ICESat Capability for Elevation Change Studies with Sets of 33-day and 8-day Cycles

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1 Introduction

Elevation Change detection over the continental ice sheets has been carried out previously using radar satellite altimeters by crossover analysis; calculating the difference in elevation between an ascending and descending pass when it crosses over the same location but is separated temporally. The radar altimeters had a large footprint over the ice sheets, which varied from the pulse limited diameter of 1.2km in the non-sloping regions to the 20km beam-limited footprint over sloping topography. Though the radar satellites flew in repeat orbits at a period of 17 or 35 days, the tolerance of the repeat ground track was +/-2km. The density of coverage over the ice sheets decreases with latitude so that crossover coverage is sparse below ~ 76 deg. Repeat track analysis will expand the number of elevation change measurements considerably between 60 and 76 deg from the equator. Yi showed that repeat track analysis could be used with radar data by using a grid or the repeat tracks themselves to model the cross track slope and then aligning the tracks to a reference orbit. This methodology has long been used for ocean elevation change calculations due to the ability to correct for the cross track gradient over the relatively smooth ocean. Over the ice sheets the precision of the change measurement calculated this way will be directly dependent on how large the cross track distance is and if it is not within 50m then how well the cross track slope can be modeled.

The laser altimeter of GLAS has different characteristics than radar altimeters. The repetition rate is faster at 40Hz compared to 20 Hz, the footprint is significantly smaller at 70m in diameter and the capability to repeat orbital tracks to within 35m exists by using the spacecraft precision pointing. Due to these differences, precise elevation changes can be calculated using both crossovers and repeat track analysis over the ice sheets with GLAS data. The crossover density is a function of latitude so that there will be many cases where repeat track analysis will be the only data available for elevation change detection.

The ICESat mission has 3 lasers. The first laser operated from February 21 – March 29 2003. The spacecraft was in an 8-day repeat cycle orbit for this whole time period, however it was not pointing to the reference track over the ice sheets. Therefore the spacing between repeat tracks varied from hundreds of meters to 1 km. The second laser has operated so far for 53 days; September 25th through November 18th, 2003. It first completed 10 days in the same 8-day repeat orbit as for laser 1, however it was precisely pointing to the 8-day reference orbit over the ice sheets. It then transitioned to a 91-day repeat orbit and completed 45 days of the 91-day orbit before the laser was turned off. It was precisely pointing to the 91-day reference orbit over the ice sheets for the full 45 days. There were misalignment issues with laser 2. The bore sight alignment was improved by heating the laser and raising the bench temperature 2 deg on October 14th and raising the bench temperature a total of 4 more degrees on the 28th and 29th of

October. Definite improvement in elevation precision was shown after each of these temperature increases. The data for the initial part of laser 2 can probably be used, but the elevation precision will be best for the last 20 days after the affect of the 2nd heating settled in.

We will present in this paper the following:

1. The coverage of the cross over data set from the current data between laser 1 from March 2003 and laser 2 data.
2. The coverage of the existing 8-day precision pointing repeat track data with exact pointing and coverage of repeats 3 and 4 from laser 1
3. Elevation difference distributions between repeat tracks for laser 1 8-day data
4. The coverage of the last 33 days of laser 2 data
5. The precision of the GLAS data from laser 1 and both phases of laser 2 from crossover analysis using currently released data (release 12) and a small subset of data for which more precise pointing is calculated.
6. Repeat track analysis expectations based on current data distribution
7. Suggestions for continuing ICESat operations that would maximize elevation change calculations over the ice sheets given the limited lifetime of the lasers.

2 Data Coverage

Data coverage will be affected not only by the ground track spacing, but also by the cloud coverage. Forward scattering and detector and amplifier saturation further affect the precision of the calculated elevation. In this section we show the data coverage based on a successful Gaussian fit to the return waveform after editing out all laser 1 data that had the high gain saturation flag set. This flag was set in approximately 5% of the laser 1 data. All the data used here are from release 12 of the GLAS ice sheet product GLA12.

The existing data coverage over Greenland for crossovers and full rate data is shown in Figure 1. Figure 1a shows the distribution of the existing crossovers that could be used to look at the short-term semi-annual elevation changes between Fall and Winter of 2003. This is the data set distribution formed by crossing all the laser 2 data with the 8-day repeat cycle 4 of laser 1. Only repeat cycle 4 of laser 1 was used because this has the best coverage and a consistent set of gain parameters. Data for the other cycles from laser 1 can be used, but will require special processing due to more pronounced saturation. Figure 1b shows the coverage from the last 33 days of laser 2 data where the laser was pointed at the 91-day reference orbit. Figure 1c shows the coverage from all the laser 2 8-day repeat data that also had exact pointing to the reference orbit. Note that there is very poor coverage of Southern Greenland during the 8-day repeat orbit phase of laser 2. Figures 1d and 1e show the coverage for repeat cycles 3 and 4 from laser 1. The 8-day repeat coverage was much better for laser 1 than for laser 2 but repeat ground track differences for laser 1 varied from 100m to 500m from the reference track for these cycles.

Figures 2a-e shows the corresponding data over the Antarctic ice streams. The 8-day repeat phase coverage is better here than over Greenland (fig 2c), however it is still more affected by clouds than the last 33 days of the 91-day repeat phase (fig 2b).

3.0 Precision of GLAS data as calculated from Crossover Analysis

Historically crossing arc analysis has been used to determine the precision of the satellite altimetry data. Crossovers residuals over the ice sheets for GLAS are calculated as follows:

- The latitude and longitude for each pass of data on GLA12 is fit to a quadratic. A pass is considered to be 250 contiguous seconds of data.
- A preliminary crossover location is calculated as the intersection of these functions for every pass that crosses any other pass.
- For any two passes that cross each other, another quadratic is fit to each pass latitude and longitude using only data within 3.3 km of the preliminary location. The final crossover location is defined by the intersection of these new functions.
- A quadratic function is also fit to time vs longitude for each pass using the 3.3 km surrounding the crossover location and the time is evaluated at the crossover longitude.
- The elevation for each half of the crossover is calculated by linearly interpolating between the elevations on the two surrounding data records.
- The elevation residual is calculated as the ascending pass elevation minus the descending pass elevation for like laser crossovers. When laser 2/ laser 1 crossover residuals are calculated, they are always laser 2 elevation minus laser 1 elevation.

Precision is calculated from a set of crossovers as the standard deviation of the elevation residual distribution after editing outliers using a 3 sigma convergent edit to remove outliers from the precision calculation. Between 2 and 7 % of the data was removed due to this editing.

Figure 3 shows the crossover residual standard deviation for all GLAS data in approximately 8-day time periods to minimize the influence of temporal changes to the surface. These are continental-wide statistics calculated separately for Greenland and Antarctica using the release 12 data without any of the pointing refinements expected in later releases. Most time periods had over 3500 crossovers over Antarctica and around 200 over Greenland. For laser one we split the data by ICESat repeat cycle so repeat cycle 1 and 6 do that contain a full 8 days of data. There was so little data for repeat cycle 6 that we did not have enough crossovers over Greenland to calculate the statistics for that period. For laser 2 the first time period includes all 10 days of the 8-day repeat data and then the rest of the time periods during the 91-day repeat orbit are approximately 8 days each. The vertical red lines mark the approximate times at which the bench heating occurred. It could take up to two days for the affect of the bench heating to be felt.

The standard deviation values for laser 1 vary from 53 cm to 28 cm over Antarctica and from 60cm to 20 cm over Greenland. The elevation precision is best for repeat cycle 4 which had gain parameters set optimally. The attitude solution used for release 12 included no LRS information and a preliminary set of laser offsets. The gain algorithm used for laser 1 did not adjust correctly when intermittent clouds were present and caused many returns to be saturated due to this. In addition, changes were made in the gain parameters during the first 3 repeat cycles that could detrimentally affect elevation precision. The spacecraft changed from sailboat to airplane mode during repeat cycle 5 and there are some problems in the pointing solutions that occurred due to this. Even with all these factors present, the precision is high enough to look at larger elevation changes. When the pointing information is improved with LRS data (or models where it is missing) and better laser offsets, the elevation precision of laser 1 will improve.

The precision of laser two data varies from 58 to 23 cm over Antarctica and from 168 to 35 cm over Greenland. The largest values over Greenland are probably due to cloud cover causing non-even distribution of the crossovers (see fig 1c). There were bore sight misalignment problems at the beginning of laser two that were fixed by heating. The first significant heating of two degrees took place Oct 14th and another one to raise the bench temperature an additional 4 degrees took place October 28-29th. After the 2nd heating the elevation measurements (the last two time periods on the histogram) show the highest precision. The pointing solutions used for release 12 laser two data used the laser one offsets and no LRS. Preliminary tests have shown that using more valid laser two specific offsets and LRS input will improve the precision from at least from October 18th on to around 20 cm as seen in figure 4. Improvement to 15 cm has been seen when pointing solutions are further refined for specific days. There is every reason to believe that this will be reduced even further as more refined solutions are calculated for pointing.

The elevation precision has always been expected to decrease as the topographic slope increases. Figure 5 shows crossover statistics as a function of slope for laser 1 and laser 2 over Antarctica that prove this hypothesis. The slope used was calculated from the NASA 5 km radar altimetry grid. All the data was used for these calculations so laser 1 includes 36 days of data and laser 2 includes 55 days of data. Therefore the standard deviations would be higher than those shown in figure 3 due to the influence of temporal changes over these larger time spans. The values vary from 32 cm at very low slopes to 90 cm at the steeper slopes for laser 1 and from 42 cm to 132 cm for laser 2. The higher values for laser 2 are probably due to bore sight misalignment problems which have more affect over sloping terrain. This precision as a function of slope is considerably better than what was achieved with the satellite radar altimetry.

Figure 6 shows crossover statistics as a function of slope for laser and radar altimetry over Antarctica. The laser 1 data is the same as for figure 5, however we have now added laser 1 crossovers with ERS-2 and ERS-2 crossed with itself. The radar crossovers (ERS-2/ERS-2) vary from 69 cm at slopes less than 0.05 deg to 5.92m at slopes between .5 and .75 deg showing that the laser has considerably better precision than the radar at all slopes, but especially at the higher slopes. For radar we did not have enough crossovers above .75 deg to calculate the statistics because the altimeter could not maintain track in the higher slopes. The laser/radar crossovers vary from 73 cm at slopes less than 0.05 deg to 35m at slopes from .75 to 1.0 deg showing that the laser has much better accuracy over the ice sheets than the radar. Most of this degradation in the laser/radar crossovers at the higher slopes is due to our inability to model the large slope-induced error seen in radar altimetry. The radar data was corrected for slope-induced error using the NASA/GSFC model that corrects the elevations but leaves the geolocation at the sub-satellite position.

4.0 Calculation of Elevation Change

Elevation change has been calculated for previous radar altimetry missions using crossing arc analysis since the repeat tracks repeated only to within +/- 2 km. The GLAS mission has been designed to allow for precision pointing giving us the capability to point to within 35 m of a reference track. This makes repeat track analysis a reasonable method for calculating elevation change.

A science objective for the ICESat mission was to calculate seasonal and inter-annual changes over 100 km square regions. The accuracy would be met by the inherent precision of the individual measurement combined with averaging over all the elevation change measurements within the 100 km^2 region.

Figures 1a and 2a show the distribution of the available crossover set between laser 2 and laser 1 for Greenland and the ice streams of Antarctica. At the more polar latitudes there are many crossovers within each 100 km^2 region, but as you get farther from the pole you get many regions where there are no crossovers or so few that the elevation change calculation has too large an error to be useful. For these regions repeat track analysis would be the only method available.

Figures 7a and b show the distribution of the crossover residuals between laser 2 and laser 1 on a continental basis using release 12 data. For laser 1, only repeat cycle 4 was used and for laser 2 the last 19 days (Nov 1-18th) were used. The standard deviations of the crossover residuals of 44 and 32 cm for Greenland and Antarctica respectively are very promising given that release 12 data was used. The errors in pointing are further exemplified by the mean values with magnitudes of 9 and 35 cm. We processed two days of laser 2 data with an improved pointing solution and recalculated the crossovers over Antarctica between it and laser 1 as shown in figure 9. The magnitude of the mean reduced to 20 cm. This should reduce considerably more with better pointing solutions that are expected in the future making the calculation of elevation change from cross laser crossover and repeat track analyses a real possibility for this data.

Repeat Track analysis over the ice sheets where the spacecraft uses precision pointing to repeat to within 35m of the reference track should give the same precision as crossover analysis but more detail on distribution of the change relative to glacial features in the latitudes farther away from the poles. Essentially you have the equivalent of a crossover for every measurement along the repeat track. The difference in coverage between the crossovers and the along track data shown in figures 1 and 2 show that in order to calculate elevation changes over many of the more interesting regions we will have to use repeat track analysis. Figures 1b and 2b show the last 33 days of laser 2 coverage over Greenland the Antarctic ice sheets. Figures 1c and 2c show the only 8-day repeat data that we have where the laser was pointing to the reference track over the same regions.

A measure of how close all the 8-day cycles were from the reference track in shown in Figure 9. This gives for each cycle the distribution of the distance of the reference track for all Antarctic data. Cycles 28 and 29 were the laser 2 cycles that were pointing to the ground track, the previous cycles were held within +/- 1 km tolerance. Note that cycles 28 and 29 have distances distributed evenly around 0.0 as expected for pointing. The other cycles are mostly offset by hundreds of meters from the reference track, though for cycle 4 there is a cluster of data within +/- 50m and cycle 3 has a small percentage of data within 50m.

How the cross track distance varies along each track is shown in Figure 10 where the cross track distance from the reference track is shown for different cycles of representative tracks from the 8-day repeat data over Antarctica. This figure shows that there are many locations where cycles 3, 4, and 29 come fairly close together. This was investigated closer for tracks 61 and 76. The distribution of the elevation differences between cycles 3 and 4 for these tracks is shown in Figure 11. These elevation differences were calculated between measurements from different cycles that were close to each other. No cross- or along-track adjustment was applied to the data and still the standard deviation of the differences was 11.8 cm around a 12.4 cm mean for track 76 which is in a smoother area and 15.8 cm around a 3 cm mean for track 61 which traverses over an undulating surface. This shows that at least for some of the data we can use the laser 1 non-pointing repeat tracks to do repeat analysis at a precision that is comparable to crossovers and sufficient to obtain some of the science objectives. For release 12 data this example gives better precision than the crossover analysis does because the attitude error varies as the sun angle with respect to the orbital plan changes. For repeat tracks separated by only 8 days the sun angle would be similar so the attitude error affect will be less than for crossovers.

5.0 Conclusions and Suggestions for future GLAS operations

Short term elevation change calculations from Winter to Fall of 2003 can be made where we have crossovers between laser 2 and laser 1 (Figures 1a, 2a) and in many locations where we have repeat data between cycles 3, 4, and 28 and 29 even though there was no exact pointing for the laser 1 8-day tracks over the ice sheets and the cross-track differences between cycles of the same tracks were hundreds of meters. The precision of this repeat track analysis will be directly related to the smoothness of the region and how far the repeats wander from each other.

Figures 1b and 2b show the last 33 days of precision pointing repeat data available from laser 2. Repeating these same ground tracks could potentially give us an elevation change measurement everywhere along these tracks giving enough measurements within each 100 km^2 region to calculate seasonal elevation changes that will meet ICESat mission requirements once the pointing solutions are improved. This will be the only way to calculate any elevation changes in the many regions where there are no crossovers.

To optimize the capability to calculate elevation change from Feb/Mar 2003 with later data we would want to repeat the 8-day orbit. This will also give us 6-month measurements using the laser 2 data. To optimize elevation change calculations between Sep/Oct 2003 and later seasons, it would seem appropriate to repeat the same 33 days that correspond to the last 33 days of existing laser 2 coverage. This maximizes the regions covered over the ice sheets from which we can calculate elevation change.

In conclusion, the authors support repeating one 8-day orbit cycle and the last 33 days of the Sep/Oct 2003 91-day cycle for the Feb 2004 laser 2 turn on. Whether the 8-day cycle is first or last should be decided based on orbit maneuver considerations that would minimize the amount of time transferring between reference orbits.