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# The GLAS Algorithm Theoretical Basis Document for Laser Footprint Location (Geolocation) and Surface Profiles

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**July 2014**

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## 1.0 INTRODUCTION

Analysis of altimetric data acquired by the Geoscience Laser Altimeter System (GLAS) requires an accurate determination of the laser spot location on the Earth's surface (ice, land, water, clouds), or geolocation of the laser spot. The spot location with respect to the Earth center of mass (or geocenter) is determined by both the orbital location of GLAS in an appropriate reference frame and the direction of the laser beam described in the same reference frame. With these two position vectors, the location of the laser spot can be inferred in typical geodetic coordinates (geodetic latitude, longitude and height above a reference ellipsoid), using a Terrestrial Reference Frame (TRF) whose origin is coincident with the center of mass of the Earth. The validation of these coordinates utilizes experiments that provide a direct determination of the coordinates which can be compared to the inferred position.

In the following sections, an overview of the mission and mission requirements is provided. This Algorithm Theoretical Basis Document provides the "roadmap" for altimetry processing. An overview of the Ice, Cloud and land Elevation Satellite (ICESat) mission, which will carry GLAS, is described in the following section along with a summary of the science objectives. The remaining sections focus on geolocating the spot on the Earth's surface illuminated by GLAS, leading to the basic Level 1B elevation data product. This elevation product will be used for studies of surface change, including change of elevation in the polar ice sheets, and the generation of surface topography, including digital elevation maps.

(Note: this version is an update to the original, so the sentence tense is future; it has not been changed to past tense, even though most events have taken place).

## 2.0 BACKGROUND

The ATBD for the generation of the laser spot location, or geolocation of the laser spot, is described in the following sections. The laser spot location is the basis of the following GLAS data products: Level 1B GLA06 and several higher-level products. This ATBD draws on the content of other documents, as noted. The objective of this algorithm is to produce the spot location for each laser pulse with appropriate corrections, described in an International Earth Rotation Service (IERS) Terrestrial Reference Frame (ITRF). This data product will include the three-dimensional coordinates of the laser spot, given in terms of geodetic latitude, longitude and height above a reference ellipsoid. The various corrections will be made available on the data record.

### 2.1 Mission Overview

The Geoscience Laser Altimeter System (GLAS) is an integral part of the NASA Earth Science Enterprise (ESE). GLAS is a facility instrument designed to measure ice-sheet topography and associated temporal changes, as well as cloud and atmospheric properties. In addition, operation of GLAS over land and water will provide along-track topography. GLAS is being designed and constructed by the NASA Goddard Space Flight Center (GSFC). The mission, known as the Ice, Cloud and land Elevation Satellite (ICESat) is managed at GSFC and the spacecraft is being provided under contract to Ball Aerospace, Boulder, CO. The instrument and spacecraft are designed with a three year lifetime requirement and a five year goal.

The nominal launch period is December 2002. Toward this launch date, GLAS completed Preliminary Design Review (PDR) in January 1998 and the Critical Design Review (CDR) is scheduled for March 1999. The spacecraft completed mid-term design review in December 1999.

The GLAS instrument is designed to provide the altitude of the instrument above the surface of the Earth or cloud. This altimeter measurement is obtained using a diode pumped Q-switched Nd:YAG laser operating in the near infrared (1064 nanometers). A portion of the emitted energy is frequency doubled (532 nm, green) to provide atmospheric backscatter measurements, which can be used to study aerosol and other atmospheric characteristics. The laser operates with 75 mJ at 1064 nm and 35 mJ at 532 nm, with a pulse repetition rate of 40 Hz.

The nominal laser pointing direction is the geodetic nadir, i.e., perpendicular to a surface defined by an ellipsoidal model of the Earth, but off-nadir pointing up to 5° is a requirement. The orbit altitude is about 600 km, the perigee is fixed in an average sense near the north pole and the inclination is near 94°. During the initial post-launch period, which will be used for verification of instrument performance and validation of the data products, the nadir point will repeat every 8-days to support several overflights of ground verification sites. During the primary science phase, the ground track will repeat with a 183-day cycle (as noted in Appendix A, this repeat cycle was changed to a 91-day cycle, which was used through all operation periods after Laser 1). The orbit characteristics are summarized in Table A.1 in Appendix A. The orbit will be controlled by drag-compensation maneuvers to ensure maintenance of the reference ground track. These maneuvers will occur at an interval of 3-5 days during high solar activity, but less frequently under less intense solar and geomagnetic activity. Less frequent maneuvers (six month) to account for luni-solar perturbations on the inclination will be performed. Mission considerations derived from the science requirements are given in the GLAS Science Requirements Document (1997).

**Table 2-1 Orbit Characteristics**

| Elapsed Time from Launch (days) | Mission Phase | Repeat Cycle (days) | Orbit Revolutions per Cycle | Semimajor Axis (km) | Eccentricity |
|---|---|---|---|---|---|
| 0 to 30 | Commissioning of spacecraft | ~8 | ~ 119 | ~ 6971.5 | ~0.0013 |
| 30 to 60 | Commissioning of GLAS | 7.989 | 119 | 6971.5 | 0.0013 |
| 60 to 180 | Cal/Val | 7.989 | 119 | 6971.5 | 0.0013 |
| 180 to EOM | Science Mapping | 182.758 | 2723 | 6970.0 | 0.0013 |
| | Alt. Sci. Map. | 91 | 1354 | 6970.2 | 0.0013 |
| EOM: End of Mission<br>Note: Cal/val will begin with 8 day repeat and end with 183 (91) day repeat. Transition will occur a TBD time within the cal/val phase. | | | | | |

## 2.2 Science Objectives

The GLAS is a laser altimeter designed to measure ice-sheet topography and associated temporal changes, as well as cloud and atmospheric properties. In addition, operation of GLAS over land and water will provide along-track topography.

The detailed requirements are available in the GLAS Science Requirements (1997). The science goals are as follows:

• Cryosphere:

*The primary cryospheric science goals of GLAS are to measure long-term changes in the volumes (and mass) of the Greenland and Antarctic ice sheets to sufficient accuracy to assess their impact on global sea level, and to measure seasonal and interannual variability of the surface elevation in sufficient spatial and temporal detail to permit identification of long-term trends and to help explain those trends. A further goal is to provide a precise elevation topography of these ice sheets and describe the nature of surface characteristics (e.g., roughness), including sea ice.*

• Land Processes:

*The primary land processes science goal of GLAS is to conduct topographic measurements of the Earth's land surface on a global basis in order to contribute to a global grid of ground control points for georeferencing of topographic maps and digital elevation models. The secondary land processes science goal is to detect topographic change at the meter per year level or better in selected regions of limited spatial extent.*

• Atmospheric Science

*The primary atmospheric science goal of the GLAS cloud and aerosol measurement is to determine the radiative forcing and vertically resolved atmospheric heating rate due to cloud and aerosol by directly observing the vertical structure and magnitude of cloud and aerosol parameters that are important for the radiative balance of the earth-atmosphere system, but which are ambiguous or impossible to obtain from existing or planned passive remote sensors. A further goal is to directly measure the height of atmospheric transition layers (inversions) which are important for dynamics and mixing, the planetary boundary layer and lifting condensation level.*

## 2.3 Altimetry Overview

The laser altimeter measures the time required for a laser pulse of 5 nanosecond duration to complete the round trip from the instrument to the Earth's surface and back to the instrument. This time interval can be converted into a distance by multiplying by the speed of light, and the one-way distance can be obtained as half the round trip distance. The one-way distance, a scalar quantity, cannot alone provide a satisfactory profile of the surface because multiple sources of ambiguity are associated with a scalar quantity. Removal of these ambiguities can be obtained from additional information, as illustrated in Figure 2-1. The surface profile is generated from a series of individual spot locations in the direction of spacecraft motion.

As shown in Figure 2-1, the coordinates of the spot on the Earth's surface, illuminated by the laser, can be obtained if two primary vectors are known. First, the instrument position vector of an appropriate reference point in the laser instrument must be known with respect to a geodetic coordinate system, i.e., a Terrestrial Reference Frame (TRF). Second, the altimeter scalar height must be augmented with directional information to form an altimeter vector. The sum of the instrument position vector and the altimeter vector results in the laser spot position vector with respect to the TRF. The laser spot vector is clearly inferred from the other two vectors. The TRF coordinates of the laser spot represent the fundamental altimeter product (Level 2). With a series of such spot coordinates along a surface track, the surface profile with respect to the TRF is available.

Assuming the scalar height determined by the laser pulse round trip travel time represents the distance from a reference point within the GLAS instrument to the average position within the laser spot on the Earth's surface.

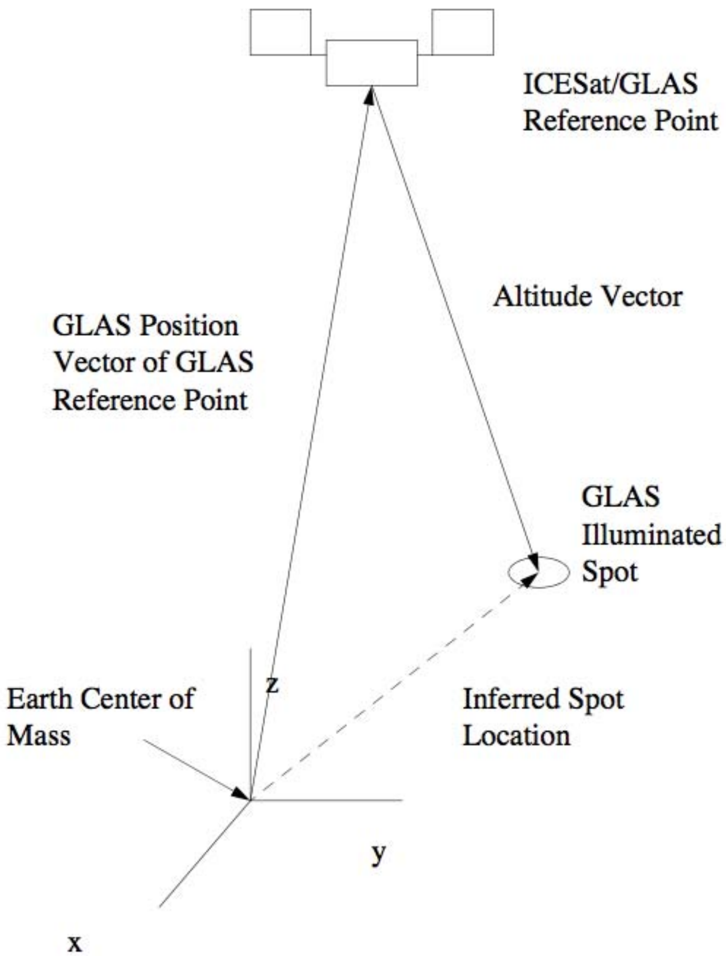


**Figure 2-1 Altimetry Concept**

## 2.4 Assumptions

This ATBD assumes that raw data downlinked to the ground have been converted into appropriate formats for processing by other components of the system. It is assumed that the Level 0 data have been converted into Level 1A, which has contributed to the generation of the following data products:

- instrument position vector, generated by the POD (precision orbit determination)
- laser pointing vector (a unit vector), generated by PAD (precision attitude determination) and laser pointing with respect to spacecraft axes,
- scalar altimeter height, generated by waveform analysis
- the scalar altimeter height has been corrected for the following:
    - tropospheric delay
    - surface change resulting from luni-solar tides

Each of the preceding data products have contributing error sources. These error sources are described later in the overall altimetry error budget. The following error sources are not included in the initial altimetry product generation. These error sources will be the subject of additional analysis and study in the post-launch period for evaluation and model development to provide enhanced corrections. The expected error sources requiring additional evaluation are:

- post-glacial rebound: the melting of the polar ice sheets over the last several thousand years has caused the crust of the Earth to rebound. Models, such as ICE-4G (Peltier, 1994) exist, but the models are based on assumptions about the viscosity of the mantle and the dependency of the models on longitude is uncertain. The actual rate of post-glacial rebound is locally dependent on the history of ice loads during the transition from the last glaciation. This history is better known in the northern hemisphere, but it is very poorly known in Antarctica. Assuming that post glacial rebound signals in Antarctica are of the same order of magnitude as in the northern hemisphere, we can anticipate a rebound rate reaching tens of mm/yr. However, the time-dependent signature of this phenomenon on the geoid is quite different from that of a change in total ice mass. The operation of the ESSP dedicated gravity mission, GRACE (http://www.csr.utexas.edu/grace/), simultaneously with GLAS will aid in separating these signals. Consequently, corrections for post-glacial rebound will require post-launch study and evaluation before a correction can be adopted. The initial data releases of GLAS will not include this correction, but it will be considered for inclusion in later reprocessing and data releases.

- atmospheric backscatter: transmission of the laser pulse through thin clouds will produce scattering effects, which effectively lengthen the path taken by photons returning to GLAS. The effects on the altitude are expected to range from a few millimeters to tens of centimeters, depending on the size of particles in the atmosphere (e.g., ice). A model to correct for these effects will be studied in the post-launch period. Laser spot coordinates obtained under clear sky conditions, which are unaffected by scattering, will be identified for use in higher level processing for the generation of surface change. Additional discussion can be found in the waveform ATBD by Brenner et al. [2000]. As in the case of post glacial rebound, further study in the post-launch period is required, which may lead to the adoption of corrections to account for this effect.

- laser beam directional refraction: atmospheric refraction is assumed to delay the round-trip measurement with no effect on the laser spot location. This effect is expected to be small for the nadir-looking data, but may be significant for off-nadir operations. Possible effects will be evaluated in the verification/validation tests during the post-launch period.

The GLAS altimetry products are similar to those generated by a radar altimeter, such as TOPEX/POSEIDON(T/P). The standard T/P product, the “geophysical data record” (GDR) contains the equivalent of the radar spot coordinates in the along-track direction of the satellite. Products that have led to sea level variations, for example, are not a standard data product but these higher level products are derived from the GDR. With the GLAS equivalent of the T/P GDR, the following higher-level products can be derived:

- surface topography, including digital elevation maps, of the ice sheets and land features

- temporal variations of the surface, especially the ice sheets, obtained by evaluation of the surface profile evolution with time.

This ATBD has been formulated under the assumption that the post-launch verification phase has been completed. This phase will allow “tuning” of the parameters used in the production of inputs to the determination of laser spot location described in this ATBD and will also enable verification of the instrument performance.

## 3.0 ALTIMETRY ALGORITHM DESCRIPTION

### 3.1 Overview

The following sections are organized with the determination of GLAS altitude, or range, summarized first, followed by a summary of the applied corrections to the range. The section is completed with the combination of all terms into the altimeter spot location, or geolocation of the laser spot, which contributes to most GLAS data products, but especially GLA06, GLA09, GLA12 through GLA15. The Level 1 and Level 2 GLAS data products are summarized in Table 3-1.

**Table 3-1 GLAS Data Products**

| Product | Description | Level |
|---|---|---|
| GLA01 | Altimetry Data File | 1A |
| GLA02 | Atmosphere Data File | 1A |
| GLA03 | Engineering Data File | 1A |
| GLA04 | SRS and GPS Data File | 1A |
| GLA05 | Waveform-based Elevation Corrections File | 1B |
| GLA06 | Elevation File | 1B |
| GLA07 | Backscatter File | 1B |
| GLA08 | Boundary Layer and Elevated Aerosol Layer Heights File | 2 |
| GLA09 | Cloud Height for Multiple Layers File | 2 |
| GLA10 | Aerosol Vertical Structure File | 2 |
| GLA11 | Thin Cloud/Aerosol Optical Depth File | 2 |
| GLA12 | Ice Sheet Products File | 2 |
| GLA13 | Sea Ice Products File | 2 |
| GLA14 | Land Products File | 2 |
| GLA15 | Ocean Products File | 2 |

The specific input data and their source used in the generation of the laser spot location are given in Table 3-2. In this table, ANC denotes Ancillary data products. For example, ANC08, is the data product that gives the geocentric position vector of the GLAS instrument in space, based on the Precision Orbit Determination processing.

**Table 3-2 Input Data for Geolocation**

| GLAS ID | Source | Product Level | Description |
|---|---|---|---|
| ANC01 | NMC | | Meteorological data for troposphere delay |
| GLA01 | I-SIPS | 1A | GLAS waveforms and timing |
| GLA02 | I-SIPS | 1B | Troposphere delay, tide corrections |
| ANC08 (POD) | CSR | 1B | Time of instrument position (GPS-Time) Geocentric position of instrument<br>Transformation matrix between ICRF and ITRF<br>Nominal interval: 30 sec (interpolate to 1/ 40 sec) |
| ANC09 (PAD) | CSR | 1B | Time of pointing direction (GPS-Time) Transformation matrix between<br>space- craft-fixed axes and ICRF Nominal interval: 1/40 sec |
| ANC37 | MOC/ISF | 1B | Spacecraft center of gravity |

## 3.2 One-Way Range

### 3.2.1 Conceptual

The laser range measurement produced by GLAS is based on the laser pulse round trip time of flight,

$$\Delta t = t_R - t_T \qquad (3.1)$$

where $\Delta t$ is the round trip pulse travel time, $t_T$ is the laser transmit time and $t_R$ is the receive time. It is assumed that both times are measured with the same clock and the clock drift over the time interval $\Delta t$ is small. Since the altimeter measures range in the near-nadir direction, for the 600 km altitude the measured time interval is about 4 ms (~2 ms each way). It follows that the two-way range, $\rho$ is

$$\rho = c\Delta t \qquad (3.2)$$

where c is the speed of light (IAU adopted value=299,792,458 m/sec).

With the frozen orbit design described, for example, by Lim and Schutz [1995], the perigee will be located over the north pole and apogee is over the south pole. Since the orbit inclination is 94° and the orbit is “frozen,” the apogee and perigee points are actually offset from the pole. Nevertheless, in the vicinity of perigee and apogee the radial velocity component of the orbit is essentially zero. Thus, the altimeter height, $h$ , can be represented by

$$h = \rho / 2 \qquad (3.3)$$

and the time tag assigned to this measurement, $t_m$ , is the time at which the pulse reaches the surface, given by

$$t_m = t_T + \Delta t / 2 \tag{3.4}$$

With the frozen orbit, the maximum radial orbit velocity is about 10 m/sec when the spacecraft crosses the equator. In the 4 ms time required for the pulse round trip, the spacecraft moves a maximum of 4 cm in the radial direction. Thus, to an approximation of better than 4 cm, the measured quantities can be converted into the equivalent of an "instantaneous" height equal to $h$ and assigned the time tag of $t_m$. Note that $t_m$ is the approximate time when the laser pulse illuminated a spot on the Earth surface (or cloud). More definitive evaluations of Eqs. (3.3) and (3.4) (for example, Tapley, et al., 2004) show the approximations from these equations to have an accuracy of about 1 mm.

### 3.2.2 GLAS Measurements

The GLAS laser emits a 1064 nm pulse at a 40 Hz rate, with each pulse having a 5 nsec duration. Part of the outgoing pulse is extracted and digitized for transmission to the ground. A detailed description of the instrument can be found in the GLAS Preliminary Design Review [1998] and the Critical Design Review [1999]. The bins of the digitized pulse are time-tagged with the instrument oscillator, which produces a clock tick with a known offset from GPS-Time. The transmitted pulse is expected to be Gaussian, based on laboratory tests of the Goddard Space Flight Center Instrument Team. The digitized pulse is transmitted to the ground, where it is fitted with a Gaussian in the I-SIPS ground processing. The determination of the absolute time, $t_T$, is performed during the I-SIPS processing. Nominally, the transmit time will be taken to be the time associated with the centroid of the pulse.

The pulse received at the instrument after reflection from the Earth's surface is digitized in GLAS and subsequently analyzed in the I-SIPS to determine the receive time, $t_R$. The ideal return pulse will be Gaussian and the nominal receive time will be the centroid of the return pulse. Various factors will contribute to broadening of the pulse, skewing the pulse or multiple peaks. These factors are discussed in the ATBD for the waveform analysis as given by Brenner, et al. [2000].

The altimeter height is determined by the analysis given in the preceding section, Section 3.2.1, from the transmit and receive times. The altimeter height, or range in the general case of off-nadir pointing, measures the distance from a measurement reference point (MRP) within the instrument to a point on the Earth's surface. In principle, the transmit and receive times refer to the pulse arrival at specific points within the instrument, but the measurement should be referred to a known point on the instrument or spacecraft, the MRP. Specification of the MRP location is essential for verification and validation, as well as enabling GLAS measurements to be used in conjunction with any follow-on instruments. Determination of the MRP will be made during the Instrument Team pre-launch calibration tests during instrument integration and test (I&T). These tests will use the GLAS instrument to range to a target at a carefully measured distance, which will provide calibration corrections to the measured round trip time. Expressed as a correction to the one-way range, this pre-launch calibration correction is represented by $\rho_c$.

### 3.3 Troposphere Delay

The atmospheric delay correction is given by Herring and Quinn [1999]. The range correction is primarily dependent on the surface pressure at the laser spot location, and is also dependent on temperature and water vapor partial pressure along the ray path. The surface pressure component contributes about 2 mm delay for each millibar. Experiments conducted using the NCEP Global Analyses to model surface pressure show that a 5 millibar or better accuracy can be achieved, yielding a 1 cm or better accuracy of the tropospheric delay model. The NCEP fields are interpolated to the location and time tag of the laser footprint. The correction for this component is $\Delta h_{trop}$ and the magnitude of this correction is approximately 2 m in the nadir direction. This term is sometimes referred to as the “dry troposphere” contribution. The “wet” component at optical frequencies is small (usually < 1 mm).

### 3.4 Solid Earth and Ocean Tide Corrections

The solid Earth tide corrections are given by McCarthy [1996] and the ocean loading corrections are described by Yi et al. [1999]. For data collected in the ocean areas, a correction that is consistent with TOPEX/POSEIDON will be used. This correction, based on CSR 3.0 global ocean tide model is summarized by Bettadpur and Eanes [1995]. The correction for all tide effects and rebound contributions is $\Delta h_{tides}$. The amplitude of ocean tide corrections is dependent on location (bays and estuaries can create meter-level amplitudes ), but open-ocean amplitudes are ~ 20 cm. The solid Earth amplitude is ~20 cm as well, but it is somewhat more complicated with the effects of ocean loading on the solid Earth.

### 3.5 Height Vector

The measured height, h, can be corrected for the preceding components to produce a corrected height, $h_c$,

$$h_c = h - \Delta h_{trop} - \Delta h_{tides} - \rho_c \tag{3.5}$$

The laser pointing direction is determined by 1) the mounting of the transmit optics with respect to the spacecraft-fixed axes and 2) the stability of the laser pointing as a function of temperature and other characteristics. Furthermore, launch vehicle loads can produce changes in pre-launch measurements of laser pointing. Such changes must be determined through appropriate verification and validation experiments. The a priori laser pointing is represented by a unit vector, $\mathbf{u}_p$, in the nominal laser direction. In spacecraft-fixed axes, the corrected laser height vector is given by

$$\mathbf{h}_c = h_c \mathbf{u}_p \tag{3.6}$$

where the unit vector $\mathbf{u}_p$ can be expressed in terms of spacecraft-fixed components as

$$\mathbf{u}_p = C_x\mathbf{u}_x + C_y\mathbf{u}_y + C_z\mathbf{u}_z \tag{3.7}$$

where $\mathbf{u}_x$, $\mathbf{u}_y$ and $\mathbf{u}_z$ are unit vectors associated with the spacecraft (x,y,z)-axes, respectively and the coefficients $C_x$, $C_y$, and $C_z$ represent direction cosines for the nominal (pre-flight) laser beam direction. Based on the discussion in Section 3.2, the vector $\mathbf{h}_c$ is measured with respect to a known point within the laser instrument to the illuminated spot on the surface. As described, the vector $\mathbf{h}_c$ is the instantaneous height vector at the time $t_m$ and the components are expressed with respect to the spacecraft-fixed axes.

### 3.6 Laser Spot Coordinates

There are two approaches in common use with altimetry data: one is an accurate approximation (accurate to sub-mm level), which involves an iterative process to determine the transmitted pulse surface reflection time. The other approach is accurate to approximately mm-level and requires a time tag adjustment. Both approaches are described in Tapley, et al. (2004). The POD process (Rim and Schutz, 1999) determines the position of the spacecraft center of mass ($\mathbf{R}_{sc}$), but the GLAS measurement reference point from which the vector $\mathbf{h}_c$ is measured is not coincident. Hence, the displacement $\Delta\mathbf{r}_{ref}$ illustrated in Figure 3-1 will be included in the POD file. The laser spot location is the sum of the vectors, provided they are expressed in the same coordinate system. As shown in Figure 3-1, the vector $\mathbf{R}_{sc}$ is expressed in the ICRF, but $\Delta\mathbf{r}_{ref}$ and $\mathbf{h}_c$ are expressed in spacecraft-fixed axes. The PAD process provides the transformation matrix between the spacecraft axes and the ICRF, $T_{sc/ICRF}$, the nonrotating celestial frame as described in the PAD ATBD (Bae and Schutz, 1999). Thus, the laser spot position in the ICRF is:

$$\mathbf{R}_{spot} = \mathbf{R}_{sc} + T_{sc/ICRF}\left(\Delta\mathbf{r}_{ref} + \mathbf{h}_c\right) \tag{3.8}$$

The 3x3 transformation matrix, $T_{sc/ICRF}$, will be based on pre-launch measurements to calibrate the orientation of the instrument star tracker with respect to the spacecraft-fixed axes.

The last transformation is the conversion of the spot location into Earth-fixed axes, specifically the IERS Terrestrial Reference Frame (ITRF). The vector $\mathbf{r}_{spot}$ is obtained as follows:

$$\mathbf{r}_{spot} = T_{ICRF/ITRF}\mathbf{R}_{spot} \tag{3.9}$$

The 3x3 transformation matrix, $T_{ICRF/ITRF}$, is dependent on precession, nutation and changes in Earth rotation, represented by UT1 and Earth spin axis components. This transformation matrix is required in the POD processing. The elements of the respective matrices are given by McCarthy [1996] and Seidelmann [1992], but the Earth orientation components are reported to the International Earth Rotation Service by GPS, SLR and Very Long Baseline Interferometry Analysis Centers.

The components of this vector in the ITRF are

$$(x, y, z)_{spot} \tag{3.10}$$

which can be further transformed into geodetic coordinates by adopting an ellipsoid with mean radius $a_e$ and flattening, $f$. The relation between these coordinates is:

$$\begin{aligned} x_{spot} &= (N + h^{'})\cos\phi_g \cos\lambda = r\cos\phi\cos\lambda \\ y_{spot} &= (N + h^{'})\sin\phi_g \sin\lambda = r\cos\phi\sin\lambda \\ z_{spot} &= ((1-e^2)N + h^{'})\sin\phi_g = r\sin\phi \end{aligned} \tag{3.11}$$

where ($h^{'}, \phi_g, \lambda$) are the geodetic coordinates of the laser spot with respect to the ellipsoid and ( $r, \phi, \lambda$) are the geocentric spherical coordinates, as illustrated in Figure 3-2. Furthermore,

$$\begin{aligned} f &= (a_e - b) / a_e \\ N &= a_e / \left[1 - e^2 \sin^2 \phi_g\right]^{1/2} \end{aligned} \tag{3.12}$$

and

where $b$ is the polar radius and $e^2 = 2f - f^2$.

The transformation matrix between ICRF and ITRF can be converted into quaternions. These quaternions can be further represented by second-degree polynomials over a short interval, e.g., 1 sec. Interpolation of the polynomial coefficients can be performed at any time and the interpolated quaternions can be converted back into the 3x3 transformation matrix. Tests with this technique show that the ICRF/ITRF transformation matrix generated by the interpolation retains 12 decimal digits of accuracy, much better than the required accuracy to support arc second level pointing.

The preceding algorithm is summarized in Section 4.6.

## 3.7 Output

The altimeter height vector will generate a file containing the following information:

- Time, given in GPS-System Time, corresponding to the adjusted measurement time, $t_m$
- Geodetic coordinates of each laser spot: $(h^{'}, \phi_g, \lambda)$

The series of such measurements over time provides the profile of the topography of the illuminated surface (ice, land, water, clouds). (Figure 3-1) The time series of the spot locations will be used for the generation of higher-level products, including altimeter crossovers, which will be used to remove common error sources and will be a key analysis approach for the detection of surface change. Analysis described in the waveform ATBD [Brenner, et al., 2000] provides information about the quality of the coordinates and the potential influence of surface features. (Figure 3-2)

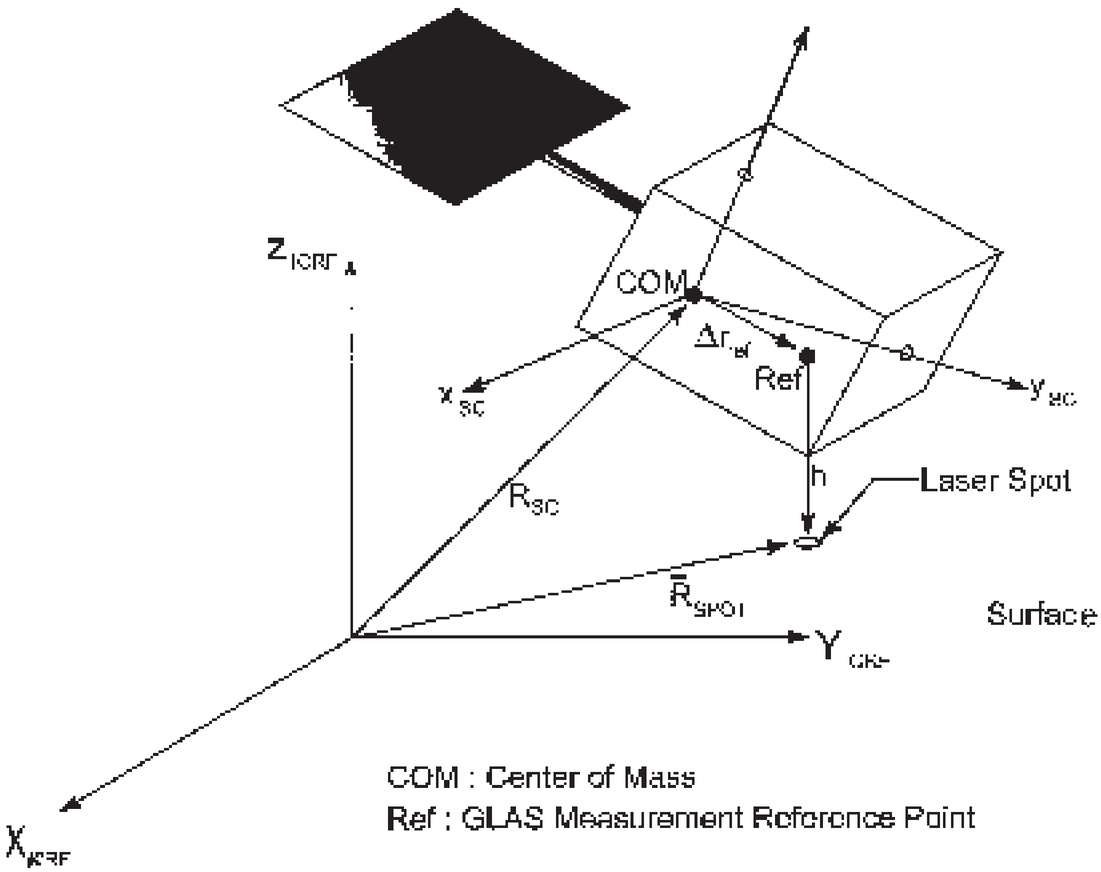


**Figure 3-1 Position Vectors**

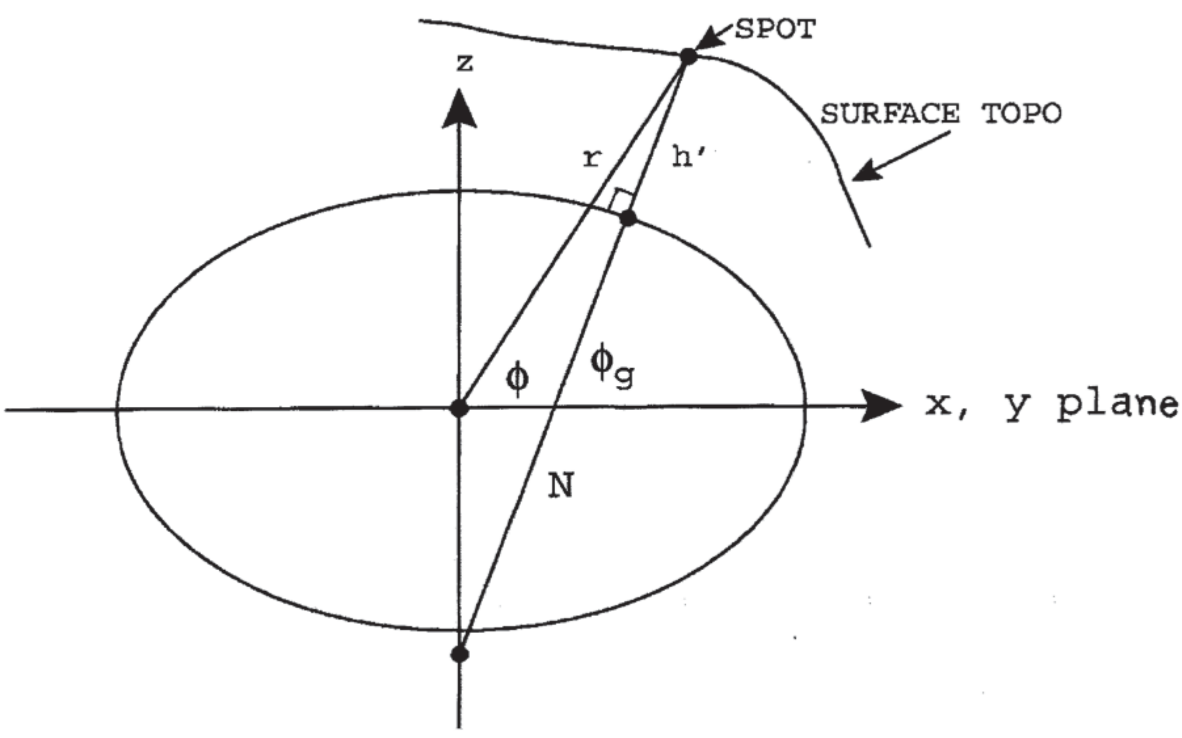


**Figure 3-2 Geocentric and Geodetic Coordinates**

## 4.0 IMPLEMENTATION CONSIDERATIONS

### 4.1 Standards

The standards adopted for this stage must be consistent with the standards adopted in the ATBDs leading to coordinates of the laser spot, including the POD and PAD standards. Specific physical constants required with the algorithm are consistent with those used by radar altimeter satellites (TOPEX/POSEIDON and JASON), as given by Benada (1997):

- Speed of Light: $c = 299{,}792{,}458 m/\sec$
- Ellipsoid Parameters: $a_e = 6378136.30m$ and $1/f = 298.257$

The above values may be updated during GLAS operation, but the uncertainties in the ellipsoid parameters are currently at the few decimeter level or better and the speed of light is a defining constant (as adopted by the International Astonomical Union)

### 4.2 Ancillary Inputs

The input data required for this algorithm are:

- The Level 1B altimeter data, containing altimeter range and waveforms [see Brenner, et al., 2000].
- The output from the POD, containing spacecraft center of mass position in the ICRF as a function of time and the transformation matrices between ICRF and ITRF, consistent with those used in the POD process [see Rim and Schutz, 2002].
- The output from the PAD, containing the transformation matrix (or quaternions) as a function of time, to enable orientation of the spacecraft-fixed axes with respect to the ICRF [see Bae and Schutz, 2002].
- Meteorological data to enable computation of the troposphere delay, dependent on temperature, pressure and humidity at the laser spot location [see Herring and Quinn, 1999].
- Time-dependent models for solid Earth tides, ocean tides, and ocean loading effects [see Yi, et al., 1999; McCarthy, 1996; and Bettadpur and Eanes, 1994].

### 4.3 Accuracy

The accuracy of the result will be determined by the accuracy of the respective products that contribute to the algorithm result. The expected errors are given in Table 4-1 the GLAS single shot error budget.

### 4.4 Computational

The algorithm relies on the results generated by other components product generation. As a result, the laser spot location is obtained by simple vector operations and the application of 3x3 transformation matrices. In fact, operations to read the files generated from the POD and the PAD processes, as well as interpolation of meteorological data, will require more computer time than the time required for the matrix operations leading to the result.

The laser spot location requires storage of time and three coordinates. At the pulse rate of 1/40 sec, one full day will require about 115 MB to store these four quantities at full precision (64 bit). The operations can be readily performed using a modest performance workstation, e.g., HP725.

**Table 4-1 Altimeter Single Shot Error Budget**

| Error Source | Contribution |
|---|---|
| • Level 1A Instrument error sources (assume: 1° surface slope) | 10 cm |
| Slope and surface roughness influence on precision, including biases | |
| (Instrument range precision per pulse) | |
| • Platform requirement | |
| Determination of altimeter reference point relative to spacecraft | |
| center of mass | 0.5 cm |
| • Level 1B error sources (assume: 1° surface slope) | |
| Radial orbit error (based on GPS, error assumed random) | |
| Assume: 5 cm for spacecraft center of mass | 5 cm |
| Horizontal orbit position error (based on GPS, assumed random) | |
| Assume: 20 cm | 1 cm |
| Attitude/pointing error as a function of slope (5 cm/″ pointing/° slope) | |
| Assume: 1″ attitude on 1° slope | 5 cm |
| Atmosphere delay error | |
| Surface pressure (0.23 cm/mb) | |
| Assume: 10 mb surface pressure error | 2 cm |
| Surface temperature (0.9 cm/50°K) | |
| Assume: 25°K error | < 1 cm |
| Surface relative humidity (0.05 cm/50%) | |
| Assume: 100% error | 0 cm |
| Clock synchronization: | |
| Assume: < 10 μs with respect to GPS time (consistency with GPS-derived ephemeris: height error is 4 mm for 10 μs) | < 1 cm |
| Other error sources (expected to be < 1 cm, but currently under study) | < 1 cm |
| Solid tides and ocean loading over ice sheets | |
| Ice sheet loading/rebound | |
| Atmospheric forward scattering | |
| RSS | 13 cm |
| Note: long term systematic (time scale: 5 years) error contributions: | < 1 cm |

## 4.5 Product Validation

Detailed discussion of the validation of the laser spot location is contained in the GLAS Validation Plan [1998]. The spot location is dependent on several individual error sources and the data product validation will attempt to identify and examine those error sources. As an example of such validation, a technique that can "capture" a laser spot on the Earth surface will provide an unambiguous in situ measure of validation. In summary, one planned approach to capturing a spot, or a series of spots, is to image them during an over-flight of a verification site. The image will be made with a CCD camera from an aircraft and the image will contain reference points, or fiducial points, that enable determination of the coordinates of the laser spot with respect to the fiducial points. As a result, the validation approach provides a direct determination of the spot coordinates, which can be compared to the standard data product generated by the summation of the orbit position vector and the laser altitude vector [see Figure 2-1]. The planned primary verification area is White Sands Space Harbor (NM). The flatness of the site will aid in verifying the range (altitude) measurement without errors associated with slope and the albedo of the site is similar to ice. During the cal/val phase (see Table 2-1), the orbit will be designed to overfly White Sands and with the 8-day repeat orbit, there would be about 10 opportunities. In the main mission phase, opportunities for using White Sands exist using off-nadir pointing, but the opportunities are less frequent (about 25 day intervals). These opportunities are important to enable verification/validation at any time in the mission, especially after the instrument is reconfigured (switch to a different laser, switch detectors, etc.).

In addition, the validation implementation includes plans to validate the time tag, $t_m$, by using an array of ground-based detectors linked to a GPS timing receiver. Included in the array of about 200 m x 200 m will be retroreflectors placed on stalks at different heights. These retroreflectors will enable identification of the specific GLAS return pulse in the data stream so that it can be correlated with the pulse that illuminated the array. Although GPS time transfers have an accuracy of tens of nanoseconds, the validation goal is to validate the time tag at the 10 microsecond level (Science Requirements, 1997).

## 4.6 Implementation Summary

The following section summarizes the procedure to be followed to generate the GLAS laser spot location on the Earth's surface.

Given:

POD file containing t, X, Y, Z, Xdot, Ydot, Zdot in ICRF for GLAS reference point (in GPS-T or UTC)

PAD file containing $t, \cos\alpha, \cos\beta, \cos\gamma$ in ICRF (time-tagged at laser transmit time in GPS-T or UTC)

ICRF/ITRF transformation matrix file

Laser pulse: transmit time, $t_T$ ; echo receive time, $t_R$

Determine:

Geodetic coordinates of GLAS illuminated spot on surface

Procedure:

1. Generate time of pulse arrival on the surface, $t_m$

$$t_m = t_T + \Delta t \tag{4.1}$$

where $\Delta t = (t_R - t_T)/2$

2. Generate scalar range (altitude)

$$\rho = c\Delta t \tag{4.2}$$

3. Evaluate POD at time $t_m$, for position of GLAS reference point in ICRF, $\mathbf{R}$

4. Evaluate ICRF/ITRF transformation matrix at $t_m$, $T(t_m)$

5. Form the altitude vector, $\mathbf{H}$, in ICRF by multiplying $\rho$ times the direction cosines given at $t_T$, $\mathbf{H}$

$$\mathbf{H} = \begin{bmatrix} \rho\cos\alpha \\ \rho\cos\beta \\ \rho\cos\gamma \end{bmatrix} \tag{4.3}$$

6. Compute the inferred spot location in ICRF

$$\mathbf{R}_{spot} = \mathbf{R} + \mathbf{H} \tag{4.4}$$

7. Compute the inferred spot location in ITRF by application of transformation matrix

$$\mathbf{r}_{spot} = T(t_m)\mathbf{R}_{spot} \tag{4.5}$$

8. Compute geodetic latitude, longitude and height from $\mathbf{r}_{spot}$ (as given by Eq. ) and assign the time tag, $t_m$

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Many of the above documents are available on GLAS web addresses:

- Science http://www.csr.utexas.edu/glas/
- Project http://icesat.gsfc.nasa.gov
- Instrument http://ltpwww.gsfc.nasa.gov/eib/glas.html
- Data System http://glas.wff.nasa.gov

# GLOSSARY/ACRONYMS

| | |
|---|---|
| ANC | Ancillary data products |
| ATBD | Algorithm Theoretical Basis Document |
| CDR | Critical Design Review |
| ESE | Earth Science Enterprise |
| GDR | Geophysical Data Record |
| GLAS | Geoscience Laser Altimeter System |
| GPS | Global Positioning System |
| GRACE | Gravity Recovery And Climate Experiment |
| GSFC | Goddard Space Flight Center |
| ICESat | Ice, Cloud, land Elevation Satellite |
| IERS | International Earth Rotation Service |
| ISIPS | ICESat Science Investigator-led Processing System |
| ITRF | IERS Terrestrial Reference Frame |
| MRP | Measurement Reference Point |
| NASA | National Aeronautics and Space Administration |
| PAD | Precision Attitude Determination |
| PDR | Preliminary Design Review |
| POD | Precision Orbit Determination |
| TBD | To Be Determined |
| TRF | Terrestrial Reference Frame |
| UTC | Coordinated Universal Time |

# APPENDIX A ICESat Mission Outline

The Ice, Cloud and land Elevation Satellite (ICESat) was launched on 13 January 2003 0045 UTC from Vandenberg AFB into a 600 km orbit (near zero eccentricity) and $94^{o}$ inclination. The Geoscience Laser Altimeter System (GLAS) instrument onboard ICESat made its first laser range measurement of the Earth on 21 February 2003 and its last range measurement on 11 October 2009. The three lasers employed by GLAS did not perform as long as expected, and following the failure of Laser 1 on 5 March 2003 the ICESat mission was modified to meet the requirement for capturing a multi-year time series of ice sheet elevations (Schutz et al., 2005). For the modified mission scenario, the spacecraft entered a 91-day repeat science orbit (compared to a planned 183-day repeat) and the lasers were activated for about 33 days of this 91-day repeat, two or three times per year during the same repeat tracks. This campaign mode operation is summarized in Table A.1, and other significant parameters and events are listed in Table A.1. ICESat laser campaigns are designated by a laser number (L1, L2 or L3), followed by a letter in the sequence of operation. Following campaign L2f, attempts to restart any of the lasers were not successful. The spacecraft was put through a series of engineering tests in early 2010. De-orbit maneuvers were carried out in June and July 2010. The spacecraft was "passivated" on 14 August and reentered the Earth's atmosphere on 30 August 2010 over the Barents Sea northeast of Norway.

**Table A.1: ICESat Laser Operation Campaigns**

| Campaign | Year | Day of year | Calendar Dates | Number of days (d) | Repeat orbit (d) | Repeat tracks1 |
|---|---|---|---|---|---|---|
| L1a | 2003 | 051-088 | 20 Feb-21 Mar | 37 | 8 | 001-072 to 006-023 |
| L2a | 2003 | 268-277/ 277-322 | 25 Sep-4 Oct/ 4 Oct-21 Nov | 54 | 8/ 91 | 028-088 to 029-100/ 1098 to 0421 |
| L2b | 2004 | 048-081 | 17 Feb-21 Mar | 33 | 91 | 1284 to 0421 |
| L2c | 2004 | 139-173 | 18 May-21 Jun | 34 | 91 | 1283 to 0434 |
| L3a | 2004 | 277-313 | 3 Oct-8 Nov | 37 | 91 | 1273 to 0452 |
| L3b | 2005 | 048-083 | 17 Feb-24 Mar | 35 | 91 | 1258 to 0426 |
| L3c | 2005 | 140-174 | 20 May-23 Jun | 34 | 91 | 1275 to 0421 |
| L3d | 2005 | 294-328 | 21 Oct-24 Nov | 34 | 91 | 1282 to 0421 |
| L3e | 2006 | 053-087 | 22 Feb-28 Mar | 34 | 91 | 1283 to 0424 |

| | | | | | | |
|---|---|---|---|---|---|---|
| L3f | 2006 | 144-177 | 24 May-26 Jun | 33 | 91 | 1283 to 0421 |
| L3g | 2006 | 298-331 | 25 Oct-27 Nov | 33 | 91 | 1283 to 0423 |
| L3h | 2007 | 071-104 | 12 Mar-14 Apr | 33 | 91 | 1279 to 0426 |
| L3i | 2007 | 275-309 | 2 Oct-5 Nov | 34 | 91 | 1280 to 0421 |
| L3j | 2008 | 048-081 | 17 Feb-21 Mar | 33 | 91 | 1282 to 0422 |
| L3k | 2008 | 278-293 | 4 Oct-19 Oct | 15 | 91 | 1283 to 0145 |
| L2d | 2008 | 330-352 | 25 Nov-17 Dec | 22 | 91 | 0096 to 0423 |
| L2e | 2009 | 068-101 | 9 Mar-11 Apr | 33 | 91 | 1286 to 0424 |
| L2f | 2009 | 273-284 | 30 Sep-11 Oct | 11 | 91 | 1280 to 0084 |

1 There are 119 tracks in the 8-day orbit and 1354 tracks in the 91-day orbit. Cycle numbers are included for the 8-day repeat periods.

# APPENDIX B Notes on Reference Frames and Reference Ellipsoids

Since Elevation is not directly measured by GLAS (it is inferred using POD and PAD and GLAS range), as described in Section 3.6 of this document. As a consequence, the reference frame used to describe the laser spot location (or geolocation) is determined by the POD and PAD processes. Since the IGS ephemerides were adopted for POD, these ephemerides and the coordinates of GPS receivers (used in the POD process) define the Reference Frame. This reference frame was changed by the IGS in 2008, but the IGS regenerated all of the GPS ephemerides, which were then used in the ICESat POD, so the reference frame of the recent reprocessing used the ITRF 2008. The WGS-84 reference frame was not used because it was inaccessible to the ICESat processing. In particular, the coordinates of the GPS receivers were available only in the ITRF, not in WGS-84. Nevertheless, the WGS-84 reference frame is closely aligned to WGS-84 (Those responsible for WGS-84 have taken steps to ensure that WGS-84 is closely aligned to ITRF). From the POD and PAD generation, the laser spot coordinates are generated in ITRF using the methodology of this document described in Section 3.6 of this document. From the ITRF values (x,y,z), the coordinates of the laser spot can be determined as geodetic coordinates (after adopting a Reference Ellipsoid and the appropriate parameters). Commonly used Reference Ellipsoids include the WGS-84 Ellipsoid and the ellipsoid used with TOPEX-POSEIDON (T/P) altimeter data. The WGS-84 Ellipsoid can be regarded as a descendent of the CRS1980 (see, for example, Hofmann-Wellenhof and Moritz (2006). The ellipsoid parameters of the WGS-84 and the T/P Ellipsoids are given below:

| Semimajor Axis | Inverse Flattening |
|---|---|
| WGS-84 6378137m | 298.257223563 |
| T/P 6378136.3 m | 298.257 |