SPACEBORNE LASER ALTIMETRY: 2001 AND BEYOND

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Abstract:

In July 2001, a spaceborne laser altimeter will be launched into a near-polar, near-circular orbit to measure changes in polar ice-sheet topography, as well as along-track land and ocean topography. The ice-sheet measurements will address fundamental questions about the growth or shrinkage of the polar ice-sheets and their contribution to current and future global sea level rise or fall. The measurements, which also include cloud heights, will be made using a 1064 nm laser pulse. An atmospheric channel, using a 532 nm pulse, will measure aerosol vertical profiles and other atmospheric properties.

Introduction:

The global retreat of mountain glaciers in the last century has been obvious since the 19th century (Houghton et al., 1995). Even though the melt-water from these glaciers has contributed to the present-day sea level rise of 2 mm/yr (Nerem et al., 1997), the large ice sheets of Greenland and Antarctica contain enough ice to raise sea level by 80 meters if they completely melted. Such complete melting is not imminent, but these ice sheets are expected to exhibit early signs of human-induced climate change. The West Antarctic Ice Sheet shows signs of instability and some models suggest that it could collapse within a few centuries in response to global warming (Oerlemans, 1989).

The Geoscience Laser Altimeter System (GLAS) is a spaceborne laser designed to 1) measure the altitude between the instrument and Earth's surface and 2) measure the vertical distributions of clouds and aerosols. Measurement of altitude, when combined with precise position knowledge of the instrument in space and precise laser pointing knowledge, enables high accuracy determination of surface profiles with respect to the Earth's center of mass. The altitude measurements will be made using laser pulses with wavelengths of 1064 nm (near infrared) and the atmospheric properties will be measured using a 532 nm (green) wavelength. The laser will be pointed in the geodetic nadir direction during typical operations.

GLAS is a facility instrument within NASA's Earth Science Enterprise. The Ice, Cloud and Land Elevation Satellite (ICESAT) mission provides overall project management. The GLAS instrument, under development at NASA Goddard Space Flight Center, will be carried by a commercial spacecraft provided by Ball Aerospace (Boulder, Colorado). The ICESAT Observatory (spacecraft plus instrument) is scheduled for launch in July 2001 from Vandenberg (CA). The ICESAT Observatory will have an altitude of about 600 km and an orbit inclination of 94°. The mission has a 3-year lifetime requirement, with a 5- year goal. It is planned that follow-on orbiting instruments will extend the observation period to 15-yrs and longer.

Science Requirements Summary:

With the mission focus on the Greenland and Antarctica polar ice sheets, the need for a near-polar orbit is readily evident. Unfortunately, no single set of orbit parameters can provide an optimal viewpoint for all science requirements. To reduce instrument power, the instrument designers prefer a very low altitude, but precision orbit determination (POD) and orbit lifetime demands higher altitudes. Furthermore, an exact polar orbit produces few crossover points, regarded as an essential approach for analysis of the data. Various trades were considered, but the lowest acceptable altitude for precision orbit determination (POD) was determined to be approximately 600 km. Based on the need to cover the West Antarctic ice streams and the desire to optimize the crossover geometry, the inclination was chosen to be 94º, which results in latitude coverage to 86º north and south of the equator.

The cryosphere measurement requirements acknowledge the regional variability known to exist on the large ice sheets. For example, the accuracy of elevation change in the vicinity of the West Antarctic Ross ice streams is 1.5 cm/yr in a 100 x 100 km^2 (latitude range: ~80ºS to 86ºS) where surface slopes are <0.6º, but on the East Antarctic plains where surface slopes are <0.2º, the accuracy requirement is 0.5 cm/yr in a 200,000 km^2 area.

The GLAS instrument uses three lasers, but only one laser will operate at a time with the shot repetition rate of 40 Hz. Based on laboratory lifetime tests, two lasers will be required to meet the lifetime

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requirements and the third laser provides redundancy. Each laser uses a diode-pumped Q-switched Nd:YAG slab. The laser beam emitted from the GLAS instrument has a 0.110 mrad divergence which illuminates a spot on the Earth's surface with a diameter of about 66 m. The separation of illuminated spots on the Earth's surface will be about 172 m. The pulse energy at 1064 nm is about 75 mJ and the pulse width is about 5 ns. The surface-reflected 1064 nm photons are collected in a 100 cm telescope constructed of Beryllium. The GLAS laser energy and the 1 meter telescope ensure the capture of surface returns, even in the presence of thin clouds and haze. The instrument is designed to operate under both day and night conditions. A pair of Si analog detectors are used to measure the return pulse; only one detector operates at a time and a flip mirror allows selection of the respective detector. An A/D converter digitizes the return pulse with a 1 GHz sample rate.

A small part of the outgoing laser energy is extracted into instrumentation that enables determination of the laser pointing direction. The extracted energy is input to a Laser Reference System (LRS), which uses CCD technology to provide an image of the far field pattern of the laser. Changes in the pointing direction with respect to spacecraft-fixed axes will be illustrated by changes in the laser spot image on the CCD. The laser pointing direction with respect to a terrestrial reference frame will be determined with the use of a commercial star camera/tracker in combination with the LRS, referred to as the Stellar Reference System (SRS). Both the star camera and the SRS will be directed toward the zenith direction, but the SRS has a smaller field of view (0.5º vs. ~8º). A star will appear in the SRS that is common to the star camera at an average interval of 5-10 min, which will assist in the characterization of the spacecraft jitter. The combination of the star camera, the SRS and a gyroscope provide the data that will enable determination of the laser spot location in a terrestrial reference frame.

The spatial position of the instrument in a terrestrial referenence frame will be determined using a dual frequency GPS receiver that records pseudorange and carrier phase. The ground-based SLR network will provide tracking data that will support validation of the GPS-determined orbit as well as a passive backup tracking system.

With GPS and/or SLR, the ITRF position vector of a reference point within the spacecraft can be determined, $\mathbf{r}_{ref}$. The laser pulse travel time from the instrument to the surface provides the scalar altitude, but when combined with the pointing information from the SRS, star camera and gyroscope, an altitude vector r_h is available. Hence, the ITRF location of the illuminated laser spot on the Earth's surface is the vector sum given by $\mathbf{r}_{ref} + \mathbf{r}_h = \mathbf{r}_{spot}$. The spot coordinates in the ITRF can be readily converted into geodetic latitude, longitude and ellipsoidal height.

The preceding description of the process whereby the surface spot location is implied from the measurements applies to all surface applications: ice, land, and ocean/lakes. The cryosphere science requirements are the dominant factors in the determination of the instrument design for surface altimetry. Hence, the requirements for land and ocean/lake profiles are generally encompassed by the cryosphere requirements.

Surface altimetry is accomplished using the 1064 nm pulse. This laser pulse, after reflection from the surface, will be digitized within the GLAS instrumentation. The digitized waveform will enable investigation of other surface properties, such as surface roughness, vegetation canopy heights and other characteristics. The on-board tracking algorithm will use a digital elevation model to assist with the detection of the surface.

Atmospheric backscatter profiles will be measured using the 1064 nm and 532 nm channels. The 1064 nm atmospheric measurements will be used to profile the heights and vertical distribution of clouds and dense aerosols every shot, resulting in 75 m vertical and 175 m horizontal resolution. The 532 nm atmospheric backscatter measurements are used to measure the vertical distribution of optically thin aerosols during both day and night.

Spacecraft Description:

The NASA Goddard GLAS instrument will be carried using a commercial derivative spacecraft provided by Ball Aerospace in Boulder, Colorado. A similar spacecraft will be launched in November 1998 for Quikscat. The ICESAT bus mass is about 670 kg and the instrument mass is about 300 kg; thus, the total observatory mass is about 970 kg. Total power requirements result in a solar panel array size of about 8 m^2, with a constraint that yaw maneuvers to reorient the solar panels be minimized. The maximum area-to-mass ratio of the observatory will be about 0.01 m^2/kg. The specific launch vehicle will be determined in August, 1998, but the spacecraft can accommodate either of the available options. The launch date is July, 2001, from Vandenberg, California.

Mission Description:

Two orbits will be used for the mission. The immediate post-launch orbit will have an 8-day ground track repeat to enable several overflights of verification sites during the 90-120 day verification period. The orbit will be frozen; thus, perigee will remain essentially fixed at 90º for the adopted 94º inclination. With a mean orbital semimajor axis of 6971.5 km and an eccentricity of 0.0013, the ground track will repeat in 119 orbital revolutions in 7.989 days. The 8-day repeat orbit will be further designed to enable overflights of specific verification sites and provide near-simultaneous measurements with the MODIS imaging instrument on EOS-AM.

The post-verification phase orbit will repeat in 183-days (182.758 days) after 2723 revolutions. The orbital semimajor axis is 6970.0 km and the eccentricity is 0.0013. After one complete "183-day cycle", the ground track spacing between same-direction tracks at the equator will be about 14.7 km. Two subcycles exist within the 183-day cycle which produce near-repeat tracks: 8-days and 25-days. The ground track pattern for 25-days will essentially repeat in the subsequent 25-days, but the pattern will be shifted westward at the equator by 14.7 km. The near-repeat 8-day pattern occurs with an eastward shift of about 100 km. Orbit decay will be controlled with periodic thrusting to maintain the ground track repeat characteristics to within 1 km at the equator.

The orbit inclination was chosen to provide coverage of features in the West Antarctic and to provide crossovers to support detection of elevation change. Based on the adopted orbit parameters, the crossovers (formed by differencing the altimeter measurements at the points where the ascending and descending tracks intersect) will be approximately orthogonal in the latitude band from 84º to 85º (North or South). In the 183-day repeat cycle, the orbit geometry produces a crossover density that rapidly increases as the maximum latitude allowed by the inclination is approached, as illustrated in Table 1. In the region above 85º (N or S), the crossover angle exceeds 90º, approaching 180º.

Table 1. Number of Crossovers in 100 km x 100 km

Latitude Range (N or S)	Number of Crossovers
70º - 71º	~ 230
75º - 76º	~ 550
80º - 81º	~ 1675
84º - 85º	~ 11,500

Error Analyses:

The single shot error budget for the laser spot location is summarized in Table 2. Since the instrumentation is designed to operate continuously, this error budget applies to cryosphere, land and ocean/lake applications. For purposes of this error budget, it has been assumed that the laser pointing error is 1.5 arcsec and the surface slope is 1º. It has been assumed that the dual frequency GPS receiver and ground-based laser ranging data collected during the verification phase will be used to improve the gravity model and other parameters used to support POD. Current gravity model covariance matrices, such as EGM-96, predict the radial orbit error for ICESAT to be > 15 cm, which exceeds the value in the Table 2. Ongoing efforts to improve the gravity field, combined with dedicated gravity missions such as CHAMP and GRACE, should produce a reduction in this predicted value, but significant reduction may only occur after the launch of the ICESAT Observatory. Nevertheless, simulations have been conducted by Rim et al. (1996) that demonstrate tuning of the gravity field during the verification phase can be expected to approach the radial orbit error in Table 2. An additional assumption is that a shift in the centroid of the return pulse produced by atmospheric scattering will be correctable to 10%.

Table 2. Single Shot Error Budget

Source	Error (cm)
Instrument precision	10
Radial orbit determination	5
Pointing determination	7.5
Troposphere delay	2
Atmospheric scattering	2
Other (c.g. location, etc.)	1
RSS	13.8

As an example to demonstrate that this error budget can meet the science requirements, consider a 100 km x 100 km region at 80º latitude. Although 1675 possible crossovers will be available within each 183-day cycle (inter-cycle crossovers), crossovers can be formed between different cycle combinations (intra-cycle). With the assumptions that 6 cycles are completed (3-yr mission), approximately 250 crossovers occur in each cycle, and the individual crossover error is 20 cm, it can be shown that the 1.5 cm/yr requirement can be met. For this example, crossovers between the first and third cycles, the first and fifth cycles, and the first and sixth cycles, were formed. More detailed analyses have been conducted with realistic orbit and attitude errors and with more complete simulations of secular and periodic variations of the surface elevation. These simulations demonstrate that the dominant error source on flat surfaces is the orbit error, whereas on sloped surfaces, the pointing error dominates, depending on the slope.

Data Products and Validation:

The altimeter data products will include the geodetic coordinates of each surface laser spot centroid expressed in an appropriate ITRF. These coordinates will be geodetic latitude, longitude and ellipsoidal height. In addition, the digitized waveform, statistical information, and corrections applied to the raw measurements will be available.

GLAS data collected during the first 90 to 120 days will be used to verify the instrument performance and, if necessary, generate calibration corrections. In addition, the data products generated during the verification period will be subjected to intense scrutiny to assess their validity.

One planned approach to verification/validation is to use selected sites that enable a direct determination of $\mathbf{r}_{\text{spot}}$. This directly determined vector will be compared with the inferred vector, which is the standard data product. The directly-determined spot location will be accomplished by capturing an image containing the GLAS-illuminated spots at verification sites. The primary site is currently planned to be White Sands, New Mexico, at the Shuttle landing facility. The surface is very flat and smooth. The image of the spots will contain fiducial reference marks whose coordinates will be determined in the ITRF using GPS. With the fiducial marks in the image, the ITRF coordinates of the laser spot will be determined in the ITRF as well. This verification process will characterize the performance of the LRS/SRS and provide data for the validation of the POD, PAD, and the corrections applied to the altimeter measurement.

Fundamental changes in system configuration, such as changing lasers and/or detectors, will warrant initiation of special verification activities. If these configuration changes occur during the 183-day repeat cycle, use of off-nadir pointing provided by the spacecraft will be used to facilitate pointing the laser altimeter at the verification sites.

Other techniques for validation will be used. For example, a spacecraft roll maneuver over the oceans will enable determination of attitude corrections, as will operation of the instrument over undulating, but well-characterized, surface topography.

The data products from ICESAT will be distributed through the NASA EOSDIS. Except for the initial verification period, these products will be available to the international community within 2-3 weeks after the measurements have been collected.

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http://www.csr.utexas.edu/glas/
http://icesat.gsfc.nasa.gov

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