# GLAS/ICESat 500 m Laser Altimetry Digital Elevation Model of Antarctica and 1 km Laser Altimetry Digital Elevation Model of Greenland, Version 1

## USER GUIDE

**How to Cite These Data**

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

John P. DiMarzio 2007. *GLAS/ICESat 500 m Laser Altimetry Digital Elevation Model of Antarctica, Version 1*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/K2IMI0L24BRJ. [Date Accessed].

Or

John P. DiMarzio 2007. *GLAS/ICESat 1 km Laser Altimetry Digital Elevation Model of Greenland, Version 1*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/FYMKT3GJE0TM. [Date Accessed].

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

FOR CURRENT INFORMATION, VISIT https://nsidc.org/data/NSIDC-0304 or https://nsidc.org/data/NSIDC-0305

National Snow and Ice Data Center

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# 1 DETAILED DATA DESCRIPTION

The Geoscience Laser Altimeter System (GLAS) instrument on the Ice, Cloud, and land Elevation Satellite (ICESat) provides global measurements of elevation, and repeats measurements along nearly-identical tracks; its primary mission is to measure changes in ice volume (mass balance) over time. These digital elevation models (DEMs) of Antarctica and Greenland are derived from GLAS/ICESat laser altimetry profile data and provide new surface elevation grids of the ice sheets and coastal areas, with greater latitudinal extent and fewer slope-related effects than radar altimetry.

These DEMs are generated from the first seven operational periods (from February 2003 through June 2005) of the GLAS instrument. They are provided on polar stereographic grids at 500 m grid spacing for Antarctica and 1 km grid spacing for Greenland. The grids cover all of Antarctica north of 86° S and all of Greenland south of 83° N. Elevations for both ice sheets are reported as centimeters above the datums, relative to both the WGS 84 Ellipsoid and the EGM96 Geoid, in two separate elevation data files. A data quality map of the interpolation distance is distributed for each ice sheet. ENVI header files are also provided.

This user guide applies to the following GLAS/ICESat data sets:

NSIDC-0304 (GLAS/ICESat Laser Altimetry Digital Elevation Model of Antarctica)

NSIDC-0305 (GLAS/ICESat 1 km Laser Altimetry Digital Elevation Model of Greenland)

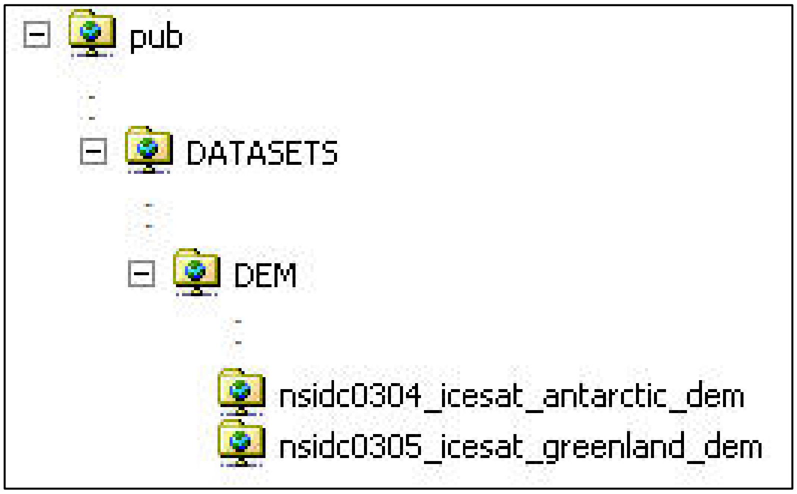
## 1.1 Format

The data are in 4-byte (long) signed integer binary files (big endian byte order).

## 1.2 File and Directory Structure

The DEM files are located on the HTTPS server in the directory:
`https://daacdata.apps.nsidc.org/pub/DATASETS/DEM/`.

Within the DEM directory, there is a separate subdirectory for each data set, as illustrated below.




## 1.3 File Naming Convention

Data files are named according to the following convention.

`NSIDC_Rrrssss_ddddd_vvvvv_uu.dat`

where NSIDC indicates the grid was created at NSIDC (derived from data provided by the authors) and

| | | |
|---|---|---|
| `Rrr` | = | Region of coverage for the DEM data set (`Ant` = Antarctica; `Grn` = Greenland) |
| `ssss` | = | Grid spacing (`1km` or `500m`) |
| `ddddd` | = | Datum (`wgs84` = WGS 84 Ellipsoid datum; `egm96` = EGM96 Geoid datum) |
| `vvvv` | = | Type of values in grid (`elev` = elevation; `dist` = mean distance) |
| `uu` | = | Unit of measurement (`cm` = elevation values reported as integer values in centimeters; `mm` = distance values reported as integer values in millimeters) |

The data files are described in the following table.

Table 1. Data File Descriptions

| **Antarctica DEM Data Set** | |
|---|---|
| File Name | Description |
| `NSIDC_Ant500m_wgs84_elev_cm.dat` | Elevation (centimeters) relative to WGS 84 ellipsoid datum |
| `NSIDC_Ant500m_egm96_elev_cm.dat` | Elevation (centimeters) relative to EGM96 Geoid datum |
| `NSIDC_Ant500m_dist_mm.dat` | Mean distance (millimeters) from contributing GLAS data for each grid cell |
| **Greenland DEM Data Set** | |

| File Name | Description |
|---|---|
| NSIDC_Grn1km_wgs84_elev_cm.dat | Elevation (centimeters) relative to WGS 84 Ellipsoid datum |
| NSIDC_Grn1km_egm96_elev_cm.dat | Elevation (centimeters) relative to EGM96 Geoid datum |
| NDISC_Grn1km_dist_mm.dat | Mean distance (millimeters) from contributing GLAS data for each grid cell |

ENVI header files are also provided for each data file. These header files are named the same as the data files, but with an additional .hdr extension appended to the file name; for example, `NSIDC_Ant500m_wgs84_elev_cm.dat.hdr`.

The three data files for each DEM are distributed in compressed (zipped) form. Each compressed file has a `.gz` extension appended to the end of the file name; for example, `NSIDC_Ant500m_wgs84_elev_cm.dat.gz`.

## 1.4 File Size

File sizes for each DEM data set are shown in the following table. The three data files (two elevation and one mean distance) are all the same size for each DEM (they all contain the same number of grid cells). The sizes shown are uncompressed. The three data files for each DEM are distributed in compressed (zipped) form; the ENVI header files are not compressed.

Table 2. File Sizes

| DEM Data Set | Size Per Data File | ENVI Header File Size |
|---|---|---|
| Antarctica | 425,382,144 bytes | 481 bytes |
| Greenland | 29,055,208 bytes | 504 bytes |

## 1.5 Volume

The total distribution volume for each DEM data set is listed below. The three data files for each data set are distributed in compressed (zipped) form; the ENVI header files are not compressed for distribution.

Table 3. File Volumes

| DEM Data Set | Total Volume Uncompressed | Total Volume with Compressed Data |
|---|---|---|
| Antarctica | 1,276,147,875 bytes | 433,997,915 bytes |
| Greenland | 87,167,136 bytes | 25,141,042 bytes |

## 1.6 Spatial Coverage

The following table shows the spatial coverage and the grid resolution for each DEM data set.

Table 4. Spatial Coverages

| DEM Data Set | Spatial Coverage | | Grid Resolution |
|---|---|---|---|
| Antarctica | Southernmost Latitude: | 86.0° S | 500 m |
| | Northernmost Latitude: | 63.0° S | |
| | Westernmost Longitude: | 180.0° W | |
| | Easternmost Longitude: | 180.0° E | |
| Greenland | Southernmost Latitude: | 60.0° N | 1000 m |
| | Northernmost Latitude: | 83.0° N | |
| | Westernmost Longitude: | 73.0° W | |
| | Easternmost Longitude: | 11.0° W | |

### 1.6.1 Projection and Grid Description

The data grid projections are polar stereographic, projected from the TOPEX/Poseidon Ellipsoid. However, the horizontal location differences between TOPEX/Poseidon and WGS 84 postings are so small (less than one meter) that the projection ellipsoid can be considered to be WGS 84. (See: Appendix AHow does the GLAS ellipsoid compare with WGS 84?)) The latitude of true scale is 70° S (Antarctica) or 70° N (Greenland). (Note that some other data sets covering Antarctica are projected to 71° S, not 70° S; the 70° S latitude of true scale is the choice of the data providers.) For the EGM96-referenced grids, the ellipsoid-projected data is modified by a geoid correction for each grid cell (the geoid is the approximate local sea level elevation relative to the ellipsoid). The central longitude of the projection (parallel to the image y-axis) is 0° extending up from the South Pole for Antarctica and 45° W extending down from the North Pole for Greenland. The center of the Antarctic grid is not the South Pole. The grid spacing is 500 m for Antarctica and 1 km for Greenland. The full projection information is provided in the ENVI header files associated with each of the data files.

The data are provided in image-formatted grids of binary numbers. Data image arrays have upper-left, row-by-row organization. Image grid size is shown in the following table.

Table 5. Image Grid Sizes

| DEM Data Set | Columns | Rows |
|---|---|---|
| Antarctica | 11352 | 9368 |
| Greenland | 2611 | 2782 |

Projection plane corner points are shown in the following table.

Table 6. Projection Plane Corner Points

| Antarctica DEM Data Set | | | | | | |
|---|---|---|---|---|---|---|
| **Center Point of Corner Grid Cell** | | | | | | |
| | **Column** | **Row** | **x** | **y** | **Latitude** | **Longitude** |
| Upper Left | 0.0 | 0.0 | -2812000.0 | 2299500.0 | -57.3452815 | -50.7255753 |
| Upper Right | 11351.0 | 0.0 | 2863500.0 | 2299500.0 | -57.0043684 | 51.2342036 |
| Lower Left | 0.0 | 9367.0 | -2812000.0 | -2384000.0 | -56.8847122 | -130.2911169 |
| Lower Right | 11351.0 | 9367.0 | 2863500.0 | -2384000.0 | -56.5495152 | 129.7789915 |
| **Outer Corner of Corner Grid Cell** | | | | | | |
| | **Column** | **Row** | **x** | **y** | **Latitude** | **Longitude** |
| Upper Left | -0.5 | -0.5 | -2812250.0 | 2299750.0 | -57.3422816 | -50.7250190 |
| Upper Right | 11351.5 | -0.5 | 2863750.0 | 2299750.0 | -57.0013764 | 51.2336047 |
| Lower Left | -0.5 | 9367.5 | -2812250.0 | -2384250.0 | -56.8817144 | -130.2915680 |
| Lower Right | 11351.5 | 9367.5 | 2863750.0 | -2384250.0 | -56.5465248 | 129.7794862 |
| **Greenland DEM Data Set** | | | | | | |
| **Center Point of Corner Grid Cell** | | | | | | |
| | **Column** | **Row** | **x** | **y** | **Latitude** | **Longitude** |
| Upper Left | 0.0 | 0.0 | -890000.0 | -629000.0 | 79.9641229 | -99.7495626 |
| Upper Right | 2610.0 | 0.0 | 1720000.0 | -629000.0 | 73.2101234 | 24.9126514 |
| Lower Left | 0.0 | 2781.0 | -890000.0 | -3410000.0 | 58.2706251 | -59.6277136 |
| Lower Right | 2610.0 | 2781.0 | 1720000.0 | -3410000.0 | 55.7592932 | -18.2336764 |
| **Outer Corner of Corner Grid Cell** | | | | | | |
| | **Column** | **Row** | **x** | **y** | **Latitude** | **Longitude** |
| Upper Left | -0.5 | -0.5 | -890500.0 | -628500.0 | 79.9630236 | -99.7861964 |
| Upper Right | 2610.5 | -0.5 | 1720500.0 | -628500.0 | 73.2074291 | 24.9327117 |
| Lower Left | -0.5 | 2781.5 | -890500.0 | -3410500.0 | 58.2653993 | -59.6335252 |
| Lower Right | 2610.5 | 2781.5 | 1720500.0 | -3410500.0 | 55.7536121 | -18.2303578 |

## 1.7 Temporal Coverage

Data used to produce the DEMs were collected from the GLAS instrument from February, 2003 to June, 2005.

The DEM data providers (DiMarzio et al.) used data from the following GLAS/ICESat lasers and data acquisition periods to generate these DEMs. The DEM data are an average of those data.

- Five cycles of 8-day repeat data from Laser 1 (February-April, 2003)
- One 8-day cycle from Laser 2A (September, 2003)
- 41 days of data from the 91-day repeat pattern from the Laser 2A data acquisition period: the 33-day sub-cycle and an additional 8 days beyond that
- Five cycles of 33-day sub-cycles from the Laser 2B, 2C, 3A, 3B, and 3C acquisition periods, the last of which (3C) ended in June, 2005

## 1.8 Parameter or Variable

The parameter is elevation above the datum (WGS 84 Ellipsoid or EGM96 Geoid), measured in centimeters. The supporting distance files contain the mean distance, in millimeters, to the contributing data for each grid cell.

### 1.8.1 Parameter Range

The minimum and maximum data values for each data file are shown in the following table.

Table 7. Minimum and Maximum Data Values

| **Antarctica DEM Data Set** | | |
|---|---|---|
| File Name | Minimum | Maximum |
| `NSIDC_Ant500m_wgs84_elev_cm.dat` | 1 | 422547 |
| `NSIDC_Ant500m_egm96_elev_cm.dat` | 1 | 426194 |
| `NSIDC_Ant500m_dist_mm.dat` | 4 | 996087 |
| **Greenland DEM Data Set** | | |
| File Name | Minimum | Maximum |
| `NSIDC_Grn1km_wgs84_elev_cm.dat` | -89838 | 400459 |
| `NSIDC_Grn1km_egm96_elev_cm.dat` | 1 | 395636 |
| `NDISC_Grn1km_dist_mm.dat` | 6 | 994056 |

**Note**: The very large negative values in the Greenland DEM data are artifacts of the re-projection and re-gridding process and are limited to the grid corner areas. Users should ignore values that are outside the coast of Greenland.

### 1.8.2 Sample Images

The following images were created using hill-shading in ENVI from the EGM96 Geoid elevation data.

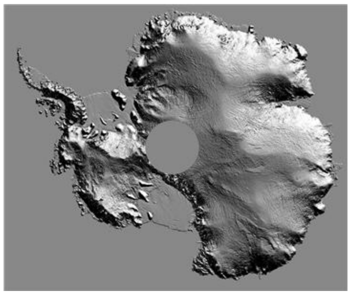


Figure 1. Antarctica DEM Data Set

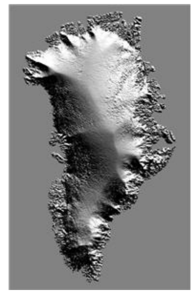


Figure 2. Greenland DEM Data Set

### 1.8.3 Sample Data Record

The following data sample was created from the `NSIDC_Grn1km_egm96_elev_cm.dat` file using the Unix command "`od -t d4`". This command interprets each 4-bytes as signed integers and displays the values. In this sample, only a few data values from the file are illustrated, and each row of four data values is preceded by its byte-offset in the file (such as 3221540). The asterisks indicate that all the data in that part of the file are zeroes.

```
0000000      0      0      0      0
*
3221540      0      0      0   8236
3221560      0      0      0      0
*
3221640      0      0      0   3562
3221660      0      0      0      0
*
3246040      0      0      0  55906
3246060  47321  34042  14507      0
3246100      0      0      0      0
*
3246160      0   1265   2615   2619
3246200   1896      0      0      0
3246220      0      0      0      0
*
3272340      0      0      0  46945
3272360  48231  53159  51417  48451
3272400  34656  16470   8105      0
3272420      0      0      0      0
*
3272460      0      0      0   2336
3272500   2026   3224   2043   1092
3272520      0      0      0      0
*
```

# 2 SOFTWARE AND TOOLS

View the data files using IDL, ENVI, or other commercial off-the-shelf software for image processing. ENVI header files are distributed with the data files.

## 2.1 Quality Assessment

Slope and elevation accuracy of the DEMs is best near the latitudinal limit of satellite coverage (±86°), and provides a good representation of the ice sheet and mountain areas (based on comparison with satellite images). DEM accuracy decreases as track spacing between ICESat profiles increases equatorward.

As a quality and accuracy indicator, the mean distance of all contributing GLAS surface spot data to the grid cell center was recorded in a separate identical grid for each ice sheet. These mean distance files are provided with the elevation data.

# 3 DATA ACQUISITION AND PROCESSING

## 3.1 Theory of Measurements

Satellite laser altimetry is an active measurement technique using on-board laser light along with a detector telescope and timing system to measure range to a reflecting spot on the Earth's surface from the satellite. Precision orbit determination (POD) and precision attitude determination (PAD) are used to calculate a ground location of the laser spot.

Several additional corrections are required, including atmospheric refraction, return waveform analysis for complex or multi-level returns, and detector saturation correction. The measurement is susceptible to obscuration by thick clouds, and thin clouds can affect the reported surface elevation (in general making it appear too low). Clouds also reduce the amount of returned (reflected) energy, and an automatic gain adjustment is applied to the detectors after a few low-energy shots are received. Gain settings range from a minimum of 13 (maximum returned energy) to a maximum of 250 (weak energy return). Characteristics of the surface, such as slope or roughness, can also modify the return waveform.

## 3.2 Data Acquisition Methods

Please see the GLAS/ICESat L1B Global Elevation Data (GLA06) documentation for a description of the acquisition of individual elevation points from the ICESat/GLAS sensor.

### 3.2.1 Data Source

These DEMs were generated using data from the GLAS/ICESat L1B Global Elevation Data (GLA06) data set. This source data set includes the removal of the solid tides and the application of atmospheric corrections (Brenner et al., 2003).

## 3.3 Derivation Techniques and Algorithms

Several criteria and filters were applied to the total data set to minimize the number of low-quality elevation points in the data used for gridding. Off-nadir data acquired during "round the world scans" (a calibrating technique for testing pointing accuracy) were not used. Other non-surface return data (for example, cloud-impacted, fog-impacted, or blowing-snow-impacted elevations) were filtered out by only selecting data points with relatively low gain (that is, high surface return power; gain was limited to <50). No saturation correction was applied to the selected data because the saturation correction was still under development at the time of DEM generation. Saturation can cause errors (elevation underestimates) of up to 50 cm during high power laser operations periods, such as Laser 2A and 3A (Abshire et al., 2005).

Individual elevation point data were gridded onto a polar stereographic projection, combining many elevation points for each grid cell. Satellite altimetry data are unevenly spaced due to obscuration and variations in track spacing. For each grid node, a bi-quadratic surface was fitted to all elevations within a circular region surrounding the node (hereafter referred to as the "cap"). This was accomplished via a singular value decomposition (SVD) algorithm (Zwally et al., 1990). In the fitting routine, a weight (w) is assigned to each elevation within the cap according to

$$w = 1/(d^2\sigma_0)$$

Where:

| | | |
|---|---|---|
| d | = | the distance from the spot elevation to the grid node center |
| $\sigma_0$ | = | the expected error of each elevation |

The expected error value ($\sigma_0$) was set to 20 cm for all observations based on the standard deviation of crossover differences (DiMarzio et al., 2004; see also Shuman et al., 2006). When the fit quality estimate from the SVD algorithm indicates insufficient data within the cap for a valid bi-quadratic surface fit, the cap size was increased to include more data. Once a valid fit was found, an interactive procedure was used in which elevations differing by more than three standard deviations from the fitted surface are eliminated, and the SVD algorithm was re-applied.

Error estimates associated with each node ($\sigma_g$) are determined by the output of the SVD algorithm and the weighted root-mean-squared differences of the remaining elevations with the fitted surface.

If $\sigma_g$ was greater than 30 m, the estimate was declared invalid and the cap-fitting and error-estimation process was redone with a larger cap size. If no cap size (below 20 km) yields a valid elevation, then a bi-linear fit to the nearest data was applied. Cap sizes ranged from 2 km to 20 km for Antarctica and from 5.5 km to 20 km for Greenland.

The grid spacing is 500 m for Antarctica and 1 km for Greenland. The reduced grid spacing for Antarctica fully exploits the greater data density available in the areas just north of 86° S.

### 3.3.1 Validation and Accuracy

The DEM data providers (DiMarzio et al.) evaluated the GLAS/ICESat laser altimetry Greenland DEM data set by comparing it to airborne laser altimetry data. Airborne Topographic Mapper (ATM) data over Greenland have a reported accuracy of ±10 cm (Krabill et al., 2002). Using all ATM data within 600 m of the GLAS/ICESat 1 km gridded DEM nodes, a comparison of elevation data over northwestern Greenland (the region of densest ATM tracks) indicates ATM elevations are generally lower than the GLAS/ICESat Greenland DEM elevation data. The overall mean difference between the ATM and GLAS/ICESat DEM data is -41 cm (ATM elevations below GLAS/ICESat DEM elevations), with an error range of ±44 cm. The mean difference varies with slope: for regions with <0.1° slopes, the mean difference is -32 ±43 cm; for regions with 0.1° to 1.0° slopes, the mean difference is -66 ±61 cm.

A second evaluation compared the GLAS/ICESat laser altimetry Greenland DEM to a 5 km gridded radar altimetry DEM data set (Zwally and Brenner, 2001). This comparison indicates a mean difference of -2 ±9 m. The mean difference varies with slope: for regions with <0.1°slopes, the mean difference is 1 ±5 m; for regions with 0.1° to 1.0° slopes, the mean difference is -24 ±20 m.

NSIDC conducted a separate evaluation of the GLAS/ICESat laser altimetry Antarctic and Greenland DEMs, using filtering, shaded-relief processing, and comparison to satellite image mosaics of the ice sheets. Horizontal spatial resolution of these DEMs is approximately 7.5 km, despite the finer gridding scale for the data. This is likely a result of the large "cap" region and the simple surface-fitting routine used to evaluate the grid elevations. In several areas, large spike and divot errors (features not present in the image mosaics) deviated from the likely surface elevation by several tens of meters. A somewhat smaller dimple pattern due to gridding algorithm limitations is also present throughout both data sets. NSIDC provides these DEMs as unfiltered; however, for many regional mapping applications, the user may find that a 7.5 km low-pass-filtered version of the DEMs will give a better representation of the true surface (smoothed to that same scale), with subdued dimple, spike, and divot features, relative to the distributed DEM data.

As a quality and accuracy indicator, the mean distance of all contributing GLAS surface spot data to the grid cell center was recorded in a separate identical grid for each ice sheet. This interpolation distance file is distributed with the elevation data.

### 3.3.2 Error Sources

Several localized elevation artifacts associated with cloud effects, track mislocations, and gridding algorithms are present in the grids. DEM accuracy decreases as track spacing between ICESat profiles increases equatorward.

## 3.4 Sensor or Instrument Description

Please visit the official NASA Goddard Space Flight Center (GSFC) ICESat/GLAS Web site for details about the ICESat platform and GLAS instrument.

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

# 4 REFERENCES AND RELATED PUBLICATIONS

Abshire, J. et al. 2005. Geoscience Laser Altimeter System (GLAS) on the ICESat mission: on-orbit measurement performance. *Geophysical Research Letters* v. 32, L21S02, doi:10.1029/2005GL1024028.

Brenner, A. et al. 2003. Derivation of range and range distributions from laser pulse waveform analysis for surface elevations, roughness, slope, and vegetations heights, Algorithm Theoretical Basis Document (ATBD) v.4.1, available at http://www.csr.utexas.edu/glas/atbd.html.

DiMarzio, J. P., A. C. Brenner, and H. J. Zwally. 2004. Comparison of Envisat and ERS radar altimetry for ice –sheet elevation change studies. ESA Envisat Symposium, Salzburg, Austria, September 9, 2004.

Krabill, W. et al. 2002. Aircraft laser altimetry measurement of elevation changes of the Greenland Ice Sheet: technique and accuracy assessment. *J. Geodynamics* 34, 357-376.

Shuman, C., H. J. Zwally, B. Schutz, A. Brenner, J. DiMarzio, V. Schuedo, and H. Fricker. 2006. ICESat Antarctic elevation data: preliminary precision and accuracy assessment. *Geophysical Research Letters* 33, L07501, doi:10.1029/2005GL025227.

Zwally, H. J., A. C. Brenner, J. A. Major, T. V. Martin, and R. A. Bindschadler. 1990. Satellite radar altimetry over ice, Vol. 1. Processing and corrections of Seasat data over Greenland. *NASA Reference Publication 1233*.

Zwally, H. J. and A. C. Brenner. 2001. "Ice sheet dynamics and mass balance." In: *Satellite Altimetry and Earth Science*, L-L. Fu and A. Cazenave, Eds., Academic Press, Ch. 9, 351-369.

## 4.1 Related Data Collections

ICESat/GLAS Data at NSIDC

## 4.2 Related Websites

ICESat Reference Orbit Ground Tracks

GLAS/ICESat L1B Global Elevation Data (GLA06)

## 4.3 Citing These Data

As a condition of using these data, you must cite the use of this data set using the following citation. For more information, see our Use and Copyright Web page.

The following examples show how to cite the use of these data sets in a publication. The citation to use depends on which data set you use. List the principal investigators, year of data set release, data set title and version (if applicable), publisher information (NSIDC), and indicate digital media distribution.

DiMarzio, J., A. Brenner, R. Schutz, C. A. Shuman, and H. J. Zwally. 2007. *GLAS/ICESat 500 m laser altimetry digital elevation model of Antarctica*. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

DiMarzio, J., A. Brenner, R. Schutz, C. A. Shuman, and H. J. Zwally. 2007. *GLAS/ICESat 1 km laser altimetry digital elevation model of Greenland*. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

# 5 CONTACTS AND ACKNOWLEDGMENTS

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# 6 DOCUMENT INFORMATION

## 6.1 Publication Date

June 2007

## 6.2 Date Last Updated

3 January 2022

# APPENDIX A: HOW DOES THE GLAS ELLIPSOID COMPARE WITH WGS 84?)

ICESat/GLAS and WGS-84 ellipsoid and geoid conversions
Terry Haran 20 May 2004

$Header: /NSIDC_CVS/FILES/tmh/glas/ellipsoid/README_ellipsoid.txt,v 1.10 2004/05/20 17:35:13 haran Exp $

This document is a README for several ICESat/GLAS IDL programs developed at NSIDC to handle conversions between various ellipsoids and geoids.

Converting Latitudes and Elevations between Ellipsoids

Three programs convert latitudes and elevations between the WGS-84 and the TOPEX/Poseidon ellipsoids. The latter ellipsoid is the ellipsoid used for all ICESat/GLAS elevations. See "How does the GLAS ellipsoid compare with WGS84?" at http://nsidc.org/data/icesat/faq.html#p9 for more details.

wgs2top.pro - this IDL procedure converts arrays of latitudes and elevations from the WGS-84 ellipsoid to the TOPEX/Poseidon ellipsoid.

top2wgs.pro - this IDL procedure converts arrays of latitudes and elevations from the TOPEX/Poseidon ellipsoid to the WGS-84 ellipsoid.

convert_ellipsoid.pro - this IDL procedure is called by wgs2top and top2wgs to actually perform the indicated ellipsoid conversions.

See the header in each file for the calling sequence and argument specifications for each procedure.

Also included is a test script (test_ce.pro) that calls the above programs for latitudes from -90 to +90 degrees at 1 degree intervals and produces screen plots of the differences in latitude and elevation between the different ellipsoids. The WGS-84 elevation was fixed at 3000 meters for each WGS-84 latitude. The test script is invoked by typing @test_ce at the IDL prompt. The screen plots have been captured in these gif files:

test_ce_0_latitude_degrees.gif - this plot shows calculated TOPEX/Poseidon latitudes minus given WGS-84 latitudes as a function of the WGS-84 latitudes. The minimum/maximum difference =~ -+1.23e-7 degrees at -+45 degrees, respectively.

test_ce_1_latitude_cm.gif - the same plot as in latitude_degrees.gif except that the difference in latitude has been converted to centimeters measured on the surface of an ellipsoid that is the "average" of the TOPEX/Poseideon and WGS-84 ellipsoids. The minimum/maximum difference =~ -+1.37 cm at -+45 degrees, respectively. These differences would probably be considered negligible for most applications so that TOPEX/Poseidon latitudes could be considered equivalent to WGS-84 latitudes.

test_ce_2_elevation.gif - this plot shows calculated TOPEX/Poseidon elevation minus given WGS-84 elevation (3000 meters) in cm. The minimum difference = 70.0000 cm at the equator = the WGS-84 equatorial radius (awgs = 637813700.000 cm) minus the Topex/Poseidon equatorial radius (atop = 637813630.000 cm). The maximum difference = 71.3682 cm at the poles = the WGS-84 polar radius (bwgs = 635675231.4245 cm) minus the Topex/Poseidon polar radius (btop = 635675160.0563 cm). These differences would probably be considered significant for many applications. However, for latitudes north/south of +-40 degrees, respectively, many applications could simply assume that TOPEX/Poseidon elevations are 71 cm higher than WGS-84 elevations.

Converting Elevations between Ellipsoids

Since the demonstrated differences in latitude between these ellipsoids is so small, it is possible to approximate the change in elevation between ellipsoids for a particular latitude using an empirically-derived formula:

```
delta_h = h2 - h1 =  -((a2 - a1) * cos(phi)^2 + (b2 - b1) * sin(phi)^2
  where
    phi is latitude.
    h1 and h2 are elevations for ellipsoids 1 and 2, respectively.
    a1 and a2 are equatorial radii of ellipsoids 1 and 2, respectively.
    b1 and b2 are polar radii of ellipsoids 1 and 2, respectively.
```

This formula greatly simplifies the calclulation of the change in elevation compared to the exact method used in convert_ellipsoid.pro. There are four IDL programs using this alternate approach:

wgs2top_delta_h.pro - a function that, given a latitude in degrees, returns the value in meters that should be added to a WGS-84 elevation to obtain a TOPEX/Poseidon elevation.

egm2wgs_delta_h.pro - a function that, given a latitude in degrees, returns the value in meters that should be added to a EGM96 ideal ellipsoid elevation (see Converting Geoid Elevations between Ellipsoids and Tide Systems below) to obtain a WGS-84 elevation.

egm2top_delta_h.pro - a function that, given a latitude in degrees, returns the value in meters that should be added to a EGM96 ideal ellipsoid elevation to obtain a TOPEX/Poseidon elevation.

compute_delta_h.pro - a function called by each of the above three functions that, given a latitude in degrees, actually computes the particular delta_h value.

The test script test_ce.pro mentioned above calls the first three of these alternate functions and creates three additional screen plots captured in these gif files:

test_ce_3_std_vs_alt.gif - this plot shows the test_ce_2_elevation.gif plot (above) minus the differences in elevation computed using wgs2top_delta_h.pro. Note that the minimum difference is only -0.0012 cm and the maximum difference is 0.0000 cm. This demonstrates the validity of using the alternative formula.

test_ce_4_egm2wgs_elev.gif - this plot shows calculated EGM96 ideal ellipsoid elevation minus given WGS-84 elevation in cm. The minimum difference = -54.0000 cm at the equator = the EGM96 ideal ellipsoid equatorial radius (aegm = 637813646.000 cm) minus the WGS-84 equatorial radius (awgs = 637813700.000 cm). The maximum difference = -50.7614 cm at the poles = the EGM96 ideal polar equatorial radius (begm = 635675180.6631 cm) minus the WGS-84 polar radius (bwgs = 635675231.4245 cm).

test_ce_5_egm2top_elev.gif - this plot shows calculated EGM96 ideal ellipsoid elevation minus given TOPEX/Poseidon elevation in cm. The minimum difference = 16.0000 cm at the equator = the EGM96 ideal ellipsoid equatorial radius (aegm = 637813646.000 cm) minus the TOPEX/Poseidon equatorial radius (atop = 637813630.0000 cm). The maximum difference = 20.6068 cm at the poles = the EGM96 ideal polar equatorial radius (begm = 635675180.6631 cm) minus the TOPEX/Poseidon polar radius (btop = 635675160.0563 cm).

Converting Geoid Elevations between Ellipsoids and Tide Systems

ICESat/GLAS products use the EGM96 geoid for geoid height data. The EGM96 Document, Section 11, "The EGM96 geoid undulation with respect to the WGS84 ellipsoid" (http://cddisa.gsfc.nasa.gov/926/egm96/doc/S11.HTML) explains how to convert geoid height data between different tide systems, and how geoid height data for the WGS-84 ellipsoid were calculated. Implicit in the WGS84 discussion is the information needed to convert geoid heights between ellipsoids as well.

Pre-release 16 ICESat/GLAS geoid height data were referenced to the WGS-84 ellipsoid in a tide-free system. This is the same ellipsoid and tide system used to generate the data available on the NIMA web "WGS 84 EGM96 15-Minute Geoid Height File and Coefficient File" (http://earth-info.nima.mil/GandG/wgsegm/egm96.html). Quoting from this page:

"The geoid undulations value are calculated by applying a correction term that converts a pseudo-height anomaly calculated at a point on the ellipsoid to a geoid undulation value. In addition, a correction term of -0.53 m is added to the prior result to obtain the geoid undulation with respect to the WGS 84 ellipsoid."

The -0.53 meters mentioned above is "zeta0," the zero degree height anomaly, the calculation of which is covered in section 11.2 of the EGM96 Document. Two methods of calculating zeta0 are provided. These methods are implemented in two IDL programs:

zeta0.pro - a function that, given values for gm0 and u0, returns a value for zeta0 in meters using the formula:

zeta0 = (gm_ideal - gm0) / (r * gamma) - (w_ideal - u0) / gamma

where

gm_ideal = 3.986004418e14 m^3/s^2

w_ideal = 62636856.88 m^2/s^2

r = 6371007.0 m

gamma = 9.797645 m/s^2

zeta0_alt.pro - a function that, given values for a and f (the equatorial radius and flattening, respectively, of the target ellipsoid), returns a value for zeta0 in meters using the formula:

zeta0 = (a_ideal - a) * (f_ideal - f) / 3

where
a_ideal = the equatorial radius of the EGM96 ideal ellipsoid
= 6378136.46 m
f_ideal = flattening of the EMG96 ideal ellipsoid
= 1 / 298.25765

The test script test_z0.pro (invoked by typing @test_z0 at an IDL prompt) calls the above two functions using values for both the WGS-84 ellipsoid and the TOPEX/Poseidon ellipsoid. The WGS-84 gm0 and u0 values are provided in section 11.2 of the EGM96 Document. The TOPEX/Poseidon gm0 and u0 values were provided in a document entitled GeoidFix2.doc (converted to GeoidFix2.pdf and included here) from Dr. Nikos Pavlis. The output from test_z0.pro is:

```
wgs: gm0: 3.986004418e+14  u0: 62636851.710  zeta0_0: -52.77 cm
top: gm1: 3.986004415e+14  u1: 62636858.570  zeta0_1:  17.73 cm
zeta0_1 - zeta0_0:  70.50 cm

wgs: a0: 6378137.0  1/f0: 298.257223563  zeta0_0_alt: -52.98 cm
top: a1: 6378136.3  1/f1: 298.257000000  zeta0_1_alt:  17.55 cm
zeta0_1_alt - zeta0_0_alt:  70.53 cm
```

Note that both of the above methods use a spherical approximation for the ellipsoid which results in a single constant value for zeta0. In addition, both methods appear to really be a conversion from the EGM96 ideal ellipsoid to the target ellipsoid (WGS-84 or TOPEX/Poseidon). I propose a third method: define zeta0 as simply delta_h for a conversion from the EGM96 ideal ellipsoid to to the target ellipsoid as a variable function of latitude; hence the IDL functions egm2wgs_delta_h.pro and egm2top_delta_h.pro mentioned above. Looking again at test_ce_4_egm2wgs_elev.gif and test_ce_5_egm2top_elev.gif mentioned above, we see that the range of delta_h values for each target ellipsoid are a close match to the corresponding zeta0 values listed above.

The following IDL program can be used to convert geoid height values into another set of a geoid height values relative to a different ellipsoid and/or using a different tide system:

convert_geoid.pro - a function that calculates an array of conversion values to add to an array of unconverted geoid height values to convert them into another set of geoid height values relative to a different ellipsoid and/or using a different tide system. The function performs the following calculation:

```
total_conversion = -conversion_from_ellipsoid +
                   conversion_to_ellipsoid +
                   conversion_tide
```

Both conversion_from_ellipsoid and conversion_to_ellipsoid can be specified as either single value zeta0 values, or can be variable delta_h values that are a function of latitude; conversion_tide values are always a function of latitude. See the header to convert_geoid.pro for more details on the calling procedure.

The test script test_cg.pro (invoked by typing @test_cg at an IDL prompt) calls the above function using a variety of parameters, and produces plots that have been saved as the following gif files:

test_cg_0_wc2tc.gif - a plot using default values for specifying

```
from_ellipsoid, to_ellipsoid, from_tide, and to_tide, namely:
  from_ellipsoid = -0.53 = constant WGS-84 zeta0 value in meters
  to_ellipsoid = 0.175 = constant TOPEX/Poseidon zeta0 value in
    meters
  from_tide = "tide-free"
  to_tide = "mean-tide"
Thus this plot represents the values that must be added to ICESat/GLAS
pre-release 16 WGS-84 tide-free geoid height values to obtain release 18 and
later TOPEX/Poseidon mean-tide geoid height values. The effective
formula used to generate this plot is:
  total_conversion = -conversion_from_ellipsoid +
                     conversion_to_ellipsoid +
                     conversion_tide
    where
      conversion_from_ellipsoid = -0.53 meters
      conversion_to_ellipsoid = 0.175 meters
      conversion_tide = 1.3 * (9.9 - 29.6 * sin(lat)^2) / 100 meters
And to do the conversion:
  height_18 = height_pre16 + total_conversion
    where
      height_18 = release 18 and later TOPEX/Poseidon mean-tide geoid
        height values in meters
      height_pre16 = pre-release 16 WGS-84 tide-free geoid height values

test_cg_1_wc2tv.gif - the same plot as test_cg_0_wc2tc.gif, except that
to_ellipsoid has been changed from the single zeta0 value of 0.175
to a two element array specifying the equatorial and polar radii,
respectively, of the TOPEX/Poseidon ellipsoid to be used to calculate a
variable zeta0 using compute_delta_h as a function of latitude:
  from_ellipsoid = -0.53 = constant WGS-84 zeta0 value in meters.
  to_ellipsoid = [6378136.300000, 6356751.600563] = [atop, btop]
  from_tide = "tide-free"
  to_tide = "mean-tide"
Note that this plot is very similar to test_cg_0_wc2tc.gif, but
presumably slightly more accurate, since the spherical approximation for
the ellipsoid has been replaced with formula for the change in ellipsoid
elevation as a function of latitude.

test_cg_2_diff.gif - this plot is simply test_cg_1_wc2tv.gif minus
test_cg_0_wctc.gif. Note that the difference ranges from -1.5 cm at the
equator to 3.1068 cm at the poles.

test_cg_3_tc2tv.gif - this plot is created by specifying a conversion
from TOPEX/Poseidon mean-tide geoid heights using a constant zeta0
value of 0.175 meters to TOPEX/Poseidon mean-tide geoid heights using a
variable zeta0 as a function of latitude:
  from_ellipsoid = 0.175 = constant TOPEX/Poseidon zeta0 value in
    meters
  to_ellipsoid = [6378136.300000, 6356751.600563] = [atop, btop]
  from_tide = "mean-tide"
  to_tide = "mean-tide"
Note that this is plot is identical to the previous plot, but uses a
single call to convert_geoid.
```

Correcting the Geoid Height Parameter for Different Data Releases

Pre-release 16 ICESat/GLAS geoid height data were referenced to the WGS-84 ellipsoid in a tide-free system. The zero degree height anomaly used for the WGS-84 ellipsoid was a constant value of -53.0 centimeters. In release 16 and release 17 data, an attempt was made to correct the geoid height data so that it would be relative to the TOPEX/Poseidon ellipsoid in a mean-tide system. The zero degree height anomaly used for the TOPEX/Poseidon ellipsoid was a constant value of 18.1 centimeters. This value appears to have been incorrectly calculated and should have been 17.5 centimeters. Moreover, the correction calculation failed to subtract out the zero degree height anomaly for the WGS-84 ellipsoid, i.e. -53.0 centimeters.

The following IDL program can be used to correct geoid height values from a particular data release so that the resulting values are relative to the TOPEX/Poseidon ellipsoid, and are in a mean-tide system:

```
 correct_geoid_delta_h.pro - a function that calculates an array of
 correction values to add to an array of uncorrected geoid height values
 for a particular data release. Given an array of latitudes (phi) and a
 release number (release), the function performs the following
 calculation:
  delta_h = q0 + q1 * sin(phi)^2
  where
   delta_h is an array of values in centimeters that should be added to a
    corresponding array of geoid heights in centimeters at the
    corresponding latitudes indicated by phi for the indicated
    release.

   By default the release keyword is 14, and all values for which
   the release keyword is less than 16 are treated the same way.

   By default, the resulting values are relative to the TOPEX/Poseidon
   ellipsoid using a constant zero degree height anomaly of 17.5
   centimeters.  If the keyword variable_zeta0 is set, then the
   resulting values are relative to the TOPEX/Poseidon ellipsoid using
   a variable zero degree height anomaly that is a function of
   latitude.

   The values of q0 and q1 are determined as follows:
    If the keyword variable_zeta0 is not set, then
     If release is less than 16, then
      q0 = 83.37
      q1 = -38.48
     If release is greater than or equal to 16 and less than 18, then
      q0 = 52.40
      q1 = 0
     If release is 18 or higher, then
      q0 = 0
      q1 = 0
    If the keyword variable_zeta0 is set, then
     If release is less than 16, then
      q0 = 81.87
      q1 = -33.8732
     If release is greater than or equal to 16 and less than 18, then
      q0 = 50.90
      q1 = 4.6068
     If release is 18 or higher, then
      q0 = -1.5
      q1 = 4.6068
```

See the comments in the REFERENCE section of the header in correct_geoid_delta_h.pro for the derivations of q0 and q1.