

Exploration of the use of interpolated surfaces in measuring ice volume changes from ICESat laser altimetry data

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Background

The Ice, Cloud, and land Satellite was launched in 2003 with the goal of measuring ice sheet mass balance. ICESat carried a single instrument called the Geospatial Laser Altimeter System (GLAS), which operated for seven years before the satellite was retired in 2009 and deorbited in 2010. The ICESat mission was designed to provide highly accurate global altimetry data capable of measuring subtle changes in the elevations of ice sheets (Abdalati et al.). Combining ICESat measurements with gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) allows for scientists to measure mass balance of the ice sheets and account for post-glacial rebound.

ICESat operated in a repeating ground-track orbit, meaning that the orbit was designed in such a way as to allow the satellite to pass along the same ground paths at regular intervals. In the case of ICESat, this interval was approximately 91 days (Abdalati et al.). This enables the direct comparison of elevations at different temporal resolutions, but decreases the point density of the dataset.

The GLAS instrument was a dual-wavelength full-waveform laser altimeter. The instrument operated by emitting laser pulses at a two wavelengths – one visible green and one in near infrared – at a frequency of 40 Hz. The light from the laser would travel to the surface of the Earth, where it illuminated a spot approximately 65m in diameter and was reflected back to the telescope on the satellite. The intensity of the returned light was recorded as a function of time. Knowing the location of the satellite and the time-of-flight of the laser pulse, an elevation could be calculated relative to a reference ellipsoid (Abdalati et al.). The ICESat data products essentially consist of millions of individual point elevations; different data products use different metrics of where “ground” is located in the returned waveform.

GLAS proved to be an exceptionally accurate instrument, providing ice sheet elevations with precision and accuracy of ~ 2 and ~ 14 cm per laser shot, respectively. GLAS carried three lasers, each intended to operate continuously for up to 2 years. However, on-orbit anomalies resulted in the premature failure of the first laser and damage to the second laser. To lengthen the life of the mission, ICESat operations were switched from continuous observations to a campaign mode, in which elevation measurements were made along repeating ground tracks for 33-day sub-cycles of the 91-day repeat orbit (Abdalati et al.). The revised strategy allowed for seasonal observations of ice sheet levels, but at the cost of a further reduction in spatial and temporal resolution.

Problem Statement

Several methods of calculating changes in ice sheet volume using laser altimetry have been developed since the launch of ICESat. Common methods involve the comparison of individual point elevations whose illuminated “footprints” are known to overlap. The goal of this project is to understand whether or not ice volume change could instead be estimated using surfaces generated from ICESat point elevations. The basic procedure is as follows:

- Obtain ICESat data for a particular region from different campaigns
- For each campaign, create an interpolated surface from the ICESat elevations
- Calculate difference maps between the surfaces from successive campaigns
- Use the difference maps to calculate the volume of ice gained or lost during the time between campaigns

It should be possible to note an increase in ice mass from fall to spring and ice mass loss from spring to fall.

Data Collection

ICESat GLA06 data was obtained from the Center for Space Research at the University of Texas at Austin for a $5^{\circ} \times 5^{\circ}$ area in the center of the Greenland ice sheet (Zwally et al.). Figure 1 shows the spatial extent of the elevation data overlain on a stereographic map of Greenland.

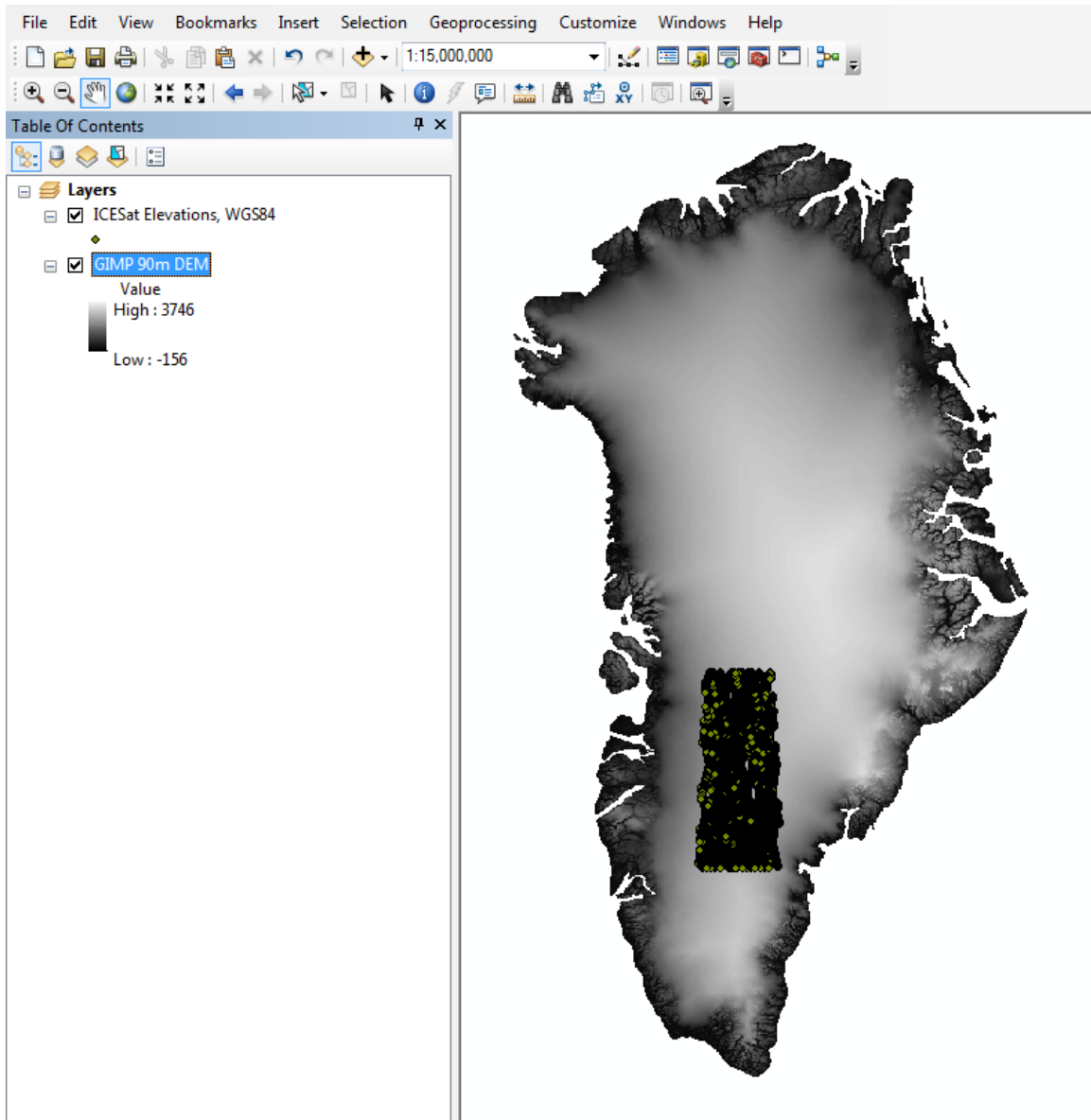


Figure 1 - Locations of ICESat elevations for the test region in Greenland. The area is approximately $5^{\circ} \times 5^{\circ}$ in spatial extent. The coordinate system of the data frame is the NSIDC Polar Stereographic North projection.

The GLA06 data product provides the elevation of the centroid of the returned waveform. Over ice sheets, this is generally the elevation of the ice surface. The test region was chosen such that the topography of the ice would be relatively smooth and no major outlet glaciers were located within the region's boundaries. While hundreds of variables are available for each ICESat data point, only a small subset of these variables were necessary for the completion of this task (Zwally et al.):

- Latitude and longitude
- Elevation
- Campaign
- Track number
- Laser gain
- Beam coelevation

The campaign and track number were collected along with latitude, longitude, and elevation to allow for the division of the data set by time. Laser gain and coelevation were also collected to allow for filtering of the data if necessary. The ICESat data was in a CSV (comma separated variable) text file format.

A digital elevation model of Greenland was obtained from the Greenland Ice Mapping Project (GIMP) at the Byrd Polar Research Center at Ohio State University (Howat et al.). The DEM has a resolution of 90m and is available as a GeoTIFF file in a polar stereographic projection. The GIMP 90m DEM is created from a number of elevation sources, including ICESat data, and is one of the best currently available elevation sources for Greenland. The DEM is also available at a 30m resolution, but a 90m DEM was satisfactory for the purposes of this project. The DEM contains elevations relative to the WGS84 ellipsoid.

Data Preprocessing

ICESat elevation data requires pre-processing under most circumstances as it is provided relative to a relatively uncommonly used reference ellipsoid – the

Jason/TOPEX ellipsoid. The Jason/TOPEX ellipsoid was defined for use on the TOPEX/Poseidon and Jason-1 satellites, as seen in Table 1 below (Zwally et al.):

Table 1 - Comparison of Jason/TOPEX and WGS84 ellipsoid parameters

	Jason/TOPEX	WGS84
Equatorial Radius (a)	6378136.3 m	6378137.0 m
Polar Radius (b)	6356751.600563 m	6356752.314245 m
Reciprocal flattening (1/f)	298.257	298.25722356
Eccentricity (e)	0.081819221456	0.081819190843

The ellipsoid used by GLAS is about 70cm smaller than WGS84 ellipsoid. Consequently, both the geodetic latitude and the ellipsoidal elevation must be converted prior to comparison with WGS84 elevations. The conversion of the ICESat points to the new ellipsoid was accomplished in MATLAB using a function that iterates to find the WGS84 geodetic latitude and elevation that correspond to the Jason/TOPEX geodetic latitude and elevation according to a set of geometric relations.

After all points have been converted to WGS84, the elevations are compared to elevations in the GIMP DEM to enable filtering of the ICESat data set by elevation difference. ICESat elevations are fairly susceptible to heavy cloud cover and the publicly-available product will often have elevations that are clearly not representative of actual terrain. This can occur regardless of location, although some areas are more inclined to have cloud-contaminated elevations than others. Point elevations were extracted in MATLAB from the GIMP DEM at the exact latitude and longitude coordinates of the ICESat footprints using bilinear interpolation of the raster data set. As with the originally collected data, the converted points and elevation difference values from the DEM comparison were output as CSV files.

ArcGIS Processing

Data Import

The CSV file containing ICESat data relative to the WGS84 ellipsoid was imported into ArcGIS. In order to access the data in the CSV and enable any attribute filtering

or selection, the XY data was selected and the coordinate system was defined as WGS84. The elevation point data was then exported to a shapefile.

The primary purpose of the GIMP DEM was to provide a reference for defining elevation differences needed to filter ICESat data, but the raster was also used as a reference during GIS processing. GeoTIFF files are easily imported into ArcGIS and already contain all necessary geospatial data. The spatial reference for the project was set to that matching the GIMP DEM – the WGS84 NSIDC Polar Stereographic North coordinate system. The datum is a standard polar stereographic projection that has been rotated such that the y-axis runs through the middle of Greenland at 45°W.

Projection Conversion

It was necessary to convert the WGS84 latitude and longitude coordinates to coordinates of easting and northing in the desired polar stereographic north projection. If the coordinates are left in their original latitude and longitude coordinates, the interpolated raster created from the point elevations is in the WGS84 geographic coordinate system instead of the polar stereographic north projection. The projection change also allows for the later calculation of surface volume in the correct units. The points were converted using Data Management Tools > Projections and Transformations > Feature > Project. The settings used in the Project tool are shown in Figure 2.

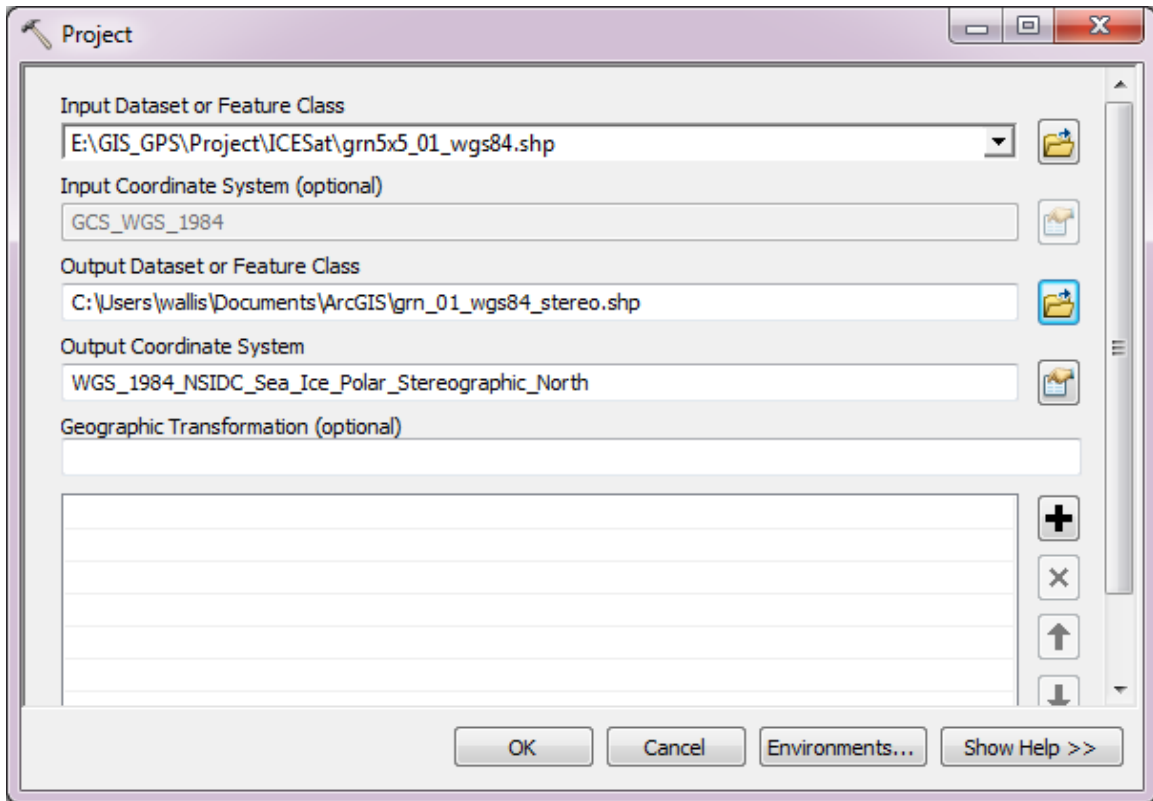


Figure 2 - Feature Project Tool

Data Filtering

The ICESat data were filtered according to elevation difference compared with the GIMP DEM and separated by campaign into individual shapefiles as shown in Figure 3.

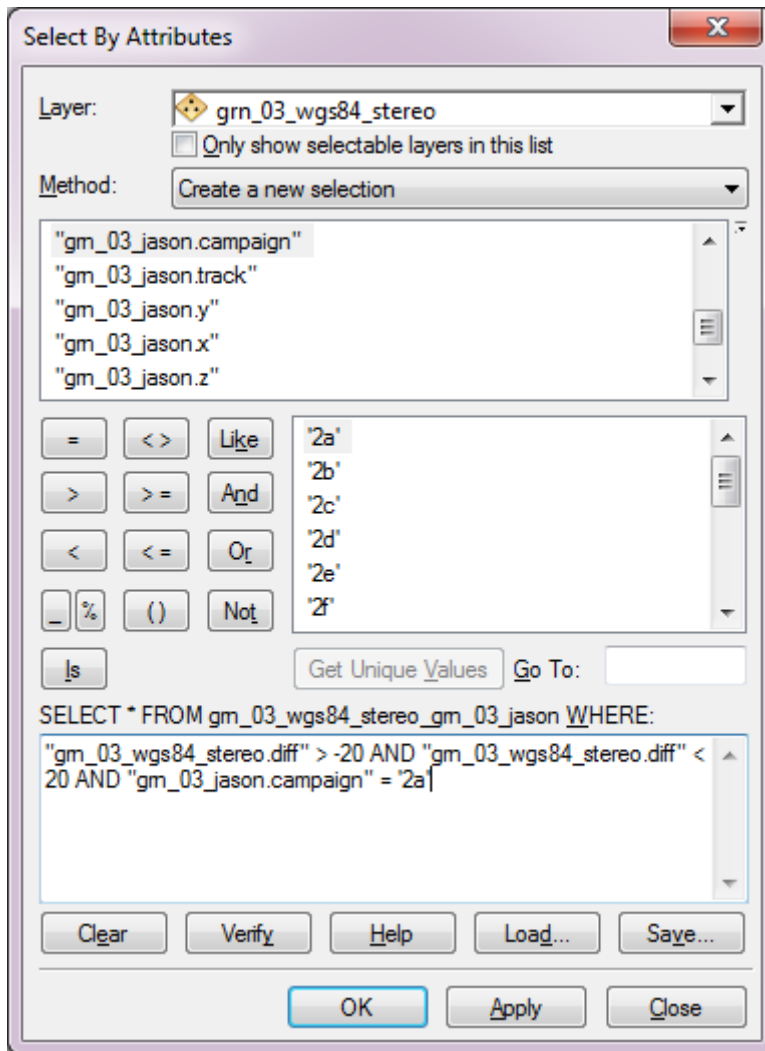


Figure 3 - Conditions used in the Select by Attributes tool to filter outlier ICESat elevations and select data from a single campaign.

The filter threshold was set to ± 20 m. This got rid of all cloud elevations as well as saturated ICESat returns (i.e. where range to the surface is over-estimated). A more sophisticated filter may be useful in fine-tuning the procedure, but for this initial exploration a simple filter was sufficient for removing obviously bad elevations.

Raster Interpolation

Several methods for generating a surface from the ICESat elevations were examined, and it was found that the Natural Neighbor raster interpolation was both the simplest and the closest in topography to the reference GIMP DEM. The surface was

created using 3D Analyst Tools > Raster Interpolation > Natural Neighbor. The cell resolution for the output surface was set to 500 m. The selection of the cell size was based on the resolutions of Greenland DEMs created solely from ICESat data. The settings used with the Natural Neighbor tool are shown in Figure 4.

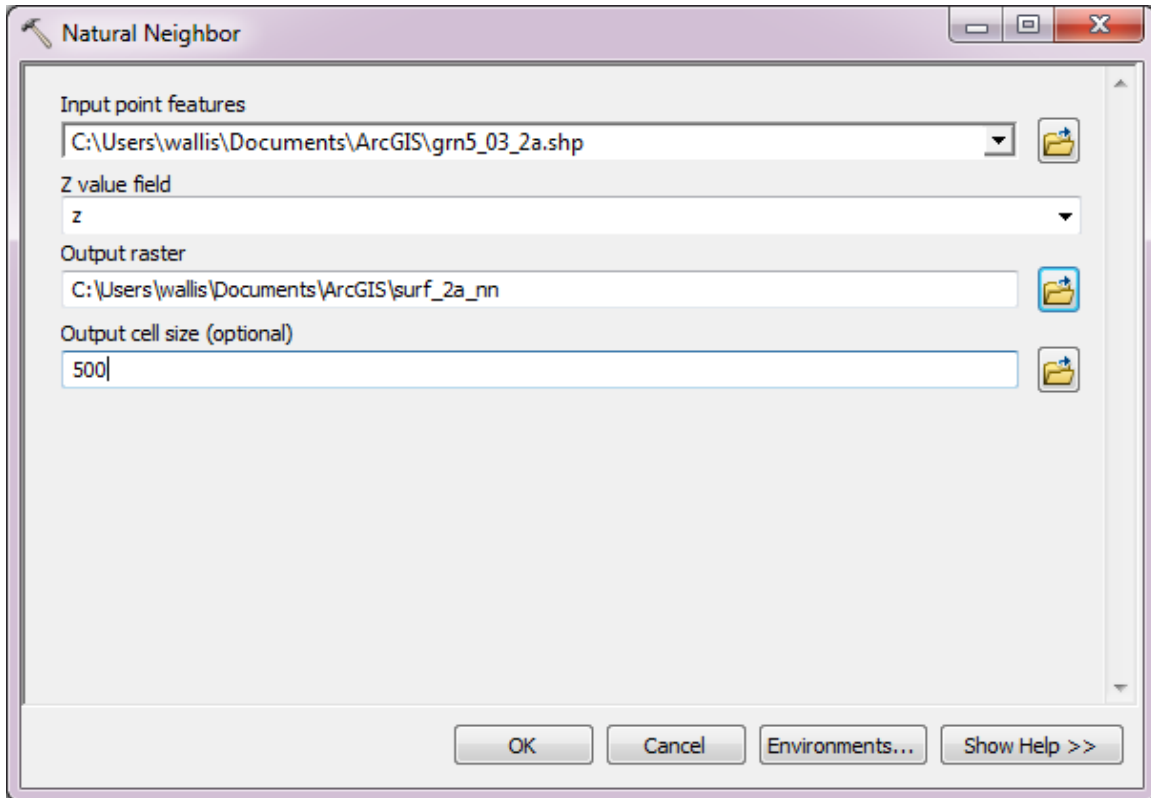


Figure 4 - Natural Neighbor Raster Interpolation tool

The resulting interpolated raster surface for campaign 2a is shown in Figure 5. The interpolated surface is shown relative to the GIMP 90m DEM.

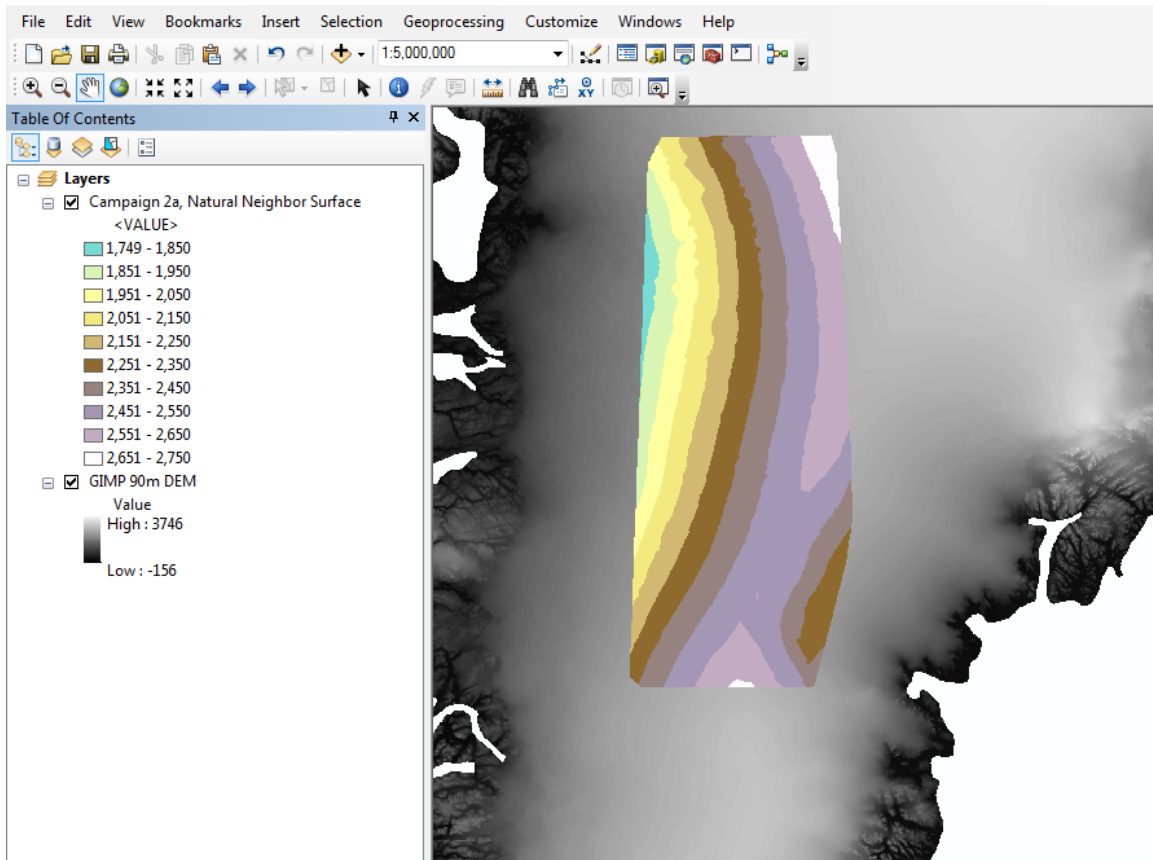


Figure 5 - Nearest Neighbor Interpolated surface for ICESat campaign 2a. Shown alongside the GIMP 90 m DEM for reference.

Raster surfaces were interpolated for most of the ICESat campaigns. Several of the campaigns were short-lived due to mission operations issues, and those campaigns were not included in this analysis. The output rasters contained floating-point values of elevation in meters.

Difference Rasters

The difference in interpolated rasters was calculated for each successive set of campaigns. The ICESat campaign details are given in Table 2 below. Only those campaigns that are bolded were used in this project.

Table 2 - Summary of ICESat campaigns

Campaign ID	Days Operational	Start	End
1a/1b	38	Feb 2003	Mar 2003
2a	55	Sep 2003	Nov 2003
2b	34	Feb 2004	Mar 2004
2c	35	May 2004	Jun 2004
3a	37	Oct 2004	Nov 2004
3b	36	Feb 2005	Mar 2005
3c	35	May 2005	Jun 2005
3d	35	Oct 2005	Nov 2005
3e	34	Feb 2006	Mar 2006
3f	33	May 2006	Jun 2006
3g	34	Oct 2006	Nov 2006
3h	34	Mar 2007	Apr 2007
3i	37	Oct 2007	Nov 2007
3j	34	Feb 2008	Mar 2008
3k	16	Oct 2008	Oct 2008
2d	23	Nov 2008	Dec 2008
2e	34	Mar 2009	Apr 2009
2f	12	Sep 2009	Oct 2009

The differences were computed using Spatial Analyst > Map Algebra > Raster Calculator to subtract the older of two rasters from the newer. The syntax used to subtract two raster surfaces is shown below in Figure 6.

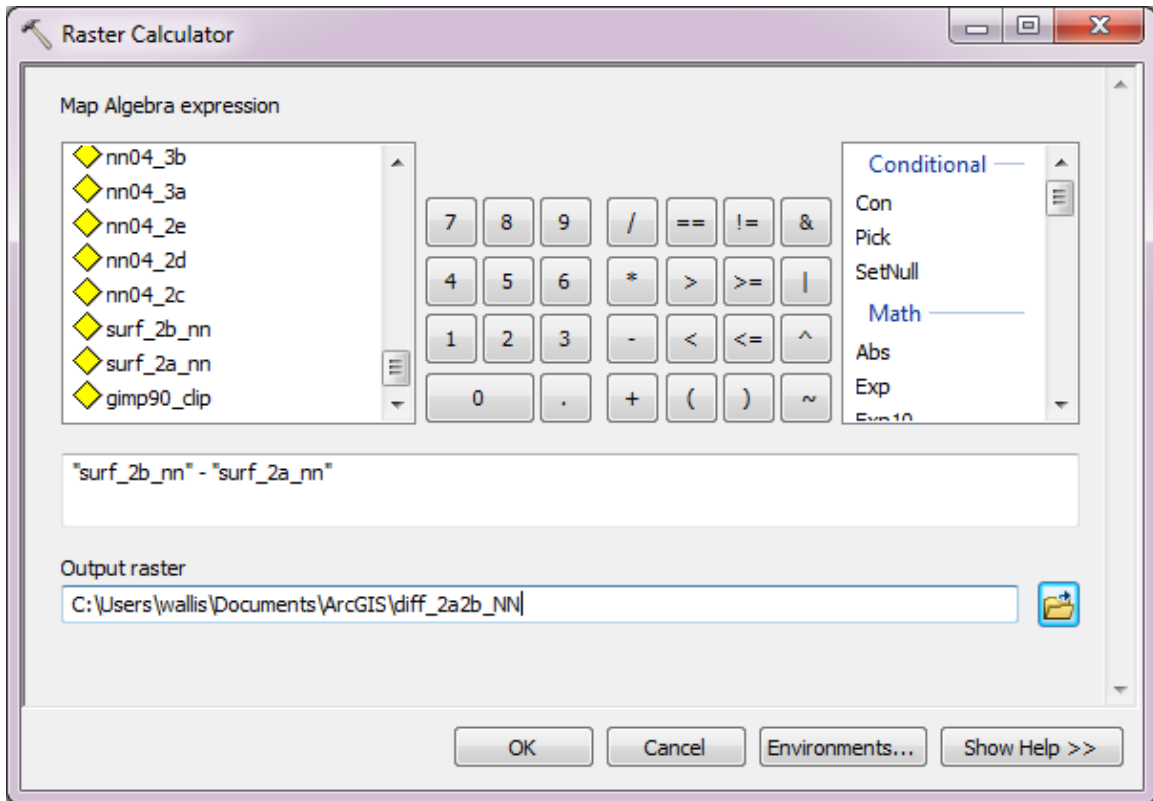


Figure 6 - Raster Calculator tool

The difference rasters were then clipped to a smaller area (using Spatial Analyst > Extraction > Extract by Rectangle) to ensure that all of the difference rasters were of the same extent. The interpolated surface rasters were limited in extent to those locations where ICESat was present, so the rasters are slightly different shapes depending on the spatial distribution of the ICESat points in each campaign. The clipped difference raster for the comparison between campaigns 2a and 2b is shown in Figure 7. The difference raster is shown relative to the GIMP 90m DEM for reference.

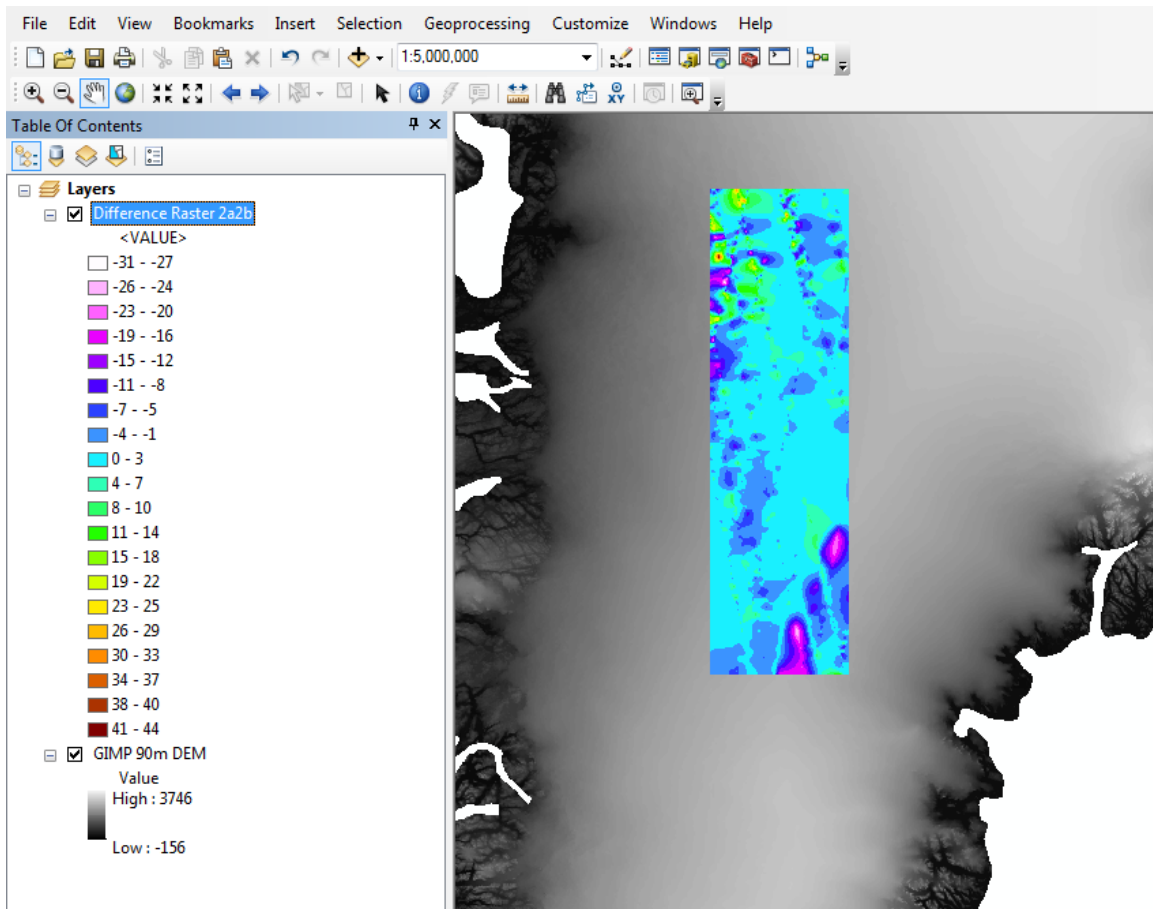


Figure 7 – Clipped difference raster for the comparison between campaigns 2a and 2b. Shown alongside the GIMP 90 m DEM for reference.

Ice Volume Change

Once difference rasters had been computed and clipped for each inter-campaign interval, ice change volume was computed using 3D Analyst > Functional Surface > Surface Volume. Due to the way in which the difference maps were defined, the volume change must be computed twice, once for positive change (ice accumulation) and once for negative change (ice loss). The settings used to compute the positive volume change with the Surface Volume tool are shown in Figure 8 below.

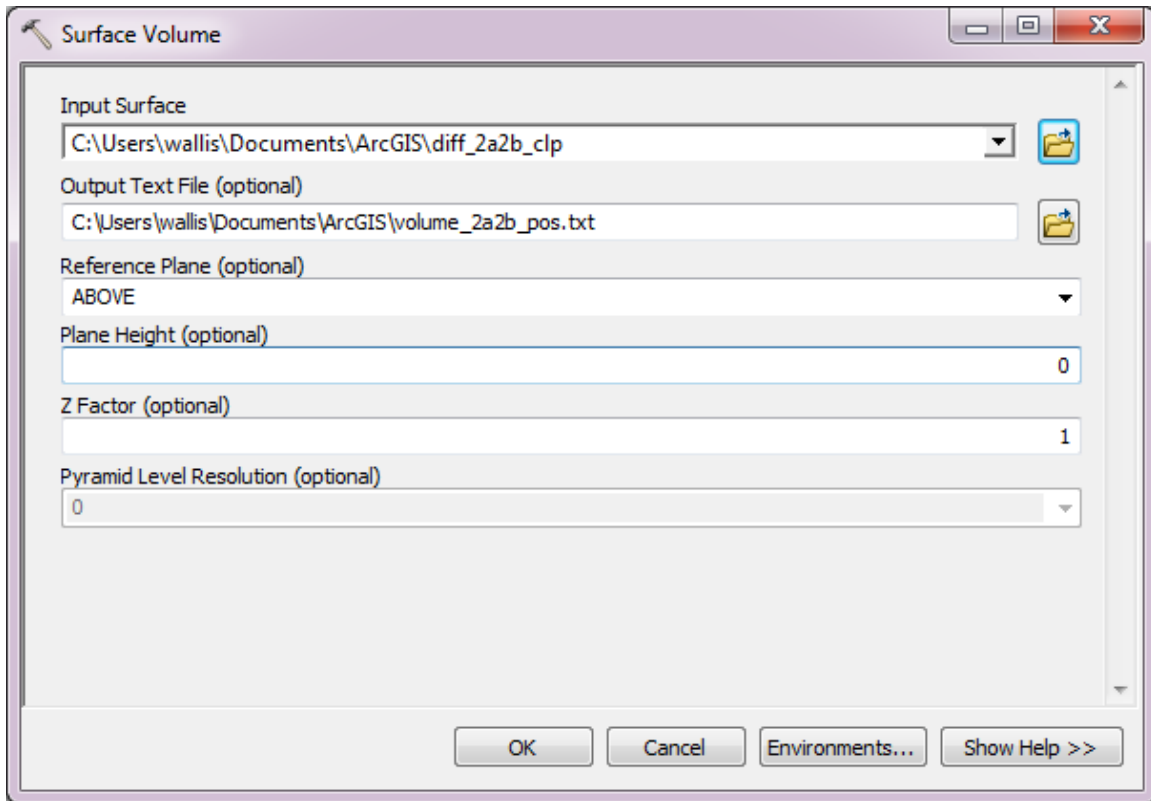


Figure 8 - Surface Volume tool, with settings for positive (upwards) volume calculation

The above settings calculate positive volume changes. The reference plane is switched to BELOW from ABOVE to calculate negative volume changes. The output units for the surface volume calculations were in m^2 and m^3 for area and volume, respectively. The net ice volume change is then the positive volume less the negative volume.

Results

The results from the ice volume calculations obtained from differencing interpolated surface rasters are summarized in Table 3 below:

Table 3 - Ice Volume Change calculation results for all campaign comparison periods

Campaign Comparison	Volume Change [km ³]	Seasonal Change
2a2b	-20.50	F -> Sp
2b2c	+65.51	Sp -> Su
2c3a	-40.01	Su -> F
3a3b	-19.68	F -> Sp
3b3c	+12.67	Sp -> Su
3c3d	+12.09	Su -> F
3d3e	+29.14	F -> Sp
3e3f	-158.07	Sp -> Su
3f3g	+143.56	Su -> F
3g3h	-38.63	F -> Sp
3h3i	+30.72	Sp -> F
3i2d	-176.61	F -> W (+1 year)
2d2e	+196.28	W -> Sp

The region over which these changes occur is approximately 63450 km². The Greenland ice sheet contains about 2.62x10⁶ km³ of ice, so these numbers are not necessary unreasonable. However, the fact that no pattern can be seen in the seasonal variations indicates that the method may not be sound. Additionally, that the volume changes from some campaign comparisons are significantly greater in magnitude than others (and again, with no discernable pattern) suggests this may not be the best method for examining ice sheet mass balance from ICESat data.

The apparent failure of this method may be due in part to the nature of the ICESat data product. Part of the issue with creating a surface from ICESat elevations is the uneven spatial distribution resulting from the satellite's repeat ground track; test regions at lower latitudes will have less point density than those at high latitudes. Some areas will also show sparse data coverage as a result of poor quality returns, further reducing the spatial point density. These problems are exacerbated by the campaign mode of operations ICESat was forced to use as data was only taken on a third of the planned orbits.

While this method does not appear to work for ICESat elevations, it may be a useful approach when working with other lidar data sets (or any point elevation data set). Airborne laser altimetry allows for data collection with very high point density and

accuracy and little cloud contamination. A significant level of data processing and filtering is necessary under most conditions, but a high-resolution surface can generally be fit to the filtered point cloud. In such a case, airborne laser altimetry missions flown over an ice sheet at two different times would allow for a regional analysis of ice mass change using the methods presented here.

Airborne altimetry is not a practical method for measuring large-scale ice volume changes, as the cost and time are prohibitive. Space-based laser altimetry monitoring of the ice sheets will resume with the successor mission to ICESat, the Ice, Cloud, and land Satellite-2 (ICESat-2). ICESat-2 is expected to launch in 2016 and will carry a photon-counting laser altimeter that is expected to provide data products with much higher point density. Additionally, the data collection method used for ICESat-2 puts less stress on the lasers than the full-waveform method employed on ICESat, hopefully negating the need for operating in a campaign mode. It is possible that this method of calculating ice volume change would be more successful using ICESat-2 point cloud data as an input.

References

- W. Abdalati and H.J. Zwally, "The ICESat Laser Altimetry Mission," Proceedings of the IEEE, vol. 98, no. 5, pp. 735-751, May 2010.
- I.M. Howat, et al. "Greenland Ice Mapping Project (GIMP) Digital Elevation Model," [Online], Byrd Polar Research Center, Ohio State University. Available: <http://bprc.osu.edu/GDG/gimpdem.php> [Accessed 15 Nov 2013].
- H.J. Zwally, et al. "GLAS/ICESat L1B Global Elevation Data (GLA06) Release Version 31", National Snow and Ice Data Center, University of Colorado Boulder. Available: <http://nsidc.org>