Reduction of ICESat systematic geolocation errors and the impact on ice sheet elevation change detection

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[1] The Ice Cloud and land Elevation Satellite (ICESat) has been acquiring unprecedented observations of our planet's varied surfaces with impressive precision. However, systematic errors remain in the data including orbital variation and long-term bias trend pointing errors. These errors are particularly troublesome because they cannot be separated from true surface elevation change and confound instrument range bias determination. We present a method to correct these systematic pointing errors to the sub-arcsecond level. We demonstrate the impact of these errors and their corrections on Greenland and Antarctica ice sheet surface elevation change observations and sea surface anomaly observations, as well as instrument range bias determination. While further improvements in the ICESat data will certainly be made, the analysis presented here demonstrates a major error source can be significantly reduced, resulting in improved surface elevation accuracies for ice sheet elevation change detection. **Citation:** Luthcke, S. B., D. D. Rowlands, T. A. Williams, and M. Sirota (2005), Reduction of ICESat systematic geolocation errors and the impact on ice sheet elevation change detection, *Geophys. Res. Lett.*, *32*, L21S05, doi:10.1029/2005GL023689.

1. Introduction

[2] Since its launch on January 12, 2003, NASA's Geosicences Laser Altimeter System (GLAS) orbiting on board the Ice, Cloud and land Elevation Satellite (ICESat) has been acquiring measurements of the Earth's varied surfaces with unprecedented precision and accuracy (B. Schutz et al., Overview of the ICESat mission, submitted to *Geophysical Research Lettrs*, 2005). However, systematic pointing errors (SPE) still remain and prevent these data from meeting their full potential for ice sheet elevation change detection. The SPE are comprised of transmit path pointing errors and/or field of view shadowing receive path errors. The errors are thermal-mechanically driven and are dominated by: (1) long-term bias trend errors (systematic secular trends and long period variation on the order of weeks to months) and (2) orbital variation (systematic variation with the satellite orbital period revolution). The SPE induce elevation errors that are geographically correlated and change on time scales of orbital period, weeks and months. These elevation errors are of particular concern because they cannot be separated from true surface elevation change. Additionally, the elevation errors induced from the SPE significantly confound range bias determination.

[3] Here we present a technique for calibrating and correcting these orbital variation and bias trend SPE at the sub-arcsecond level. The corrections derived from this technique were used in the development of Release 21 data for Laser 2a. We present the results of the application of these pointing related corrections to two laser operations periods with vastly different processing status: Laser 2a and Laser 3a. Laser 2a represents ICESat's best performing time period where full Stellar Referencing System (SRS) pointing corrections were available and applied (J. M. Sirota et al., The transmitter pointing determination on the Geoscience Laser Altimeter System, submitted to *Geophysical Research Letters*, 2005) along with Instrument Star Tracker (IST) distortion corrections. While Laser 3a, due to instrument specific problems, does not yet have SRS processing or modeling or IST distortion corrections applied. We investigate the elevation accuracy improvement gained from the SPE correction for these two different ICESat operation periods, including ice sheet change detection computed between Laser 3a (Oct. 7, 2004–Nov. 7, 2004) and Laser 2a (Sept. 25, 2003–Nov. 18, 2003).

2. Geolocation Parameter Calibration

[4] Laser pointing, ranging, timing and orbit errors must be compensated in order to accurately geolocate the laser altimeter surface returns. The laser range observations can be exploited in an integrated residual analysis to accurately calibrate these geolocation/instrument parameters [*Luthcke et al.*, 2002]. This approach has been successfully applied to Shuttle Laser Altimeter (SLA) and Mars Global Surveyor (MGS) laser altimeter data significantly improving the resulting geolocation [*Luthcke et al.*, 2002 and *Rowlands et al.*, 1999]. Here we apply this approach, processing ICESat altimeter range observations from ocean scans (OS) and "round"-the-world scans (RTWS) along with dynamic crossovers [*Rowlands et al.*, 1999] in order to calibrate and correct the SPE long-term bias trends and orbital variation.

[5] OS and RTWS are specifically designed calibrations that use commanded spacecraft attitude maneuvers and ocean altimeter range observations to recover pointing, ranging and timing parameters. The parameters are estimated from a batch reduction of the altimeter range residuals using Bayesian least-squares differential corrections. The maneuver is a conic-like small amplitude (3° or 5°) deliberate roll and pitch deviation of the spacecraft attitude from nominal nadir pointing. Each 20 minute OS has two complete conic-like revolutions around the local nadir direction. The RTWS calibration maneuvers are simply

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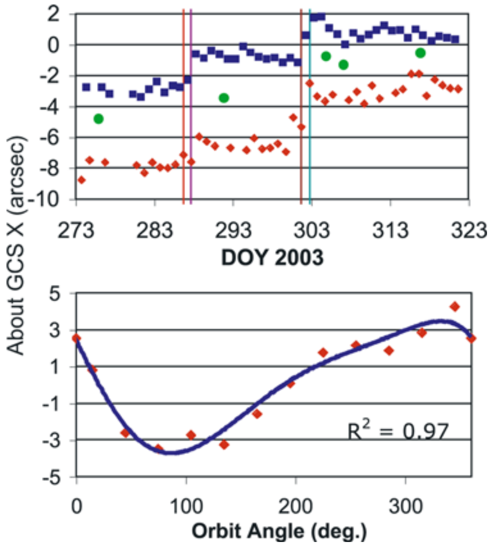

Figure 1. Laser 2a SPE scan calibration results about GCS X axis. (top) Calibration results from individual OS. Blue points are from OS performed near orbit midnight while red points are from orbit noon. Vertical lines represent times of commanded instrument temperature changes. (bottom) Orbital variation recovery from the first RTWS; red points are bias estimates, while blue line is polynomial fit.

OS maneuvers performed continuously for a complete orbit revolution. Detailed error analysis and application show these maneuvers are a strong filter for isolating pointing errors from other error sources [*Luthcke et al.*, 2000 and 2002]. Additionally, these calibrations are independent from the ice sheet data used in determining ice sheet surface elevation change.

[6] For ICESat, the OS maneuvers are performed nominally twice per day over the mid-Pacific: one is done approximately at orbit noon and one approximately at orbit midnight to capture any instrument thermal-mechanical variation. Pointing biases in both the GLAS Coordinate System (GCS) X and Y axes, along with a range bias, are estimated through the reduction of the ocean surface altimeter range residuals from each OS. The RTWS calibrations are performed nominally every 8 days and provide a means to estimate remaining SPE orbital variation as a function of orbit angle (angle between the satellite position vector and the sun vector projected in the orbit plane where 0° is orbit 6AM and 90° is orbit noon). Through the reduction of the range residuals from the RTWS, pointing biases in both the GCS X and Y axes are nominally estimated every 7.7 minutes or every 30° in orbit angle. The resulting OS and RTWS calibration history facilitate sub-arcsecond calibration of SPE (orientation and amplitude) at time scales of ~8-minutes to months [*Luthcke et al.*, 2002].

[7] Figure 1 presents a sample of the SPE calibration history for the Laser 2a Release 19 data. The calibrations for only one orientation component, namely the rotations about the GCS X-axis are shown, but similar pointing errors are observed about the GCS Y-axis. The OS and RTWS calibration histories have been computed for the latest release of each ICESat observation period. These calibrations show significant SPE remain in the data even for the best ICESat operations period (Laser 2a) with SRS data applied. Additionally, Figure 1 shows that the errors are clearly correlated to instrument temperature changes. As mentioned previously, due to instrument problems, no SRS data has yet been applied to the Laser 3a data. As a result, the Laser 3a data show significantly larger pointing related errors than Laser 2a (over a factor of 3 larger), but with similar dominant orbital variation.

3. Correction and Validation

[8] In order to correct the SPE remaining in the ICESat data we used the extensive OS and RTWS calibration time series to develop orbital variation and bias trend SPE correction functions. The calibrations were based on the latest releases of the data (that did not contain the SPE corrections) for both Laser 2a (Release 19) and Laser 3a (Release 18). We then applied these pointing correction functions to the ICESat attitude time series and recomputed the geolocation for both the Laser 2a and Laser 3a data. These corrections were verified and implemented to create the Release 21 version of the Laser 2a data. Overall the mean and standard deviation of the OS calibrations were reduced from 2.81 ± 3.99 arcsec (total angle, Release 19) to 0.00 ± 0.94 arcsec with our SPE corrections applied (Release 21).

[9] As an independent verification of the scan-derived SPE corrections we processed all of the ICESat Laser 2a ~nadir pointing (no OS or RTWS) ocean altimeter range observations, i.e. data not used in the derivation of the corrections. Sea surface residuals were then computed using the GSFC mean sea surface, correcting for tides and inverse barometer effect [*Wang*, 2001 and *Ray*, 1999]. A range bias was estimated separately from global ascending and descending ocean altimeter range residuals every 8 days. Figure 2 shows the significant reduction in the discrepancy between range biases determined separately from ascending and descending ocean range residuals due to the corrections accounting for the large SPE orbital variation and bias trend.

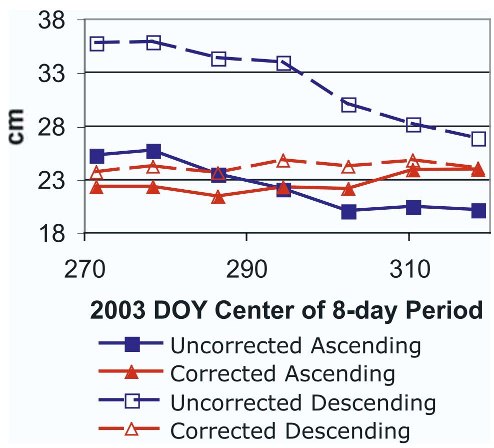

Figure 2. Global range bias estimated separately from 8-day ascending and descending Laser 2a ocean ~nadir altimeter range observations before (Uncorrected: Release 19) and after scan-derived SPE correction is applied (Corrected: Release 21).

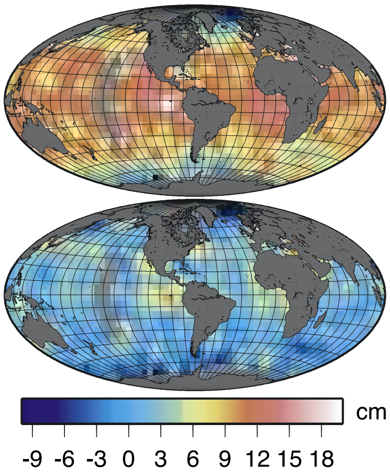

Figure 3. Difference between Laser 2a descending and ascending altimeter derived sea surface anomalies (SSA) before (top: Release 19) and after scan-derived SPE correction is applied (bottom: Release 21).

The resulting global range bias derived from ocean altimeter data is now stable at the centimeter level with a mean and standard deviation of 23.37 ± 0.61 cm (computed from the range bias estimates shown in Figure 2). The improvements gained from the scan-derived SPE corrections are clearly demonstrated in Figure 3, which shows a dramatic reduction in the discrepancy between descending minus ascending altimeter derived sea surface anomalies (SSA) after the SPE correction is applied.

[10] The orbital variation component of the SPE is largest in the mid-latitudes (near orbit noon and midnight), and smallest at high latitudes. Even so, 8-day ice sheet crossover analysis, where surface change should be minimal, can be used as another independent verification of the scan derived corrections. Figures 4 and 5 illustrate two examples of the reduction in ice sheet crossover discrepancies achieved when applying the scan derived pointing corrections. Figure 4 also shows the results of an additional solution ("combined solution") where the crossover discrepancies were combined with the scan maneuver range residuals in the derivation of the SPE corrections.

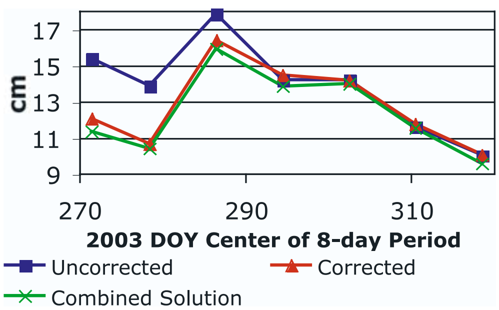

Figure 4. Root Mean Square of Laser 2a crossover discrepancies computed in 8-day bins using data from low sloping (<1°) regions of the Antarctica and Greenland ice sheets.

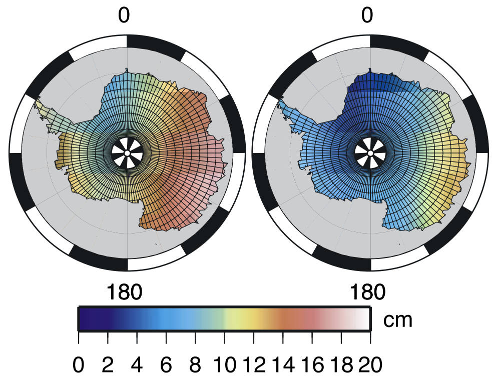

Figure 5. Laser 3a block-averaged (5° × 5°) 8-day crossover discrepancies over Antarctica, (left) before and (right) after scan-derived SPE corrections are applied.

In addition to pointing corrections, timing biases were estimated in each combined 8-day solution. The results of this combined solution show only marginal improvement over the solution using the data exclusively from scan maneuvers (Release 21) and independent of ice sheet crossover discrepancies. We infer that the scan maneuver derived corrections do not have significant remaining errors at high latitudes over the ice sheets where there were no data contributing to the solution. Additionally, the recovered timing bias of −0.22 ± 0.45 msec indicates there are no significant timing bias errors remaining in these ICESat data, consistent with that given by L. Magruder et al. (In situ timing and pointing verification of the ICESat altimeter using a ground-based system, submitted to *Geophysical Research Letters*, 2005).

4. Impact on Ice Sheet Change Detection

[11] In the analysis presented above we have chosen to correct both Laser 2a and Laser 3a data such that we can use these data, separated by one year, to study the impact of the SPE on ice sheet change detection. To accomplish this goal we computed ice sheet altimeter crossover discrepancies (Laser 3a minus Laser 2a), both before and after applying the SPE corrections. We then averaged these crossover discrepancies in geographical bins and computed an interpolated image of these Laser 3a-Laser 2a discrepancies. As noted above the Laser 3a (Release 18) data does not yet have the IST distortion correction applied. Even so, we proceeded with the analysis because its purpose is to investigate the impact of the SPE on surface elevation change detection noting that the high frequency IST distortion error can be reduced in the crossover discrepancy spatial averaging. Furthermore, the impact of the IST distortion error on the amplitude and spatial distribution of the SPE-induced surface elevation change error is negligible given the relatively long time scales of the scan-derived corrections.

[12] The results shown in Figure 6 clearly demonstrate that the SPE cause geographically correlated change error that obscures the ice sheet surface elevation change signal. The impact of the SPE on one year of ICESat derived ice sheet surface elevation change is demonstrated in the

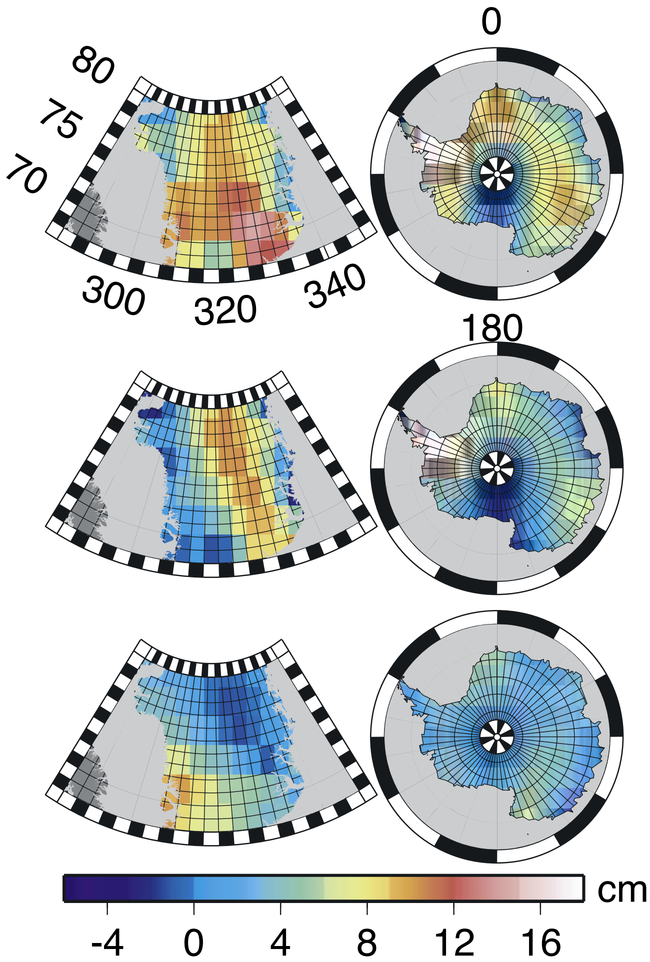

Figure 6. One year of (left) northern Greenland and (right) Antarctica regional ice sheet surface elevation change derived from block-averaged (3° lon. by 2° lat.) and smoothed Laser 3a minus Laser 2a crossover discrepancies, (top) before and (middle) after scan-derived SPE correction is applied. The difference (bottom), uncorrected surface elevation change (top) minus the corrected (middle).

difference between the "before" and "after SPE correction" grids (Figure 6 (bottom)). This difference demonstrates that the SPE cause ice sheet surface elevation change errors that range from −3 to 11 cm with a mean of 2.8 cm for Greenland, and −1 to 7 cm with a mean of 2.6 cm for Antarctica. Fortunately, as shown in this paper, we have at least one method to detect and correct these systematic errors for each ICESat operations period, and therefore, we can be reasonably confident that future releases of the ICESat data will have this dominant error source removed.

5. Conclusion

[13] Through specifically designed spacecraft attitude maneuvers and ocean altimeter range residuals, ICESat SPE (orbital variation and bias trend) have been calibrated for each laser operations period with sub-arcsecond precision. The calibration histories and independent validation tests show the ICESat elevation accuracy is significantly degraded by the SPE, resulting in geographically correlated surface elevation errors that change slowly in time. These SPE induced elevation errors obscure ice sheet surface elevation change signal and confound instrument range bias determination. We have shown that scan calibrations can be used to derive SPE correction functions that successfully minimize these errors. Further improvements in the ICESat elevation accuracy will certainly be made, but the analysis presented here demonstrates a major error source can be minimized resulting in improved surface elevation accuracies for ice sheet change detection.

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References

Luthcke, S. B., D. D. Rowlands, J. J. McCarthy, E. Stoneking, and D. E. Pavlis (2000), Spaceborne laser altimeter pointing bias calibration from range residual analysis, *J. Spacecr. Rockets*, *37*, 374–384.

Luthcke, S. B., C. C. Carabajal, and D. D. Rowlands (2002), Enhanced geolocation of spaceborne laser altimeter surface returns: Parameter calibration from the simultaneious reduction of altimeter range and navigation tracking data, *J. Geodyn.*, *34*, 447–475.

Ray, R. D. (1999), A global ocean tide model from TOPEX/Poseidon altimetry: GOT99, 2, *NASA Tech. Memo., NASA/TM-1999–209478*, 58 pp.

Rowlands, D. D., D. E. Pavlis, F. G. Lemoine, G. A. Neuman, and S. B. Luthcke (1999), The use of laser altimetry in the orbit and attitude determination of mars global surveyor, *Geophys. Res. Lett.*, *26*, 1191–1194.

Wang, Y. M. (2001), GSFC00 mean sea surface, gravity anomaly, and vertical gravity gradient from satellite altimeter data, *J. Geophys Res.*, *106*, 31,075–31,083.

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