~~Building on the methodology of Armitage and Ridout (2015), we~~ Based on studies of snow penetration depth as a function of microwave wavelength (Ulaby et al., 1984), we expect CS2's Ku-band pulse to penetrate further into the snow pack than AltiKa's Ka-band, but unlike previous studies (Guerreiro et al., 2016; Armitage and Ridout, 2015) we do not try to quantify this penetration depth. Based on the results of Guerreiro et al. (2017); Schwegmann et al. (2016) and Kurtz et al. (2014), we assume that the effects of snow penetration and biases due to sampling area cannot be separated, and instead correct for both simultaneously by calibrating satellite freeboards with independent freeboard data. We make use of ~~independent~~ snow depth and laser freeboard data from OIB to asses the deviation of AltiKa and CS-2 satellite freeboards from the snow surface and snow/ice interface respectively. We assume this deviation to result from the combination of competing effects; ~~penetration depth~~snow penetration, biases due to sampling area and surface roughness, and effect of the threshold retracker on the satellite waveforms. ~~Following Guerreiro et al. (2017), we~~ Like Guerreiro et al. (2017), we use satellite Pulse Peakiness (PP) as a characterisation of the surface and compare each satellite's deviation from its expected dominant scattering horizon ($\Delta f$) against ~~satellite pulse peakiness~~PP. Using the relationships between $\Delta f$ and ~~pulse peakiness, we~~ PP, we then calibrate both AltiKa and CS-2 freeboards to bring them in line with the snow surface and snow/ice interface respectively. ~~We then estimate snow depth~~ Finally we estimate Dual-altimeter Snow Thickness (DuST) as the difference between the calibrated AltiKa and CS-2 ~~freeboard. The advantage of our approach is its applicability to any freeboard data sets providing they can be calibrated with an independent measure of snow/ice freeboard.~~freeboards.

In the next section we outline the data sets used and discuss why the properties of the area sampled by the satellite footprint can create a bias on freeboard which is inseparable from the physical snow penetration of the signal. In Sects. 2.5 and 2.6 we calibrate the AltiKa and CS-2 freeboards and then present the results of this calibration applied to the 2015-16 growth season and discuss the retrieved snow depth estimates with reference to large-scale weather phenomena in Sect. 3.1. We provide an analysis of the uncertainty on our gridded DuST product and compare with OIB snow depth data not included in the calibration in Sect.3.2. Finally in Sect. 3.2, we apply to DuST methodology to freeboards from the ICESat and Envisat satellites.

## 2 Data and methods

### 2.1 AltiKa

The Satellite for Argos and AltiKa (herein referred to as AltiKa), was launched in spring 2013 as a joint mission between the Centre National d'Etudes Spatiales (CNES) and the Indian Space Research Organisation (ISRO). AltiKa's pulse-limited Ka-band radar altimeter, which operates at a central frequency of 35.75 GHz, retrieves surface elevations up to 81.5° ~~. The first sea ice freeboard estimates using AltiKa data were presented in Armitage and Ridout (2015), who~~ latitude. Armitage and Ridout (2015) used a 'Gaussian plus exponential' retracker to retrieve lead elevations (after ~~Giles et al. (2007)~~Giles et al. (2007)) and a 50% threshold retracker over floes. AltiKa freeboard data used in this study are derived using the same processing algorithm and the reader is referred to the supplementary material in ~~Armitage and Ridout (2015)~~ Armitage and Ridout (2015) for further details.

### 2.2 CryoSat-2

CS-2 was launched by the European Space Agency in 2010, tasked with the specific role of monitoring the Earth's cryosphere. The satellite has an orbital inclination of 88°, giving it far better coverage over the poles than previous radar altimeters, and, unlike AltiKa, CS-2 employs along-track SAR processing to achieve an along-track resolution of approximately 300 m, improving the sampling of smaller floes and making it less susceptible to snagging from off-nadir leads (Wingham et al., 2006). As with AltiKa, lead elevations are retrieved using the 'Gaussian plus exponential' model fit and for floes a 70% threshold retracker was determined as offering the best average elevation from CS-2's unique SAR waveforms ~~(Tilling et al., 2017)~~(Wingham et al., 2006). The CS-2 freeboard data used in this study were processed by the Centre for Polar Observation and Modelling (CPOM) and readers are referred to ~~Tilling et al. (2017)~~ Tilling et al. (2017) for further details on the method.

### 2.3 Sources of AltiKa / CryoSat-2 freeboard bias

We define AltiKa / CS-2 freeboard bias as the portion of the AltiKa minus CS-2 freeboard difference that does not originate from the difference in snow penetration of the two radars. In line with radar theory (Rapley et al., 1983) and in light of recent findings by ~~Guerreiro et al. (2017)~~ Guerreiro et al. (2017) we expect such a bias to be the result of the difference in footprint sizes between the two altimeters and the consequences of this during freeboard processing. The differences between AltiKa and CS-2 of interest to this study are summarised in Table 1.

In an initial stage of AltiKa and CS-2 freeboard processing, waveforms are classified as either lead or floe according to thresholds for Pulse Peakiness (hereafter PP), defined as:

$$\mathrm{PP} = N\frac{p_{max}}{\Sigma_i\, p_i}$$

where $N$ is the number of range bins above the 'noise floor' (calculated as the mean power in range bins 10-20), $p_{max}$ is the maximum waveform power (the 'highest peak'), and $\Sigma_i\, p_i$ is the sum of the power in all range bins above the noise floor (Peacock and Laxon, 2004). It should also be noted that further waveform parameters are used to identify lead and floes; Stack

**Table 1.** AltiKa and CS-2 (SAR mode) operation characteristics

| | Period of operation | Operating frequency | Footprint size | Footprint area | Sampling interval | Latitude limit |
|---|---|---|---|---|---|---|
| AltiKa | Feb 2013 - present | 35.75 GHz (Ka-band radar) | 1.4 km diameter (pulse-limited) | 1.5 $\mathrm{km}^2$ | 0.17 km | 81.5° |
| CryoSat-2 SAR | April 2010 - present | 13.57 GHz (Ku-band radar) | 0.3/1.7 km along/across track (Doppler cell) | 0.5 $\mathrm{km}^2$ | 0.3 km | 88° |

Standard Deviation (SSD) for CS-2 (Tilling et al., 2017) and backscatter coefficient $\sigma_0$ for AltiKa (Armitage and Ridout, 2015). Since PP is the criterion shared by both it is the focus of our discussion here.

Waveforms originating from smooth, specular leads demonstrate a rapid rise in power followed by a sharp drop off, giving them a high PP. Returns from floes typically demonstrate a more gradual rise in power and slower drop-off, equivalent to a lower PP. PP can therefore be used to distinguish floe and lead returns, and eliminate those not clearly identifiable as one or the other. For AltiKa(CS-2), waveforms with PP less than 5(9) are designated as originating from ice floes. Waveforms with PP greater than 18 are classified as leads for both satellites (Armitage and Ridout, 2015; Tilling et al., 2017).

Waveforms that exhibit a mixture of scattering behaviour will have a PP in the 'ambiguous' range (5<PP<18 for AltiKa and 9<PP<18 for CS-2) and are discarded. Since AltiKa has a larger footprint, its waveforms are more likely to be ambiguous and therefore discarded than CS-2, which can resolve smaller floes within the same region. The result of this is a bias in AltiKa towards higher freeboards (only larger floes, which tend to be thicker, are captured), especially over seasonal, lead-dense areas.

The impact of surface roughness on pulse-limited altimetry is well documented (e.g. ~~Rapley et al. (1983); Raney (1995); Chelton et al. (2~~ Generally, a rougher surface leads to dilation of the footprint and a widening of the leading edge of the waveform return. For a homogeneously rough surface with a Gaussian surface elevation distribution, the 50% power threshold represents the mean surface elevation within the pulse-limited footprint. However, for a heterogeneously rough surface, such as that of multi-year sea ice, the waveform leading edge can take a complex shape ~~,~~ where the half-power point does not necessarily represent the average elevation within the footprint and using a 50% threshold retracker might lead to a biased surface height retrieval ~~. Since AltiKa does not benefit from the~~ (Rapley et al., 1983; Raney, 1995; Chelton et al., 2001). Despite its along-track Doppler processing and effective sharpening of the waveform response~~that~~ , CS-2 ~~does, it is more susceptible to a freeboard bias over rough sea ice due to this effect.~~ may also be susceptible to an elevation bias due to surface roughness. This was demonstrated by Kurtz et al. (2014) who advocate the use of a physical model retracker in order to better resolve CS-2 surface elevation.

AltiKa is also more sensitive than CS-2 to off-nadir ranging to leads due to its larger footprint. ~~Error occurs when~~ This occurs when an off-nadir ~~leads dominate the waveform~~ lead dominates the waveform response, resulting in an overestimate of the range to the lead, an underestimate of sea surface height, and a positive bias on the local floe freeboard (Armitage and Davidson, 2014). To minimise this effect, lead waveforms for AltiKa are discarded if their backscatter per unit area, $\sigma^0$, is less than 24 dB, under the assumption that off-nadir leads return less power to the antenna compared with those at nadir (Armitage and Ridout, 2015). However, ~~It~~ it is unlikely that this ~~criteria~~ criterion eradicates the problem altogether and we expect that the freeboard bias due to snagging is larger in the AltiKa data compared to CS-2.

To overcome ~~these problems, Guerreiro et al. (2016)~~ the CS-2/AltiKa freeboard bias, Guerreiro et al. (2016) employed degraded SAR mode CS-2 data in their comparison, where the synthetic Doppler beams are not aligned in time and are summed incoherently to obtain a pseudo-pulse-limited echo. Since this offers a footprint and waveform more closely resembling that of AltiKa, it was assumed that observed elevation differences between AltiKa and degraded CS-2 were the result of differences in snow penetration only.

Rather than separating the contributions of freeboard difference in this way, we ~~instead adopt~~ here introduce an approach that calibrates AltiKa freeboard to ~~the level of the snow~~ align it to the snow surface and CS-2 to the ice/snow interface (we assume in general that CS-2 penetrates further than AltiKa due to its longer wavelength (Ulaby et al., 1984)). As such, penetration properties and sources of freeboard bias are corrected in one step without needing to consider the contribution of each. ~~It is apparent that different freeboard products derived through different processing chains via different groups, arenot consistent (Stroeve et al., 2018). Short of any evidence in support of which product is better, the appeal of this methodology is its applicability to any freeboard data sets. By calibrating satellite freeboards with an independent data set, biases are systematically corrected for~~

While the comparisons of Guerreiro et al. (2016) derived snow depths with those from OIB are encouraging, the assumption of zero penetration for AltiKa and full penetration for CS-2 introduces limitations, and is counter to observational results (Giles and Hvidegaard, 2006; Willatt et al., 2011; Armitage and Ridout, 2015; Nandan et al., 2017) - and indeed their own model simulations - in support of a spatially and temporally variable penetration depth as a function of snow characteristics. Here we offer a methodology that both accounts for variable AltiKa and CS-2 snow penetration and is simple; freeboard data can be utilised as they are, without reprocessing. This is in contrast to the method of Guerreiro et al. (2016) which relies on the ability to process one of the satellite data sets to achieve comparable footprints and thus alleviate the biases due to difference in sampling areas. It is fortunate that CS-2 pseudo-LRM has a similar footprint to AltiKa (1.7km diameter and 1.4km diameter respectively), but how for example could the methodology be applied to CS-2 and ICESat-2 in order to retrieve contemporary snow depth estimates once AltiKa ceases functionality? Although herein we demonstrate our methodology applied to the AltiKa and CS-2 satellites, our intention is to outline an approach that can be applied more broadly. Ahead of the launch of ICESat-2 and the unique opportunity that its coincidence with CS-2 provides, we demonstrate the applicability of our method to the Envisat (same operating frequency as CS-2) and ICESat satellites.

### 2.4 Operation IceBridge

In order to evaluate the deviation of each satellite's retrieved elevation from its ~~expected~~ "expected" dominant scattering horizon (the snow surface for AltiKa and the snow/ice interface for CS-2), we use ~~data~~ laser freeboard and snow depth from NASA's 2013-2016 OIB spring campaigns. ~~At time of publication, OIB products from 2014 to 2016~~ It is important to note that a variety of research groups process OIB Snow Radar data in different ways and the results vary significantly (for the 2013-2015 period, campaign-average snow depths differ by up to 7 cm over first-year ice and 12 cm over multi-year ice (Kwok et al., 2017)).

Evidently the lack of singular, robust independent data set presents a limitation to our methodology since our aim is to calibrate to the "true" snow and ice freeboards. In an attempt to offer the best Dual-altimeter Snow Thickness product possible, we employ OIB snow depths processed from Snow Radar data by the NASA Jet Propulsion Laboratory (JPL) as these demonstrated best agreement with ERA-interim reanalysis data and the Warren climatology for the 2013-2015 period (Kwok et al., 2017). We return to a discussion on this limitation in Sect. 3.2.

Our methodology requires a comparison of CS-2 radar freeboard with OIB radar freeboard. To calculate this we use the snow freeboard, retrieved using OIB's ATM laser altimeter, from which snow depth can be subtracted. Currently, ATM freeboard data are only available from the National Snow and Ice Data Centre (NSIDC), and for the 2014 to 2016 period these exist solely in Quick Look format: a first-release, expedited version, which demonstrates reduced accuracy compared with the final release products (Kurtz, 2014). In the interest of consistency we also use the ATM laser freeboard Quick Look product for ~~2013, and acknowledge that our calibrations will be improved with the release of archival OIB products.~~ 2013.

~~Publicly available OIB products do not include a sea ice freeboard parameter but do output, at 40 along-track resolution, coincident measurements of snow freeboard (i.e. total height of ice plus snow above water) from an ATM laser altimeter, and snow depth, retrieved with the Kansas Snow Radar to within 5 accuracy (Kurtz, 2014).~~ Sea ice freeboard $f_i$ is ~~retrieved by subtracting~~ calculated by subtracting OIB JPL snow depth $h_s$ from ~~the~~ OIB Quick Look laser freeboard $f_l$. ~~Re-arranging Eq. (??), ice~~ Ice freeboard is then converted to radar freeboard $f_r$ by:

$$f_r = f_i - h_s\left(\frac{c}{c_s} - 1\right) \tag{1}$$

The OIB radar freeboard represents the freeboard that would be retrieved by a satellite altimeter whose pulse penetrated through to the ice/snow interface (Armitage and Ridout, 2015). We choose a value of $c/c_s$ of 1.28 after ~~Kwok (2014)~~Kwok (2014). In the following discussion, AltiKa and CS-2 freeboard refers to the *radar* freeboard, that is the freeboard retrieved by the satellite before the correction for light propagation through the snow pack ~~, given by Eq. (??),~~ is applied.

### 2.5 AltiKa calibration with Operation IceBridge

For each day of the three spring campaigns 2013-2015, OIB laser freeboard data are averaged onto a 2°longitude x 0.5°latitude grid. Grid cells containing less than 50 individual points are discarded to remove speckle noise. Along-track AltiKa freeboard and PP data for the ±10 days surrounding the campaign day are then averaged onto the same grid and grid cells with less than 50 points are similarly discarded. This grid and time window were chosen because they ~~offered the best spatial and temporal resolution possible whilst ensuring enough coverage to minimise the noise~~produced the maximum number of grid cells where a grid cell must contain at least 50 airborne and satellite points.

Satellite freeboard and PP grids are then interpolated at the average position of the OIB data within each valid OIB grid cell. Further, high resolution (10 km gridded) ice type data from the Ocean and Sea Ice Satellite Application Facilities (OSI SAF, http://osisaf.met.no) are interpolated at the same point to determine whether multi-year or seasonal ice is being sampled. $\Delta f_{AK}$, defined as ATM laser freeboard minus AltiKa freeboard, plotted against AltiKa PP is shown in Fig. 1. Data from 2013, 2014 and 2015 and their corresponding linear regression fits are plotted in red, blue and grey respectively to demonstrate year to year consistency. ~~Further, multi-year~~ Multi-year and first-year ice are distinguished by star and square markers in order to illustrate the variation of ~~pulse peakiness~~PP, and thus roughness, with ice type.

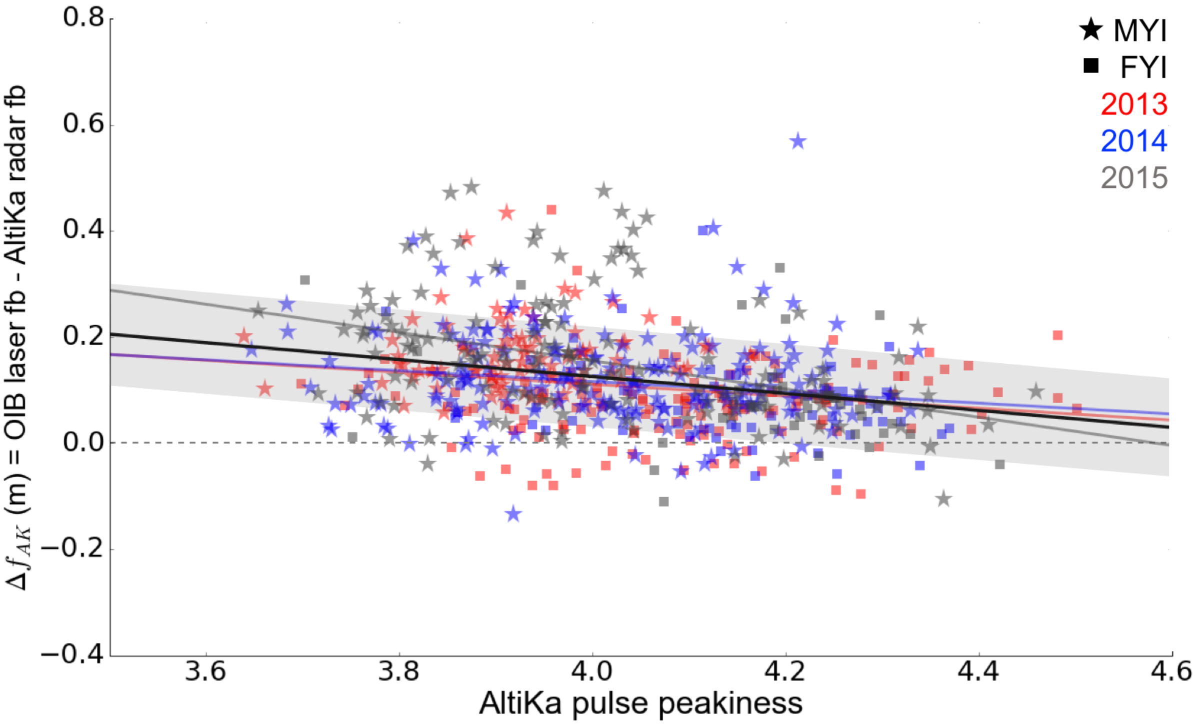


**Figure 1.** $\Delta f_{AK}$, defined as OIB laser freeboard minus AltiKa radar freeboard, plotted against AltiKa Pulse Peakiness, for the OIB spring campaigns of 2013 (red), 2014 (blue) and 2015 (grey). Multi-year and first-year ice are plotted with stars and squares respectively, the horizontal grey dashed line marks zero. The combined (all years) linear regression fit (CLRF), shown by the black line, has slope of -0.16 and intercept of 0.76. The shaded area around the CLRF shows the 68% prediction interval, corresponding to a standard error (SE) on $\Delta f_{AK}$ of 9.4 cm.

The combined (all years) linear regression fit (CLRF) is shown by the black line and has slope of -0.16 and intercept of 0.76. The shaded area shows the 68% prediction interval about the CLRF, corresponding to a standard error (SE) on $\Delta f_{AK}$ of 9.4 $\mathrm{cm}$. The CLRF is greater than zero for most PPs, implying that the freeboard needs to be increased to align with the snow/air interface, though moreso ($\sim$0.2 $\mathrm{m}$) for low peakiness values (rougher ice) than for high peakiness values (smoother ice), where the correction approaches zero. This suggests that freeboard over rough ice is biased low, which could be attributed to difficulty in identifying the average footprint surface elevation as outlined in Sect. 2.3. It could also suggest that AltiKa ~~penetrates further~~ exhibits greater snow penetration over rough ice than seasonal ice, in support of the assumption that i) rough, multi-year ice has a thicker snow cover and ii) seasonal ice is likely subject to brine wicking which prevents radar propagation through the snow (Nandan et al., 2017). Ultimately we cannot separate the influence of individual sources of bias and physical penetration and therefore these observations are purely speculative.

~~$\Delta f_{AK}$, defined as OIB laser freeboard minus AltiKa radar freeboard, plotted against AltiKa Pulse Peakiness, for the OIB spring campaigns of 2013 (red), 2014 (blue) and 2015 (grey). Multi-year and first-year ice are plotted with stars and squares respectively. The combined (all years) linear regression fit (CLRF), shown by the black line, has slope of -0.16 and intercept of 0.76. The shaded area around the CLRF shows the 68% prediction interval, corresponding to a standard error (SE) on $\Delta f_{AK}$ of 9.4 .~~

### 2.6 CS-2 calibration with Operation IceBridge

The procedure for calibrating CS-2 with OIB is identical to that outlined above for AltiKa, but here $\Delta f_{CS}$ is defined as OIB radar freeboard (see Sect. 2.4) minus CS-2 radar freeboard. For consistency and comparability with AltiKa, we remove CS-2 data above 81.5° N from our analysis. $\Delta f_{CS}$ plotted against CS-2 PP is shown in Fig. 2. The CLRF, shown by the black line, has a slope of ~~0.07~~ 0.06 and negative intercept of ~~-0.51~~ -0.46. As before, the shaded area around the CLRF shows the 68% prediction interval, and corresponds to a ±~~7.5~~ 8.4 cm uncertainty (1 Standard Error) on $\Delta f_{CS}$. ~~Since CS-2 has better coverage over the pole, there are more data points retrieved for CS-2 (1423 as opposed to 656 for AltiKa), giving its regression smaller prediction intervals.~~

For ~~most~~ all of CS-2's PP range ~~(up to ~7),~~ the CLRF is negative. It is most negative at lower PP, indicating that CS-2's freeboard lies higher above the snow/ice interface over rough ice. This is in agreement with rougher ice exhibiting a thicker snow cover and the radar pulse therefore being limited from getting as near to the snow/ice interface as where the snow is thinner. ~~Above PP of 7, the CLRF becomes positive, suggesting that CS-2's freeboard lies below the snow/ice interface for smooth ice. We do not expect CS-2's pulse to penetrate into the ice pack, and attribute this to a poor fit of the linear regression to data points with peakiness above ~7.~~ This deviation could also be the result of a failure of the empirical retracker to retrieve accurate surface elevation over rough ice as demonstrated by (Kurtz et al., 2014). As before, since we cannot separate the influence of individual sources of bias and physical penetration, these suggestions are speculative.

## 3 Results and Discussion

### 3.1 Case Study November 2015 to April 2016

To derive snow depth, along-track freeboard measurements for AltiKa and CS-2 are calibrated as a function of PP according to the combined linear regression fits (CLRFs) derived in the previous section, and then averaged onto a 1.5° longitude by 0.5° latitude monthly grids. A finer grid resolution than for the calibration analysis is afforded given the coverage of one month's worth of data as compared to the 21 days (±10 days window) averaged previously. The calibrated CS-2 freeboard is subtracted from calibrated AltiKa freeboard, and multiplied by a factor $c_s/c$ = 0.781 to convert to snow depth. Figure 3 summarises the retrieved monthly Dual-altimeter snow thicknesses (DuST) from November 2015 to April ~~2016, smoothed using a Gaussian convolution filter with a standard deviation of 30 .~~ 2016. The delineation of multi-year and first-year ice is shown by the

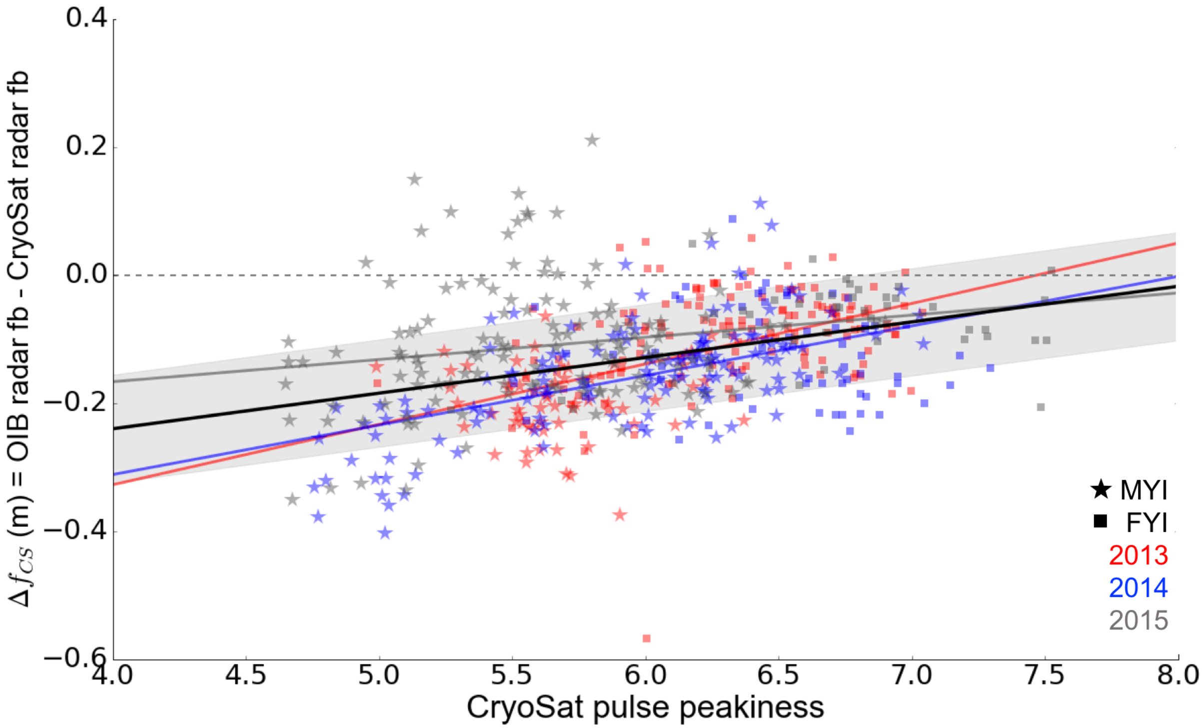


**Figure 2.** $\Delta f_{CS}$, defined as OIB theoretical radar freeboard minus CS-2 radar freeboard, plotted against CS-2 Pulse Peakiness, for the OIB spring campaigns of 2013 (red), 2014 (blue) and 2015 (grey). Multi-year and first-year ice are plotted with stars and squares respectively, the horizontal grey dashed line marks zero. The combined (all years) linear regression fit (CLRF), shown by the black line, has slope of ~~0.07~~ 0.06 and intercept of ~~-0.51~~ -0.46. The shaded area around the CLRF shows the 68% prediction interval, corresponding to a standard error (SE) on $\Delta f_{CS}$ of ~~7.5~~ 8.4 cm.

dashed black lines, adapted from OSI SAF Quicklook daily sea ice type maps for the 15th day of each month, available at http://www.osi-saf.org.

Spatial distribution of snow depth follows the expected pattern of a thin snow cover over seasonal ice (up to ~~20~~ 25 cm) and thicker snow over multi-year ice (30-40 cm) (Warren et al., 1999), which in recent years is limited to regions north of the Canadian Archipelago (CAA) and Greenland, and the Fram Strait. However, seasonal deposition of snow occurs between November and April, corresponding with the locations of predominant cyclone tracks in winter (e.g. the Aluetian Low on the Pacific side, and the North Atlantic Storm tracks). In particular, snow predominantly accumulates within the Chukchi Sea, and within the Kara, Barents and East Greenland Seas. As well as precipitation events, ice drift governs snow distribution through the advection of snow-loaded sea ice parcels around the ocean. Therefore in order to understand the seasonal evolution of the snow cover, we compare snow depth maps with monthly sea ice motion vectors from the National Snow and Ice Data Centre (NSIDC, available at https://daacdata.apps.nsidc.org), shown in Fig. 4. We expect snow accumulation west of Banks Island in the CAA is the result of westward transport of multi-year ice by the Beaufort Gyre. Snow depths in the Kara Sea appear

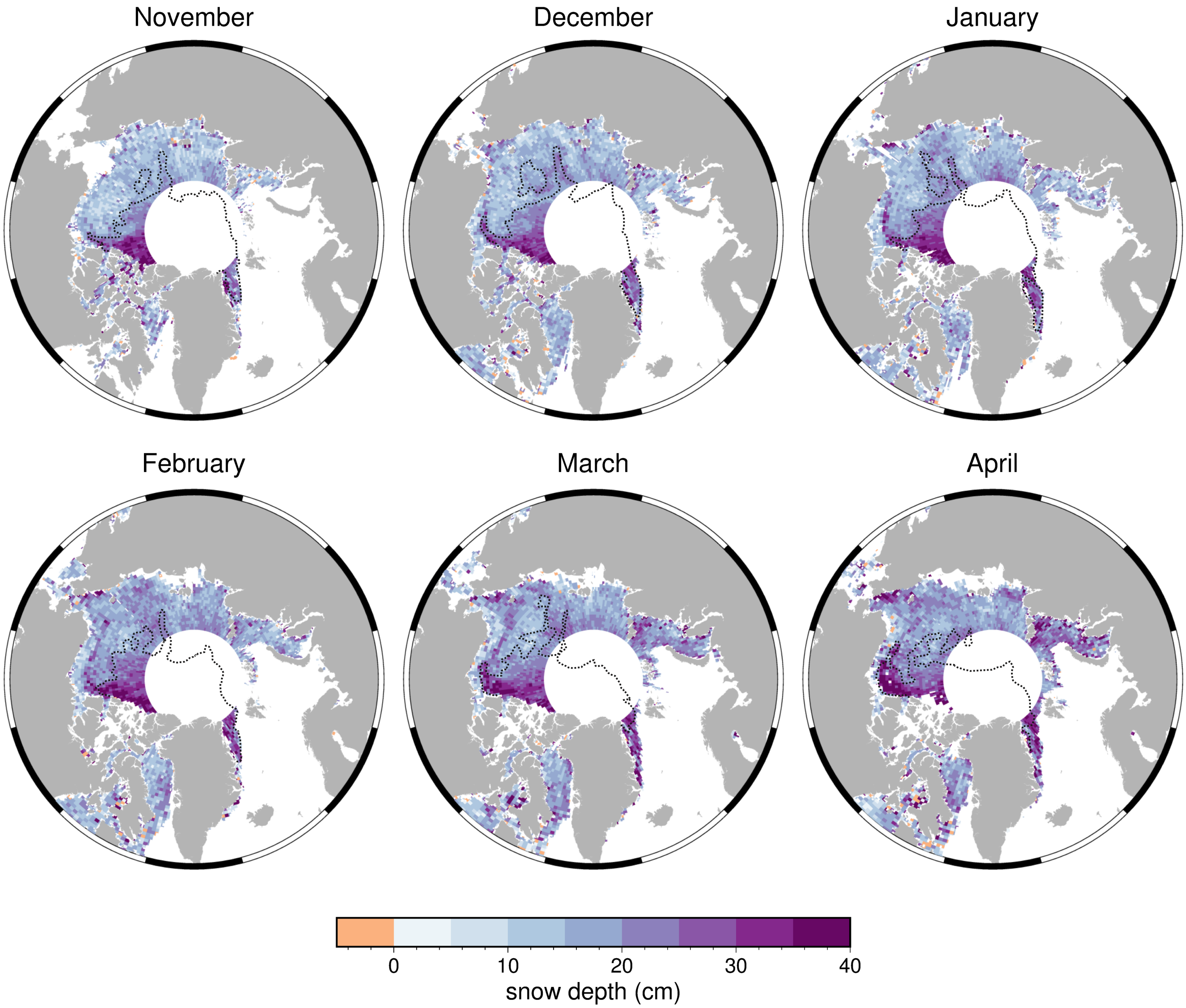


**Figure 3.** Monthly snow depths for the growth season November 2015 (top left) to April 2016 (bottom right), derived from AltiKa minus CS-2 calibrated freeboard~~, smoothed using a Gaussian convolution filter with a standard deviation of 30~~. The multi-year ice boundary for each month is shown by the dashed black line, adapted from the OSI SAF Quick look sea ice type map for the 15th day of the month, available at http://www.osi-saf.org/.

high given the advection of ice out of this region throughout the season, however we cannot rule out anomalous precipitation events. Typically 20-40 extreme cyclones occur each winter within the North Atlantic, but in recent years there has been a trend towards increased frequency of cyclones, particularly near Svalbard (Rinke et al., 2017). These cyclones, while they transport heat and moisture into the Arctic and may impact the sea ice edge location (Boisvert et al., 2016; Ricker et al., 2017), can also be associated with increased precipitation. ~~At the same time it is important to note that OIB only operates in the Western Arctic and therefore the Siberian seas are unconstrained by observations which may lead to erroneous snow depths.~~

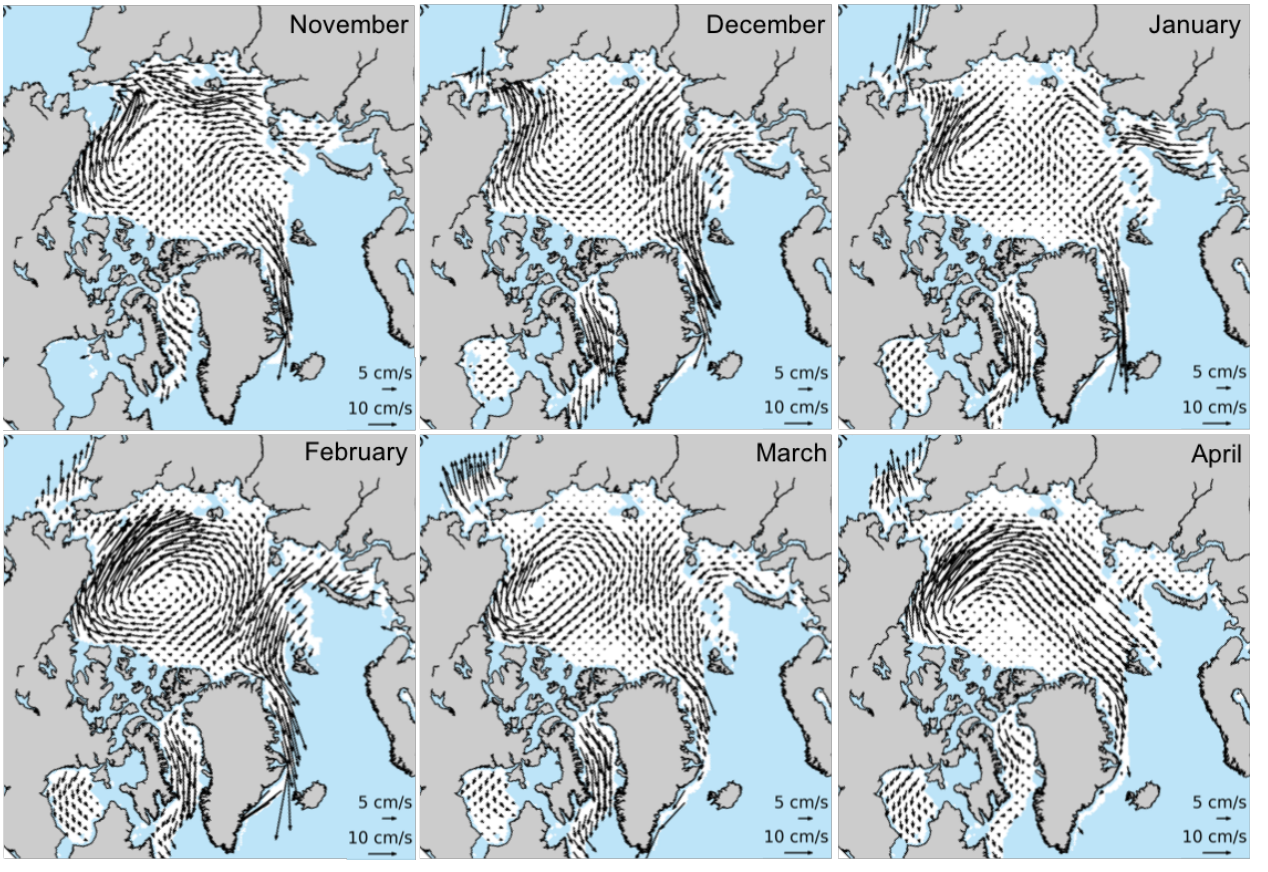


**Figure 4.** NSIDC November 2015 to April 2016 monthly mean sea ice drift vectors. Adapted from images retrieved from https://daacdata.apps.nsidc.org/pub/DATASETS/nsidc0116_icemotion_vectors_v3/browse/north/.

To understand where greatest accumulation of snow occurs over the season, we also plot the difference between November 2015 and April 2016 snow depth in Fig. 5. Snow accumulation is highest in the Western Beaufort sea, in particular adjacent to the coast of Canada. We attribute this to the advection of snow-loaded multi-year ice by the Beaufort Gyre, supported by the visible shift of the multi-year ice boundary through the season (Fig. 3). Accumulation also occurs in the Fram Strait, which we expect to be the result of southward advection of multi-year ice from the central Arctic Ocean in December and April, as well as snow deposition from the North Atlantic Storm tracks. High accumulation in the southern Chuckchi Sea could also be explained by strong advective currents pushing snow-loaded ice into this area, particularly from November to January, as well as snow precipitation from the Aleutian Low. Negative snow depth changes are generally small, and are predominantly visible in the centre of the Beaufort and Laptev Seas. In accordance with Fig. 4 we expect these negative accumulations to be the result of advection transporting snow-loaded ice parcels out of these regions and perhaps new ice formation.

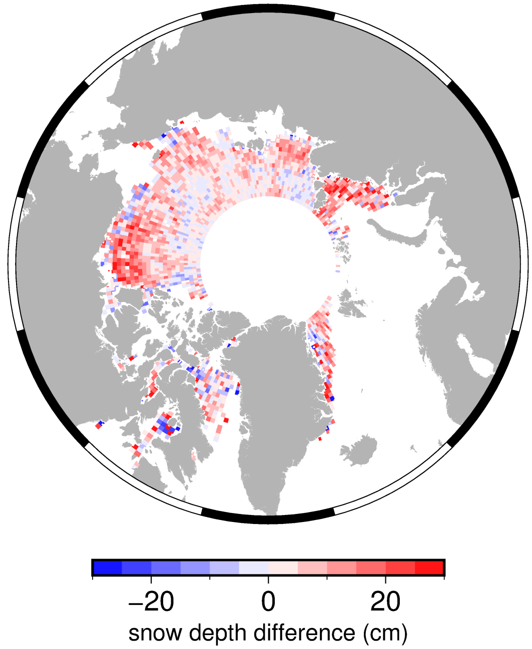


**Figure 5.** April 2016 minus November 2015 DuST~~snow depth~~.

~~Since OIB campaigns only operate in the western Arctic Ocean, north of the CAA and in the Lincoln and Beaufort Seas, no observations from the eastern Arctic go into our calibrations. Thus, the calibration functions derived are unconstrained outside of this area and we have less confidence in the snow depths in the eastern Arctic. Further, the calibration relationships are only strictly valid in spring, when OIB operates, so caution is warranted in using these products for seasonal variability of snow depth analysis.~~

~~A secondary limitation is the large~~ One limitation of the AltiKa CS-2 DuST product is the data gap associated with AltiKa's upper latitudinal limit of 81.5° North. This region contains a large proportion of the Arctic's thick multi-year ice and thus observations of snow depth could provide valuable insight as the icepack transitions from multi-year to first-year ice. Furthermore, for a snow depth product to be useful for integration into sea ice thickness retrievals as discussed in the introduction, one that extends to CS-2's latitude range is desirable. Application of the DuST methodology to the CS-2 and ICESat-2 satellites would generate a snow depth product up to 88° ~~is desirable~~. Alternatively, dual-frequency operation from the same satellite platform would open the potential for snow depth retrievals along the satellite track.

A secondary limitation of the methodology is the extent of the OIB campaigns; since they only operate in the western Arctic Ocean, north of the CAA and in the Lincoln and Beaufort Seas, no observations from the eastern Arctic go into our calibrations. Thus, the calibration functions derived are unconstrained outside of this area and we have less confidence in the snow depths in the eastern Arctic. Further, the calibration relationships are only strictly valid in spring, when OIB operates, so caution is warranted in using these products for seasonal variability of snow depth analysis.

### 3.2 ~~Error~~ Uncertainty calculation

The uncertainty calculation performed in this section assumes that the OIB products used in the analysis contain no systematic bias. We expect random noise to be minimised by grid averaging, but any systematic error would offset the calibration linear regression fits and alter snow depth retrievals. As discussed in Sect. 2.4, the recent study by Kwok et al. (2017) highlights the differences that exist between OIB Snow Radar data processed using various existing algorithms. It is not within the scope of this study to asses the sensitivity of our DuST product to the different OIB Snow Radar input data, but remains the subject of future work. One purpose of the Kwok et al. (2017) inter-comparison was to identify the strengths and weaknesses of each processing technique in order to inform the design of an optimised algorithm and generate an improved Snow Radar product. We acknowledge that our methodology would benefit from such an effort and suggest that for future applications of this methodology - in particular to CS-2 and ICESat-2, the next-generation of OIB snow depths should be investigated.

The equation for calculating snow depth, $h_s$, by our methodology is:

$$h_s = 0.781\cancel{*}\Big((f_{AK} + \Delta f_{AK}) - (f_{CS} + \Delta f_{CS})\Big) \tag{2}$$

Where $f_{AK}$ and $f_{CS}$ are AltiKa and CS-2 freeboard and $\Delta f_{AK}$ and $\Delta f_{CS}$ are the AltiKa and CS-2 freeboard corrections (see Sects. 2.5 and 2.6)

. From propagation of errors on Eq. (2), the uncertainty on snow depth, $\sigma_{h_s}$, is given by:

$$\cancel{\sigma_{h_s} = 0.781 * \sqrt{\sigma^2_{f_{AK}} + \sigma^2_{\Delta f_{AK}} + \sigma^2_{f_{CS}} + \sigma^2_{\Delta f_{CS}}}}$$

$$\sigma_{h_s} = 0.781\Big(\sigma^2_{f_{AK}} + \sigma^2_{\Delta f_{AK}} + \sigma^2_{f_{CS}} + \sigma^2_{\Delta f_{CS}} + 2\sigma_{f_{AK}\Delta f_{AK}} - 2\sigma_{f_{AK} f_{CS}} - 2\sigma_{f_{AK}\Delta f_{CS}} - 2\sigma_{\Delta f_{AK} f_{CS}} - 2\sigma_{\Delta f_{AK}\Delta f_{CS}} + 2\sigma_{f_{CS}\Delta f_{CS}}\Big)^{\frac{1}{2}} \tag{3}$$

~~The~~ Where the first four terms are the errors on the four variables in Eq. 2 and the last six terms are the covariances between them.

We obtain values of $\sigma_{f_{AK}}$ = 9.4 cm and $\sigma_{f_{CS}}$ = 8.4 cm from the 68% prediction intervals on the calibration fits, represented by the shaded areas in Figs. 1 and 2 ~~, provide a $\pm1$ Standard Error (SE) estimate on $\Delta f_{CS}$ of 7.5 and $\Delta f_{AK}$ of 9.4~~ respectively.

Since our snow product is monthly-gridded we are interested in monthly-gridded snow depth uncertainty. Therefore $\sigma_{f_{AK}}$ and $\sigma_{f_{CS}}$ are the errors on the monthly-gridded satellite freeboards to which the calibration corrections are being applied. ~~Tilling et al. (2017) provide an estimate of monthly-averaged freeboard error for~~ According to Tilling et al. (2017), the error on monthly-gridded CS-2 ~~, for their grid, of 2 . This~~ freeboard is dominated by ~~uncertainty on sea surface height estimation, which they calculate to have a standard deviation of 4 . Sea surface elevation is calculated from~~ the uncertainty on the interpolated sea-level anomaly (SLA), calculated from the SLAs of waveforms identified as leads (see Sect. 2.3). Lead ~~elevations~~ SLAs within a 200 km along-track window ~~about~~ centred on each floe measurement are fit with a linear regression to estimate the ~~sea surface elevation~~ SLA beneath the floe and thus calculate the freeboard. As such, along-track floe measurements are not decorrelated at length scales less than 200 km and ~~sea surface~~ the interpolated SLA uncertainty is not reduced from grid-cell averaging of data from the same satellite pass. Since the interpolation is performed along-track, separate satellite passes over each grid cell over the month *are* decorrelated, and thus the error is minimised by $1/\sqrt{N}$, where $N$ is the number of passes over a grid cell in one month. ~~Tilling et al. (2017) calculate that for their grid N averages 4 or more.~~

~~For our chosen snow depth grid of~~ To calculate this error we reprocessed one month (January 2016) of CS-2 and AltiKa data, recording for each floe freeboard retrieval the 68% prediction interval on the linear regression fit across the 200 km window. These errors, averaged on our 1.5° longitude by 0.5° latitude ~~, we evaluate monthly along-track CS-2 data in order to quantify the number of passes per grid cell. Due to~~ grid are shown in Fig. 6 (a). Since this error decorrelates from one satellite pass to the ~~diverging of satellite tracks with decreasing latitude, we find N varies between ~2 at lower latitudes (70°)to ~5 at our highest latitude of 81.5°. This results in a reduction of the 4 standard deviation on sea surface height to an error between ~3 and 1.8 , latitude depending~~next, we divide by the number of satellite passes in a month (Fig. 6 (b)) to retrieve the final interpolated SLA uncertainty, shown in Fig. 6 (c). Since this error dominates the freeboard retrieval (Tilling et al., 2017), this approximates to the monthly uncertainty on AltiKa and CS-2 freeboard, $\sigma_{f_{AK}}$ and $\sigma_{f_{CS}}$.

~~Since the same 200 along-track window is applied during AltiKa freeboard processing, we similarly assign a 4 standard deviation on sea surface height retrieval for AltiKa. However, AltiKa has many more passes than~~

The last six terms of Eq. (3) are the covariances of the four variables. We calculate these by gridding all AltiKa and CS-2 ~~between 70 and 81.5 since it does not survey the pole. For AltiKa we find average monthly~~ data from March 2013 to January 2018 and finding the correlation-covariance matrix. The value for each term is summarised in Table 2.

**Table 2.** Covariances between terms for snow depth uncertainty calculation

| Covariance term | $\sigma_{f_{AK}\Delta f_{AK}}$ | $\sigma_{f_{AK}f_{CS}}$ | $\sigma_{f_{AK}\Delta f_{CS}}$ | $\sigma_{\Delta f_{AK}f_{CS}}$ | $\sigma_{\Delta f_{AK}\Delta f_{CS}}$ | $\sigma_{f_{CS}\Delta f_{CS}}$ |
|---|---|---|---|---|---|---|
| Value | 0.0013 | 0.0063 | -0.0027 | 0.0010 | -0.0010 | -0.0027 |

All terms are substituted into Eq. 3 to find the uncertainty $\sigma_{h_s}$ on monthly gridded snow depth, shown for January 2016 in Fig. 7. The uncertainty is higher at lower latitudes where there are less satellite passes per grid cell~~vary from ~5 at 70° to ~40 at 81.5°. This results in areduction in sea surface interpolation error to 1.8 and 0.6 respectively~~, and over the thick multi-year ice to the north of the CAA where fewer leads available for the linear regression increase the uncertainty on the interpolated SLA, particularly for CS-2 (see Fig. 6 (a)). As a conservative estimate ~~of the error on our snow depth product, we assign $\sigma_{f_{AK}}$ and $\sigma_{f_{CS}}$ values of 1.8 and 2.8 respectively, giving a final error on~~ we assign our monthly gridded snow depth ~~$\sigma_{h_s}$ of 9.7~~ product an average uncertainty of 8 cm ~~, from Eq. (3).~~ for all months.

The main contribution to snow depth ~~error~~ uncertainty is the prediction intervals from the calibration functions (see Sects. 2.5 and 2.6). This uncertainty could be reduced with the addition of more data points, i.e. more seasons of coincident satellite

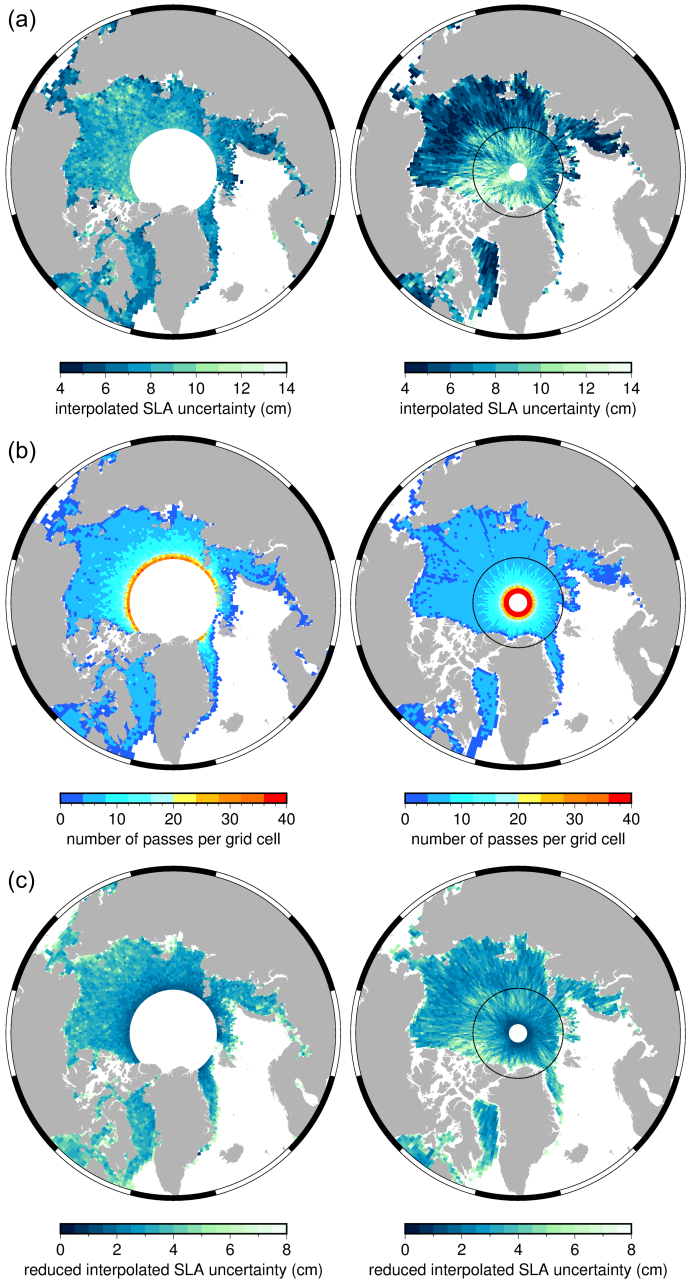


**Figure 6.** Satellite freeboard error calculation for January 2016 for AltiKa (left) and CS-2 (right). (a) Monthly gridded sea-level anomaly (SLA) error. (b) Number of tracks per (1.5° lon × 0.5° lat) grid cell per month. (c) SLA error divided by the square root of the number of tracks, i.e. (a)/$\sqrt{(b)}$ gives the reduced monthly error on freeboard. The black circle on the CS-2 maps show the upper latitude limit of DuST (81.5° N).

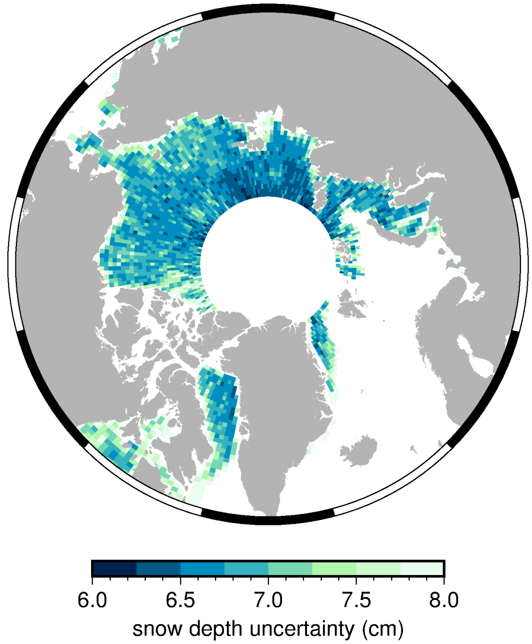


**Figure 7.** January 2016 snow depth uncertainty.

and OIB measurements. At time of publication OIB data for ~~spring~~ springs 2017 ~~had~~ and 2018 have not been made publicly available.

~~Since during comparison of satellite and OIB laser and radar freeboard we discarded grid cells with less than 50 points, we expect random error on OIB freeboards to be minimised such that they will not dominate the final snow depth uncertainty. However, any systematic bias that exists on these products due to processing technique or measurement error will impact the calibration functions and therefore our final snow depth retrievals. An example of a systematic bias would be the false detection of air/snow and snow/ice interfaces from snow radar data. A recent study by Kwok et al. (2017) found that different research groups' treatment of returns in order to locate these interfaces are not consistent, leading to different snow depth estimates from the same data. In this study we have only used the OIB Quick Look data set since this was what was available at the time, in particular given our need for coincident ATM laser freeboard in order to find radar freeboard. We acknowledge however that it would be worthwhile to investigate the difference on DuST snow depth retrievals using snow radar data processed by other research groups in order to asses the sensitivity of our product.~~

## 4 ~~Discussion~~

### 3.1 Comparison with Operation IceBridge

We compare snow depth retrieved by our methodology with OIB snow depths from ~~Spring~~ spring 2016 following the same procedure outlined in Sects. 2.5 and 2.6. For each day of the 2016 campaign, OIB snow depths are averaged onto the 2° longitude x 0.5° latitude grid and grid cells containing less than 50 individual points are discarded to remove speckle noise, as before. Calibrated AltiKa and CS-2 freeboards for the ±10 days surrounding the campaign day are averaged onto the same grid and grid cells with less than 50 AltiKa or CS-2 points are discarded. Gridded calibrated CS-2 freeboard is subtracted from gridded calibrated AltiKa freeboard and multiplied by factor $c_s/c = 0.781$, as previously. The resulting snow depth grid is then interpolated at the average position of the OIB data within each valid OIB grid cell. The Dual-altimeter Snow Thickness (DuST) retrieved for each point is plotted against OIB snow depth~~,~~ .

In order to compare with more than one OIB campaign, we repeated the original calibration analyses outlined in Sects. 2.6 and 2.5, successively omitting each of the 2013-2015 OIB seasons and using the other three years' data to derive calibration functions and generate snow depths for the omitted year. DuST snow depths were then compared against OIB snow depths by the method outlined in the previous paragraph. Results for all four years are shown in Fig. 8 ~~(b). We find a root-mean-square deviation (RMSD) of 7.6 and a mean difference of 2.1 . The linear regression fit, shown by the dashed black line, yields a correlation coefficient of r = 0.73. Figure 8(a)shows OIB snow depth plotted over DuST for the corresponding period.~~ and summarised in Table 3.

~~Comparison between OIB snow depth data for the 2016 campaign season and DuST snow depth. Satellite data for the ±10 days around each OIB campaign day is corrected according to the derived calibration functions. Gridded calibrated AltiKa minus calibrated CS-2 is then sampled at the average position of OIB data within each grid cells to retrieve a corresponding Dual-altimeter snow thickness (DuST). (a) OIB snow depth plotted over DuST for the ±10 days around each OIB campaign day. (b) OIB snow depth vs. DuST. We find a RMSD of 7.6 and mean difference of 2.1 . The linear regression fit, shown by the dashed black line, yields a correlation coefficient of r = 0.73~~

Since OIB data was used to calibrate the satellite freeboards, this cannot be considered a validation exercise. However, if OIB is considered as providing true snow depth estimates (see discussion in Sect. 2.4 and 3.2), then the results suggest the ability to use the derived calibration relationships to predict snow depth when OIB does not operate, e.g. in future. The poor agreement between DuST and OIB for 2013 as compared to subsequent years could relate to the persistence and treatment of radar sidelobes in the 2013 data (Kwok et al., 2017). Our analysis would benefit from the inclusion of additional OIB campaign data in the calibration and comparison. At present OIB data for 2017 and 2018 are not available.

~~Comparison of DuST and OIB snow depths for the a) 2013 b) 2014 and c) 2015 spring campaigns. Statistical results for all years are summarised in Table 3.~~

~~Since OIB data from 2013-2015 was used to calibrate the satellite freeboards, this cannot be considered a true validation exercise. However, if OIB is considered as providing accurate snow depth estimates, then the 2016 comparison with our product~~

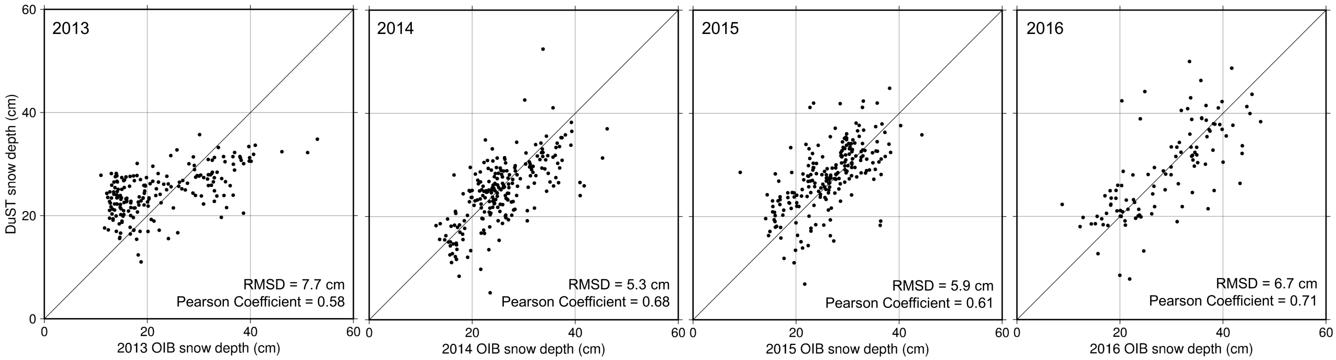


**Figure 8.** Comparison of DuST and OIB snow depths for the 2013, 2014, 2015 and 2016 spring campaigns. Statistical results for all years are summarised in Table 3.

**Table 3.** Results of OIB and DuST comparison for the years 2013-2016.

| | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|
| Root-mean-square deviation (RMSD) | ~~4.9~~ 7.7 cm | ~~6.5~~ 5.3 cm | ~~6.7~~ 5.9 cm | ~~7.6~~ 6.7 cm |
| Difference in means | ~~1.2~~ 2.12 cm | ~~2.6~~ 0.92 cm | ~~0.3~~ 1.29 cm | ~~2.1~~ 0.03 cm |
| ~~Correlation coefficient, r~~ Pearson Coefficient R | ~~0.80~~ 0.58 | ~~0.65~~ 0.68 | ~~0.64~~ 0.61 | ~~0.73~~ 0.71 |

~~implies both the ability to upscale OIB snow depths to the wider Arctic and use the derived calibration relationships for future snow depth estimates (e.g. when OIB is no longer operational).~~

~~The original analysis outlined in Sects. 2.6 and 2.5 was repeated, successively omitting each of the 2013-2015 OIB seasons to derive calibration functions and generate snow depths for the omitted year. DuST snow depths were then compared against OIB snow depths by the method outlined above. Results are shown in Fig. ?? and summarised in Table 3.~~

### 3.2 Application of DuST to ICESat-Envisat

The methodology outlined above demonstrates the ability to calibrate satellite freeboards with an independent data set in order to derive snow depth. It can be applied to any two coincident freeboard data sets and could be ~~usefully applied once~~ applicable to ICESat-2 once it is launched later this year. In view of this possibility, we ~~have~~ applied the methodology to ~~a comparison of~~ the ICESat and Envisat satellites, whose periods of operation overlapped between 2003 and 2009.

The Radar Altimeter 2 (RA2) instrument operated on the Envisat satellite from 2002 until 2012. It was a pulse-limited Ku-band radar altimeter which like SIRAL, operated at a central frequency of 13.575 GHz. NASA's ICESat mission featured a Geoscience Laser Altimeter System (GLAS) in order to accurately measure changes in the elevation of the Antarctic and Greenland ice sheets. This laser was also used to estimate ice thickness from laser freeboard retrieval (e.g. ~~(Kwok et al., 2007)~~Kwok et al. (2007)). Between 2003 and 2009, ICESat completed 17 observational campaigns; once every spring (Feb/March) and autumn (Oct/November) as well as three in the summers of 2004, 2005 and 2006.

ICESat had a 70 m diameter footprint, so we assume that biases due to footprint size or retracking method are negligible and that it offers accurate estimates of the snow freeboard. We use available ICESat freeboard data (version 1) from NSIDC, (Yi and Zwally, 2009), in our analysis. Envisat freeboard data were processed by CPOM and the reader is referred to ~~Ridout and Ivanova (2013)~~ Ridout and Ivanova (2013) for further details on the algorithm.

Following the procedure outlined in Sect. 2.5, Envisat freeboard is calibrated to the snow/ice interface. Envisat has a larger footprint than AltiKa~~due to its lower operating frequency and higher bandwidth~~, nominally 2-10 km diameter (Connor et al., 2009). As such, the waveform returns are more often classified as ambiguous (showing a complex mixture of scattering behaviour) and discarded, as discussed with reference to AltiKa in Sect. 2.3. As a result, Envisat data are sparsely populated and in order to have sufficient coverage for comparison with OIB data and 50 or more points per grid cell (to reduce speckle noise), it was necessary to increase both the grid resolution and time window as compared with the calibration procedure performed for AltiKa and CS-2.

Satellite data for the $\pm$15 days surrounding each 2009-2012 OIB campaign day were averaged onto a ~~onto a~~ 3°longitude x 0.75°latitude grid. $\Delta f_{ENV}$, defined as OIB radar freeboard minus Envisat freeboard, plotted against Envisat PP is shown in Fig. 9(a). ~~Data from 2009, 2010, 2011 and 2012 and their corresponding linear regression fits are plotted in orange, purple, blue and grey respectively to demonstrate year to year consistency. As before, multi-year and first-year ice are distinguished by star and square markers in order to illustrate the variation of PP with ice type.~~ The combined (all years) linear regression fit (CLRF) is shown by the black line and has slope of -0.23 and intercept 0.50. The shaded area shows the 68% prediction interval about the CLRF, corresponding to a $\pm$5 cm standard error (SE) on $\Delta f_{ENV}$.

Dual-altimeter Snow Thickness (DuST), retrieved by subtracting calibrated Envisat freeboard from ICESat freeboard is shown in Fig. 9(b) for the ICESat laser period '3E' (22nd February 2006 to 27th March 2006). Snow depth ~~agrees with expected spatial distribution and magnitude, with~~ spatial distribution follows the expected pattern of thicker snow (30 ~~+~~ to 40 cm) over multi-year ice to the north of the Canadian Archipelago and in the Fram Strait, and thinner snow cover (< 20 cm) over seasonal ice. Overall higher magnitudes as compared with March 2016 (Fig. 3) could be the result of a decline in multi-year ice fraction and precipitation over the past decade. Though validation is required, the result demonstrates the viability of combining laser and calibrated radar freeboard to retrieve snow depth.

## 4 Conclusions

Using independent snow and ice freeboard data from OIB, we derived calibration relationships to align AltiKa to the snow surface and CS-2 to the ice/snow interface, as a function of their pulse peakiness. Calibrated CS-2 and AltiKa freeboard data were then combined to generate spatially extensive snow depth estimates across the Arctic Ocean between 2013 and 2016.

The Dual-altimeter Snow Thickness (DuST) product was evaluated against OIB snow depth by successively omitting each year of OIB data from the calibration procedure, returning root-mean-square deviations of ~~4.9, 6.5, 6.7 and 7.6~~ 7.7, 5.3, 5.9 and 6.7 cm for the years 2013, 2014, 2015 and 2016 respectively. While the OIB snow depth data cannot be considered statistically independent validation of the DuST product, this evaluation does demonstrate the ability to up-scale OIB snow depths to the

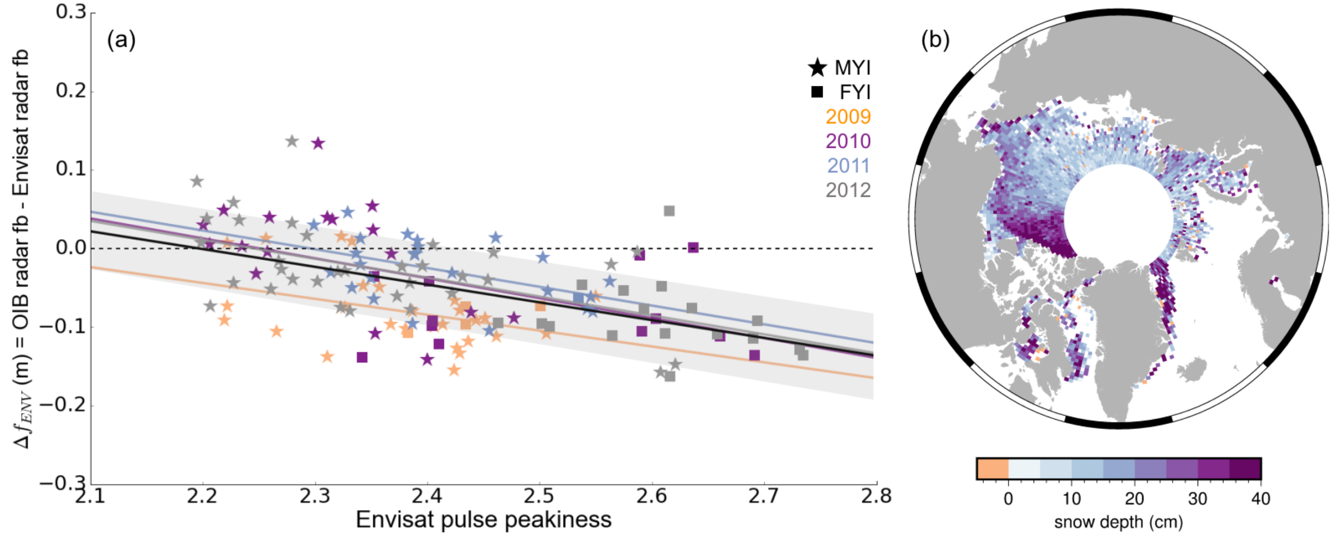


**Figure 9.** (a) Envisat calibration relationship, derived from comparison of coincident OIB and Envisat data. Data and corresponding linear regression fits for 2009, 2010, 2011 and 2012 and shown in orange, purple, blue and grey respectively. Star and square symbols represent multi-year and seasonal ice respectively, the horizontal grey dashed line shows zero. (b) Snow depth for ICESat's '3E' laser period (22nd February 2006 to 27th March 2006), retrieved by subtracting calibrated Envisat freeboard from ICESat freeboard and multiplying by a factor 0.781.

wider-Arctic~~.~~, i.e. predict OIB snow depths for an unsampled region and year. However, the DuST snow depth estimates remain unconstrained and unevaluated outside of the Western Arctic and the spring season, due to a lack of coincident data.

~~A more thorough validation using ice mass balance buoys as well as comparisons with other derived snow products is the~~ We used OIB Snow Radar data processed by NASA JPL in our analysis since this demonstrated best agreement with ERA-interim and the Warren climatology for the years 2013-2015, however our methodology would benefit from the development of an optimal Snow Radar processing algorithm and snow depth product. Investigating the sensitivity of our product to the discrepancies between existing OIB Snow Radar data versions remains the subject of future work. ~~Looking further ahead, the~~

The upcoming MOSAiC ice drift campaign in autumn 2019 will provide a unique opportunity for ~~validation~~ validating DuST in regions not sampled by OIB (e.g. the eastern Arctic) and throughout a full annual cycle. A dedicated dual-radar study is planned during the MOSAiC experiment, using in-situ and on-aircraft Ku-Ka band radar to quantify radar backscatter at each frequency together with snow depth and ice thickness measurements. This in conjunction with AltiKa and CS-2 observations will provide valuable insight into the validity of our calibration functions and retrieved DuST snow depths.

Our methodology can also be applied to retrieve snow depth from coincident satellite radar and laser altimetry, which will have particular relevance when ICESat-2 is launched (scheduled late 2018). Here, we ~~demonstrated~~ tested the applicability of the method to the ICESat and Envisat satellites, offering promising potential for the future retrieval of snow depth on Arctic sea ice from CS-2 and ICESat-2, with better coverage over the pole.

*Competing interests.* The authors declare that they have no conflict of interest.

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