Reviewers' Comments – In Black

PhD Student's Comments – In Blue

I thank the reviewers for the suggestions and comments which helped a lot in improving the scientific quality and readability of the thesis.

Maulik Jain – PhD Thesis Review
Alejandro Egido / Luciana Fenoglio-Marc / Rene Forsberg

The Thesis analyzes the implementation of several SAR altimetry waveform retrackers, and their application in the Arctic Ocean.

The dissertation is structured in nine main chapters, that could be related to three main parts; the first part, chapters 1 to 3, reviews the problematic of measuring radar altimeter waveforms from polar ocean, presents basic altimetry concepts and the existing waveform retrackers, and finally reviews the sea surface height variability in the area. The second part, chapters 4 to 7, presents more in depth the existing retrackers and evaluates their performance. Finally, the third part explores the combination of physical and empirical retracking and compares the obtained results with conventional retrackers.

As a general comment, we would say that despite the fact that the Thesis follows the organization outlined above, this structure is not clear enough in the document and therefore it is difficult to follow. It would be better to actually divide the document in parts and well-differentiated chapters.

I have rearranged the chapters of the thesis to make a more continuous scientific story. I have merged the chapter for description of the primary peak empirical retrackers and the retracker performance evaluation of the primary peak empirical retrackers. Secondly, I have merged the chapter on the description of the SAMOSA3-C retracker and the retracker performance evaluation of the SAMOSA3-C retracker. The student's version of the retracker is now called SAMOSA3-C retracker.

Further, I have made a separate chapter for the accuracy analysis of the different retrackers. Thus the accuracy analysis is now well differentiated from the precision analysis and annual variation analysis. The SAMOSA3-C retracker comes out as the retracker with the best accuracy among the different retrackers. This has been clearly mentioned and described now in the chapter on accuracy analysis.

The comittee has the following comments regarding style and format:

- It seems that the document was written very hurriedly. Throughout the dissertation there are grammatical errors, and it is full of repetitions of full sentences and paragraphs, which hampers the readability of the document. Colloquial expressions shall be avoided ("a lot", "done", ...). In some sections, multiple references to tables or figures back and forth. The PhD candidate should thoroughly review the Thesis in order to correct these errors and avoid repeating concepts unnecessarily. Many of the graphs and detailed arguments for the investigations in Chapters 6-7 could more appropriately be put in an Appendix and replaced by an expanded summary, there appears to be a lot of "cut-and-paste" text parts here making readability low.

I have modified the thesis in order to remove the grammatical errors and removed repetitions wherever present. I have removed the back and forth referring to multiple tables/figures. In chapters with a lot of graphs, the graphs have been moved to the end of the chapter in an appendix style format.

- In the same line as the previous comment, the graphs are difficult to interpret. The colors selected to represent the data (as for example in Figure 7.2 and the rest similar to it) do not allow to clearly differentiate the data types. If colors are not enough to separate among the different datasets, other type of representation shall be used. In addition, the x-axis for that type of graphs shall be changed, as the way selected to represent months of the year is very confusing. It would be better to show the x-axis as MM/YYYY, and the y-axis as the SI unit "cm" and not "centi-meter".

I have replotted all the graphs throughout the thesis and changed the axes as recommended by the reviewers. I have used different plotting styles (dashed circle, triangle, square, diamond….) along with different colors to better illustrate the graphs.

More comments concerning the style and format:

- The numbering of sections is confusing. For more clarity, sections, subsections and sub-subsections shall be numbered using only numbers as usual. For example 1.A.1 should be 1.1.1. For completeness we remark that the letters A, B, C etc. are usually used for the Appendix.

I have changed the numbering of the sections to 1.1.1 style.

- Equations: The number of each equation shall be positioned in the right margin. The numbers at the center of the page together with the equation are difficult to distinguish from the equation in some cases. (e.g. (6.25)).

I have moved the equation numbers throughout the thesis to the right margin.

- Tables: the format used is not homogeneous. The text in the table is not clear in Table 6.2 where is written "Value of the parameter in the SAMOSA3 Retracker" No value was given. Therefore we suggest to improve tables and check more carefully. A running title identifying the chapter on each right page shall make easier the reading.

I have made all the tables in the thesis homogeneous and used more suitable texts in the tables. I have added a running title on each right page to improve readability.

- Figures: Many figures need to be improved adding boundaries and correcting typing mistakes (e.g. Tide Guage should be "Tide Gauge" (e.g. Fig. 3.2, 3.3, 3.4 etc.). We suggest to draw the tide gauge anomalies and not the readings and to add vertical lines to make more immediate the comparison with altimetry (see comment later).

I have improved the figures and removed the typing mistakes. I plot the anomalies in the tide gauge graphs now instead of the readings.

- The style need some improvements, as in Chapter 6.1 SAMOSA3 retracker where the same 3 or 4 bibliographic references are repeated many times in the same page.

I have changed the style for better readability.

Content and Technical comments:

- A novel retracker – the Primary Peak COG retracker – is developed as the major new development in the thesis work. Some explanation of how the retrackers were implemented would have been useful (MATLAB?), including confirmation if all retracker codes where programmed by the ph.d. student himself.

I have added the detail that the programming was done by me and added confirmation that the programs were implemented in MATLAB.

- The overall idea of evaluating the performance of different retrackers by looking at seasonal signals, in an area with a simultaneous seasonal change in sea ice cover (like Test Region 1), is somewhat questionable, especially considering the loss of the data in the ice margin zone (Fig. 8.1). Seasonal effects could very well also be influenced by "snagging", i.e. the peaky returns from nearby leads, not directly in nadir. The effects of the non-nadir lead reflections is not mentioned at all in the thesis, and should be included, e.g. in Section 4; off-nadir reflections, if classified as leads, would give a biased SSHA. Cross-Arctic plots of SAR altimetry passes, from open ocean in the test area into thick ice, would readily show these effects.

I have discussed in the thesis at appropriate sections that taking into account the effects of non-nadir reflections will improve the performance of the retrackers. However, due to the lack of in-situ data in the Arctic, retracker performance evaluation using seasonal signals is used. Tide gauges are only available at the coast. While in the test areas, the data is very extensive and is located in areas with no presence of tide gauges. In this thesis, both direct comparisons with tide gauge data and observation of the seasonal signals is used for retracker performance evaluation.

To assess the accuracy of the altimetry data, the author in invited to add direct comparisons of altimeter and tide gauge at near locations in each of the regions. This is the common methodology used to assess the accuracy in in-situ validation studies. The metric used shall include in this case correlation, standard deviation of the differences, amplitude and phase differences. Instead here the comparison was done over a larger region and many other factors could affect the results. Tables showing the statistics are missing. Therefore we suggest to do this analysis for a few stations in each study area and to discuss the results in details.

I have made direct comparisons of altimetry and tide gauge data and this is a very appropriate tool for measuring the accuracy of the retrackers. I have provided the results in suitable tables with all the statistics. The statistics show that the SAMOSA3-C retracker is the most accurate retracker amongst the different retrackers.

- As written in the previous point, the comparison of co-located altimeter and tide gauge time-series shall also quantify the agreement of their phases of the seasonal cycle. Figure 7.14 and 7.15 apparently show a difference in the annual phase of the basin average of altimeter and the tide gauge record in the North Sea, which is not noticed in the thesis. A plot the co-located tide gauge and altimetry on the same figure shall allow to better appreciate the differences. The comparison in the North Sea is not affected by ice and therefore a good agreement between co-located tide gauge and altimetry is expected. The metrics described above shall be collected in Tables and discussed in details in the text.

I have implemented the suggestions of the reviewers as mentioned and provided the statistics of the results in suitable tables.

- The simple lead understanding as shown in Fig. 1.3, is *not* a typical lead situation in the Arctic Ocean. Instead what the author calls "sea ice mélange" is typical Arctic Sea Ice (the "mélange" word should not be used). An Envisat radar plot from early 2012, showing a detailed example of sea ice conditions north of Svalbard, overlaid with near-simultanous detected open lead waveforms, would have been a useful illustration and confirmation of the performance of lead-type retracking (such an example could easily be done using data from "seaice.dk").

As suggested by the reviewers, I have not use the word 'melange' in the thesis and just called it 'sea ice'. I have removed the confusing illustrations of the lead situation and provided a better explanation.

- The DTU13 field is used as reference for the SSHA, but the reference given is 2009. Data behind DTU13 and reference system must be outlined, in order to understand the differences in SSHA bias between the different retrackers.

I have provided further details about the DTU 13 mean sea surface in the text and provided a more recent reference than 2009.

- The attempt to adapt the SAMOSA3 model to the Arctic Ocean is extensively discussed in the Thesis. Despite the fact that the 1Hz standard deviation in the SSH measurements is smaller for SAMOSA3 than the other considered retrackers, the SAMOSA3 retracker does not seem to follow the seasonal signal of the tide gauges. The author tried to explain this behavior, however, a cause for this was not found. The reviewers has some specific comments regarding this issue:

  - When the full waveform retracking is performed, the estimation of the three main parameters, i.e. Pu, SWH, and SSH is closely linked to each other. In other words, if one parameter changes, the rest of them change to try to provide the best waveform fit. Normalizing the radar waveforms is a common practice, especially if all the system parameters are not known. However, it is erroneous to consider that Pu does not need to be fitted. As was shown in the CP4O ESA project, the thermal noise in the SAR waveforms needs to be considered in order to scale properly the waveforms. Otherwise, the waveforms are shrunk or stretched depending on the surface backscattering properties, which can bias the estimation of SWH, and also SSH. Please, refer to http://www.satoc.eu/projects/CP4O/docs/CP4O_WP4000_Starlab_ATBD_v1.0.pdf. In order to consider the effect of the thermal noise

on the SAR waveforms, the noise plateau needs to be measured after normalization, added to the noiseless and normalized waveform model, perform the waveform retracking estimating also Pu, and denormalized the estimated Pu with the initial normalization value.

The SAMOSA model was originated as an Open Ocean model. For that reason, the radar backscattering and the antenna gain can be considered Gaussian and integrated within a single analytical equation, as shown in equation 6.19 (By the way, there is a typo in that equation). Therefore, the model is not well suited for quasi-specular reflections, as in the case of sea ice leads. This can be avoided, by modifying certain parameters of the model, as (partially) shown in the Thesis. However, it is not understood why for the SAMOSA3 Lead Mode the mss is estimated. This shall be better explained. Alternatively, in this situation one could assume that the mss is also constant (and very small), so that the mss term dominates in the first exponential of Eq 6.19, and therefore just estimate the SSH. This could also be explored as a possibility.

In order to evaluate the fitting of the SAMOSA3 model to the data, a correlation value is provided. Correlation is usually referring to the linear relationship between two random variables, so this does not seem to be the best parameter to show the resemblance between the SAR waveform and the model. It would be better to use a parameter such as the Goodness of fit.

- The author claims that SAMOSA3 is not well suited for the Arctic Ocean as it is not able to follow seasonal variability over a certain region. However, in order to compare the results, an extensive average is performed for all the data points within the area for each month. Computing the average removes essential information needed to understand how the retracker performs. In order to determine the SAMOSA3 retracker performace in terms of accuracy, and to actually determine whether it can estimate sea level change in the Polar Ocean, at least an along track comparison and statistics shall be obtained with respect to the rest of the retrackers for several sea state conditions. Please, refer to http://www.satoc.eu/projects/CP4O/docs/CP4O_WP4000_Starlab_PVR_v1.0.pdf for an example on this type of analysis.

In the above comment, the reviewers advised about exploring a number of possibilities to improve the performance of the retrackers. The reviewers' suggestion that *Pu* should be fitted turned out to be very useful. In the thesis, comparisons have been made with the sea surface height values from the SAMOSA3 retracker (from ESA's GPOD service.) The difference between the SAMOSA3 (GPOD) retracker and the student's SAMOSA3-C retracker is that the SAMOSA3 (GPOD) retracker fits the amplitude *Pu* as well. It is found that fitting the amplitude results in very high accuracy. Thus it resolves the problem faced by the SAMOSA3-C retracker as implemented by the student. The student's motivation to not fit the amplitude was in order to reduce the computation time of the retracking procedure. Thus, it is concluded that the SAMOSA3-C retracker should be implemented by fitting the amplitude for better performance.

Also, direct comparisons with tide gauge data have been done to judge the accuracy of the retrackers. The SAMOSA3 (GPOD) retracker where the amplitude is fitted performs with the best accuracy. This is followed by the student's version of the SAMOSA3-C retracker which performs with better accuracy than the primary peak retrackers.

- The ESA retracker and the PP ones are almost in counterphase, as shown in figure 7.2. I wonder whether there is an error in the interpretation of the data, which leads to an erroneous sign in the altimetry equations (Eq. 2.2, or Eq. 5.1). If this is not the case, the author shall explain why the ESA retracker monthly mean sea surface height anomaly is shifted with respect to the others.

I have double checked that there is no error in the equations and their MATLAB implementation. The ESA retracker is not well documented in literature as mentioned in the introduction of the thesis. The student has taken the ESA SSH's directly from the Cryosat-2 satellite dataset and has not computed them himself. In absence of a mathematical description of the ESA retracker the student cannot provide a qualified reason for the behavior of the ESA retracker. This is suitably mentioned in the thesis.

- It is interesting that the primary peak retracker performs better than the ESA product, as that represents an actual improvement in the estimation of sea level variations in the Arctic region, as is shown also in the *Advances of Space Research* paper. This should be stressed further in the conclusions as a major achievement of this research. The combination of physical and empirical retrackers, as shown in chapter 8, could represent a further improvement, however, the issues encountered with the SAMOSA3 retracker in the Arctic need to be answered first.

After evaluating the SAMOSA3-C retracker with fitting of amplitude and including accuracy analysis using tide gauge data the conclusion has been suitably improved. The importance of fitting the amplitude has been stressed upon. Accuracy analysis using tide gauge data shows the good performance of the SAMOSA3-C retracker. The advantages of the combined physical empirical retracker have been stressed upon as important conclusions in the thesis.

Overall the work of Thesis is a good basis for improved Arctic Ocean SAR altimetry sea level determination and understanding of errors. The submission of a revised ph.d. thesis following the comments above would make the Thesis a useful document for a broad range of research applications.

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