Overview of the ICESat Mission

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[1] The Geoscience Laser Altimeter System (GLAS) on the NASA Ice, Cloud and land Elevation Satellite (ICESat) has provided a view of the Earth in three dimensions with unprecedented accuracy. Although the primary objectives focus on polar ice sheet mass balance, the GLAS measurements, distributed in 15 science data products, have interdisciplinary application to land topography, hydrology, vegetation canopy heights, cloud heights and atmospheric aerosol distributions. Early laser life issues have been mitigated with the adoption of 33-day operation periods, three times per year, designed to document intra- and inter-annual polar ice changes in accordance with mission requirements. A variety of calibration/validation experiments have been executed which show that the elevation products, when fully calibrated, have an accuracy that meets the science requirements. The series of papers in this special ICESat issue demonstrate the utility and quality of the ICESat data. **Citation:** Schutz, B. E., H. J. Zwally, C. A. Shuman, D. Hancock, and J. P. DiMarzio (2005), Overview of the ICESat Mission, *Geophys. Res. Lett.*, *32*, L21S01, doi:10.1029/2005GL024009.

1. ICESat Mission Science Objectives and Requirements

[2] The primary purpose of ICESat is the determination of inter-annual and long-term changes in polar ice-sheet volume (and inferred mass change) to sufficient accuracy to assess their impact on global sea level [*Zwally et al.*, 2002]. A specific objective of ICESat is to reduce the uncertainty in the known ice sheet mass balance through determination of polar ice elevation change with better than 2 cm/yr accuracy over 100 km × 100 km areas, averaged over three or more years of seasonal and interannual variability. To achieve this objective, ICESat has utilized narrow beam laser altimetry, with state-of-the art instrumentation, to determine the geodetic coordinates of a series of points on the ice sheet with vertical accuracy at the decimeter level. Although ICESat has been designed to meet the demanding requirements of cryosphere applications, its design supports numerous multidisciplinary applications.

2. Measurement Concept and Implementation

[3] The elevation of a spot on the Earth's surface illuminated by a spaceborne laser is determined from the sum of two vectors: the position vector of the laser instrument plus the range vector (the position vector of the illuminated spot centroid with respect to the instrument, alternatively referred to as the altitude vector). The resultant vector is the position of the spot (or footprint), which can be readily transformed into geodetic latitude, longitude and height (or elevation) with respect to a reference ellipsoid. The fundamental data product consists of this geolocated spot and its surface arrival time (time tag).

[4] This measurement concept was implemented on ICESat using GLAS, which was designed, constructed and tested at NASA Goddard Space Flight Center (GSFC) to meet the science requirements. Ball Aerospace Corporation built the spacecraft bus to provide a source of power, communication and on-orbit command and control. The combined GLAS and spacecraft bus are collectively known as ICESat. In the ICESat terminology, altimetry is used for range measurements to the Earth's surface, whereas lidar is used for measurements related to laser backscattering within the atmosphere.

[5] GLAS has three lasers (designated Laser 1, 2 and 3) mounted on a rigid optical bench, with only one laser operating at a time [*Zwally et al.*, 2002; *Abshire et al.*, 2005]. Each laser produces a 1064 nm pulse for altimetry and lidar, but a doubler crystal produces a 532 nm wavelength pulse, which yields a more sensitive determination of the vertical distribution of clouds and aerosols [*Spinhirne et al.*, 2005]. The operating laser pulses at 40 Hz and the transmitted laser pulse illuminates a spot on the Earth's surface with a diameter of ~65 m, except when optically thick clouds obscure the surface. Successive spots are separated on the Earth's surface by 172 m. The laser pulse is also referred to as the laser shot. The echo pulse is captured by a 1 m diameter telescope and directed to an analog detector, then digitized by a 1 GHz sampler, along with a digitized record of the transmit pulse. Each pair of digitized transmit and corresponding echo pulses is telemetered to the ground for analysis. These digitized pulses are referred to as laser waveforms. From the waveform data, the transmit time and the echo receive time are determined, from which the pulse time of flight (TOF) is computed. The one-way range, or magnitude of the range vector, is half the TOF multiplied by the speed of light. In addition, this one-way range is subjected to corrections, such as propagation delay in the troposphere.

[6] During the 4 ms pulse TOF from ICESat, the digitizer creates 4 million samples, starting just before the transmit pulse. GLAS on-board processing identifies the transmit and the echo pulses in the 4 ms record for telemetering to the ground. The on-board search for a valid echo pulse uses a $1^\circ \times 1^\circ$ digital elevation model, with surface type, and

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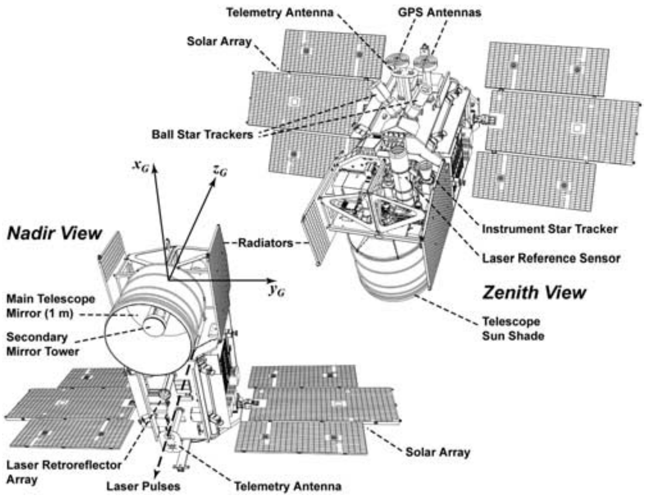

Figure 1. ICESat nadir (Earth-facing) and zenith views. Thrusters used for orbit modification are located on the far side (not shown) opposite the GLAS telescope.

real-time ICESat position to estimate the expected TOF. For the implemented surface types of ice and land, there are 544 samples (or bins), whereas sea ice and water uses 200 bins. The effective one-way distance associated with 544 bins is 81.6 m and 30 m for 200 bins, which represents the maximum elevation change within a single spot that can be recorded.

[7] The direction of the range vector from ICESat/GLAS (Figure 1) is obtained using an Instrument Star Tracker (IST) with an 8° field of view (FOV) and Hemispherical Resonator Gyroscopes (HRG). The process by which the orientation, or attitude, of the GLAS optical bench is determined is referred to as Precision Attitude Determination (PAD), but the actual result yields the laser path orientation in space. The instrumentation is described by M. Sirota et al. (The transmitter pointing determination in the Geoscience Laser Altimeter System, submitted to *Geophysical Research Letters*, 2005, hereinafter referred to as Sirota et al., submitted manuscript, 2005). The Laser Reference Sensor (LRS) images the transmitted laser far-field, as well as an optical source mounted on the IST (Collimated Reference Source, CRS) and stars that appear in its 0.5° FOV. The CRS is based on the 532 nm pulse. The IST and LRS operate at 10 Hz, but an additional camera (Laser Profile Array, LPA) images the far-field pattern of each laser shot at 40 Hz.

[8] Prelaunch calibration measurements were made to determine the reference location for range measurements made by GLAS. The physical location of the GLAS reference point for range measurements is on the optical bench, located near the center of the telescope. The measurement of the laser transmit direction with respect to the optical bench could not be made in the laboratory. As a consequence, the LRS and on-orbit calibration experiments were designed to enable that determination after launch.

[9] The determination of the position of the GLAS reference point in space is made using the GPS tracking system. This process is referred to as Precision Orbit Determination (POD). Two JPL BlackJack receiver/antenna combinations are available for redundancy, but only one receiver has been used to date. The POD methodology uses data provided by the International GPS Service and the International Earth Rotation Service. A laser retroreflector array (LRA) on the nadir side supports ranging from the collaborating stations of the International Laser Ranging Service and although these data are withheld from the POD process, they are used to assess the accuracy of the GPS-derived POD.

3. Mission Description

[10] ICESat was launched on a Delta-2 rocket from Vandenberg AFB at 0045 UT on January 13, 2002, into a 600 km altitude orbit with a 94° inclination. The inclination was chosen to provide coverage of changing ice features in West Antarctica allow comparison of derived elevations at crossover points (intersections between ascending and descending tracks) that are commonly used in altimeter analyses. The orbit is maintained with approximately 10-day maneuvers to compensate for natural orbit decay in order to produce a ground track that is always close (±1 km at the equator) to an ideal, exact repeat track, referred to as the reference track. Two reference orbits (or tracks) have been used by the mission (Table 1): an 8-day exact repeat and a 91-day exact repeat (with a 33 day sub-cycle). The 8-day interval was adopted to enable frequent repeats of ground calibration sites and the longer interval was adopted to provide denser track coverage for science applications.

[11] The normal spatial orientation of ICESat can be described with the axes shown in Figure 1. The minus-z_G axis is 0.3° from geodetic nadir (i.e., perpendicular to the Earth ellipsoid). Two basic ICESat orientations (attitude) are used to take best advantage of the Sun geometry. In the sailboat (SB) mode, the y_G axis (plus or minus) is closely coincident with the satellite velocity vector. In the airplane (AP) mode, the x_G axis (plus or minus) is closely aligned with the velocity vector. A specific attitude mode is used continuously for approximately six months. The 0.3° off-nadir angle is a fixed rotation of the spacecraft away from the Earth (a "pitch-up") by this angle about an axis approximately perpendicular to the velocity vector to mitigate detector damage from specular reflections of laser pulses from mirror-like surfaces (e.g., still water).

[12] The agile spacecraft allows special off-nadir pointing maneuvers to be performed that enable the laser to be pointed at a selected target of opportunity (TOO), which may lie slightly off the nominal nadir track, as well as to maintain pointing at the reference track to compensate for orbit drift. Pointing the laser at TOOs is commonly per-

Table 1. Laser Operation/Science Campaign Summary

Laser/ Campaign	Start Date Y-M-D	End Date Y-M-D	Orbit Repeat, days	Orientation
1	2003-02-20	2003-03-21	8	SB
1[a]	2003-03-21	2003-03-29	8	AP
2a	2003-09-25	2003-10-04	8	SB
2a	2003-10-04	2003-11-18	91/33+	SB
2b[b]	2004-02-19	2004-03-21	91/33	SB
2c	2004-05-18	2004-06-21	91/33	AP
3a	2004-10-03	2004-11-08	91/33	SB
3b	2005-02-17	2005-03-24	91/33	SB
3c	2005-05-20	2005-06-23	91/33	AP

[a]SAM for 13 hours starting 2003-03-26.
[b]SAM for 11 hours starting 2004-02-19.

formed as a rotation about the axis perpendicular to the velocity vector (a "roll" maneuver). Such off-nadir pointing is allowed up to ±5°, i.e., to locations up to ±50 km away from the reference track. In the polar regions (>59° latitude in the Arctic, <−60° in the Antarctic), ICESat is commanded to always point at the reference track to compensate for natural orbit drift and enable near repeats (±100 m) of the tracks. (Beginning in May, 2005, the lower limit in the Arctic was reduced from 59° to 46°). Special maneuvers are performed to support calibration/validation by rotating the satellite so as to scan a cone of 5° aperture about the nadir vector. These Scan Maneuver Calibrations (SMC) are conducted twice per day over the Pacific and approximately weekly over an entire orbital revolution (round-the-world scan), as described by *Luthcke et al.* [2005].

4. On-Orbit Performance

[13] Laser 1 was commanded to start firing on February 20, 2003. The March 29 failure of this laser resulted in a modified operating plan, which called for approximately 30 day operation periods, three times per year [*Abshire et al.*, 2005].

[14] The laser operation periods through March 2005 are summarized in Table 1. Each period has been assigned a campaign or operations period identifier, such as Laser 2a (or simply L2a), to denote the operating laser (2) and the operations period (a). For all campaigns after L2a, the same 33 day sub-cycle of the 91 day repeat orbit was used corresponding to the last 33 days of L2a (denoted by 91/33 in Table 1). ICESat has entered a special safety orientation (Sun Acquisition Mode, SAM) for several hours because of detected anomalies, during which there are no useable data.

[15] Early analysis of L2a suggested that the laser direction was not optimally aligned with the telescope FOV. Over sloped surfaces, when the illuminated spot is close to the edge of the telescope FOV, an effective range bias is introduced. Some temperature adjustments were made on-orbit during L2a to correct this boresight alignment or FOV shadowing problem, but remaining long wavelength effects have been corrected by on-orbit SMC. In general, the laser/optical bench temperatures were maintained within a narrow range, or with small, discrete changes, throughout the other operation periods.

[16] All instrumentation operated at or near expected performance during L2a. During other campaigns, for example, diminished laser energy in the 532 nm channel has affected both atmospheric channel measurements and the CRS image in the LRS. During L2a, the CRS gave evidence of IST motion with respect to the optical bench that correlated with the on-orbit day/night thermal cycle. However, it has been shown that these motions could be corrected in PAD by using the LRS data (Sirota et al., submitted manuscript, 2005). During campaigns with diminished 532 nm energy, these corrections have required innovative strategies, but our analyses suggest that data products can be corrected in spite of these difficulties.

[17] From tracks obtained during L2a over the gently sloped region of Lake Vostok in East Antarctica, the derived surface elevation shows ∼3 cm noise [*Abshire et al.*, 2005], mostly from the GLAS scalar range measurement. This exceptional precision has been observed on other surfaces including salt flats [*Fricker et al.*, 2005], lakes and rivers. Saturation of the 1064 nm detector can occur over ice and other surfaces and will produce a distorted echo waveform. The nonlinear response of the detector is dependent on the echo pulse energy, but corrections for saturation are under test.

[18] The GLAS altimeter channel penetrates optically thin clouds. Although the results vary with time and location, approximately 60% of the transmitted pulses over Antarctica have recorded surface echo pulses (C. Shuman et al., Ice sheet elevations from ICESat: 2003–2005, submitted to *Geophysical Research Letters*, 2005). Depending on the nature of the clouds (particle size and altitude), a forward scattering effect can introduce a bias [*Abshire et al.*, 2005; *Spinhirne et al.*, 2005; *Fricker et al.*, 2005]. To mitigate this effect, cloud-clearing methods have been developed and applied [*Smith et al.*, 2005and forward scattering correction algorithms are under development.

[19] Although ICESat is a stable orbital platform, it does exhibit 1 Hz oscillations induced by the solar array motion. These oscillations produce tens of meters cross-track motion of the laser spot on the Earth's surface with respect to the nadir track.

5. ICESat Data Products

[20] Generation of the data products from the ICESat measurements is performed by the ICESat-Science Investigator-led Processing System (I-SIPS), located at GSFC. A Science Computing Facility (SCF) tool enables a user to request, access, visualize, and analyze the science data products and engineering data. An innovative sub-setting capability is used in the SCF to meet the special requirements of extracting spatial data sets from the large sequentially-organized files. Calibrated data products are available from the National Snow and Ice Data Center (NSIDC). The raw data collected on ICESat and transmitted to the ground are Level 0 and these data are archived at I-SIPS and NSIDC. A Level 1A product is generated from Level 0 with reversible conversions to engineering units. Level 1B products contain various corrections required for the generation of the science data products (Level 2).

[21] Fifteen data products (see http://www.nsidc.org) are generated by I-SIPS, identified as GLAxy, where xy denotes a two digit number (e.g., GLA12 contains ice elevations). A nearly equal number of ancillary products are generated to support the GLAxy generation, denoted as ANCxy (e.g., ANC09 is PAD). For each of the main components, the methodology used to process the measurements into data products is summarized in an Algorithm Theoretical Basis Document (ATBD). For example, to derive the coordinates of the illuminated laser spot centroid (which includes the elevation) on the Earth's surface, the POD, PAD and waveform analysis are combined as previously described and the full methodologies are given by the ATBDs. Elevation data products use an Earth ellipsoid with equatorial radius = 6378136.3 m and flattening = 1/298.257.

[22] The accuracy of the geolocated laser spot position depends on the individual accuracies of each of the product contributors. The POD product has been shown to exhibit 2 cm radial accuracy [*Rim et al.*, 2005] based on data

acquired with the LRA, but the laser pointing knowledge (PAD) has been dependent on the laser operations period and the level of understanding of instrumental corrections from the IST and LRS, as well as temporal variations over an orbital revolution. The PAD understanding has improved with time and subsequent releases of the data products have been made based on these improvements. Since an error of 1 arcsec in laser pointing knowledge, combined with a surface slope of 1°, will introduce an effect of 5 cm on the inferred spot elevation, PAD has received much attention.

[23] For example, L2a Release 18 had residual day/night variations not accounted for by the LRS and Release 19 was based on Release 18, but corrections for the IST FOV distortions were addressed. The estimated pointing accuracy of L2a Release 18 is 15 arcsec and Release 19 is 5 arcsec. In general, all other campaign periods have current pointing knowledge accuracy at the 15–20 arcsec level (all are identified with release number <21), but ongoing efforts are expected to bring all campaign products to the required 2 arcsec accuracy. Release 21 for L2a is available, which is based on all known instrumental corrections, plus SMC. The SMC, which are estimated to have 1 arcsec precision, have provided corrections to laser pointing errors resulting from boresight FOV and residual effects from day/night orbital variations. Based on various tests, Release 21 has a pointing knowledge accuracy (1-σ) of $\sim$2 arcsec (or surface horizontal geolocation of 6 m). Users are cautioned that pointing accuracy cannot be immediately inferred from the Release Number and they should obtain accuracy information from NSIDC.

[24] Various calibration/validation experiments have been performed using L2a Release 21 and data from other operation periods. The experiments described by *Magruder et al.* [2005] have validated the data product time tag to microsecond level and show geolocation errors of 3.5 arcsec, within 3-σ of the estimated accuracy. *Fricker et al.* [2005] used GPS ground surveys to show that the absolute accuracy of L2a Release 21 over salar de Uyuni (after saturation correction) is $\sim$2 cm. *Martin et al.* [2005] used accurate terrain models that have been independently generated by the NASA Airborne Terrain Mapper in the Western U.S. and in the Dry Valley's of Antarctica to show that L2a Release 21 range bias is less than 2 cm and pointing errors are less than 2 arcsec (1-σ). *Harding and Carabajal* [2005] present analyses that are directed at validating GLAS waveforms, especially the vertical structure within a laser footprint.

6. Summary

[25] The ICESat mission is Earth's first polar orbiting satellite to carry a laser altimeter, and it continues to provide surface elevation of the ice sheets and other surfaces, with unprecedented accuracy and along-track resolution. The global data products offer a diverse and scientifically rich data set for multidisciplinary applications. Although instrumental issues have delayed the completion of full calibrations of the elevation products, the full set of data is being reprocessed with the goal of reaching the high accuracy exhibited by the Laser 2a Release 21, now available at NSIDC.

[26] **Acknowledgments.** The dedicated work of several talented teams (science, instrument, spacecraft, and operations) is gratefully acknowledged. Further information of their efforts, the overall mission, access to data, acronyms and the ATBDs can be found at icesat.gsfc.nasa.gov, www.csr.utexas.edu/glas/, and nsidc.org/data/icesat/. Thanks to Helen Fricker and Bernard Minster for their helpful comments.

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