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Anticipating CRISTAL: An exploration of multi-frequency satellite altimeter snow depth estimates over Arctic sea ice, 2018-2023

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General comment

The study presented in this paper is one of the most advanced analyses of multi-frequency altimetric measurements of sea ice and its snow cover. In a first phase, it provides measurements of the sea ice freeboard using the Ka AltiKa radar altimeter on the Saral satellite, obtained using the LARM physical retracker. This result is already an innovation, as it is the first Ka-band radar freeboard product that provides a realistic topography of sea ice; previous studies focused exclusively on the Ka/Ku differential for snow depth retrieval. This freeboard is then used in combination with the Ku radar freeboard obtained with LARM retracker applied on CryoSat-2 to estimate snow depth. An initial analysis then evaluates this solution against that obtained by combining Ku radar and lidar (KuLa), as well as with airborne snow thickness measurements and the Lagrangian model SnowModelLG. This analysis shows that the snow depth estimate obtained with KuKa seems realistic at the beginning of winter but greatly underestimates this thickness throughout the winter accumulation, even if a slight thickening is observed.

To better understand the origins of this underestimation, an in-depth comparative analysis of each of the freeboards involved in these thickness measurements is provided below, with the aim of better understanding the reasons for these discrepancies: Are they due to retracking problems? to the effects of surface roughness on retracking? to overestimation or underestimation of penetration (or more precisely, variations in the backscatter ratios from air/snow and snow/ice surfaces, and snow volume)?

The results show that it is a combination of these different aspects and allows some of them to be quantified, such as the effect of surface roughness on Ka radar freeboard, which seems to have a negligible effect except in rare situations (high freeboard and low roughness). Nevertheless the Ka freeboard obtained with LARM is underestimated on average relative to IceSat-2, and this is more pronounced for low freeboards aiming to lower snow depth retrieval with KaKu than with LaKu that can reach to only a third of this last one.

The last section presents a simulation of the next CRISTAL dual-frequency altimetry mission which suggests that Ka-band may be underestimated by 10% the total freeboard and the Ku-band overestimated by 3% the ice freeboard. The last section presents a simulation of the upcoming CRISTAL dual-frequency altimetry mission, which suggests that the Ka band could underestimate the total freeboard by 10% and that the

Ku band could overestimate the ice freeboard by 3%. These results are very promising but show that there is still room for improvement. The authors propose various avenues for further study and also emphasize the importance of additional baseline measures.

Given the originality, scientific quality, significance of the implications, and quality of the presentation, I recommend publication of this article with a few minor revisions.

Detailed remarks

Lines 19 and 22: In the following sentences, could you clarify what the percentages refer to? *"a median elevation 3% above the snow-ice interface"*, *"median elevation 10% below the air-snow interface"*.

Line 41: CRISTAL will be ready for launch at the end of 2027. This remains the official date for the time being.

Lines 65 and 71: I don't believe that Ku could penetrate 60-90% of the snow depth and Ka 0-40% whatever is the snow depth…

Line 93-95: could be interesting to specify (if possible) from which order of magnitude of altitude the coherent radar reflection becomes dominant for the following analyses; i.e., when going from ground to airborne measurements? or from airborne to space measurements?

Line 148: to be coherent with titles 2.1 and 2.3, the title 2.2 should be: "SARAL AltiKa Observations" as SARAL is the satellite and AltiKa the altimeter.

Line 193: 350kg/m3 for the snow density seems a high value. Could it be justify? Even if the impact is low it could worth to adapt this value.

Line 296: Strange sentence: *With revised classes the waveforms previously classed as ambiguous are now generally classed as sea ice.*

Line 330: Now the snow density varies from 266 to 329 kg/m3 which is not coherent with the previous 350kg/m3 line 193. Could you specify the used speed propagation equation?

Line 496: See last comment (for line 674).

Figure 10a: It's strange to mix-up Ku-band, Ka-band and laser freeboards (both for satellite and airborne)! They should not measure the same surface (air-snow versus snow-ice). Have you applied corrections for the snow impacts (load + speed propagation)? Please justify.

Figure 10b: Which data are used here? LARM? TFMRA? Both? Also it's strange to see a CS2 freeboard greater than IS2 and SRL. The offset is not clearly shown (add arrows?) and it makes the comparisons difficult.

Figure 11: Very interesting plots but Figures 11a and 11c show exactly the opposite

results. I suppose there is an error on the name of the y-axis for 11c (should be SRL-IS2 instead of IS2-SRL).

Line 561: It would be useful to recall here in a short sentence the concept of Mie scattering, as it is very important for understanding the interactions between snow and radar waves.

Line 605: This very important section is not as clear as the previous ones. It could be much clearer if you shortly introduce the objective of the following demonstration instead of just the introductive word 'here'.

Lines 496 and 674: All the analyses regarding the threshold to be used to retrieve coherent results are very interesting but it is important to have in mind that the threshold approach is stable only if its value corresponds to the steepest slope of the waveform leading edge and far from its maximum, i.e. between 30% to 50% as shown Figure 10a in Laforge et al. 2021 https://doi.org/10.1016/j.asr.2020.02.001. For example, in the extreme case of a 100% threshold, this corresponds to take the maximum of the waveform sampled by the altimeter, i.e., a measurement of the epoch on a sampling gate and therefore with a resolution equal to that of the altimeter (about 20 cm for CryoSat-2 SAR). While this does not affect averages over large areas, it does significantly increase the noise in each measurement. Laforge et al. 2021 propose an alternative that involves correcting the range rather than the threshold, as is done for Sea State Bias in the open sea (see Figure 10). I think it is important to keep this alternative in mind. However, retrackers based on a physical model are clearly the best option.