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Interactive comment on "Interferometric swath processing of Cryosat-2 data for glacial ice topography" *by* L. Gray et al.

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Author reply to reviewer 2

Again we would like to thank the reviewer for the positive review and will respond to the useful suggestions as outlined below.

Comment... In general the author could find an appellation to distinguished swath processed CryoSat heights, CryoSat height is ambiguous and could refer to either heights from swath processing or to Level 2 height products. Also the paper would benefit from the inclusion of additional commas.

Answer: We have struggled with how to describe our height results. Originally we used the phrase 'swath mode processed' but dropped this because it might imply an 'official'

swath mode, which wasn't ever the case. We will check whenever 'height' is used in the text to make sure that there is no ambiguity with L2 or 'poca' derived results. The phrase 'swath processed' will be used.

Comment... P 3133, Title: Although it is the second version of the Satellite, I believe the mission is still considered by ESA as CryoSat, not CryoSat-2. This is also true for the abbreviation, CS-2, used later in the text.

Answer: The '-2' will be dropped in both the title and manuscript text.

Comment... P 3134, L16: The idea of increase in height measurement density is not developed in the paper, can the authors be more specific about exactly how many more points are available from swath processing?

Answer: In the abstract we indicate that swath processing 'generates almost 2 orders of magnitude more data than traditional radar altimetry,...'. It is difficult to be more specific because of the varying limitations (across- and along-track slopes, coherence, thermal noise, etc.). Even if we gave a specific example (e.g. for the Feb. 23 data set described in section 4) it might be misleading in that each swath processed height estimate may not be strictly independent.

Comment... P 3139 L15-16: "Less than those"

Answer: Fixed.

Comment... P 3139 Formula 5: Can the author double check the sign of the right term? In the CryoSat handbook, positive phase convention is for signal coming from the right hand side of the spacecraft.

Answer: There is no doubt about our results; a left-right flip due to an incorrect phase sign would produce serious mapping errors.

Comment... P 3141, L22: It should be "2011"

Answer: Fixed.

Comment. . . P 3141, section 4. This section could benefit from further justification and specifics. Why are the data filtered? From fig. 5 it is not obvious that the level of noise would affect much the unwrapping, or does it? What filter is used? What is the origin and characteristics of the filtered noise? Why is the unwrapping performed line by line rather than in 2-dimension?

Answer: The interferogram output provided in the L1b file suffers from both residual speckle and thermal noise. Filtering, as described, reduces the resulting phase noise and, through the phase to angle relation, improves the geocoding of the height estimates and thereby reduces height noise. The price of phase filtering is a loss of spatial resolution. However, this is less important for swath processing than for the algorithms that estimate the phase of the 'point-of-closest-approach'. The cross-track footprint size decreases rapidly with delay time (Fig. 2a). Normally the delayed footprints in the original 512 data samples are separated by much less that 100m so that the low-pass filtering, and resulting oversampling, allows a re-sampling in the cross-track direction at $\sim$ 100m spacing without a loss of information. More on sampling and resolution below.

There is no need for 2-dimensional phase unwrapping: At the coherence levels at which we are working the phase noise is low enough that phase unwrapping on a line-by-line basis is perfectly adequate. This would be true even without the phase filtering. One-dimensional phase unwrapping is trivial and fast in relation to the complexity of 2-dimensional algorithms.

As explained in the text, the real and imaginary parts of the interferogram are recreated and filtered separately. The filter is a low-pass smoothing filter and the effect is most readily seen by inspection of the bottom block of Fig 6. Some of the comments above will be incorporated into an expanded section 4.

Comment. . . P 3142 L9: "In the L1b : : :" The implication of this sentence is not clear. Can the authors develop?

Answer: The 'delay-Doppler' processing referred to earlier in the text generates 64

return estimates, or 'looks', at 64 discrete beams fore and aft of nadir. After registering these are summed in the delay-Doppler processing and the result is given in the ESA L1b file. The summing process greatly reduces speckle and phase noise. This comment will be considered when we improve section 4.

Comment. . . P3143, L1: Why has this resolution been chosen?

Answer: The choice of spatial sampling in longitude and latitude is somewhat arbitrary and is designed in our work so that the results are not under-sampled. The relationship to resolution is discussed below.

Comment. . . P3143: What is the true resolution of the swath processed height product? Is it the range resolution of the L1b bins? Are the values of adjacent bins correlated in any way? Can this be assessed/discussed with the dataset and models available to the authors? Ultimately knowing the true spatial resolution of the swath processed CryoSat heights is critical.

Answer: We need to distinguish carefully between resolution and sampling. In radar terminology the 3 dB output resolution is the half power width of an input idealized impulse function. The output of the delay Doppler processing, the L1b files, include waveform data (512 samples of power, phase and coherence) spaced (sampled) $\sim$ 300m apart in the along-track direction. The resolution in the along-track direction depends on the processing and with the weighting now used in the official ESA algorithm we believe the 3 dB resolution in the along-track direction is $\sim$ 380m. Ideally then to satisfy a Nyquist sampling criterion in the along-track direction the complex output data could be up-sampled to provide waveform data every $\sim$ 190m so that the extracted phase, and consequently any along-track mapping, is not under-sampled. While we didn't do this in the current work, it is a possible future addition to our processing.

The cross-track dimension is more complicated because the ground range, cross-track, surface pixel resolution depends on the local surface incidence angle (related to the cross-track slope): Firstly, in the slant range (essentially nadir) direction the situation

is fairly straightforward. The first stage in processing is equivalent to the I,Q (complex) receiver data being digitized (sampled) every 3.125 nsecs. This corresponds to a spacing in air of $\sim$ 47 cm. While this is adequate sampling for complex data (considering the 300 MHz effective bandwidth of the receiver), when the phase is extracted and used for a mapping product the Nyquist sampling criteria is no longer satisfied so there is the possibility of aliasing. This is the reason for the change in waveform sampling in the current ESA L1b processor (the waveform data is now sampled at twice the original rate). We didn't need to use the higher sampled data in our work because (as explained in the text) we are working with delayed returns and the cross-track extent of the footprint is much smaller than that at the 'poca' position. The slant range resolution based on the receiver bandwidth of 300 MHz is $\sim$50 cm. As explained in the text, with the phase filtering that we adopted the slant range resolution is reduced to $\sim$ 2.5m. At a local incidence angle of 1° the cross-track surface resolution is then $\sim$ 143m. With the low pass filtering there will be correlation between adjacent bins but after the resampling to the regular grid the correlation, and over-sampling, will be reduced. The idea is to adequate sample the elevation field for most slopes, we believe this has been done in the current scheme. The cross-track resolution (footprint size) in planimetry then depends on local slope and can't be defined exactly a-priori.

We will improve section 4 to include some of the comments above and describe in more detail what was done.

Comment. . . P3143, L26: What are these statistics on the non-filtered dataset?

Answer: The processing for the Feb. 23 descending pass was repeated to illustrate the effect of the phase filtering. The comparison with the East-West ALS laser data was repeated with and without phase filtering. In both cases $\sim$ 100 height values were compared. As stated in the text, with filtering the mean difference was -0.28m with an STD of 0.44m but if the filtering stage was omitted the mean difference changed to -0.32m with an STD of 0.74m. This illustrates the benefit of the filtering stage for swath processing of CS data even though the ground footprint size in the cross-track

dimension was increased.

Comment. . . Fig. 3: Difficult to distinguish the colours, maybe the slope values could be added at the end right of the curves or different colour used or thicker lines.

Answer: The plot will be redone to address this problem.

Comment. . . Fig. 10: The agreement between data and model is very good for the low latitudes but seems to worsen for the higher latitude; what may be the reason for this degradation?

Answer: It is not clear why this is the case. However, even at the higher latitudes the modulation in the simulated power is related to the modulation in the received power although the colours are different.

Interactive comment on The Cryosphere Discuss., 7, 3133, 2013.