We would like to thank the three reviewers for the care and time they have taken in providing thoughtful and helpful reviews. Also, we would like to thank Tommaso Parrinello, ESA, and Michele Scagliola, Aresys, for providing new information on CryoSat relevant to one of the issues raised in our paper.
In the response below, the reviewer comments are in italics and our replies are in normal font.

Anonymous Referee #1

This paper gives details of improved processing techniques for CryoSat-2 data, using swath-processed data to illuminate some apparent errors in the released data, and demonstrating the use of swath-mode data to monitor supraglacial lake heights in Greenland. The paper will be primarily of interest to radar altimetry specialists, but provides useful information about how to handle the CryoSat dataset and should improve the glaciological community' ability to make sense out of these data. The authors provide good evidence for their conclusions about the dataset, and show interesting examples for how the data can use used to measure lake-level changes.

The writing is generally clear, although I would recommend a careful reading and the addition of commas to some of the longer sentences.

Some commas have been added.

The figures, for the most part, make good use of space, and provide a good illustration of the physical principals at work. I make some editorial comments below, which should be relatively easy to correct.

Throughout: "skidoo" should be "Ski-Doo" or "snowmobile"

Done; skidoo changed to snowmobile.

Section 3: Give a citation for the discussion of look angle and roll angle, either to the CS2 documentation or to a paper.

The key reference (Galin et al. 2013) has been included, and the comment added that the negative sign in equation 2 arises because the instrument is being used in the mode where transmission is from the left antenna, and both are used for reception. As pointed out in the Galin et al. paper, the relation between phase and the interferometric look angle should be $\beta = \pm \mathrm{asin}(\chi/kB)$, where the sign depends on which antenna is used for transmission. Since launch, the left antenna has been used for transmission, hence our use of the negative sign in equation 2.

6:27 Define the look angle (relative to nadir?)

Defined in lines 6:23 and 6:24, and explained further in the following paragraphs.

7.25: It would be helpful to say "in this section" rather than "here"

Done.

8.10: should be "change was small"

Changed.

8.15-30: Experiments should be described in the past tense, results can be described either in past or present tense.

Past tense is now used to describe both the experiment and the results.

8.21: add comma after "further"

Done.

Section 3.3: This section needs some introductory material about the difference between the retrackers available from ESA and the retracker used here. Without this discussion, readers not familiar with the details of CS2 tracking are likely to be confused by the comment at 10:3-4 about retrackers that use all of the waveform.

Additional text has been added at the appropriate place in section 3.3, and an additional reference has been included giving some details of the retrackers used in the ESA L2 products: This is; Buffard J.: CryoSat-2 Level 2 product evolutions and quality improvements in Baseline C. ESA report XCRY-GSEG-EOPG-TN-15-00004. Available from https://earth.esa.int/web/guest/document-library

10:5-10: Could phase ambiguity play a role in the location differences between the two products? If not, should explain why.

Yes, it could, but in this example the major problem is that the L2 retracker has been fooled by the peaks in the middle of the waveform. Figure 7A and B have been redone to provide more information. By working back from the L2 positions the phase can be calculated from the calculated look angle. Then the position in the waveform with this phase can be marked, this has been done in Fig 7A. This shows that the L2 retracker often picks a position in the middle of the waveform close to a local maximum. The appropriate text and figure caption have also been improved to make this clear.

10: 11-12: Why not edit the L2 data based on coherence and return power? Both are available through comparison with the L1B data.

Figure 8 has been redone using editing as suggested by the reviewer. Some of the L1b waveforms are rejected in our processing. The L2 results for exactly these waveforms are now also removed so that the comparison between the ATM-L1b and ATM-L2 height differences is as fair as possible. In Fig. 8A, the statistics do not include the 39 L2 height values with errors greater than 20 m, even so the L2 results are significantly worse than with processing from the L1b files.

10:24: Add a hyphen: "roll-angle"

When 'roll angle' appears as a descriptor, e.g. 'roll-angle bias', a hyphen has been added.

10:24: Should point out that there is a minimum error at about 0.007 degrees

The minimum error at ~ 0.0075° ±0.0025° has been added. Any time the roll-angle bias (or the equivalent phase bias) is referred to an estimate of the error in this value has been added.

14:9: "would" should be "may"

Changed.

14:13 : I don't understand this sentence: What does "realistic" mean in this context?

The offending sentence has been removed and this part of the 'Discussion' has been changed, also to satisfy comments from the other reviewers.

14:22- "can be" should be "was"

Corrected.

14:30: Why is a retracker not required? If you plotted power vs. range for the lake returns you would see the same kind of pattern you see for a POCA return, so why not pick the first slope for the lake return?

A retracker is required in the situation where a sequence of time samples include more and more of the surface. The 'retracker' is then needed to estimate when in time the surface return occurs. When looking at a lake return in the middle of a waveform one could also use a retracker, but there will always be multiple areas contributing to each point in the 'lake' area of the waveform. For this reason, we opted to use standard cross-track InSAR processing, and use the phase from each range pixel for mapping. Then the accuracy of an average height result can be estimated using the consistency of the height results from the strong returns in the waveform, which have been assumed to originate from a flat lake surface.

15:4â˘Aˇ Tit's worth noting that sun-synchronous orbits are limited to +- 81 degress, so central Antarctica and the arctic sea ice would be missed.

The last two sentences in section 5, 'Discussion', have been removed. The ongoing discussion of a follow-on CryoSat mission is perhaps beyond the scope of this paper.

Figure 7: To me, this looks like increasing longitude and increasing range are in opposite directions. It would be helpful to reverse the range panel so that the two are easier to compare. It would also be helpful to plot the ESA L2 range on the radargram.

This figure has been improved, as described above, but in our opinion reversing the range window in Fig. 7A didn't make it easier to see the link between the POCA geocoding solution and the waveforms.

Figure 9: It would be helpful to note the differences in x scale between the two rows of histograms.

Figure 9 has been redone with the same x axis for all the histograms.

Anonymous Referee #2

The manuscript by Gray et al., provides an analysis of CryoSat SARIn mode for the study of surface elevation over the Devon Ice cap and over a sector of the West Greenland Ice Sheet. The manuscript describes an improved calibration of the satellite's attitude and a fine tuning of the signal characteristic to obtain precise height measurements. There is then a detailed and informative discussion about the signal properties observed above supra-glacial lakes and of supra-glacial lakes elevation determination during a 6-year period.

The paper provides rigorous, thorough, novel and relevant observations of CryoSat's performances over ice caps and ice sheets. My comments address the clarity of the manuscript that I think would benefit from improving on the following points:
The paper should make it clearer where the improvements in processing are (title) compared to previous work. As written only the improvement on calibration is explicit.
The paper should make it clearer when the roll-biased corrected heights have been used to generate bias and dispersion from airborne dataset.

As the paper emphasis is on the improved SARIn mode calibration through a detailed comparison of the CryoSat results against surface height measurements, and less on processing methodology, we have changed the title to 'A revised calibration of the interferometric mode of the CryoSat-2 radar altimeter improves ice height and height change measurements in west Greenland'. But we have also tried to illustrate the effect of the improvements through the examples included, including the work on supraglacial heights.

Through the paper there is variability in the tuning of the various technical steps (e.g. processing's thresholds, filtering and binning) for different height products and area that often seems arbitrary. It would be good to have more details on the observations that led the authors to tune the processing the way they did so as to educate the reader.

We have attempted to do this in a number of places in the text. In particular, we found that the west Greenland site was more challenging than the west Devon site, due to the 'rougher' topography, and this lead to more stringent data editing. This is explained and documented.

The link between the calibration and the supra-glacial lake survey is not particularly explicit, the two parts are somewhat disjointed. What observation over the lakes led you to develop this improved calibration? I would like to see more on relating the impact of the better calibration with the gain in precision in the lake height measurement maybe via a dedicated section or by a better articulation of the two sections.

We acknowledge that this is true. Rather than answer the question 'what observation over the lakes led you to develop this improved calibration?', we have tried to show that the improved calibration, coupled with our methodology, allows more precise ice height estimates, including the heights of the supraglacial lakes.

Here are detailed comments related to specific page and line numbers:

Title: CryoSat-2? ESA prefers this appellation.

We have changed the title, although in recent ESA publications, and in the programme of the upcoming ESA CryoSat meeting, the '2' is often absent.

Title: It is relatively clear that the paper provides an improved calibration however the improvement in processing upon previous work is not clear.

The title has been changed.

P1L15-16: How did you come up with these numbers? I could not find them in the manuscript.

The numbers reflect many comparisons of surface and CryoSat heights, including other test areas. As the abstract should reflect only the work in the paper, we now use the standard deviations from Fig 9A and 9C to reflect the relative precision of POCA and swath results from the west Greenland site. The revised text is… "While individual swath processed heights are normally less precise than edited POCA heights, e.g. standard deviations of ~3 m and ~1.5 m respectively for the West Greenland site, the increased coverage possible with swath data complements the POCA data and provides useful information for both system calibration and improving digital elevation models (DEMs)."

P1L23: If I understood correctly this value of 0.5m is obtained from a consistency check between ascending and descending orbit path of CryoSat data, which can both be affected by a systematic bias, and not from validation with an auxiliary dataset. If so then I would rephrase this sentence and use a different word than accuracy.

The text has been changed to '… a height precision of ~0.5 m for…'. We have checked throughout the text to make sure that we haven't used 'accuracy' when 'precision' would be more appropriate.

P2L9: 'Point-Of-Closest-Approach'

Changed.

P2L17: This is another nice piece of work on the subject: http://ieeexplore.ieee.org/document/7542661/

This reference has been added.

P2L20: and ice sheet margins

This phrase has been added.

P2L21: not sure what 'borrows heavily' means?

The text has been simplified… "The new approach uses bursts of pulses in which… "

P3L12: Hawley et al., GRL 2009 maybe also for a bit of history

The reference, and an appropriate sentence, have been added.

P3L13: With respect to use of L1b product and generation of swath altimetry, it would be worth mentioning some recent work generating and applying swath altimetry to derive geophysical variables over ice sheets: Christie et al., GRL, 2016 (10.1002/2016GL068972), supra-glacial lakes: Ignéczi et al., GRL, 2016, (in *the sup. mat. 10.1002/2016GL070338), Ice Caps: Foresta et al., GRL, 2016 (10.1002/2016GL071485)*

These references have been added.

P3L26: This sentence "Our method in working : : :" is awkward.

The sentence has been changed, and simplified.

P4L12: What reference power is used to calculate the logarithmic values?

The text has been changed to… The L1b files contain two echo scaling parameters for each waveform which allow a calibration of the waveform power to watts, the logarithmic (dB) values used in the results are then with respect to 1 watt.

P4L10: Not sure to what this last sentence refers to.

The sentence was included to provide the background information to show that 'cross-overs' are not appropriate for calibration of the SARIn mode results.
"The position of the POCA footprint derived from each waveform will be in the plane including the satellite position, and the lines defined by the cross-track and nadir directions. The POCA area will be centred on the closest point in the intersection of this plane with the terrain surface, so that when ascending and descending orbits cross the two POCA footprints will not be the same when there is a cross-track slope. Consequently, it is not appropriate to compare results from the interpolated orbital cross-over point."

P5Section2.2: What criteria do the authors used to identify swath returns from POCA returns? There seems to be a process by which these two records are identified within a waveform but the methodology/criteria to achieve this are not described.

Our earlier papers, and the work of others (e.g. the Smith et al., 2016 reference), provides the necessary background on this. In our algorithm if the average of the first 5 values in the waveform are above a certain level then no POCA value is calculated, but swath mode results may be. This has been added.

P5L14: What distance is this? In the ground plane? Does the surface slope matters and how does that value varies with the slope? It is not clear how this values relates to the 4-bin filter described above.

All the geocoded footprints from one waveform are mapped into the zero Doppler plane, so that the POCA footprint and any swath footprints from the same waveform will be mapped to a straight line on the ice surface, irrespective of the surface topography. This is a straightforward consequence of the Delay-Doppler processing on data from a yaw-steered satellite.

P5L12-15: The binning step is unclear? As written it reads as if it is a consequence of the filtering, is it? Why do both? This section, and the need for binning/filtering, needs more justification.

Low pass filtering of complex waveform data has been used and described in this and in previous work (the Gray, Smith and Nilsson references), the benefit is reduced phase noise and therefore

better POCA and swath mode footprint geocoding. A comment to this effect has been added to section 2.1.
After the waveform smoothing the results of swath processing can be spaced a few tens of meters apart in the cross-track direction depending on the cross-track slope, and, as explained, may be oversampled. Consequently, it makes sense to carry out further averaging for swath mode results, this has been done by binning the results after the geocoding stage. The nominal separation of the footprint centres is 100 m in the cross-track direction. The text has been improved to help make this clear.

P5L18: What are the gains of using this alternative setup for summer data? It would be good to describe further the motivation/justifications behind this customised processing.

The lake features are small and few in number, so it is simpler to avoid the swath mode binning stage and look at each set of strong returns separately.

P5L20: In Gray et al., 2013, the range of acceptable cross-track slopes for swath processing is between 0.5 and 2o. Are the authors revising this range? If so it would be interesting to have a paragraph or so discussing this.

The original range of acceptable slopes (average cross-track slopes of ~0.5° to ~2°, Gray et al., 2013) was based on modelling using antenna gains etc., and was supported by the results from the western slopes of Devon Ice Cap. Experience from other sites and further comparisons with surface elevations have shown that, not unexpectedly, the best results are obtained with a slightly smaller range. The text on P8L9 has been expanded as follows…
The western portion of Devon Ice Cap has suitable cross-track slopes for swath mode height estimation for both ascending and descending passes, and this area was used in the demonstration of swath mode processing (Gray et al. 2013). While the possible range of average slopes can be ~0.5° to ~2°, here we have restricted the use of results to E-W slopes of ~0.7° - 1.5° over a distance of >5 km as this range generally provides a better suppression of the ambiguous range contribution.

P5Section2.3: What constrained was applied on the time difference between CS+ and validation data?

The rational for the selection of the time period for the CryoSat results is provided… 'Virtually all the reference height data for both sites were obtained under cold conditions in April or early May and we assumed that any accumulation or change in the backscatter conditions between January and mid-May would lead to a relatively small change in the CryoSat height. This provided the rationale for comparing all the CryoSat results from the January to May passes with the April or May reference height data.'
However, we also redid Fig. 8 (to satisfy a comment from reviewer 3), and used a smaller time window for the CryoSat data. (passes from 16 Feb. to 23 Apr.). Although there were now fewer CryoSat height samples, the results were similar to the previous figure.

P8L16: fig. 5 is mentioned before fig. 4

The reference to Fig. 5C has been removed.

P9L15: How was 0.0075o determined from the data in fig. 4/5? What is the uncertainty attached to this value?

The value was estimated from the cross-over of the lines from the experiment in which roll-angle bias is varied between -.2° and +.2°. Clearly, the value of 0.0075° is an estimate, and it is also hard to quantify the uncertainty as it will involve which star-tracker was used, and the position in the orbit. We have used an uncertainty of ±0.0025° in this value and explained that this just an estimate based on a relatively small sample.

P11L4: Is this after the bias correction is applied? How does this changes with a bias of 0.0075o applied?

Yes, the roll-angle bias has been applied, and the text on P10L16-19 states this. Also, the caption for Fig. 9 make it clear what has been done.

P11L8: Why "appears"? Could this be checked?

We are convinced that our explanation of the height bias is correct, but have not used 'is' in place of 'appears to be' because it is hard to prove, and we haven't done so.

P12 L14-18: A few references would be helpful in this paragraph.

The references below have been added after the comment related to the use of DEMs.

P12L23: A sentence or 2 on the use of surface topography to map and model supra-glacial lakes is warranted here: e.g. GIMPDEM: Leeson et al., 2015 doi:10.1038/nclimate2463, and GIMPDEM and CryoSat-Swath DEM: Ignéczi et al., GRL, 2016 10.1002/2016GL070338

See above

P13 L6 'for the six ascending passes'. Is that seven passes?

Yes, six replaced by seven.

P13L15: The amplitude of the decrease is as large as the increase in both L1 and L2, albeit with a different timing - it seems therefore to be a significant signal. Could you expand on the relative differences and on the reason behind this signal? Especially since drainage as a cause is excluded.

While the melt water created through the warm temperatures in summer 2012 at the positions of L1 and L2 did not drain in the dramatic way that supraglacial lakes often drain in the ablation zone, the water may have percolated through the firn in a manner similar to the recharging of firn aquifers, as has been recently observed in SE Greenland. New text, and two key references to the existence and study of firn aquifers in Greenland have been added, but in the final analysis we simply can't be certain why the year-to-year height signals decrease as shown, or why the height change is different for L1 and L2.

P13L23: Sentence starting by "If we assume : : :" seems incomplete.

Fixed… 'If we assume a lake area of 2 ± 0.5 km^2 this implies a filling rate of ~0.2. 10^6 – 2.10^6 m^3 melt water added per day.'

P13L31: Is it an advantage of swath or is it because of your choice to limit the swath *data to small look angles (P5L20)?*

The description on P5L20 refers to the methodology for supraglacial lake height estimation. In this case, good results will only be obtained when the lake is beneath, or very nearly beneath the satellite, i.e., the look angles are very small. In general, the most reliable swath mode results over glacial ice are also obtained when the look-angle is small, the coherence high, and the waveform power above a certain limit.

P14L13: I would soften/rephrase this statement; Foresta et al., GRL, 2016 show that there are no significant differences between rates of height change from POCA and from Swath over Icelandic ice caps. Second the greater spatial coverage offered by swath can lead to measure of height change where POCA fails and so provide a 'better' solution (Smith et al, TC, 2016). Finally it depends on the surface slope (direction and magnitude). I would rephrase the paragraph using the studies of height change over Iceland and Thwaites to show existing evidences for the benefit of swath for height change measurements, and listing the various associated caveats.

We have expanded the text at this point and added reference here to the Foresta et al. and Smith et al. papers. It should be noted that Foresta et al. used the L2 POCA results rather than values derived from the L1b files. Also, in the Smith et al. work 'meter scale biases', correlated over tens of kilometers but independent orbit-to-orbit, were partially corrected by combining with the POCA data.

P15Section6: Is a bullet-point conclusion appropriate for TC conclusions? I leave this to the editor to decide.

? We admit bullet form is unusual, but we think it is 'efficient'.

P15L16-17: Where did the paper demonstrate the relative accuracy?

As commented above, we have reviewed the complete manuscript to make sure that 'accuracy' or 'accurate' are not used where 'precision' and precise' would be more appropriate.

Fig3. Transect in fig. 1 seems to be missing

The transect has been added, and the captions modified.

Fig8. Specify time-period and/or CS2 passes used

The time period for the CS2 data has been added to the figure caption.

Fig9. Same as for Figure 8

As above.

Fig10 '(A) 16 passes plotted: : :' There is only one plot on panel A. Delete '(top)' at the end of the first sentence since the panels are labelled A and B.

Fixed.

Fig15. Add latitude on y axis and possibly range window on x axes

The caption has been changed so that the directions of the x and y axes (increasing range and increasing along-track position (N up) are clear.

Fig17. Units (m) are missing on both x and y axes

Units have been added.

Anonymous Referee #3

The manuscript of Gray et al. discusses improvements in POCA and swath processing of Cryosat-2 data. Comparing the satellite data to elevations from airborne surveys, GPS transects and DEMs, they show that their approach of using the point of inflexion generally provides better results than the standard ESA POCA data for two regions. Further improvements are obtained by introducing an additional roll angle correction. Whereas the improved performance of slope-dependent and threshold retrackers has been discussed before in other studies (including some of the first author), the findings about the roll angle correction are important. The manuscript is well written and the presented analysis is meticulous and thorough and illustrated with appropriate illustrations, which make the paper accessible for non-radar specialist (although some background knowledge is still required). The application to lake height changes makes it interesting for the broader glaciological audience that The Cryosphere targets. As one of the other reviewers also pointed out, section 4 feels a bit disjointed. It would be good to discuss if and how the improvements discussed in the other sections contributed to these results.

Could these results be obtained with the standard data provided by ESA?

It isn't clear which results are being referred here. The revised calibration could not have been done with the standard L2 data, nor the work on supraglacial lake height. So we think the answer is no!

The only weak part I could identify in the manuscript is section 4.1 on the effect of surface melt on SARIn waveforms. Although the reasoning is logical, this part is rather speculative ('We speculate: : :' appears 3 times) and doesn't add much to the paper. I would suggest to keep this part for a separate paper, backed up with in-situ/model data of the local snowpack characteristics (possibly at a different location where such data are available).

This section has not been removed, but has been improved. First, it is well known that the introduction of even a small amount of liquid water in snow dramatically alters the emissivity and backscatter (Ulaby et al., 1986). This is the basis of the well documented change in both microwave emissivity and backscatter with the onset of melt in snow over Greenland. For example, a significant drop in QuikSCAT 13.3 GHz backscatter was shown to be linked to melting from weather station data (Nghiem et al., 2001). The presence of water droplets in snow increases absorption, reduces the penetration depth, which in turn leads to an increase in brightness temperature and decrease in radar backscatter (Wang et al., 2016). With this background, and by including these references, we have provided a more convincing and less speculative link between the drop in CryoSat returns and the onset of melt in the snow. Further, we feel that the link between spikes in the summer waveforms, and specular reflection from a wet surface, is sufficiently clear that it also warrants inclusion. In summary, we hope that this short section will inspire a graduate student somewhere to systematically explore the links between the largely under-appreciated CryoSat data, other active and passive airborne and satellite data, and surface measurements. For this reason, we would like to continue to include this short section in the paper.

Ulaby, F., Moore, R., and Fung, A.: Microwave Remote Sensing: Active and Passive, Vol. 2, Norwood, Massachusetts, Artech House, 816–920, 1986.

Nghiem, S. V., Steffen, K., Kwok, R., and Tsai, W.-Y.: Detection of snowmelt regions on the Greenland ice sheet using diurnal backscatter change, J. Glaciol., 47(159), 539-547, doi: https://doi.org/10.3189/172756501781831738, 2001.

Wang, L., Toose, P., Brown, R. and Derksen, C.: Frequency and distribution of winter melt events from passive microwave satellite data in the Pan-Arctic, 1998-2013, The Cryosphere, 10, 2589–2602, doi:10.5194/tc-10-2589-2016, 2016.

Most textual comments have already been raised by the other two reviewers. Below a list of additional suggestions:

P3L7: '[L2i contains] also the waveform': is this so? As far as I'm aware, the L2i data contains some waveform parameters (leading edge slope, max wavepower, etc.) but not the full waveform?

The sentence has been changed to… 'An additional L2i product is available which contains the same geocoded height solution as the L2 product, but also information on the waveform which can be used to help eliminate poor data and solutions.'

P5L14: 'binning and averaging the results in segments' : please clarify how you did the binning and averaging (e.g., the width of the segments).

The text re binning and averaging has been improved, as noted for reviewer 2.

P6L17: It's unclear to me how you estimated the error by looking at the cross-track slope. Or did you inspect the cross-track slope to remove bad measurements?

If the 'lake' had a slope in the range direction this would indicate an error. If the slope was significant the measurement was removed, but a slope of a few tens of centimeters over hundreds of meters was used to help estimate the overall height error.

P7L5: I suggest to use a symbol for the phase. The ph might be interpreted as p times h.

Done, the symbol χ is now used for phase.

P7EQ4: is this equation correct? Shouldn't it be -ph/KB + ph/KB(: : :)-: : :

A sign error was corrected in equation 4.

P8L17: please provide separate numbers for the bias for ascending and descending Passes

These numbers have been added… The histogram of the difference between the reference and CryoSat swath mode heights obtained with the pre-launch baseline estimate (1.1676 m, Bouzinac, 2012) showed a bimodal distribution and the average bias changed between ascending and descending passes, ~-0.5 and ~2.5 m respectively.

P8L30: what's the range of the sun elevation angle for the 2012 ascending passes?

Thanks to the work of Scagliola et al. (2017), tracking the sun elevation angle to infer whether solar heating was involved in the roll-angle problem is now unnecessary. The main problem in the roll-angle issue appears to be a problem in processing the star tracker data. Reference to plate bending as the cause of the roll-angle problem has been removed, and the references to the solar elevation angle. Appropriate text has been added and reference to the new work included.

P10L9-15: figure 8a (ESA L2) is based on 951 pairs, fig 8B (max slope retracker only 599). I assume that during the processing of the max slope retracker data, faulty data was already (partly) removed? For a fair comparison, numbers for the same pairs should be compared. NB: in figure 9A, there are suddenly 1608 pairs for the POCA data. Where does this difference come from?

Figure 8 has been redone such that results from exactly the same waveforms have been compared, as described in the comment to reviewer 1. The difference in the number of samples used between Fig 8A and 9A arises simply because data from more passes were used in Fig 9A. This makes no difference to the conclusions.

P15L9: the choice for the 0.0075 deg bias is poorly motivated.

The text around the additional roll bias has been improved, as described for reviewer 2.

P10L28: two of the passes in fig 10B show a minimum std at _0.015 deg. Any idea why this is?

We think the variation in the position of the STD minima arises because of the pass-to-pass error in the roll angle, due to the incorrect processing of the 'optical aberration' in the star-tracker algorithm. This arises due to the variation in the relative motion of the star-tracker with respect to the field of stars. The dominant time period for this problem is then the orbital period.

P13L25: SARIn data certainly has advantages, but it doesn't allow to estimate total lake volume as with Landsat/MODIS. Seems correct to point out this limitation.

This is clear, we present the CryoSat results not as a competitor to the use of optical satellites but as another tool which might complement the study of these lakes, and the variation in surface melt year-to-year around Greenland.

P14L10: 'POCA better suited for temporal height changes': Forresta et al, GRL, 2106 recently estimated volume changes for Iceland using swath data and found that swath leads to more accurate results than POCA data. It would be good to briefly discuss how uncertainties in the swath data affect such estimates.

This part of the Discussions has been expanded, as described in the response to reviewer 2.

P15L6: a 73-day repeat would lead to a larger inter-groundtrack separation, i.e. a less dense coverage.

The comments related to a follow-on mission have been removed as beyond the scope of this paper.

A revisedImproved processing and calibration of the interferometric mode of the CryoSat-2 radar altimeter improves iceallows height and height change measurements of supraglacial lakes in west Greenland.

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Abstract. We compare geocoded heights derived from the interferometric mode (SARIn) of CryoSat to surface heights from calibration-validation sites on Devon Ice Cap and West Greenland. Comparisons are included for both the heights derived from the first return (the 'point-of-closest-approach' or POCA) as well as heights derived from delayed waveform returns ('swath' processing). While swath processed heights are normally less preciseaccurate than edited POCA heights, e.g., standard deviations of ~3 m and ~order 1.—5 m respectively for the West Greenland siteinstead of order 1- 2 m, the increased coverage possible with swath data complements the POCA data and provides useful information for both system calibration and improving digital elevation models (DEMs). We show that the pre-launch interferometric baseline coupled with an additional roll correction (~0.0075° ±0.0025°), or equivalent phase correction (~0.0435 ±0.0145 radians), provides an improved calibration of the interferometric SARIn mode.

We extend the potential use of SARIn data by showing the influence of surface conditions, especially melt, on the return waveforms, and that it is possible to detect and measure the height of summer supraglacial lakes in West Greenland. A supraglacial lake can provide a strong radar target in the waveform, stronger than the initial POCA return, if viewed at near normal incidence. This provides an ideal situation for swath processing and we demonstrate a height precisionaccuracies of ~ 0.5 m for two lake sites, one in the accumulation zone and one in the ablation zone, which were measured every year from 2010 or 2011 to 2016. Each year the lake in the ablation zone was viewed in June by ascending passes and then 5.5 days later by descending passes which allows an approximate estimate of the filling rate. The results suggest that CryoSat waveform data and measurements of supraglacial lake height change could complement the use of optical satellite imagery and be helpful as proxy indicators for surface melt around Greenland.

1 Introduction

Temporal change in ice sheet surface elevation derived from satellite altimeters has been used in mass balance estimates and the associated contribution to sea level rise, (e.g. Davis and Ferguson, 2004; Rémy and Parouty, 2009; Shepherd et al., 2012; Hurkmanns et al., 2014; Zwally et al., 2015). Satellite radar altimeters have traditionally operated at Ku band (~ 13 GHz) and used parabolic transmit/receive dish antennas with a diameter of ~ 1 m, so that the main beam illuminates an area beneath the satellite with a diameter of ~15 km and area of ~180 km^2. With a typical bandwidth of ~ 300 MHz the range resolution is ~ 50 cm and, as delay time increases beyond the point at which the first surface returns are received, an increasing area contributes to the received signal. These returns are termed 'pulse limited', with the initial signal originating from the area within the main beam closest to the satellite, often referred to as the 'Point-Of-Closest-Approach'~~point-of-closest-approach'~~ (POCA). With these parameters, the diameter of the initially sampled POCA area over the ocean is ~ 1.2 - 1.5 km, but this isn't necessarily the case over glacial ice. The initial area contributing to the leading edge of the waveform (the delay time variation in received power) over an ice cap or ice sheet depends on the ~~ice cap~~ topography. All we know is that it must originate from somewhere within the area illuminated by the main antenna beam and that part of the POCA surface area must be orthogonal to the incident wave. Considering the large variability in ice cap topography and surface conditions, it is not unexpected that the waveforms from glacial ice will vary significantly in shape and power. The fact that the geographic position of the POCA is, a priori, unknown is one of the major problems in traditional radar altimetry and methods to get around this limitation have been studied extensively (Brenner et al., 1983, Bamber, 1994, Brenner et al., 2007, Hurkmanns et al., 2012, Levinsen et al., 2016).

The European Space Agency (ESA) launched CryoSat as the first in their 'Earth Explorer' series of satellites, which are designed to explore and demonstrate new techniques and methods in Earth observation. As such, CryoSat was designed to include a new mode of operation to address some of the limitations of traditional radar altimetry when used over sea ice, ice caps, and ice sheet margins.~~caps.~~ The new approach ~~borrows heavily from coherent imaging radar technology and~~ uses bursts of pulses in which the frequency of the pulses within each burst is high enough that coherent Doppler processing can be used to focus the energy in the along-track direction, and ultimately create a footprint for which the along-track position is known, but the footprint centre can still be displaced from the sub-satellite track dependent on the cross-track slope. The along-track processing approach is referred to as 'Delay-Doppler' and was pioneered by Raney (1998). The suggestion that cross-track interferometry could solve the cross-track footprint position problem in radar altimetry is due to Jensen (1999). For glacial terrain the new 'SARIn' mode of operation provides a relatively small geocoded footprint which allows, for the first time, a systematic comparison of satellite radar altimeter elevations with surface heights from surface and airborne campaigns.

The first CryoSat satellite equipped with the Synthetic Aperture Interferometric Radar Altimeter (SIRAL) was launched in 2005 but failed to enter orbit. A replacement satellite was launched in 2010 and, as of March 2017~~October 2016~~, is still operating satisfactorily, almost four~~three~~ years beyond its design life. CryoSat operates in three modes: a conventional low resolution mode (LRM) which is used over oceans and the interior of Antarctica and Greenland, a synthetic aperture mode (SAR) for use over sea ice, and the interferometric SARIn mode over all the other glacial ice areas on Earth. A comprehensive description of CryoSat is given by Wingham et al. (2006). Here we are concerned primarily with SARIn mode calibration and with demonstrating some unique capabilities of this new mode of satellite radar altimetry. These depend primarily on the ability to geocode the position of the relatively small footprint.

After the initial commissioning phase of the satellite in spring and summer 2010, intermediate and final products were available from ESA. For glacial ice the ESA level 2 (L2) product contains the position and height of the geocoded POCA positions. An additional L2i product is available which contains the same geocoded height solution as the L2 product, but also information on the waveform which can be used to help eliminate poor data and solutions. An intermediate product (L1b) has also been made available which includes the waveform power, phase, coherence, satellite position and velocity, etc., and all the corrections and timing information necessary to calculate the position and height of the POCA footprint. This has been useful to those users wishing to study processing techniques; for example, by having access to the intermediate L1b product it has been possible to demonstrate that the returns which are time delayed beyond the initial POCA position can be used in areas with suitable cross-track slopes to create 'swath processed' elevations (Gray et al., 2013). Initially, airborne data had been used to demonstrate~~Indeed,~~ the possibility of swath mode processing of Delay-Doppler data (Hawley, et. al., 2009). The L1b products have also been used in several studies of change in Antarctica and Greenland (e.g. Helm et al., 2014, Nilsson et al., 2016, Christie et al., 2016, Smith et al. 2016), smaller Arctic ice caps (Gray et al. 2015, Foresta et al., 2016), and lake height (Kleinherenbrink et al. 2014). In these studies, the authors claim improvements in the results over the standard level 2 product, due to the specialized processing.

Three versions of the various CryoSat products have been distributed by ESA since commissioning; these are the so-called baseline A, B and C products. Details of the improvements can be found through the ESA Earth Online web site devoted to the CryoSat mission (https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/cryosat). Here we have used only the latest baseline C products, particularly because the waveforms in these products span a range window distance of ~ 240 m, twice the distance available in the baseline B products. Some comparisons are also made between results derived from the baseline C L1b files and those provided in the L2 products.

In this study we use CryoSat and surface height data from two well-studied sites in the Canadian Arctic and Greenland to improve the calibration of the SARIn mode. Further, we show that the waveforms do change significantly with surface melt and that it is possible to detect the formation of supraglacial lakes. By using a modified swath processing scheme, we also show that it is possible to measure lake height and height change.

2 Methods

Our processing methods ~~were described~~ in ~~working with the L1b files, were described in~~ Gray et al. (2013) and Gray et al. (2015). The current Matlab processing provides both POCA and swath mode results, and here we note any changes since the earlier work. The method to generate POCA heights are comparable to those described in Helm et al. (2014), Nilsson et al. (2016) and Smith et al (2016), and were motivated by similar concerns, particularly the performance of the L2 'retracker': this is the algorithm designed to find the position of the POCA return in each waveform.

The Delay-Doppler processing (Raney, 1998) for the SARIn mode of CryoSat is described in Wingham et al. (2006) and Kleinherenbrink et al. (2014). In this method 64 pulses are used in each transmitted burst and fast Fourier transform processing is used to create 64 unfocussed beams so that, with appropriate superposition of results from a sequence of bursts, multiple 'looks' can be averaged for each ground footprint. In practice there are less than 64 looks contributing to each waveform in the L1b file, normally ~ 57. In the along-track direction the footprints are separated by ~ 280 – 300 m and the resolution is ~ 380 m (Bouzinac, 2015). In the cross-track direction the footprint size is dictated by the cross-track slopes and by any smoothing of the waveform in the processing. The~~It is important to note that the~~ position of the POCA footprint derived from each waveform will be in the plane including the satellite position, and the lines defined by the cross-track and nadir directions. The POCA area will be centred on the closest point in the intersection of this plane with the terrain surface so that when ascending and descending orbits cross the two POCA footprints will not be the same when there is a cross-track slope. Consequently, it is not appropriate to compare results from the interpolated orbital cross-over point. The L1b files contain two echo scaling parameters for each waveform which allow a calibration of the waveform power to watts, ~~and these have been used in this work to derive~~ the logarithmic (dB) values used in the results are then with respect to 1 watt.

2.1 Selecting the POCA position from the SARIn waveform

If the altimeter response from terrain was 'predictable' it would be beneficial to use the complete waveform in the estimation of the position in delay time of the surface, and this is the basis of the ESA L2 processing. However, our experience with the L1b SARIn waveforms over glacial ice shows that the shape and magnitude of the waveform can vary significantly, even in one area at one time (see examples in section 4). The average return power as a function of delay time from the first surface sample will vary with the illuminated surface area, the reflectivity of the surface and any near surface layering on the ice cap. The cross-track slope and fixed sampling in delay time (3.125 ns) defines the basic cross-track footprint size so that the waveform shape beyond the POCA depends primarily on the variation in topography in the cross-track direction. This is essentially independent of the position of the POCA, hence our decision to estimate the POCA position based on the first significant leading edge in the waveform. Our approach (Gray et al. 2015) uses the point of inflexion (maximum slope) on the first significant waveform increase, and is similar to that adopted by Nilsson et al. (2016) and Smith et al. (2016). Helm et al. (2014) used a threshold level of the first significant leading edge for their work in Greenland and Antarctica, following the work of Davis (1997) who advocated a threshold retracker to minimize the dependency on varying microwave penetration into, and backscattering from, various snow-firn-ice layers. The importance of the cross-track footprint size in dictating the shape of the waveform has been demonstrated by the success of the straightforward waveform simulation based primarily on topography shown in Gray et al. (2013).

Although the L1b waveforms already represent averaged values, some additional smoothing has been done on the complex waveform data. The low-pass filter uses a 3 dB width of ~ 4 samples and is designed to avoid introducing any bias in the waveform phase. Smoothing theAveraging of SARIn waveform data is performed only in the range direction with a relatively small impact on the cross-track footprint size (Gray et al. 2015), and none on the along-track resolution. The resulting reduction in phase noise improves the POCA footprint geocoding, as the phase provides the cross-track look angle. It is not appropriate to average any of the L1b waveform data in the azimuth direction because there can be jumps in the delay time to the first waveform sample. Geocoding SARIn data depends on the L1b waveform phase to provide the cross-track look angle. The processing steps to generate geocoded heights are described in Gray et al. (2015) using the results of the calibration described in section 3 below. Solutions are derived for the phase at the estimated POCA position in the waveform, and for this phase +2π and -2π. Comparison with the height of the reference DEM is used to select the most likely of the three solutions. Some waveforms are not used for POCA generation. This can occur for various reasons; the coherence at the POCA point is less than 0.7; the power for the average of the first 5 waveform values is too high (> -150 dB, for baseline C); the ratio of the maximum waveform power to the average of the first 5 values is too low (< 6 dB), or there is not a clear leading edge in the waveform. These criteria are rather arbitrary and may be changed for different sites, depending on the results. For example, we found that using a more stringent POCA coherence requirement improved the overall results for the west Greenland site.

2.2 Swath mode processing

The techniques used to process the returns delayed beyond the POCA position are essentially as described in Gray et al. (2013). In that work the bias errors associated with the uncertainty in the baseline roll angle (Galin et al.,. 2013) were reduced by comparing the derived E–W slope on the western flank of Devon Ice Cap with the reference data slope, and changing the baseline roll angle to minimize this error. This step has not been undertaken here as it presumes a good quality reference DEM which is not necessarily available.

Waveform smoothing can lead to a situation in which results may be oversampled in the cross-track direction. The swath processed results from any one waveform will form a straight line in the cross-track direction and the final samples in cross-track are generated by binning and averaging the results in segments of the cross-track line. The separation between ground-range cross-track samples is nominally ~100 m. Criteria for minimum values of the filtered coherence and returned power are set, and are usually ~0.84 and -150 dB, respectively, for baseline C data. The phase unwrapping and ambiguity checking method is similar to that described by Smith et al. (2016).

The swath processing of the summer CryoSat data for supraglacial lake height (section 4.2) omitted the cross-track binning stage and produced an elevation for each sample in the waveform. Only heights derived from waveform samples with phase values equivalent to small look angles (< ~ 0.2°), high power (> ~ -140 dB), and high coherence (> 0.95) were used. These minimum values virtually guarantee that there will be a small contribution from the range ambiguous zone, and that phase unwrapping or ambiguity checking is unnecessary. The resulting geographic positions were compared to the best available visible imagery, usually Landsat 8 images, and north, south, east and west boundaries around the lake feature were set. The resulting height estimate was then obtained by averaging all estimates within the lake boundary.

2.3 Measuring the height difference between the reference surface and CryoSat heights.

We used two methods to compare the derived CryoSat heights with the surface reference data. For Devon Ice Cap the reference data included inter-calibrated snowmobile~~skidoo~~-based differential GPS transects, and airborne scanning laser altimeter data from both the NASA Airborne Terrain Mapper (ATM; Krabill et al., 2002, Krabill, 2014) and the TUD ALS (https://earth.esa.int/documents/10174/134665/ESA-CryoVEx-ASIRAS-2014-report) systems. For the Greenland site, we have relied on the ATM data collected on NASA IceBridge flights. The first method stepped through all the CryoSat results and searched for reference heights within 400 m of the centre of the CryoSat footprint. The height differences between the CryoSat and reference heights were corrected for the slope between the centres of the two footprints using interpolation with the reference DEM. If there were many reference values, as can be the case for the west Greenland site, then a second simpler method was used: a search was made for reference points within 50 m and the height differences were tabulated and averaged without the slope correction stage. Virtually all the reference height data for both sites were obtained under cold conditions in April or early May and we assumed that any accumulation or change in the backscatter conditions between January and mid-May would lead to a relatively small change in the CryoSat height. This provided the rationale for comparing all the CryoSat results from the January to May passes with the April or May reference height data.

2.4 Estimating height errors in the CryoSat data

Ku band radar waves can penetrate the surface and the CryoSat-to-surface height bias will vary depending on the conditions of the surface and near surface (Gray et al., 2015; Nilsson et al., 2015). Consequently, we use the standard deviation of the height differences about the mean height difference as the primary measure of the quality of the CryoSat measurements. The relatively small error in the ATM or ALS laser surface heights (~ 20 cm, Krabill et al., 2002) is ignored, and any impact due to the difference in the footprint size is not considered.

When estimating the height errors for the supraglacial lakes it is not appropriate to quote the standard error (standard deviation divided by the square root of the number of samples averaged), because the samples will not be independent and there is the possibility of small bias error in the result. The errors were therefore estimated on a case-by-case basis by looking at any cross-track slope across a lake feature, using the standard deviation itself, and checking independent estimates from ascending and descending passes over the same feature. The standard deviation about the mean was typically ~0.5 m, and the mean difference between the ascending and descending passes over the same accumulation zone lake feature in August was ~ 0.25 m. Table 1 includes the error estimates from two lakes and shows that relatively good precision~~accuracy~~ can be achieved for these strong targets, better than the potential error for individual POCA estimates.

3 Results: SARIn mode calibration

The key parameters for SARIn mode geocoding are the range to the surface, and the satellite look angle between the normal to the WGS84 ellipsoid and the footprint centre in the cross-track plane. The former involves consideration of timing and the retracker algorithm for the POCA results, but it is the latter which requires careful calibration for both POCA and swath mode results.

The satellite look angle, α, is related to two other angles through:

$$\alpha = \beta - \delta \qquad (1)$$

Where β is the interferometric angle defined below, and δ is the roll angle of the interferometric baseline, all defined in the cross-track plane containing the line normal to the WGS84 ellipsoid. The angle β is related to the interferometric phase through (Galin et al., 2012):~~:~~

$$\beta = -\mathrm{asin}(\chi \sout{ph}/kB) \qquad (2)$$

Where χ~~ph~~ is the phase provided in the L1b file, k is the wavenumber, ~~and~~ B is the length of the interferometric baseline, and the Cryosat altimeter transmits through the left antenna and receives from both.~~.~~ The sense of the look and interferometric angle is as follows: For zero roll an observer siting on the CryoSat satellite facing in the direction of motion with their feet pointing towards the Earth will 'see' a footprint to the right of the sub-satellite track when the look angle α is positive. The roll angle δ is also provided in L1b files. For the same observer configuration, a positive roll angle corresponds to the left antenna being higher than the right hand one.

Any bias in the look angle, $\Delta\alpha$, can then be related to biases in the baseline; ΔB, phase; $\Delta\chi$~~ph~~, and roll angle; $\Delta\delta$, through:

$$(\alpha + \Delta\alpha) = -asin\left(\frac{(\chi + \Delta\chi)}{k(B + \Delta B)}\right)\sout{\left(\frac{(ph + \Delta ph)}{k(B + \Delta B)}\right)} - (\delta + \Delta\delta) \qquad (3)$$

Using the approximations that $\sin(x) = x$ for small x and $B \gg \Delta B$, leads to an expression for the bias in roll angle as:

$$\Delta\alpha = -\frac{\Delta\chi}{kB} + \frac{\chi}{kB} \sout{= \frac{\Delta ph}{kB} - \frac{ph}{kB}} \left(\frac{\Delta B}{B}\right) - \Delta\delta \qquad (4)$$

The CryoSat satellite and processing chain contains careful controls which should minimize any extraneous inter-channel phase shift $\Delta\chi$~~ph~~ on the satellite (Bouzinac, 2015). Even if a residual phase bias exists, due perhaps to an uncompensated path length difference between the two receivers, it can be expressed in the same form as the roll~~-~~angle correction $\Delta\delta$ and the two can be considered together. The second term in equation (4) reflects the possibility of a bias between the actual and pre-launch measurement of the interferometric baseline; the distance between the two antenna phase centres. This was part of the post-launch SARIn mode calibration carried out by Galin et. al. (2013). This work used results from satellite roll manoeuvres over mid~~-~~latitude ocean tracks to show~~present evidence~~ that the interferometric angle should be scaled by a factor of 0.973 ± 0.002, which is equivalent to scaling the baseline by a factor of 1.0277. The third term in Eq. (4), the uncertainty in the baseline roll angle $\Delta\delta$, is ~~potentially the most~~ important because~~, as documented by Galin et. al. (2012),~~ the baseline roll angle is derived from one of three star trackers mounted on a support bench on the satellite. Galin et al., (2013) identified a problem with the reported roll angle and suggested that this was due bending of the support bench under a changing thermal environment. However, recent work by ESA (Scagliola et al., 2017) showed that the roll-angle problem arose, at least partly, because of an error in processing the star-tracker data. ~~which apparently bends.~~ Consequently, there is currently an unknown bias in the reported value of the baseline roll angle which can vary pass-to-pass. In the following sections,~~, presumably as the satellite experiences a varying history of solar illumination. Here~~ we use SARIn data over well-documented glacial ice to investigate any residual bias in the roll angle provided in the L1b files, and to study the influence of changing the baseline length in processing L1b files.

3.1 Calibration test sites

We used~~use~~ data from two sites, the western flank of Devon Ice Cap (Fig 1), and an area in western Greenland including the Jakobshavn Glacier (Fig. 2), as both have excellent reference surface height data. Our calibration approach depends on the presence of a predominantly east-west slope which is why the test area in Fig. 1 is limited in the north-south direction. By using terrain with an east-west slope we obviate the necessity for roll-tilting the satellite. Figure 3 illustrates the difference in ~~the nature of~~ the slopes for the two test sites. The significant increase in slope variation in the west Greenland site represents a more challenging situation for satellite radar altimetry than the more modest slope variation on the western flank of Devon Ice Cap, and this is the reason~~why~~ we have concentrated on comparing the results from these two test sites.

3.2 Calibration based on data from Devon Ice Cap

The western portion of Devon Ice Cap has suitable cross-track slopes ~~(average slope ~0.7° - 1.5° over a distance of >2 km)~~ for swath mode height estimation for both ascending and descending passes, and this area was used in the demonstration of swath mode processing (Gray et al. 2013). While the possible range of average cross-track slopes can be ~0.5° to ~2°, here we have restricted the use of results to E-W slopes of ~0.7° - 1.5° over a distance of >5 km as this range generally provides a better suppression of the ambiguous range contribution. Figure 1 shows the positions of the spring 2011 surface height reference data obtained from NASA and ESA supported overflights, and from surface snowmobile~~skidoo~~ dGPS transects, all superimposed on a colour representation of the reference DEM. The sub-satellite tracks of 15 CryoSat passes are also shown. Results from all the passes in this time period were compared to the reference surface heights as conditions on Devon Ice

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Cap change little between January and May, and we assume that any change in surface height or change in the bias between the surface and CryoSat height wasis small with respect to the error in the CryoSat heights.

The histogram of the difference between the reference and CryoSat swath mode heights obtained with the pre-launch baseline estimate (1.1676 m, Bouzinac, 2012) showed a bimodal distribution (Fig. 5C) and the average bias changed between ascending and descending passes, ~-0.5 and ~2.5 m respectively.. As we could find no reasonable geophysical explanation for this difference, the possibility of a roll--angle bias was investigated. If there wasis a roll--angle bias on an ascending pass the swath-processed height estimates wouldwill be displaced either up- or down-slope depending on the sense of the bias. However, with a descending pass and the same roll--angle bias, the results will be displaced in the opposite direction and the height bias will have the opposite sign from that obtained with the ascending pass. To investigate this effect further, all the data in this time period werewas reprocessed with an additional roll--angle bias added to the value provided in the L1b file. Figure 4 illustrates the results of an experiment in which the 15 2011 passes (7 ascending and 8 descending) wereare each reprocessed 9 times with an additional roll correction varying from -0.02° to +0.02°. The results wereare then compared to the reference height data collected in early May 2011. As expected, the sense of the height difference changes between ascending and descending passes but the curves do not overlap well. While the results from the 8 2011 descending passes do cluster nicely this wasis not the case for the 2012 data (Gray et al. 2016), and neither year shows consistent results for the ascending pass results. The satellite was in Earth shadow for the first 7 2011 descending passes over the test site and the sun elevation angle for the 8th pass on May 21 was only 4.7°, as it had just come out of earth shadow. However, the sun elevation angle history at the satellite for the 2011 ascending passes and all the passes in 2012 was more variable, implying that plate bending due to solar heating is implicated in the roll angle problem.

Consequently, it appears that the roll angle provided in the L1b file has a time variable bias, apparentlypresumably due to a problem in processingvariable bending of the bench supporting the star-tracker data (Scagliola et al., 2017). trackers as the thermal environment changes. The uncertainty in the roll angle in this example appears to be of order 0.006° or ~ 100 μradians, not inconsistent with the observations in Galin (2013). While there will be a contribution from the range ambiguous zone in swath mode processing, which could introduce a small bias, this does not appear to be the primary source of these differences. The roll--angle uncertainty, and resulting unknown bias in the baseline roll angle, appears to be a limitation to the use of swath mode heights. Note that in Fig. 4 there is essentially no slope to the plots of the height difference versus roll--angle bias for the POCA height estimates. This is direct consequence of the fact that while the POCA estimates are mapped incorrectly when there is a roll--angle error, the derived height can still be appropriate for the wrong position because the incident wave may still be essentially perpendicular to the surface (Gray et al., 2013).

The variable E-W cross-track slope also provides a suitable test area to check the phase to cross-track angle conversion dictated by the baseline (Eq. 2 above). Figure 5 illustrates the results of an experiment in which the results obtained with a phase-to-angle conversion based on the pre-launch baseline are compared to the calibration given by Galin et al. (2013). The two histograms on the left used the pre-launch baseline while the histograms on the right used the angle scaling from Galin et al. (2013). Figure 5C shows the bimodal distribution referred to earlier, and Fig. 5A shows the improved results with a significantly narrower error distribution when a bias of 0.0075° is subtracted from the roll angle provided in the L1b file. The uncertainty in this additional roll bias has been estimated as ±0.0025°. When the phase-to-angle is scaled by 0.973 (Fig. 5B and 5D) the results show a broader distribution and poorer results.

3.3 Calibration based on data from west Greenland

We use IceBridge data from an area in central western Greenland (Fig. 2, insert) including the Jakobshavn Glacier, an area which has shown significant surface height loss in recent years due to both change in output flux and surface mass balance (Joughin et al., 2008, Qi and Braun, 2013), and has excellent reference surface height data (Krabill et al. 2002, Krabill 2014).

Figure 2 illustrates the positions of the reference surface height data obtained from the four NASA IceBridge flights flown on Mar. 31, and Apr. 6, 7, and 23, 2011 superimposed on a black and white representation of the GIMP DEM (Howat et al. 2014). This DEM was used as the reference DEM for all the CryoSat processing in this area. Data from the ATM L2 files have been used for this work and compared with height results from all the CryoSat passes between 16 Feb.~~mid-January~~ and 23 April~~mid-May~~.

It is important to recognize the differences in this test site in relation to that on Devon Ice Cap. The two profiles in Fig. 3 show that even in the accumulation area of this part of west Greenland the slope variation is much larger than on the EW profile interpolated from the airborne laser altimeter flown over of Devon Ice Cap. The difference is also very apparent in the CryoSat results: Figure 6 compares two image representations of the waveform power for 22 km segments of the Feb. 7 2011 ascending pass over Devon Ice Cap and the April 21 2011 descending pass over the west Greenland test site. For the ascending pass over Devon Ice Cap the POCA position will be on the left close to the beginning of the 240 m range window, as indicated by the stronger return signals in red. However, for the west Greenland site the peak return is often in the middle of the waveform. The difference in the signals may be influenced by the different conditions but it is clear that the dominant reason for the differences in waveforms is due to differences in the cross-track slopes. The larger slope variation in west Greenland clearly influence the CryoSat returns, and the waveform shape is now much more variable than those from the Devon test site. This situation favours a~~will adversely impact any~~ retracker which looks for the first significant leading edge, rather than one that assumes a particular model for the waveform and then fits the waveform to that model, as is the case for the ESA L2 SARIn product. Some details of the retrackers used in the baseline C L2 products are given in Buffard (2015).~~uses all the waveform.~~

Figure 7 compares the results obtained with our geocoding and that obtained with CryoSat L2 retracker. Our processor picks out the POCA position satisfactorily (black dots on Fig. 7A) and leads to the mapping solution shown in Fig. 7B. The positions of the CryoSat L2 solutions are shown in Fig. 7B as purple~~red~~ dots, and are often different by many kilometres. The solutions are close~~agree~~ only when the waveforms show a clear maximum close to start of the waveform (e.g. at ~ 70.05

N). Using the position of the L2 solution, the off-nadir look angle and equivalent phase can be calculated. Then the position in the waveform with that phase is identified and marked as purple dots in Fig. 7A. This shows that the L2 retracker normally does not identify the point-of-closest-approach correctly, primarily because of the strong peaks in middle of the waveform.

In comparing our CryoSat POCA height results with the ATM surface height results we found that the results here were not as precise as those obtained over the Devon test site. However, when slightly more stringent editing was used, in particular by increasing the minimum POCA coherence requirement to 0.8 from 0.7, then the results were improved. The histograms of the ATM minus CryoSat heights for ~~all~~ the 2011 spring data are shown in Fig. 8. Again the poor results from the baseline C CryoSat L2 files are apparent (Fig 8A), particularly the much larger number of height errors greater than 20 m. Results from exactly the same waveforms have been used in this comparison, as the L2 results were removed for those waveforms already removed through the L1b editing. While it is unfair to compare results from an operational algorithm which must work everywhere to one which can be tuned for different areas and includes editing based on the coherence and the return power, it is fair to say that the current L2 retracker is ~~west Greenland site appears to be~~ inherently unsuitable for the west Greenland site.~~a retracker which uses the whole waveform.~~ The L2 results are better in other areas, such as the ridges on Austfonna, ice rises and ice shelves in Antarctica, and parts of the Devon Ice Cap. In these areas~~, where~~ the waveforms show~~waveform shows~~ a more consistent shape and the dominant return is close to the start of the waveform.

The comparison between results obtained with the angle scaling factor from the Galin et al. (2013) calibration (Fig. 9A and C),~~)~~ and without (Fig. 9B and D),~~)~~ mirrors the results discussed in the previous section for Devon Ice Cap. The results imply that the pre-launch baseline coupled with an additional roll-angle offset (or equivalent phase shift) improves the results for both west Greenland and Devon Ice Cap.

There is an important difference in the results for this test site in relation to Devon. For Devon, the ATM - POCA height difference was essentially independent of the roll-angle offset between -0.02° and 0.02° (Fig. 4), but this was not the case for the west Greenland site. A comparison of the average ATM - POCA height difference over 16 passes as a function of the additional roll-angle bias (Fig. 10A~~10, top~~) shows that the CryoSat POCA height is not independent of the roll-angle bias but increases for both positive and negative ~~roll angle~~ bias errors from a value of ~0.0075° ±0.0025°.~~.~~ As the CryoSat results are mapped incorrectly in the cross-track direction, the larger cross-track slopes imply that the distance in the cross-track direction which is essentially orthogonal to the incident wave is smaller in west Greenland than for the relatively smooth surface of western Devon Ice Cap. Consequently, this will lead to a CryoSat POCA height error as the mapping process takes the centre of the footprint outside the region which is orthogonal to the incident wave. Figure 10B~~10 (lower)~~ shows the variation in the standard deviation of the swath mode ATM - CryoSat heights for each pass (dotted lines), and the average over all 16 passes (black line). The offset in the position of the minimum from zero roll-angle bias also supports the contention that on average there is a difference between the actual baseline roll angle and the value reported in the L1b file based on one of the 3 star trackers, or that there is an equivalent phase shift. For batch processing, we have used the L1b roll angle minus~~with an additional roll angle bias of~~ 0.0075°, but this may change with more experience with the bias~~ and its variation with the time history of solar illumination on the satellite~~.

There is another discrepancy in these results that warrants explanation. From Fig. 9A~~9~~ we see that the average ATM - POCA height difference is -0.16 m~~, (Fig. 9A),~~ but with the same waveform data the height difference from swath mode processing is +0.91 m (Fig. 9C), so that the two processing methods are giving average heights different by 1.07 m. With the Galin et al. (2013) calibration the discrepancy is even worse; 2.52 m. Further, there is an apparent discrepancy with the results from Devon Ice Cap where previously (Gray et al. 2015), and now, we see the CryoSat height as being somewhat below the physical surface. The explanation for the anomalous average ATM – POCA result for west Greenland, where the average CryoSat POCA height is slightly above the surface, appears to be related to the results in Fig. 10A. If there is an error in the roll ~~-~~angle this will lead to an increase in detected height irrespective of the sign of the roll ~~-~~angle error. This will lead to an asymmetric distribution and the mean height will be biased high. Note that the distribution in Fig. 9A is somewhat asymmetric, more so than that in Fig 9C for the swath processed data where the sign of any roll ~~-~~angle error would dictate the sign of the height error. For areas like the west Greenland test site this implies that the roll ~~-~~angle bias error will tend to bias the average POCA height high with respect to the surface.

4 Unique capabilities of the SARIn mode.

In this section we use our methodology and revised calibration to demonstrate some unique capabilities of the SARIn mode, first by illustrating signature change with surface conditions in West Greenland, and secondly by showing that it is possible to detect supraglacial lakes in the waveform data and estimate the surface height and height change with relatively good precision~~accuracy~~.

4.1 The effect of surface melt on SARIn waveforms

The influence of melt on SARIn signatures should be considered when presenting temporal height change for any region which may have undergone surface melt (Nilsson et al., 2015, Gray et al., 2015). Figure 11 illustrates one example of the influence of melt on the strength of the SARIn waveform data. The position of this July 14 2011 descending pass is shown in Fig. 12A and begins at ~ 2200 m elevation, crosses the Jakobshavn Glacier at ~ 1000 m, then the elevation increases slightly before ending at ~ 1100 m. At high elevations, the returns are comparable to those obtained under cold winter-spring conditions, but at lower elevations, ~ 1700 - 1900 m, there is a decrease of ~15 - 20 dB in average waveform power. It is well known~~We speculate~~ that the introduction of even a small amount of liquid water in snow dramatically alters the emissivity and backscatter (Ulaby et al., 1986). For example, a significant drop in QuikSCAT 13.3 GHz backscatter was shown~~this is due~~ to be linked to melting from weather station data (Nghiem et al., 2001). The presence of water droplets in snow increases absorption, reduces the penetration depth, which in turn leads to an increase in brightness temperature and decrease in radar backscatter (Wang et al., 2016). Consequently, we associate the relatively low reflectivity at these elevations to ~~and high absorption of~~ a damp snow layer~~, in which the moisture is distributed as small droplets.~~ At lower elevations (< 1600 m) not only is the average return larger but also the waveform-to-waveform variability is much higher, indicative of occasional specular reflection from a wet surface facing the radar. ~~Again, we speculate that at this stage the moisture has increased and coalesced to the point that there is occasional coherent reinforcement of the return signal from a wet and therefore reflective surface.~~ Also, the strongest returns in most of the waveforms in this area are not from the leading edge but vary in position across the waveform so that a retracker that uses all of the waveform won't accurately measure the position and height of the POCA.

Figure 12 illustrates the average waveform power plotted against elevation for 5 descending passes (Fig. 12A) acquired during the summer of 2011. At elevations up to ~ 1300 m the June 18 pass (Fig. 12D) shows the high waveform-to-waveform variability that we suggest~~speculate~~ is due to occasional specular reflection, but this was not observed in the earlier passes in April (Fig. 12B) and May (Fig. 12C). By July 14 (Fig. 12 E) the region with strong and variable power includes elevations up to ~1600 m and the August pass (Fig. 12F) shows some strong waveform returns at even higher elevations. Comparable results were obtained from the five repeat passes 369 days later in 2012, but the descending pass on July 20 2013 showed the wet snow signature at lower elevations (~ 1500 m) without any indication of occasional specular reflections. This is consistent with the relatively colder conditions at that time in 2013 with respect to both 2011 and 2012 (see e.g. Fettweis 2016, http://climato.be/melt-2016). The supporting material includes figures equivalent to Fig. 12 for all the years from 2012 to 2016.

4.2 Supraglacial Lakes

During summer melt around the periphery of the Greenland Ice Sheet water pools in surface depressions as supraglacial lakes (Echelmeyer et al., 1991), forming first at lower elevations and then to higher elevations as melt progresses. With increasing positive air temperatures, surface melt water will infiltrate to lower elevations so that the snow at the edges of the depression will tend to become saturated and melt before the snow in the centre of the depression. In many cases, small supraglacial streams form which will add energy to melt snow or ice where they enter the surface depression.

Optical satellite imagery and DEM data have~~has~~ been used to study the distribution, extent, depth and drainage of these features when there is an open water surface (Box and Ski, 2007, McMillan et al. 2007, Sneed and Hamilton 2007, Liang et al., 2012, Fitzpatrick et al. 2014, Leeson, et al., 2015, Pope et al., 2016, Ignéczi et al., 2016). While Landsat and MODIS imagery have been used to estimate total lake volume of relatively large areas (e.g. Pope et al., 2016), the limitations due to clouds and atmospheric conditions hamper routine use for quantitative melt estimates. Here we demonstrate that CryoSat SARIn data can provide complementary information to that available from visible satellites by showing that measurements of surface height and height change can be derived from SARIn data over individual supraglacial lakes. SARIn data can be obtained reliably day or night and in all weather conditions, but is very limited in surface coverage.

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If CryoSat passes directly over a typical unfrozen supraglacial lake one would expect a strong specular reflection which would not be at the leading edge of the waveform, as it must be surrounded by ice at higher elevations. Even if the lake has some snow cover or a partially unfrozen surface, the flat surface will still enhance the return and could lead to a strong peak in the waveform. Figure 13 illustrates some strong signals in the middle of the waveforms of a 50 km section of the 7 August 2011 ascending pass over the test area in west Greenland. These may originate from extended surfaces orthogonal, or nearly orthogonal, to the incident wave. We have selected one such strong signal, labelled as 'L1' in Fig. 13, which is detected in results from ascending and descending passes from all the summers from 2010 to 2016. The supplementary material contains a sequence of 14 summer MODIS images from 2012 to 2016 which show that the L1 and L2 features are above the snow line for all 5 years and that the surface of these depressions did not become totally ice free. Figure 14 shows the positions of the sub-satellite tracks superimposed on a summer 2016 Landsat 8 image, and that there were dark regions, presumably wet snow, at the positions of the topographic lows marked as L1 and L2. The relative strength of the CryoSat return signals for the seven~~six~~ ascending passes for both features are shown in Fig. 15 and the year-to-year derived height in Fig. 16 with details provided in Table 1. The sequence of dates for the repeat ascending passes are Aug. 4, 2010; Aug. 7, 2011; Aug. 9, 2012; Aug. 12, 2013; Aug 16, 2014; Aug. 19, 2015, and Aug. 21, 2016 reflecting the 369.25-day repeat orbit cycle. The repeat descending passes are 5.5 days after the ascending passes~~later~~.

Our interpretation of the strengths of the lake signatures and the surface elevation is as follows: Considering the low surface velocity (~ 3.5 m/year, Joughin et al., 2012, 2016),~~)~~ and elevation (~1600 m) at this position, it is unlikely that either of these depressions drained in the manner of the lakes in the ablation zone in any of the summers. The increase in height from the summer 2010 to 2012 (Fig. 16) may~~appears to~~ reflect the ~~increase in~~ melt at these positions, which was~~this position,~~ particularly strong in 2012 (see e.g. Fettweis, http://climato.be/melt-2016). However, the decrease in elevation in subsequent years is then a problem. The discovery that water can persist for years in firn aquifers (Koenig et al., 2014, Forster et al., 2014), suggests that the decrease in elevation after 2012 may reflect a slow percolation of the meltwater into the firn. Clearly, the~~The~~ specific causes of the ~~subsequent~~ decrease in elevation of L1 and L2 after 2012, and the difference between the L1 and L2 height change, are not known.

The Landsat 8 image from July 6 2016 (Fig. 17) includes one 2.4 x 1 km lake at 70.37 N, 49.79 W, and ~1020 m in elevation, which was detected in the CryoSat waveforms from all the ascending and descending repeat passes listed on Fig. 17 between 2011 and 2016. By the time of the Landsat 8 image in 2016 most of the snow had melted and we surmise that melt had been on-going during June and early July for the years 2011 – 2016 at this position, and at the times of the CryoSat over-passes (Fig. 17 and Table 2). Figure 18 illustrates the lake height for all passes except for the 2013 descending pass which was too far to the west of the lake for reliable results. In contrast to the high elevation, low melt 'lake' described above, now there is a clear height increase in the 5.5 days between the ascending and descending passes over the lake. This allows an estimate of the filling rate at the time of the two passes. If we assume a lake area of 2 ± 0.5 km^2 this implies a filling rate of ~ ~~(~~~0.2. 10^6 – 2.10^6 m^3 melt water added per day.~~).~~ This lake does drain sometime after the start of July, see the

MODIS sequence in the supplementary material, but appears not to have drained at the times of any of the CryoSat overpasses.

5 Discussion

In this section we discuss the two SARIn processing approaches and~~,~~ the limitations and successes of the current CryoSat SARIn products for glacial ice. ~~, and then speculate on some of the characteristics of a future interferometric radar altimeter for monitoring ice cap change.~~

There are two important advantages with swath processing: firstly, there is no need for a retracker and, secondly, the swath data is obtained predominantly from the region directly beneath the satellite and the look angles for the swath footprints can be less than those for the POCA (for those areas with cross-track slopes appropriate for swath processing). With the small look angles, the footprint illumination cross-track is essentially uniform. Consequently, assuming a small contribution from the range ambiguous area, the phase should represent the geometric centre of the footprint so that the range, satellite state vectors, and the various angles should lead to reliable heights. Unfortunately, the roll-~~-~~angle problem discussed earlier compromises the swath mode results as the resulting cross-track mis-mapping will normally lead to a height error (Gray et al., 2013).

POCA processing requires a retracker and the look angle can extend into the range in which the illumination cross-track is affected by the antenna pattern variation so that the phase may not reflect the geometric centre of the footprint. Rather it may~~would~~ be displaced towards the sub-satellite track. With interferometric swath processing, precise knowledge of the baseline and baseline angles is important (Rosen et al. 2000), and with the CryoSat roll-~~-~~angle problem individual POCA heights are normally more precise~~better suited to temporal height change estimation~~ than swath mode heights. For height change estimates, however, both POCA and~~Consequently, while the average~~ swath mode results can be combined as long as any bias is accounted for. Foresta et al. (2016) used primarily swath mode results in a study of elevation change of Icelandic ice caps, showing the improved ~~to the~~ surface coverage of swath mode, and that height change information could be derived from these results. Also, Smith et al. (2016) combined swath and POCA data to document surface~~may be more realistic than the POCA results under some conditions,~~ height change ~~results are normally better based~~ on the Thwaites Glacier. But in this case 'meter scale biases', correlated over tens of kilometres but independent orbit-to-orbit, were partially corrected by combining with the POCA ~~CryoSat POCA~~ data.

The known problem ~~of bending~~ in processing the star-tracker data (Scagliola et al., 2017),~~support plate~~ and the resulting varying error in the reported value of the baseline roll angle, can ~~does~~ have an impact on the precision~~accuracy~~ of the CryoSat height results. Any roll-~~-~~angle error translates directly into a cross-track mapping error so that the resulting height error then depends on the angle between the incident wave and the tangent to the cross-track surface. If this angle is 90° and the surface slope changes slowly over a few hundred meters, then the error is ~~very~~ small as the geocoding algorithm

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produces the correct elevation for the mis-mapped footprint. Although we show that the roll ~~-~~angle problem had essentially no impact on the Devon POCA results, it did have an impact on the POCA results from the west Greenland test site. In this case the cross-track slopes varied more rapidly than for Devon and lead to the situation where an incorrect roll angle could lead to an increase in the CryoSat height with respect to the surface irrespective of the sense of the roll ~~-~~angle error. This we suggest is the origin of the unrealistic result that the average POCA height was~~can be~~ slightly above the physical surface for the west Greenland site.

POCA heights originate from ridges and peaks and, when the cross-track slope is appropriate for swath processing, the swath mode results will normally originate from the area beneath the satellite so the two approaches are complementary in surface coverage. As discussed above, there can be a bias between POCA and swath heights which needs to be considered if the results are merged. The potential height error for individual estimates is normally less for POCA data than for swath mode heights but the exception is the precision~~accuracy~~ with which one can estimate the height of relatively large supraglacial lakes when the lake is beneath the satellite and viewed at close to normal incidence. In this case, we have a very strong signal in the middle of the waveform, any range ambiguous contribution should be small, and no retracker is required for the geocoding solution. Further, with this viewing geometry the problem of an incorrect roll angle leads to a small error in the lake surface height and a precision~~accuracies~~ of ~ 0.5 m is~~are~~ possible for the surface height of a large lake. Work is underway to better evaluate the extent to which CryoSat data can help in quantifying the time and extent of melt around Greenland.

The ability to geocode the relatively small footprint possible with the SARIn mode over glacial ice creates a huge advantage for this mode over the traditional low resolution radar altimetry. Future radar altimeters employing coherent along-track processing, either fully focussed or Delay-Doppler, coupled with cross-track interferometry, could play a very important role in monitoring change on many ice caps and glaciers.~~ However, a sun synchronous orbit, preferably dawn-dusk to minimize the impact of changing solar illumination on the interferometric baseline, could improve the results. As users are primarily concerned with change year-to-year a 73 or 365-day repeat cycle would also be ideal, if possible.~~

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6 Conclusions

Here we list the specific conclusions arising from our analysis of the SARIn data over Devon Ice Cap and west Greenland.

1. A more consistent fit can be obtained between CryoSat and surface heights using the prelaunch baseline coupled with an additional roll ~~-~~angle bias of ~ 0.0075°. Although the additional bias may originate with the angle measurement, it could equally well be an equivalent, additional phase correction of ~0.0435 radians to the value of 0.612 radians currently used in the baseline C product (Bouzinac, 2012).

2. A retracker which uses the first significant leading edge of the waveform normally leads to more reliable elevations than a retracker that uses the whole waveform, this appears to be particularly true for areas like West Greenland in which the shape of the waveform is very variable and the peak signal is often in the middle of the waveform.
3. Swath mode results complement the POCA results but are normally less precise~~accurate~~. The exception is the precision~~accuracy~~ with which the heights of supraglacial lakes can be obtained when the satellite flies almost directly over the lake.
4. The uncertainty in the CryoSat baseline roll angle affects primarily swath mode results but can also impact the precision~~accuracy~~ of POCA results when the surface topography is comparable to that in the west Greenland test site.
5. While more work is required to establish to what extent CryoSat SARIn waveforms and heights can improve our knowledge of melt in the ablation zone of the Greenland Ice Sheet, these initial results are encouraging that CryoSat SARIn data can help provide useful information on the variation of year-to-year melt.

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Year L1	Date	Pass direction	Local time	~~Sun elevation angle (deg.)~~	Min dB	Standard deviation, m (no. of samples)	Look angle (deg.)	Height (m)	Height error (estimated, ± m)
2010	Aug 4	Ascending	1:03	~~0~~	-130	0.52 (61)	0.08±0.006°	1606.5	0.5
	Aug 9	Descending	13:33	~~36~~	-135	0.58 (61)	-0.18±0.006°	1606.3	0.6
2011	Aug 7	Ascending	6:48	~~14~~	-130	0.48 (51)	-0.05±0.006°	1609.1	0.5
	Aug 12	Descending	19:18	~~14~~	-134	0.41 (57)	-0.22±0.006°	1609.5	0.5
2012	Aug 9	Ascending	12:33	~~31~~	-125	0.63 (52)	-0.05±0.006°	1613.8	0.6
	Aug 15	Descending	1:03	~~-7~~	-127	0.29 (59)	-0.2±0.006°	1614.3	0.4
2013	Aug 12	Ascending	18:16	~~19~~	-135	0.59 (73)	-0.1±0.006°	1612.5	0.6
	Aug 18	Descending	6:46	~~9~~	-139	0.33 (48)	-0.2±0.006°	1612.8	0.4
2014	Aug 16	Ascending	0:01	~~-2~~	-138	0.56 (75)	0.05±0.006°	1610.8	0.6
	Aug 21	Descending	12:32	~~32~~	-130	0.46 (74)	-0.18±0.006°	1611.2	0.5
2015	Aug 19	Ascending	5:46	~~6~~	-138	0.64 (48)	-0.04±0.006°	1610.2	0.6
	Aug 24	Descending	18:16	~~16~~	-139	0.45 (34)	-0.15±0.006°	1610.3	0.5
2016	Aug. 21	Ascending	11:31	~~27~~	-140	0.49 (34)	-0.02±0.006°	1606.1	0.5
	Aug. 27	Descending	0:01	~~-14~~	-140	0.51 (18)	-0.17±0.006°	1606.7	0.6
L2									
2010	Aug 4	Ascending	1:03	~~0~~	-120	0.75 (41)	0.01±0.006°	1571.5	0.7
2011	Aug 7	Ascending	6:48	~~14~~	-134	0.42 (57)	-0.14±0.006°	1573.1	0.5
2012	Aug 9	Ascending	12:33	~~31~~	-130	0.35 (54)	-0.1±0.006°	1576.0	0.4
2013	Aug 12	Ascending	18:16	~~19~~	-135	0.32 (16)	-0.16±0.006°	1573.2	0.5
2014	Aug 15	Ascending	0:01	~~-2~~	-135	0.37 (30)	-0.03±0.006°	1572.1	0.4
2015	Aug 19	Ascending	5:46	~~6~~	-137	0.43 (32)	-0.13±0.006°	1572.5	0.5
2016	Aug. 21	Ascending	11:31	~~27~~	-133	0.47 (27)	-0.10±0.006°	1573.1	0.5

Table 1.
Information on the conditions and results of the analysis of the CryoSat data for the two lake features L1 (70.275 N, 48.56 W) and L2 (70.178 N, 48.55 W) shown in Figs 13 and 14. The 'Min dB' column reflects the lower limit of the sample power used in the averaging of the height estimates contained within the window around the surface depression.

Year	Date	Pass direction	Local time	~~Sun elevation angle (deg.)~~	Min dB	SD height (no of samples)	Look angle (deg.)	Height (m)	Height error (estimated ± m)
2011	June 14	ascending	9:33	~~31~~	-125	0.74 (38)	0.03±0.006°	1014.7	0.7
	June 20	descending	22:03	~~9~~	-130	0.59 (41)	-0.07±0.006°	1016.8	0.6
2012	June 16	ascending	15:18	~~37~~	-115	0.77 (56)	0.003±0.006°	1020.4	0.8
	June 22	descending	3:48	~~6~~	-120	0.80 (45)	-0.01±0.006°	1022.3	0.8
2013	June 19	ascending	21:02	~~15~~	-130	0.57 (48)	-0.02±0.006°	1017.1	0.6
	June 25	descending							
2014	June 23	ascending	2:46	~~8~~	-130	0.37 (23)	0.06±0.006°	1018.7	0.4
	June 28	descending	15:16	~~41~~	-135	0.53 (22)	0.03±0.006°	1020.2	0.5

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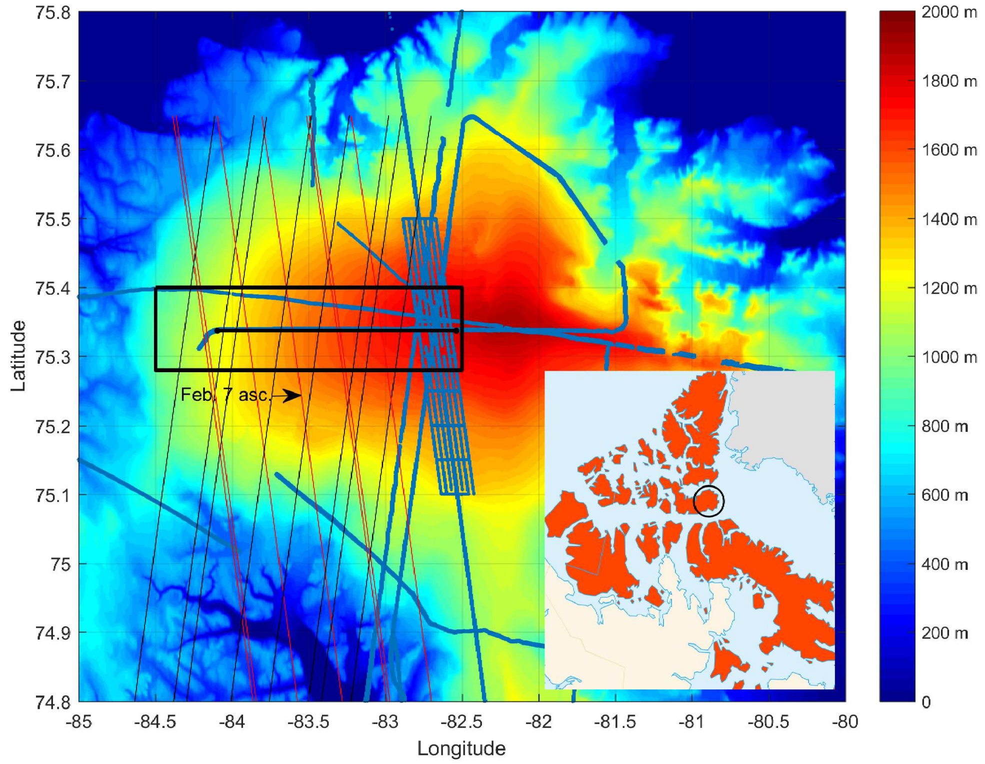
2015	June 26	ascending	8:31	~~27~~	-130	0.67 (39)	-0.001±0.006°	1017.6	0.7
	July 1	descending	21:01	~~13~~	-130	0.87 (29)	-0.07±0.006°	1020.1	0.9
2016	June 28	ascending	14:16	~~43~~	-130	0.74 (62)	0.03±0.006°	1021.4	0.7
	July 4	descending	2;46	~~1~~	-130	0.64 (29)	0.02±0.006°	1022.1	0.6

Table 2.
Information on the conditions and results of the analysis of the CryoSat data for the lake shown in Figs 17 and over-flown by CryoSat on the dates shown.



75.8
75.7
75.6
75.5
75.4
75.3
75.2
75.1
75
74.9
74.8
Latitude
-85
-84.5
-84
-83.5
-83
-82.5
-82
-81.5
-81
-80.5
-80
Longitude
Feb. 7 asc.
2000 m
1800 m
1600 m
1400 m
1200 m
1000 m
800 m
600 m
400 m
200 m
0

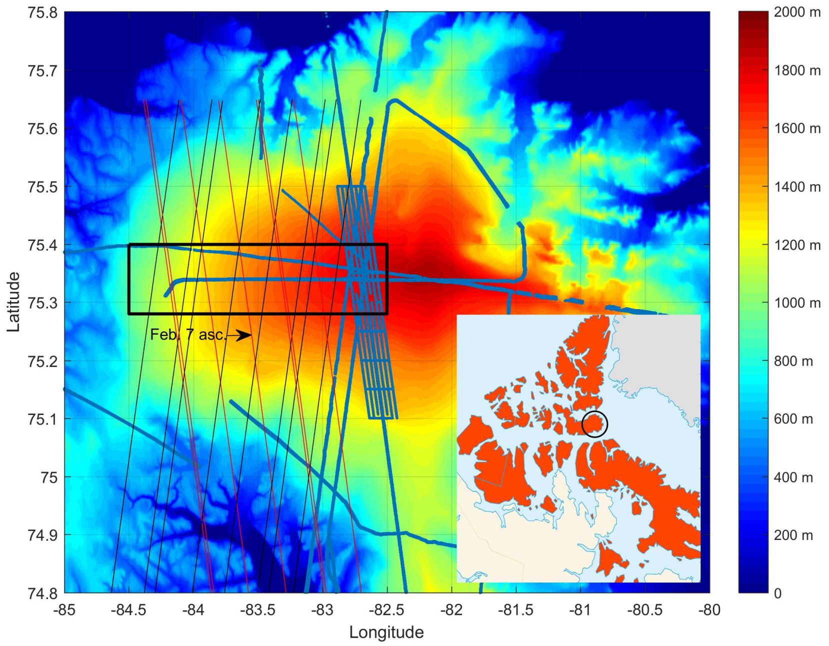


Figure 1: Location of the test area on the western slopes of the Devon Ice Cap (black rectangle). The sub-satellite positions of the spring 2011 ascending and descending passes crossing the test area are shown by the red and black lines respectively. The positions of the reference surface height data are shown in blue, the elevation profile in Fig 3C as a black line, and the sub-satellite track for the waveform power in Fig 6A is labelled.~~.~~ The insert shows the position of Devon Ice Cap (circled) in the Canadian Arctic Archipelago.

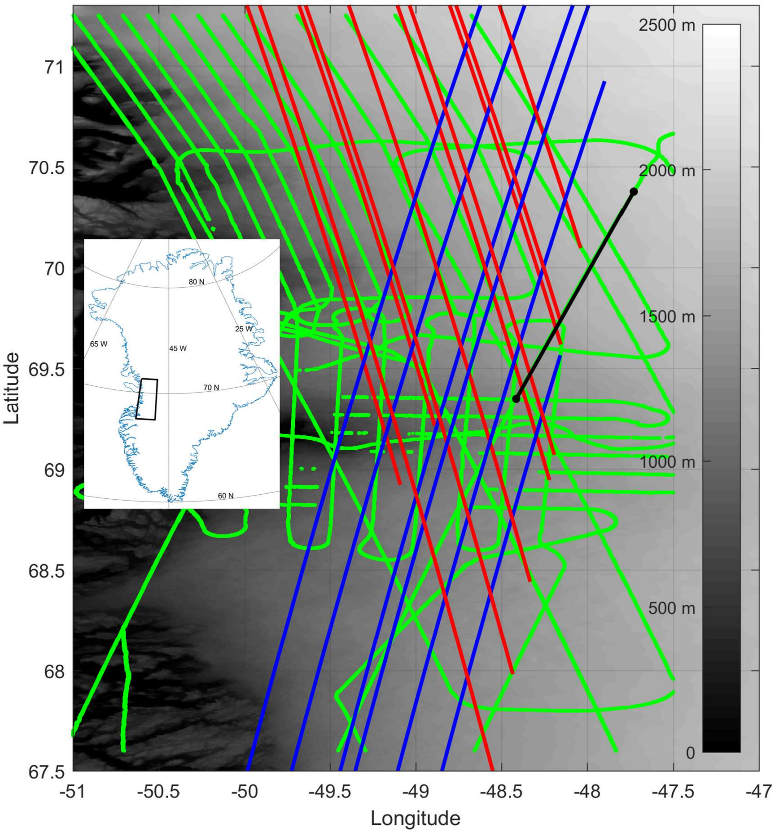


Figure 2: The positions of the reference ATM surface elevations flown by NASA IceBridge missions over the west Greenland site in spring 2011 are shown in green. Sub-satellite CryoSat tracks for the period Jan. 20 to May 16 2011 are shown by red (ascending) and blue (descending) lines. The inset map shows the position of the test area in Greenland and the background image is a black-white representation of the GIMP reference DEM (Howat et al., 2014). The position of the height profile in Fig. 3A is shown by the black line.

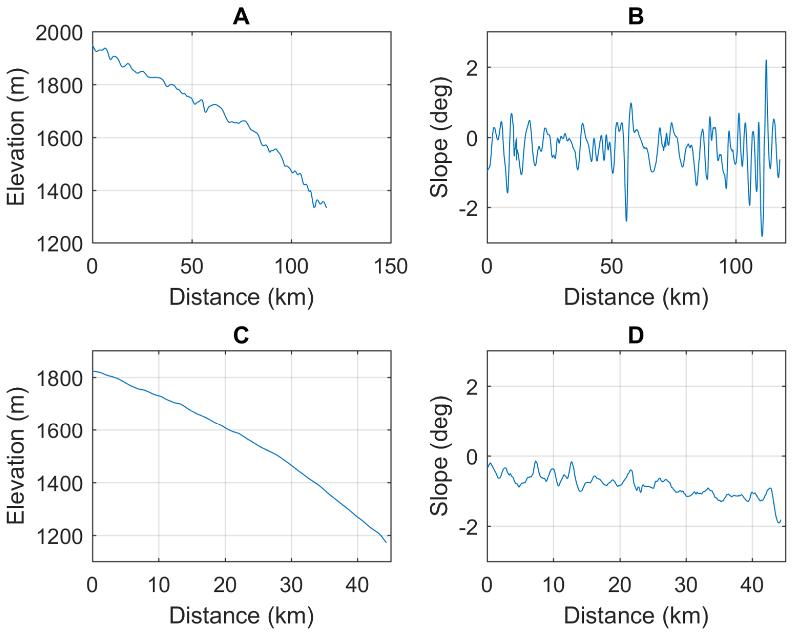


Figure 3: Illustration of the difference in slopes for a typical west Greenland transect (70.37°N, -47.73°W to 69.35°N, -48.42°W, black line in Fig. 2) derived from an ATM flight line from Apr. 6 2011 (box A; elevation and box B; slope) and the EW transect (black line in Fig. 1) from western Devon Ice Cap (box C; elevation and box D slope, Fig. 1).

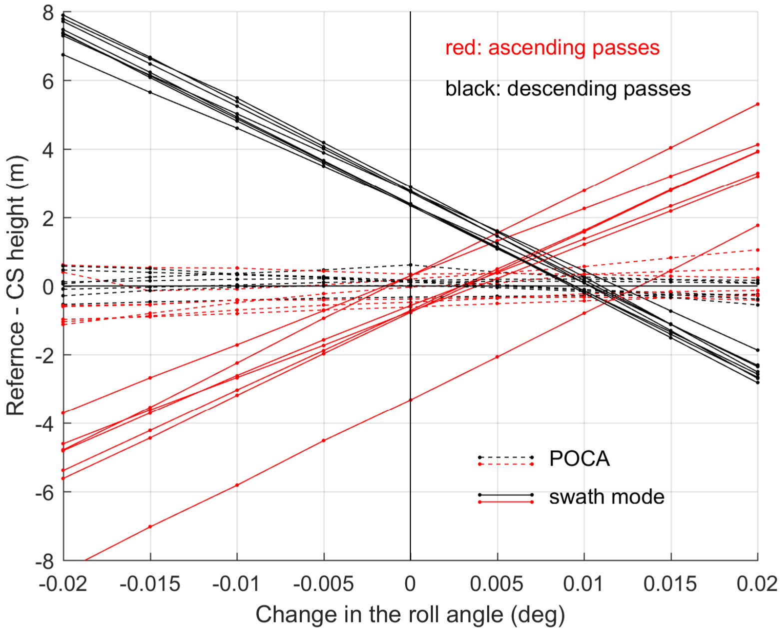


Figure 4: Illustration of the changing bias between the reference and CryoSat (CS) swath mode heights for the Devon test site as an additional roll bias is subtracted from the roll figure given in the L1b file. Results for 7 ascending and 8 descending passes in the winter-spring of 2011 are shown in red and black, respectively. The reference - POCA height variation with the added roll-angle bias is shown with the dashed lines.

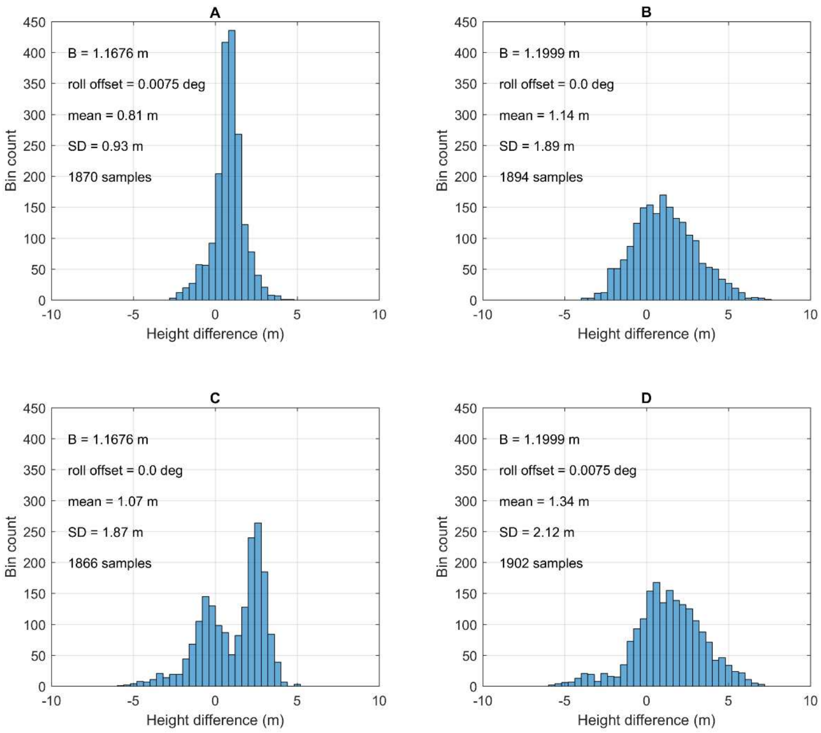


Figure 5: Histograms of the reference minus CryoSat swath heights for Devon Ice Cap: (A) pre-launch baseline and a roll-angle offset of 0.0075°; (B) modified baseline with zero roll offset; (C) pre-launch baseline with zero roll offset; and (D) modified baseline with a roll offset of 0.0075°.

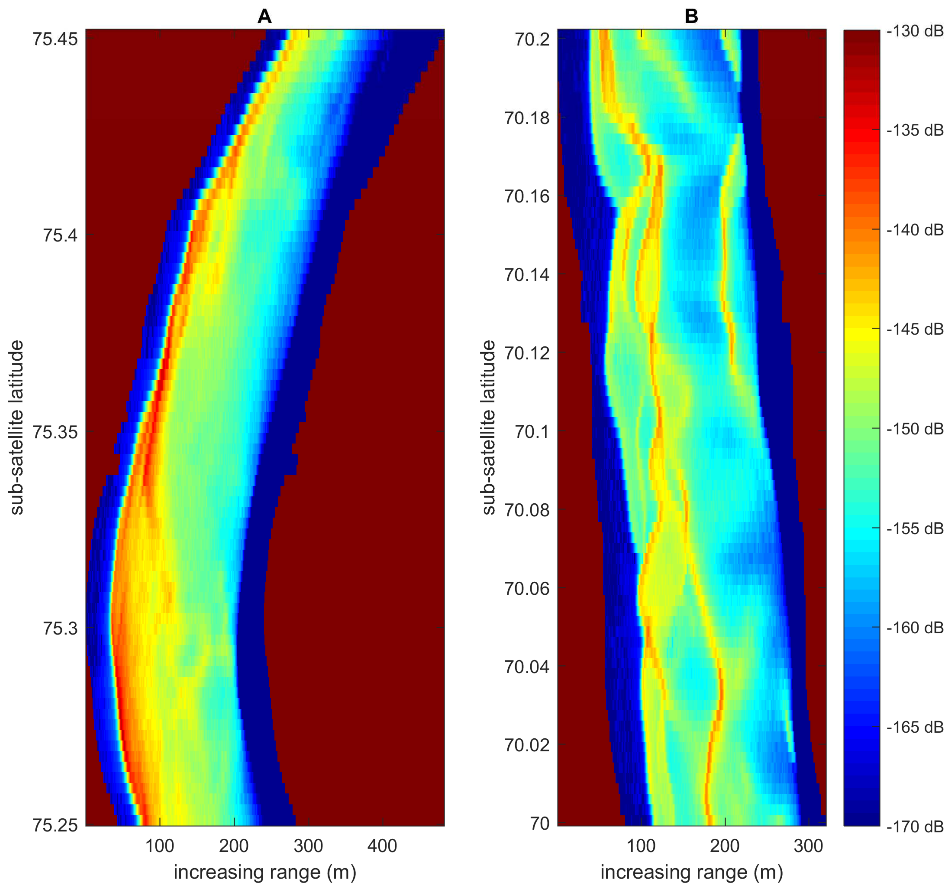
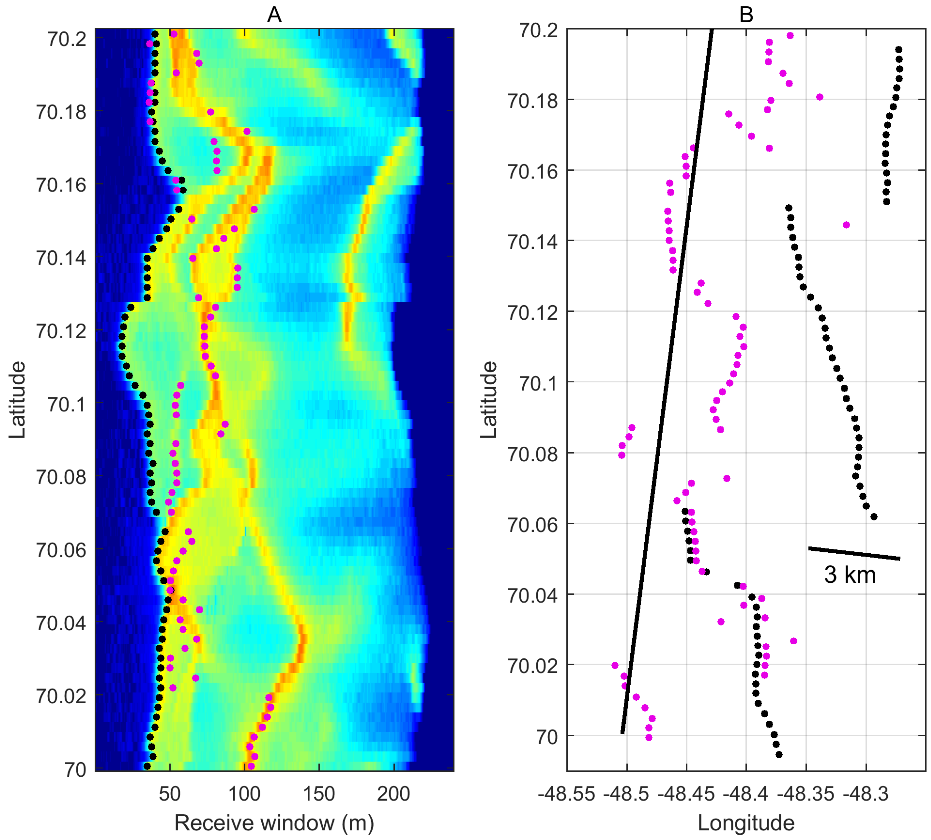


Figure 6. Waveform power for 22 km segments of (A) the Feb. 7 2011 ascending pass over Devon Ice Cap (Fig. 1) and (B) the April 21 2011 descending pass (Fig. 12A) over the west Greenland test site. The return power in dB is represented in colour and the individual waveforms have been shifted in the x direction depending on the time delay to the first sample and the satellite elevation above the WGS84 ellipsoid.



A
B
70.2
70.18
70.16
70.14
70.12
70.1
70.08
70.06
70.04
70.02
70
Latitude
50
100
150
200
Receive window (m)
-48.55
-48.5
-48.45
-48.4
-48.35
-48.3
Longitude
3 km

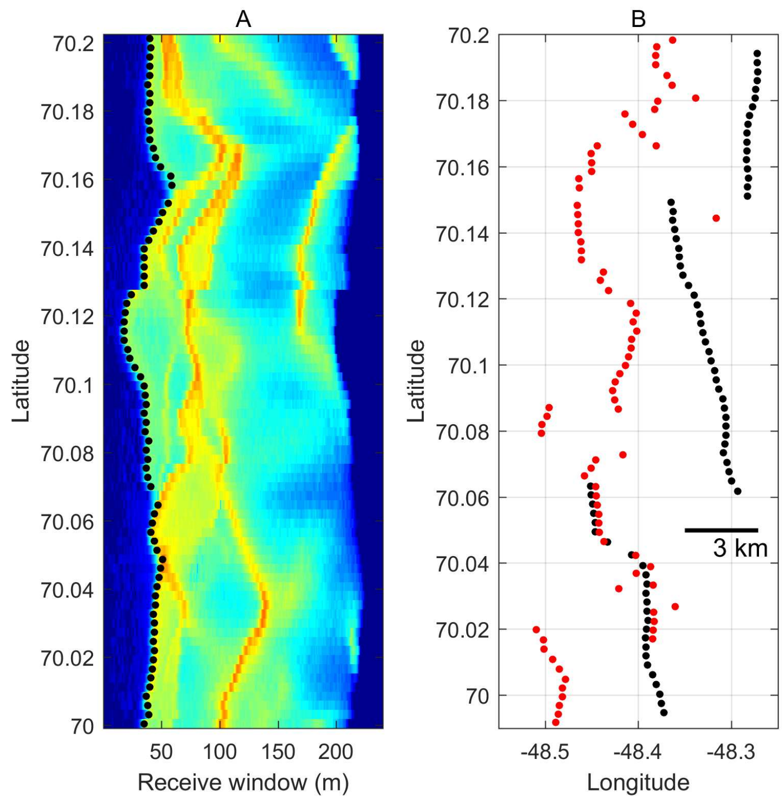
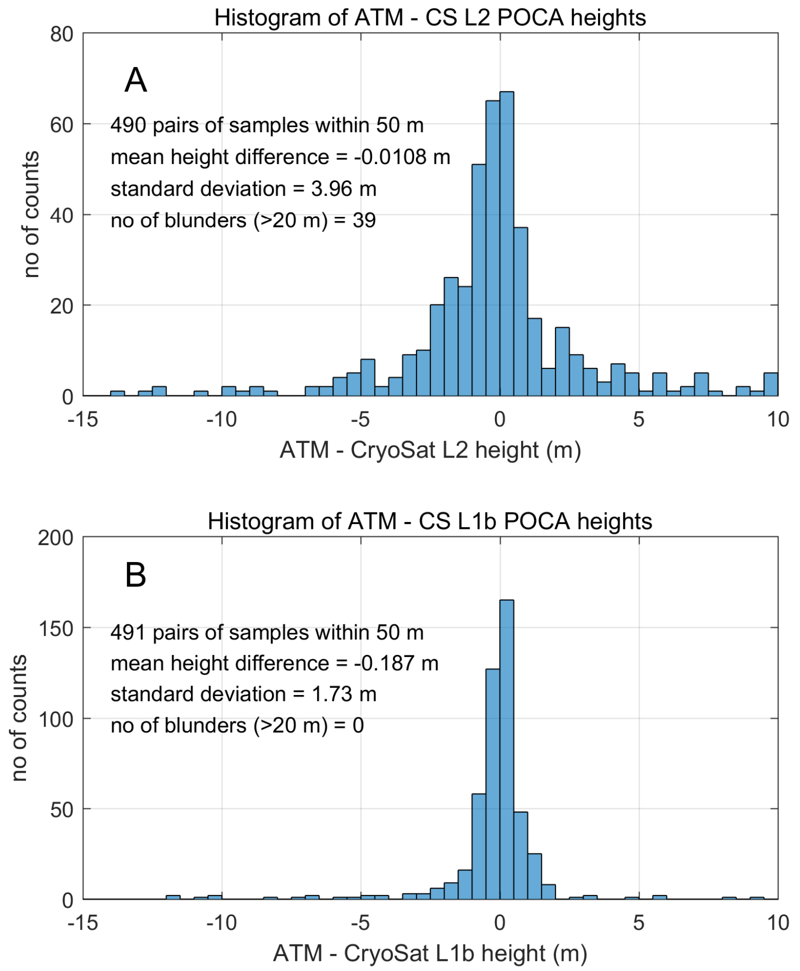


Figure 7. (A) Waveform power without any x axis shifts using the same dB colour scale as in Fig. 6B. The detected POCA positions are shown in (A) for each waveform with black dots, and they clearly correspond to the leading edge of the waveforms. The purple dots are the estimated positions in the waveforms of the L2 POCA solution. (B) Geographic positions of the geocoded footprints (black dots) are compared to the positions of the ESA L2 solutions (red dots). The solid black line is the sub-satellite track.


Histogram of ATM - CS L2 POCA heights
A
490 pairs of samples within 50 m
mean height difference = -0.0108 m
standard deviation = 3.96 m
no of blunders (>20 m) = 39
no of counts
ATM - CryoSat L2 height (m)
Histogram of ATM - CS L1b POCA heights
B
491 pairs of samples within 50 m
mean height difference = -0.187 m
standard deviation = 1.73 m
no of blunders (>20 m) = 0
no of counts
ATM - CryoSat L1b height (m)

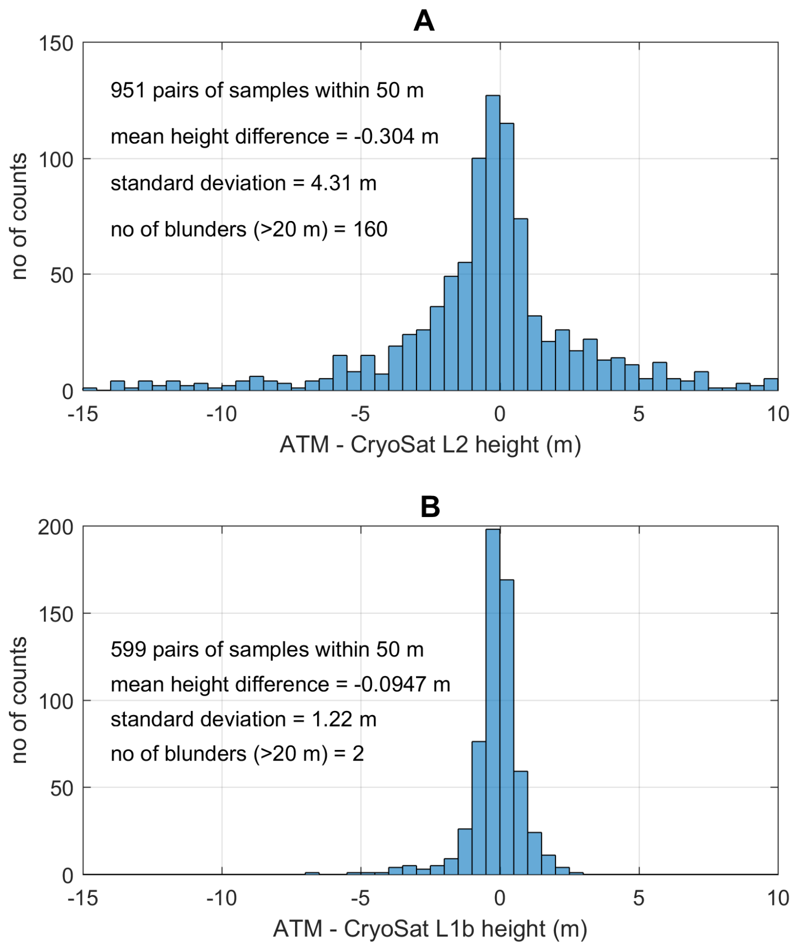
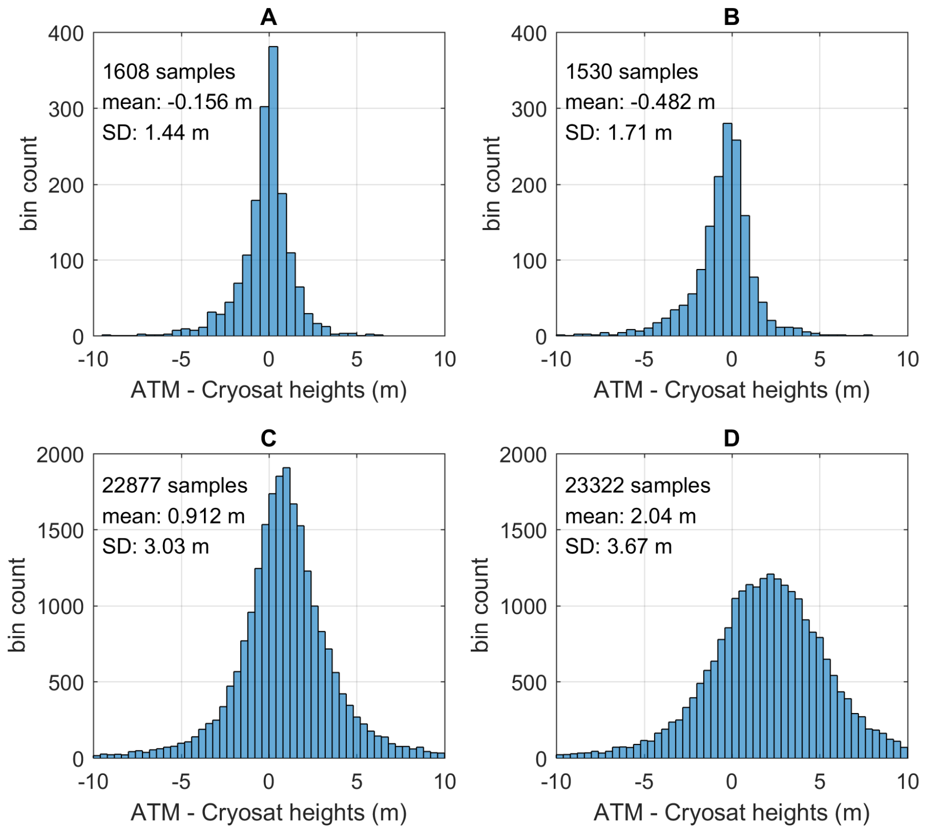
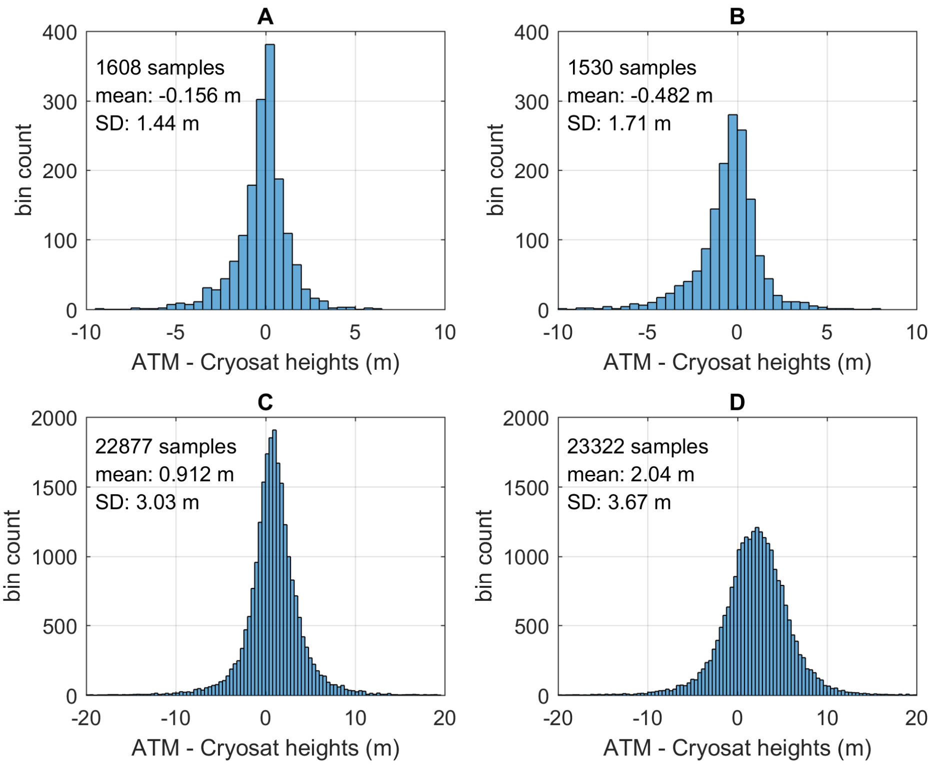


Figure 8. Comparisons of the ATM - CryoSat POCA height difference histograms for the west Greenland test site. (A) the ESA L2 solution: (B) Results from the current maximum slope leading edge retracker. The mean and standard deviation in Fig 8A have been calculated after removal of the 39 blunders. Cryosat data from all the passes between Feb 16 and April 23 2011 have been used in this comparison, and results from the same waveforms used in both cases.



A
1608 samples
mean: -0.156 m
SD: 1.44 m
bin count
ATM - Cryosat heights (m)
B
1530 samples
mean: -0.482 m
SD: 1.71 m
bin count
ATM - Cryosat heights (m)
C
22877 samples
mean: 0.912 m
SD: 3.03 m
bin count
ATM - Cryosat heights (m)
D
23322 samples
mean: 2.04 m
SD: 3.67 m
bin count
ATM - Cryosat heights (m)



5 **Figure 9. Comparisons of the west Greenland ATM – CryoSat height difference histograms for the solution using the pre-launch baseline coupled with an additional roll offset (A; POCA, C; swath mode solutions). Boxes B and D use the Galin et al. (2013) calibration for the POCA and swath solutions respectively. Results from the CryoSat passes for the period Jan. 20 to May 16 2011 have been used.**

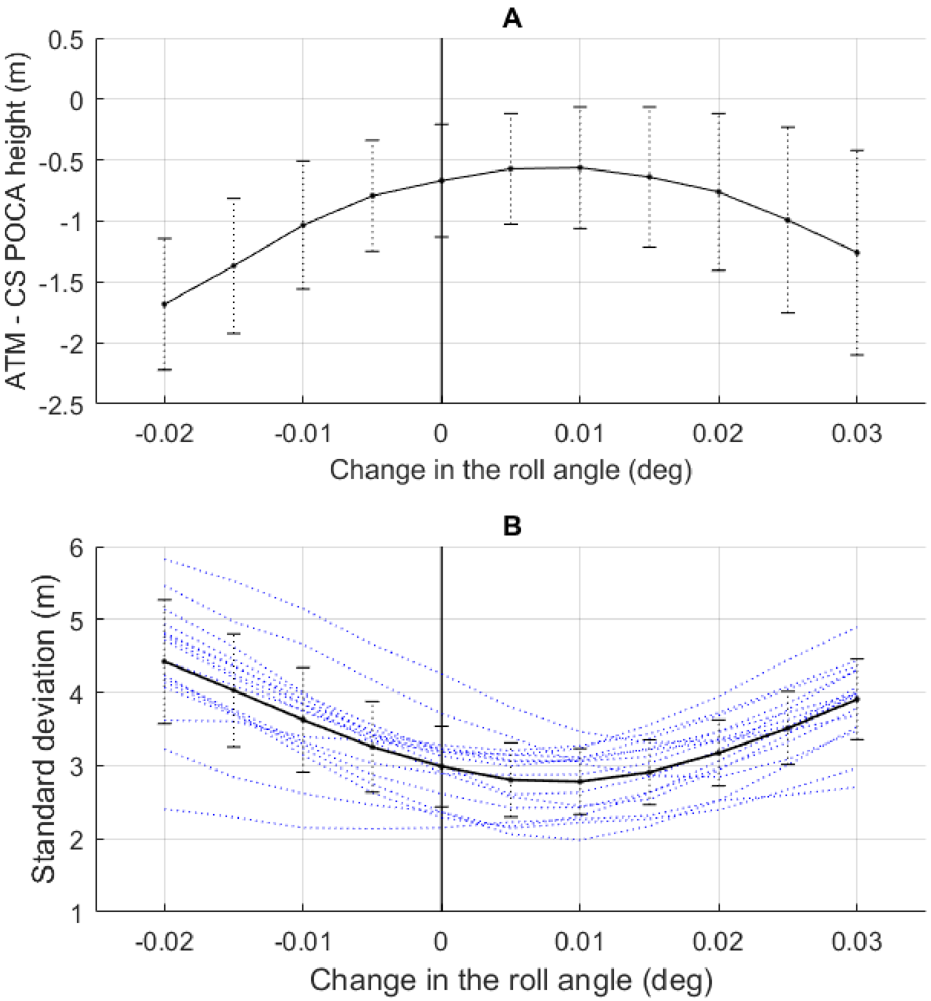


Figure 10. Illustration of the average of the ATM – CryoSat height differences for: (A) 16 passes plotted against the additional roll-angle bias used in the processing. ~~(top).~~ The error bars are ± 1 standard deviation about the mean. (B) Variation in the standard deviation (SD) of the ATM – CryoSat height difference for the individual passes (blue dotted lines) and the average over all the passes (solid black line).

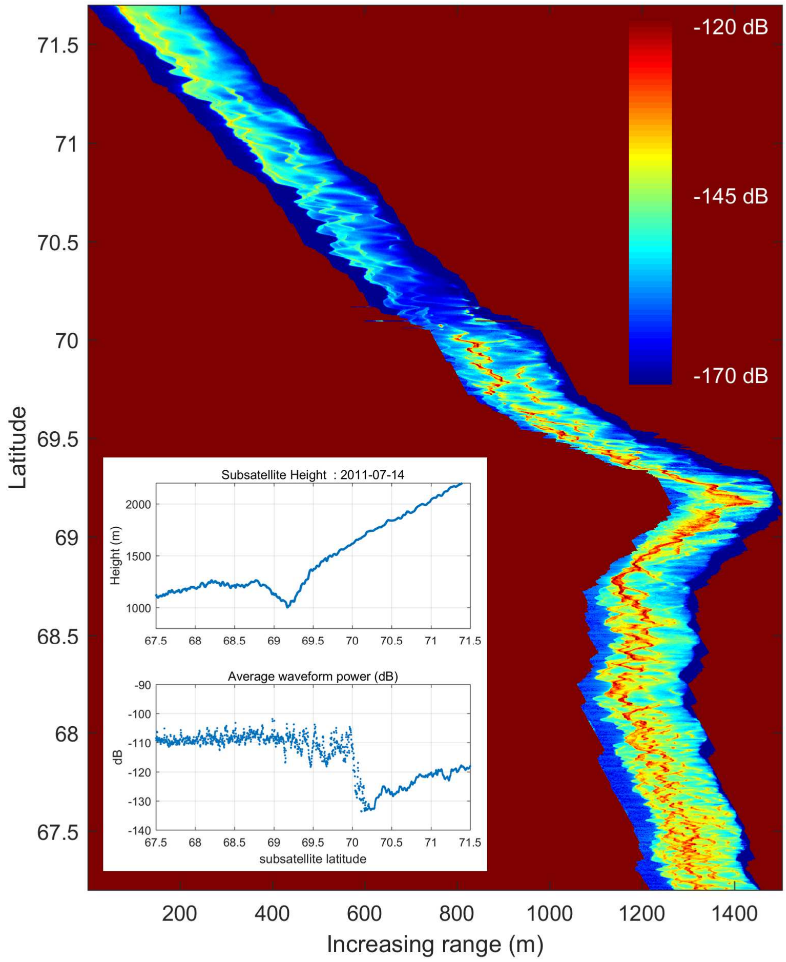
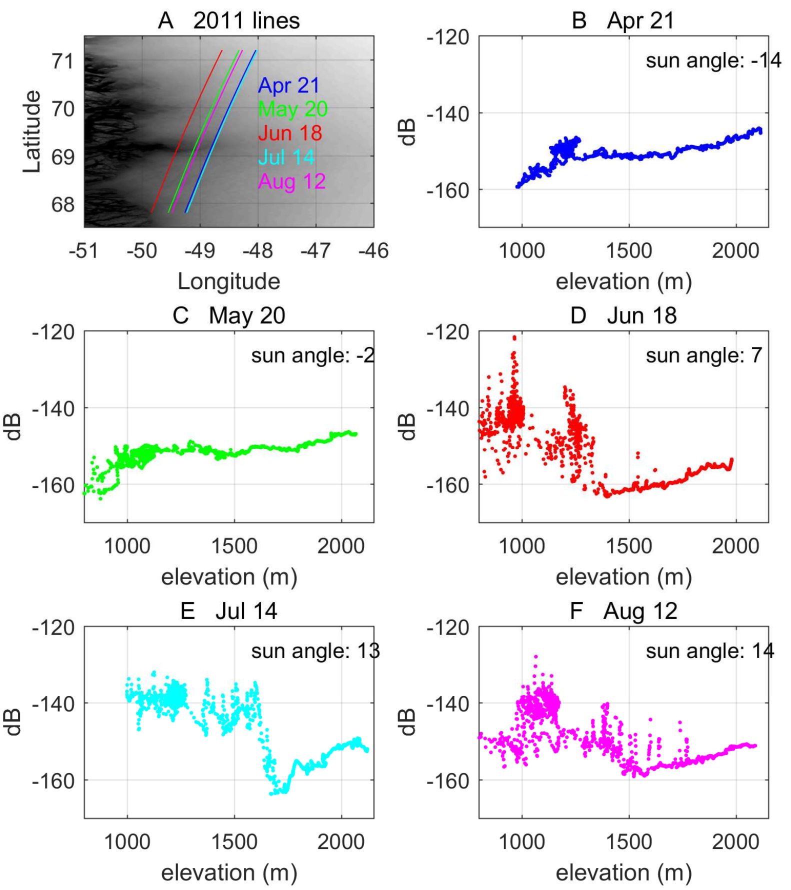


Figure 11. The background image illustrates the swath waveform power in colour with a dB scale for the July 14 2011 descending pass over the west Greenland test area (Fig. 12A). The waveforms making up this pseudo-image have been shifted in the x direction to account for the changing delay time to the first sample and the varying satellite height above the WGS84 ellipsoid. The insert shows the sub-satellite terrain elevation and the waveform average power both plotted against latitude.



A 2011 lines
Latitude
Longitude
Apr 21
May 20
Jun 18
Jul 14
Aug 12
B Apr 21
sun angle: -14
C May 20
sun angle: -2
D Jun 18
sun angle: 7
E Jul 14
sun angle: 13
F Aug 12
sun angle: 14
dB
elevation (m)

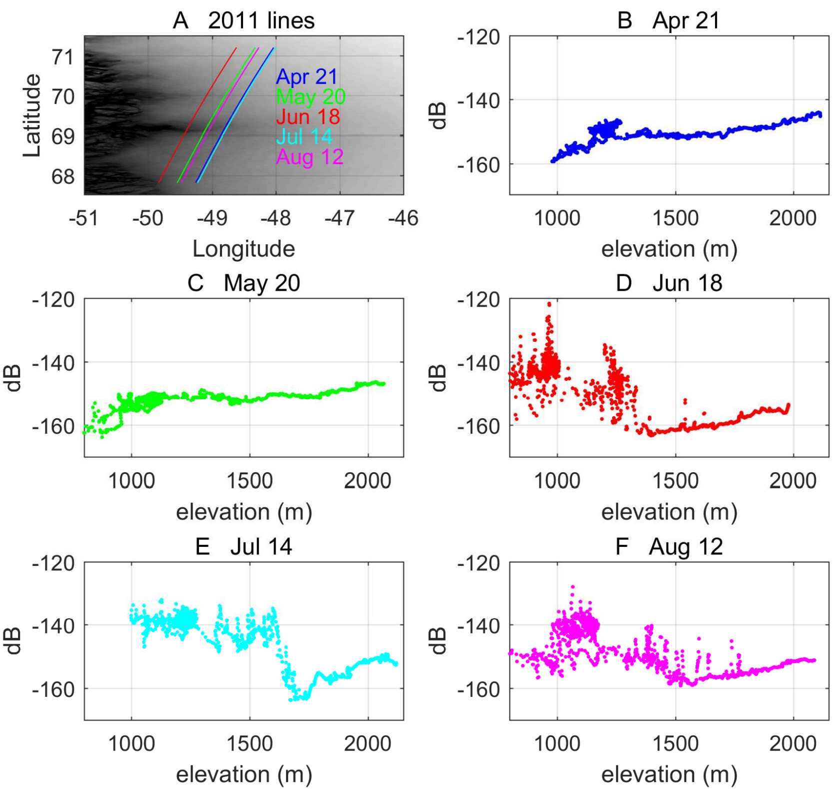
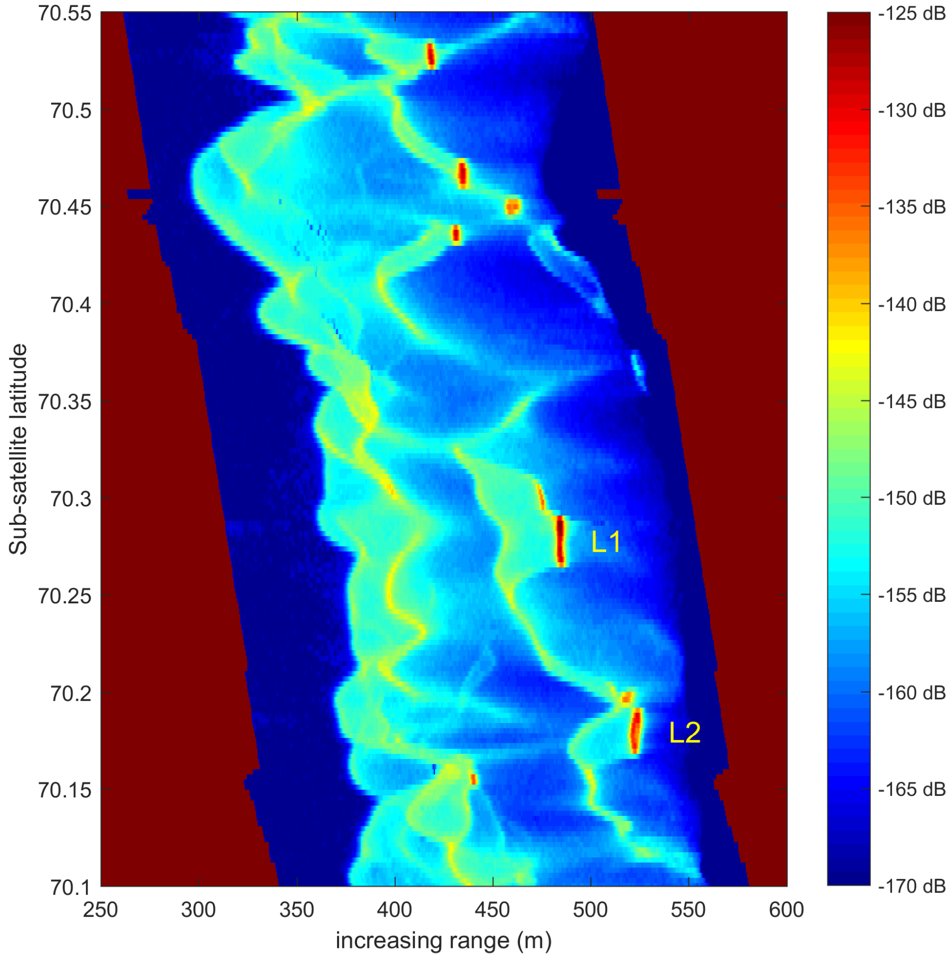


Figure 12. Plots of the average waveform power for the five 2011 descending passes shown in (A). The five plots are from descending passes on (B) April 21, (C) May 20, (D) June 18, (E) July 14 and (F) Aug. 12, and illustrate average waveform power as a function of elevation.



5 **Figure 13. Illustration of part of the waveform power from an ascending pass over west Greenland on 7 August 2011 (Fig. 14). The bright returns labelled as L1 and L2 are at elevations ~ 1609 m and 1573 m, respectively, and represent topographic lows where water could collect.**

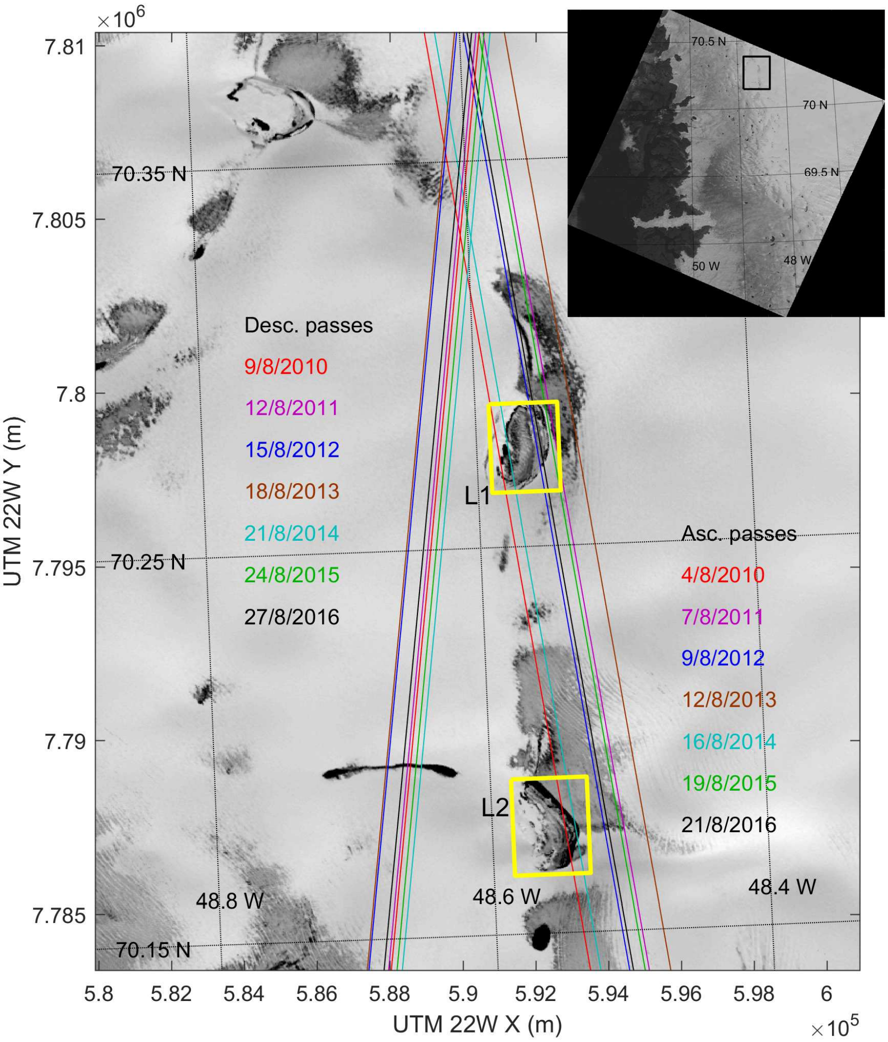
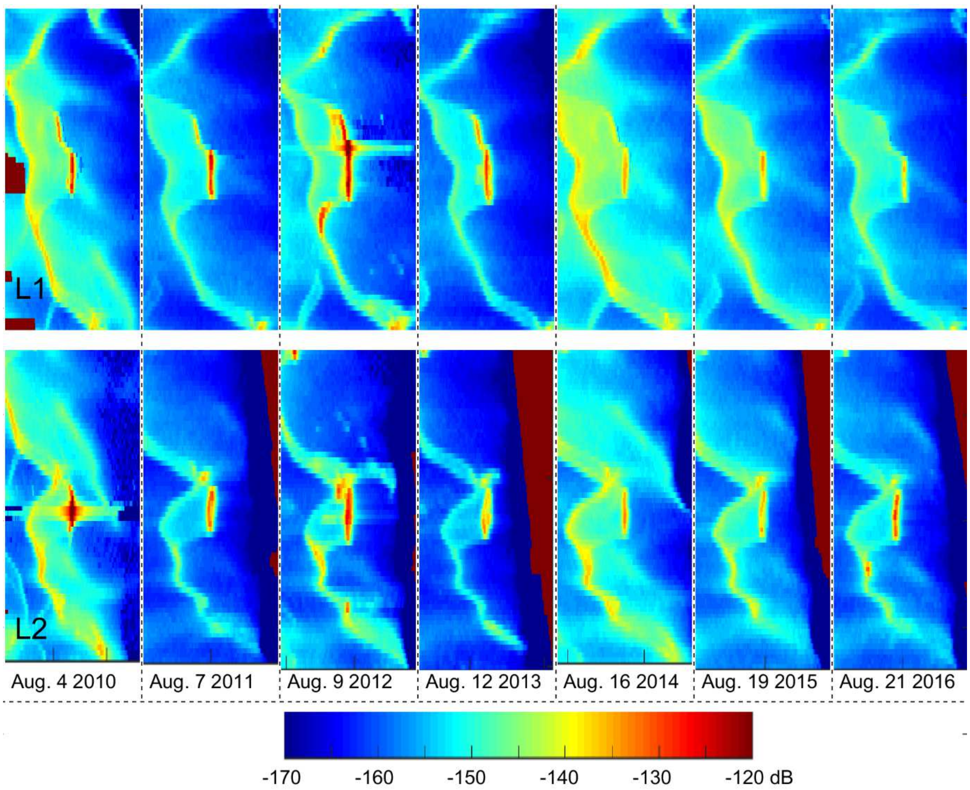


Figure 14. Ascending and descending sub-satellite repeat tracks over, or close to, the L1 and L2 features for all the years from 2010 to 2016 superimposed on part of the Landsat 8 image of August 9 2016 (inset image).



5 **Figure 15. 'Images' of part of the CryoSat waveforms for the areas including 'L1' (top) and 'L2' (bottom) in west Greenland for the August dates in each year from 2010 to 2016. The x and y axes of each 'image' are increasing range and increasing along-track position (North up).**

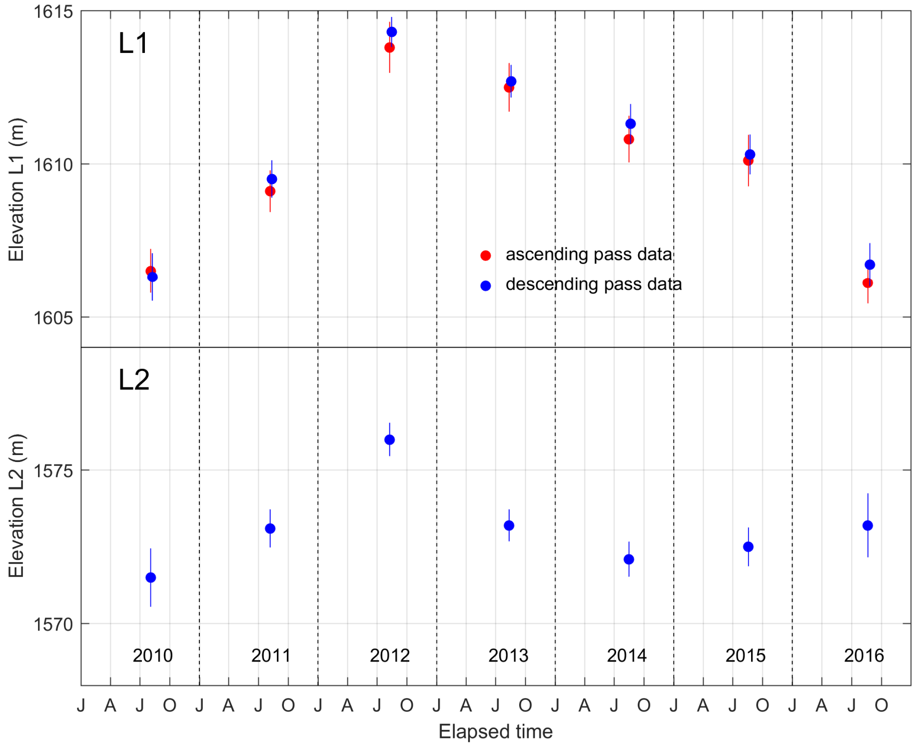
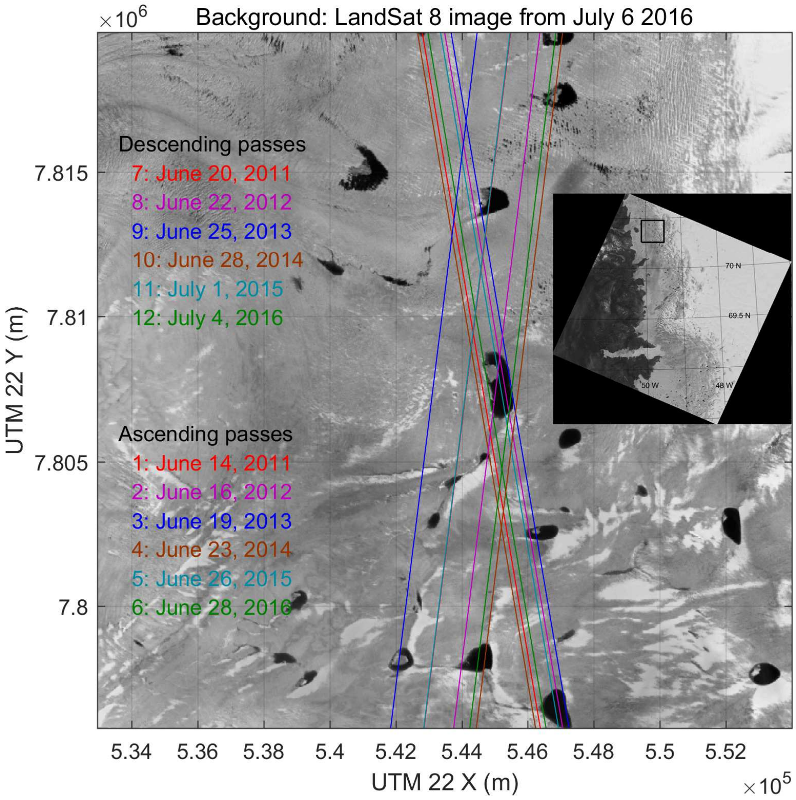


Figure 16. Surface elevation of L1 (top) and L2 (bottom) between the summers of 2010 and 2016.



Background: LandSat 8 image from July 6 2016
×10^6
7.815
7.81
7.805
7.8
UTM 22 Y (m)
Descending passes
7: June 20, 2011
8: June 22, 2012
9: June 25, 2013
10: June 28, 2014
11: July 1, 2015
12: July 4, 2016
Ascending passes
1: June 14, 2011
2: June 16, 2012
3: June 19, 2013
4: June 23, 2014
5: June 26, 2015
6: June 28, 2016
5.34
5.36
5.38
5.4
5.42
5.44
5.46
5.48
5.5
5.52
UTM 22 X (m)
×10^5
70 N
69.5 N
50 W
48 W

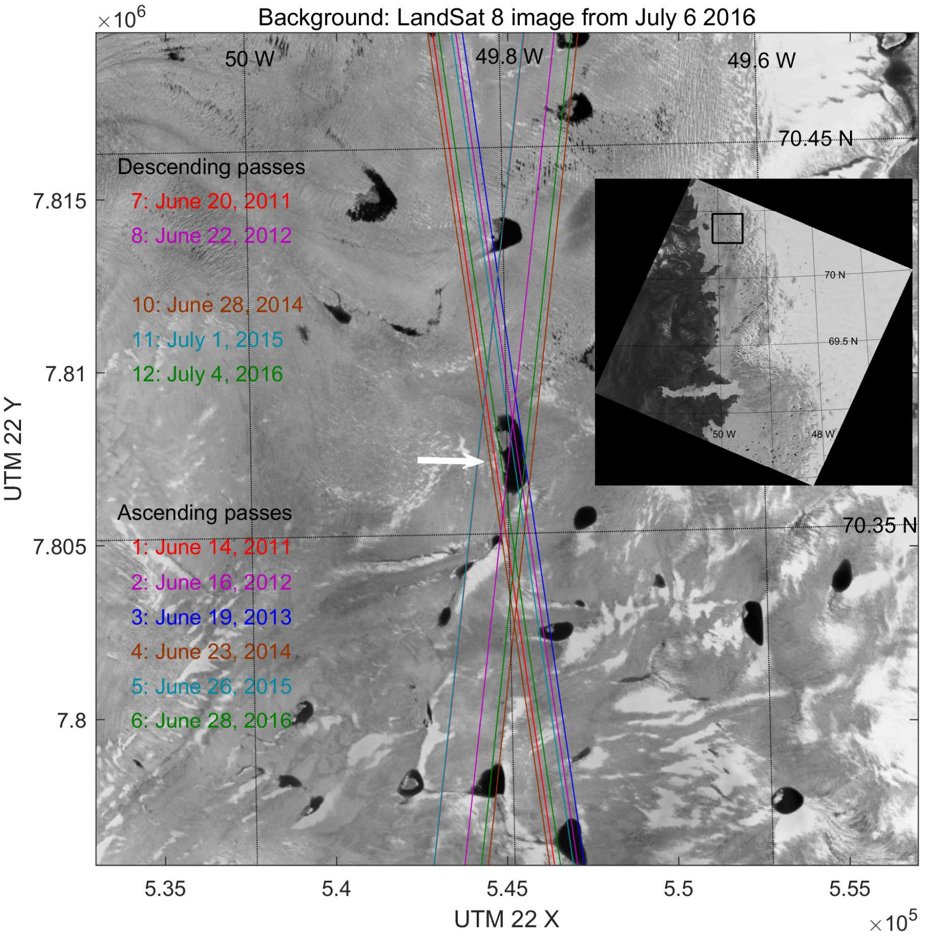


Figure 17. Landsat 8 image from July 6 2016 of an area in the ablation zone of the west Greenland test site which includes a lake (white arrow) viewed by CryoSat on all the repeat ascending and descending passes listed on the image. The insert image shows the blow-up position in the full Landsat 8 frame.

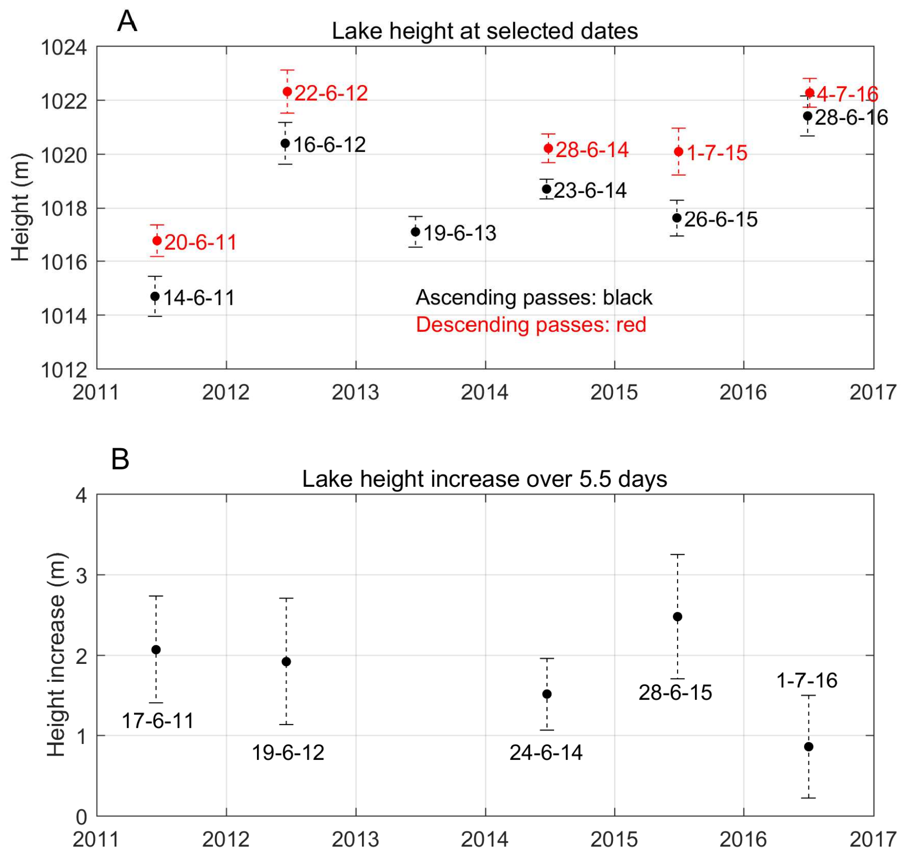


Figure 18. (A) Surface height of the lake in Fig. 17 at the times of the overpasses: (B) Height increase during the 5.5 days between the ascending and descending passes. The dates listed in the lower plot are at the middle of the 5.5-day period between the ascending and descending passes.