In situ timing and pointing verification of the ICESat altimeter using a ground-based system

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[1] To provide validation of the ICESat laser altimeter time of measurement and geolocation, a ground-based technique was implemented at White Sands Space Harbor (WSSH), during the Laser 2a and 3a operational periods. The activities used an electro-optical detection system and a passive array of corner cube retro reflectors (CCR). The detectors and the CCRs were designed to provide an independent assessment of the laser footprint location, while the detectors also provide timing verification. This ground-based system unambiguously validated the elevation product time tag to 3 μsec ± 1 μsec. In addition, the ground equipment provided in situ geolocations of the laser pulse. Comparing the in situ results to the ICESat GLA14 data product the positions differ by 10.6 m ± 4.5 m for Laser 2a (Release 21) operations and 7.5 m ± 6.6 m for Laser 3a (Release 23). These comparisons correlate to pointing validations at this site, for the specific overflight configurations. **Citation:** Magruder, L., E. Silverberg, C. Webb, and B. Schutz (2005), In situ timing and pointing verification of the ICESat altimeter using a ground-based system, *Geophys. Res. Lett.*, *32*, L21S04, doi:10.1029/2005GL023504.

1. Introduction

[2] Since the launch of the Ice, Cloud and land Elevation Satellite (ICESat) in January 2003, ongoing efforts have been made to calibrate the Geoscience Laser Altimeter (GLAS) instrument. The calibration methods that have been developed and implemented are collaborative efforts to not only provide verification of the GLAS measurements but also other data products associated with ice, land and ocean altimetry. One calibration methodology is a ground-based system designed to provide an independent assessment of the laser footprint geolocation and the absolute time of arrival (time tag of the elevation product). The ground-based system process is unique in the fact that it does not require GLAS data products to produce a geolocation and measurement time, specifically the range measurement. This independent validation essentially provides verification of GLA14 (Global Land Surface Altimetry Data product) which contains geodetic latitude, and longitude of the surface illuminated laser spot and its time of arrival.

[3] The GLA14 data product releases for Laser 2a (Release 21) and Laser 3a (Release 19) operational periods have included the most current pointing corrections available [*Bae et al.*, 2004; *Luthcke et al.*, 2005]. These corrections offer the most accurate assessment of the geodetic latitude and longitude for the GLA14 products to date. The GLA14 geolocation determination of the footprint indicates the accuracy level of the laser pointing [*Schutz et al.*, 2005]. The ground-based system provides validation of the geolocation and thus an assessment of the pointing accuracy for a particular location along the ICESat ground track at a specific date and time. The results of the ground-based methodology will contribute data toward determination of the overall pointing accuracy as the process is complex and it is known that temporal and spatial variations exist throughout the ICESat orbit. The technique will also provide validation of the processing and algorithms responsible for the transformation of the lower level data products to the higher level GLA14 for a particular spacecraft configuration.

2. Ground-Based System Methodology

[4] The ground-based verification system utilizes many zenith pointed electro-optical devices designed to ‘capture’ the laser pulse on the surface. These electro-optical detectors are comprised of simple analog circuitry and a silicon PIN photodiode. They operate autonomously on 6 Volts (4 AA batteries) which enable them to be placed in a variety of patterns along the ICESat ground track. The detectors were designed and tested to provide laser photon detection with a minimum energy density of 1 nJ/cm^2 (full-width-half-maximum of a Gaussian profile). This criterion was based on the pre-launch “beginning of life” characteristics of the three GLAS lasers. Each detector within the ground array is placed with a differential GPS and the coordinates were determined with an uncertainty of ±1 m. The detectors register the arrival of the incoming GLAS photons, depending on the user-set threshold of the circuits. If the threshold is exceeded a light emitting diode (LED) is illuminated on the device. The geodetic coordinates of the triggered detectors provide the information needed to determine the centroid of the GLAS footprint.

[5] To record the time of arrival of the GLAS footprint on the surface, a small subset of the detectors are hardwired to a central timing system synchronized to a commercial GPS receiver. If triggered, the timing detectors will send a transistor-transistor-level (TTL) signal through the cables for registration of the event time relative to GPS. This timing process, in addition to the design and testing of the detector methodology is described by *Magruder et al.* [2003a, 2003b].

[6] In addition to the detectors, 1.2 cm diameter corner cube retro-reflectors (CCR) were placed within the calibration area along the ICESat ground track. These CCRs were used as a means to tag the reflected GLAS pulse with a

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unique return waveform signature in order to identify which pulses illuminated the instrumented region on the ground. This enables unambiguous comparison to be made between the ICESat time of measurement and the in situ data acquired with the detectors. To create the unique waveform signature the CCRs are placed on top of poles of varying heights (1.5 m, 3 m, 4.5 m or 6 m) which provides a unique temporal separation between the return photons from the CCRs and the photons reflected from the ground. The diameter of the CCRs ensures that there is similar signal from the CCRs as there is from the surface reflections. GLAS echo waveforms are represented as an envelope of returned laser energy (reflected photons) as a function of time. The return waveform from a CCR would appear as a spike within the Gaussian profile that is typical from a flat surface [*Abshire et al.*, 2005]. Since CCR waveform returns are a function of the height of the CCR illuminated, the pattern and height at which the CCRs are deployed govern the return waveform, therefore each combination has a unique waveform signature. The footprint geolocation can be determined through analysis of these unique signatures, in addition to providing a waveform tag within the ICESat data for timing comparison to the ground-based in situ measurement.

3. Ground-Based Calibration Implementation and Data Collection

[7] The detector and CCR arrays were deployed at White Sands Space Harbor (WSSH) in New Mexico. This site was chosen due to its secure perimeters and location relative to the ICESat reference ground tracks. In addition to the direct ICESat overflights of WSSH, there are other calibration opportunities at this location using the ICESat off-nadir pointing capabilities. The pointing capability is constrained to 5°, which will enable targeting of the calibration site up to ±52 km from the ground track of the spacecraft in the cross-track direction. For the WSSH location off-nadir pointing will provide at least four opportunities for calibration efforts during the 33-day laser operational campaigns within the 91-day repeat ground track orbit.

[8] The ground-based system, at times, used up to 400 detectors, placed in a rectangular grid pattern along the spacecraft ground track. This grid covers an area of approximately 250 m by 350 m, where the longer length is along-track. A little over half of the 400 devices were placed with 10 m by 10 m grid spacing for laser footprint position determination. Each of these detectors operated autonomously. The remaining detectors were placed in a northerly adjacent grid where the devices were devoted to position and timing or position determination only. The detectors used for position and timing were the devices wired to the timing system. The timing system could accommodate 96 individual timing inputs, which translated into eight columns of twelve detectors. The spacing for the timing array was 15 m in the along track direction and 19.5 m in the cross track direction. The remaining detectors were staggered within and around the timing array in order to cover a larger cross track area and improve the accuracy of the in situ geolocation given a denser central array. The geolocation determination using the detector system has an uncertainty of ±4.5 m (1.5 arcsec) given a crosstrack and alongtrack spacing of 10 m. The 1.5 arcsec uncertainty includes error contributions from detector sensitivity, positioning, geometric spacing and atmospheric scintillation [*Magruder*, 2001; *Magruder et al.*, 2003a]. The timing array provides a geolocation with an uncertainty of ±2.2 arcsec (6.6 m), a value containing all aforementioned error sources and a spacing of 15 m by 19.5 m.

[9] The CCRs were placed within the timing array with a 45 m by 58.5 m spacing, along-track and cross-track respectively. Each of the five CCR columns were installed with a different height relative to the adjacent column in order to produce a return waveform signature dependent on the footprint position within the array. The array is tilted approximately 8° from true north so that it is aligned with the satellite ground track during ascending passes, i.e. when ICESat moves northward. However, the array can provide the geolocation and the timing of the laser footprint for either ascending or descending passes if illuminated.

[10] Since the launch of ICESat there have been numerous opportunities for calibration data acquisition at WSSH. During Laser 2a operations there were seven opportunities (4 ascending and 3 descending). One year later, the third GLAS laser had its first operational period, Laser 3a, during which there were several additional WSSH overflights. This paper will discuss one overflight each from Laser 2a and Laser 3a and the results obtained from the ground-based calibration effort. Each of the overflights presented provide an unambiguous assessment of the laser timing as well as geolocation solutions from both the detector system and the CCR array signatures.

4. Timing Results

4.1. Laser 2a

[11] The ICESat Laser 2a overflight of the WSSH calibration site on day of year (DOY) 280 2003 was an ascending pass at 20:59 local time. The predicted ground track for this overflight was 23.9 km east of the detector array centerline, and therefore targeting the array required an off-nadir pointing angle of 2.6°. The configuration of the ground detector array differed slightly from that previously described. Instead of using an extended position array south of the timing detector area, 77 position detectors were placed among the 96 timing detectors (seven position detector columns in between the eight timing columns). This denser detector array covered a total area of 165 m (along track) by 137 m (cross track).

[12] ICESat overflew the target area at WSSH at the predicted time; 02:59:44 UTC. Three of the timing detectors and three autonomous position detectors registered the arrival of a GLAS footprint on the surface. Five of the six triggered devices (including the three timing detectors) were in the northern portion of the array, and one was in the southern portion of the array (Figure 1).

[13] A mean timestamp for the arrival of the GLAS footprint was calculated from the three timing data points, at 118767584.575261708 s J2000 with a standard deviation of 195 ns. This timestamp includes all corrections and delays associated with the hardware, such as the signal delay through the cable from the detector to the timing station [*Magruder et al.*, 2003a]. The mean time stamp supplied by the timing system has microsecond level

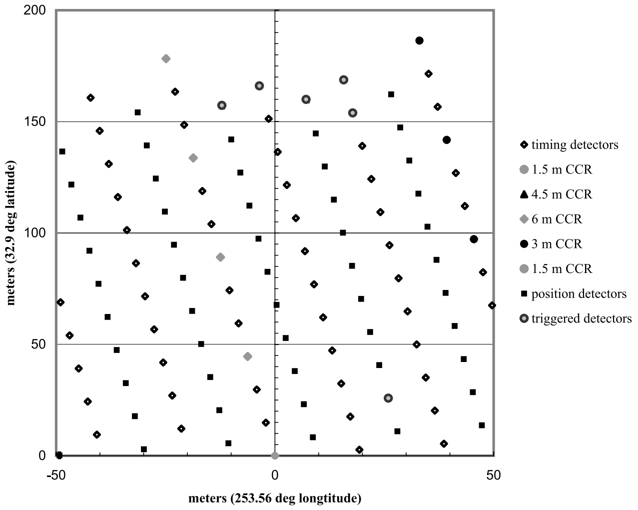

Figure 1. Ground detection results from ICESat calibration overflight on DOY 280, 2003.

accuracy, as determined through laboratory and field testing [*Magruder et al.*, 2003b].

[14] The corresponding GLAS return waveforms (GLA01 data product) for the DOY 280 2003 overflight were analyzed for CCR signatures. As expected, these CCR 'hits' were easily identified among the typical return waveforms from the otherwise flat, homogenous WSSH surface (Figure 2). The waveform shown is the second of two GLAS footprints that illuminated the CCR array, however, the first hit displays the same temporal signature since the ground track is aligned with the CCR pattern for ascending passes. In Figure 2, the first peak in the waveform is from the CCR and the second peak is from the ground. From the strength of these two peaks we conclude that the illuminated CCR was located within the central portion of the far field pattern of the GLAS footprint, a reduced peak would be expected if the CCR was located in the outer edge of the GLAS pulse. More analysis of the CCR signature waveforms for geolocation determination will be addressed in a subsequent section.

[15] Once the particular pulse that illuminated the target array was identified, the corresponding GLAS data was used in comparison with the independent timing provided by the detector system. For this pulse, the GLA14 data product contains a transmit time of 118767584.573263 s (J2000) and a transit time of 1.996 ms. The transit time accounts for the elevation of WSSH ($\sim$1165 m), the off-nadir angle of 2.6°, and the 5 mrad pitch bias of the spacecraft. The transmit time plus the transit time constitutes the calculated GLAS time of measurement, 118767584.575259 sec. In comparison, the time-tag determined by the ground-based system and the GLA14 timing data differ by 3 μsec $\pm$ 1 μsec. This result is consistent with the result determined from a previous pass on DOY 272 2003 (L. A. Magruder et al., ICESat Altimetry Data Product at White Sands Space Harbor, submitted to *IEEE Transactions on Geoscience and Remote Sensing*, 2005, hereinafter referred to as Magruder et al., submitted manuscript, 2005). The ICESat overflights of WSSH have unambiguously verified the GLAS timing data product associated with Laser 2a operations to well within the mission requirement of 0.1 msec timing knowledge.

4.2. Laser 3a

[16] The ground-based calibration technique was also implemented during the ICESat Laser 3a operational period. The first opportunity for timing verification for Laser 3 was on DOY 293 (October 19th) 2004, an ascending pass during local daylight hours. The predicted ground track was 23.7 km west of the detector array centerline which required, an off-nadir pointing angle of 2.6°. For this overflight, 96 timing detectors were deployed and the CCRs remained in the same relative positions. During the ICESat overpass at 08:58:24 am local time, two of the timing detectors registered the arrival of an ICESat footprint. These two triggered detectors were located 45 m south of the northern edge of the timing array and were in the second and third column from the east side. The mean time of arrival based on data from the two detectors was 151469904.860243413 sec (J2000) with a standard deviation of 47 ns. The GLA14 data product for this captured footprint is a transmit time of 151469904.858243 sec, and a transit time of 1.997 msec. The calculated GLAS time of measurement is 151469904.860240 sec. In comparison to the in situ data from the ground-based detection system, there is a difference of 3 μsec $\pm$ 1 μsec. These results consistent with those found for Laser 2a timing and again validate the timing data product within the mission criteria.

5. Geolocation Results

5.1. Laser 2a

[17] An independent assessment of the laser footprint geolocation can be made with the detector array and with the CCR signatures introduced into the GLAS waveforms. Each detector and CCR location within the array was determined using differential GPS. The placement and spacing associated with the detector system support a resultant geolocation with an accuracy level of 1.5 arcsec (4.5 m). The CCR signature analysis provides geolocation results with accuracies on the order of 3.3 arcsec (10 m) in

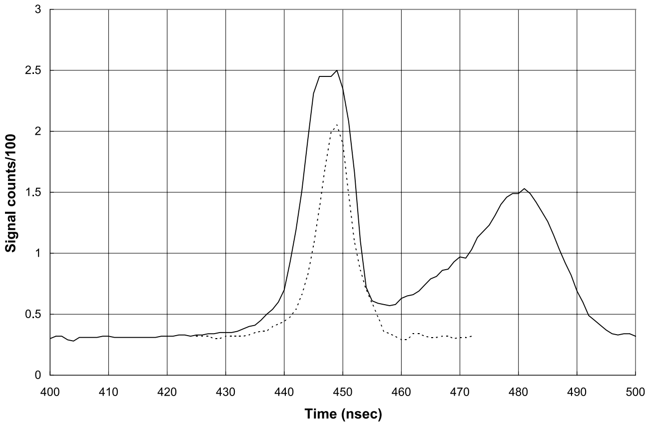

Figure 2. Return GLAS waveform for DOY 280 indicating a CCR signature. The digitized transmitted signal is shown as the dotted line while the return GLAS signal is the solid line.

the longitudinal direction (Magruder et al., submitted manuscript, 2005).

[18] For DOY 280 (Laser 2a), the five triggered detectors in the northern portion of the array provided a mean position (latitude and longitude) based on their collective coordinates. The calculated spot position determined by the detector array was 32.97072°N and 253.56955°E. After analysis of the DOY 280 CCR signature (Figure 2), the CCR geolocation solution was consistent with a footprint located at 149.5 m east of the CCR array western edge. This position was 5 m cross track from the solution determined with the ground detection system. The difference in the in situ geolocation data for the CCR and the detector array is most likely due to the decreased accuracy associated with the CCR waveform analysis technique as the process does not accommodate errors associated with waveform saturation nor does it offer much precision in the latitudinal direction due to the symmetry in the CCR North-South pattern.

[19] For the WSSH overflight on DOY 280 2003 (Laser 2a), the GLA14 geolocation corresponding to the footprint that illuminated the ground equipment is 32.970664°N and 253.569458°E. In comparison to the geolocation determined by the detector methodology, the two solutions agree to within 10.6 m. The GLA14 data product is also within 15 m of the solution based on the CCR signature analysis. These comparisons infer that for the satellite configuration during the WSSH overflights the pointing accuracy of ICESat is on the order of 3.5 arcsec ± 1.5 arcsec. This comparison validates the geolocation data product as compared to GLA14 Release 21 which includes all available pointing corrections from ocean scans [*Luthcke et al.*, 2005]. Figure 3 illustrates the relative WSSH ground-based instrumentation geolocation solutions for DOY 280.

5.2. Laser 3a

[20] For the verification of ICESat geolocation and the pointing for DOY 293 during Laser 3a operations over WSSH, the two triggered detectors provided a mean spot position of 32.970375°N and 253.569634°E. The CCR signature within the return waveform indicates a small spike approximately 50 ns before the ground return. The analysis of the CCR return, with consideration of the off-nadir angle and position/heights of the CCRs provides a geolocation solution of 32.97038°N and 253.569669°E. In comparison to a recent preliminary GLA14 data product release (equivalent to Release 23) which determines the geolocation to be 32.970396°N and 253.569590°E, the ICESat footprint geolocation is verified to 7.5 m (2.5 arcsec) ± 6.6 m for the specific spacecraft configuration over WSSH with the ground-based methodology. The geolocation position uncertainty (±6.6 m) is greater than the uncertainty established during Laser 2a operations due to the difference in geometric detector spacing. The location of the triggered detectors and the comparison of the geolocation solutions are illustrated in Figure 4.

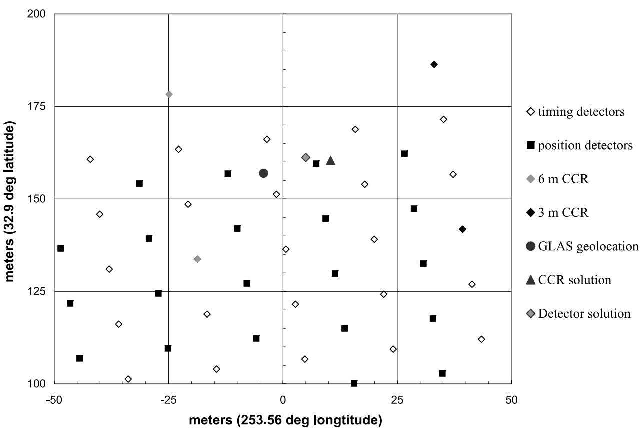

Figure 3. Geolocation solution comparison of the GLAS altimetry data product with the ground-based equipment at WSSH on DOY 280 2003.

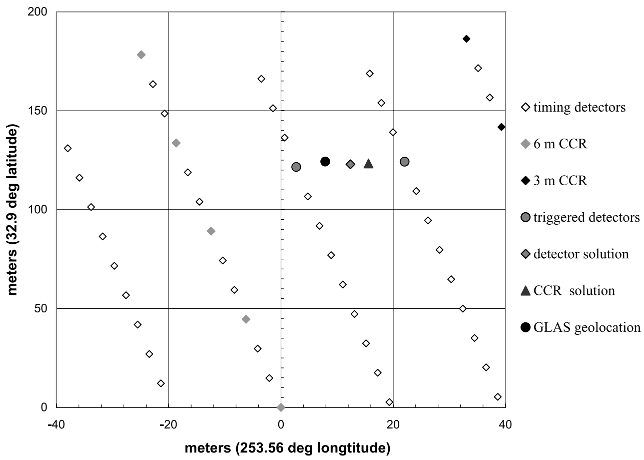

Figure 4. Geolocation solution comparison of the GLAS altimetry data product with the ground-based equipment at WSSH on DOY 293 2004.

6. Conclusions

[21] In the pursuit of providing independent validation of the ICESat pointing and timing, a ground-based detection system and a passive CCR array were implemented at WSSH. Overflights during the fall of 2003 (Laser 2a) and the fall of 2004 (Laser 3a) provided opportunities for timing and pointing verification of GLAS Laser 2 and Laser 3 respectively. During two particular overflights the altimeter time of measurement was unambiguously verified by the independent ground-based system to be accurate within 3 μsec ± 1 μsec. This exceeds the ICESat mission requirement for timing knowledge of 0.1 msec for both lasers. In addition, these two overflights provided solutions for independent laser footprint geolocations. The geolocation solutions were compared to the latest release of GLA14 data product for Laser 2a (Release 21), and Laser 3a (Release 23), which include available corrections known to date. The comparison indicates that the pointing knowledge for Laser 2a operations is within 3.5 arcsec ± 1.5 arcsec (10.5 m ± 4.5 m) and for Laser 3a operations the accuracy is on the order of 2.5 arcsec ± 2.2 arcsec (7.5 m ± 6.6 m) at the site of the detector array.

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