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

James B. Abshire[1], Xiaoli Sun[1], Haris Riris[1], J. Marcos Sirota[2], J. F. McGarry[1], Steve Palm[3], Donghui Yi[4], Peter Liiva[2]

(1) NASA Goddard Space Flight Center, Code 690, Greenbelt MD 20771 USA, Email: James.Abshire@gsfc.nasa.gov
(2) Sigma Space, 4801 Forbes Blvd, Greenbelt MD 20706 USA, Email: marcos.sirota@sigmaspace.com
(3) SSAI Inc, Code 613.1, NASA Goddard, Greenbelt MD 20771 USA, Email: spp@virl.gsfc.nasa.gov
(4) SGT Inc, Code 614.1, NASA Goddard, Greenbelt MD 20771 USA, Email: Donghui.Yi@gsfc.nasa.gov

Abstract: The GLAS instrument on NASA's ICESat satellite has made over 1.1 billion measurements of the Earth surface and atmosphere through March 2006. During its first nine operational campaigns it has vertically sampled the Earth's global surface and atmosphere on more than 3600 orbits with vertical resolutions approaching 3 cm. The first set of papers have been recently published [1].This paper highlights some of the on-orbit measurements to date.

1. Instrument description and ground testing

The Geoscience Laser Altimeter System (GLAS) is a precision space lidar developed for the Ice, Cloud and land Elevation Satellite (ICESat) mission [2]. The GLAS instrument combines a 3 cm precision 1064-nm laser altimeter with a laser pointing angle determination system [3] and 1064 and 532-nm cloud and aerosol lidar [4]. GLAS was developed by NASA-Goddard as a medium cost and medium risk instrument.

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, measures its emission angle relative to inertial space, and measures the transmitted pulse waveform and the echo pulse waveform from the surface. GLAS also measures atmospheric backscatter profiles. The 1064-nm pulses profile backscatter from thicker clouds, while those at 532-nm use photon-counting detectors and measure the height distributions of optically thin clouds and aerosol layers [5]. A GPS receiver on the spacecraft provides data for determining the spacecraft position, and provides an absolute time reference for the instrument measurements and altimetry clock.

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 [6]. Before launch, the three GLAS lasers were qualified [7] and fired a total of 427 million shots, or 11% of the planned orbital lifetime. This pre-launch testing 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 temperature and instrument orientation. Several of the 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 further address these issues before launch.

2. Space operation of lasers and laser energy history

After the ICESat launch, GLAS Laser 1 started firing on February 20, 2003, and was operated continuously through the Laser 1a 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 though 3c 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 array parts used in all the flight lasers [8]. The problem was in an inaccessable area in a commercial part and was latent in its effects, so its symptoms were not evident in the earlier pre-launch part lifetests or in flight laser tests. Since they all used the same part types, all flight lasers were impacted.

To maximize its duration, the ICESat mission was re-planned to operate the remaining two GLAS lasers for three 33-day campaigns per year [2]. This reduced the GLAS measurement duty cycle from 100% to 27%. Laser 2 was used for campaigns 2a - 2c. Laser's 2 energy decline during campaigns 2b and 2c is thought to be caused to a slow process associated with 532-nm photons and trace levels of material out-gassing. To mitigate this, Laser 3 was operated at a lower temperature and has experienced a slower energy decline rate than Lasers 1 and 2.

GLAS measures the far field pattern of the operating laser with its Stellar Reference System (SRS) (Sirota et al., 2005). The measured patterns are usually gaussian, but show differences between lasers and changes with laser energy and time. On the Earth's surface, the laser spot diameters, the equivalent area circular spot diameter has been about 64 m. The changes in the far field patterns are likely caused by changes in the spatial distribution of light from the laser diode pump arrays.

The three GLAS lasers have fired over 1.1 billion shots in space through the end of campaign 3e. 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 ~520 million shots. If its energy trend continues, Laser 3 should operate for another 5-6 campaigns.

3. On-orbit science measurements

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 discussed in more detail in papers contained in [1].

a. Ice sheet altimetry - The ICESat ice sheet altimetry measurements have dramatically improved the accuracy of elevation measurements of the Antarctica and Greenland continents [9]. The strong echo pulses from the flat, bright ice surfaces preserves the 6 nsec GLAS laser pulse shape and allows its altimeter receiver to measure with < 3 cm rms shot-to-shot precision. As an example, Figure 2 shows the standard deviation of the ICESat elevation products across the flat ice surface above Lake Vostok Antarctica. 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 and ice shelf rifts.

The GLAS design was based on excess capability (or margin) in laser energy, which allowed for laser energy decline and surface altimetry measurements through some clouds. For the 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 as shown in Figure 3. 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.

b. Altimeter receiver echo pulse shape and dynamic range - 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 laser energies to flat ice surfaces through a clear atmosphere produce stronger than expected echo pulses, which cause some nonlinear response and pulse distortion in the detector. 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. These effects have been reproduced in ground tests, and their errors will be corrected in future data releases.

c. Trees and vegetation - GLAS has acquired numerous profiles across Earth's vegetated areas. Figures 4a and 4b 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.

d. Atmospheric backscatter profiles - The performance of the GLAS atmospheric measurements is summarized by Spinhirne et al. (2005). Profiles acquired during Laser 2 at 532-nm respectively are shown in Figure 5. 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 far-field pattern from the laser, which has further reduced the detected signal.

e. Optical receiver and timing evaluation - The 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.

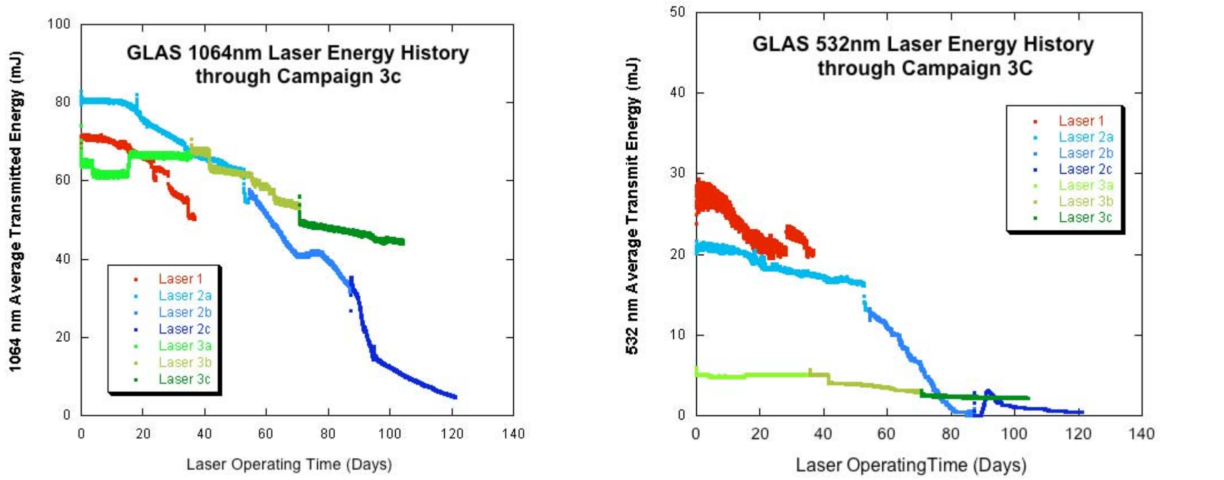
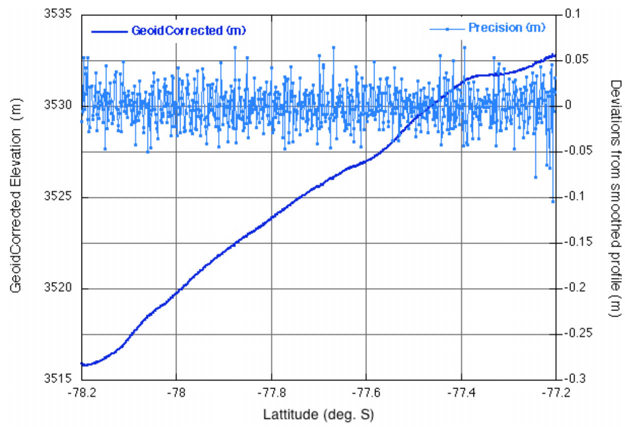


Figure 1 - GLAS laser pulse energy history for all operating periods to date at a). 1064 nm b) 532 nm. Laser 3 was last used for campaign 3c, and Lasers 2 and 3 are still operational.

Figure 2. 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.



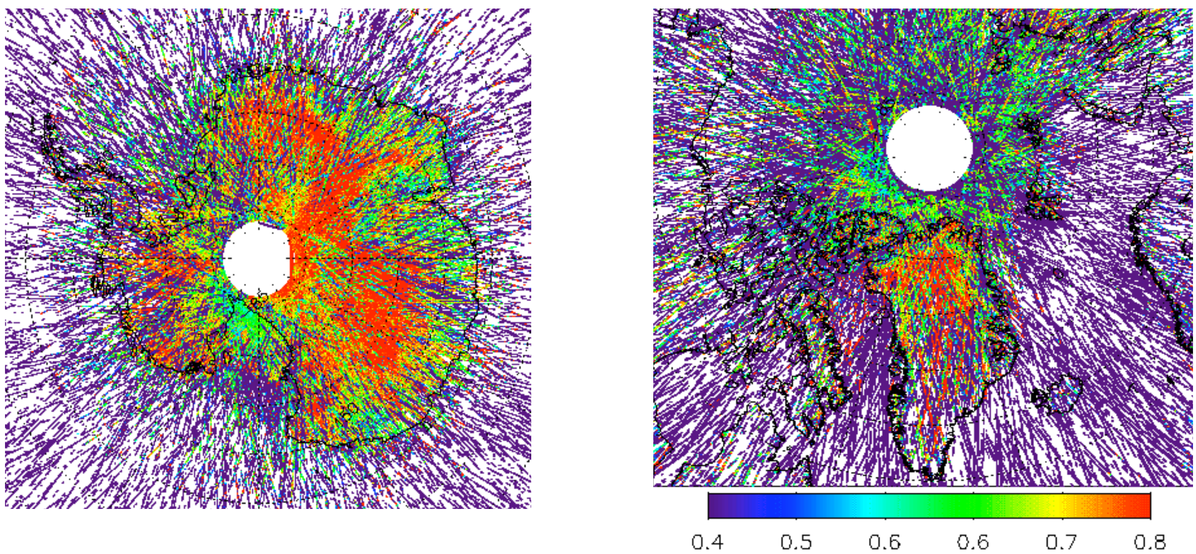


Figure 3. Measurement of relative echo pulse energies over the south (left) and the north polar region (right) for Laser 2b. Red and blue indicate stronger and weaker echo pulses respectively. Echo pulses are strong over Antarctica and near northern and central Greenland, with weaker echoes and more outages from clouds over southern Greenland.

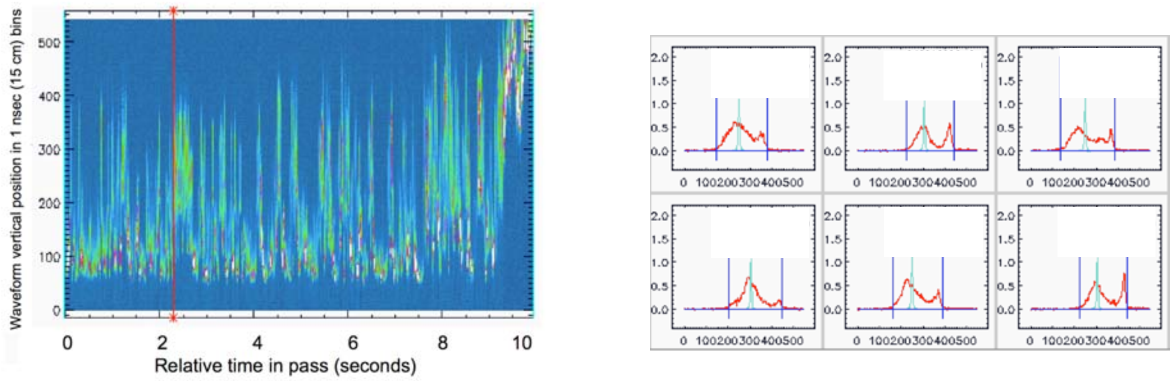


Figure 4 a) A sample of stacked echo pulse waveforms color coded for echo pulse power, for an ICESat pass across a forested area, near Greenbelt MD, on 10/13/2003. The record shows pulse scattering from tree canopies and the ground surface. b) Sample echo pulses from trees at the location of the red line in (a), plotted from 0 to 500 bins

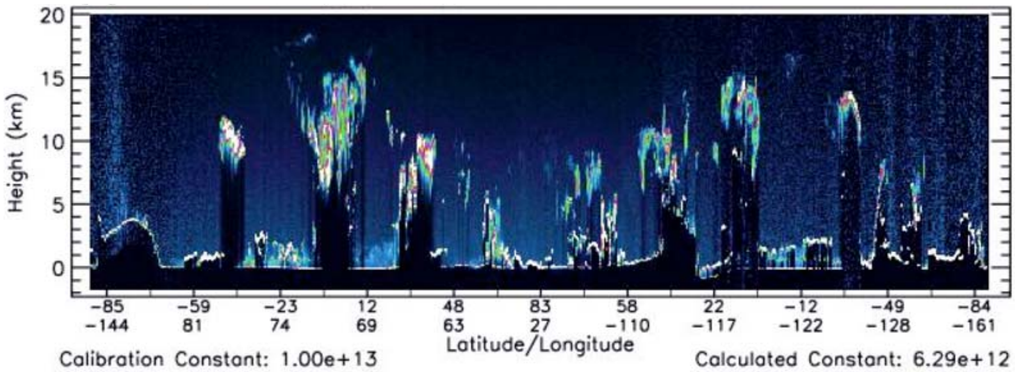


Figure 5 - A sample orbit of 532 nm atmospheric backscatter profiles from 11/15/2003, with the backscatter intensity color encoded from 1e-8 to 1e-5 /m/ster.

5. Summary

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, Laser 3's 1064-nm performance shows promise for another 5-6 campaigns. The ICESat mission has already established a uniquely precise global pathfinder data set, and has initiated a series to be continued by its subsequent campaigns and by follow-on missions.

References:

1. *Geophysical Research Letters*, Special Issue on the ICESat Mission, 2005. Avail from: http://www.agu.org/journals/ss/ICESAT1/

2. Schutz, B., J. Zwally, C. Shuman et al., ICESat mission overview, 2005, in [1].

3. Sirota, J. M., et al., The Transmitter Pointing Determination in the Geoscience Laser Altimeter System, 2005, in [1].

4. Zwally, H.J., et al., ICESat's laser measurements of polar ice, atmosphere, ocean, and land, *Journal of Geodynamics*, Vol. 34, pp. 405–445, 2002.

5. Abshire, J. B., et al., Geoscience Laser Altimeter System (GLAS) on the ICESat Mission: On orbit Measurement Performance, 2005, in [1].

6. Riris, H. et al., A System to Characterize the Geoscience Laser Altimeter System (GLAS), In: *Technical Digest CLEO 2003*, Optical Society of America, Washington, DC, 2003.

7. Afzal, R. S., et al., Performance of the GLAS Laser Transmitters In: Photonics West, *Proceedings of the SPIE, Vol .6100*, Paper 6100-49, January 2006.

8. IGARB report, NASA. Executive Summary available from www. icesat.gsfc.nasa.gov/docs/, 2003.

9. Shuman, C. A., et al., ICESAt Antarctic Elevation data: Preliminary Preliminary Precision and accuracy Assessment, Geophysical Research Letters, Vol. 33, Paper L07501, 2006.