GLAS/ICESat L1 and L2 Global Altimetry Data, Version 33, 34

USER GUIDE

This user guide applies to following sets:

GLAS/ICESat L1A Global Altimetry Data (GLA01), Version 33

GLAS/ICESat L1B Global Waveform-based Range Corrections Data (GLA05), Version 34

GLAS/ICESat L1B Global Elevation Data (GLA06), Version 34

GLAS/ICESat L2 Antarctic and Greenland Ice Sheet Altimetry Data (GLA12), Version 34

GLAS/ICESat L2 Sea Ice Altimetry Data (GLA13), Version 34

GLAS/ICESat L2 Global Land Surface Altimetry Data (GLA14), Version 34

GLAS/ICESat L2 Ocean Surface Altimetry Data (GLA15), Version 34

FOR QUESTIONS ABOUT THESE DATA, CONTACT NSIDC@NSIDC.ORG

FOR CURRENT INFORMATION, VISIT https://nsidc.org/data/GLA01 (GLA05, GLA06, GLA12, GLA13, GLA14, and GLA15)

National Snow and Ice Data Center

How to Cite These Data

As a condition of using these data, you must include a citation:

Zwally, H. J., R. Schutz, C. Bentley, J. Bufton, T. Herring, J. Minster, J. Spinhirne, and R. Thomas. 2011. *GLAS/ICESat L1A Global Altimetry Data, Version 33*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/ICESAT/GLAS/DATA121. [Date Accessed].

Zwally, H. J., R. Schutz, C. Bentley, J. Bufton, T. Herring, J. Minster, J. Spinhirne, and R. Thomas. 2014. *GLAS/ICESat L1B Global Waveform-based Range Corrections Data, Version 34*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/ICESAT/GLAS/DATA125. [Date Accessed].

Zwally, H. J., R. Schutz, C. Bentley, J. Bufton, T. Herring, J. Minster, J. Spinhirne, and R. Thomas. 2014. *GLAS/ICESat L1B Global Elevation Data, Version 34*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/ICESAT/GLAS/DATA126. [Date Accessed].

Zwally, H. J., R. Schutz, C. Bentley, J. Bufton, T. Herring, J. Minster, J. Spinhirne, and R. Thomas. 2014. *GLAS/ICESat L2 Antarctic and Greenland Ice Sheet Altimetry Data, Version 34*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/ICESAT/GLAS/DATA225. [Date Accessed].

Zwally, H. J., R. Schutz, C. Bentley, J. Bufton, T. Herring, J. Minster, J. Spinhirne, and T. Ross. 2014. *GLAS/ICESat L2 Sea Ice Altimetry Data, Version 34*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/ICESAT/GLAS/DATA226. [Date Accessed].

Zwally, H. J., R. Schutz, C. Bentley, J. Bufton, T. Herring, J. Minster, J. Spinhirne, and R. Thomas. 2014. *GLAS/ICESat L2 Global Land Surface Altimetry Data, Version 34*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/ICESAT/GLAS/DATA227. [Date Accessed].

Zwally, H. J., R. Schutz, C. Bentley, J. Bufton, J. Minster, J. Spinhirne, and R. Thomas. 2014. *GLAS/ICESat L2 Ocean Surface Altimetry Data, Version 34*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/ICESAT/GLAS/DATA228. [Date Accessed].

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NOTE: National Snow and Ice Data Center (NSIDC) access to GLAS binary products GLA01 to GLA15 was removed 01 August 2017. Documentation for the binary products has been retained for informational and provenance purposes. All GLAS data remain available in HDF5 format, products GLAH01 to GLAH15.

This document covers seven data sets:

GLA01: Level-1A altimetry data include the transmitted and received waveforms from the instrument.

GLA05: Level-1B waveform parameterization data include output parameters from the waveform characterization procedure and other parameters required to calculate surface slope and relief characteristics. Geolocated to the center of the laser footprint

GLA06: Level-1B elevation data include surface elevation, surface roughness assuming no slope, surface slope assuming no roughness, and geodetic and atmospheric corrections for range measurements. Geolocated to the center of the laser footprint.

GLA12 - GLA15: Level-2 altimetry data provide surface elevations for ice sheets (GLA12), sea ice (GLA13), land (GLA14), and oceans (GLA15). Data also include the laser footprint geolocation and reflectance, as well as geodetic, instrument, and atmospheric corrections for range measurements.

1 DATA DESCRIPTION

This document covers seven data sets as listed in Table 1.

Table 1. GLAS Data Sets Described in this Document

Short Name	Long Name
GLA01	GLAS/ICESat L1A Global Altimetry Data
GLA05	GLAS/ICESat L1B Global Waveform-based Range Corrections Data
GLA06	GLAS/ICESat L1B Global Elevation Data
GLA12	GLAS/ICESat L2 Antarctic and Greenland Ice Sheet Altimetry Data
GLA13	GLAS/ICESat L2 Sea Ice Altimetry Data
GLA14	GLAS/ICESat L2 Global Land Surface Altimetry Data
GLA15	GLAS/ICESat L2 Ocean Altimetry Data

GLA01 contains all altimetry information transmitted from the spacecraft, including the long and short waveforms. The number of received samples is either 200 or 544. These change at the frame boundary and are nominally set by the onboard surface-type mask. In normal operations, GLAS receives 200 samples over sea ice and ocean, and 544 samples over ice sheet and land. The transmit pulse, received echo samples, and associated digitizer addresses are transferred from

Level-0 telemetry without calibration or unit changes. This is the only product that contains the altimeter transmitted and received waveforms, which may be required by altimetric scientists investigating the instrument health. This product is not intended for use by the general science community.

GLA05 is an intermediate product that contains important information calculated from the waveform. GLA05 is used for creating GLA06 and Level-2 elevation products. The higher products contain scientific parameters derived from algorithms that specifically use GLA05 as input. GLA05 contains parameterizations of both the transmitted and received pulses and other characteristics from which elevation and footprint-scale roughness and slope are calculated. The received pulse characterization uses two implementations of the retracking algorithms: one tuned for ice sheets, called the standard parameterization, used to calculate surface elevation for ice sheets, oceans, and sea ice; and another for land (the alternative parameterization).

GLA06 is a product that is analogous to the geodetic data records distributed for radar altimetry missions. It contains elevations previously corrected for tides, atmospheric delays, and surface characteristics within the footprint. Elevation is calculated using the ice sheet parameterization. Additional information allows the user to calculate an elevation based on land, sea ice, or ocean algorithms.

1.1 Surface Type Mask

GLA12 to GLA15, the Level-2 elevation products, are regional products archived at 14 orbits per granule, starting and stopping at the same demarcation (± 50° latitude) as GLA05 and GLA06. Each regional product is processed with algorithms specific to that surface type. Surface type masks define which data are written to each of the products. If any data within a given record fall within a specific mask, the entire record is written to the product. Masks can overlap: for example, non-land data in the sea ice region may be written to the sea ice and ocean products. This means that an algorithm may write the same data to more than one Level-2 product. In this case, different algorithms calculate the elevations in their respective products. The surface type masks are versioned and archived at NSIDC, so users can tell which data to expect in each product. GLA06 is used in conjunction with GLA05 to create the Level-2 altimetry products.

Each data granule has an associated browse product that users can quickly view to determine the general quality of the data in the granule. Browse products consist of image plots of key parameters and statistics.

1.2 Format

1.2.1 Header

GLAS products are direct-access files with all records the same length. The first records at the beginning of each file contain metadata in ASCII format. The record length varies from product to product. The first two entries in the headers are the record length of all records in that file and the number of records that contain header information. This allows product readers to verify the record length and jump directly to the first data record, if necessary. The following is a small portion of the header of sample GLA12 granule `GLA12_531_2123_002_0071_0_01_0001.DAT`.

```
Recl=6600;
Numhead=3;
size_mb_ecs_data_granule=48.33984375;
time_between_contiguous_records=1;
instrument_short_name=GLAS;
platform_short_name=Icesat;
sensor_short_name=LaserAlt;
```

Refer to Header Descriptions for definitions of header keywords.

1.2.2 Data Records

The data records contain elements in scaled integer binary format with the following criteria:

- Record size is a multiple of eight.
- 4-byte elements are aligned on 4-byte boundaries.
- Arrays start on 4-byte boundaries.
- Byte order is big-endian (Unix).

GLA01, GLA05, and GLA06 are written as 1 second records, so each record contains one frame (40 shots) of data. The data are time-ordered with no duplicate data across granules.

The following figure from Jester and Lee (2002) summarizes the data structure for different byte sizes.

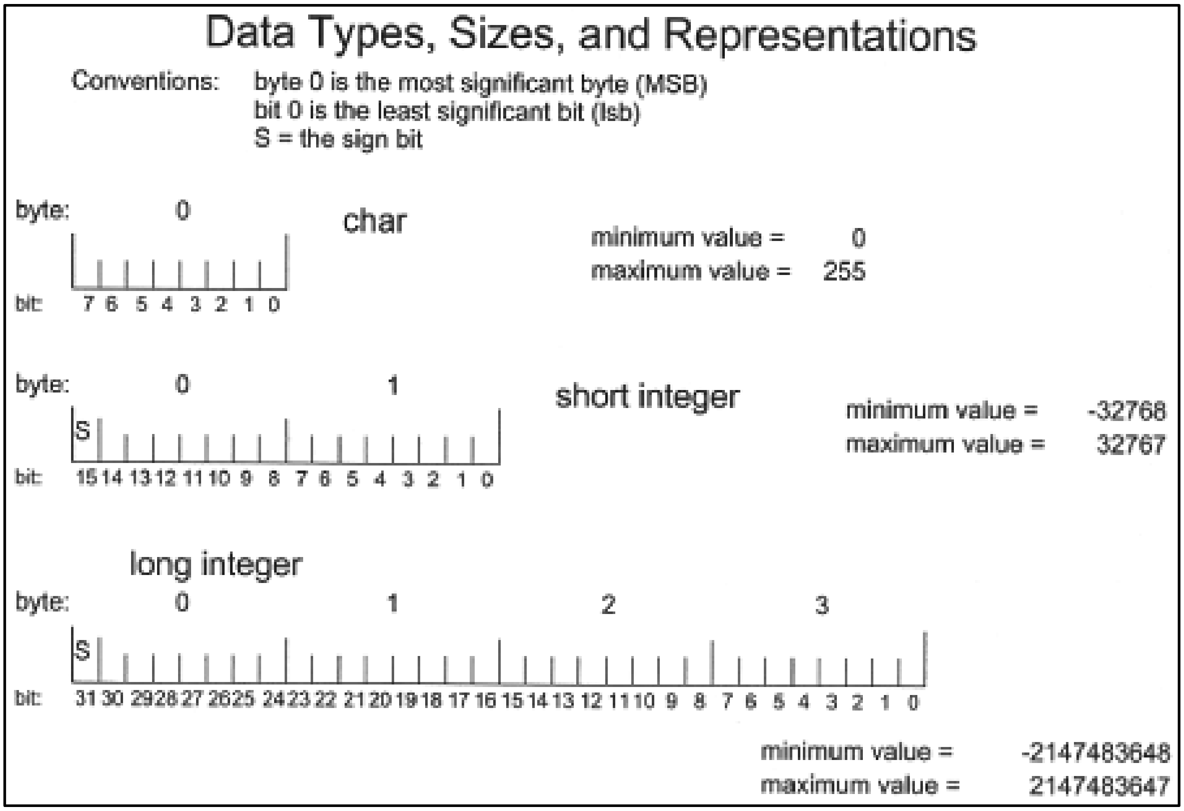

Figure 1. Data Types, Sizes and Representations

1.2.3 Invalid values

Not all data from GLAS are suitable for science processing, and some data may be missing. Invalid values indicate that data are either invalid or missing and should not be used for processing. Values vary by data type, but they are always set to large numbers to indicate invalid data (Lee 2002) as shown in Table 2.

Table 2. Data Type and their Invalid Value

Data Type	Invalid Value
1-byte integer	gi_invalid_i2b (same as "127")
2-byte (short) integer	gi_invalid_i2b (same as "32767")
4-byte (long) integer	gi_invalid_i4b (same as "2147483647")
4-byte real	3.40282E+38 x7F7FFFFF
8-byte real	1.797693094862316E+308 x7FEFFFFFFFFFFFFF

An invalid value of **n/a**, **N/A**, or **NA** means not applicable. A value of **no** means there is no invalid value associated with that parameter. A value of **null** means the actual invalid value is null. This occurs in GLA01 and GLA02 parameters copied directly from Level-0 raw data, which contain unsigned integers that cannot use invalid values. Instead, flags are set if the value is invalid.

When comparing data from different products, the record index is consistent as long as all products represent the same version of data. To compare products from different versions, update your oldest product to the latest version. For example, to compare data from a GLA01 Release-12 file and GLA12 Release-18 file, order a new GLA01 Release-18 file to replace the older version. The ICESat/GLAS Data Releases page describes changes and limitations with each release of data.

1.2.4 Surface-type mask

Surface-type mask data (available via HTTPS) are stored as an 10800 by 5400 byte array, where each byte represents the surface type for one 30 second grid cell on the earth. Each 10800-byte record represents a 360° latitude band. The first record starts at the North Pole, and the records follow at 30 second intervals to the South Pole.

Valid pixel values range from 1 to 15. The surface types are bit-coded, and any combination of surface type is allowed. The bit coding is:

1 = ice sheet
2 = sea ice (winter maximum extent)
4 = land
8 = ocean

Please see ICESat/GLAS Surface-Type Mask for a disclaimer and further details.

1.3 File Naming Convention

The file naming convention is as follows:

```
glaxx_mmm_prkk_ccc_tttt_s_nn_ffff.dat
```

Where:

Table 3. File Naming Convention

Variable	Description
`xx`	Product number (01, 05, 06, 12, 13, 14, or 15)
`mmm`	Release number for process that created the product
`p`	Repeat ground-track phase (1 = 8-day, 2 = 91-day, 3 = transfer orbit)
`r`	Reference orbit number; this number starts at 1 and increments each time a new reference orbit ground track file is obtained.

Variable	Description
`kk`	Instance number, incremented every time the satellite enters a different reference orbit.
`ccc`	Cycle of reference orbit for this phase; the cycle number restarts at 1 every time the instance number changes. The cycle number then increments within the instance (kk) every time Track 1 for that orbit is reached. Most instances begin in an arbitrary track (not 1) because of how the tracks are numbered.
`tttt`	Track within reference orbit; tracks are defined from a reference orbit. Each track begins and ends at the ascending equator crossing. Tracks are numbered such that Track 1 is the closest track to Greenwich Meridian from the east and then contiguous in time after that. For transfer orbits, for which we have no predefined reference orbit, Track 1 is the first track for which we have data for that instance (kk).
`s`	Segment of orbit
`nn`	Granule version number; the number of times this granule is created for a specific release
`ffff`	File type; numerical, assigned for multiple files as needed for data of same time period for a specific data product; a multifile granule

Note: Beginning with Release-28, a new convention is used for the release number (mmm) in file names.

Please see the following documents on the ICESat Technical References page for more information:

- ICESat/GLAS YXX Release Numbers
- ICESAT/GLAS CSR SCF Release Notes for Orbit and Attitude Determination

1.3.1 File Naming Convention for Special-Request Data

Please see the Description of Special Request ICESat/GLAS Files for information about binary file naming for special request data from the ICESat/GLAS Data Subsetter.

1.4 File Size

Table 4 lists approximate file sizes for each product.

Table 4. Approximate File Size of Products

Product	File Size
GLA01	9 MB
GLA05	25 MB
GLA06	7 MB
GLA12	104 MB

Product	File Size
GLA13	107 MB
GLA14	209 MB
GLA15	279 MB

1.5 Spatial Coverage

GLAS/ICESat coverage is global between 86° N and 86° S with occasional off-nadir pointing to the poles or other targets of opportunity. GLA01, GLA05, and GLA06 files span 1/4 orbit, split at ± 50° latitude. GLA12-15 files span 14 orbits.

Note: GLAS binary products are no longer available to search and order.

1.5.1 Spatial Resolution

GLAS is a profiling instrument that collects data only where the altimeter points, nominally along the ground track. At 40 pulses per second, the centers of 60 m spots illuminated by the laser on the earth's surface are separated in the along-track direction by 172 m from a 600 km altitude orbit.

1.6 Temporal Coverage

Please refer to the Data Release Schedule for the temporal coverage of specific products and descriptions of past releases.

Also see the visit the Date Conversion Tool to see the Pass ID for a user-specified year, day, and time.

1.6.1 Temporal Resolution

Data were captured on 8-day and 91-day repeat orbits.

1.7 Parameter or Variable

1.7.1 Parameter Description

Please see the following tables of data records for each product. Data records describe data product structure and parameters.

- GLA01 Records
- GLA05 Records
- GLA06 Records

- GLA12 Records
- GLA13 Records
- GLA14 Records
- GLA15 Records

The GLAS Altimetry Data Dictionary provides further detail about the format of individual parameters, including scaling factors and ranges.

1.7.2 Flags common across all data sets

ICESat/GLAS data files contain flags that indicate the quality of input data, output data, and data corrections. If quality is reasonable, the data use and frame quality flags are set to zero. A non-zero data use or frame quality flag indicates an abnormal situation during processing; the user should review the corresponding flag for that product for further interpretation. The following flags are common across most GLAS altimetry data sets (see the GLAS Altimetry Data Dictionary or more details and/or to view byte structure).

i_APID_AvFlg indicates which Level-0 packets (APIDs) for each second are available, missing, or filled. This flag is separated into Altimeter Digitizer, Photon Counter, Cloud Digitizer, GPS/DEM, and C&T sections.

i_OrbFlg indicates quality of orbit, whether predicted or precision, loss of GPS data, maneuver-degraded, etc.

i_AttFlg1 denotes at 1 Hz rate whether the attitude angle is large, and whether it is the result of a programmed ocean sweep, target of opportunity, or steering to a reference track.

i_AttFlg2 denotes at 40 Hz rate whether the attitude is calculated or predicted, and if there are noted problems with attitude sensor.

i_FrameQF denotes all bad data (no signal in whole frame) or all good data with science team-recommended corrections applied. This quality flag pertains to the entire frame.

i_rngCorrFlg denotes which geophysical or instrument corrections have been applied to the range before it was used to calculate the elevation.

i_CorrStatFlg indicates which algorithm or model was used for each geophysical correction that potentially has multiple sources.

i_atmQF indicates the waveform-detected presence of cloud layers and some measure of optical depth.

i_ElvuseFlg indicates whether the elevations on this record should be used or not. This flag pertains to each shot.

i_timecorflg indicates the correction status of the time-tag.

1.7.3 Usage Guidance

See the GLAS Altimetry Product Usage Guidance (PDF, 260 KB) for details on working with the GLAS altimetry parameters.

2 SOFTWARE AND TOOLS

NOTE: Access to GLAS binary data and tools was removed 01 August, 2017. All GLAS data are available in HDF5 format.

3 DATA ACQUISITION AND PROCESSING

3.1 Theory and Measurements

A complete description of the physical and mathematical algorithms used in the generation of the data products can be found in the Algorithm Theoretical Basis Documents (ATBD).

Satellite altimeters measure the time it takes a laser pulse to travel from the source to the earth's surface and back to the receiver. The GLAS laser pulse illuminates an approximately 60 m ellipsoidal footprint. Surface elevation is determined from the subtracting the GLAS-measured range vector from the altitude vector giving the satellite orbit above the earth. The range is corrected for instrument artifacts and atmospheric delays. Tides are then applied to the resultant elevation (Zwally et al. 2002). Surface height measurements represent a mean value over the footprint area. Surface slope and roughness within a footprint increase the return pulse width, or the time interval over which the signal is returned.

Over the Greenland and Antarctic ice sheets, the return waveform resembles a simple Gaussian curve with a single peak, in the absence of forward scattering by clouds. The number of Gaussian peaks in the returns depends on the surface type. A single Gaussian peak is expected over oceans, sea ice, and ice sheets. Multiple peaks may result over land and irregular ice sheet surfaces, particularly crevasses, cliffs, and areas of ice fog and low clouds. The return signal is represented as a sum of Gaussian peaks plus a bias (Brenner et al. 2000). The modeled waveform is defined as:

$$w(t) = \varepsilon + \sum_{m=1}^{N_p} A_m \exp\left[-\frac{(t - t_m)^2}{2\sigma_m^2}\right]$$

where:

N_p = number of peaks in the waveform

A_m = amplitude of the mth peak

ε = bias (noise level) of the waveform

t_m = peak position

σ_m = standard deviation of the mth peak

The following graphs show examples of waveforms over two different surfaces.

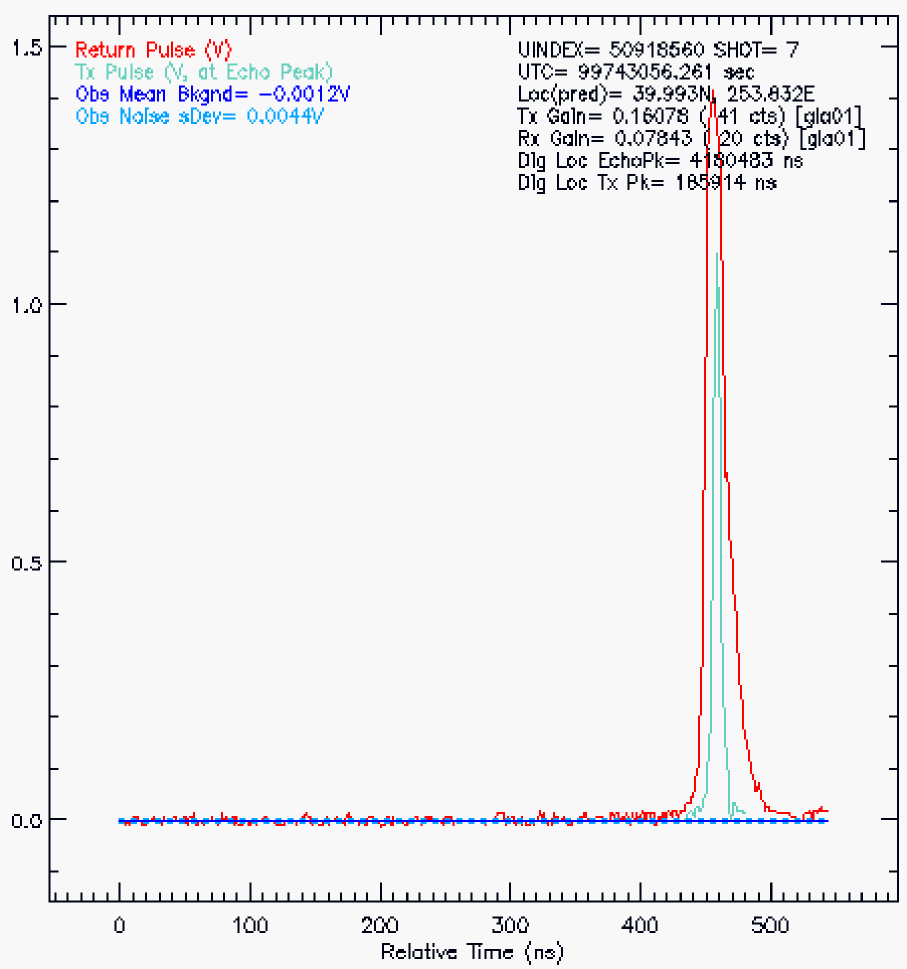

Figure 2. Sample narrow waveform for a flat, uniform surface

The relative time axis in Figure 2 represents two-way travel time. Two adjacent returns separated by a relative time difference (delta_t) in nanoseconds correspond to a height difference of delta_h in centimeters such that:

delta_h = c / 2 * delta_t

where:

c is the speed of light in cm/nsec

c = (3 x 10^{10} cm/sec) / (1 x 10^{9} nsec/sec)

c = 30 cm/nsec

So, a relative time difference of 1 nsec corresponds to a height difference of 15 cm.

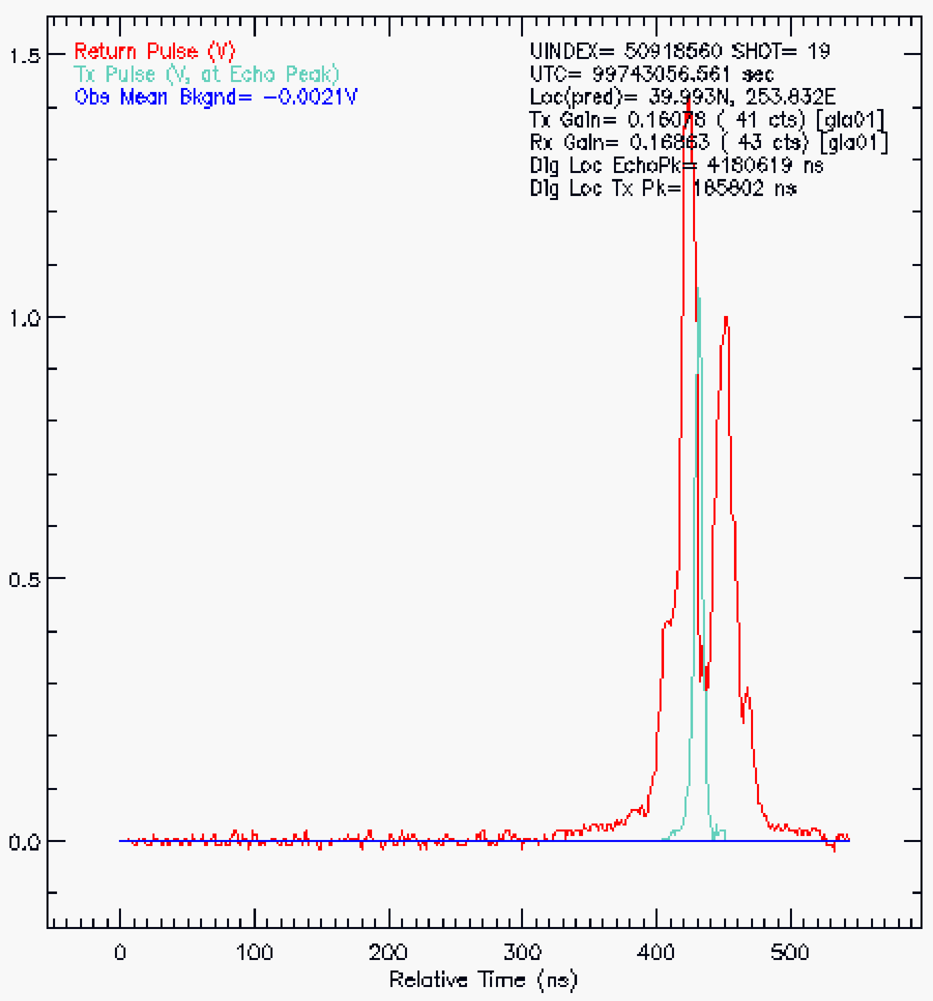

Figure 3. Sample bimodal waveform, with the highest peak most likely representing a tree or building in the scene

The relative time axis in Figure 3 represents two-way travel time. Two adjacent returns separated by a relative time difference (delta_t) in nanoseconds correspond to a height difference of delta_h in centimeters such that:

delta_h = c / 2 * delta_t

where:

c is the speed of light in cm/nsec
c = (3 x 10^{10} cm/sec) / (1 x 10^{9} nsec/sec)
c = 30 cm/nsec

So, a relative time difference of 1 nsec corresponds to a height difference of 15 cm.

3.1.1 Surface elevation

A standard parameterization is used to calculate surface elevation for ice sheets, oceans, and sea ice, using the elevation of the maximum peak and no more than two Gaussian functions with a minimum spacing of 30 ns (4.5 m) between Gaussian centers. For land elevations, the centroid of the return signal is used; a maximum of six Gaussians is allowed with 5 ns (75 cm) minimum spacing.

GLAS reports a mean elevation for each ice sheet surface measurement. When multiple peaks are present, the position of the centroid of the maximum peak determines the range. The maximum peak is used because detector saturation causes a small ringing peak that does not represent the surface. This range is corrected for atmospheric delay. The corrected range, satellite position above the ellipsoid, and off-nadir pointing angle are input for calculating surface elevation.

The increment in range between the last and first peaks allows users to recalculate the surface elevation based on the first peak. The number of peaks indicates the surface variability. The range to the centroid of the received waveform, the range from the beginning to end signals, and the skewness and kurtosis of the received waveform are also useful in evaluating surface characteristics.

NOTE: See the Error Sources section for important updates and corrections to surface elevation for Release 34.

3.1.2 Surface roughness

Researchers can measure the level of surface roughness by studying the waveform. The broader the received pulse, the greater the roughness (Brenner et al. 2000, Schutz 2002). Surface roughness and slope are interrelated. The following equation for surface roughness of a rough, flat surface assumes zero slope:

$$sdev(\xi) = \left[Var(\Delta\xi)\right]^{1/2} = \frac{c}{2}\left(E(s_P^2) - s_l^2 - s_h^2\right)^{1/2}$$

where:

$\Delta\xi$ = surface roughness (m)
S_P = RMS received pulse width (s)
S_l = RMS transmitted pulse width (s)
S_h = RMS width of receiver impulse response (s)
c = effective velocity of light (m/s)
E = laser energy (millijoules)

The following equation for surface slope of a flat, smooth surface assumes zero roughness:

$$\tan S = \frac{c}{2z\tan q_T}\left(E(s_P^2) - (s_l^2 + s_h^2)\right)^{1/2}$$

where:

S = slope
c = effective velocity of light (m/s)
z = altimeter height above the terrain (m)
q_T = halfwidth divergence angle of the laser beam
E = laser energy (millijoules)
S_P = RMS received pulse width (s)
S_l = RMS transmitted pulse width (s)
S_h = RMS width of receiver impulse response (s)

Surface slope and roughness values are only accurate for single-pulse waveforms.

Land surface relief is the range of elevations within the footprint caused by slope and roughness. For footprints lacking vegetation or cultural features, the interpretation of the land surface elevation is similar to that of ice sheets, sea ice, and oceans. For footprints that contain vegetation or cultural features, the surface height distribution created by slope and roughness is combined with the height distribution of those features.

3.2 Data Acquisition Methods

The GLAS onboard digitizer temporarily records signals from the entire time-of-flight of the 1064 nm pulse, to a range of 765 km from the spacecraft. This produces over five million digitized samples spaced at 1 ns (15 cm) resolution. The samples are then filtered and analyzed to extract only the transmitted pulse and surface echoes (Zwally et al. 2002). The primary altimeter algorithm does not include an acquisition or tracking phase, which is used to get the range within the small tracking window. GLAS instead uses an onboard 1-km resolution DEM (derived from a combination of Shuttle Radar Topography Mission (SRTM) and Global 30 Arc-Second Elevation Data Set, GTOPO30) to select the region of the waveform to be searched for the ground return. The DEM includes a surface type classification.

The algorithm bounds the search area of the digitized waveform using a priori information stored in this DEM. The algorithm queries the DEM once per second to determine minimum and maximum values of the range window for a given surface type. This determines the number of elements in the return waveform and the vertical range it covers. Using the digital waveform information within this DEM bounded region ("range window"), the algorithm searches for the surface echo backward in time from the end of the range window to the start. The raw digitizer address (approximately 1 ns per address) for any location on the received echo must be calculated, taking compression into account.

One thousand digitizer elements are available for downlink. Because only 544 or 200 samples (depending on surface type) are telemetered, the received echo is compressed in either of two ways. If there is no signal for a given time interval (set by command), then an r-type compression (defined below) is used; otherwise, p,q,n-type compression is used. The values of r, p, q, and n remain constant within the 1-second frame; however, the switch to and from r-type compression can occur at any time in the frame.

For r-type compression, 1000 samples are averaged in groups containing r samples going backwards in time. The value r is a function of surface type. Once the 1000 pre-selected samples are exhausted, the remaining downlink space is filled with zeros.

For p,q,n-type compression, the first n downlink samples are generated by averaging p raw digitized elements. The rest of the downlink samples are generated by averaging q raw digitized elements until the space allocated for the downlink is filled (544 or 200 samples). If an echo is too long to fit in the allocated space using the specified p,q, and n, the echo is truncated and an error flag is set. If the 1000 raw elements are exhausted before filling the downlink space, then the remaining 544 or 200 samples are filled with zeros. See McGarry et al. (2002) for more information.

3.2.1 Data Source

Please refer to the Ancillary Data Products list in Section 6 of the ICESat/GLAS Long Term Archive for details of ancillary files used to create GLAS standard products.

3.3 Derivation Techniques and Algorithms

The primary goals of the waveform and surface elevation algorithms are as follows:

- Define and determine the range to the mean surface elevation from the waveforms.
- Define mean surface elevation by correcting the range for all known errors and applying tides.
- Identify and interpret multiple surfaces within the return.
- Determine surface roughness, reflectivity, variability, and slope based on waveform characteristics.

The GLAS algorithms were adapted from existing waveform analysis algorithms including those from the Shuttle Laser Altimeter, satellite radar altimeters, and aircraft laser altimeters over land and ice sheet surfaces. The GLAS instrument records signals from four types of surfaces: ice sheets, sea ice, land, and ocean. The science requirements differ for these different surfaces. The algorithms described in this section are the same for all surface types. Different input parameters, however, lead to differences in the final results (Brenner et al. 2000).

Because of the complexity of the Earth's surfaces, The ICESat laser altimeter waveforms are complex and need to be processed on the ground to determine the location on the waveform that represents the elevation and surface characteristics within the footprint. Based on the assumptions that the surface within the laser footprint is a combination of a smooth sloping surface and a rough (random distribution) flat surface, and the transmitted pulse has a Gaussian shape, the received waveform can be modeled as a Gaussian.

Multiple Gaussian functions are used to model waveforms resulting from multi-layer surfaces. Parameters such as mean surface elevations, pulse amplitude, pulse width, and signal noise level can be extracted through inverse model fitting. Although the centroid of the waveform can be used to represent the mean surface, this is not always preferable. Over multi-layer surfaces, it is more helpful to identify the individual layers and their associated mean elevations. Distortion of the waveform shape by non-surface characteristics such as atmospheric forward scattering or detector/amplifier saturation causes the centroid of the waveform to misrepresent the actual mean surface. These effects can be diminished by fitting a Gaussian to the return and using the centroid of the Gaussian as the mean surface elevation.

The initial estimates and covariance matrix are set to optimize the fit to the leading edge of the return for the maximum-peak Gaussian. Two Gaussians are allowed to account for the extended tail of the returns that have high forward scattering components, or two distinct surfaces in the footprint.

A standard parameterization is tuned to ice sheet-type surfaces, which normally have one major reflection point. An alternative parameterization is tuned to more complex land surfaces with multiple reflection points; the last reflection should be from the surface. The results of the algorithm are useful for discerning the nature of ice sheets and land undulations, and perhaps multiple vegetation canopies near the land surface. For smooth terrain without intervening reflections, the results of both parameterizations are identical.

For land surfaces, the algorithm characterizes the return pulse by fitting Gaussian distributions to each mode (peak) in the waveform. Surface elevation over land is derived from the centroid of the return.

Inferences of sea surface elevation and ocean wave height are determined from an average of many consecutive footprints, since the 60 m footprint resolution of GLAS covers less area than a typical ocean wave. The maximum wave height is calculated from the highest and lowest surface elevations inferred from all the pulse widths for wavelengths less than twice the footprint diameter (approximately 120 m). Generally, a sea ice footprint contains a combination of rough and smooth ice. The average elevation is typically represented by the centroid of the latest Gaussian peak in the return pulse (Brenner et al. 2000).

3.4 Processing Steps

The processing steps for the waveform algorithm are as follows (Brenner et al. 2000):

1. Characterize the transmitted pulse and calculate the start time of the range.
2. Characterize the received waveform to determine if there is a signal. Then determine the point on the waveform (the last reflection) for estimating the range and preliminary footprint location on the earth.
3. Smooth the waveform and determine initial estimates for the waveform parameters.
4. Fit the waveform using the procedure described in the Theory of Measurements section.
5. Calculate range to mean surface and surface elevation distribution.
6. Calculate a corrected range to the mean surface.
7. Correct transmit time and time-system delays, and calculate the orbit.
8. Calculate footprint coordinates and mean surface elevation, incorporating pointing values from the PAD.
9. Calculate region-specific parameters.

Results of this waveform processing are used as input to calculating GLA06 and GLA12-15.

3.4.1 Processing History

Please refer to the following for more information about changes and known errors with each data release:

- ICESat/GLAS Data Releases
- NASA Wallops Flight Facility's Release Notes

3.5 Error Sources

GLAS Release 34 Correction of Release 33 Data Issues

1. Correction to the ICESat Data Product Surface Elevation due to an Error in the Range Determination from Transmit-Pulse Reference-Point Selection (Centroid vs Gaussian)
    - It was determined that an important correction to the surface elevations on the ICESat products was not applied. The range from which the surface elevation should have been calculated is from the midpoint of the Gaussian peak on the transmit pulse to the midpoint of the Gaussian peak on the received pulse. However the location of the centroid of the transmit pulse was inadvertently used and the difference (defined as G–C) between the transmitted pulse centroid and Gaussian peak was never applied. The effect of this error of omission varies on a shot-to-shot basis and for the calibration passes over the Salar de Uyuni in Bolivia varied from ± 6 cm over the mission. Similar results were found when tabulating the track-averaged corrections (G–C) over Antarctica. Note that the (G–C) values are fairly constant within a campaign, so any elevation data adjustments made to data release 633 or older for "campaign-level" biases that were determined to an independent reference surface would eliminate the G–C error from the elevation data on an average basis.
    - The surface elevations on GLA06 (global elevation product), GLA12 (ice sheet), GLA13 (sea ice), and GLA15 (ocean) are affected. The GLA14 (land) elevations are computed using the centroid of the received pulse, as well as the centroid of the transmit pulse, and therefore the elevation calculation on GLA14 is correct as intended. However, GLA14 data users who use the range Increment for the up to six Gaussian fitted peaks may want to use the G–C correction also.
2. Dry Troposphere Correction Jitter
    - It was reported that at times the dry troposphere range correction contained several centimeters of jitter. The issue was traced to the threshold range being used to determine the dry troposphere correction in regions of rapidly changing shape of the return signal waveforms. This was normally in poor signal areas or very rough terrain. At times the threshold range relative to the standard fit would jump tens of meters and induce several centimeter changes in the dry troposphere correction. Changes were made to use the centroid range to determine the troposphere correction. The centroid closely follows the standard fit range.
    - During the investigation it was determined that the GSAS code was using only one of the 6–hour met files for the pressure inputs. Code was modified to properly interpolate between the two 6–hour met files.

3. The GLAS product high resolution DEM was determined to have issues in the Southern Latitude when the source was SRTM data. It was reported to have wrong values that showed as banding.
    - There was an interpolation error in the southern latitudes during the creation of the SRTM track files (ANC51). The code error caused the DEM values to be correct at the mid point latitude between the interpolation points, with increasing errors on either side. This resulted in the banding error seen when comparing GLAS SRTM DEM values with the source SRTM DEM. The higher the DEM gradient the larger the error so they were significant over Australia. The code was fixed and track files were re–created.
4. The order of preference for which values are used when the SRTM and CDED overlap was changed. Starting with this release the SRTM is always used in the overlap region.
5. Some parameters on GLA14 were invalid when i_elev was valid.
    - It was determined that if any standard fit for a one second was invalid, checks were not made to determine if GLA14 had valid elevations during that second. Changes were made to provide the parameters based on a valid alternate fit if the standard fit was invalid for a shot.
6. GLA12, 13, 14 and 15 atmosphere character confidence flag was always zero.
    - It was determined that the atmosphere confidence flag from GLA09 was not being placed on GLA12, 13, 14, and 15. Changes were made to correctly put the confidence flags on the products.
7. Occasional mismatch of GLA09 atmosphere characteristic flag value and the value reported on GLA06 and 14.
    - On occasion the atmosphere characteristic flag was zero on GLA06 and 14 when a non-zero value was on GLA09. It was determined that the time tolerance check for the one second GLA06 time to the GLA09 time tag did not allow for sufficient jitter between the time tags. This caused a GLA09 record not to be selected as the source for the values. Several other parameters were also found to be invalid.
8. Saturation Correction - see Saturation Correction Guidance.

For further detail, see the GSAS V6.1 Release Notes May 2014 document.

3.6 Quality Assessment

Browse products in PNG graphic format contain quality information.

The i_FrameQF quality flag is set to "1" if there is a problem calculating individual parameters, or the flag is set to "0" if there are no problems.

Browse images that accompany each data file contain the statistics listed below. Quality control for land and ice sheet products begins with calculating the percent of measurements for which no signal was found. For those measurements in which a signal was found, the following are tabulated (Brenner et al. 2000):

- Percentage of measurements for which the fitting procedure is successful

- Percentage of measurements that may be degraded from detector saturation (see Saturation Correction Guidance)

Each data granule has a set of histograms displaying statistical information about waveform characteristics. These are only provided for signals with successful fits:

- Differences between the centroid of the received waveform and the centroid of the Gaussian fit to the last peak
- Number of peaks in each of the smoothed waveforms
- Standard deviation of the fit to the received waveform
- Skewness of each peak return (for single Gaussian fits only)
- Kurtosis of each peak return (for single Gaussian fits only)
- Percent of saturated signal compared to a real signal within the signal region

For measurements in which a signal is found and successfully processed, the mean and standard deviation of the following quantities are calculated for each 100 km strip along the ground track.

- Number of peaks in the smoothed waveform
- Number of peaks in the Gaussian fit
- Standard deviation of the fit to the received waveform for each measurement
- Skewness of each pulse return
- Differences between the centroid of the received waveform and the centroid of the Gaussian fit to the last peak
- Maximum smoothed amplitude
- Reflectance
- Ice sheet roughness (assuming a flat surface)
- Surface slope (assuming a smooth surface)
- Surface elevation

3.6.1 Validation by Source

The GLAS Science Team has developed a set of procedures for verifying and calibrating Level-1 science products to ensure that appropriate geophysical interpretations can be drawn from the data products and to reduce the level of geophysical uncertainty in the data. A formal calibration-validation (CV) plan is pending. More information will be available in the near future.

3.7 Sensor or Instrument Description

The Geoscience Laser Altimeter System (GLAS) instrument on the Ice, Cloud, and land Elevation Satellite (ICESat) provides global measurements of polar ice sheet elevation to discern changes in ice volume (mass balance) over time. Secondary objectives of GLAS are to measure sea ice roughness and thickness, cloud and atmospheric properties, land topography, vegetation canopy heights, ocean surface topography, and surface reflectivity.

GLAS has a 1064 nm laser channel for surface altimetry and dense cloud heights, and a 532 nm LIDAR channel for the vertical distribution of clouds and aerosols.

Data are sampled 40 times per second.

Please refer to the official ICESat/GLAS Web site at NASA GSFC for details of the ICESat platform and GLAS instrument.

Also see ICESat Reference Orbit Ground Tracks for a summary of the orbits for each laser operational period.

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4.1 Related Data Collections

Other ice sheet altimetry data sources include:

- Radar altimetry polar ice sheet data (Goddard Space Flight Center Ice Altimetry)
- Shuttle Laser Altimetry data

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6 DOCUMENT INFORMATION

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