Responce to RC1

Response to the Interactive comment on “Comparison of CryoSat-2 and Envisat freeboard height retrieval” by Kévin Guerreiro et al.

First of all, we would like to thank all three reviewers as well as the Editor for their constructive comments and advices that truly helped to improve the first version of our manuscript.

The response to the reviewers is developed as follows:

-The first section provides general comments on the changes and reviews.
-The second part is a detailed answer to each reviewer.
-The last part is a summary of all changes operated in the new version.

<u>I-General comments and modifications:</u>

+ About the freeboard height retrieval

The freeboard height methodology is now further detailed in the new version of the manuscript. In particular, a new section with an along-track analysis is now provided and the retrieval steps are further discussed. We also combine optical imagery with radar altimeter measurement to improve the flow/lead detection and we make the appropriate changes in the freeboard height retrievals.

+ About the Envisat freeboard estimates

First of all, we would like to remind the reviewers that this manuscript would potentially be the first study showing Envisat circumpolar Arctic freeboard maps. In previous published studies, only ice thickness maps were presented and we therefore have no other published study on this topic to rely on.

Regarding the negative Envisat freeboard estimates: as this effect was already described and corrected in sea-ice studies (Giles et al., 2008, Laxon et al., 2013) and ocean studies (Giles et al., 2012, Armitage et al., 2017) we thought that it was not necessary to spend too much time on this topic. Considering the reviewers comments, we now give more insights and explanations on this phenomenon. In particular, the along-track analysis section should truly helps to understand the negative freeboard estimates obtained with Envisat.

Regarding the spatial variability of the native Envisat freeboard estimates: the 2010-2012 period is unfortunately not a good period to observe a high variability of radar freeboard height as the MYI fraction is very low. Having said that, if you look at our estimates for let's say March 2007 (see bellow) you will see that the native Envisat freeboard estimates still capture some coherent spatial variability despite the negative freeboard estimates.

+ About the structure of the manuscript

Following reviewers comments, the structure of the manuscript was modified in order to highlight more clearly the goal of the study: improving Envisat freeboard retrievals in the aim of producing accurate Arctic ice thickness estimates.
In addition to the extra section concerning the along-track analysis, we decided to follow the reviewers comments and to remove the time-series section. These results will be further developed in a new study.

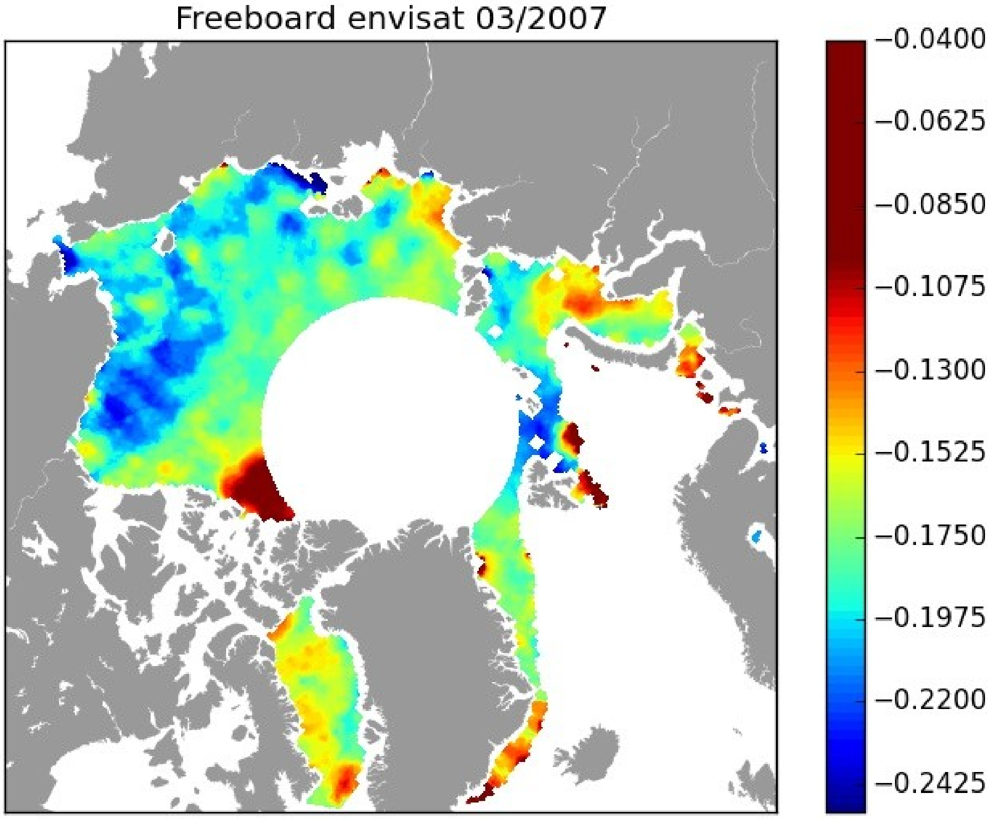

Figure 1: Envisat "native" radar freeboard for March 2007.

II-Detailed answer to referee #1:

1. The Envisat FB product before PP correction Looking at figure 2 middle column, one can see that the Envisat freeboards are unrealistic. For one, they are negative – something that the authors just attribute to "the difference of ice surface characteristics between leads and ice floes as well as the use of a threshold retracker drive a large bias on the estimation of Envisat freeboard height". I am confident that the culprit is elsewhere.

As it is now further explained in the new version of the manuscript, most freeboard studies (Laxon et al., 1994; Giles et al., 2008; Laxon et al., 2013) and sea level studies (Giles et al., 2012; Armitage et al., 2017) artificially correct the bias due to the difference of specularity between rough ice and leads or rough ocean and leads by using 2 different retracking algorithms. The physical origin of this bias was certainly not enough detailed in the first version of the manuscript. In the new version we try to give more insights about this phenomenon.

We've tested the TFMRA retracking scheme for Envisat as well in the CCI project, and we've arrived at more or less similar looking freeboard maps as with the original CCI retracking scheme. We seem to be missing the thinnest and the thickest ice, but freeboards are positive as they are supposed to be and the thickness pattern reflects reality (even with the thinnest and thickest ice missing). And furthermore, we do not see very high freeboards in the marginal ice zone.

Considering the current literature and our personal experience, we would be quite surprised that positive sea-ice freeboard estimates can be retrieved with a single threshold retracker (TMFRA in that case) and without applying any further correction. We haven't found such results on line but if you provide us with a dataset or with published results, we would be happy to compare both datasets.

I try to be a good reviewer and speculate possible causes for the Envisat freeboards being much off. My guess is that this may be due to off-nadir leads or new ice dominating significant number of waveforms. The authors give very little notice to filtering out mixed waveforms. Or filtering in general – it is hardly mentioned anywhere in the paper. They argue that they should keep in the waveforms with intermediate PP since they represent thin and undeformed ice. Fair enough, but at the same time they are letting in a lot of waveforms with deformed ice in the nadir and flat areas off-nadir which will lead into the retracker catching the off-nadir rise and biasing the elevation estimate low. This is consistent with the lowest freeboards seen in the area with lot of deformed ice (there will always be a significant number of flat new ice or leads around). This is less of a problem in the area of new ice near the margins, where the ice is more or less flat all around and in likelihood there is a specular surface in the nadir as well. All consistent with the pattern in figure 2. The authors hint that the use of TFMRA retracker is robust for off nadir reflections (page 5, lines 16-19). That is somewhat true, but it does not remove the need to filter out dubious waveforms – even Helm et al 2014 that the authors cite for the TFMRA have a filtering scheme to remove "bad waveforms" before retracking. I suggest the authors build one too and check if that improves their not-PP corrected freeboards. The SI-CCI scheme most likely filters too much waveforms, but I would still argue that some kind of filtering is required. Finally , much less likely culprit than previous one , but worth mentioning still since applying an inverted snow correction (that is, a bug in code) results into something bit like the maps in Figure 2. The main reason I'm mentioning this is that I once had that bug in my code and the Figure 2 reminds me much of it. Don't waste too much time on this, but do check your snow propagation correction code.

In the new version of the manuscript, we use optical imagery to identify PP observations for which the waveform echoes are likely biased by mixed surfaces (leads+floes). Based on this new meethodology, the CryoSat-2 and Envisat freeboard is-recalculated. As a result, we observe that the freeboard is somehow improved on MYI. However, despite the use of this filter, the radar freeboard remains quite negative.

2. Theoretical justification of the PP correction The manuscript fails to explain the theoretical background of why exactly small PP (or more diffuse waveforms or heavily deformed ice) results into retracker picking up the tracking point later in the waveform that it would if the waveform was more peaky (less diffuse and most likely originating from less deformed ice). The authors state that "ice surface diffusion has a higher impact on LRM altimeters" but this needs to be backed up by something solid because from the evidence authors give. Because of the unrealistic Envisat FB, I do not believe that the disagreement of the Envisat and CS-2 freeboards is mainly due to surface diffusion. If the authors do not, theoretically step by step, explain the process of ice surface diffusion impacting LRM altimeter estimates, a good referee could (and should) claim that it is just as likely that what we are seeing here instead is something profoundly wrong with the Envisat FB retrieval and that something is connected to pulse peakiness.

In the new version, we try to further explain how the surface specularity/diffusion acts on the LRM radar signal and why it impacts the freeboard height retrieval. In particular, we add a section on waveforms shape and on-track freeboard retrievals.
In all sea-ice studies, the PP is used as a proxy of surface diffusion/specularity to identify leads and ice floes. It is therefore the most relevant parameter according to the literature to be used as a proxy for surface roughness. In particular, it has been shown in the study by Zygmuntovska et al. (2013) that the PP is a fairly good proxy to distinguish rough MYI from specular FYI.

The y(PP) is problematic anyway. Naturally, applying any correction derived from the difference of the two freeboard datasets will make the two agree. Strongest point the authors give for the use of the y(PP) correction is the improvement it brings to the fit of BGEP data throughout the Envisat period. This is all good and well, but looking at figure 6, the only real improvement is the level correction of about 1 – 1,5 m to the (unrealistic and often even negative) Envisat draft estimates. I would argue that what we see here is the constant term of y(PP) – there must be one since the dashed line in figure 5 does not cross zero – just fixes the large negative bias that the somehow broken Envisat freeboard method produces.

Figure 1 (in this document) shows a native Envisat freeboard map. As mentioned earlier, this map clearly displays coherent spatial variations with thicker values over MYI and thinner values of FYI as shown over Antarctic sea-ice in the study by Schwegmann et al. (2015). The native Envisat freeboard estimates bring therefore essential informations for the final estimates without which the corrected Envisat estimates would be highly inaccurate.
Clearly, the figure showing comparison with the BGEP moorings shows that the most important correction is the sea-level one (constant correction). However, the large improvement in the correlation coefficient is only due to correction of the bias driven by the variability of specularity of ice floes (the correlation coefficient does not depend on any potential constant bias). In order to further highlight this improvement we now show both the Envisat and Envisat/PP correlation coeffcient, average bias and RMSD in a table.

After the harsh critique above, I should mention that the idea presented in the manuscript is

most definitely on the right track! A PP based correction would improve the problems of Envisat FB retrieval drastically. I know of similar attempts in the altimetric community lately. After fixing their uncorrected FB estimates and giving a theoretical justification of how the correction works, this will be a really good paper and I commend the authors for coming up with the idea and publishing it first. Problem with the manuscript at the moment is, that even if the final result of corrected Envisat freeboards seems to comply with validation data, the paper fails to give rigorous explanation exactly what are the processes why their methodology works.
Thanks for your encouragements. Your comments truly helped to identify sections that needed to be clarified. We hope that the modifications in the freeboard height retrievals as well as the new explanations provided will be more convincing for any potential reader.

1. Pan-arctic claim
The authors claim that they have created a pan-Arctic thickness estimate. They have not, since they have excluded all of the Arctic above 81,5 N. Thus I recommend the authors follow the lead of Giles et al and stick with "circumpolar" (or something similar) to emphasise that their estimate does not cover all of the Arctic.
That's right. While the last section has been removed, we will stick to "circumpolar" instead of Pan-Arctic for now and in our future studies.

2. TFMRA parameters
Nowhere in the paper the authors state, which threshold value they use for the TFMRA. 50%? It should be mentioned. Like other TFMRA parameters as well.
50% indeed. More details are now provided in the new version of the manuscript.

3. Local sea level interpolation
The description of the sea level interpolation is thin (page 5, lines 20 – 24). Not sure if the interpolation of leads could contribute to the unrealistic negative freeboards, but it is worth checking. Nevertheless, the authors must include a better description of the sea level interpolation – how exactly is it done? Taking a mean of all lead elevations within 25 km or some kind of along-track interpolation?
This section was slightly modified to be more clear. Basically, for each 25 km segment we check if there is a lead. If not, no freeboard is estimated. If they are leads, the freeboard is estimated as the difference between the level of floes and the average level of leads.

4. PP correction – are leads included?
On page 5, line 27 it is stated that PP is also averaged into gridded maps. Does this include the waveforms that are classified as leads?
No, only ice floes echoes are kept to construct the gridded PP fields. It is now clearly stated in the manuscript.
If it does, this will have a consequence to the PP correction – that is, areas with lot of leads will eventually have a stronger correction in the direction of thinner ice.
That is correct. It is important here to highlight an interesting phenomenon: usually leads are associated with off-nadir reflections. However, in our study, the regions with a high PP (potentially characterized by a high density of leads) are the regions with the lower underestimation of surface elevation. This result suggests therefore that leads have the same impact than specular sea-ice: they tend to decrease the size of the effective radar footprint making waveform echoes sharper and reducing the altimetric range (when using an empirical threshold retracker.

5. Mathematical description of y(PP)
The authors really must give a more thorough description of the y(PP). Is the y(PP) constant throughout the winter? I reckon it is the black dashed line in Figure 5, and constant over time

and place and calculated on the gridded level and not for individual measurements, but a mathematical formulation would be most welcome.

We now provide with a mathematical description of y(PP) so anyone can reproduce our results. We do keep a constant y(PP) during winter and we show that the Envisat/PP radar freeboard is relatively similar (low RMSD) as CryoSat-2 during all months of the period of study.

III-Summary of changes #1:

With respect to the new version manuscript order:

→ The abstract and introduction have been slightly re-written to clearly express the aim of this study and the key steps.

→ The freeboard processing is now more detailed (sea level, TFMRA retracker, etc). In addition, we add a comparison with Landsat images to validate the use of our PP thresholds.

→ Changes in the freeboard processing chains were applied, all freeboard estimates were re-calculated and figures were updated.

→ The ice density parametrization has been modified and is now more in phase with the literature (882 kg/m³ for MYI and 917 kg/m³).

→ A short analysis of CryoSat-2 and Envisat waveforms is now provided (sect 3.1)

→ An analysis of along-track radar freeboard is now provided (section 3.2).

→ Section 3.3 and 3.4 have been inverted.

→ The section showing ice thickness time series has been removed and will be part of a future study.

→ Tables with statistical parameters were improved

→ In general, the physical impact of ice surface properties on the radar signal is more clearly explained.