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Geoscience Laser Altimeter System (GLAS) on the ICESat Mission: On-orbit measurement performance

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[1] The GLAS instrument on NASA's ICESat satellite has made over 904 million measurements of the Earth surface and atmosphere through June 2005. During its first seven operational campaigns it has vertically sampled the Earth's global surface and atmosphere on more than 3600 orbits with vertical resolutions approaching 3 cm. This paper summarizes the on-orbit measurement performance of GLAS to date. **Citation:** Abshire, J. B., X. Sun, H. Riris, J. M. Sirota, J. F. McGarry, S. Palm, D. Yi, and P. Liiva (2005), Geoscience Laser Altimeter System (GLAS) on the ICESat Mission: On-orbit measurement performance, *Geophys. Res. Lett.*, *32*, L21S02, doi:10.1029/2005GL024028.

1. Instrument Description and Ground Testing

[2] The Geoscience Laser Altimeter System (GLAS) is a new generation space lidar developed for the Ice, Cloud and land Elevation Satellite (ICESat) mission [*Schutz et al.*, 2005]. The GLAS instrument combines a 3 cm precision 1064-nm laser altimeter with a laser pointing angle determination system [*Sirota et al.*, 2005] and 1064 and 532-nm cloud and aerosol lidar [*Zwally et al.*, 2002]. GLAS was developed by NASA-Goddard as a medium cost and medium risk instrument.

[3] GLAS uses the 1064-nm laser pulses to measure the two way time of flight to the Earth's surface. The instrument time stamps each laser pulse emission, and measures its emission angle relative to inertial space, the transmitted pulse waveform and the echo pulse waveform from the surface. GLAS also measures atmospheric backscatter profiles. The 1064-nm pulses profile the backscatter from thicker clouds, while the 532-nm pulses use photon-counting detectors to measure the height distributions of optically thin clouds and aerosol layers [*Abshire et al.*, 2003]. A GPS receiver on the spacecraft provides data for determining the spacecraft position, and provides an absolute time reference for the instrument measurements and the altimetry clock.

[4] Before launch, GLAS measurement performance was evaluated with "inverse lidar" called the Bench Check Equipment (BCE). The BCE also monitored the transmitted laser energy and the other critical instrument measurements [*Riris et al.*, 2003]. Before launch, the three GLAS lasers were qualified [*Afzal et al.*, 2002] and fired a total of 427 million shots, or 11% of the planned orbital lifetime. This pre-launch testing also uncovered a few issues. The co-alignment of the laser beams to the receiver field of view was found to vary more than expected, with instrument temperature and orientation. Three of the eight 532-nm detectors failed during instrument vacuum testing. Laser 3 also showed an unexplained small drop in its 532 nm energy. Unfortunately, due to project deadlines, it was not possible to correct these issues before launch.

2. Space Operation of Lasers and Laser Energy History

[5] After the ICESat launch, GLAS Laser 1 started firing on February 20, 2003, and was operated continuously through the Laser 1 campaign. The GLAS 1064-nm measurements showed strong echo pulses from the surface and cloud tops and better than expected atmospheric profiles. Operation of the 532-nm detectors was delayed. Figure 1 shows the 1064 and 532-nm energy histories to date for all lasers, with Laser 1 shown in red. After day 10, Laser 1 showed unusual and faster than expected energy decline, and it failed on day 38. NASA formed an independent GLAS anomaly review board (IGARB) to investigate the cause. It discovered unexpected manufacturing defects in the laser diode pump arrays used in the flight lasers [*Kichak*, 2003]. The problem was in an inaccessible area in a commercial part and was latent in its effects, so its symptoms were not evident in the earlier pre-launch part life tests or in pre-flight laser tests. All flight lasers have been impacted by this issue, since all flight lasers used the same part types.

[6] To maximize its duration, the ICESat mission was re-planned to operate the remaining two GLAS lasers for three 33-day campaigns per year [*Schutz et al.*, 2005]. This reduced the GLAS measurement duty cycle from 100% to 27% per year. Subsequently Laser 2 was used for campaigns 2a–2c. Laser 2's energy decline is thought to be caused by a slow process associated with the frequency doubler and trace levels of out-gassing. To mitigate this, Laser 3 has been operated at a lower temperature and has experienced a slower energy decline rate than Lasers 1 and 2.

[7] GLAS measures the far field pattern of the operating laser with its Stellar Reference System (SRS) [*Sirota et al.*, 2005]. The measured beam patterns have a nominal elliptical Gaussian shape but show differences between lasers and have changed with laser energy and time. Figure 2 shows some samples of the laser far field patterns measured to date. The laser spots changed somewhat through the campaigns. On the Earth's surface, the laser spot diameters, at the exp(-2) relative energy points along the minor and major axes diameters, have averaged 52 m × 95 m for Campaigns L1-L2c, and 47 × 61 m for L3a and L3b. The equivalent area circular spot diameter has been about 64 m. The changes in the laser far field patterns are thought to be

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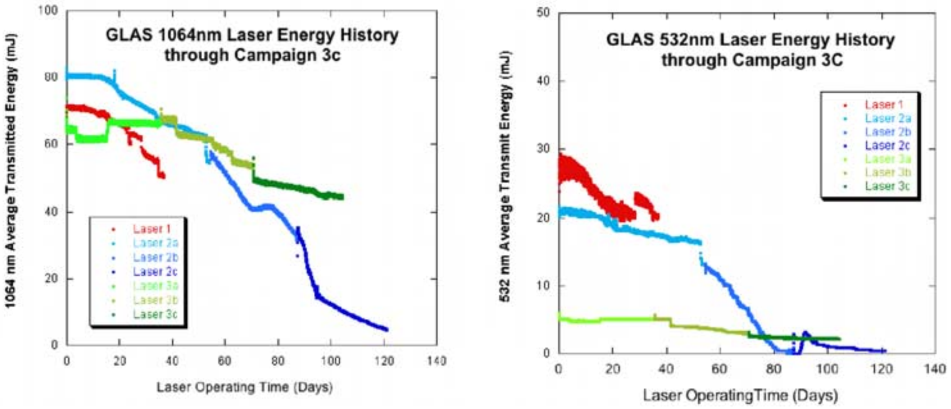

Figure 1. GLAS laser pulse energy history for all operating periods to date at (a) 1064 nm and (b) 532 nm. Laser 3 was powered off at the end of Laser 3c, and Lasers 2 and 3 are still operational. Some of the changes in laser energy were caused by commanded changes in laser temperature.

caused by changes over time in the spatial distribution of light from the laser diode pump arrays.

[8] The three GLAS lasers have fired over 904 million shots in space through the end of campaign 3c. Laser 1 fired for 126.8 million shots and Laser 2 fired for 417.5 million shots. Laser 3 has been operated at 13.8 and 16 deg. C and has produced ~360 million shots. If its energy trend continues, Laser 3 should be useful for about another 6 campaigns.

3. On-Orbit Science Measurements

[9] GLAS has vertically sampled the Earth's surface and atmosphere with unprecedented coverage, accuracy and vertical resolution. This section gives a few highlights of each GLAS science measurement type, which are all discussed in more detail in subsequent papers of this Special Issue.

3.1. Ice Sheet Altimetry

[10] The ICESat ice sheet altimetry measurements have dramatically improved the accuracy of elevation measurements of the Antarctica and Greenland continents (C. A. Shuman et al., Ice sheets from ICESat: Summary, submitted to *Geophysical Research Letters*, 2005, hereinafter referred to as Shuman et al., submitted manuscript, 2005). The strong echo pulses from the flat, bright ice surfaces preserves the 6-nsec wide GLAS laser pulse shape and allows its altimeter receiver to measure with <3 cm rms shot-to-shot precision. As an example, Figure 3 shows the standard deviation of the ICESat elevation products across the flat ice surface above Lake Vostok Antarctica (Shuman et al., submitted manuscript, 2005). The <2.5 cm standard deviation is the GLAS range precision and matches that measured before launch. The <80 m diameter footprints and 3 cm vertical resolution of GLAS have also enabled accurate measurement of sea-ice freeboard heights and thickness [*Zwally et al.*, 2002] and ice shelf rifts (H. A. Fricker et al., ICESat's new perspective on Ice Sheet Rifts: the Vertical Dimension, submitted to *Geophysical Research Letters*, 2005).

[11] The GLAS design was based on an initial 10 dB margin (excess capability) in laser energy, which allowed for laser energy decline with use and surface altimetry measurements through some cloud attenuation. For the

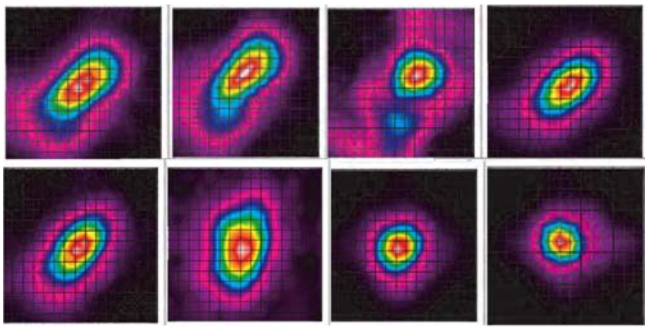

Figure 2. Sample GLAS images of the laser far field patterns measured during different campaigns. (top) Laser 1 (2/20/03), Laser 1 (3/4/03), Laser 1 (3/26/03), Laser 2a (9/26/03). (bottom) Laser 2b (2/18/04), Laser 2c (5/18/04), Laser 3a (10/4/04), and Laser 3b (2/18/05).

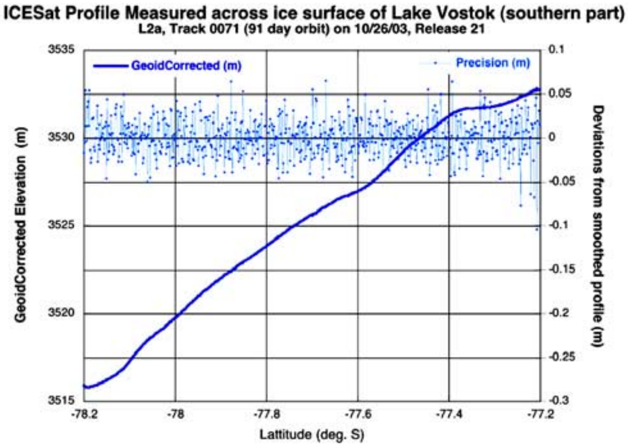

Figure 3. ICESat elevation products across the icesheet above Lake Vostok, along Track 0071 on 10/26/03. The rms deviation of <2.5 cm for the individual elevation measurements is the GLAS range precision.

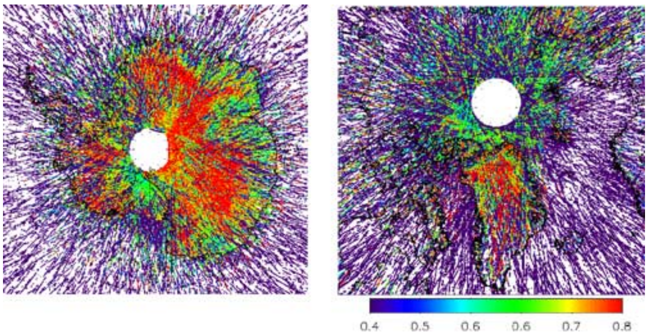

Figure 4. Measurement of relative echo pulse energies over the south (left) and the north polar region (right) for Laser 2b. Red and blue indicate stronger and weaker echo pulses respectively. Echo pulses are strong over Antarctica and near the North Pole and northern and central Greenland, with weaker echoes and more outages from clouds over southern Greenland.

mission to date the surface measurement probabilities have been >50% for the polar regions. The GLAS measurements have provided dense coverage of Antarctica, and northern and central Greenland (Figure 4) [*Sun et al.*, 2004]. As expected, there are weaker echo signals and more outages due to thicker clouds in some coastal regions of Antarctica and particularly near the coasts of southern Greenland.

3.2. Altimeter Receiver Echo Pulse Shape and Dynamic Range

[12] The altimeter receiver, flight electronics and in-flight algorithms have operated almost identically as in pre-launch testing, and a large percentage of recorded echo pulse shapes are as expected. On orbit the 1064-nm altimetry detector and receiver have recorded echo pulses from 0.05–13 fJ energy with no distortion, yielding a linear dynamic range of 260. Measurements made with high transmit energies to flat ice surfaces through a clear atmosphere produce stronger than expected echo pulses (energies > 13 fJ), which cause some nonlinear response and pulse distortion (saturation) in the detector assembly. The much stronger echoes from flat-water surfaces cause significant distortion, which delays the onset of the center of the pulse and biases (lengthens) the range measurement [*Fricker et al.*, 2005]. These effects have been reproduced in ground tests, and their errors will be modelled and corrected in future data releases.

3.3. Trees and Vegetation

[13] GLAS has acquired numerous profiles across Earth's vegetated areas [*Harding and Carabajal*, 2005]. Figures 5a and 5b shows examples of echo pulses measured on 10-13-2003 when ICESat overflew a forested area north of Greenbelt MD. They show the tree height extent and the two lobed echo pulses are characteristic of scattering from tree canopies and the underlying ground surfaces.

3.4. Laser Pointing Determination

[14] The operation of the SRS is described in more detail by *Sirota et al.* [2005]. The SRS system response is very repeatable, and its cameras have recorded all the laser far field patterns as expected. Measurements from Laser 2a have been shown to have pointing determination accuracy of better than 2 arcsec, and reprocessing of measurements from other campaigns is expected to achieve comparable accuracy.

3.5. Atmospheric Backscatter Profiles

[15] The performance of the GLAS atmospheric measurements is summarized by *Spinhirne et al.* [2005]. Profiles acquired during Laser 2a at 1064 and 532-nm respectively are shown in Figures 6a and 6b. They show the surface echoes from the Antarctic continent, and the much higher clouds present over the equatorial regions. The 1064-nm profiles have lower sensitivity, but are available for all operation periods. The 532-nm profiles have much better SNRs for weak aerosol backscatter due to their more sensitive photon counting detectors. The best 532-nm profiles were measured during Laser 2a and 2b, when the 532-nm energy was the highest. Laser 2c and Laser 3 have lower 532-nm energy, which has reduced the detected signal. The 532-nm profiles for Laser 3 also indicate a broadened

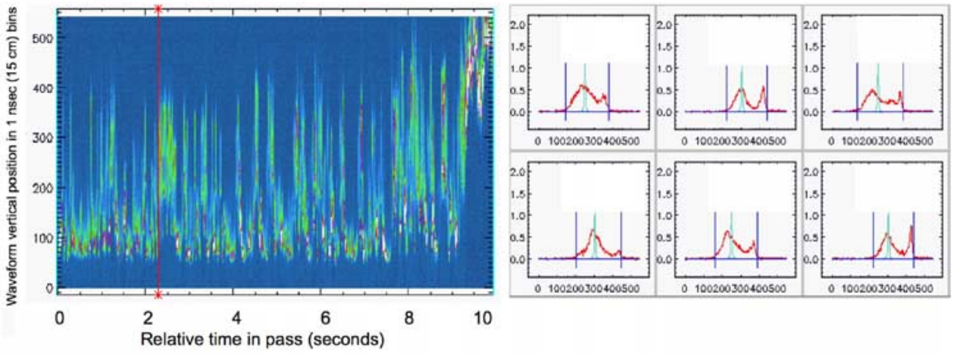

Figure 5. (a) A sample of stacked echo pulse waveforms, which are color coded for echo pulse power, for an ICESat pass across a forested area, near Greenbelt MD on 10/13/2003. The record shows pulse scattering from tree canopies and the ground surface. (b) Sample echo pulses from trees at the location of the red line, plotted from 0 to 500 digitizer bins.

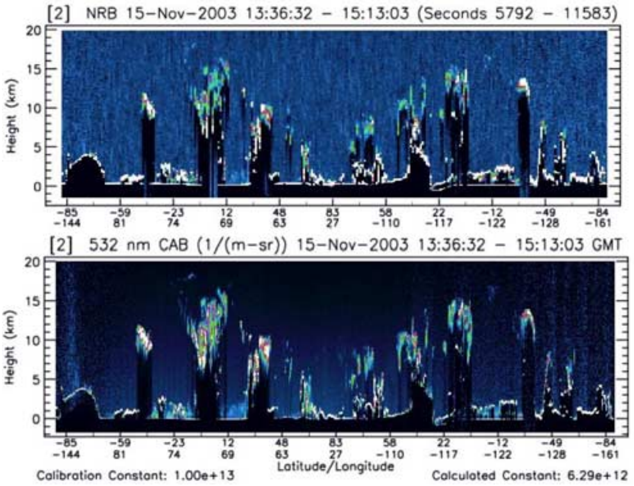

Figure 6. A sample orbit of atmospheric backscatter profiles acquired on 11/15/2003. (a) 1064-nm profiles, with the backscatter intensity color encoded from 5e-5 to 5e-4/m/ster. (b) 532 nm profiles, with the backscatter intensity encoded from 1e-8 to 1e-5/m/ster.

far-field pattern from the laser, which has further reduced the detected signal.

3.6. Laser-to-Receiver Receiver Alignment

[16] The alignment of the lasers relative to the receiver field of view is within pre-launch predictions, although it is different for each laser and changes with instrument heat pipe temperatures. When the laser far-field image is off center relative to the receiver, the receiver can cause a position dependent spatial attenuation of the laser footprint. Although this can bias height measurements made over sloped surfaces, *Luthcke et al.* [2005] have developed an approach which compensates for them.

3.7. Optical Receiver and Timing Evaluation

[17] The GLAS optical receiver was evaluated on orbit using the sun illuminated Earth and a built-in optical test source. These allow evaluation of the receiver optical path, detector and electronics. The results show the altimeter receiver response has no detectable increase in noise from radiation or decrease in sensitivity. The altimeter clock has been monitored by comparing its accumulated counts to the 0.1 Hz time marks from the GPS receiver. The results show the range errors from frequency change are <1 cm [*Sun et al.*, 2004]. The accuracy of the GLAS measurement time stamps has been evaluated by registering the arrival time of laser pulses from GLAS at a ground based detector array [*Magruder et al.*, 2005] and the errors were found to be <3 usec.

4. Ongoing Work

[18] Several activities are underway to model and remove errors and improve the accuracy of the processed GLAS measurements. The range error caused by echo pulse distortion has been accurately measured. The results will first be applied to measurements over flat surfaces and subsequent versions will be used for those over sloped and water surfaces. Work is also underway to better understand and model laser to altimeter receiver angular alignment.

5. Summary

[19] The GLAS instrument has provided a new, precise and global view of the vertical dimension of the Earth surface and atmosphere. The altimeter range resolution is <3 cm for flat surfaces. Even with clouds, the altimetry surface measurement probabilities over the polar regions are >50%. Although the GLAS duty cycle was reduced from 100% to 27% per year after problems with the lasers were found, Laser 3's 1064-nm performance shows promise for another 6 campaigns. The ICESat mission has already established a pathfinder set of measurements, which will enable an accurate and longer time series with the remaining ICESat measurements and with future missions.

[20] **Acknowledgments.** Designing and developing GLAS required a dedicated effort from a large and very talented instrument team over many years. We are indebted to Ron Follas, Eleanor Ketchum, the GLAS Instrument Team Leaders and members, and to David Hancock and Peggy Jester. We appreciate the leadership of Bob Schutz, Jay Zwally, and Waleed Abdalati, and the support of the Science Team and their colleagues and the ICESat mission team.

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