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Development of Onboard Digital Elevation and Relief Databases for the Advanced Topographic Laser Altimeter System

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Development of Onboard Digital Elevation and Relief Databases for the Advanced Topographic Laser Altimeter System

by

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Dedication

To John, my rock.

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Abstract

Development of Onboard Digital Elevation and Relief Databases for the Advanced Topographic Laser Altimeter System

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The Ice, Cloud, and land Satellite-2 (ICESat-2) is planned to launch in 2016 carrying the Advanced Topographic Laser Altimeter System (ATLAS). ATLAS will be the first space-based photon-counting laser altimeter to be put into operation, and is tasked with observing the Earth's ice sheets, sea ice, and vegetation.

The environment in which ATLAS will be operating is expected to introduce a significant amount of noise into the received signal; this necessitates that a set of onboard Receiver Algorithms be developed to reduce the data volume and data rate to acceptable levels while still transmitting the relevant ranging data. The algorithms make use of signal processing techniques, along with three databases, the Digital Elevation Model (DEM), the Digital Relief Map (DRM), and the Surface Reference Mask (SRM), to find the signal and determine the appropriate dynamic range of vertical data surrounding the surface for downlink. The focus of this study is the development of the DEM and DRM databases.

A number of elevation data sets are examined for use as inputs for the databases. No global data sets of sufficient quality and resolution are available for the development of the project, so best-available regional elevation data sets were selected instead. Software was developed in MATLAB to produce the DEM and DRM data bases from the input data sets. A method for calculating relief from a gridded elevation data set along the flight path of a satellite was developed for the generation of relief maps used to create the DRM. Global DEM and DRM databases were produced by mosaicking individual DEM and DRM tiles from each input data set into global grids.

A technique was developed to determine the accuracy of the DRM by using ICESat ground elevations to evaluate the accuracy of an input elevation data set. By comparing values of DRM accuracy to values of DRM relief, estimates of DRM accuracy as a function of relief magnitude were determined and used to define values of DRM padding in the receiver algorithm.

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Chapter 1: Introduction

1.1 ICESat and ICESat-2

In January 2003, the National Aeronautics and Space Administration (NASA) successfully placed the Ice, Cloud, and land Elevation Satellite (ICESat) into a near-polar orbit. ICESat carried onboard a single instrument, the Geoscience Laser Altimeter System (GLAS), designed to capture spatial and temporal variations in the topography of the Greenland and Antarctic ice sheets. The ICESat mission represents the first successful effort to measure ice-sheet elevation change using a space-based laser altimeter. ICESat operated from 2003 to 2009, providing the highly accurate, multi-year elevation data needed to determine ice sheet balance, as well as cloud property information and global topography and vegetation data [1].

The GLAS instrument was a full-waveform laser altimeter system that emitted laser pulses at two wavelengths – one in the infrared (1064 nm) and one in the visible spectrum (532 nm) – at a frequency of 40 Hz. Once emitted, laser pulses travelled to the surface of the Earth, illuminating a "footprint" approximately 65 m in diameter. Successive ICESat footprints were spaced approximately 170 m apart along the ground track of the satellite [1]. A significant number of the incident photons from each laser pulse were reflected back to the satellite to be captured by the GLAS receiver telescope. The GLAS instrument then recorded a digitized waveform of the returned signal to be telemetered back to Earth for further processing [1]. Ground-based analyses applied Gaussian fits to the waveforms to identify the transmit and receive times for each pulse centroid. Knowing the transmit and receive times for each waveform, the one-way range between the satellite and the ground is half the time-of-flight of the laser pulse multiplied by the speed of light. Combining the range vector with precision orbit and attitude information for the satellite, the position of the laser footprint can be transformed into geodetic latitude, longitude, and elevation with respect to a reference ellipsoid.

GLAS had three lasers, each intended to operate continuously for up to 2 years to enable a five-year mission. 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 measurements in a 91-day repeating orbit, to a campaign mode in which elevation measurements were made along repeat ground tracks for 33-day sub-cycles [1]. This revised strategy allowed for measurement of seasonal variations in ice sheet levels, but at the cost of lowered spatial and temporal resolution. Despite the changes to ICESat's operations, the mission was able to deliver global laser altimetry data at an accuracy of approximately 15 cm [2].

As a result of the success of ICESat, the National Research Council's (NRC) 2007 Earth Science Decadal Survey recommended that NASA pursue the development of a follow-on mission to continue the collection of laser altimetry data after the decommissioning of ICESat [1]. In response, NASA has tasked Goddard Space Flight Center (GSFC) with the development and deployment of the Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) mission. ICESat-2 is slated to launch in 2016, and will begin operations to satisfy its science objectives [3]:

- Quantify polar ice-sheet contributions to current and recent sea-level change, as well as ice-sheet linkages to climate conditions.
- Quantify regional patterns of ice-sheet changes to assess what drives those changes, and to improve predictive ice-sheet models.
- Estimate sea-ice thickness to examine exchanges of energy, mass and moisture between the ice, oceans, and atmosphere.

- Measure vegetation canopy height to help researchers estimate biomass amounts over large areas, and how the biomass is changing.
- Enhance the utility of other Earth-observation systems through supporting measurements.

Like its predecessor, ICESat-2 will carry a single laser altimeter instrument, the Advanced Topographic Laser Altimeter System (ATLAS). However, unlike GLAS, which was a full-waveform system, ATLAS is a single photon detection ranging instrument. The ATLAS laser produces a visible green beam (532 nm) with a repetition rate of 10 kHz. Each laser pulse will be split six separate beams with the use of a diffractive optical element. The six laser footprints will each have an approximate diameter of 10 m, but will vary in terms of energy, as there will be three spot pairs of relatively high/low energy levels. The beam pairs will be separated by ~2.5-3.5km on the Earth's surface and each spot will be approximately 90 m from its adjacent spot in the same pair [4]. Although the science objectives remain the similar to its predecessor, ICESat-2 will have slightly different orbital parameters as it will utilize a 500 km average altitude with an inclination of 92°. Given these elements, the satellite nadir ground track should repeat every 91 days. ICESat-2 is expected to launch in 2016 [4].

The laser ranging technology developed for ICESat-2 is very different than the full-waveform, high power approach used in the previous mission. As such, many new processing algorithms are required to produce the desired cryospheric data given the new type of measurement approach. However, even prior to producing the science products, there is a need for onboard processing and analysis. The expected rate of solar background noise affecting ATLAS data collection necessitates the development of onboard receiver algorithms designed to manage both data volume and data rate. The ATLAS Flight Science Receiver Algorithms are onboard algorithms designed to reduce the telemetry bandwidth to fit within the downlink constraint of 577.4 Gb/day and to prevent the data rate from going above the hardware limit of 80 Mb/s. Without the algorithms, it is expected that the data volume could rise to values greater than 15 times the allowable bandwidth and the data rate could reach greater than 30 times the hardware limit [4].

The algorithms accomplish these tasks by performing onboard signal processing on received photon events. Three onboard databases are used by the receiver algorithm during signal processing – one to determine where to look for data, and two to determine what data to include in downlink telemetry.

1.2 Database Description

The Digital Elevation Model (DEM) is an onboard database which will be used to specify a vertical range window in which the receiver algorithm will search for signal [4]. The range window is defined by two values in the DEM – a maximum and minimum elevation over a defined area. The algorithm indexes into the database using the latitude and longitude of each laser spot.

The Digital Relief Maps (DRMs) are onboard databases containing the maximum relief values over a specified ground track distance in a given area. The DRMs are used to specify the bandwidth of the signal that will be included in the data telemetry. Two DRMs are required by the receiver algorithm, one corresponding to a ground track length of 140m (DRM-140), and another corresponding to a ground track length of 700m (DRM-700). These two characteristic lengths used to define the DRMs were determined based on how the algorithm processes photon events. When searching for a signal peak within the range window, the onboard receiver algorithm accumulates the returns acquired from 200 successive laser shots into a single histogram, referred to as a Major

Frame. Based on the repetition rate of the laser and the average orbital altitude, the spacecraft will have covered 140m of ground track on the surface of the Earth during the time it takes to transmit 200 laser pulses [4]. The values in the DRM-140 represent the maximum difference in terrain height over this horizontal distance. A Super Frame is equivalent to 5 successive Major Frames, or 1000 laser shots. The values in the DRM-700 represent the maximum difference in terrain height over the horizontal distance travelled during the time it takes to transmit 1000 laser pulses for the Super Frame. The Super Frame is intended to help facilitate surface finding through statistical analysis when the signal might not be as obvious over the smaller extent of the Major Frame [4]. As with the DEM, the DRM is also indexed as a function of latitude and longitude so the process of finding the relevant relief values is based on the geolocation of the individual laser footprints.

The Surface Reference Mask (SRM) is a database of information on the surface type and its associated characteristics. The SRM is used alongside the DRMs to determine signal bandwidth in the telemetry, as well as in deciding what data is included in the downlink telemetry. The SRM is referenced by latitude and longitude. The four surface types identifiable using the SRM are land, land ice, sea ice, and ocean. Additional bits specify whether vegetation is present, if a coastline is present, and whether an area is of particular interest. The receiver algorithm uses the SRM to define values of padding that are added to the telemetry window to account for uncertainties in relief and the signal location [4]. Surface types can also be used to change the conditions under which data is downlinked. For example, ocean returns are only downlinked for the higher-intensity beams when signal is found in the Major Frame, while telemetry for the other three surface types depends on whether or not signal has been found in either the Major or Super Frame and what the conditions are at the footprint (i.e. day or night, strong or weak beam, presence of clouds, etc.). The SRM has been developed independently from the DEM and DRM at the Center for Space Research at The University of Texas at Austin.

1.3 Database Use in Receiver Algorithm

Before the receiver algorithm can search for ground signal within a Major Frame, it must first determine a geolocation reference point for the laser spot on the surface. Spacecraft position, velocity, attitude, and attitude rates relative to the spacecraft body are provided by the spacecraft bus to the flight software once per second. The laser pointing vectors are then rotated from the instrument body reference system to the Earth Centered Earth Fixed (ECEF) reference system and translated to the surface of the WGS84 ellipsoid. The location of each laser spot on the Earth ellipsoid is calculated in real time and extrapolated forwards in time up to 3 seconds to account for processing delays. This receiver algorithm uses the estimate of the latitude and longitude location of the laser spot on the ellipsoid, along with the calculated range from the spacecraft to the ellipsoid to index into the databases to create the range window and select telemetry bands for downlink [4].

The latitude and longitude of the laser spot are used to index into the DEM and determine the relevant maximum and minimum elevations for that particular location. Combining these heights with the calculated range information provides a start and end value to use as the vertical window in which the algorithm will search for the surface signal. Surface-dependent margin is added to these starting and ending ranges in order to compensate for any uncertainties in the DEM values and the range calculations. These elevation values are converted to values of time (in units of clock cycles from laser fire event) that define when the software should start and stop storing received time tags. The altimetry range window (including margin) cannot exceed 6km due to hardware limitations. The received time tags that fall outside of the range window are not stored [4].

In order to search for the perceived ground signal, the receiver algorithm hardware generates histograms of received photon events across the entire altimetry range window, as defined by the onboard DEM. The integration time for the histogram is 0.02 seconds, equivalent to 200 laser shots. As mentioned previously, this 200-shot accumulation of data, is referred to as a Major Frame (MF). The software then searches for signal in each Major Frame. For each histogram, a threshold is defined based on the background noise rate and the number of bins in the histogram. If at least one bin in the Major Frame histogram has a count at or above the threshold, the Major Frame is considered to contain signal. If signal is found, the receiver algorithm determines which bins of the histogram contain the signal. Whether or not signal is found in a Major Frame, five consecutive Major Frames are combined into a Super Frame (SF), using the MF along with the two previous and two subsequent MFs. The Super Frame allows for a wider statistical search for surface signal. If valid signal is found in at least 3 of the 5 Major Frames with the Super Frame, the signal calculation is considered successful, and the signal location in the central Major Frame is determined by linear interpolation from the nearby frames. If signal is not found in the MF, and is also not found in 3 of the 5 MFs, the signal location is extrapolated from the signal location in previous Major Frames where the signal was found. If SF calculations generate a signal location that agrees with the MF calculations or if no SF signal location can be found, then SF calculations are abandoned. Otherwise, if the SF signal location is far away from the MF signal location, both telemetry bands are saved for downlink [4].

Once the vertical location of the signal has been determined, the DRM is used to select the telemetry band, i.e. the vertical range/elevation band containing the signal that will be downlinked. For Major Frames that have signal, the latitude and longitude of the spot location are used to index into the DRM-140 and determine a value of relief for the region. For frames using interpolated or extrapolated signal location (i.e. where the Super Frame is used to locate signal), the DRM-700 is used in place of the DRM-140 to select an appropriate telemetry band. The relief from the DRM is scaled based upon the surface type (using the SRM), and padded to compensate for uncertainty in the relief values. Over land and land ice, the scale factor is 2, denoting a doubling of the relevant DRM relief value for those areas. For ocean and sea ice surfaces, the relief is unchanged. This padding added to the DRM value is dependent upon surface type and also the magnitude of the relief. Once the software has determined the extent of the telemetry band, the band is draped over the signal location, with the signal in the middle of the relief band, and the corresponding bins in the altimetry histogram are supplied to the hardware. The hardware will then telemeter time tags for all photon receive events that fall within those histogram bins [4]. It should be noted that these are the default setting of the receiver algorithm. The number of Major Frames required to find Super Frame signal location, the scaling factors, and use of DRM-140 vs. DRM-700 relief are, among other settings, controlled by parameters that can be changed on-orbit.

1.4 Database Requirements

Specifications governing the design of the onboard databases are dictated both by the receiver algorithm design and the instrument itself. One of the primary driving requirements is that the total onboard memory allocation for all three databases is less than 3.2 MB [4]. In order to store global databases at sufficient resolutions, the values of elevation and relief are encoded such that the data can be stored in one byte, and all land surface descriptors used by the SRM (land or ocean, ice covered or not, vegetated surface, etc.) can be stored in a single bit.

Additionally, the hardware cannot support an altimetry range window larger than 6 km. This constraint necessitates that the difference between the maximum and minimum elevations in the DEM be no greater than 5.5 km, as a 250 m margin is added to either side of the nominal range window. In order to meet both the range window constraint and the onboard memory constraint, the DEM is constructed in a three-tiered system. The primary DEM grid provides global maximum and minimum elevation values at a resolution of 1°x1°. For locations where the difference between a maximum and minimum elevation exceeds 5.5 km, a secondary grid is created at a resolution of 0.25°x0.25°. Similarly, a 0.05°x0.05° resolution tertiary grid is created for those regions where the 5.5 km limit is exceeded in the secondary grid [4]. The three-grid procedure is critical in meeting the memory limitations – if more memory was available, a single-level, high resolution DEM could be used instead.

Another crucial requirement for the database development is that the values in the DEM be elevations relative to the surface of the Earth ellipsoid, more specifically, the WGS84 ellipsoid. The spacecraft will not have a reference geoid available for use by the receiver algorithm, such that the position and attitude information used to calculate range from the satellite to the surface is referenced to the WGS84 ellipsoid [4]. DEM values referenced to the geoid instead of the ellipsoid could lead to significant errors in the range window calculations and result in the system's inability to capture or recognize valid ground signals.

As mentioned previously, there is a 250 m margin added to the DEM values used in determining the altimetry range window. This margin includes 150 m of elevation padding to account for errors in the elevation data used to create the DEM [4]. In order for the uncertainty in the DEM to be fully accounted for by the 150 m of padding, the requirement for the 3-sigma accuracy of the DEM must be less than or equal to this 150 m.

In terms of requirements on the DRM, it must provide values of maximum relief at two length scales, 140 m and 700 m. These length scales are applied along flight paths (ground tracks) consistent with a 92° inclination orbit [4]. Calculating relief along the flight path ensures that the DRM fully captures the relief for a given area without unnecessarily inflating the relief values. The DRM directly affects data volume, so relief needs to be as close to truth as possible but without clipping relevant elevations. The resolution of the DRM-140 and DRM-700 is to be 0.25°x0.25°, but a balance must be struck between memory and data volume in deciding the resolution of the DRM. A lower resolution DRM would take up less onboard memory, but result in higher relief values and would likely increase the data volume. A higher resolution DRM could lower the data volume to some extent, but would necessitate more onboard storage capacity.

Uncertainties in spacecraft motion and the data extrapolation algorithm require that each value in the DEM and DRM, alternately referred to as DEM and DRM tiles, have a 2 km border [4]. In other words, when calculating the minimum and maximum elevation values for a particular area, the elevation values within 2 km of that area are included in addition to the elevation values within the area. This spatial buffer requirement is another approach within the receiver algorithm's plan to ensure that the system will capture the full topographic extent in the telemetered data from on-orbit.

Finally, the onboard databases must provide global coverage despite the fact that the inclination of the orbit will preclude travel over regions beyond 88° latitude [4]. The global product allows for off-nadir pointing as well as any possible mission changes to inclination or reference ground track configuration.

Chapter 2: Data Source Selection

The DEM and DRM are constructed from existing, publicly-available digital elevation models. Several regional elevation data sources covering large portions of the globe have been released in recent years; however, no global elevation products currently exist that satisfy both the resolution and accuracy requirements of this project. One of the challenges in producing global products is the determination of how to combine products from various sensors at differing resolutions and projections. A full description of available elevation data sources can be found in Appendix A.

2.1 Selection Criteria

Accuracy of the input elevation data is of paramount importance in selecting data sources for the onboard database. Input DEM accuracy has a cascading statistical effect on several segments of the receiver algorithm. Lower accuracy in an input DEM often presents itself as clipped peaks and filled valleys, elevation errors which could result in a narrowed range window and a potential loss of science data in the downlink [5]. The margin added to the range window is partially intended to compensate for these types of errors, but the margin assumes a 3-sigma accuracy less than or equal to 150m [4]. If errors in the input DEM are greater than this, then some data could still be lost prior to the onboard signal processing. Poor input DEM accuracy also affects the quality of the DRM. In the case where poor accuracy results in topographic smoothing, the corresponding DRM values would be erroneously lower and the telemetry bands might not be able to fully capture the ground return. In the case where poor accuracy is a result of outliers and point errors in the input data, the values in the DRM would likely be much larger than reality and result in an unnecessary increase in the data volume.

Resolution is also a significant factor in data source selection. The availability of a high resolution data set must be balanced against the accuracy of that data set. For instance, the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) provides 30m (1 arc-second) resolution elevation data between 83° N/S, while the Shuttle Radar Topography Mission (SRTM) data set provides 90m (3 arc-second) elevation data between 60N/S [5] [6]. However, when comparing the two DEM sources, the ASTER product shows large spikes and pits in the data that cannot represent actual topography in addition to significant artifacts from the data processing that are not apparent in the SRTM product. Thus, despite ASTER's three-fold increase in resolution, it is preferable to use SRTM in the regions where it is available in order to avoid these types of errors. Editing of the ASTER dataset to suit the purposes of DEM and DRM development is outside the scope of this task.

In actuality, the resolution of the input DEM data set becomes more critical for the production of the DRM. Relief is calculated by comparing neighboring elevations along 140m and 700m flight path segments. So, for a 1km resolution DEM, any relief calculation between two neighboring elevation values would be, at minimum, along a 1km flight path segment rather than the 140 and 700 length scales. Consequently, to calculate realistic relief for the desired flight path lengths, a higher resolution input DEM is preferred.

The data collection method used to create each input DEM data set is also a factor in the data source selection. Every collection method has various strengths and weaknesses, and it is important to understand how the resultant products are affected by the sensor performance and collection scenarios in addition to understanding how these various parameters might affect the mosaicking process when creating the global product for the onboard database.

2.2 Final Selection of Input Data Sources

Figure 1 indicates what sources are used in each region to develop the DEM and DRM databases. Detailed descriptions of each data set can be found in Appendix A.

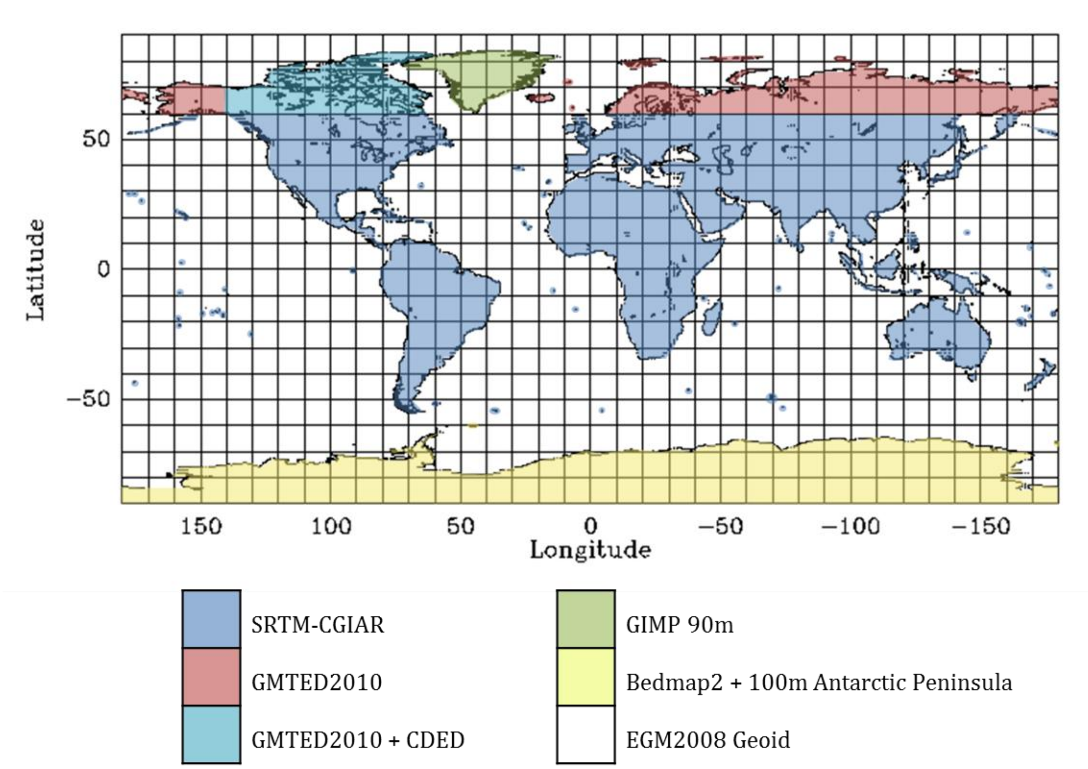


Figure 1: Illustration of input data sources used to generate DEM and DRM databases

An SRTM derived data set produced by the CGIAR Consortium for Spatial Information, referred to here as SRTM-CGIAR, was selected as the primary data source for its accuracy and resolution. SRTM elevation data is available between 60° N and 60° S, providing coverage for approximately 83% of the globe at a resolution of 90 m [7]. Several voids are present in the original SRTM product; however, several void-filled products, including SRTM-CGIAR, have been produced to provide seamless coverage between 60° N/S. SRTM-CGIAR is a void-filled digital elevation model produced using best available regional elevation models to fill gaps in SRTM coverage [8]. The SRTM products have been extensively validated by the developers as well as independent reviewers, and it is widely regarded as one of the best available elevation datasets [7].

The Global Multi-resolution Terrain Elevation Data (GMTED) 250 m elevation products were selected as the data sources for areas north of 60° N, except Greenland. GMTED is a global, multi-resolution data set produced from the best-available data sources in each region. The data set consists of several data products, including minimum, mean, and maximum elevations [9]. The highest resolution (250 m) maximum and minimum products are used to produce both the DEM and DRM databases. GMTED was selected for use after it was determined that ASTER v2.0 products contained more errors that could be accounted for in the scope of this project. Despite its increased resolution compared to GMTED (30 m vs. 250 m), ASTER showed single point errors from the extreme elevation and relief values in a given area that were especially problematic in the construction of the DEM and DRM.

The Canadian Digital Elevation Database (CDED) is used in conjunction with GMTED to develop the DRM over Canadian territory north of 60N. CDED is available at higher resolutions than GMTED (30 m and 90 m) [10], which is desirable when calculating relief for the DRM. In cases where the CDED DRM showed greater relief than the GMTED DRM, the CDED values were used in the final product. CDED was used as the input data source for producing GMTED in Canada, so the resulting elevation and relief databases produced from CDED and GMTED are, in general, very similar.

The 90 m elevation product distributed by the Greenland Ice Mapping Project (GIMP) is used as the source of elevation data over Greenland. The true resolution of the GIMP data set varies from approximately 40 m to 500 m over the ice sheet, as the various products used to create the data set were collected using different instruments [11]. The

ASTER v2.0 product is available at a 30 m posting over Greenland, but showed errors in excess of hundreds of meters over the ice sheet [6] and was deemed unsuitable for the development of the DEM and DRM without a considerable editing and void-filling effort. Excluding the ASTER data set, GIMP has the highest resolution of any publicly available elevation product over Greenland.

Two products were selected for use in the development of the DEM and DRM over Antarctica – the 1 km surface elevation product developed by the Bedmap2 project and a 100m elevation product covering the Antarctic Peninsula. The Bedmap2 product is the most recent continent-wide product to be released, and is a combination of several regional data sets [12]. The resolution is not ideal, especially for the development of the DRM, but the product is the best available source to cover the entirety of the Antarctic continent. The ASTER 100 m Antarctic Peninsula data set [13] is used to supplement the Bedmap2 product for both the DEM and DRM. This data set has limited coverage, but the increase in resolution and its extensive verification provides a better product over the regions that are covered.

The EGM2008 geoid is used as the elevation source for the oceans. The working group dedicated to ocean applications and science within the ICESat-2 Science Definition Team selected the EGM2008 over other available geoid models. These geoid heights relative to the WGS84 ellipsoid are used to set the maximum and minimum elevations over the oceans in the DEM. The DRM is set to be uniformly zero over the oceans. The SRM is used to verify that the DEM and DRM values contain EGM2008 geoid heights and zeroes, respectively, where appropriate.

Finally, a canopy height model developed by Simard, et al. [14] is used to create global vegetation height maps. These elevation values are incorporated into the DEM and DRM to ensure that both databases can capture the full dynamic range of surface and vegetation. Simard's canopy height model gives heights for all vegetation types rather than only for areas specifically classified as forests. Differing metrics can be used to evaluate canopy height. Simard's model uses the RH100 waveform metric (i.e. total distance between the beginning of the canopy signal and the ground peak) instead of an alternative: the Lorey's height (used in the vegetation map produced by Lefsky et al., 2010), which is the basal area weighted height of all trees in the region [14]. For the purposes of adding vegetation to the DEM and DRM, it is advantageous to use the tallest vegetation height for any given area to maximize the likelihood that the full canopy will be captured. In general, Simard's RH100 metric will provide, overall, a higher elevation value than approaches using the Lorey's height metric [14]. Simard's map is selected for this particular application with the motivation to not exclude any vegetation elevations. The canopy height map was generated using ICESat waveforms, which were correlated with various climatological data to produce a map at the desired 1 km resolution. Root mean square error of the data set is estimated at 6.1 m [14].

2.3 INPUT DEM ACCURACY

The accuracies associated with each input data source are shown below in Table 1. Note that each data set meets the 150m 3-sigma accuracy requirement.

Table 1: Reported accuracies for the selected input data sources

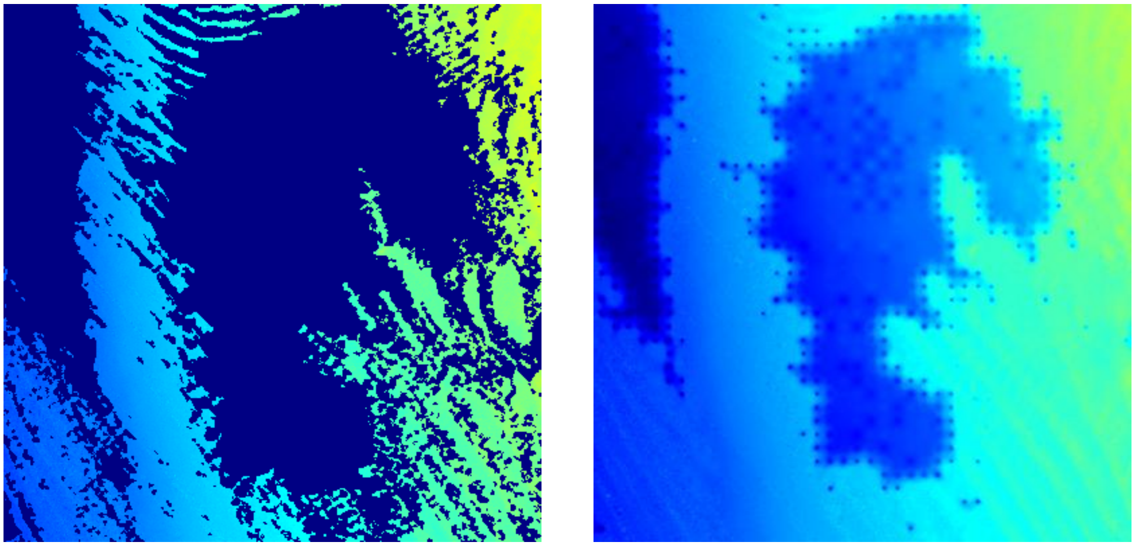
Input DEM	Resolution	Reported Accuracies (3σ)
SRTM-CGIAR	90 m	<30 m [7]
GMTED2010	250 m	<90 m [9]
CDED	30 m	<19 m [10]
GIMP	90 m	<30 m for most surfaces, <90 m in areas of high relief [11]
Bedmap2	1 km	<30 m for most of ice sheet, <130 m over mountains [12]
Antarctic Peninsula	100 m	<75 m [13]

2.4 Known Source Data Issues

Several issues with the various data sources have become apparent throughout the development of the DEM and DRM. These are described here for future reference.

2.4.1 SRTM-CGIAR

The developers of SRTM-CGIAR used a number of techniques to fill the voids in the original data set [8]. Vector contours and control points were used in interpolating over voids to avoid clipping peaks and filling valleys [15]. Depending on the region, secondary elevation sources are used to void fill, but some artifacts from the process remain in the distributed data set. For instance, Figure 2b below shows a region in southern Africa where the void filling process has filled the gaps in coverage (Figure 2a), but "pits" in the data remain at regular intervals of approximately 30 arc-minutes. These artifacts do affect the DEM and DRM values; however, accuracy analysis of several void regions indicates that the overall accuracy of the product is not greatly diminished and it is still preferable to use a void-filled data set.



(a) (b)

Figure 2: (a) Subset of SRTMv2 elevation data set in Africa [7], (b) Subset of filled SRTM-CGIAR data set in same region in Africa [8]

Despite the void-filling effort, some errors that affect small areas still exist. For example, a few regions in the Himalayas (shown in Figure 3) contain “pits” of zero elevation values near the peaks of mountains.

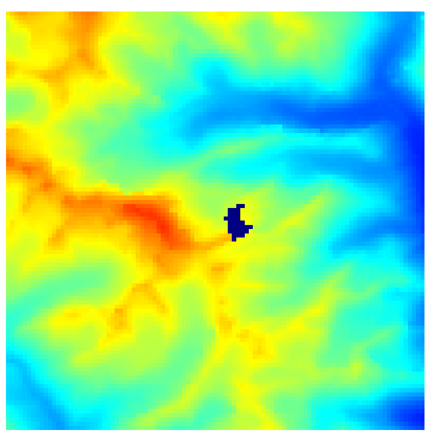


Figure 3: Subset of SRTM-CGIAR data set exhibiting anomalous zero elevation values near a peak in the Himalayas [8]

The effects of the pits are limited – the pixels can be masked out and re-filled from surrounding elevations – but the errors must be searched out and the edits performed by hand.

Another issue to be cognizant of when working with SRTM, or any other product collected using Interferometric Synthetic Aperture Radar (InSAR), is that the elevations do not necessarily represent ground elevations. InSAR signals cannot fully penetrate dense canopies or buildings, giving an elevation that is somewhere between the ground elevation and the top of the canopy or structure. This is most readily seen in the Amazon River Basin (example shown in Figure 4), where large (~40m) vegetation biases are evident. From the figure below, it would seem that the Amazon River is surrounded by tall canyon walls, but this spike in elevation at the edge of the river is actually due to the dense rainforest canopy. No corrections are made to the SRTM product for this vegetation bias. Vegetation heights are added to the DEM and DRM regardless of vegetation bias in any given region. The bias characteristic of SRTM does have an advantage, namely that no adjustments for urban buildup need be made to the DEM or DRM.

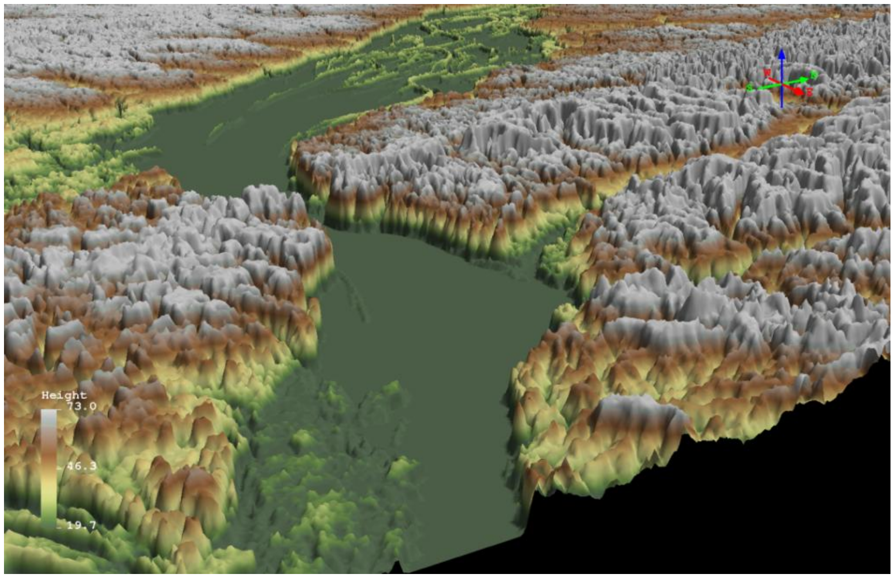


Figure 4: Terrain model of an area along the Amazon River in Brazil showing an apparent bias in elevations caused by dense vegetation [8]

2.4.2 GMTED2010

GMTED is a global product produced using the best-available data sets in any given region. The quality of the product is location-dependent, as some of the regional data sets used are more accurate than others. The GMTED developers used the National Elevation Dataset (NED) over Alaska, the Canadian Digital Elevation Database (CDED) over Canada, and the Digital Terrain Elevation Data (DTED2) over Eurasia. [9].

GMTED products are similar to SRTM-CGIAR in that they are referenced to the EGM96 geoid. However, most of the products used for regions outside of SRTM coverage are not referenced to EGM96, and have not been converted to the geoid during the production of GMTED. NED-Alaska, CDED, and DTED are referenced to the National Geodetic Vertical Datum of 1929 (NGVD29), the Canadian Geodetic Vertical Datum of 1928 (CGVD28), and Mean Sea Level (MSL), respectively. The horizontal datums were corrected such that all data sets were referenced to WGS84 [9]. While it would seem that the difference in vertical datums would induce large errors into the final data set, differences between the various vertical reference datums and the EGM96 geoid are on the order of a few meters, or in some cases, centimeters [9] [16] [17]. Vertical reference datum differences of this magnitude are less than the given accuracies of the elevation products. Conversion of GMTED to ellipsoidal heights can be accomplished by assuming the entire product is vertically referenced to the EGM96 geoid without incurring large errors.

2.4.3 GIMP

The GIMP data set was created from a number of regional DEMs collected using several different methods of data collection. The disparate data sets are registered horizontally and vertically to ICESat elevations to ensure that the output product is consistent. However, the resolution of each input data set is not consistent. The true resolution of the product ranges from 40 m to 500 m, but the quality of the data set is also highly dependent on location. Over the interior of the ice sheet, the elevation error is on the order of ±1 m, and increases to ±30 m at the periphery. Larger errors are expected in areas of high relief and at major outlet glaciers, which show rapid elevation change near their termini [11]. Some unexpectedly high values of relief have been observed in these regions, but no efforts to validate or edit the data set have yet been undertaken.

2.4.4 Bedmap2

The Bedmap2 resolution of 1 km is not necessarily ideal for the purposes of the onboard DEM and DRM database development. The 1 km resolution inhibits a relief calculation at the desired 140 m and 700 m length scales. Despite this non-ideal resolution, Bedmap2 is still the best available and most recent continent-wide elevation source for Antarctica. The primary source for the Bedmap2 surface elevation product is Bamber’s 1 km Antarctic DEM [12]. The values in Bamber’s product are averaged elevations, which result in overall lowered relief values and frequently missed mountain peaks within the DEM. The developers of Bedmap2 augmented Bamber’s DEM in areas where it was known to be less accurate, but due to the relatively low resolution, several mountain peaks are still underrepresented [12]. Because of both the resolution and data processing methods, particular care must be taken in validation of the DEM and DRM in Antarctica. The issues with Bedmap2 can be largely ameliorated on the Antarctic Peninsula by the inclusion of the higher resolution DEM of the peninsula [13].

Chapter 3: DEM Generation

A general description of the development and production of the DEM database is presented in this section.

3.1 Requirements

Requirements on the onboard DEM database flow down from specifications imposed on the receiver algorithm by the operational requirements of the ATLAS instrument and flight software [4]. These requirements are summarized below:

- The DEM must provide maximum and minimum elevations relative to the WGS84 ellipsoid.
- The DEM is to be constructed in three tiers: the first tier provides global maximum and minimum elevations at a resolution of 1°x1°. The second tier provides maximum and minimum elevations at a resolution of 0.25°x0.25° for those first tier tiles where the elevation difference between maximum and minimum exceeds 5500 km. The third tier provides maximum and minimum elevations at a resolution of 0.05°x0.05° for those second tier tiles where the elevation difference between maximum and minimum exceeds 5500 km. If tiles in the third tier of the DEM exceed the range window limit, no action is taken.
- The values in the onboard DEM are to be encoded such that all possible elevations are positive and can be stored in one byte of data.
- The DEM must have a global 3-sigma accuracy of 150 m or better.
- Each tile within the DEM, regardless of resolution, must have a 2 km border.
- Each DEM tile, regardless of resolution, must be indexed by the geodetic latitude and longitude of its southwest corner.

3.2 DEM GENERATION

A separate method is used to create the DEM in the polar region from that used for the rest of the globe. The primary difference in approach is based on the difference in data source projections. Between latitudes of 60° S and 84° N, the input data sources used are (with the exception of the GIMP DEM) distributed in the geographic projection, and the DEM is processed using this projection. Antarctic data sets are distributed in a polar stereographic south projection, so a separate method has been developed to create the DEM that does not require re-projection of the Antarctic data. Re-projection of data at far north and south latitudes to a geographic projection induces errors as longitude values approach singularity at the poles.

3.2.1 Geographic Methodology

The geographic projection is well-suited to the production of the DEM for most of the globe for a number of reasons. First, the SRTM-CGIAR, GMTED, ASTER, and CDED data sets are all distributed in the geographic projection, so the majority of available data sets do not require re-projection [8] [9] [6] [18]. Additionally, since the tiles in the DEM are to be referenced by latitude and longitude, it is preferable to use data sets on the same horizontal datum to avoid coordinate system conversions. Finally, the DEM is not dependent on length scales, so any distortion of the geographic projection in the high latitudes will not affect this process.

Some pre-processing of the input data sets is necessary before the DEM can be produced. The details of how each data set is ingested, modified, and processed in order to create the final output DEM is described in a later section. The general methodology is presented here. The procedures described here are specific to those data sets that contain elevations relative to the WGS84 ellipsoid and are in a geographic projection.

Algorithms have been developed in MATLAB for the production of the onboard DEM from the regional input DEM data sets selected. These MATLAB functions generate a single 1°x1° DEM tile at a time within the (larger) area specified.

The functions require several inputs: a data structure containing the elevation model and the values of latitude and longitude associated with the elevations, the latitude and longitude of the desired primary DEM tile, and a value for the overlap in kilometers. Additionally, the function can accept an optional input of a data structure containing a vegetation height map when applicable. Separate MATLAB functions have been created for each input data set resolution. The resolution is used to calculate the number of required extra cells for the desired overlap value. This overlap is then included in the calculation of the individual DEM tiles by adding the extra cells associated with the overlap to each edge of the 1°x1° region before finding the maximum and minimum elevation values for that specific tile. In a geographic projection at mid-latitudes, the latitudinal length of a cell in meters can be considered constant. For a 3 arc-second resolution map (like SRTM-CGIAR), this length is approximately 90 m, and the number of cells within a 2 km latitudinal overlap would be calculated thusly:

$$N_{lat} = ceiling\left(\frac{2000\ meters}{90\ meters}\right) = 23 \qquad (1)$$

The longitudinal length of a cell varies with the cosine of the latitude. At the equator, the longitudinal length is equal to the latitudinal length (90 m), and decreases to 0 m at the poles. As an example of how this variation is accommodated, the equation for calculating the number of extra cells, longitudinally, required for a 2 km overlap when the nominal resolution of the map is 90 m is shown below:

$$N_{long}(latitude) = ceiling\left(\frac{2000\ meters}{90\ meters * \cos(latitude)}\right) \quad (2)$$

At 60° N, the number of cells that would be equivalent to 2 km in longitude is:

$$N_{long}(60°) = ceiling\left(\frac{2000\ meters}{90\ meters * \cos(60°)}\right) = ceiling\left(\frac{2000}{45}\right) = 45 \quad (3)$$

The *ceiling* function is used in the overlap calculations in order to ensure the inclusion of a full 2 km region around the DEM tile. By the same logic, when calculating the longitudinal overlap for a 1°x1° tile, the largest number of cells determined from calculations both of the north and south borders of the tile For example, a 1°x1° region located at 70° N would require 65 extra cells along its southern border for the 2 km overlap:

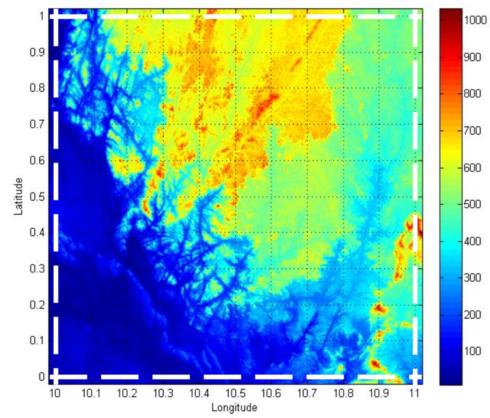
$$N_{long}(70°) = ceiling\left(\frac{2000\ meters}{90\ meters * \cos(60°)}\right) = 65 \quad (4)$$

At its northern border, the same area would require 69 extra cells for the 2 km overlap:

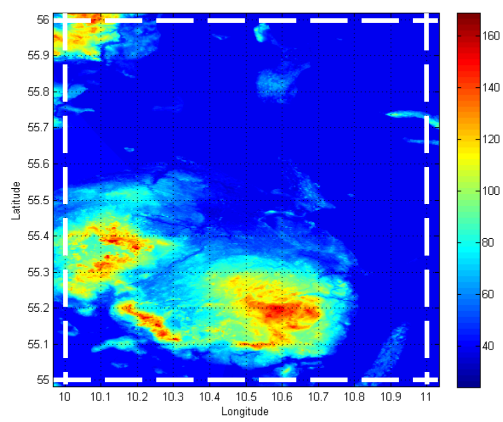
$$N_{long}(71°) = ceiling\left(\frac{2000\ meters}{90\ meters * \cos(71°)}\right) = 69 \quad (5)$$

For a tile at this latitude, the grid of cells that comprise the area without an overlap is expanded by 23 cells in the northern and southern directions and 69 cells in the eastern and western directions. Some “extra” elevation data is included along the southern edge, which is preferable to excluding elevation data along the northern edge by using the smaller of the two N_{long} values.

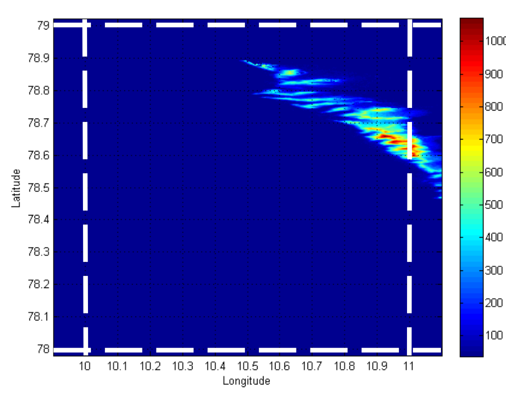
The images below in Figure 5 show the effect that latitude has on the number of extra cells that must be included for the 2 km overlap. The true boundaries of the 1°x1° areas (with no overlap) are outlined in white; the plotted area is all of the cells that would be included in calculating the DEM for each area.



(a)



(b)



(c)

Figure 5: An illustration of the effect of latitude on the number of cells required to create the 2 km overlap. The images shown are located at (a) 0° N 10° E (b) 55° N 10° E and (c) 78° N 10° E

The encoding scheme for the onboard version of the DEM was designed by the ICESat-2 receiver algorithm team as the onboard databases will be stored as binary values to keep the file sizes as small as possible. The encoding scheme ensures that all DEM values are positive and can be stored in one byte (i.e. elevation values will fall between 0 and 255) [4]. The maximum and minimum elevations are converted as follows:

$$E_{max,encoded} = ceiling\left(\frac{E_{max,actual} + 500}{48}\right) \tag{6}$$

$$E_{min,encoded} = floor\left(\frac{E_{min,actual} + 500}{48}\right) \tag{7}$$

Within the DEM generation function, the primary DEM is calculated first. MATLAB *max* and *min* functions are used to find the highest and lowest values of elevation over the area that includes the defined 1°x1° tile and including the extra cells required for the 2 km overlap. If a vegetation height map is applicable for the given area, the representative vegetation height for that region is added to the maximum height and subtracted from the minimum height. Once all of these elevations have been considered, the maximum and minimum heights are encoded for the onboard DEM product. If the difference between the decoded values is greater than 5500 m, the tile is flagged for the production of a secondary DEM and new latitude and longitude limits are defined to divide the primary tile into 16 0.25°x0.25° tiles. The same procedure is followed for each of the 16 secondary DEM tiles that exceed the 5500 m elevation difference in the production of the 25 0.05°x0.05° tiles of the tertiary product from a single 0.25°x0.25° segment. Although the same procedure is followed for the primary and secondary DEMs when the elevation differences exceed 5.5 km, if any tertiary DEM tile is flagged, no additional DEMs are created.

It is important to note that the DEM production software employs the encoding scheme when determining whether or not to create secondary and tertiary DEMs. If the encoded difference is greater than 5500 m, then the next level DEM is created. If the encoding scheme is not used in the decision process for the production of higher resolution DEM products, it is possible that secondary and tertiary DEMs would not be generated for some tiles whose actual range window does not exceed the range window limit, but whose encoded range window does exceed the limit.

Additional functionality has been developed to accommodate the creation of the DEM from GMTED maximum and minimum elevation products. This dedicated function accepts the specific data structure that contains both maximum and minimum elevation grids to calculate the maximum and minimum heights for the onboard DEM, in addition to the inputs for latitude, longitude, overlap, and vegetation. For a given area, the DEM values are taken to be the highest elevation seen in the maximum elevation layer (plus vegetation height, if applicable) and the lowest elevation seen in the minimum elevation layer (minus vegetation height, if applicable). Using the GMTED maximum and minimum layers in place of the mean elevation layer when calculating the DEM mitigates the effects of the generalization performed during GMTED's development.

3.2.2 Polar Stereographic Methodology

A separate methodology was required for the generation of the onboard DEM in the polar regions. This is primarily due to the fact that the procedure previously described to create the DEM is not applicable when the length of a degree of longitude approaches zero meters. In addition, the development of a polar region methodology allows for the creation of a DEM without requiring a conversion, specifically for Antarctica, from polar stereographic south projection to another projection. Also advantageous is the fact that the method allows the use of multiple data sets in one area, without requiring the data sets to be mosaicked into a single product. In the future, as new regional data sets may become available in Antarctica, the existing DEM in Antarctica could be easily augmented with additional elevation data. The example presented subsequently for this alternative method developed for DEM production is specific to an input data set using polar stereographic south projection and with the elevations vertically referenced to the WGS84 ellipsoid.

The polar stereographic method of generating the DEM can be thought of as the reverse of the approach used for the geographic projection – instead of searching for the points which fall within a particular area to get the DEM, each elevation point is individually placed into a histogram associated with its location. Elevation histograms are accumulated for the entire continent, and the DEM for each tile is produced from a histogram of elevation.

The first step in producing the DEM is to initialize empty histograms for each desired DEM tile. For the DEM over Antarctica, empty histograms are created for every 1°x1° tile from 180° W to 180° E and 90° S to 60° S. Secondary and tertiary DEMs can be disregarded in Antarctica as the total range of elevation values in the region is less than 5500 m. For each cell in the input data grid, the easting and northing coordinates associated with that cell are converted to latitude and longitude values. The latitude and longitude are then used to find the histogram associated with that coordinate, and the elevation value is added to the histogram. For example, at the coordinate (35500 m E, 366500 m N), the elevation is 2686 m. Converting the polar stereographic coordinate to latitude and longitude, the point is located at (5.5325E, 86.6120S). At this point, knowing the latitude and longitude, the elevation value (2686) can be added to the elevation histogram associated with (5E, 87S).

To account for the 2 km overlap required for the DEM, each coordinate is also tested to see if it comes within 2 km of any of the neighboring tiles. If the distance between the coordinate's location and one or more edges of the 1°x1° tile is found to be less than 2 km, the elevation value is also added to the histograms associated with the appropriate neighboring tiles. The distance calculations are accomplished using the Haversine formula, which provides the great-circle distance, d, between any two values of latitude (ϕ_1, ϕ_2) and longitude (λ_1, λ_2):

$$\Delta_\lambda = \lambda_1 - \lambda_2 \tag{8}$$

$$\Delta_\phi = \phi_1 - \phi_2 \tag{9}$$

$$a = \sin^2\left(\frac{\Delta_\phi}{2}\right) + \cos(\phi_1) * \cos(\phi_2) * \sin^2\left(\frac{\Delta_\lambda}{2}\right) \tag{10}$$

$$c = 2 * \text{atan2}\left(\frac{\sqrt{a}}{\sqrt{1-a}}\right) \tag{11}$$

$$d = R_{Earth} * c \tag{12}$$

The previous coordinate P_c = (5.5235° E, 86.6120° S) would be compared to the following coordinates to find the 2 km overlap for the DEM:

P_1 = (5.5235° E, 86.0° S)

P_2 = (5.5235° E, 87.0° S)

P_3 = (5.0° E, 86.6120° S)

P_4 = (6.0° E, 86.6120° S)

If, for example, the distance, d_4, between P_c and the point to the east, P_4, was less than 2 km, the elevation would be added to the elevation histogram associated with the tile to the east at (6° E, 87° S) in addition to its "native" histogram at (5° E, 87° S). If the point fell within 2 km of both the north and east sides of the tile, the value would be added to 3 histograms in total – one each for the north, east, and northeast neighbors of the native tile.

This process can be repeated for multiple elevation models at varied resolutions without having to mosaic the different models together or account for differences in resolution or projection. To produce a DEM using both Bedmap2 and the Antarctica Peninsula DEM, the histograms are first filled with elevations from Bedmap2. Then, elevations from the Antarctic Peninsula DEM are added to the elevation histograms produced from Bedmap2. If another data set was to be included, elevations from all three data sets would be placed into the same set of elevation histograms before processing the DEM. Similarly, individual peak elevations could be added to the histograms to ensure that the output DEM encompasses the full range of surface elevations.

After every elevation value has been added to the appropriate histograms, the DEM values can be pulled from those histograms. For the DEM, the minimum and maximum values are pulled from each histogram, encoded, and saved. The encoded range difference is still tested to ensure the range window is less than 5500 m, although it is not expected that any primary tiles would exceed the limit and require secondary or tertiary DEMs. However, if it is deemed necessary to produce lower-level DEMs, the same process can be performed with 0.25°x0.25° or 0.05°x0.05° histograms.

3.2.3 Vegetation Height Map

Vegetation heights can be inserted into the DEM by generating a vegetation height map and including it in the inputs to the DEM functions. Simard's Global Canopy Height model is used to create a vegetation height map for inclusion in the DEM. Several options exist for defining the vegetation height map: maximum vegetation height, some nth percentile vegetation height, or mean vegetation height. The receiver algorithm team has selected the maximum vegetation height as the metric used to construct the vegetation height model in order to be as inclusive as possible in defining the DEM.

The vegetation height model is constructed in much the same way as the DEM itself, except that only the maximum value is found and a full global vegetation map with a 2 km overlap is constructed at each tier's resolution. The variable that is input into the DEM functions is a data structure containing global maps of maximum vegetation height at resolutions of 1°x1°, 0.25°x0.25°, and 0.05°x0.05°. Because the vegetation height map is tiered in the same manner as the DEM, it is possible that the maximum elevation seen in a primary (or secondary) tile will not match the maximum elevation seen over all 16 secondary (or 25 tertiary) tiles in the same area. The same holds true for minimum elevations. This results from differences in the spatial distribution of elevation and vegetation heights. The maximum elevation in the primary DEM will only match the maximum secondary DEM elevation if the maximum elevation and the highest vegetation height are located in the same secondary DEM tile.

3.3 DEM EXAMPLES

For the 1°x1° tile located at (10° E, 0° N), the DEM would be generated from all elevations shown in Figure 6. The blue and red stars indicate the approximate locations of the maximum and minimum elevations, respectively.

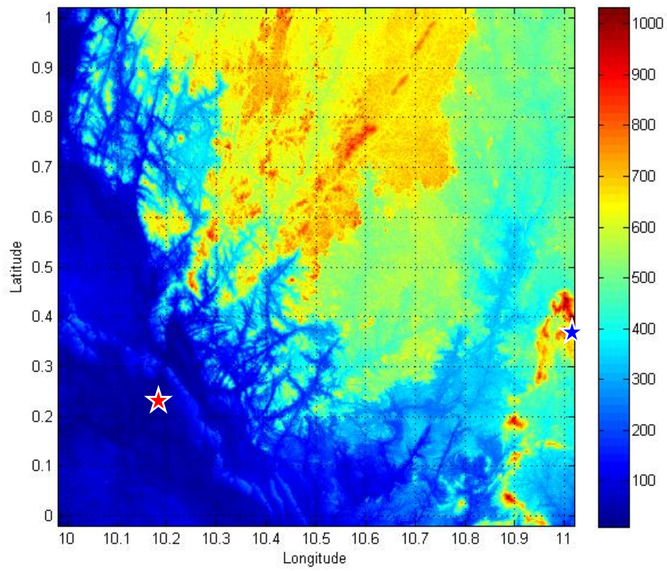


Figure 6: Image showing all elevations used to calculate a DEM tile at 0° N 10° E. Approximate locations of maximum and minimum elevations are marked by blue and red stars, respectively.

To account for the 2 km overlap, a 23-cell-wide band has been added on all four sides of the 1°x1° area. The resulting output for the area is:

```
Level    Latitude    Longitude    MaxE_Act    MinE_Act    …
1        0           10           1033        10          …
         …  MaxE_Enc    MinE_ Enc    Flag    Max_Source    Min_Source
         …  32          10           0       1             1
```

The level field describes whether the line in the file is for the primary (1), secondary (2), or tertiary (3) DEM. Longitude and latitude are given for the south west corner of the tile. Both the actual and encoded values of elevation are provided; actual elevation values are given in units of meters above the WGS84 ellipsoid. The flag field indicates whether the tile has (1) or has not (0) exceeded the encoded range window limit.

Finally, the source fields indicate the input data sets that were used to get maximum and minimum elevations for the tile. The source codes are shown in Table 2.

Table 2: Codes used to denote the elevation source used to produce an individual tile in the DEM

Source	Flag Number
SRTM-CGIAR	1
GMTED	2
CDED	3
GIMP	4
Bedmap2+ASTER 100m DEM	5
Bedmap2	6
EGM2008 Geoid	7

Chapter 4: DRM Generation

A general description of the development and production of the DRM database is presented in this section.

4.1 REQUIREMENTS

Requirements for the onboard DRM database flow down from specifications imposed on the receiver algorithm by the operational requirements of the ATLAS instrument and flight software. These requirements are summarized below:

- The DRM must provide values of relief along all possible 140 m and 700 m flight path segments consistent with a 92° orbit.
- The DRM must provide global coverage at a resolution of 0.25°x0.25°.
- Each tile in the DRM must include a 2 km border beyond the 0.25°x0.25° perimeter.
- Tiles in the DRM are to be referenced by the geodetic latitude and longitude of the southwest corner of the specific 0.25°x0.25° region.

4.2 CALCULATING RELIEF

Before exploring how the ICESat-2 onboard DRM is generated, it is first important to understand how relief is defined in this context and how the relief is calculated from elevation models. For the purposes of the ATLAS receiver algorithm, relief is defined as the maximum elevation *difference* seen across a flight path segment. The requirements on the database dictate that the DRM must provide the relief in a given region at the specific length scales of 140 m and 700 m, which correspond to the major frames and super frames within the receiver algorithm processing scheme. Relief is calculated from the input elevation models by evaluating every possible 140 m and 700 m flight path segment feasible for each coordinate location in the input data set and choosing the maximum difference of elevation among all flight segments included for a given length scale. Although calculating the difference between two elevations is not a difficult operation, defining flight paths relative to a gridded elevation product along which elevations can be compared required some additional effort as the flight path length and orientation varies according to map resolution and projection and the location of a specific flight path segment. A series of fly-over combinations were defined based on the resolution of an input data set and orientation of the flight path such that comparing elevations defined by coordinates in the fly-over combinations provided values of relief. The following discussion of how relief is calculated from a gridded data set is accompanied by examples using a 90 m resolution data set. Similar procedures are followed for data sets of different resolutions.

4.2.1 Fly-Over Combinations

In Figure 7 below, the dotted lines represent the borders of individual 90 m cells of elevation data in an input DEM grid. In this discussion, a cell refers to an individual value in a larger grid of elevations that is associated with a single value of latitude and longitude. A cell is analogous to a pixel of data in an image. The red lines represent possible ascending 140 m flight path segments centered on the "target cell," outlined in black. In this case, the target cell is a boxed area centered at a coordinate specified by the input DEM and is the size equivalent of the resolution of the input DEM. By comparing the elevations in all cells occurring under each possible flight path segment, the maximum relief can be calculated and assigned as the relief value for that particular target cell. Any flight path segments centered outside of the target cell are not considered during the relief comparisons for the aforementioned target, but will contribute to the analysis of neighboring cells.

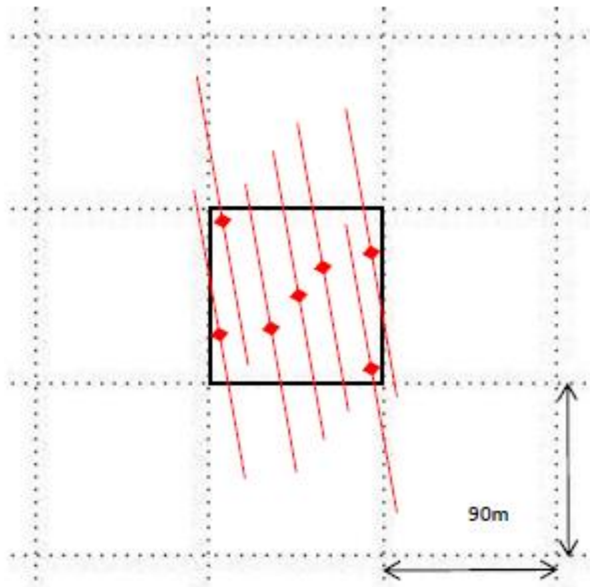


Figure 7: A 140 m flight path segment can take one of several possible paths through a target cell. Relief is calculated by comparing the elevation values in cell touched by a flight path segment. Only flight paths centered within the target cell (outlined in black) are considered in the calculation of relief for the target cell.

In order to systematically calculate relief from the input elevation data, relevant fly-over combinations have been defined to represent all possible flight path segments through a given target cell. These configurations allow for the calculation of maximum relief at a specific point (cell) within the input data set. A single relief measurement is the absolute difference between the elevations associated with any two cells that are touched by the same flight path segment. For the example shown in Figure 7 of a 140 m ascending flight path segment over a 90 m resolution input DEM, the satellite could pass over any of the following configurations of cells shown in Figure 8 during one pass:

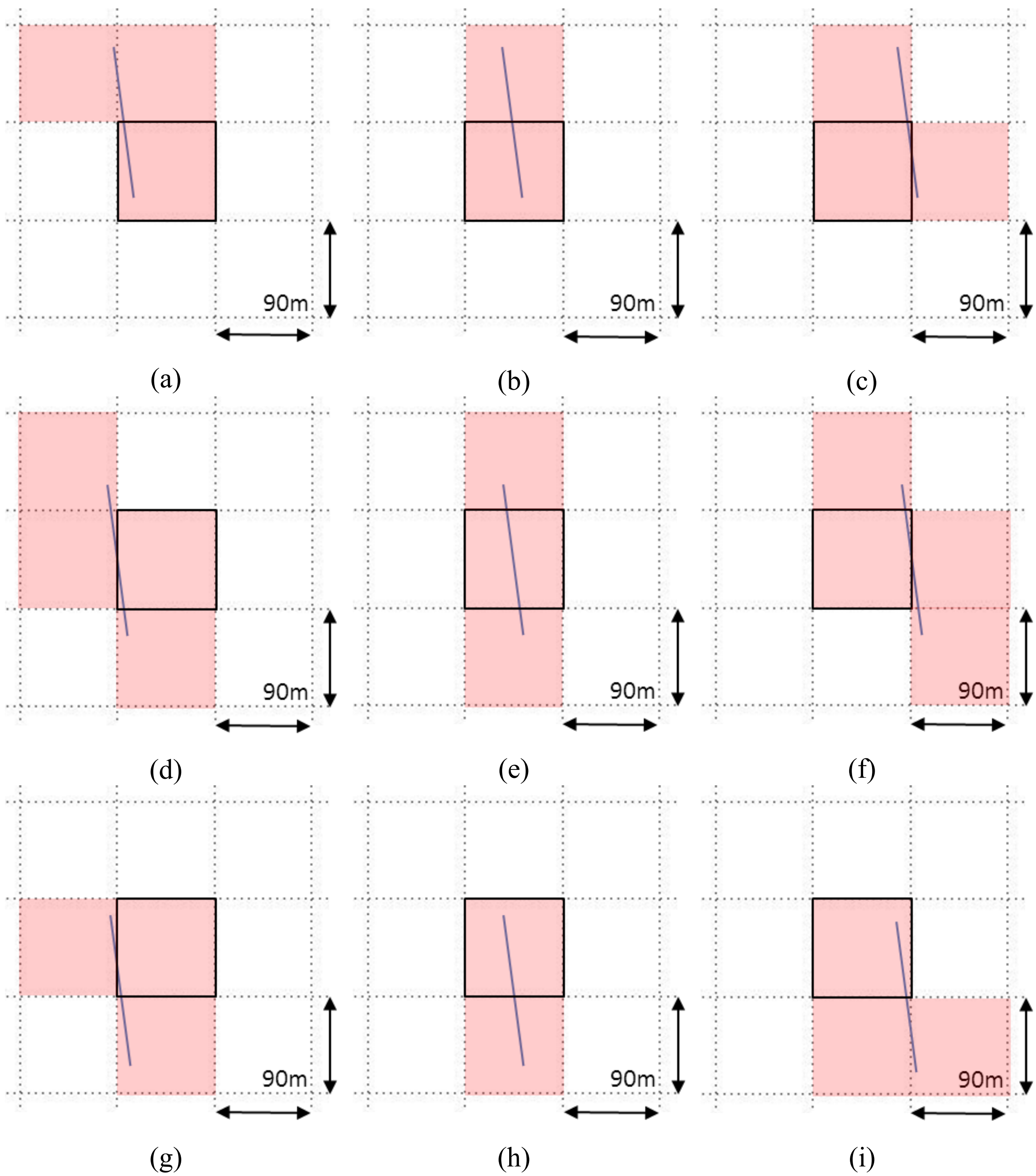


Figure 8: An ascending 140 m flight path segment could touch any of 9 combinations of cells when passing through a target cell in a 90 m resolution DEM.

For a descending flight path, the possible flight segment locations with respect to the input data are mirrored across the vertical axis, as shown in Figure 9:

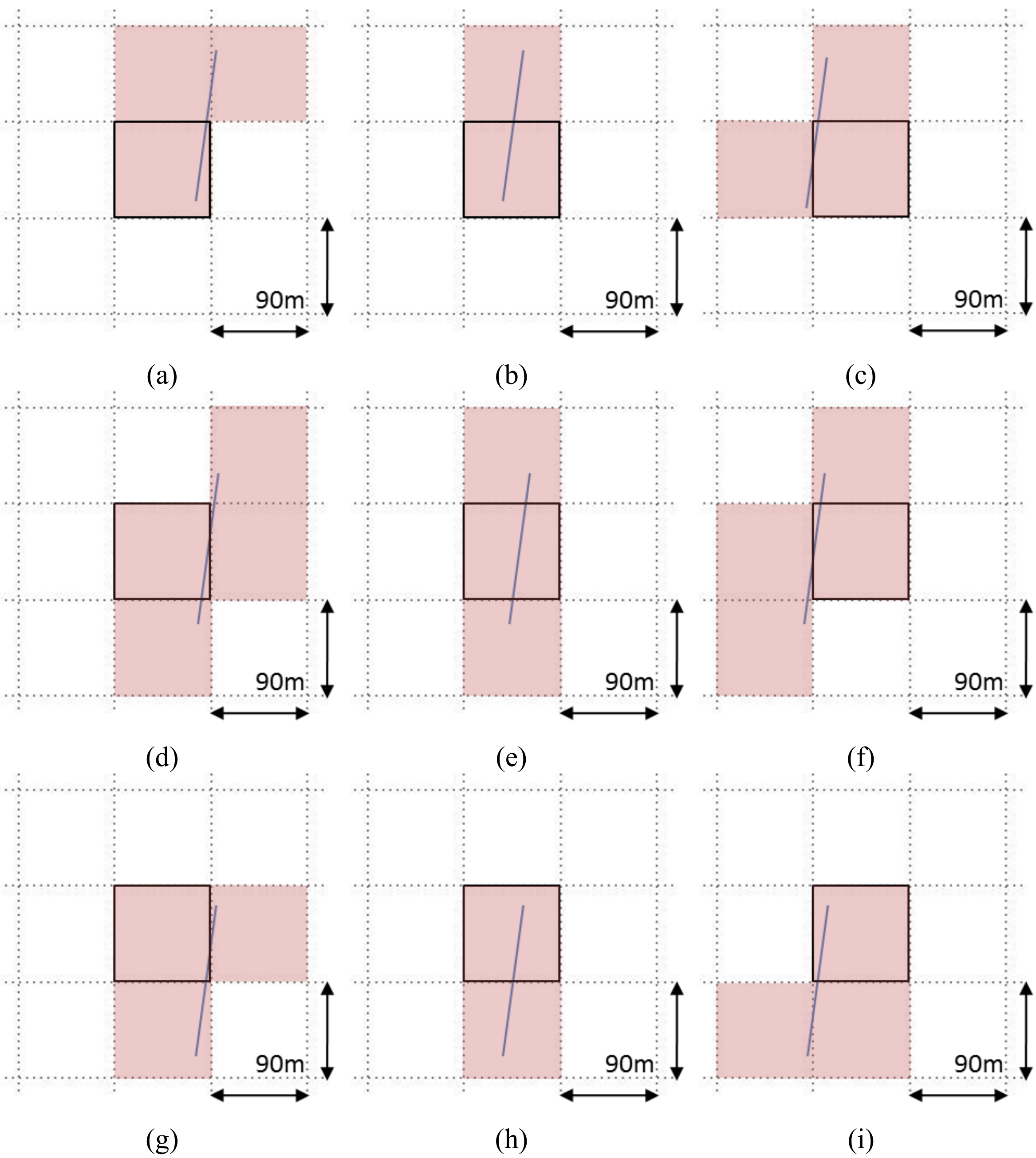


Figure 9: A descending 140 m flight path segment could touch any of 9 combinations of cells when passing through a target cell in a 90 m resolution DEM.

In order to represent the fly-over combinations within the software for relief calculations, each of the nine cells in the figure are first assigned a numerical index and a coordinate difference from the target cell as shown in Figure 10:

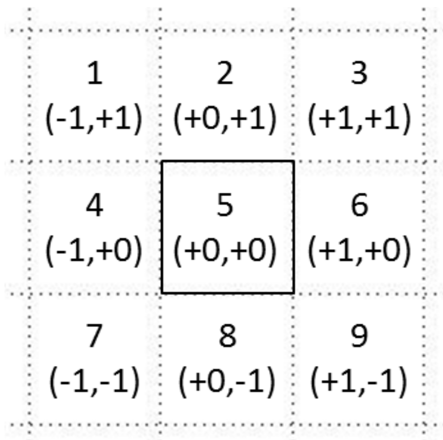


Figure 10: Each cell used to calculate relief for the target cell is assigned an index number. The location of each of the 9 cells used to calculate relief is defined in coordinates relative to the target cell.

The values in the coordinate differences assigned to each of the 9 cells is used to index into the larger grid to get neighboring elevation values in order to calculate relief. For each of the possible flight path segments, the coordinates of every pair of cells touched by a single flight path segment are recorded; the list of coordinate comparisons make up the fly-over combinations needed to calculate relief for that target cell. To represent relief across both ascending and descending 140 m flight path segments (Figure 8 and Figure 9), there are 25 pairs of coordinate comparisons in the associated fly-over combinations set, a subset of which is shown below in Table 3:

Table 3: A subset of the coordinate comparisons used to calculate relief along a 140 m flight path segment in a 90 m input DEM.

Point 1			Point 2		
Index No.	X Difference from Target Cell	Y Difference from Target Cell	Index No.	X Difference from Target Cell	Y Difference from Target Cell
1	-1	+1	2	0	+1
1	-1	+1	4	-1	0
1	-1	+1	5	0	0
⋮	⋮	⋮	⋮	⋮	⋮
7	-1	-1	8	0	-1
8	0	-1	9	+1	-1

To calculate relief for a target cell, the relief is initially set to zero, and relief for each coordinate pair is computed. As a relief value is calculated for a coordinate pair, it is compared to the current value of relief for the target cell. If the new value is greater than the current value, the current value is replaced with the new value, otherwise the calculation continues to the next coordinate pair. In this way, the largest value of relief calculated among all possible flight path segments is recorded as the final relief value for the target cell under evaluation.

It is important to note that the orientation of a non-polar flight path with respect to an input DEM coordinates is not constant throughout the orbit as it changes according to its location within the map. Additionally, the relevant fly-over combinations determined through this process have proven to be dependent on the resolution of the input DEM and desired length of the flight path segment. For these reasons, fly-over combination sets have been generated for both 140 m and 700 m flight path segments, at every possible orientation of the flight path relative to the input DEM coordinates, for ascending and descending track segments, and for all resolutions used by the selected data sources.

4.2.2 Flight Path Orientation

The fly-over combinations are defined by the orientation of the flight path with respect to the coordinate system of the input DEM. For a given input DEM, the appropriate fly-over combinations for a particular cell are selected by finding the orientation of the flight path through that cell relative to the horizontal axis of the coordinate system. This angle is defined as the flight path orientation angle (FPO). For a DEM using a geographic projection, the orientation of the flight path represented in the latitude and longitude coordinate system would be compared to a line of latitude, which is the ”horizontal axis” of the input DEM. This orientation concept is illustrated in Figure 11. Note that the flight path orientation angle is always measured as an acute angle; two flight paths, one oriented at 45° to the positive x-axis and one oriented at 135° from the positive x-axis (and thus 45° from the negative x-axis) would be said to have the same flight path orientation.

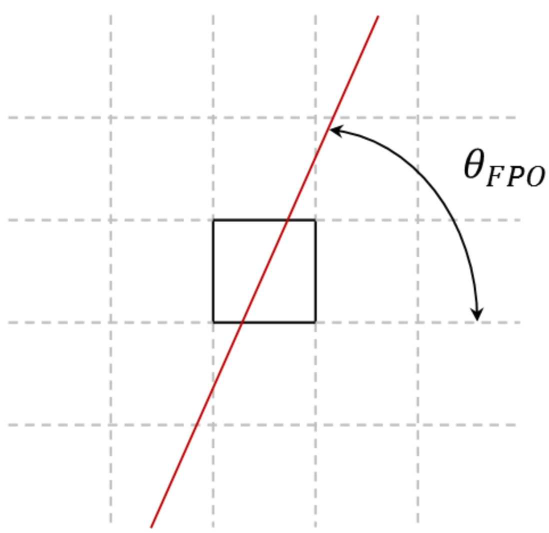


Figure 11: Flight path orientation (FPO) angle is found by comparing the orientation of a flight path through a cell to the horizontal axis of the coordinate system used by the input DEM. FPO angle is always ≤90°.

4.2.3 Flight Path Orientation Zones

The possible values of flight path orientation, θ_{FPO}, can be divided into zones based on the fly-over combinations defined for each orientation considered. Since many of the possible fly-over combinations are the same for certain values of θ_{FPO}, each orientation zone is defined for certain values of angles for which the fly-over combinations are the same. The number of zones and the fly-over combinations associated with those zones vary depending on the input DEM resolution.

As an example of this process, for a 90 m input DEM, there are 3 FPO zones for fly-over combinations used in the 140 m flight segment relief calculation and 13 FPO zones for 700 m relief combinations. The FPO zones and the values of θ_{FPO} associated with each zone for a 90 m input DEM are shown in Table 4. These combinations are defined independent of a particular projection, and can be used to select FPO zones for any input elevation grid with a 90 m resolution.

Table 4: FPO zones defined for 140 m and 700 m relief in a 90 m input DEM

DRM-140 Zone	DRM-700 Zone	θ_{FPO} Range
140-1	700-1	$83° \leq \theta_{FPO} \leq 90°$
	700-2	$76° \leq \theta_{FPO} < 83°$
	700-3	$68° \leq \theta_{FPO} < 76°$
	700-4	$64° \leq \theta_{FPO} < 68°$
	700-5	$60° \leq \theta_{FPO} \leq 64°$
	700-6	$50° \leq \theta_{FPO} < 60°$
140-2	700-7	$40° \leq \theta_{FPO} < 50°$
140-3	700-8	$30° \leq \theta_{FPO} < 40°$
	700-9	$26° \leq \theta_{FPO} \leq 30°$
	700-10	$22° \leq \theta_{FPO} < 26°$
	700-11	$14° \leq \theta_{FPO} < 22°$
	700-12	$7° \leq \theta_{FPO} < 14°$
	700-13	$0° \leq \theta_{FPO} < 7°$

When calculating relief for a particular cell, the flight path orientation angle of the ground track through that cell is found and then used to select the appropriate fly-over combinations with which to calculate relief. The establishment of this process provides an automated, systematic approach to calculating DRM values regardless of location or input DEM resolution.

4.3 Relief Map Generation

The fly-over combinations are used to calculate relief for each individual cell in an input DEM in order to produce maps of relief. DRM tiles are then generated from relief maps in much the same way as the DEM is generated from maps of elevations. Three separate methods of calculating relief have been developed, one for the mid-latitudes (between 60° N/S), one for the high-latitudes (beyond 60° N/S), and another for Antarctica. Relief maps in the mid-latitudes are computed from elevation models in geographic projections. At high-latitudes, polar stereographically projected elevation data is used in placed of geographic maps to mitigate the effects of map distortion on the relief calculations. The additional method for Antarctica is necessary due to the decreased resolution of the data set used as the elevation source.

4.3.1 Mid-Latitude method for Relief Map generation

Between 60° N/S, the relief maps are produced using geographically projected SRTM-CGIAR elevation data. In a geographic projection, the orientations of the flight paths associated with the orbit of ICESat-2 are purely a function of latitude. The geometry of this concept can be illustrated by looking at a ground track map for a low-eccentricity orbit. Figure 12 shows a sample ground track map for a nearly circular 82° orbit, and it can be seen that the orientation of the flight path is constant along any parallel of latitude.

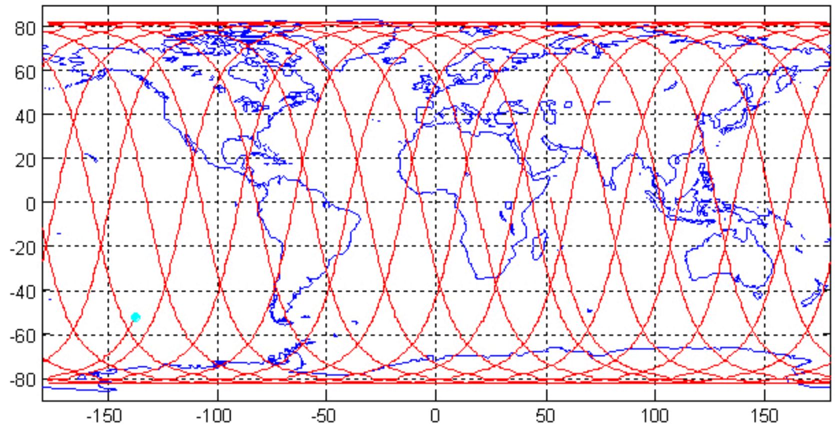


Figure 12: FPO angle for ground tracks of a nearly-circular orbit plotted in a geographic projection is purely a function of latitude

The value of θ_{FPO} will be the same along any value of latitude between 60° N and 60° S, regardless of the value of longitude. The set of fly-over combinations used to calculate the relief map for a given region among the mid-latitudes is then selected by finding the FPO zone associated with the latitude of the region.

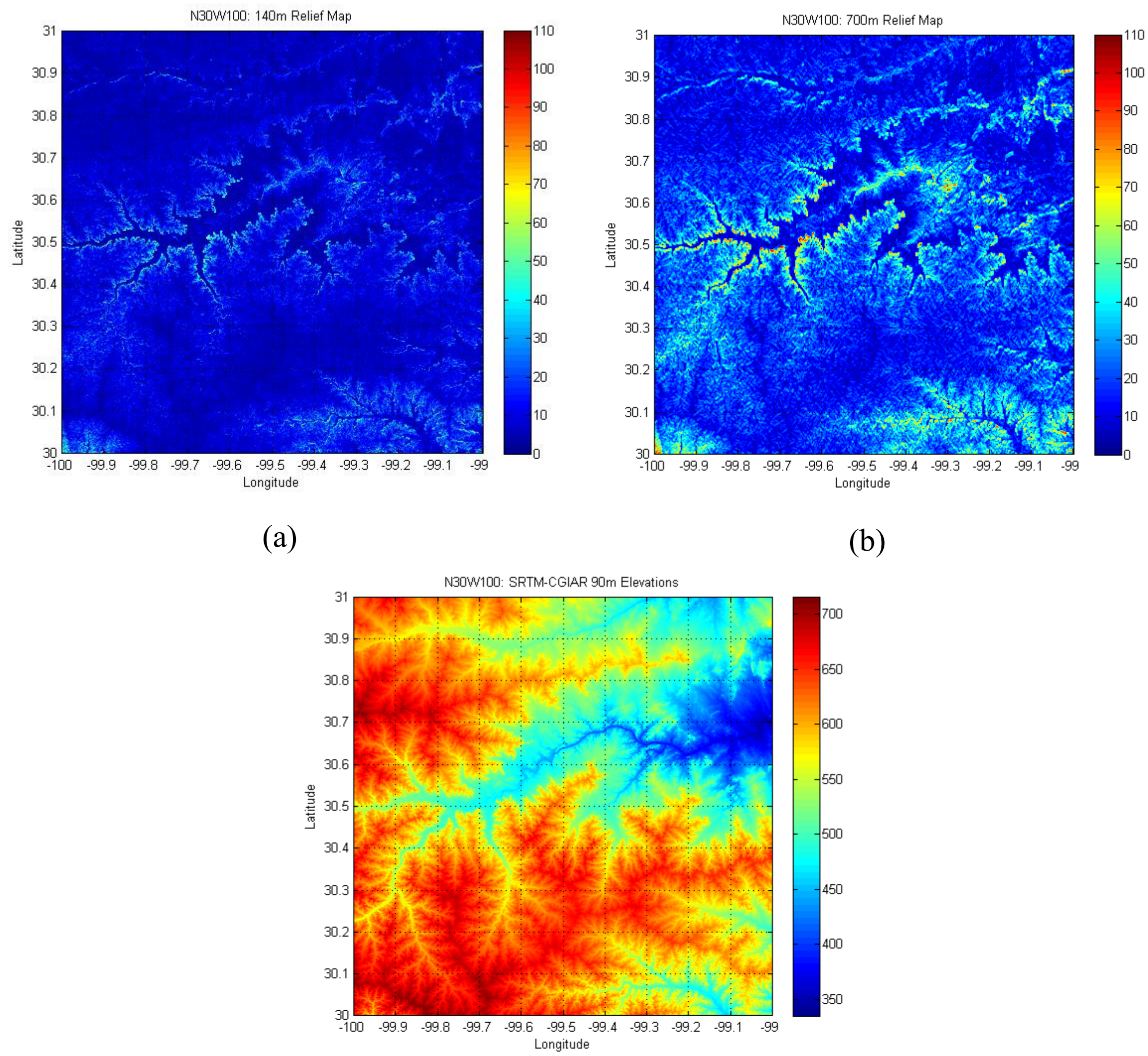
For a 92° orbit, the flight path orientation angle between 60° N/S is always greater than 78°. Looking at the FPO zones in Table 4, it can be seen that only the Zone 140-1 combinations are needed to calculate relief between 60N/S. For the 700 m relief map, fly-over combinations for two zones are applicable – Zone 700-1 between 41° N/S and Zone 700-2 between 41° N/S and 60° N/S.

Table 5: FPO Zone Selection by latitude between 60° N/S

Latitude	DRM-140 Zone	DRM-700 Zone
$0° \leq \phi < 41°$	140-1	700-1
$41° \leq \phi \leq 60°$	140-1	700-2

A relief map for a given area is produced using a grid of input elevation data and methodically selecting the appropriate fly-over combinations based on the latitude of the region and the corresponding FPO zone from the list in Table 5. Relief along both 140 m and 700 m segments is calculated for each DEM grid coordinate as described in Section 4.2, and recorded to a grid of relief values. Note that relief can only be calculated for some of the coordinates within a given grid – those points near the boundary of an input grid will not have enough neighboring cells to properly calculate relief. For 140 m relief this restriction means that it is not possible to calculate relief for those cells in the first and last row or column of an input elevation grid. For 700 m relief, it is not possible to calculate relief for the first four or last four rows or columns of an input elevation grid.

Examples of the relief maps generated for 140 m and 700 m flight path segments are shown below in Figure 13a and Figure 13b. In addition, Figure 13c also provides a look at the input elevation data used for the generation of the relief maps. These maps have a resolution equal to that of the input data product, or 90 m in the case of Figure 13c, and show the maximum relief across each individual target cell. These relief maps are intermediate products and are saved for later used in the generation of DRM tiles.



(a) (b) (c)

Figure 13: Example of relief maps calculated for (a) 140 m flight path segments and (b) 700 m flight path segments using (c) 90 m SRTM-CGIAR as the input DEM [8]

4.3.2 High-Latitude method for Relief Map generation

Beyond 60° N/S, a different approach is taken to generating relief maps. The need for this arises from the increased distortion exhibited by geographic projections as latitude increases. The distortion causes the longitudinal length of a cell in meters to decrease with the cosine of the latitude from its nominal resolution at the equator to 0 m at the poles. Since the previous approach to calculating relief maps relies on a constant cell resolution, a different approach was warranted.

In the mid-latitudes, the effects of map distortion on cell resolution in a geographic projection can be largely ignored for the purposes of calculating relief. The motion of the satellite between 60° N/S is primarily latitudinal, and any distortion experienced affects the cell only in the longitudinal direction. In the higher latitudes, however, the longitudinal distortion becomes increasingly problematic as the satellite begins to travel horizontally with respect to the geographic projection. Using the same method as in the mid-latitudes, the combinations would represent flight path segments considerably shorter than the required 140 m and 700 m lengths, and the DRM could potentially underestimate the actual relief by considerable amounts. In order to get realistic 140 m and 700 m relief values beyond 60° N/S, polar stereographic projections of elevation data are used in place of geographic projections to mitigate the possible issues associated with cell distortion and allow for better calculation of relief near the poles. However, flight paths plotted in a stereographic projection do not have a uniform orientation with respect to northing or easting coordinates as they do with latitude in a geographic projection. Instead, the flight path orientation depends on both the easting and northing coordinates of any given cell. This is illustrated in Figure 14, where a subset of ICESat ground tracks has been plotted over a polar stereographic projection of Greenland.

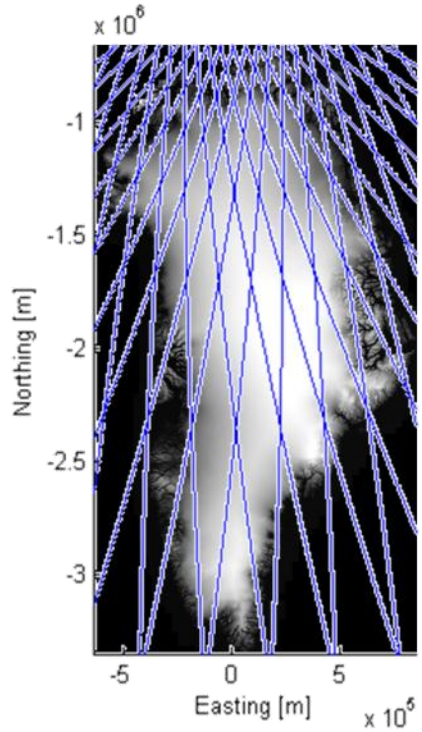


Figure 14: A subset of possible ICESat-2 ground tracks are plotted over a polar stereographic projection of Greenland [19]

The intersections of the flight paths in Figure 14 illustrate that the ascending and descending tracks through any given point can have different flight path orientation angles. Because of this, the relief must be calculated using two sets of fly-over combinations, one each for the ascending and descending values of θ_{FPO}. The relief for any cell is then determined to be the maximum value of relief calculated across both sets of fly-over combinations.

As the flight path orientation angles change relative to easting and northing coordinates, maps of the fly-over zones are generated for use in selecting the fly-over combinations. Reference ground tracks associated with the planned ICESat-2 orbit [20] are used to generate the zone maps. To find the orientation for any given easting/northing coordinate pair, ascending and descending reference ground tracks are translated such that they pass through the cell. The orientation of each translated track in easting and northing coordinates is found, and used to select the appropriate FPO zone from a table (as in Table 4). The FPO zone maps are saved and used to select the fly-over combinations when calculating relief. Examples of FPO zone maps can be seen below in Figure 15. The map on the right shows the FPO zone map associated with 140 m ascending flight paths and the map on the left shows the FPO zone map associated with 700 m ascending flight paths. Both maps are generated at a resolution of 90 m for an input data set with the same resolution. Both the FPO zones and the FPO zone maps change when the resolution of the input data set changes. For a descending path, the images are mirrored across the y-axis.

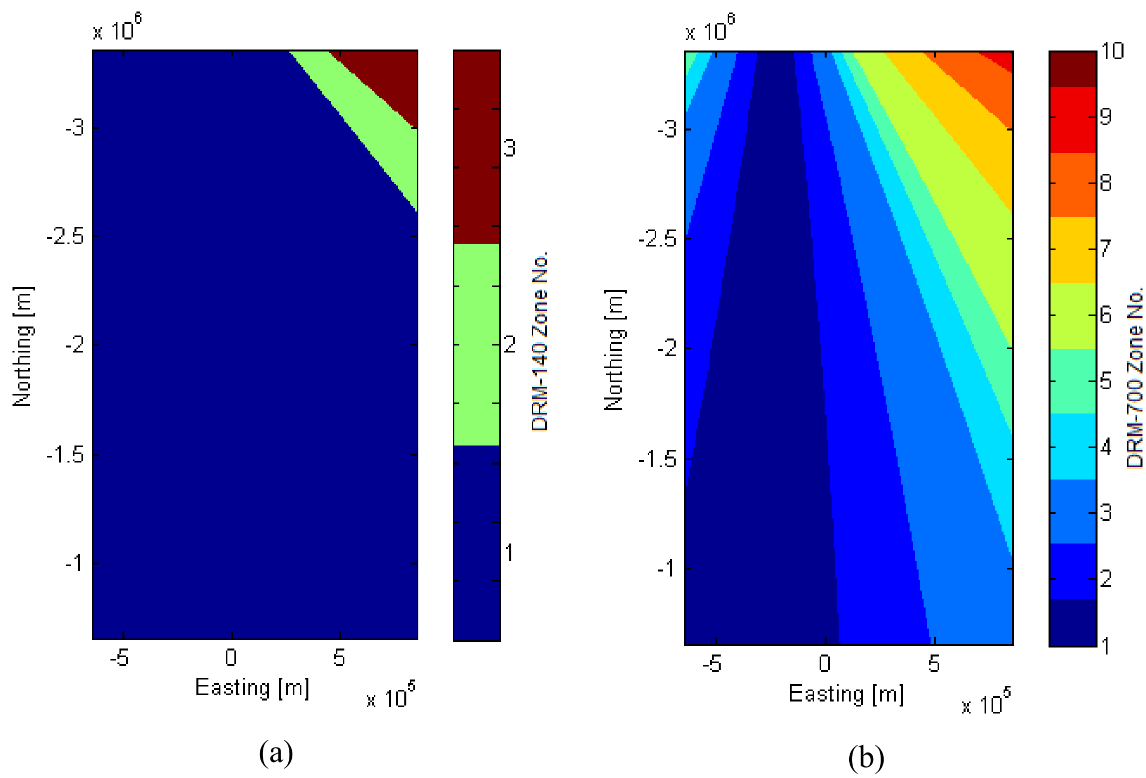
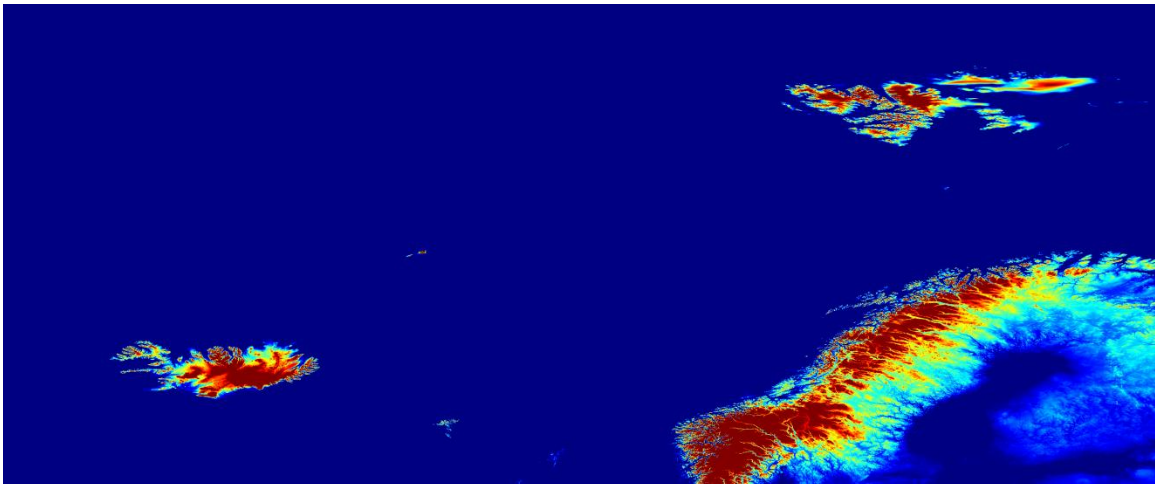


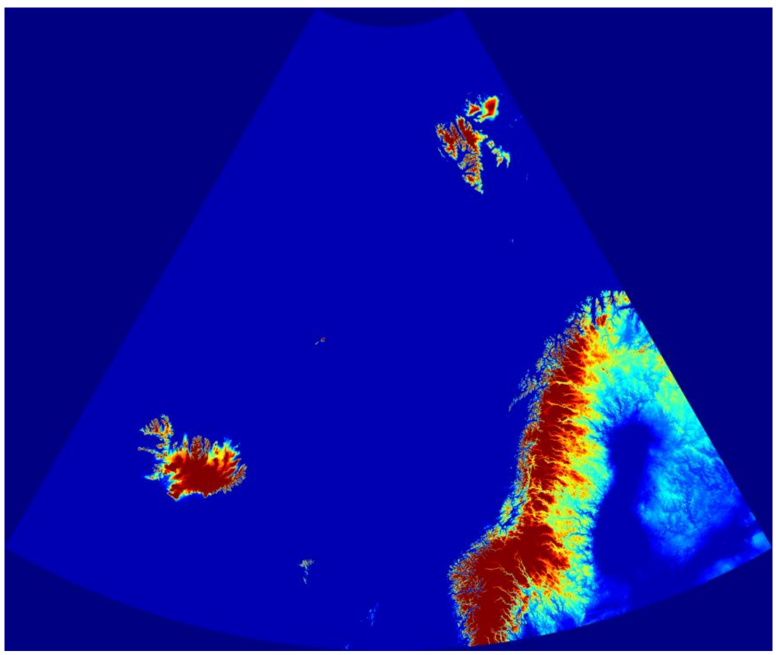
Figure 15: FPO Zone maps generated for the stereographic north map of Greenland for calculating (a) 140 m relief and (b) 700 m relief

In the mid-latitudes, the fly-over combinations encompass all cell comparisons necessary to represent the relief seen across both ascending and descending paths through the cell. This is possible because the flight path orientation of a ground track in a geographic projection is independent of whether the satellite is ascending or descending in its orbit. Since this independence is not the case for data using a stereographic projection, the fly-over combinations used for the high-latitudes only contain those cell comparisons that represent the relief for an ascending ground track. In order to get the descending fly-over combinations, the coordinates are reflected across the y-axis, i.e. the signs of the x-coordinates of the coordinate pairs in the fly-over combination are reversed.

In some cases, the input elevation data is not provided in polar stereographic projection and must be converted from geographic projection before the relief map can be generated. This is the case for elevation sources such as GMTED and CDED [9] [18]. Using ENVI, the original data set is re-projected from geographic to polar stereographic, as shown in Figure 16.



(a)

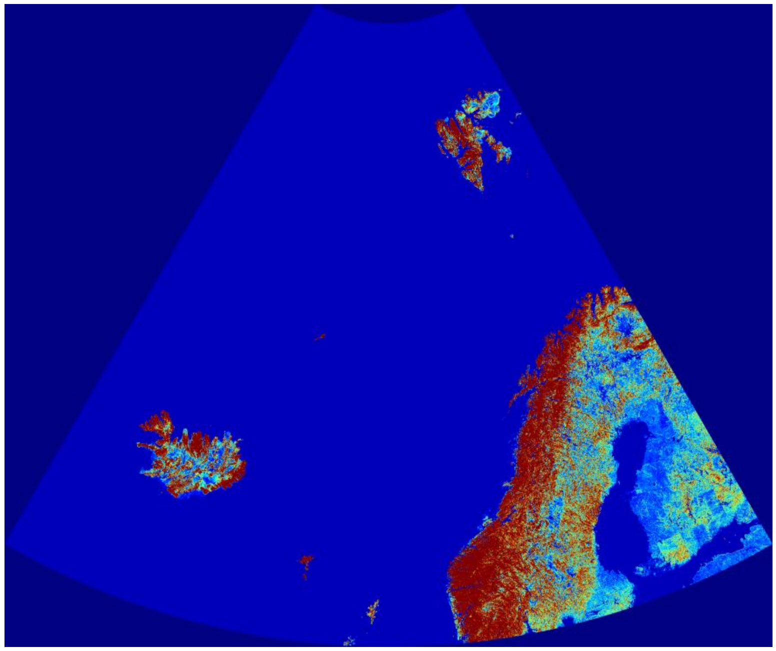


(b)

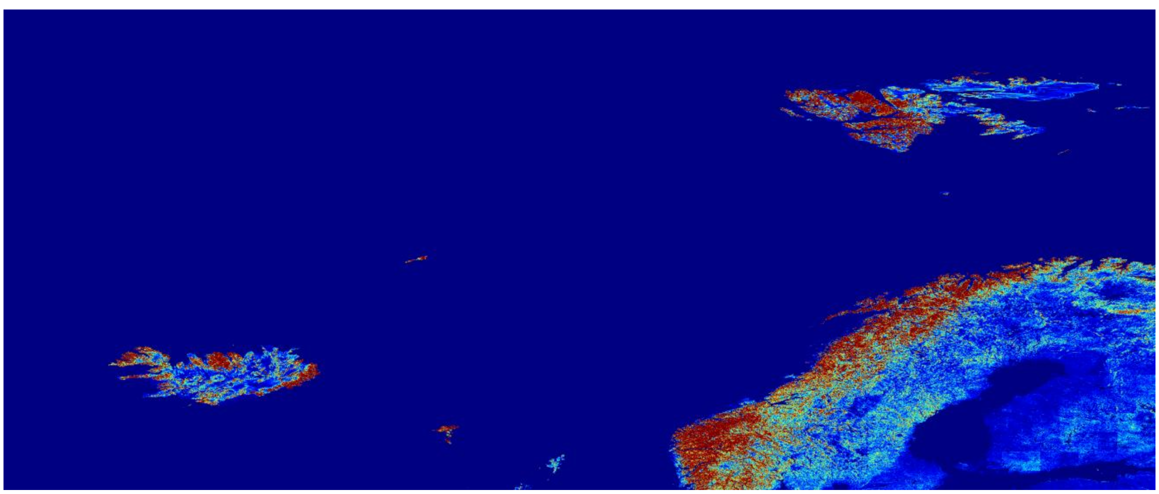
Figure 16: Data sets distributed in a geographic projection (a) that are used to produce the DRMs north of 60° N must be converted to polar stereographic north projections (b) before generating relief maps [9]

The relief at high latitudes is calculated in much the same way as in the mid-latitudes. At each point in the grid, the FPO zone maps are used to select sets of 140 m and 700 m fly-over combinations for both ascending and descending tracks. For each flight path segment length, the relief value for a target cell is the maximum value of relief seen across both the ascending and descending fly-over combination sets. The relief values are saved to relief grids at the same resolution as the input data set. As with the mid-latitudes, relief cannot be properly calculated for the cells along the border of the map as there are not enough neighboring cells to perform the full set of elevation comparisons.

The final step in producing the high-latitude relief maps is to re-project the relief map from polar stereographic to geographic so that the DRM can be consistently constructed. Figure 17a shows a stereographic 700 m relief map generated for a region including Scandinavia, Iceland, and Svalbard, and Figure 17b shows the geographic 700 m relief map obtained by re-projecting the stereographic map. Both maps have a resolution of 250 m, identical to the resolution of the GMTED data set used as an input (shown in Figure 16). The geographic relief map is used as the source for producing the DRM-700 in this region.



(a)



(b)

Figure 17: Relief is calculated from a map of elevations in a polar stereographic projection. The stereographic relief map (a) is re-projected into a geographic projection (b) before generating DRM tiles from the relief data.

This method for producing relief maps can be used from 60° N/S up to 88° N/S, and up to the poles if a manner of determining flight path orientation could be established for the region between 88° N/S and 90° N/S. At present, no method has been devised for this purpose as no land is present north of 84° N (thus the DRM is uniformly zero) and a separate method is in use for producing relief maps of Antarctica at the pole.

4.3.3 Antarctic method for Relief Map generation

Due to the decreased resolution of the Bedmap2 data set compared to the elevation data sets used in the northern hemisphere, the method for producing a relief map in the high latitudes can be simplified specifically for Antarctica. However, the modified method can actually apply to any data set with a resolution greater than 700 m, regardless of projection.

The need for relief map method modification stems from the fact that the resolution of the data set is greater than the length of the flight path segments used in the relief calculation. As such, there exists only one set of fly-over combinations for relief map generation for both ascending and descending tracks and both the 140 m and 700 m flight path segments. This simplicity of fly-over combinations allows for the production of a single relief map over Antarctica and negates the need to establish FPO zone maps. The single set of fly-over combinations is used to calculate relief at every coordinate within the perimeter of the input data set. The single resulting relief map produced from the Bedmap2 data set is shown in Figure 18.

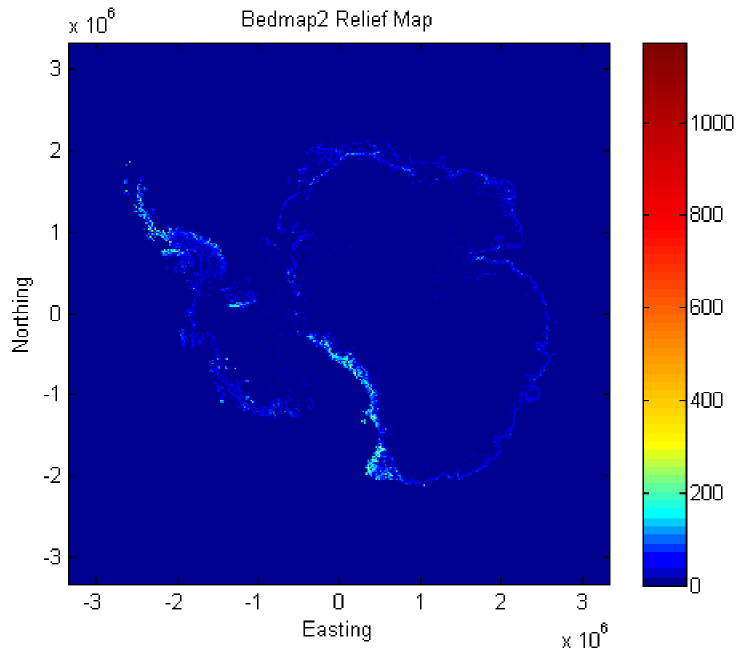


Figure 18: Relief map produced from the 1km resolution Bedmap2 Surface Elevation grid [12]. Only one relief map can be produced when the input DEM resolution is greater than 700 m.

The same approach would be taken if a lower resolution data set were to be used to produce a relief map elsewhere. In the mid-latitudes for example, the fly-over combinations would not change with latitude and there would be a single relief map from which to produce a DRM instead of two relief maps associated with the different flight path segment lengths. In the northern latitudes, an additional step would be required to re-project the data set to geographic projection from stereographic. This is not done in Antarctica as the approach to building the DRM for that region does not require re-projection of the relief map.

4.4 DRM Generation Methodology

As with the DEM, a separate method is used to create the DRM in the polar region from that used for the rest of the globe. The relief maps produced from SRTM are geographically projected, and the relief maps from GMTED and GIMP are re-projected from a polar stereographic grid to a geographic grid prior to DRM processing. The Antarctic relief map is produced in a polar stereographic projection, but the DRM is processed directly from the grid without re-projection.

4.4.1 Geographic Methodology

Between 60° S and 84° N, the relief maps have either been generated in or re-projected to a geographic projection. The DRMs are constructed directly from the relief maps in much the same way as the DEM is pulled from elevation models. Algorithms have been developed in MATLAB for the production of the onboard DRM from the relief maps. These MATLAB functions process a 1°x1° area of relief data at a time, filling in 16 0.25°x0.25° DRM tiles at a time within the specified area.

The algorithm functions require several inputs: a data structure containing 140 m and 700 m relief grids and the values of latitude and longitude associated with the relief values, the latitude and longitude of the 1°x1° tile for which the DRM is being calculated, and a value for the overlap in kilometers.

As with the DEM, MATLAB functions have been created for each input data set resolution. The resolution of the input data set affects how the overlap is calculated for each tile. This overlap is included in the calculation of the individual DRM tiles by adding the extra cells of relief associated with the overlap along the perimeter of the 0.25°x0.25° region before processing the relief for that specific tile. In a geographic projection at mid-latitudes, the latitudinal length of a cell in meters can be considered constant. For a 3 arc-second resolution map (like SRTM-CGIAR), this length is approximately 90 m, and the number of cells within a 2 km latitudinal overlap would be calculated thusly:

$$N_{lat} = ceiling\left(\frac{2000\,meters}{90\,meters}\right) = 23 \tag{13}$$

The longitudinal length of a cell varies with the cosine of the latitude. At the equator, the longitudinal length is equal to the latitudinal length (90 m), and decreases to 0 m at the poles. As an example of how this variation is accommodated, the equation for calculating the number of extra cells, longitudinally, required for a 2 km overlap when the nominal resolution of the map is 90 m is shown below:

$$N_{long}(latitude) = ceiling\left(\frac{2000\,meters}{90\,meters * \cos(latitude)}\right) \tag{14}$$

At 60° N, the number of cells that would be equivalent to 2 km in longitude is:

$$N_{long}(60°) = ceiling\left(\frac{2000\,meters}{90\,meters * \cos(60°)}\right) = ceiling\left(\frac{2000}{45}\right) = 45 \tag{15}$$

The ceiling function is used in the overlap calculations in order to ensure the inclusion of a full 2 km region around the DEM tile. By the same logic, when calculating the longitudinal overlap for a 0.25°x0.25° tile, the largest number of cells determined from calculations both of the north and south borders of the tile For example, a 0.25°x0.25° region located at 70° N would require 65 extra cells along its southern border for the 2 km overlap:

$$N_{long}(70°) = ceiling\left(\frac{2000\,meters}{90\,meters * \cos(60°)}\right) = 65 \tag{16}$$

At its northern border, the same area would require 69 extra cells for the 2 km overlap:

$$N_{long}(70.25°) = ceiling\left(\frac{2000\,meters}{90\,meters * \cos(71°)}\right) = 66 \tag{17}$$

For a tile at this latitude, the grid of cells that comprise the area without an overlap is expanded by 23 cells in the northern and southern directions and 66 cells in the eastern and western directions. Some "extra" relief data is included along the southern edge, which is preferable to excluding relief data along the northern edge by using the smaller of the two N_{long} values.

While the DEM is produced by searching a grid of elevation data for the maximum and minimum values, the DRM is produced by sorting all the relief values associated with a given area into an ordered list, and finding the value of relief at several percentiles of the resulting histogram. For both the DRM-140 and the DRM-700, values of relief at the 95th, 96th, 97th, 98th, 99th, and 100th percentiles of the histograms for each 0.25°x0.25° tile are calculated and output along with the latitude and longitude of the tile. An example histogram of 140 m relief for the DRM tile located at (-100° E, 30° N) is shown in Figure 19. The 0.25°x0.25° relief map used to generate this histogram is a subset of the relief map shown in Figure 13a. Also marked in the figure are the values of relief at the 95th-99th percentiles.

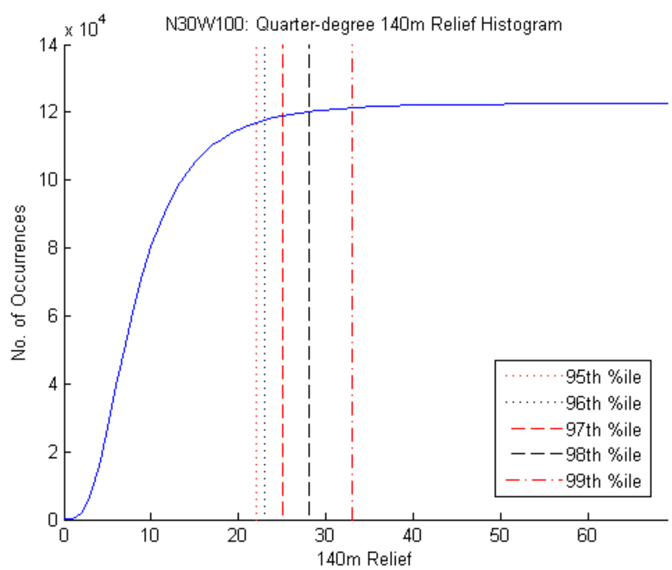


Figure 19: Cumulative histogram of all 140 m relief values in the 0.25°x0.25° tile located at 30° N 100° W

The MATLAB function *prctile* is used to compute the percentiles from the vectors of relief values in each tile. The *prctile* function in MATLAB returns percentiles of the values in an input vector. Percentiles are specified using percentages from 0 to 100. For an n-element vector, X, *prctile* computes percentiles as follows [21]:

1. The values in X are sorted and each is taken to be the $100\left(\frac{0.5}{n}\right), 100\left(\frac{1.5}{n}\right), \cdots, 100\left(\frac{n-0.5}{n}\right)$
2. Linear interpolation is used to compute percentiles for percent values between $100\left(\frac{0.5}{n}\right)$ and $100\left(\frac{n-0.5}{n}\right)$
3. The minimum or maximum values in X are assigned to percentiles for percent values outside that range.

The values in X must be of type single or double and care must be taken to manage floating point errors in the calculation of percentiles other than 0 or 100. To ensure that all values computed using the *prctile* function are integers, the values are rounded to the nearest meter before being output as a DRM tile value. It is inadvisable to use the *ceiling* function to ensure that the relief percentiles are integers as the *prctile* function is subject to floating point arithmetic errors.

4.4.2 Polar Stereographic Methodology

A separate methodology was required for the generation of the onboard DRM in the polar regions. The secondary method allows for DRM production without needing to re-project the Antarctic relief maps into a geographic projection, and also provides the opportunity to easily augment the continent-wide Bedmap2 data set with high-resolution regional data sets, such as the 100 m ASTER Antarctic Peninsula DEM. This method for generating the DRM in Antarctica directly from stereographic relief maps could be used on the stereographic relief maps produced for high-latitudes, which would negate the need to re-project those maps to a geographic projection. However, the implementation of the polar methodology is far more computationally intensive than the DRM generation method described in the previous section, making it preferable to re-project stereographic relief data to a geographic projection prior to the DRM production when possible.

The polar stereographic method of generating the DRM can be thought of as the reverse of the approach used for the geographic projection – instead of searching for the points which fall within a particular area to get the DRM, each relief point is individually placed into a histogram associated with its location. Relief histograms are accumulated over the entire continent, and the DRM for each tile is produced from a histogram of relief values.

The first step in producing the DRM is to initialize empty histograms for each desired DRM tile. For the DRM over Antarctica, empty histograms are created for every 0.25°x0.25° tile from 180° W to 180° E and 90° S to 60° S. For each cell in the input data grid, the easting and northing coordinates associated with that cell are converted to latitude and longitude values. The latitude and longitude are then used to find the histogram associated with that particular coordinate, and the relief value is added to the histogram. For example, at the coordinate (35500 m E, 366500 m N), the relief is 2 m. Converting the polar stereographic coordinate to latitude and longitude, the point is located at (5.5325° E, 86.6120° S). At this point, knowing the latitude and longitude, the relief value (2) can be added to the relief histogram associated with (5.5° E, 86.75° S).

To account for the 2 km overlap required for the DRM, each coordinate is also tested to see if it comes within 2 km of any of the neighboring tiles. If the distance between the coordinate's location and one or more edges of the 0.25°x0.25° tile is found to be less than 2 km, the relief value is also added to the histograms associated with the appropriate neighboring tiles. The distance calculations are accomplished using the

Haversine formula, which provides the great-circle distance, d, between any two values of latitude (ϕ_1, ϕ_2) and longitude (λ_1, λ_2):

$$\Delta_\lambda = \lambda_1 - \lambda_2 \tag{18}$$

$$\Delta_\phi = \phi_1 - \phi_2 \tag{19}$$

$$a = \sin^2\left(\frac{\Delta_\phi}{2}\right) + \cos(\phi_1) * \cos(\phi_2) * \sin^2\left(\frac{\Delta_\lambda}{2}\right) \tag{20}$$

$$c = 2 * \text{atan2}\left(\frac{\sqrt{a}}{\sqrt{1-a}}\right) \tag{21}$$

$$d = R_{Earth} * c \tag{22}$$

The previous coordinate P_c = (5.5235° E, 86.6120° S) would be compared to the following coordinates to find the 2 km overlap for the DEM:

P_1 = (5.5235° E, 86.5° S)

P_2 = (5.5235° E, 86.75° S)

P_3 = (5.5° E, 86.6120° S)

P_4 = (5.75° E, 86.6120° S)

If, for example, the distance, d_4, between P_c and the point to the east, P_4, was less than 2 km, the relief would be added to the relief histogram associated with the tile to the east at (5.75° E, 86.75° S) in addition to its originally assigned histogram at (5.5° E, 86.75° S). If the point fell within 2 km of both the north and east sides of the tile, the value would be added to 3 histograms in total – one each for the north, east, and northeast neighbors of the native tile.

This process can be repeated for multiple elevation models at varied resolutions without having to mosaic the different models together or account for differences in resolution or projection. To produce a DRM using both Bedmap2 and the Antarctica Peninsula DEM, the histograms are first filled with relief values from Bedmap2. Then, relief values from the Antarctic Peninsula DEM are added to the relief histograms produced from Bedmap2. If another data set was to be included, relief values from all three data sets would be placed into the same set of relief histograms before processing the DRM.

After every relief value has been added to the appropriate histograms, the DRM values can be determined for the 95th-100th percentiles of relief. Note that since the input data set used for Antarctica has a resolution of 1 km, the DRM-140 and DRM-700 are only distinct if relief values from higher resolution data sets have been added to the histograms.

4.4.3 Vegetation Height Map

Vegetation heights are added to the DRM values after the DRM has been generated from the relief maps. Simard's Global Canopy Height Model is used to create a vegetation height map that can be added to the DRM [14]. As with the DEM, the representative vegetation height is selected as the maximum vegetation height seen in an area so as to be as inclusive as possible in defining the DRM. The vegetation height model is constructed by finding the maximum vegetation height in every 0.25°x0.25° area, plus a 2 km overlap. The final product is a global vegetation height model at the same resolution as the DRM and is simply added to the 95th-100th percentile DRM values after the global DRM has been produced. The quarter-degree maximum vegetation height map is shown in Figure 20.

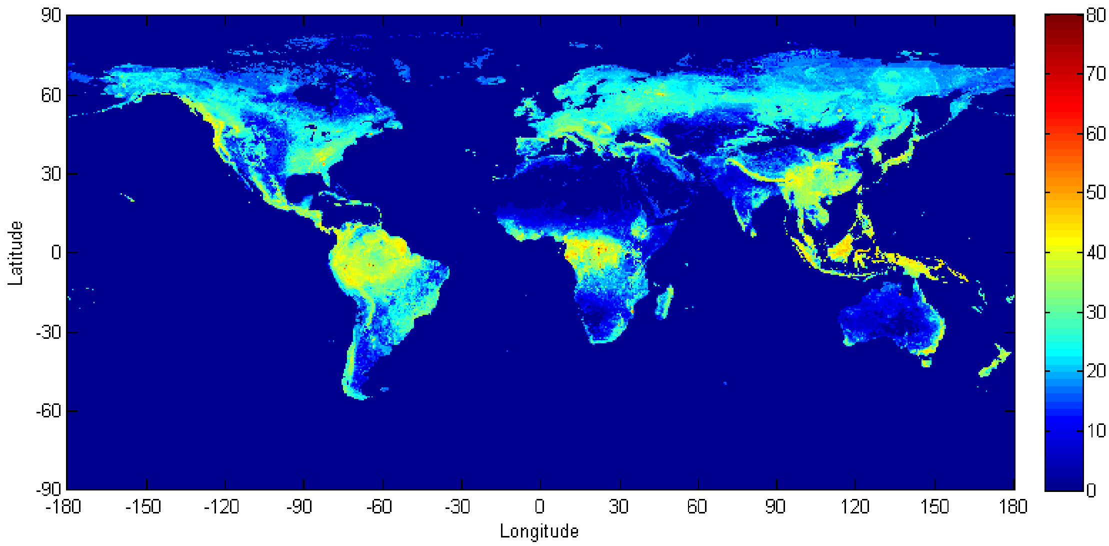


Figure 20: Maximum vegetation height map generated from Simard's Global Canopy Height Model [14] at a resolution of 0.25°x0.25°

4.5 DRM EXAMPLE

For the 0.25°x0.25° tile located at (-100° E, 30° N), the DRM-140 would be generated from all relief values shown in Figure 21. To account for the 2 km overlap, 23 extra cells have been added on the north and south sides of the 0.25°x0.25° area and 26 extra cells have been added on the east and west sides. The histogram of relief values associated with this DRM-140 tile can be seen in Figure 19.

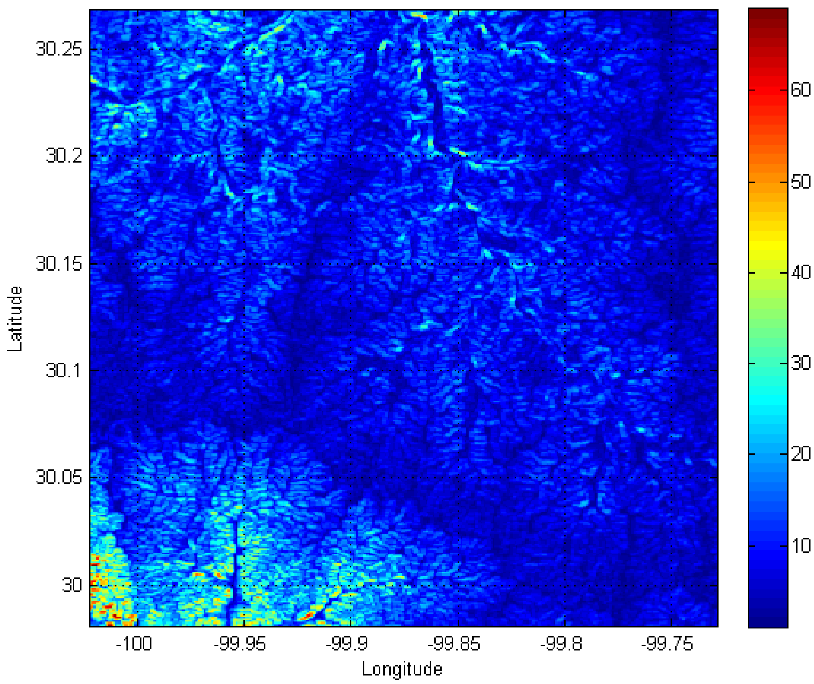


Figure 21: The 140 m relief map used to generate a DRM tile with a 2 km overlap at 30° N 100° W

The resulting DRM-140 output for the area is shown below:

Latitude	Longitude	100th %ile	99th %ile	98th %ile	97th %ile	96th %ile	95th %ile	Source
30	-100	69	33	28	25	23	22	1

Longitude and latitude are given for the south west corner of the tile. The relief percentiles are given in descending order, and the source of the relief data is denoted by a number from 1-7. The source codes are given in Table 6 below:

Table 6: Codes used to denote the elevation source used to produce an individual tile in the DRM

Source	Flag Number
SRTM-CGIAR	1
GMTED	2
CDED	3
GIMP	4
Bedmap2+ASTER 100m DEM	5
Bedmap2	6
EGM2008 Geoid	7

Chapter 5: DRM Accuracy Analysis

An analysis of the accuracy associated with various elevation sources was performed in order to determine the effects of input data resolution and collection methods, among other factors, on the accuracy of the DRM database. This accuracy analysis focused primarily on the SRTM-CGIAR and GMTED data sets, which are the most significantly used data sources for the onboard product based on area coverage. A separate accuracy analysis was also performed for the GIMP dataset using the same methodology as was used for SRTM-CGIAR and GMTED.

The results of this regional DRM accuracy analysis were used to define the values of vertical range allowance needed as padding within the telemetry band defined by the receiver algorithm. Values of relief in the DRM-140 and DRM-700 are scaled and padded to define the width of the telemetry band for a given Major or Super Frame. The scaling factor is defined based on surface type and whether or not the tile is marked as a coastline. The padding added to the scaled relief is selected based on surface type and the relief category into which it falls, and is necessary to account for possible uncertainties in the DRM. It is not possible to use the published accuracies associated with the input elevation products to define DRM accuracy since relief is derived from the input elevations and it is necessary to know accuracy as a function of the magnitude of the relief. In addition, the published accuracies are quoted in a general sense and estimated at locations where ground control is available, and do not always represent the true accuracy under certain terrain characteristics.

5.1 Methodology

In order to determine the accuracy of the DRMs generated from various input DEM data sources, it is necessary to determine a relationship between the calculated relief values and the accuracy of the data set used to generate those values. To accomplish this, the ICESat Level-1B global elevation product (GLA06) was selected as a ground reference to determine the relative accuracy of several input elevation products. The accuracy of a DRM tile is derived from the accuracy of the input DEM used to generate the relief values. Finally, a relationship between DRM relief and DRM accuracy is established in order to define the level of padding within the receiver algorithm's decision on relevant telemetry bands for specific areas of relief/topography. This analysis is to ensure that the appropriate data sent down from the spacecraft contains all pertinent ranging information based on the evaluation of the input data sources and data source accuracies.

5.1.1 Test Regions

Several regions were selected to represent areas of varying types of terrain and surface cover for this analysis in order to establish the impact of the DEM accuracy on the statistical DRM accuracy based on the nature of the topography. Both "best-case" and "worst-case" scenarios were examined in terms of the elevation range and complexity of topographic features. Some areas used in this evaluation presented very little dynamic range in terms of terrain elevations while other exhibited substantial variation. Characteristics of the various data collection method's impact on the DRM accuracies were also taken into account when selecting the regional test data. The 1°x1° tiles selected for SRTM-CGIAR and GMTED accuracy analysis in the mid-latitudes were from the following locations:

- Amazon River Basin (2 tiles)
    - (-63° E, -2° N)
    - (-64° E, 2° N)

- Andes Mountains (5 tiles)
    - (-68° E, -17° N)
    - (-67° E. -17° N)
    - (-67° E, -18° N)
    - (-73° E, -13° N)
    - (-73° E, -14° N)
- Australian Outback (1 tile)
    - (121° E, -23° N)
- Canadian Plains (1 tile)
    - (-109° E, 50° N)
- Himalayan Mountains/Tibetan Plateau (5 tiles)
    - (86° E, 27° N)
    - (87° E, 27°N)
    - (86° E, 28° N)
    - (91° E, 27° N)
    - (92° E, 27° N)
- Midwestern United States (2 tiles)
    - (-99° E, 38° N)
    - (-98° E, 32° N)
- Pacific Northwest (2 tiles)
    - (-122° E, 46° N)
    - (-122° E, 47° N)
- Rocky Mountains (1 tile)
    - (-107° E, 37° N)
- Saharan Desert (2 tiles)

- (2° E, 30° N)
- (7° E, 26° N)

Due to characteristics of the data collection method used to develop the SRTM product, the original SRTM data set is prone to mountain and desert data voids and is elevation biased in areas of heavy vegetation [5]. The SRTM-CGIAR and GMTED elevation products use different methods and elevation datasets to address the issue of data voids, so several tiles in mountainous and desert areas were selected from these sources to determine if and how the void-filling processes would affect the resulting DRM accuracy. No modifications were made in either data set for vegetation, so heavily vegetated and minimally vegetated areas were likewise chosen to understand the effects on the accuracy of the resulting DRM.

Five 5°x5° areas were selected for the accuracy analysis of the GIMP data set, two in the interior of the ice sheet, two on the coast, and one in the far North. The regions were selected to represent the varying types of terrain as well as the different data sets used in the creation of the GIMP product. The true resolution of the data set varies from 40 m to 500 m depending on the method of data collection and the data set is reportedly more accurate over ice sheets than over output glaciers and coastal regions [11].

5.1.2 ICESat Data Processing

ICESat GLA06 data was acquired for each of the test regions and transformed to the appropriate reference datum to be consistent with the input DEM source. Specifically, when the input DEMs are referenced to the EGM96 geoid, the GLA06 transformation process converts latitude, longitude and elevation values from the Jason/TOPEX ellipsoid used by ICESat [2] to the WGS84 ellipsoid used by the geoid model. The adjusted geodetic values are then used find the height of the geoid at each location. These geoid heights are added to the WGS84 elevations to get the EGM96 elevations. To enable the comparison of the along-track ICESat data to gridded elevation models, bilinear interpolation was used to determine values of elevation within the gridded model that correspond to the geolocation of the ICESat measurements.

A simple statistical filter was implemented to remove ICESat outlier data, particularly those due to cloud contamination of the signal. Using histograms of elevation differences between ICESat and the input DEM, upper and lower difference bounds were manually selected for each region. These bounding values were manually set based on percentile statistics of the elevation difference histograms in order to ensure that the maximum and minimum elevation differences seen were of approximately the same magnitude and that the obvious outliers were not included in the comparisons. In tiles where the terrain variation of elevation was lower, the number of points filtered as outliers was generally less than 1%. In tiles showing higher relief and in areas suffering from near-constant cloud cover, the number of points filtered out generally ranged from 1-5%. In some areas, cloud points were not removed using the elevation difference bounding value criteria, as the differences between the input data and the cloud elevations were actually smaller in magnitude than the differences seen between the input data and ground elevations. In these cases, the cloud elevations were manually removed.

An example of the elevation difference filtering process is presented here for a 1°x1° area in the Andes Mountains located at (68° W, 17° S). Figure 22 shows a histogram of elevation differences between ICESat and SRTM-CGIAR for all ICESat footprints available within the selected 1°x1° area. Elevation difference is calculated using $\Delta_E = E_{input\,DEM} - E_{ICESat}$, such that negative values indicate that ICESat elevations are higher than the input DEM surface, while positive differences indicate that

ICESat elevations are below the input DEM surface. In Figure 22, the extreme negative values of elevation differences in the histogram are due to cloud cover, and are filtered out by this process.

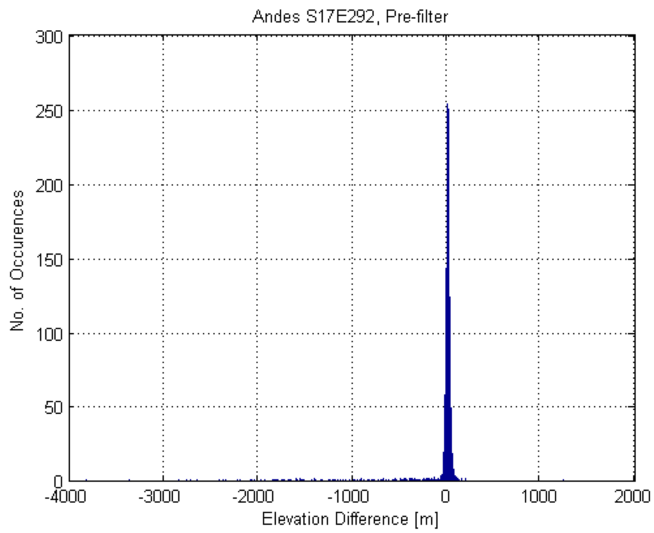


Figure 22: Histogram of elevation differences between SRTM-CGIAR and ICESat footprints prior to filtering

Another indication that there is cloud contamination within the data sets can be seen from a plot of the GLA06 elevations and the associated input DEM elevations along one track during a single ICESat campaign for a given area. Figure 23 shows the along-track elevations from ICESat and the associated SRTM-CGIAR elevations. Clouds returns are seen around 4000 m on the right side of the image in Figure 23, as the elevations are not a reasonable representation of elevation model's topography, shown by the red crosses. Some returns from breaks in the clouds are also observed.

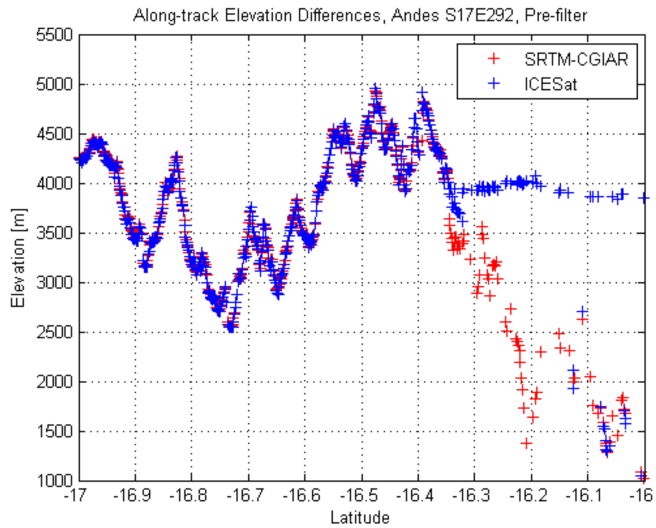


Figure 23: A profile of ICESat and SRTM-CGIAR elevations for a single pass (Track 0338, Campaign 3F) are shown prior to filtering. The presence of cloud contaminated elevations can be observed on the right side of the image.

By plotting the elevation differences along the ground track profile, as in Figure 24 below, it can be seen that the elevation differences against ICESat ground elevations are tightly clustered around zero, while the elevation differences associated with ICESat returns from clouds are dispersed and are much larger in magnitude.

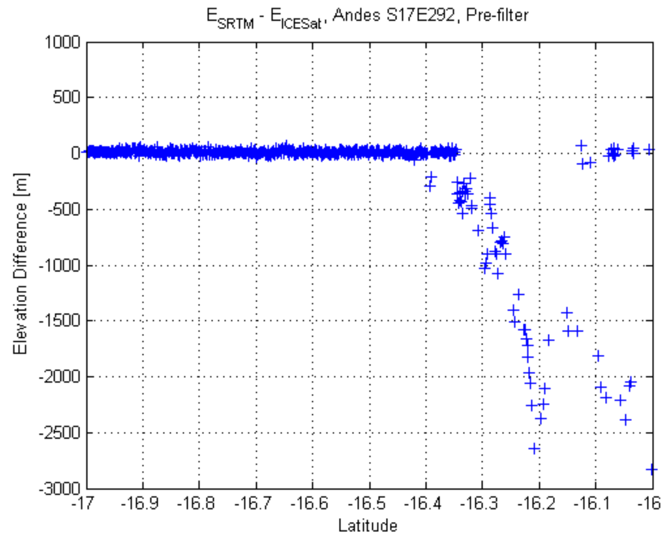


Figure 24: Elevation differences between ICESat and SRTM-CGIAR for a single pass (Track 0338, Campaign 3F) are plotted along the profile of the ground track prior to filtering. Differences associated with cloud elevation are more disperse and larger in magnitude.

The upper and lower bounds on elevation difference used to filter outlier data are set using the histogram of the elevation differences seen across all campaigns for the 1°x1° area (Figure 22) together with the along-track comparison plots of ICESat elevations and input DEM elevations (Figure 23 and Figure 24). The lower bound is set to remove the bottom 4% of elevation differences using the along-track plots. The lower bound ensures removal of obvious cloud elevations. The upper bound is set to remove the top 0.3% of elevation differences using the elevation difference histograms. The upper bound ensures that the extent of the distribution is approximately equal in length, i.e. the maximum and minimum elevation differences are similar in value. Saturation of the ICESat signal often results in over-ranging the surface estimate, so setting an upper bound removes many of the saturated elevation points. The histogram of elevation differences for the entire 1°x1° region after filtering is shown in Figure 25.

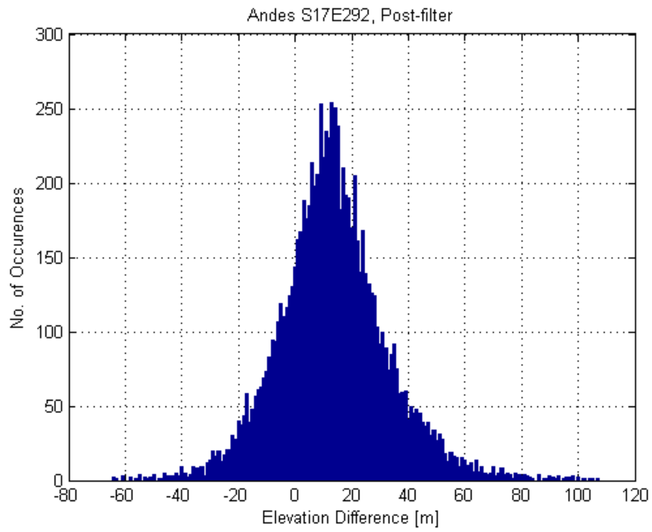


Figure 25: Histogram of elevation differences between SRTM-CGIAR and ICESat footprints after statistical filter has been applied to remove outlier ICESat footprints

The effect of the filter is demonstrated in Figure 26 and Figure 27, which show plots of the elevation profile and elevation differences after filtering, respectively. The elevation profile and the elevation differences prior to filtering are shown in Figure 23 and Figure 24, respectively. Notice in Figure 26 that the ICESat elevations that previously appeared to be cloud elevations have been removed, and Figure 27 shows that the spread of elevation differences is more localized about the mean. This provides a more adequate statistical basis for the accuracy analysis of input data set.

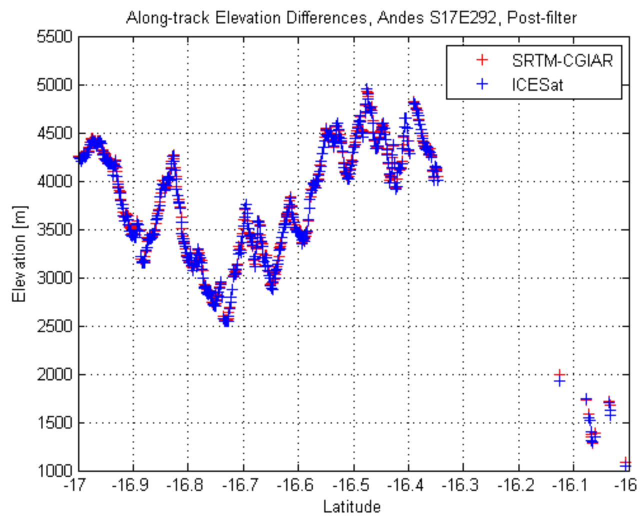


Figure 26: A profile of ICESat and SRTM-CGIAR elevations for a single pass (Track 0338, Campaign 3F) are shown after application of cloud filter. Note removal of elevations from clouds in **Error! Reference source not ound.**23.

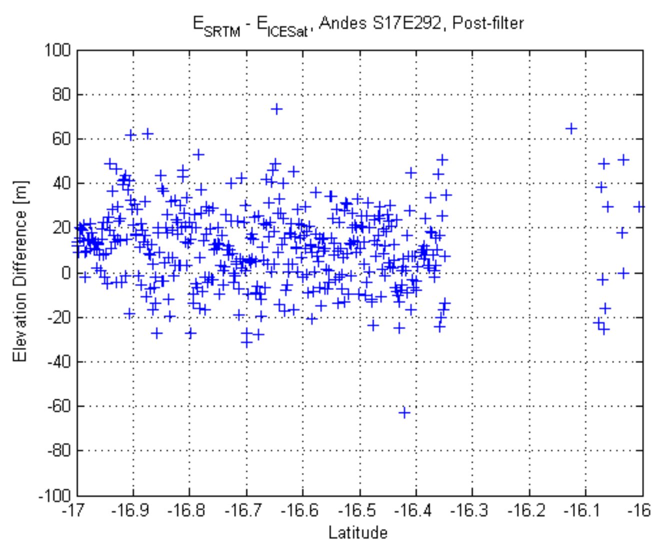


Figure 27: Elevation differences between ICESat and SRTM-CGIAR for a single pass (Track 0338, Campaign 3F) are plotted along the profile of the ground track after application of filter. Note change in y-axis scale relative to **Error! eference source not found.**24.

5.1.3 Calculating Accuracy

In order to determine DRM accuracy, the ICESat ground reference elevations are used to statistically evaluate accuracy of the DEM. The DRM accuracy for a given area is derived from the DEM accuracy for that area. By compiling values of relief and accuracy for several DRM tiles, estimates of global DRM accuracy can be defined as a function of relief magnitude. Elevation differences were compiled for every quarter-degree area in the test regions using the filtered ICESat elevation data from all available tracks and campaigns. A value of input DEM accuracy was calculated for each 0.25°x0.25° tile from the distributions of the elevation differences in that area. It should be noted that the 2 km overlap was not included in the accuracy analysis. An example of a histogram of elevation differences is shown in Figure 28 for the quarter-degree area at (68° W, 17° S).

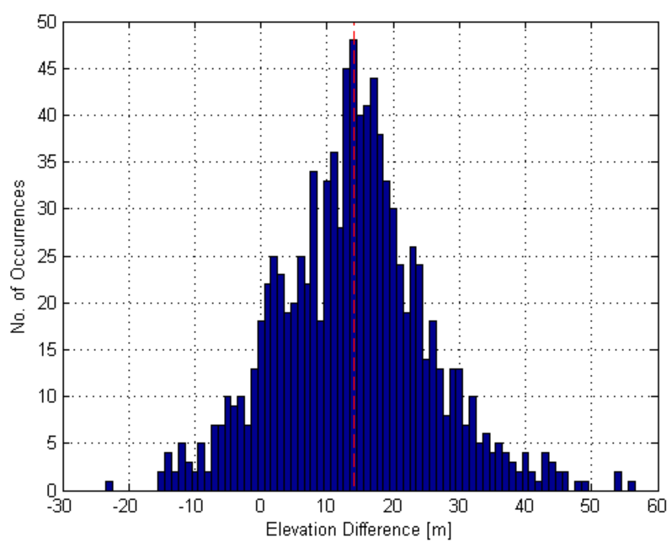


Figure 28: Histogram of elevation differences between SRTM-CGIAR and ICESat for the 0.25°x0.25° area located at 17° S 68° W.

The mean elevation difference, μ_E, is marked in Figure 28 by a red dotted line. This value is subtracted from all the elevation differences in order to center the distribution about zero. The input DEM accuracy, σ_{DEM}, is then taken to be the value for which 99.7% of the elevation differences, Δ_E, fall within the values defined by:

$$|\Delta_E - \mu_E| \leq \sigma_{DEM} \tag{23}$$

The parameter σ_{DEM} is the 3-standard-deviation width of the differences in elevation assuming a Gaussian distribution, and is the accuracy associated with the input DEM for the quarter-degree region, not the accuracy of the DRM produced from that input DEM. A histogram of the adjusted elevation differences used to calculate the DEM accuracy values is shown in Figure 29 and the value σ_{DEM} is marked by a red dotted line.

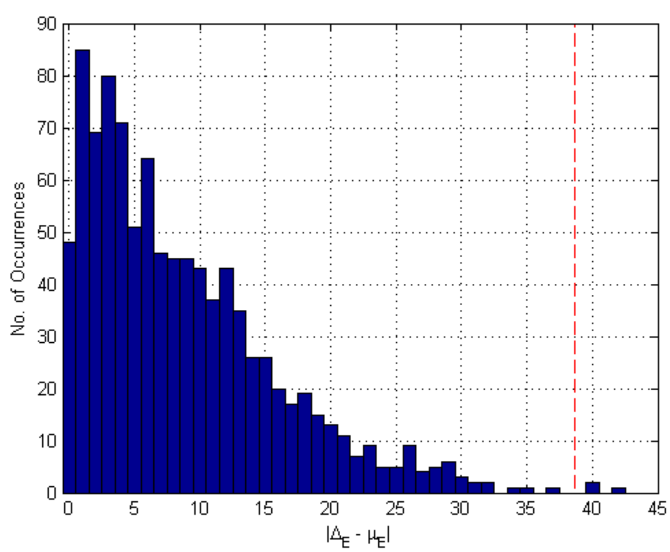


Figure 29: Histogram of the absolute values of elevation differences adjusted for the mean elevation difference

Since the DRM product is the result of differencing the maximum and minimum elevations using the input DEM, additional statistical calculations are required for the determination of a relevant DRM accuracy. Assuming that the two elevation values from the input DEM, E_1 and E_2, used to calculate the value of relief both have the same bias, μ_E, and accuracy, σ_{DEM}, the resultant accuracy of that DRM tile, σ_{DRM}, can be determined using propagation of error [22]. In the general case, the propagation of error formula implies that when subtracting value B from value A, the value of the difference, X, will have accuracy, σ_X, that is dependent on the accuracies of A and B. The accuracy associated with X is the root of the sum of the squares of the accuracies of A and B, which are σ_A and σ_B, respectively.

$$X = A - B \tag{24}$$

$$\sigma_X = \sqrt{(\sigma_A)^2 + (\sigma_B)^2} \tag{25}$$

Therefore, since the relief calculation is achieved by subtracting two values of elevation from the same data source (and therefore with the same accuracies), the resulting accuracy of the DRM tile can be determined by:

$$R = E_2 - E_1 \tag{26}$$

$$\sigma_{DRM} = \sqrt{(\sigma_{DEM})^2 + (\sigma_{DEM})^2} = \sqrt{2\sigma_{DEM}^2} = \sqrt{2}\sigma_{DEM} \tag{27}$$

Thus, the accuracy of any given DRM tile is the accuracy of the input DEM for the same region, multiplied by a factor of $\sqrt{2}$.

The bias of the input DEM, μ_E, is irrelevant to the discussion of DRM accuracy since it is assumed that every cell of elevation data within the quarter-degree tile has the same bias. Thus, when one elevation is subtracted from another, the distance between the two values is the same, independent of whether the elevations are biased positively, negatively, or not at all.

A relationship between the magnitude of relief and the resulting accuracy of the DRM can be found by comparing the DRM relief values to the calculated DRM accuracy values. When plotting DRM accuracy versus relief, it is expected that the DRM accuracy will degrade with increasing values of relief. It is also expected that the spread of the data will increase with increasing relief values as there is more variation in the input DEM accuracy for areas of highly dynamic terrain.

5.2 Results

Accuracy analyses have been undertaken for three input data sets in the mid-latitudes and for one data set over Greenland. The selected regions are the same for each of the three data sets in the mid-latitudes. Mid-latitudes analyses were focused on three data sets: the publically distributed 90 m resolution SRTM-CGIAR, a down-sampled 250 m resolution SRTM-CGIAR, and the GMTED 250 m mean elevation product. SRTM-CGIAR was evaluated at two resolutions in order to determine the effect of decreased resolution on the accuracy of the DRM product, i.e. it was used as a control in examining DRM accuracy differences due to the difference in resolution between the 90 m SRTM-CGIAR and the 250 m GMTED products. The down-sampled SRTM-CGIAR 250 m product was generated from the 90 m SRTM-CGIAR product using a weighted averaging technique. The analysis for Greenland was performed using the GIMP 90 m elevation product, as this was the source DEM used in the production of the databases.

The receiver algorithm is designed such that padding is added to the DRM to account for uncertainties according to the magnitude of the relief for a given area. Relief padding is selected based upon into which of the four categories the DRM value falls.

The relief categories are defined by the receiver algorithm requirements as $0 \text{ m} \leq R \leq 189$ m, $189 \text{ m} < R \leq 567$ m, $567 \text{ m} < R \leq 1323$ m, and $R > 1323$ m. As such, the DRM tiles included in the analysis are separated into their relevant relief categories. The results of the DRM accuracy assessments are also allocated to each of the receiver algorithm's defined relief categories. Also included for each of the four relief categories, are three specific statistics. These statistics include the mean value of DRM accuracy calculated using all relevant relief tiles, the standard deviation of the DRM accuracy values (to indicate how much the accuracy varies), and the sample size (the number of DRM tiles with relief values in that range, number of accuracy values used to compute the first two statistics).

5.2.1 SRTM-CGIAR 90m

The results of the DRM accuracy analysis specific to the 90 m SRTM-CGIAR input DEM product are shown in Table 7 and Table 8. Separate statistical calculations are required for the DRM-140 and the DRM-700 as the different length scales often change the relief category relevant for a given input tile. A single value of DEM and DRM accuracy is calculated for each tile using ICESat footprints as elevation references. The DRM accuracy for any given tile is independent of the length scale of the relief, so the DRM accuracy value for that tile is the same for the DRM-140 and DRM-700 analyses. One note of interest in viewing the results presented in Table 7 and Table 8 is that the total number of tiles used in the analysis is not equal to the total number of 0.25°x0.25° tiles in the selected test regions. This discrepancy is due to the fact that not all tiles had a sufficient number of ICESat footprints within their bounds to be included in the statistics.

Table 7: SRTM-CGIAR 90 m DRM-140 Accuracy

	Relief Range			
	$0m \leq R \leq 189m$	$189m < R \leq 567m$	$567m < R \leq 1323m$	$R > 1323m$
$mean(\sigma_{DRM})$ $[m]$	21	83	145	184
$stddev(\sigma_{DRM})$ $[m]$	19	50	79	111
Sample Size, N	117	132	29	2

Table 8: SRTM-CGIAR 90 m DRM-700 Accuracy

	Relief Range			
	$0m \leq R \leq 189m$	$189m < R \leq 567m$	$567m < R \leq 1323m$	$R > 1323m$
$mean(\sigma_{DRM})$ $[m]$	17	43	102	175
$stddev(\sigma_{DRM})$ $[m]$	16	19	62	62
Sample Size, N	94	58	119	9

The DRM accuracy appears to improve for the DRM-700 compared to the DRM-140 because some tiles move from one relief category for the 140 m calculations to a higher relief category for the 700 m calculations. Areas showing higher values of relief generally have poorer accuracy, i.e. the DRM accuracy value is larger. When tiles at the high end of one relief category in the DRM-140 move into the next higher relief category for the DRM-700, the mean value of accuracy for the lower range decreases since the “poor” accuracy values at the upper end of the relief category are no longer contributing to the mean accuracy statistic. As expected, the spread of the DRM accuracy values (i.e. the standard deviation of σ_{DRM}) increases with increasing relief, which is a direct indication that accuracy of the input DEM degrades in regions of dynamic topography. Confidence in the values obtained for DRM accuracy in the highest relief category is lower than for the other three categories as fewer tiles were available from which to compute statistics. DRM accuracy values are plotted versus relief for individual DRM-

140 and DRM-700 tiles in Figure 30 and Figure 31. Also plotted is the mean DRM accuracy value for each relief category (red diamond) and sample standard deviation of the DRM accuracy values for that range (error bars).

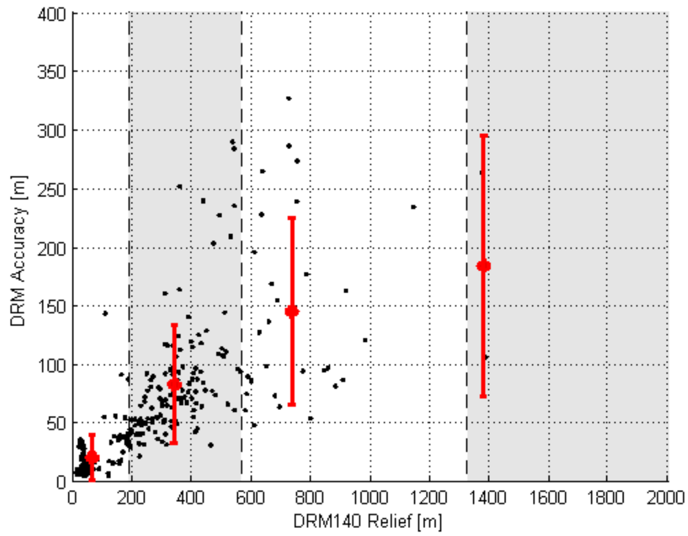


Figure 30: 90 m SRTM-CGIAR DRM Accuracy vs. DRM-140 Relief

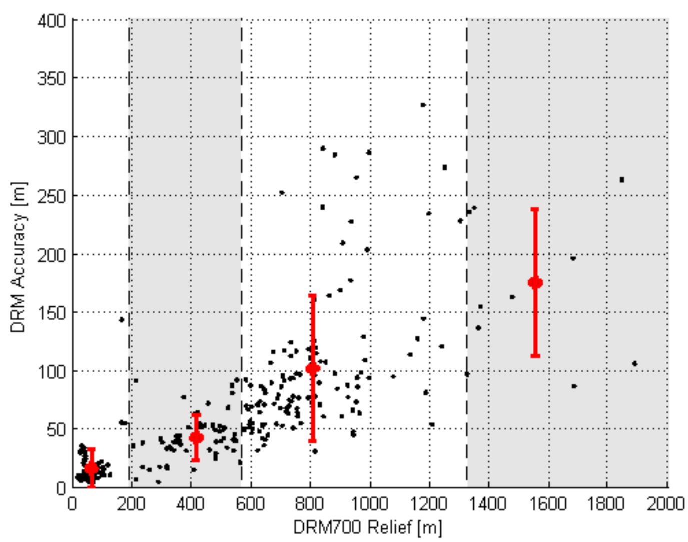


Figure 31: 90 m SRTM-CGIAR DRM Accuracy vs. DRM-700 Relief

The plot of DRM-700 accuracy in Figure 31 appears to be ”stretched” in the x-direction relative to the plot of DRM-140 accuracy in Figure 30. The stretch effect is the result of applying the fixed accuracy value for a single DRM tile to an associated increase in relief between the two length scales.

5.2.2 SRTM-CGIAR 250m

As mentioned previously, an accuracy analysis was also performed on a down-sampled version of the 90 m SRTM-CGIAR product. This reduced resolution product was determined to act as a control case for evaluating the impact of resolution and input data characteristics on the DRM accuracy. The focus here was to examine specifically the differences between SRTM-CGIAR 90 m DRM accuracies and the GMTED 250 m DRM accuracies. The results of the analysis for the down-sampled 250 m SRTM-CGIAR product are shown in Table 9 and Table 10.

Table 9: Down-sampled 250 m SRTM-CGIAR DRM-140 Accuracy

	Relief Range			
	$0m \leq R \leq 189m$	$189m < R \leq 567m$	$567m < R \leq 1323m$	$R > 1323m$
$mean(\sigma_{DRM})$ $[m]$	24	118	192	N/A
$stddev(\sigma_{DRM})$ $[m]$	19	44	63	N/A
Sample Size, N	104	136	40	N/A

Table 10: Down-sampled 250 m SRTM-CGIAR DRM-700 Accuracy

	Relief Range			
	$0m \leq R \leq 189m$	$189m < R \leq 567m$	$567m < R \leq 1323m$	$R > 1323m$
$mean(\sigma_{DRM})$ $[m]$	22	81	153	216
$stddev(\sigma_{DRM})$ $[m]$	17	29	55	59
Sample Size, N	95	63	116	6

Decreasing the resolution from 90 m to 250 m does in fact degrade the accuracy of the resulting DRMs, as can be seen by comparing Table 7 and Table 8 to Table 9 and Table 10. Additionally, the topographic smoothing that occurs as a consequence of the weighted averaging down-sampling technique creates lower extreme values of relief, so much so that no values are present in the upper-most relief category for the DRM-140. In other places, the down-sampling resulted in higher relief values, evidenced by the difference in sample sizes between the two data sets. Similar trends in DRM accuracy are seen for the 250 m data set as were seen for the 90 m data set, although the accuracy is poorer in the down-sampled case. To minimize issues with topographic smoothing with lower resolution data sets, using higher resolution elevation data when available is still preferable.

DRM accuracy values for the down-sampled SRTM-CGIAR are plotted versus relief for individual DRM-140 and DRM-700 tiles in Figure 32 and Figure 33. The mean DRM accuracy value for each relief category is plotted as a red diamond and the sample standard deviation of the DRM accuracy values for that range is indicated by the error bars.

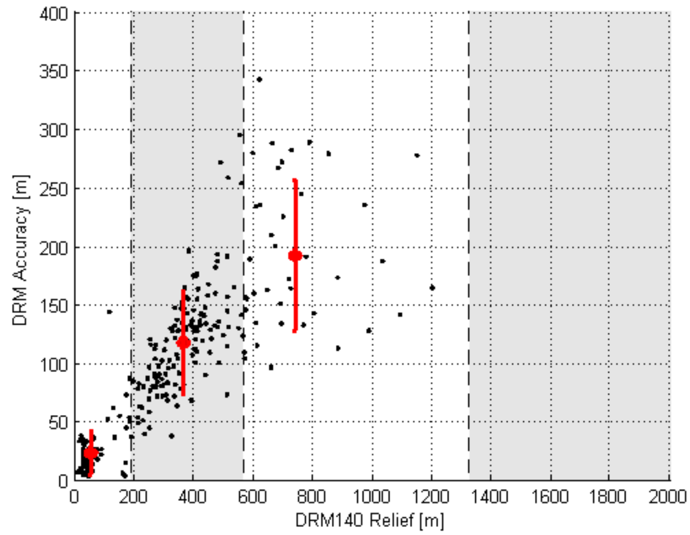


Figure 32: Down-sampled 250 m SRTM-CGIAR DRM Accuracy vs. DRM-140 Relief

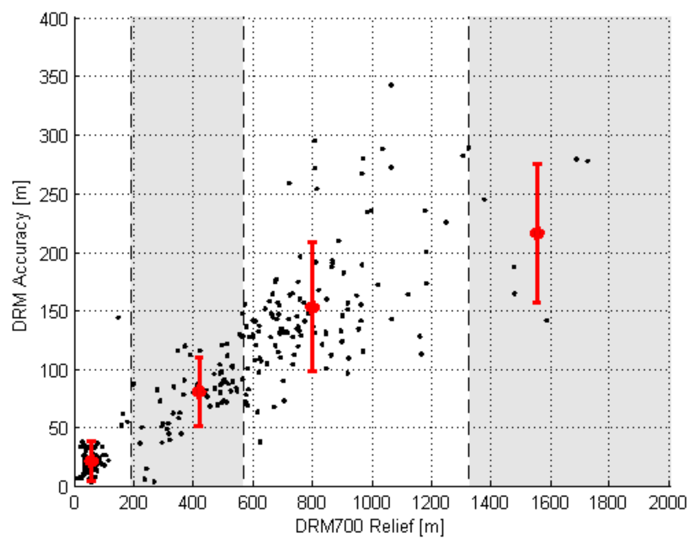


Figure 33: Down-sampled 250 m SRTM-CGIAR DRM Accuracy vs. DRM-700 Relief

5.2.3 GMTED 250 m Mean Elevation

To understand if and how differences in void-filling methodologies affect DRM accuracy, an additional accuracy analysis is performed for the GMTED 250 m mean elevation product. The results from the GMTED analysis can be compared to the results from the analyses of the 90 m and 250 m SRTM-CGIAR products to evaluate relative DRM accuracies of the data sets. A slightly modified version of the accuracy methodology was used in analyzing the accuracy of GMTED to ensure that the same ICESat footprints were being used as in the analyses of the two SRTM-CGIAR data sets. It is necessary to ensure that the same ground reference elevation data points are used to evaluate all three data sets, or the comparisons would be invalid. The ICESat data was first filtered using elevation differences compared to SRTM-CGIAR, then the filtered data set (without additional filtering) was compared to GMTED for the accuracy analysis. If the data was filtered against GMTED, it is very likely that different ICESat footprints would have been used in the SRTM analyses and the GMTED analysis, making comparisons between SRTM and GMTED results incompatible. The results of the accuracy analysis for the GMTED 250 m mean elevation product are shown in Table 11 and Table 12.

Table 11: 250 m GMTED2010 DRM-140 Accuracy

	Relief Range			
	$0m \leq R \leq 189m$	$189m < R \leq 567m$	$567m < R \leq 1323m$	$R > 1323m$
$mean(\sigma_{DRM})$ $[m]$	34	160	412	1405
$stddev(\sigma_{DRM})$ $[m]$	27	52	315	834
Sample Size, N	109	122	36	13

Table 12: 250 m GMTED2010 DRM-700 Accuracy

	Relief Range			
	$0m \leq R \leq 189m$	$189m < R \leq 567m$	$567m < R \leq 1323m$	$R > 1323m$
$mean(\sigma_{DRM})$ $[m]$	30	114	244	1374
$stddev(\sigma_{DRM})$ $[m]$	19	44	166	792
Sample Size, N	95	66	104	15

The same trends in DRM accuracy observed in the SRTM-CGIAR cases hold for the GMTED analysis, but the accuracy is poorer and the spread of the data is far larger, particular in the highest relief category. Additionally, there were outliers present in the GMTED analysis, both in the accuracy values and relief values, which weren't observed in either of the SRTM-CGIAR analyses. Both of these variations in results are likely to be a consequence of issues with the input data set. Namely, large discontinuities or errors in the input DEM produce abnormally high relief values as well as poor DRM accuracy values.

DRM accuracy values for the GMTED 250 m mean elevation product are plotted versus relief for individual DRM-140 and DRM-700 tiles in Figure 34 and Figure 35. The mean DRM accuracy value for each relief category is plotted as a red diamond and the sample standard deviation of the DRM accuracy values for that range is indicated by the error bars. Note the changes in scaling in Figure 34 and Figure 35 compared to the axes limits of Figures 30-33.

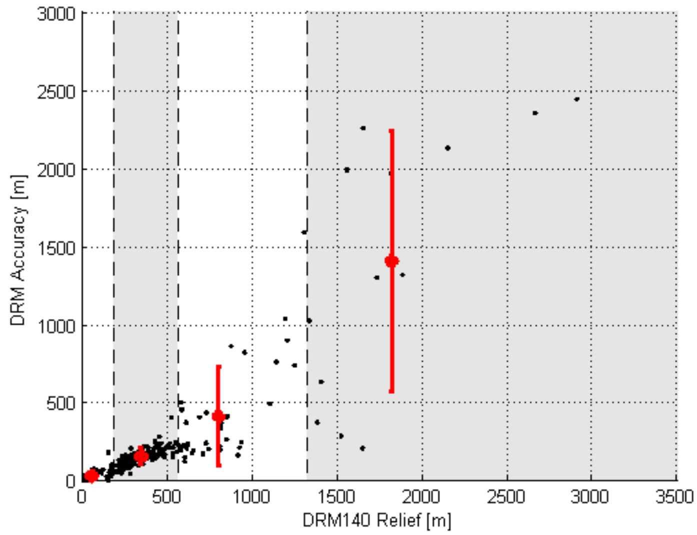


Figure 34: 250 m GMTED2010 DRM Accuracy vs. DRM-140 Relief

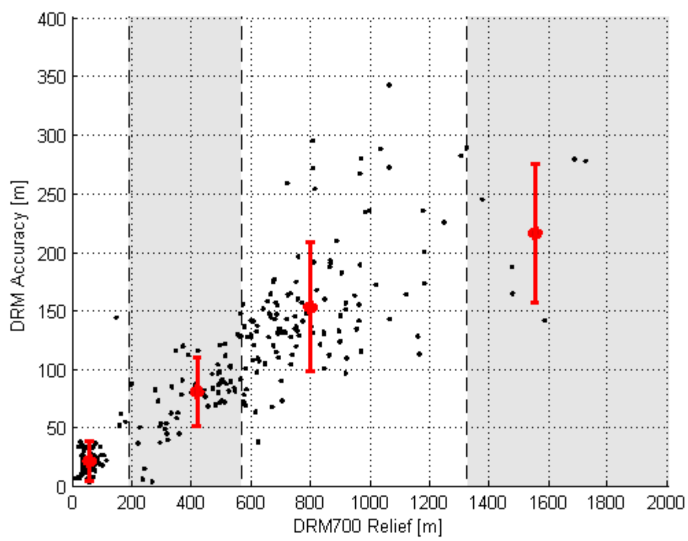


Figure 35: 250 m GMTED2010 DRM Accuracy vs. DRM-700 Relief

5.2.4 GIMP 90m

A separate accuracy analysis was performed on the GIMP 90 m elevation product in Greenland for five 5°x5° areas representing several different types of terrain and different input data sources. The GIMP data set is understood to have varying resolution and accuracy depending on the variation of collection method of the data set used for a particular area. The accuracy analysis was performed in order to better understand the DRM accuracy that could be expected from the data set as a whole. The results of the analysis are presented below in Table 13 and Table 14.

Table 13: 90 m GIMP DRM-140 Accuracy

	Relief Range			
	$0m \leq R \leq 189m$	$189m < R \leq 567m$	$567m < R \leq 1323m$	$R > 1323m$
$mean(\sigma_{DRM})$ $[m]$	14	127	355	703
$stddev(\sigma_{DRM})$ $[m]$	21	152	413	737
Sample Size, N	1343	420	69	18

Table 14: 90 m GIMP DRM-700 Accuracy

	Relief Range			
	$0m \leq R \leq 189m$	$189m < R \leq 567m$	$567m < R \leq 1323m$	$R > 1323m$
$mean(\sigma_{DRM})$ $[m]$	12	63	158	535
$stddev(\sigma_{DRM})$ $[m]$	13	51	172	565
Sample Size, N	1288	191	309	62

The trends observed for the accuracy analyses in the mid-latitudes also hold for the GIMP analysis – accuracy degrades and the dispersion of the data increases as the relief increases. DRM accuracy for the lowest relief category, 0 m ≤ R ≤ 189 m, is much better for GIMP than for SRTM-CGIAR or GMTED, but significantly poorer for the other three relief categories. Areas of low relief and high accuracy correspond to locations on the interior of the ice sheet, while high relief, poorer accuracy tiles are found in mountainous regions and along output glaciers on the coasts. These results support

GIMP documentation that indicates the data set is more accurate over inland ice sheets than along the coasts [11]. Areas showing the poorest accuracy were primarily located in regions of rapid change.

DRM accuracy values for the GIMP 90 m elevation product are plotted versus relief for individual DRM-140 and DRM-700 tiles in Figure 36 and Figure 37. The mean DRM accuracy value for each relief category is plotted as a red diamond and the sample standard deviation of the DRM accuracy values for that range is indicated by the error bars. Note the changes in scaling in Figure 36 and Figure 37 compared to the axes limits of Figures 30-35.

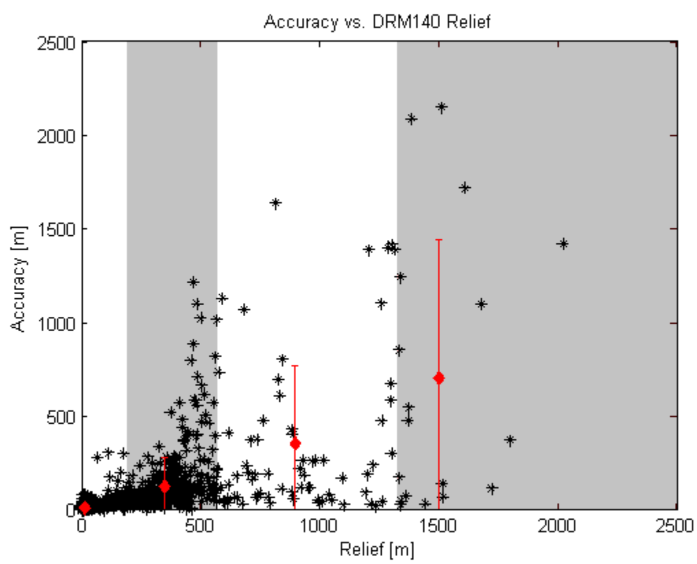


Figure 36: 90 m GIMP DRM Accuracy vs. DRM-140 Relief

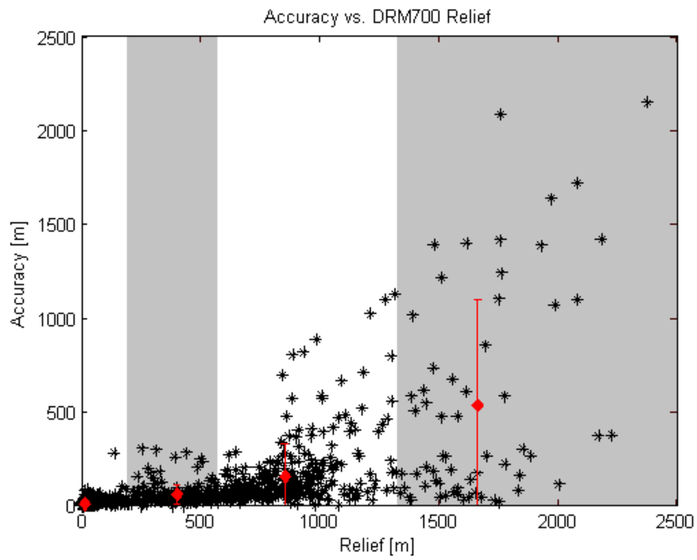


Figure 37: 90 m GIMP DRM Accuracy vs. DRM-700 Relief

5.3 Effects of Resolution on DRM Accuracy

By comparing the accuracy values of the down-sampled 250 m SRTM-CGIAR DRMs and the GMTED DRMs to the higher resolution 90 m SRTM-CGIAR DRMs, it is possible to gain an understanding of the effects of a lower resolution input DEM on the quality (or accuracy) of the resulting DRM. Figure 38 and Figure 39 show how the mean accuracy changes for the DRM-140 and DRM-700 depending on the relief category and the input DEM.

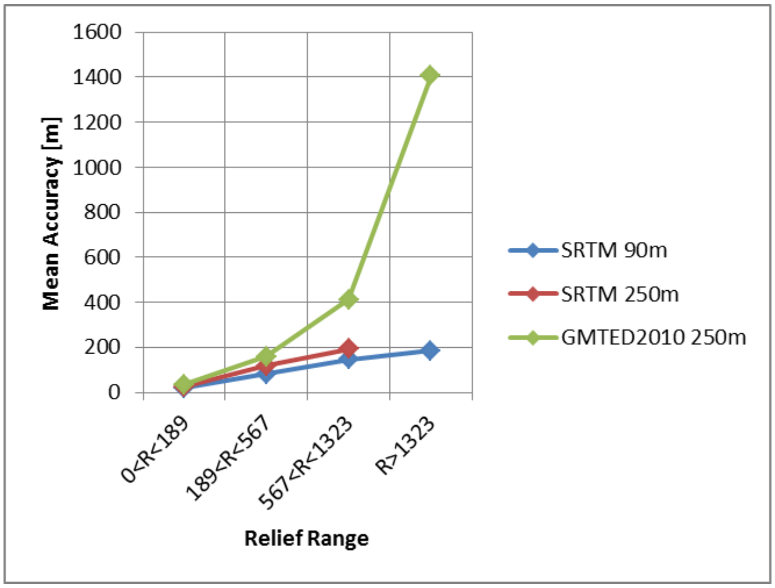


Figure 38: Comparison of Mean DRM-140 Accuracy by input DEM and relief range

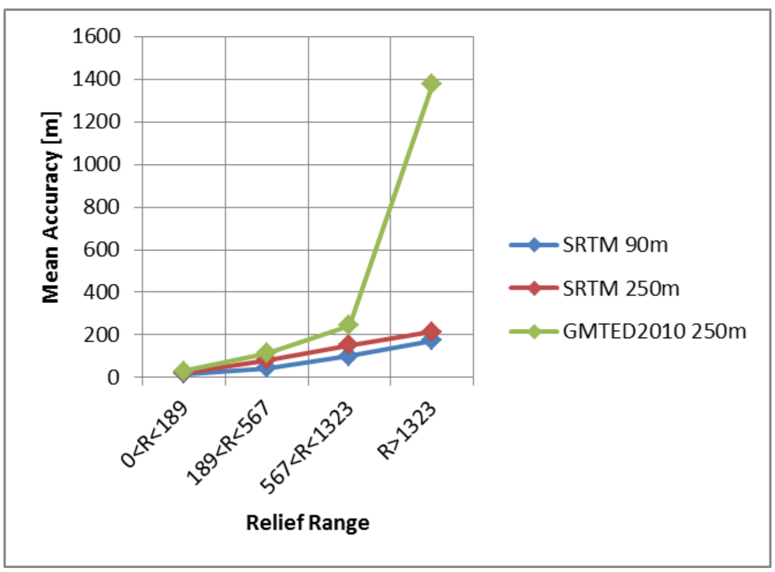


Figure 39: Comparison of Mean DRM-700 Accuracy by input DEM and relief range

From Figure 38 and Figure 39, it is evident that for lower relief categories there is degradation in the DRM accuracy due to the decreased resolution. However, the 3rd and

4th relief categories of the GMTED data set show accuracies far poorer than the other two data sets that cannot be explained by the decreased resolution. The discrepancy in accuracy between the GMTED data set and the 250 m SRTM-CGIAR data set is most likely due to errors in the GMTED data set in high relief areas. The primary data sources for GMTED and SRTM-CGIAR are the original 30 m and 90 m SRTM data sets distributed by the Jet Propulsion Laboratory (JPL), respectively, which both show large void areas in regions of high relief and shadow [8] [9]. Many methods of interpolating and filling these voids have been applied, all with varying levels of success [15]. It is likely that differences among the void-filling algorithms used by the developers of SRTM-CGIAR and GMTED are in part to blame for the dissimilarities seen in DRM accuracy.

Figure 40, Figure 41, and Figure 42 show elevation plots of a 1°x1° region in the Himalayas using the 90 m SRTM-CGIAR product, the down-sampled 250 m SRTM-CGIAR product, and the GMTED 250 m mean elevation product, respectively.

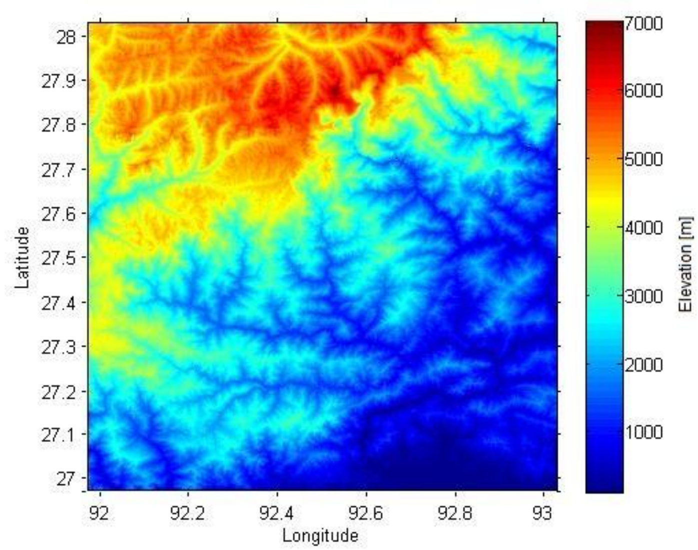


Figure 40: 90 m SRTM-CGIAR elevation model in Himalayas [8]

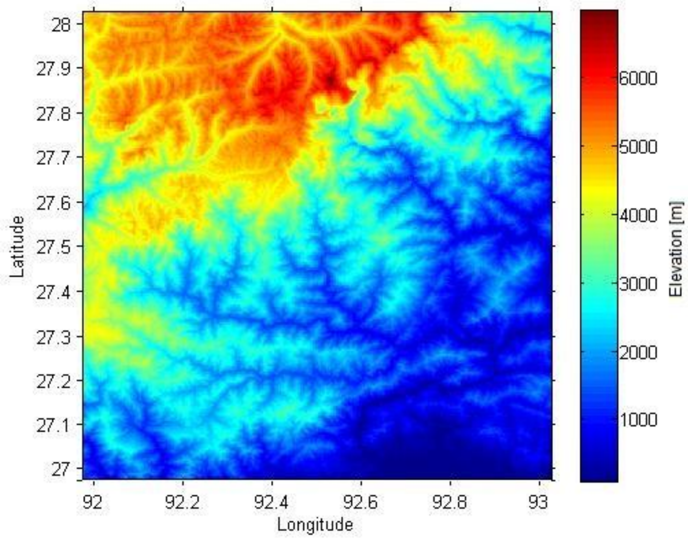


Figure 41: Down-sampled 250 m SRTM-CGIAR elevation model in Himalayas [8]

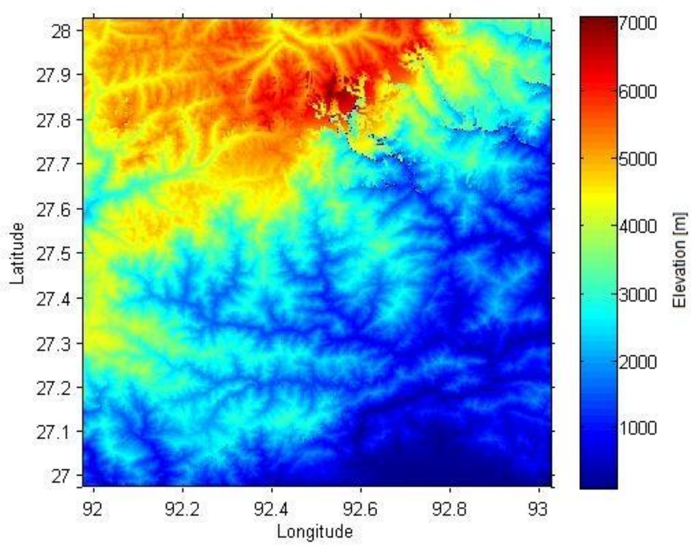


Figure 42: 250 m GMTED2010 mean elevation model in Himalayas [9]

Significant differences in surface elevation values are apparent between the image of GMTED elevation in Figure 42 and the SRTM images in Figure 40 and Figure 41. These differences appear to be coincident with specific areas of dynamic topography, which would support the hypothesis that differences in the void-filling algorithm are the probable cause of the accuracy discrepancies among the input DEMs. Figure 43 shows the elevation difference between the down-sampled SRTM-CGIAR 250 m elevation model and the GMTED 250m mean elevation product. Minor variations in elevation differences are observed in Figure 43, the majority of which appear to oscillate slightly around 0 m. These small differences are likely due to the native resolutions of the data sets used to create the down-sampled data sets – SRTM-CGIAR was down-sampled to 250 m from 90 m, while GMTED was down-sampled to 250 m from 30 m. The larger differences cannot be reasonably explained by differences in the input data sets.

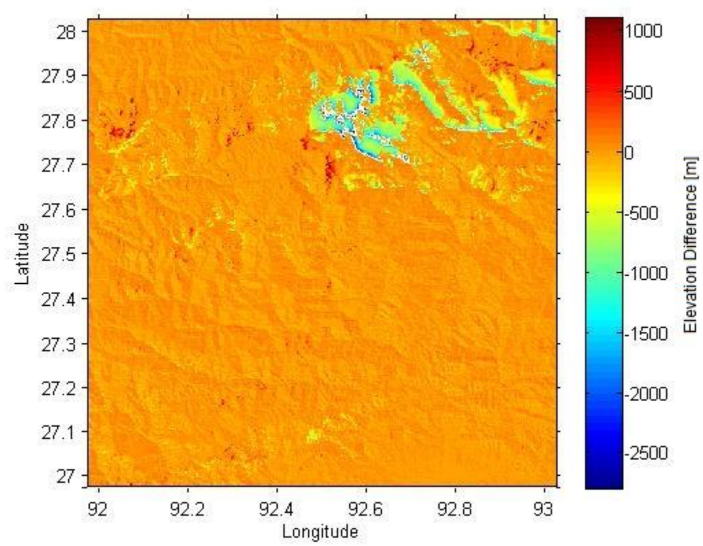


Figure 43: Elevation difference between SRTM-CGIAR 250 m DEM and GMTED2010 250 m mean DEM

Figure 44 shows the SRTM-CGIAR void mask for the same region shown in Figure 43. In Figure 44, the black areas indicate that data was available from the original SRTMv2.0 data set, while white indicates that data was unavailable and the CGIAR algorithm has to be used to fill the voids. Comparing Figure 43 and Figure 44, it is apparent that the areas of largest difference between the two sets coincide with the areas where the original SRTMv2.0 data set had voids.

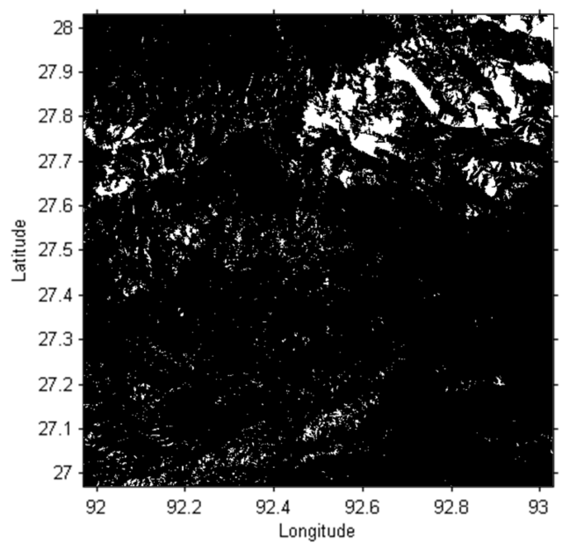


Figure 44: CGIAR void-filling mask indicates where SRTMv2.0 contained voids that required filling by CGIAR algorithms

The comparison between the accuracies obtained from the three data sets indicates that resolution of the input data set does have an effect on DRM accuracy, especially in regions of high relief. However, regional accuracy of the input DEM elevations has a greater impact on the accuracy of the DRM than does the resolution of the input DEM. This result suggests that when two data sets are available of similar accuracy but differing resolutions, it is preferable to use the higher resolution data set. Alternately, if the higher resolution data set is of poorer quality than the lower resolution product, it may be preferable to use the lower resolution data product. The second case would require a more specific analysis to determine the individual effects of resolution and accuracy on the output databases.

5.4 Implementation of Accuracy Analysis in Receiver Algorithm

The accuracy of the DRM greatly affects the data volume of the telemetry as it impacts the padding that is added to DRM relief when setting the size of the telemetry band. The total telemetry band for any area consists of the relief, which is first scaled based upon values selected from a table depending on upon the surface type, and then padded using values selected from a table depending on both the surface type and the magnitude of the relief. The scaling and padding are included to compensate for uncertainties in the values of relief in the DRM as well as location of the signal [4].

Values of padding for the relief have been set based on the results of the accuracy analyses presented here. Current values of padding based on surface type are shown in Table 15 [4].

Table 15: Values of padding used to increase the size of the telemetry window by the receiver algorithm

	Padding			
Relief, R	Ocean	Land	Sea Ice	Land Ice
$0m \leq R \leq 189m$	±15m	±24m	±15m	±24m
$189m < R \leq 567m$	±15m	±150m	±15m	±150m
$567m < R \leq 1323m$	±15m	±210m	±15m	±210m
$R > 1323m$	±15m	±510m	±15m	±510m

Chapter 6: Data Mosaicking

No single elevation data source exists that provides global coverage at a sufficient resolution for generating the ATLAS onboard DEM and DRM databases. As such, several regional elevation products have been selected to mosaic together in order to produce the desired global databases. While this has the advantage of allowing for the selection of the best available data source for any given area, it does present a new set of challenges. This section provides an overview of these concerns and will also discuss the mitigation approach for each specific issue.

6.1 Managing the 2 km Overlap

According to one of the requirements that specifically pertains to the construction of the onboard DEM and DRM, each tile must include a 2 km overlap with its neighboring tiles. The overlap is necessary to accommodate both the speed with which the satellite moves across the ground, as that affects the geospatial coverage and the accuracy with which the onboard algorithm can compute the latitude and longitude of the laser spots. Two things must be considered when processing the databases to account for the 2 km overlap: how to define subsets of the input data sets to accommodate the overlap during processing, and how to process the overlap for tiles located near the boundaries of a data set's coverage (i.e. a 1°x1° tile produced from SRTM-CGIAR at 59° N would not have a northern border, as the coverage limit is 60° N).

In order to allow for database generation over large areas and to accommodate the overlap, subsets of the input data sets, referred to here as grids, are defined in pre-processing and saved as intermediate data products. For the SRTM-CGIAR data set, the elevation data is distributed in 5°x5° tiles, making that the natural choice for the size of the intermediate subsets. To account for the overlap, an additional 0.5° border is added to each edge of every tile, making the final size of the intermediate SRTM-CGIAR subsets 6°x6°. For data sets distributed in 1°x1° sections, multiple grids are mosaicked together and saved as an intermediate data product. The size of the intermediate grids is chosen based on convenience and processing memory capacity; larger grids are easier to work with as more tiles can be processed at once, but the size of the grids (particularly when working with high-resolution data) is limited by available memory of the software. Regardless of the defined size of the subset, a 0.5° border is present on all edges of the grid. The extra border enables calculation of a 2 km overlap up to 87° N/S. The length of a degree of longitude decreases with the cosine of the latitude; the length of 0.5° of longitude decreases from 55 km at the equator to 2 km at 87.9° N/S.

Along the edges of data sets, the 0.5° border must be retrieved and patched together with other data sources. In cases where the two data sources have unequal resolutions, the data set being used to facilitate the border is resampled to a resolution matching that of the other data set. This approach is of greatest concern specifically along the northern edge of the SRTM-CGIAR data set, which is limited to providing coverage between 60° N/S. The data set used to create the northern border for any given tile along the northern edge of SRTM-CGIAR is the same data set used to produce the databases in the tiles to the north of 60° N. GMTED is the primary elevation data source for the areas north of 60° N, excluding Greenland, and is used to create a northern border for all but two of the SRTM-CGIAR elevation grids. The northern 2 km border for the remaining two SRTM-CGIAR grids is generated from GIMP 90m elevation data. The borders for the grids along the southern edge of the SRTM-CGIAR data set do not require a supplementary data set as the overlaps can be filled with ocean elevation values. Since SRTM-CGIAR is referenced vertically to the EGM96 geoid, the ocean values can be uniformly set to zero elevation. CDED is the only other data set within the global database that required a secondary data set to fill in along the borders. GMTED is used to fill in a 0.5° overlap along the Canada and Alaska border.

6.2 Vertical Datum Conversion

Requirements on the DEM database state that all elevations must be referenced to the WGS84 ellipsoid. However, since only the GIMP product provides elevations vertically referenced to WGS84 all of the other input DEM data sources require a conversion to the desired ellipsoid.

Elevations referenced to the geoid, h_{geoid}, can be converted to elevations relative to the ellipsoid, $h_{ellipsoid}$, by adding the height of the geoid above the ellipsoid at the relevant location, d_{geoid}, to the geoid elevation:

$$h_{ellipsoid} = h_{geoid} + d_{geoid} \tag{28}$$

Geoid heights for various geoid models are referenced by values of latitude and longitude. The geoid models are generally provided at resolutions far below that seen in elevation products; EGM96 is published at a 15 arc-minute spacing (equivalent to a resolution of 0.25°x0.25°) while EGM2008 is published at a spacing of 2.5 arc-minutes. Geoid heights at a particular geolocation are obtained through two-dimensional interpolation of the geoid height grid [23].

The SRTM-CGIAR, GMTED, and 100 m Antarctic Peninsula data sets are natively referenced to the EGM96 geoid [8] [9] [13] and must be converted to the WGS84 ellipsoid during pre-processing. To do accomplish the conversion, grids of EGM96 geoid heights are obtained from the publicly available geoid height model at the resolution of the geoid model. Geoid heights at the full resolution of the input elevation data set are interpolated from the geoid model using MATLAB's *interp2* function. The output from *interp2* function is rounded to the nearest meter, and added to the elevations in the input data set to get ellipsoidal elevations. Once converted, the newly converted elevation grids can be input into the functions that generate DEM tiles. Note that while geoid elevations must be converted to ellipsoid heights before producing the DEM, it is not necessary to convert geoid elevations to ellipsoid elevations before generating relief maps for the DRM. Relief calculations are only concerned with relative elevation differences, so the vertical datum is irrelevant. Additionally, the geoid fluctuates on much longer length scales than what is considered for the DRM [23], i.e. the geoid can be considered constant along a 140 m or 700 m flight path segment.

The 1 km Bedmap2 data set is originally referenced to the GL04C geoid [12]. However, the developers of Bedmap2 developed a map (shown in Figure 45) for use during production to convert ellipsoid heights to geoid heights and vice versa. The conversion map is conveniently provided alongside the other Bedmap2 products and is used here as a resource to obtain elevations relative to the WGS84 ellipsoid. The ellipsoidal elevations are calculated by adding the conversion map heights to the geoid elevations and rounding to the nearest meter [12].

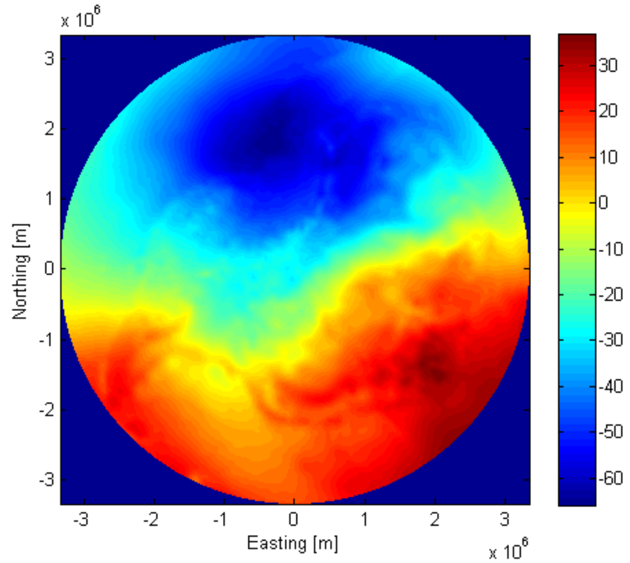


Figure 45: Bedmap2 conversion grid for transforming GL04C elevations to the WGS84 ellipsoid

6.3 Northern Latitudes Data Selection

Two input data sets are available for the areas north of 60° N, minus Greenland. The first input DEM option is to use the 3 arc-second CDED product for Canadian territory north of 60° N and use the ASTERv2.0 30 m product for Scandinavia, Russia, and Alaska. The second DEM production option is to use GMTED 250 m products everywhere north of 60° N except Greenland. DEMs and DRMs were created for each of the options to allow for a comparison between the data sets and the opportunity to determine the best approach.

Initially, it was thought that the first option would be preferable as the data sets are available in higher resolutions. However, significant issues arose in working with the ASTER product. Large elevation spikes and pits were present throughout the data, which also showed artifacts along the ground track of the satellite and contained numerous void areas. Void areas can be filled using interpolation prior to processing, but no established fixes are available for the other issues at the present time. The resulting DEM grids using the ASTER data showed large variations in minimum and maximum elevations that did not appear to correlate with actual or realistic topographical formations. The resultant DEM also required many unnecessary secondary and tertiary DEMs based on the false extremes in elevation in order to satisfy the range window requirements. To provide graphical representation of the effects on the DEM, primary DEM maximum and minimum grids obtained from ASTER over Russia are shown in Figure 46 and Figure 47.

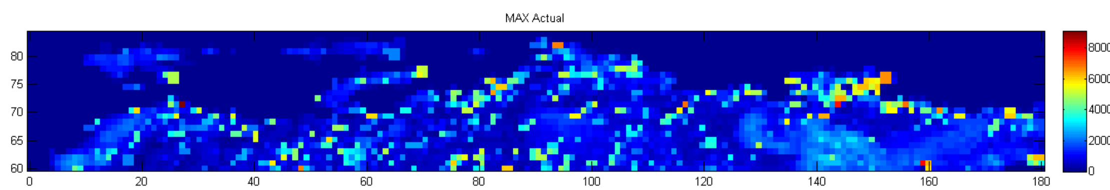


Figure 46: DEM Actual Maximum elevations (in meters) obtained over Russia from ASTER GDEM

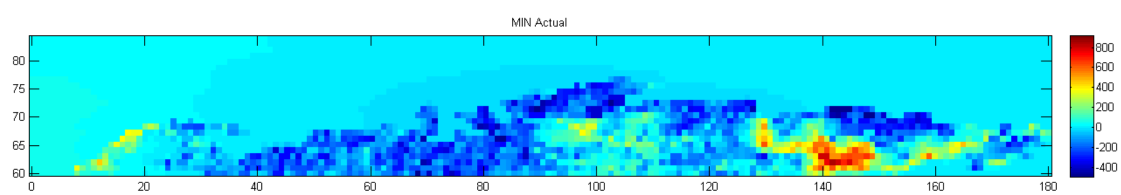


Figure 47: DEM Actual Minimum elevations (in meters) obtained over Russia from ASTER GDEM

The pits and spikes present in the ASTER data present a particular challenge in producing the DEM, since the construction relies on the elevation extreme values rather than some other geospatial statistic. These erroneous extreme values in ASTER insert themselves in the production processing of the DEM, creating false maximum and minimum elevations. Similarly, the 100th percentile DRM created using the ASTER input shows areas of unrealistic extreme relief, as shown in Figure 48.

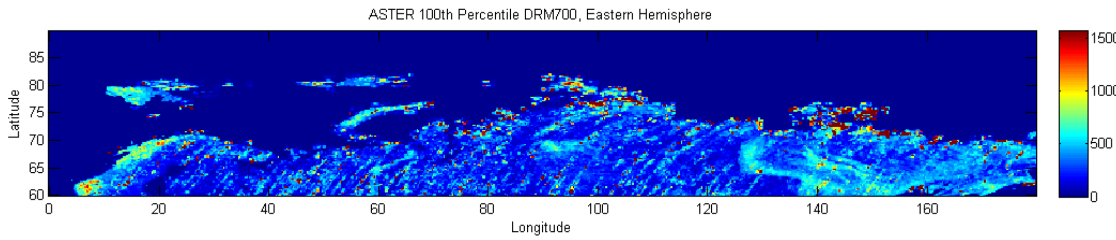


Figure 48: DRM-700 100th %ile relief values (in meters) over Russia obtained from ASTER GDEM

In order to investigate an additional input DEM option, DEM tiles were generated from the GMTED 250 m maximum and minimum elevation layers and DRM tiles were produced from its mean elevation layer for comparison to the similar products produced using ASTER. DEMs produced from GMTED showed no evidence of spikes or pits nor were there any unnecessary secondary or tertiary DEMs required due to false elevation extremes. The DRMs produced from the GMTED 250 m input appeared, upon examination, to be more representative of actual terrain. For comparison to the data shown in Figure 46 and Figure 47 for the derived ASTER products, the primary DEM maximum and minimum grids obtained from GMTED for the same region over Russia are shown in Figure 49 and Figure 50.

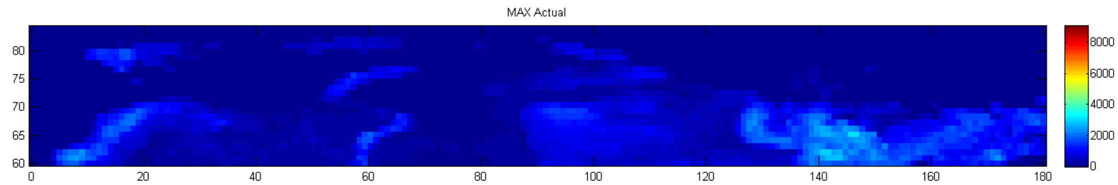


Figure 49: DEM Actual Maximum elevations (in meters) obtained over Russia from GMTED2010. Note that the color scale used is the same as that used in Figure 46

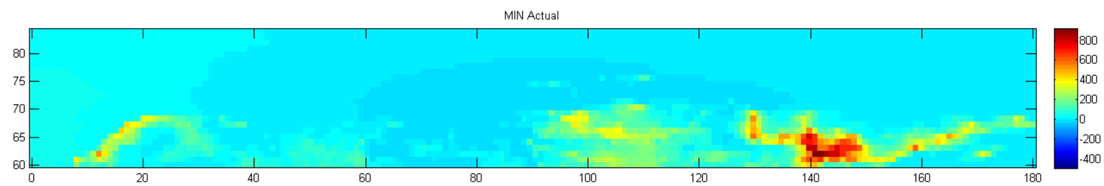


Figure 50: DEM Actual Minimum elevations (in meters) obtained over Russia from GMTED2010. Note that the color scale used is the same as that used in Figure 47

Over Canada, the DEMs and DRMs produced from CDED and GMTED inputs showed remarkable similarity. Except for a few areas of high relief, GMTED DRMs gave larger relief values than the CDED DRMs, which is a likely result of the difference in resolution between the two data sets. A plot of the difference between the 100th percentile CDED DRM-140 and the 100th percentile GMTED DRM-140 is shown in Figure 51.

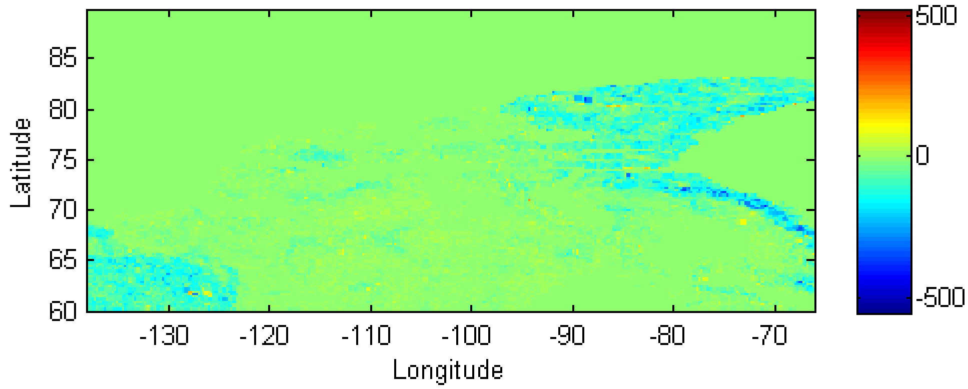


Figure 51: Difference between CDED and GMTED2010 100th %ile DRM-140 values

Differences between the DRMs produced from CDED and GMTED oscillate around 0 m across most of the region for both the DRM-140 and DRM-700 indicating that the resolution of the data set has minimal effect on the resulting DRMs. As such, GMTED can be used to generate DEMs and DRMs for all areas north of 60° N (except Greenland) without having to compensate for its decreased resolution. After comparing the databases produced from ASTER, CDED, and GMTED, GMTED was selected as the sole data source for production of the onboard DEM tiles north of 60° N. For the DRM tiles produced for north of 60° N, a hybrid approach is used – GMTED is used for all of Alaska, Canada, and Eurasia, but CDED relief values are used in place of GMTED relief values for those tiles over Canada where CDED relief is greater than GMTED relief. Note that GIMP is the sole source used for both the DEM and DRM over Greenland.

6.4 Global Mosaicking

For most of the globe, mosaicking the various data sets together is a simple process and can be done after the DEM and DRM tiles have been generated for the independent sources. The border between SRTM-CGIAR and GMTED, for example, is a straight line, so the DEM and DRM tiles can be placed side-by-side in a global grid subsequent to independent processing for each data set. To mosaic together the tiles created from SRTM-CGIAR, GMTED, GIMP, and the two Antarctica data sets, empty global grids are first created for all three levels of the DEM and both versions of the DRM. Then, the saved output files from each data set are read through and placed into the appropriate locations in the established global grid. After this process, any remaining empty tiles are assumed to be ocean and filled in with the appropriate values.

The only instance where this approach does not work is over northern Canada and Greenland, where Ellesmere Island and the northwest coast of Greenland come very close to each other. GIMP is only defined over Greenland [11], and neither GMTED nor CDED contain any data for Greenland [9] [18], so there is no overlap between the products. However, several DEM tiles in the region contain land in both Canada and Greenland.

Because of the lack of overlap between the GMTED and GIMP data sets, it is not possible to mosaic the tiles together after the DEM tiles have been processed independently. Therefore, it is necessary to combine the two data sets together using GIS software, such that output DEM tiles can be processed using elevations from both products. The data mosaicking of CDED and GIMP elevations over Ellesmere Island and northwest Greenland was accomplished using ENVI. The resulting elevation model is shown below in Figure 52.

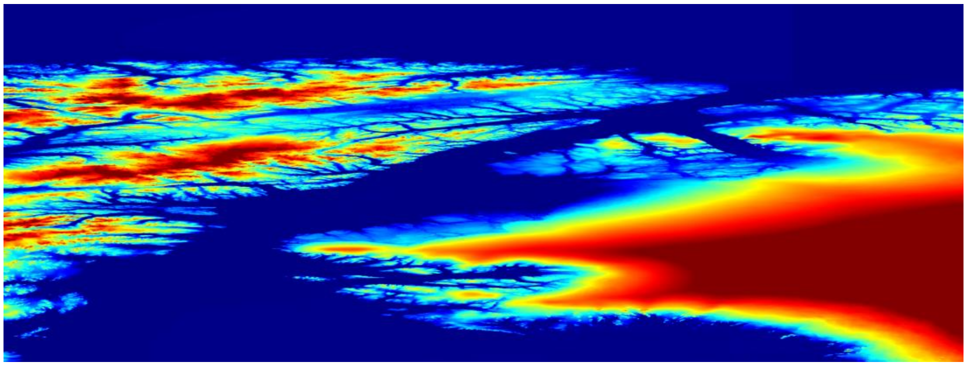


Figure 52: 90 m resolution elevation model of Ellesmere Island and Greenland produced from CDED and GIMP elevation data in a geographic projection

CDED was used in place of GMTED in this instance as it was not possible to blend the maximum and minimum layers needed for the DEM with the mean elevations from GIMP. Regardless, CDED was used as the basis for the GMTED products in Canada, so the resulting DEM tiles would be calculated using essentially the same data. DEM tiles were then generated from the high-resolution mosaicked elevation product and inserted into the global grids in the same manner as the DEM tiles from the other data sets. It was not necessary to use the CDED-GIMP mosaic to produce the DRM tiles for this region as the values for a DRM tile could be set to the larger of two DRM tiles produced independently from CDED and GIMP.

6.5 Oceans Procedure

As stated previously, several of the input data sets are distributed on the EGM96 geoid. By setting all ocean values to be zero in these data sets, the elevations resulting after the geoid to ellipsoid conversion result in geoid heights being used in the DEM over the oceans. While the actual ocean surface does vary significantly from the geoid values, the mean dynamic topography of the ocean (Figure 53) varies on the order of ±2 m, which is well within the padding values used for ocean in the receiver algorithm [24].

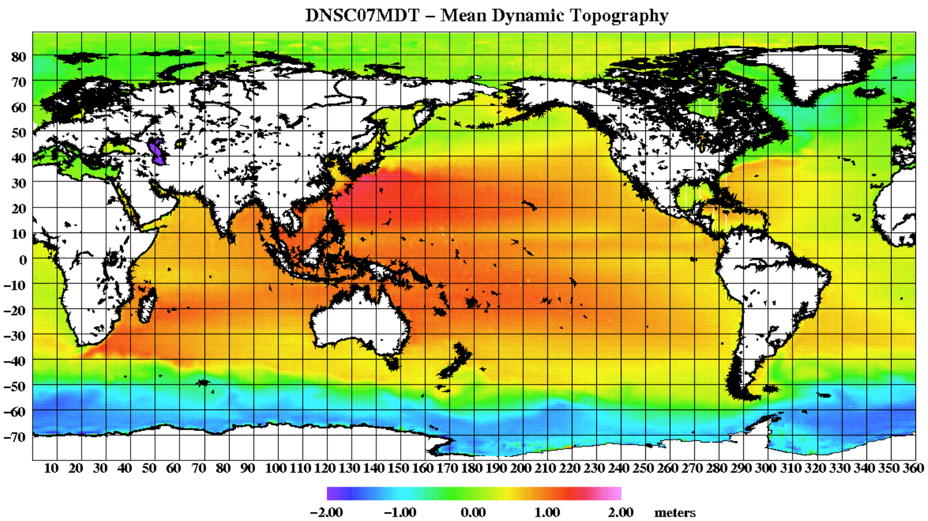


Figure 53: Mean Dynamic Topography of the ocean relative to the EGM2008 geoid model

With regard to the ocean data, the ATLAS Science Definition Team (SDT) has requested that the values used in the DEM for ocean tiles be derived from EGM2008 geoid heights above the ellipsoid, not EGM96 geoid heights. For SRTM-CGIAR, this would be a relatively easy switch as all ocean cells are masked out in the distributed product. For GMTED and CDED, however, oceans are simply marked as zero. Assuming all zero values are ocean cells would not be valid, so another approach must be taken.

Instead of converting ocean values to EGM2008 prior to processing the DEM, the DEMs are instead processed in their native geoids. After the global grids have been mosaicked together, tiles containing ocean values are checked to ensure that the range window fully captures the EGM2008 geoid heights. Differences between the two geoids are on the order of ±12 m, but the largest differences occur over land masses, Antarctica in particular. Over the oceans, differences between the geoids are generally on the order of ±2 m. The differences in meters between EGM2008 and EGM96 are shown in Figure 54.

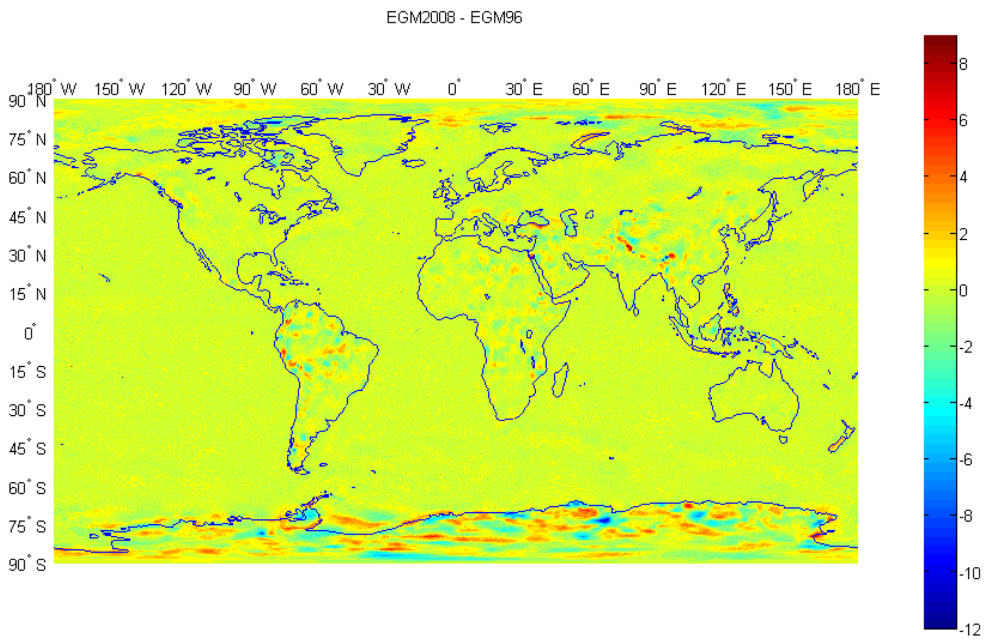


Figure 54: Difference in meters between EGM2008 geoid model and EGM96 geoid model

Ocean geoid heights are checked in post-processing using an intermediate Surface Reference Mask land product. The intermediate land mask is a 0.25°x0.25° binary grid in which a tile is marked as 1 if any land is present within the tile and zero if only ocean is present. The land mask contains a 2 km overlap similar to that employed in the DEM and DRM. For every 1°x1° tile in the DEM, a tile is considered ocean if none of the 16 0.25°x0.25° land mask tiles within the area are marked land. If the 16 tiles are a mix of land and ocean, the DEM tile is considered coastline, and if all mask tiles are land, the DEM tile is considered to only contain land. The intermediate land mask used for the ocean checks is shown in Figure 55.

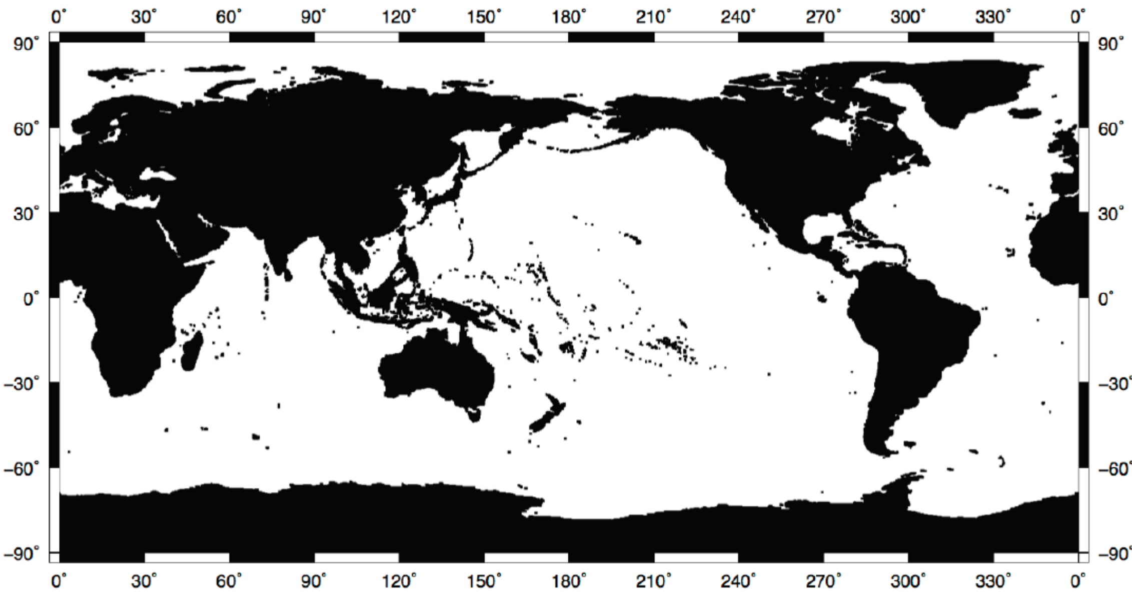


Figure 55: An intermediate land mask, designed for the production of the Surface Reference Mask, is used to define whether or not DEM and DRM tiles should be classified as ocean or land

For all DEM tiles that are identified as ocean by the intermediate land mask, both the minimum and maximum heights are checked against the EGM2008 geoid. If either of the minimum or maximum EGM2008 geoid heights for a given tile is outside the current range window, the range window is widened to include the EGM2008 values. The size of the range window is never narrowed, only widened. For DEM tiles tagged as coastline by the intermediate land mask, only the minimum DEM elevation is checked against the geoid. If the minimum EGM2008 elevation in that area is outside the range window, the minimum DEM value is replaced with the EGM2008 elevation. Again, the range window cannot be decreased by the ocean height check, only increased. Any DEM tiles identified as land only by the intermediate land mask are unchanged by ocean height checks. While some of these tiles may in fact have some ocean within their borders, the effect of disregarding the minimum ocean height check in these cells is expected to be minimal considering that the minimum values are rounded down during encoding and that the elevation differences would be entirely compensated for in the receiver algorithm by DEM and DRM padding.

An additional ocean check is performed on the DRM during post-processing in order to ensure that the DRM is uniformly zero over the oceans. In some isolated tiles, the relief maps used to calculate the DRM can contain a few values of relief equal to one. These values occur along contours where the rounded geoid heights change in value by one meter. The 0.25°x0.25° intermediate land mask is used to check every tile in the DRM-140 and DRM-700. If the tile is marked land, no action is taken to modify the DRM, if a tile is marked ocean and the value of the 100th percentile DRM is equal to 1, then the values of the 95th-100th percentiles are all set to be equal to zero. If the relief is greater than 1, it is assumed that some small area of land is present in the tile and causing larger than expected relief, and the values are left unchanged.

Chapter 7: Database Generation and Final Products

This section describes the details of how the global databases are generated from the various input data sets. The specifics of how relief is calculated and how individual DEM and DRM tiles are processed can be found in Section 3.0 and Section 4.0.

7.1 Global DEM Mosaicking Procedure

Before individual DEM tiles can be processed from the input data sets, several modifications must be made to the data sets in the pre-processing phase. These modifications include dividing large data sets into manageable subsets, including borders necessary for the calculation of the 2 km overlap, and converting any of the geoid referenced elevations to the WGS84 ellipsoid. After all necessary alterations and conversions have been made to the raw data sets, the initial generation of the DEM tiles can proceed. The global DEM is assembled after DEM tiles have been generated from each individual source data set.

After DEM tiles have been generated for each of the input data sets, the global DEM can be mosaicked together from those tiles. Global matrices are initialized with NaN values for each of the three tiers of the DEM and in each of the required output fields. The empty matrices are methodically filled in with values from the DEM tiles generated for each data set in a particular order. The specific order allows for overwriting some data with "better" data in certain regions. For example, GMTED DEM tiles are defined for all values of longitude and latitudes between 60° N and 83° N. However, the GMTED 250 m elevation products do not contain any elevation data over Greenland, so the DEM tiles for that area are filled with geoid height data instead of the true elevations. By filling in the GMTED data first, and the GIMP data second, the erroneous DEM values are overwritten by the correct values.

The global DEM is filled from the individual DEM tiles in the following order:

1. GMTED
2. GIMP
3. CDED-GIMP Mosaic
4. Bedmap2 and Antarctic Peninsula
5. SRTM-CGIAR
6. EGM2008 Geoid

GMTED data is filled in first, such that the appropriate tiles can then be overwritten with GIMP tiles. The CDED-GIMP mosaic data is then used to overwrite the GMTED and GIMP DEM tiles from 74° W to 60° W and 72° N to 83° N. Next the DEM tiles pulled from the joint Bedmap2 and Antarctic Peninsula histograms are filled in, followed by SRTM-CGIAR DEM tiles. SRTM-CGIAR is written last as it is the preferred data product and should overwrite any DEM tiles that may have already been filled between 60° N/S. Finally, any DEM tiles in the primary global DEM matrix still containing NaN values after all data sets have been processed are assumed to be ocean tiles and are filled with EGM2008 geoid heights. The secondary and tertiary global DEM matrices will still contain NaN values as only those areas requiring secondary and tertiary DEMs will contain valid elevation data.

Individual DEM tiles are filled into the global grid a line at a time. The level of the tile is checked first, to determine if the data should be placed into the primary, secondary, or tertiary global DEM matrices. The latitude and longitude of the tile are then used to find the corresponding indices in the global grid based on location. Each value, in the individual line of DEM output is placed into the appropriate position within the global matrix The end result after this process is a global matrix product that includes actual maximum and minimum elevations, encoded maximum and minimum elevations, a flag to indicate whether or not the range window exceeds the specified limit, and numerical codes that indicate the data sources used in the global product generation. Source codes are not provided in the DEM output files by the majority of the input data sets. Instead, the source code matrix is filled in alongside the elevation values. For example, if the global DEM is being filled with SRTM-CGIAR, the source code for those tiles is set to 1, while if GMTED is being used, the source code is set to 2, and so on as tiles are superseded by elevations from the corresponding data source.

Once the DEM tiles for all the input data sets have been filled in, the intermediate land mask derived for the SRM product is used to check that all ocean values fully capture the range of elevations consistent with the EGM2008 geoid. This is necessary as the majority of the data sets are not originally referenced to the EGM2008 geoid, so the ocean values would not necessarily give elevations consistent with EGM2008 geoid heights. Two .mat files were created to enable the checking of ocean values in the DEM. The first contains the 0.25°x0.25° resolution intermediate land mask used for the SRM, and a 1°x1° resolution ocean reference grid that has been resampled from the intermediate land mask. For each 1°x1° tile, if all 16 tiles in the intermediate land mask are ocean, then the value in the reference grid is set to zero, indicating only ocean is present. If the 16 tiles are a mix of land and ocean cells, the value in the reference grid is set to 1 to indicate coastline, and if all 16 tiles indicate land, the value in the reference grid is set to 2 to indicate that only land is present within the tile. This grid is used to determine which values in the global DEM must be checked. The second .mat file contains a global 1°x1° DEM with 2 km overlap created solely from EGM2008 geoid heights. This enables quick checking of the minimum and maximum values in the DEM without needing to recalculate the geoid heights from the geoid model for each tile.

For each tile in the primary DEM, the reference grid is used to determine whether the area is ocean, coastline, or land. If the area is land, no further effort is required and the evaluation moves on to the next tile. If the area is coastline, the minimum elevation in the DEM is compared to the minimum elevation in the geoid-only DEM. If the minimum elevation in the geoid-only DEM is less than the current DEM minimum elevation, the minimum elevation in the global DEM is changed to match the minimum elevation in the geoid-only DEM. The encoded minimum elevation in the global DEM is recalculated from the new minimum elevation value, and the new encoded range between the minimum and maximum DEM is checked to make sure that the total encoded range is still less than 5500 m. The minimum DEM source flag is then set to 7, indicating that geoid heights were used to calculate the minimum DEM values for that tile. If the area is marked as ocean, both the minimum and maximum elevations from the global DEM are compared to the minimum and maximum elevations in the geoid-only DEM. If either of the geoid-only DEM elevations exceed the minimum and maximum elevations as defined by the global DEM, those values are adopted In other words, the minimum and maximum values are only changed when the EGM2008 values lie above the maximum elevation or below the minimum elevation derived from the land DEMs, such that the maximum elevations can only be raised and the minimum values can only be lowered. The encoded values in the global DEM are recalculated using the new minimum and maximum elevations (if necessary), and the maximum DEM and minimum DEM source codes are set to 7 to indicate that geoid heights were used to generate the maximum and minimum DEM heights for that tile. It is necessary to reset both source codes as the ocean tiles in most areas would have previously been set to the source code used to fill in the land elevation data in the region (i.e. ocean tiles between 60° N/S would be marked SRTM-CGIAR, not EGM2008). Note that the ocean checks are only necessary to ensure that the

DEM captures EGM2008 geoid heights. If no ocean checks were performed, the DEM would still provide geoid heights for ocean tiles, but for the EGM96 geoid instead of the desired EGM2008 geoid.

The final step in processing the global DEM is to compare the difference between the maximum and minimum elevations in each tile to the largest value of relief in the DRM-700 for that area. This final step must take place after the full global DRM has been computed. For a few tiles in the DEM, the range computed using the actual maximum and minimum values is slightly less than calculated relief values over the 700 m length scale in the DRM for the same area. This occasional discrepancy occurs because relief is calculated by comparing elevations of neighboring cells. For these border target cells, it is possible that elevations used to calculate relief for that tile are not included in the calculation of the minimum and maximum elevations for the DEM. This type of calculation inconsistency will sometimes cause the 700 m relief to exceed the DEM range in some instances. While this difference would not affect the implementation of the databases in the receiver algorithm, the DEM range should completely capture the relief for the sake of consistency between the DEM and DRM databases. As such, the actual (not encoded) range window for each primary DEM tile is compared to the largest value seen across all 16 DRM-700 100th percentile relief tiles in the same area. If the relief exceeds the DEM range, half of the difference is appended to each end of the range window. In other words, the maximum elevation value in the DEM for that tile is raised by half the difference, while the minimum elevation in the DEM for that tile is lowered by half the difference. New encoded maximum and minimum elevations are computed, and the encoded DEM range is computed to verify that the elevation difference is still less than 5500 m. Should the range limit be exceeded, secondary and tertiary DEMs would have to be computed by hand and inserted into the global DEMs. Using the current sources, no instances where this would be necessary have occurred.

The global DEM matrices are then saved as .mat files and exported to text files. Separate text files are created for each level of the DEM. One header line is printed to each file containing the titles for each column:

```
Level     Latitude     Longitude     MaxE_Act     MinE_Act
     MaxE_Enc    MinE_Enc   Flag   Max_Source   Min_Source
```

The appropriate values are then printed from the global DEM to the text file. Tiles are printed from south to north starting at 90° S, then from west to east starting at 180° W. All tiles for each value of latitude at a single value of longitude are printed before moving to the next value of longitude. For secondary and tertiary DEMs, only values for which non-NaN elevations are present are included in the output text files. Values are printed in the same order as the primary DEM, so the 16 secondary DEM tiles associated with a particular primary DEM tile may not be adjacent to one another in the output text files. The DEM database is delivered to the Receiver Algorithm team in this text file format.

7.2 Final Global DEM

The final global DEM database is plotted in the figures below. Figure 56 and Figure 57 show actual maximum and minimum elevations. Figure 58 and Figure 59 show the encoded maximum and minimum elevations.

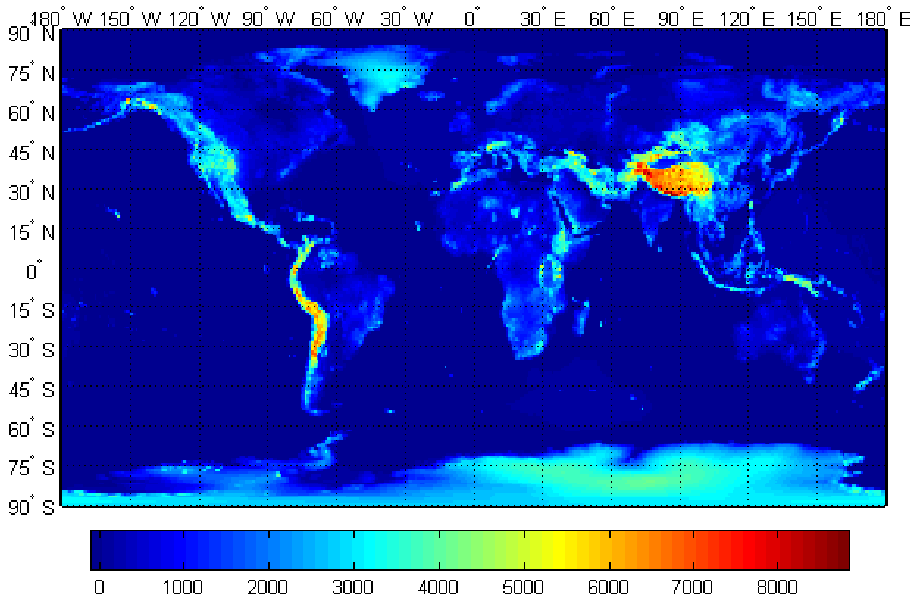


Figure 56: Global Primary DEM: Actual Maximum Elevations in meters

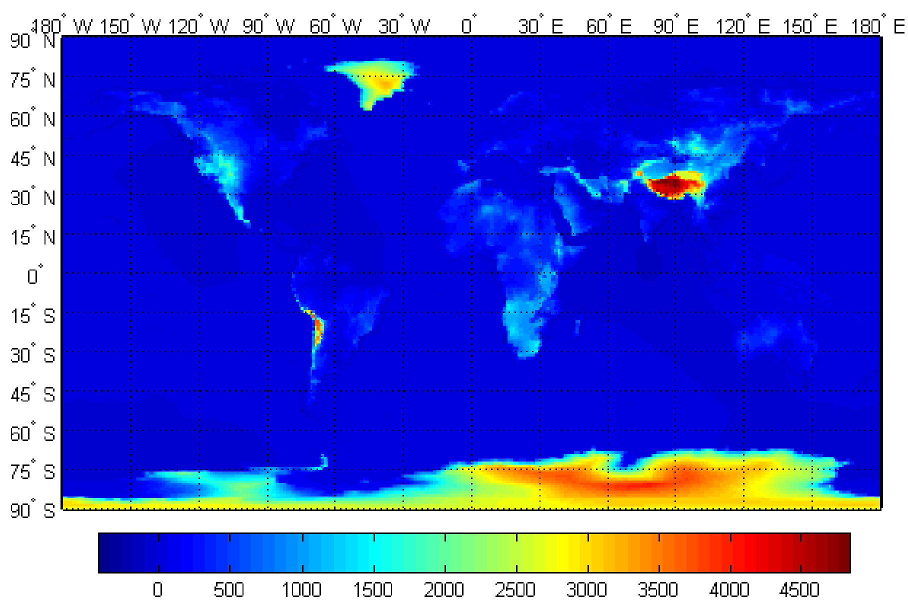


Figure 57: Global Primary DEM: Actual Minimum Elevations in meters

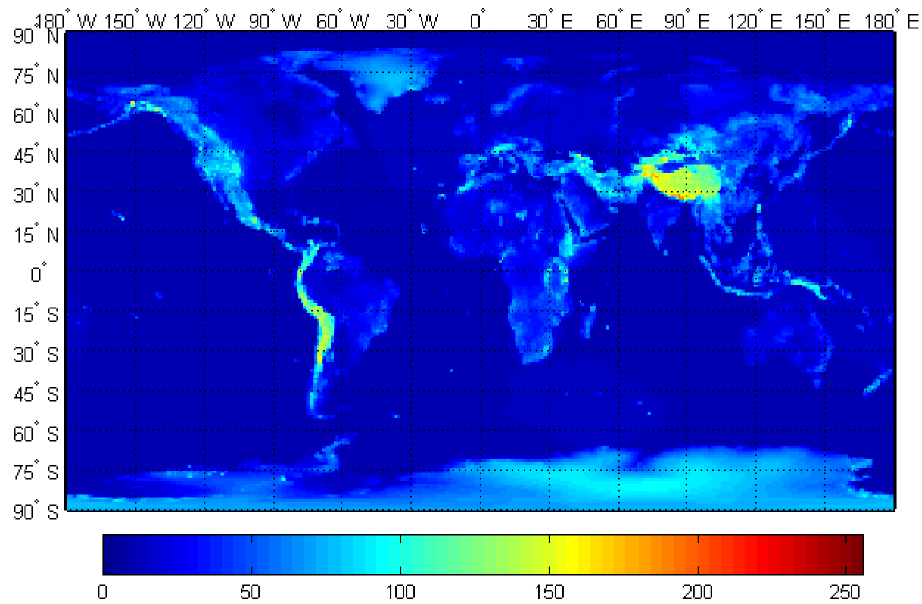


Figure 58: Global Primary DEM: Encoded Maximum Elevations

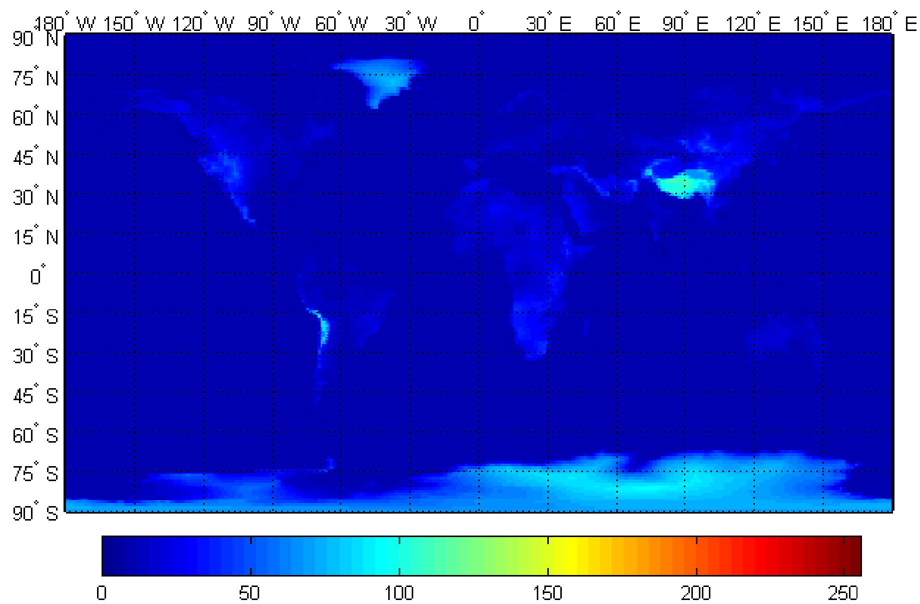


Figure 59: Global Primary DEM: Encoded Minimum Elevations

Figure 60 is a plot of the primary DEM tiles that require the production of a secondary DEM. Those tiles requiring a secondary DEM are marked in white.

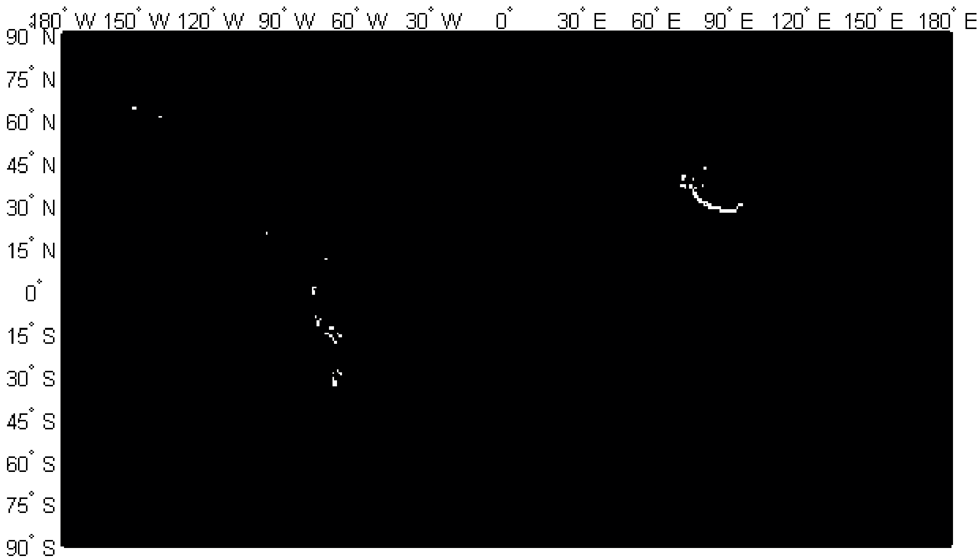


Figure 60: Global Primary DEM: Flagged primary DEM tiles

Figure 61 and Figure 62 show the distribution of sources used to generate the global maximum and minimum DEM.

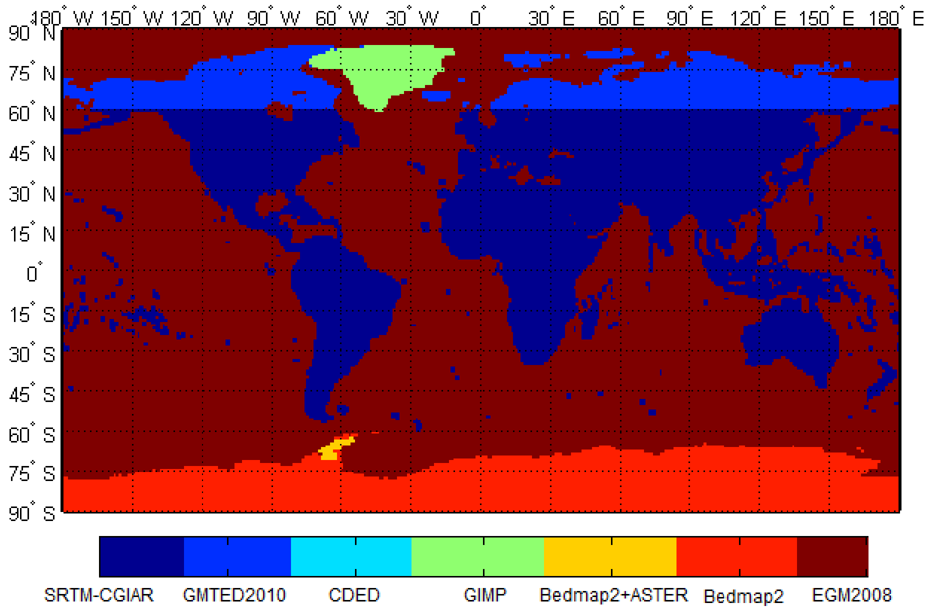


Figure 61: Global Primary DEM: Maximum DEM Source Codes

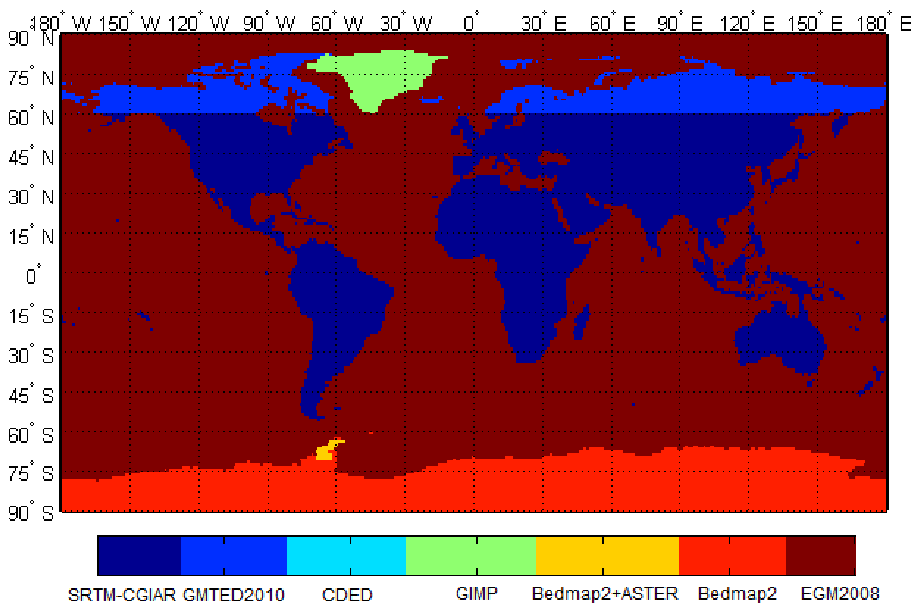


Figure 62: Global Primary DEM: Minimum DEM Source Codes

7.3 GLOBAL DRM MOSAICKING PROCEDURE

Much of the pre-processing necessary for the production of the DEM is also required for the production of DRM. In the mid-latitudes and in Antarctica, no additional modifications need be made to the elevation grids before processing relief. North of 60° N, however, some elevation grids must be re-projected to stereographic projections and FPO zone maps must be generated before relief can be computed. The relief maps must then be re-projected back to a geographic projection so that the DRM can be generated from the relief data. After all relief maps have been computed for an input data set, DRM tiles are computed for each relief map. The global DRM is generated by mosaicking these individual DRM tiles together.

After DRM tiles have been generated for each of the input data sets, the global DRM can be mosaicked together from those tiles. Global matrices are initialized with zero values for each of the percentiles specified in the DRM-140 and DRM-700 and each of the required output fields. The zero values in the matrices are overwritten by values from the DRM tiles generated for each data set. The global DRM is filled in a particular order, such that some values can later be overwritten, if appropriate. For example, DRM tiles have been produced for GMTED and CDED over Canada. GMTED DRM tiles are filled in first, and CDED DRM tiles are used to overwrite the relief values when CDED relief is greater than GMTED relief.

The global DRM is filled from the individual DRM tiles in the following order:

1. GMTED
2. GIMP
3. CDED
4. Bedmap2 and Antarctic Peninsula
5. SRTM-CGIAR

GMTED data is filled in first, followed by GIMP data. When GIMP data is inserted into the global grid, every tile is checked to ensure that the values being written to the global DRM are greater than the value currently in the tile. For most tiles, the relief will be zero, but tiles near the strait separating Ellesmere Island and Greenland may already contain non-zero relief values. CDED data is then compared to the existing values in the global DRM. For any tile in the DRM-140 global matrix where the 100th percentile CDED DRM-140 relief is greater than the 100th percentile GMTED DRM-140 relief, all DRM-140 relief percentiles for that tile are overwritten with CDED relief values. This also holds true for the DRM-700, although the tiles in the DRM-140 that are overwritten with CDED may not necessarily be overwritten in the DRM-700, and vice versa. Next the DRM tiles pulled from the joint Bedmap2 and Antarctic Peninsula relief histograms are filled in, followed by SRTM-CGIAR DRM tiles. SRTM-CGIAR is written last as it is the preferred data product and should overwrite any DEM tiles that may have already been filled between 60° N/S.

Note that for regions where multiple input DEM sources are used to generate the DRM tiles (e.g. Canada), only the 100th percentile DRM values are used to select one source over another. For tiles where different sources are used for the DRM-140 and the DRM-700, it is possible that the DRM-140 value would be greater than the DRM-700 value for percentiles between the 95th and 99th percentiles. This is due to differences in the histograms used to generate the relief percentile values. The DRM-140 and DRM-700 are delivered without modifications to the percentile relief values. It is left to the Receiver Algorithm team to determine if and how to modify the delivered DRMs in such a case as that would be necessary.

Individual DRM tiles are filled into the global grid by reading a single line of the DRM output files at a time. The latitude and longitude of the tile are then used to find the indices in the global grids associated with the location of the tile. Each value in the line of DRM output is placed into the appropriate global matrix; the end result is global matrices for 95th-100th percentiles of relief and source DEM codes for the DRM-140 and DRM-700. Source DEM codes are not provided in the DRM output files by the majority of the input data sets. Instead, the source codes are filled in alongside the relief values. For example, if the global DRM is being filled with SRTM-CGIAR, the source code for those tiles is set to 1, while if GMTED is being used, the source code is set to 2, and so on. Source DEM codes used for the DRM can be found in Table 6.

Once the DRM tiles for all the input data sets have been filled in, the 0.25°x0.25° intermediate land mask created for the SRM development is used to check that the values of relief in the DRM are uniformly zero for ocean tiles. For each 0.25°x0.25° tile, if the mask indicates land, no changes are made to the DRM. If the mask indicates ocean, then all percentile values for the DRM-140 and DRM-700 are set to zero, but only if the 100th percentile relief values is no greater than 1 m. The only tiles where ocean relief should be greater than zero are those where the rounded values of geoid heights in the tile are not uniform. The relief in these tiles should be no greater than 1. If the land mask indicates that a tile is ocean but the DRM shows relief greater than 1 m, it is assumed that there is land present within the tile's boundaries and none of the DRM percentiles are altered. Regardless of whether or not the DRM values are modified, the source codes for tiles marked ocean in the intermediate land mask are set to 7 to indicate that the area is ocean.

The final step in processing the global DRM is to add vegetation heights to all percentiles of the DRM-140 and DRM-700. The vegetation height grid used to augment the DRM contains the maximum vegetation height for every 0.25°x0.25° tile, plus a 2 km border. The vegetation height grid is a global product and of the same dimensions as the global DRM matrices, and so can be simply added to the existing relief values for each percentile.

The global DRM matrices are then saved in a .mat file named "global_drm.mat," such that the final global DRM can be used in the final processing step of the global DEM. The DRM-140 and DRM-700 are then exported to separate text files. One header line is printed to each file containing the titles for each column:

```
Latitude    Longitude    100th      99th       98th       97th
     96th      95th      Source
```

The appropriate values are then printed from the global DRM to the text file. Tiles are printed from south to north starting at 90° S, then from west to east starting at 180° W. All tiles for each value of latitude at a single value of longitude are printed before moving to the next value of longitude. The DRM database is delivered to the Receiver Algorithm team in this text file format.

7.4 Final Global DRM

The final global DRM database is plotted in the figures below. Figure 63 and Figure 64 show 100th percentile DRM-140 and DRM-700.

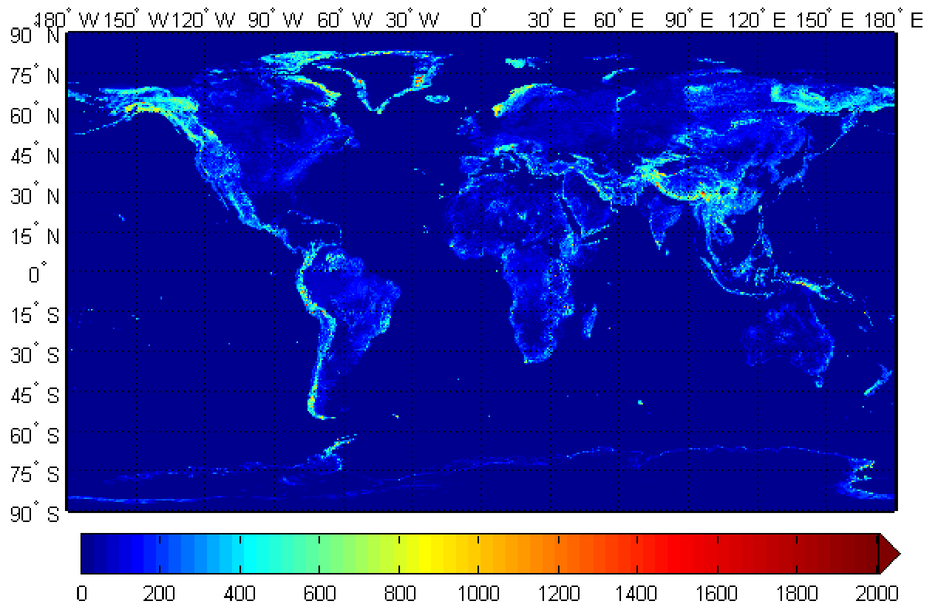


Figure 63: Global DRM: 100th %ile DRM-140 Relief in meters

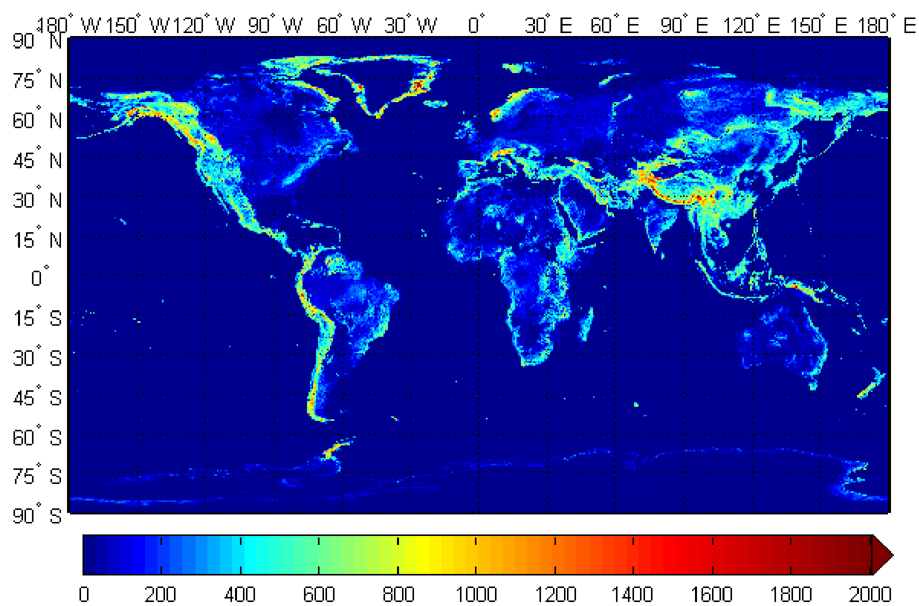


Figure 64: Global DRM: 100th %ile DRM-700 Relief in meters

To illustrate the differences in relief values for the different percentiles, histograms of relief values calculate from each percentile level of the DRM-140 and DRM-700 are shown in Figure 65 and Figure 66.

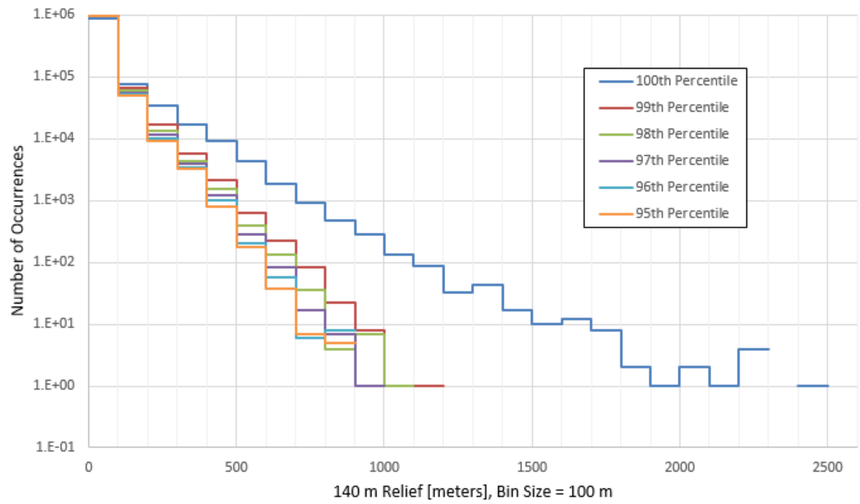


Figure 65: Histogram of DRM-140 relief values by percentile

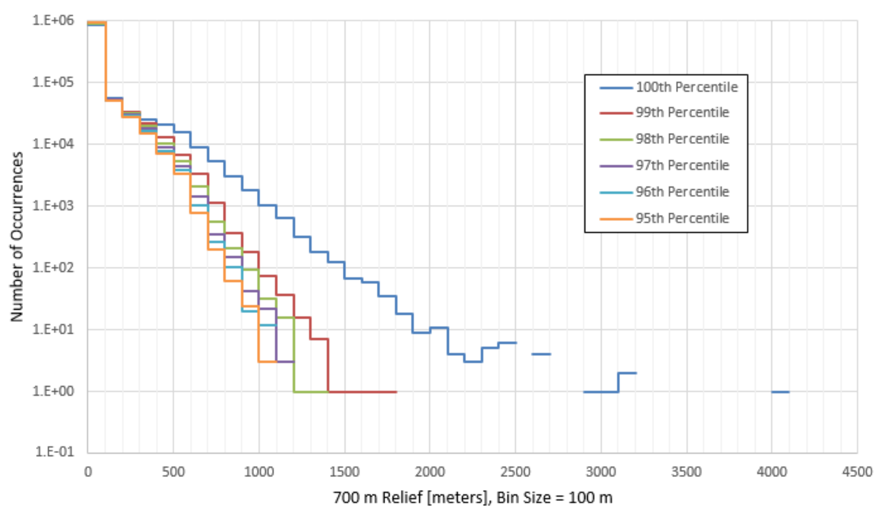


Figure 66: Histogram of DRM-700 relief values by percentile

Figure 67 and Figure 68 show the sources used to fill the DRM-140 and DRM-700.

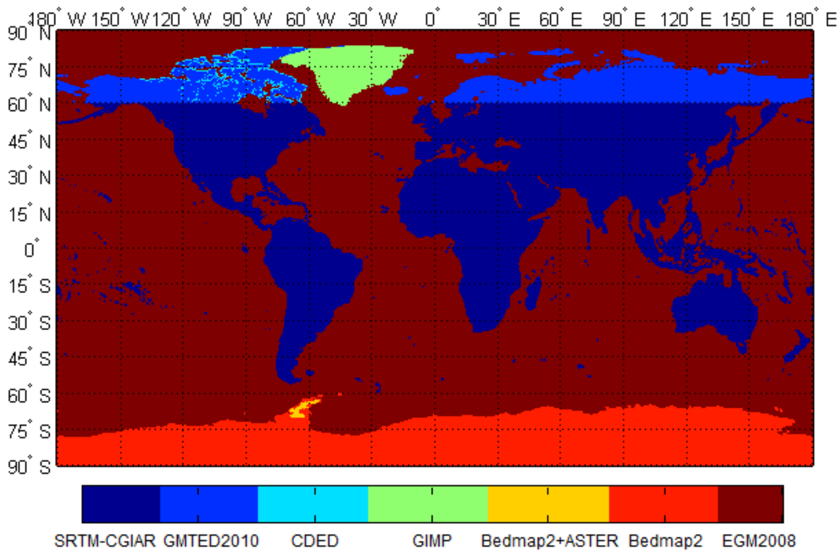


Figure 67: Global DRM: DRM-140 source codes

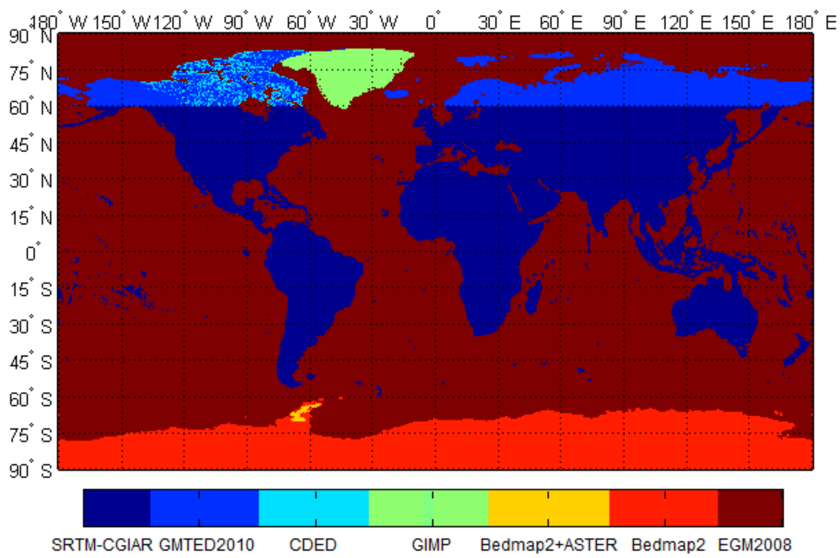


Figure 68: Global DRM: DRM-700 source codes

7.5 Database Verification

Independent verification of the global DEM and DRM databases was undertaken by the receiver algorithm team at GSFC. This section presents a summary of the results of their verification process. A set of checks were formulated to ensure that the databases are consistent with requirements and with each other. Similar DEM and DRM databases were generated by GSFC using the GMTED data set as input for comparison to the delivered DEM and DRM databases between 60° S and 90° N. ICESat-derived elevation data sets were used to evaluate the DEM in Antarctica and Greenland, and the 100 m Antarctic Peninsula data set was used to evaluate the DEM and DRM along the Antarctic Peninsula. Additionally, a list of high mountain peaks was compiled for comparison to maximum elevations in the DEM.

The consistency checks defined by the receiver algorithm team are summarized below [25]:

- **Check 1: DEM values are within allowed limits.** All elevation values must be between -500 m and 11,740 m.
- **Check 2: DEM min elevation ≤ DEM max elevation for all tiles.**
- **Check 3: Consistency between DEM tiers.** The minimum (or maximum) elevation seen over all 16 Tier 2 tiles should be the same as the minimum (or maximum) elevation in the associated Tier 1 tile. The same logic holds for the relationship between Tier 2 and Tier 3 tiles.
- **Check 4: DRM values are within allowed limits.** All relief values must be between 0 m and 4347 m.
- **Check 5: DRM-140 ≤ DRM-700.** The 140 m relief should never be larger than the 700 m relief.

- **Check 6: DRM Percentiles should be consistent.** Lower percentile values of relief should never be larger than high percentile values of relief.
- **Check 7: DRM values for the oceans should be uniformly zero.**
- **Check 8: Relief ≤ DEM range.** Both 140 m and 700 m relief should be less than the difference between the maximum and minimum elevations in the DEM.

The delivered DEM and DRM databases passed all consistency checks to the satisfaction of the receiver algorithm team, with some caveats for checks 3, 5, and 7 [25]. Check 3 requires that the maximum elevation over all 16 Tier 2 tiles match the maximum elevation in the associated Tier 1 tile. The same should hold true for minimum elevations. In a limited number of cases, the DEM fails this check. The apparent discrepancy is due to the application of vegetation heights to the minimum and maximum elevations in the DEM. Vegetation heights are applied in the same tiered manner as the elevations – i.e. the maximum vegetation height over a 1°x1° area is added to the maximum elevation over a 1°x1° area to find the Tier 1 maximum elevation, but the maximum vegetation height over a 0.25°x0.25° area is added to the maximum elevation seen over the same area to find the Tier 2 maximum elevation. If the maximum vegetation height and the maximum elevation area not in the same 0.25°x0.25° area, the Tier 1 and Tier 2 maximum elevations will not match. This is illustrated below in Figure 69.

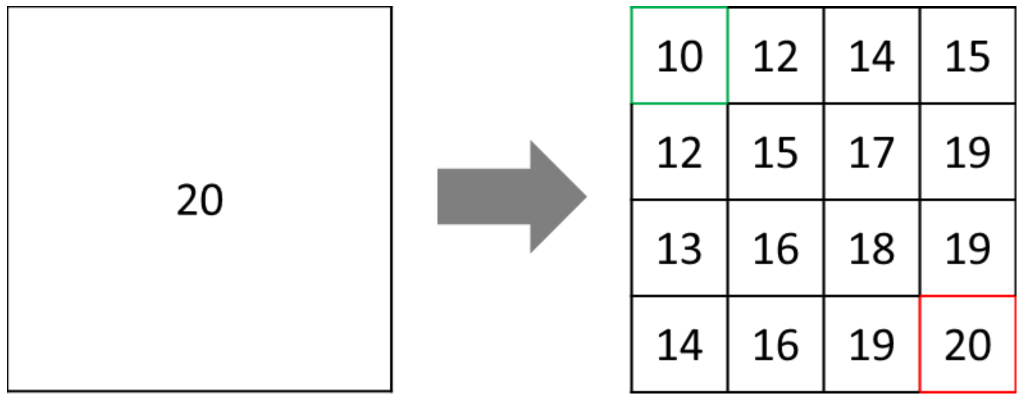


Figure 69: Illustration of the effects of applying vegetation heights to the consistency between DEM tiers. The numbers are the maximum vegetation heights in meters for each DEM tile.

The maximum vegetation height over the Tier 1 area is 20 m, while only one of the Tier 2 tiles has a vegetation height of 20 m (marked in red). If the maximum elevation is also located in the area outlined in red, no discrepancies between the tiers will be seen. If, however, the maximum elevation is located in any of the other Tier 2 tiles, there will be a difference between the Tier 1 and Tier 2 maximum elevations. If the maximum elevation is located in the area outlined in green, for instance, the difference between the Tier 1 maximum elevation and the maximum elevation seen over all 16 Tier 2 tiles will be 10 m. As long as the Tier 1 maximum elevation is greater than the maximum elevation seen over all 16 Tier 2 tiles, no true discrepancy exists. Similarly, as long as the Tier 1 minimum elevation is smaller than the minimum elevation seen over all 16 Tier 2 tiles, there is no discrepancy.

Check 5, which states that the DRM-140 should always be smaller than the DRM-700, is violated in several areas in Canada [25]. This discrepancy only occurs in cases where GMTED is used as the source for one DRM and CDED is used as the source for the other. The 100th percentile DRM values are used to select GMTED or CDED as the source for a tile, so those values will not violate Check 5, however, the lower percentile values may violate Check 5. This discrepancy is a result of different input data sets being used to generate the histograms of relief. The input data sets have different resolutions, so the resulting histograms have slightly different shapes and the percentiles between the two sources do not necessarily match. Any modifications to the databases to account for this discrepancy will be made by the receiver algorithm team. Modifications will entail increasing the appropriate DRM-700 values to match the DRM-140 value for the same tile.

Finally, Check 7, which requires that all DRM values be equal to 0 m, is violated in a large number of tiles [25]. A water mask was used during processing of the global grids to set all ocean DRM values to 0 m, but only if the existing value of relief was equal to 1 m. All tiles marked as ocean with a value of relief greater than 1 m were assumed to contain some small amount of land, and the DRM values were not changed. The majority of tiles which violate this check are along the coastline of Greenland, and result from undulations in the GIMP data set over the oceans. These elevations likely represent elevation of sea ice in the data sets used to produce the GIMP product. Should it be desired to set these values to zero, the global DRM can be reprocessed with the all ocean DRM tiles set to zero regardless of the existing value of relief.

Comparisons of the delivered DEM and DRM were made using a number of data sets. Approximations to the DEM and DRM were created at GSFC using 250 m GMTED elevation products. Tiles from the two databases were said to agree when the difference between the values was less than a test value calculated from the standard deviation of the differences between GMTED and ICESat ground control points and the value of padding for the database [26]. Agreement between the delivered DEM and the GSFC DEM is summarized in Table 16. Expanded percent agreement considers those tiles that failed to be passing if the UT DEM is inclusive of the GSFC DEM values – i.e. UT Max Value > GSFC Max Value or UT Min Value < GSFC Min Value.

Table 16: Summary of agreement analysis between DEM delivered by UT and the GSFC GMTED DEM [26]

DEM Grid	Percent Agreement between UT and GSFC	Expanded Percent Agreement between UT and GSFC
Tier 1 Maximum	99.55%	99.80%
Tier 1 Minimum	99.77%	99.91%
Tier 2 Maximum	86.55%	93.37%
Tier 2 Minimum	95.08%	100.00%
Tier 3 Maximum	74.46%	95.08%
Tier 3 Minimum	86.77%	99.47%

Similar comparisons were made between the DRM delivered by UT and the DRM created at GSFC. These results are summarized in Table 17. Expanded percent agreement considers those tiles that failed to be passing if the UT DRM is larger than the GSFC DRM values.

Table 17: Summary of agreement analysis between DRM delivered by UT and the GSFC GMTED DRM [26]

DRM Grid	Percent Agreement between UT and GSFC	Expanded Percent Agreement between UT and GSFC
DRM-140	84.69%	94.47%
DRM-700	95.87%	98.64%

Comparisons were also made between the delivered DEM in Antarctica and Greenland with ICESat-derived DEMs in those areas. Tiles from the two databases were said to agree when the difference between the values was less than a test value calculated from the uncertainties on the values in the ICESat-derived elevation product and the value of padding for the database [27]. Agreement between the delivered DEM and the GSFC DEM is summarized in Table 18.

Table 18: Summary of agreement analysis between UT DEM and GSFC DEM in Antarctica and Greenland [27]

DEM Grid	Percent Agreement in Antarctica	Percent Agreement in Greenland
Tier 1 Maximum	99%	95%
Tier 1 Minimum	100%	98%

The delivered DEM and DRM were also compared to a DEM and DRM developed by GSFC using the 100 m Antarctic Peninsula data set. Tiles from the two databases were said to agree when the difference between the values was less than a test value calculated from the standard deviation of the differences between the Antarctic Peninsula data set and ICESat ground control points and the value of padding for the database [28]. For the DEM, only 59 DEM tiles were included in the comparison, of which only 5 tiles failed. Expanding the test criteria to include those tiles where the DEM delivered by UT is inclusive of the GSFC DEM, the pass rate is 100% [28]. The delivered DRM also agrees well with the GSFC Antarctic Peninsula DRM. Results of the comparison between those data sets are summarized in Table 19.

Table 19: Summary of agreement analysis between UT DRM and GSFC Antarctic Peninsula DRM [28]

DRM Grid	Percent Agreement between UT and GSFC	Expanded Percent Agreement between UT and GSFC
DRM-140	88.40%	97.61%
DRM-700	96.69%	100.00%

Finally, the delivered DEM was compared to lists of the highest mountain peaks in the world and the highest elevations in Greenland and Antarctica [29]. The delivered DEM showed lower levels of agreement with the compiled lists of high peaks, particularly in Antarctica and Greenland. The results of the comparisons of Tier 1 and Tier 2 maximum elevations to a list of the highest peaks, the World100 largest peaks list, and a list of high elevations in Antarctica and Greenland are summarized in Table 20. Percent agreement refers to the number of Tier 1 or Tier 2 tiles where the maximum elevation plus the DEM padding is higher than all peak elevations in the tile area. No Tier 2 comparisons were made for Greenland and Antarctica peaks as no Tier 2 tiles are present in those regions.

Table 20: Summary of comparison between UT DEM Maximum elevations and elevations of tall peaks [29]

Comparison Set	Percent Agreement with Tier 1	Percent Agreement with Tier 2
Highest Peaks List	92.31%	93.10%
World100 List	85.85%	65.22%
Antarctica and Greenland	33.85%	N/A

Should any modifications be desired to include these high peaks in the databases, all changes will be made by the receiver algorithm team. Particular care must be taken to correctly modify all three tiers of the DEM and add additional DEM tiers if necessary. Additionally, modifications to the DRM may be desired in tiles containing high peaks, but a methodology for selecting a new value of relief would be required.

Chapter 8: Conclusions and Recommendations

ICESat-2 and its ATLAS instrument represent an opportunity to study the cryosphere with greater spatial resolution, temporal resolution, and accuracy than has ever been possible before. Advances in laser technology since the launch of ICESat have made it possible to develop a low-energy, high-repetition-rate laser altimetry system that can operate from a space-based platform. ATLAS will continue the groundbreaking work of its predecessor; however, it presents a number of engineering challenges that were not present during the development of GLAS. Primary among these challenges is ensuring that ATLAS is able to collect and transmit valid scientific data. Due to environmental factors, the received signals are expected to be extremely noisy, requiring onboard data processing to meet the data volume and data rate requirements of the instrument. A novel onboard receiver algorithm has been developed for ATLAS that aims to reduce the received signal to only that which is most likely to contain the desired ground signals. The receiver algorithm requires the use of three onboard databases to find and select bands of the received signal for telemetry to the ground. Further ground-based processing will result in data products that will be distributed to the wider scientific community for a number of applications.

8.1 SUMMARY

The development of two of the onboard databases is the focus of this study. The Digital Elevation Model and the Digital Relief Map are used to set a range window in which to search for ground signal and define a vertical band of the signal that will be included in the data telemetry. Fidelity of the DEM and DRM are of great importance to the successful acquisition of data onboard the spacecraft, and thus affect the success of the scientific mission as a whole.

The production of the databases required the integration of multiple elevation data sources, each covering different regions of the globe at differing resolutions and accuracies. The selection of such databases was undertaken with the goal of using the best available and most suited elevation data for any given region. Additionally, the input data sets were selected such that the final DEM would meet the requirement that the global 3-sigma accuracy of the database should be no greater than 150 m. In order to create a cohesive and consistent global DEM and DRM, several methods of combining the input data sets were devised to match the specific qualities of each data set.

A novel technique to calculate relief along specified intervals of the flight path of the satellite was developed for the production of the DRM. The manner of calculating relief involved the comparison of each individual elevation value in an input data set to the values of elevation in specific neighboring cells. The neighboring cells used in the calculation of relief for each cell in an input data set were defined according to the resolution of the input data set, the location of the cell on the globe, and the length of the flight path along which relief was being calculated. This technique is more computationally expensive than other possible methods, but allows for more precise calculation of relief over varying flight path orientations and avoids over-estimating the true value of relief at any given location. Using this technique, maps of relief were produced from the input elevation data sets at matching resolutions.

Individual DEM and DRM tiles were generated from maps of elevation and relief, respectively. Production of these tiles is governed by a number of requirements set forth by the receiver algorithm team. The requirements reflect the manner of operation of the receiver algorithm as well as properties of the instrument and the satellite's orbit. Requirements specify the resolution and tiered structure of the DEM, the resolution and length scales of the DRM, and a 2km overlap between all DEM and DRM tiles.

A method of estimating the accuracy of the DRM based on the magnitude of relief in the DRM was devised to inform the selection of values of padding utilized in the receiver algorithm. These values of padding are used to expand the width of the telemetry band in the receiver algorithm to account for uncertainties in the DRM, and are defined for several ranges of relief. Using ICESat measurements as ground reference points, the accuracy of input elevation data sets was evaluated for several test regions deemed to be representative of certain types of vegetation and topography. The elevation accuracies of the test regions were scaled by a factor of $\sqrt{2}$ to give values of DRM accuracy, which were compared to the magnitude of relief for each test region. Comparisons of DRM accuracy vs. relief magnitude for hundreds of test regions and several different data sets were provided to the receiver algorithm team at GSFC to assist in the selection of DRM padding values.

Software to generate the databases from the input data sets was developed using MATLAB. Some additional data processing required the use of ENVI, an image processing software suite. All input data sets used are publicly available, although some alterations to the data products were made during pre-processing. Each input data set was processed independently of the other data sets. The DEM and DRM tiles from each input data set were then merged to form the global DEM and DRM databases. The full suite of software, input data products, and intermediate data products was delivered along with the final databases to the receiver algorithm team at GSFC.

Independent verification of the global DEM and DRM databases was undertaken by the receiver algorithm team at GSFC. A set of checks were formulated to ensure that the databases are consistent with requirements and with each other. Similar DEM and DRM databases were generated for comparison to the delivered DEM and DRM databases in several regions. Additionally, a list of high peaks was compiled for comparison to maximum elevations in the DEM. The delivered DEM and DRM databases passed all consistency checks to the satisfaction of the receiver algorithm team. Evaluations of differences between the DEM and DRM delivered by UT and the databases generated for comparison by GSFC showed high levels of agreement. The delivered DEM showed lower levels of agreement with the compiled lists of high peaks, particularly in Antarctica and Greenland. Any future modifications to the databases will be performed by the receiver algorithm team at GSFC.

8.2 Recommendations for Future Work

Development of the databases was in some cases restricted by the availability of high-quality elevation data at sufficient resolutions. In some cases, elevation data had not been collected or had not been made available to the public. In other cases, the use of certain data sets is restricted by difficulty of implementation. Additionally, significant modifications to published data sets are outside the scope of this study, necessitating the use of only those data sets that do not show large inconsistencies or errors. However, should new data sets become available, it would be possible, if not always necessary, to incorporate new elevation and relief data into the global DEM and DRM databases. Incorporation of additional data sets should be prioritized on regions where the existing input data sets are known to be of lower quality or where successful data acquisition is most desired – Antarctica, Greenland, and the Himalayas in particular.

Performance of the ATLAS instrument using the databases developed during the course of this study should inform the development of similar onboard databases for future missions. As ATLAS will be the first space-based photon-counting system, current estimates of how it will operate and return data on-orbit are heavily based on simulations, in addition to mission heritage. As such, the development of the databases is predicated on certain assumptions about the operation of the instrument that can only be verified once the instrument is in orbit. The receiver algorithm allows for a number of on-orbit adjustments in how it utilizes the databases and processes the incoming data to account for many different operating conditions. Studies of how well the databases enable capture of science data, particularly in adverse conditions, should be taken into advisement for future missions.

Appendix A: Description of Input Data Sources

Both the DEM and DRM onboard databases are constructed from existing digital elevation. Several data products covering large portions of the globe have been released in recent years; however, no global DEMs currently exist that satisfy both the resolution and accuracy requirements of this project. Global databases are required despite the fact that the spacecraft inclination will preclude passage of the satellite over the poles. The elevation data sources explored during the course of this project are discussed in detail in this appendix.

A.1 ICESat

The Ice, Cloud, and land Elevation Satellite (ICESat) was launched in 2003 and provided global altimetry data using the Global Laser Altimetry System (GLAS) instrument until its decommissioning in 2009. ICESat coverage is limited to areas between 86N/S, since the 94° inclination orbit induced a "hole" in the polar ground track configuration at both the north and south poles. An additional limitation in ICESat's coverage is associated with its use of repeating ground tracks. This approach was ideal for satisfying the mission requirement to determine temporal variations in topography, but did not allow for denser coverage that would have been possible with off-nadir pointing of the spacecraft. ICESat was a dual-wavelength, full-waveform laser altimeter with laser footprints approximately 70 m in diameter and spaced at intervals of approximately 170 m on the surface of the Earth [2]. Because of changes in the data acquisition plan due to issues with components in the onboard instrument, ICESat did not operate continuously during its lifetime. In an effort to maintain the science objectives of the mission, the laser only operated during seasonal sub-cycles. That is, a 33-day sub-cycle of ground tracks were used in place of the planned 91-day repeat ground track.

However, despite operational changes with the instrument, the data acquired from ICESat proved to be incredibly accurate and useful in multiple scientific and engineering disciplines.

Since the launch of ICESat in 2003, several versions of the GLAS products have been produced and distributed to the scientific community. Changes were made with each data release based on better estimates of spacecraft position and attitude and/or changes in desired data parameters provided. For the purposes of this project, only the GLA06 data product is used. GLA06 is a global Level-1 elevation product that provides the elevation of the mode of the waveform.

ICESat data is used as a ground truth elevation product in evaluating the accuracy of the gridded elevation products used to generate the onboard databases. ICESat data is especially useful in defining ground truth due its extremely high accuracy; under good conditions, ICESat elevations have ~2.1 cm precision and relative accuracy of ±14 cm [2]. Because of the sampling nature of the GLAS product (i.e. the data is available in footprints, not as a gridded elevation product), it is not appropriate to use it as the sole source for the developing the databases. Most significantly, the density is not high enough in the mid-latitudes to calculate relief values for all 0.25°x0.25° DRM tiles.

A minor issue associated with using ICESat data to develop the ATLAS databases arises from the presence of cloud-contaminated data in some of the published data sets. In these cases, an ICESat elevation can differ by tens or hundreds of meters from ground truth. When plotted, obvious cloud formations can be seen in the elevation profile. The existence of outlier elevations can be managed by filtering ICESat data, but performing this filtering on a global scale is outside the scope of the effort associated with the development of the ATLAS databases.

A.2 SRTM-CGIAR

The Shuttle Radar Topography Mission (SRTM) is a data set acquired using Interferometric Synthetic Aperture Radar (InSAR). The instrument flew on the space shuttle Endeavor during an 11-day mission in February 2000. The elevation data set covers the Earth between 60N/S and provides elevations in meters relative to the EGM96 geoid model. The nominal resolution of the SRTM data set is 1 arc-second (30 m), but this data has only been released for United States territory. For the rest of the world, SRTM data is provided at a resolution of 3 arc-seconds (90 m). Version 2 of the SRTM data set (also known as the "finished" version) represents a significant editing effort by the National Geospatial-Intelligence Agency (NGA) and exhibits well-defined water bodies along with an absence of single-pixel errors [7]. However, the datasets are still heavily affected by mountain and desert no-data areas, and several areas show large voids due to the instrument being unable to collect data for about 10 orbits during the mission. The mountain and desert void areas are a result of some limitations of radar instruments, namely issues with shadowing in high relief areas and poor reflectivity over sandy surfaces. The data voids affect all summits over 8000 m, most summits over 7000 m, and many gorges and canyons. Significant voids also exist in the Sahara desert [7].

Several entities have developed algorithms to fill the voids of the SRTM data set, including the CGIAR Consortium for Spatial Information (CGIAR-CSI). The CGIAR-CSI data set provides a completely void-filled elevation data set at a of resolution 3 arc-seconds. The algorithm used to fill the data voids uses regional data sets to provide fill elevations, and involves the production of vector contours and points and the re-interpolation of the derived contours back into a raster DEM [8]. However, the void-filling algorithm is not perfect. Some void areas spanning a few pixels are present and some artifacts from the void-filling algorithms can be observed in the distributed data sets. Even so, SRTM-CGIAR represents a large improvement over SRTMv2.0 and is significantly easier to work with for the purposes of this task.

The primary concern with using the SRTM-CGIAR data set is its coverage. The data set only provides data for about 83% of the globe. It should also be noted that the data is elevation biased in areas of heavy vegetation. Even still, validation efforts performed by the Jet Propulsion Laboratory (JPL) indicate that the absolute vertical 1-sigma accuracy of the data is better than 9 m [7].

A.3 GMTED2010

The Global Multi-resolution Terrain Data 2010 (GMTED) elevation product was released by the United States Geological Survey (USGS) and the NGA in October 2010. The data set covers the entire globe and was developed as a replacement to the GTOPO30 data set. GMTED was created by mosaicking several regional data sets together to create the global product [9].

GMTED contains seven raster elevation products (minimum, maximum, mean, and median elevations, standard deviation of elevation, systematic subsampling, and breakline emphasis) at three resolutions: 30, 15, and 7.5 arc-seconds (equivalent to 1 km, 500 m, and 250 m). The exception to this coverage is the continent of Antarctica and the island of Greenland – these areas are only available in the 30 arc-second resolution products and only for the mean elevation product. The global vertical accuracy of GMTED varies according to resolution and region. At 7.5 arc-seconds, the root mean square error (RMSE) ranges between 26 and 30 m [9].

The resolution of GMTED is not ideal for the development of the databases. GMTED was not initially chosen for use as an input for database generation, but it proved to be more accurate than the other databases available in some areas (Eurasia and

Alaska in particular). The effects of lowered resolution can be mitigated by using the maximum and minimum products instead of mean elevations. Some accuracy issues were noted in the assessment of GMTED quality in high relief areas, likely due to issues with the void-filling algorithm. For this reason, it may be preferable to avoid use of GMTED as an input data source in areas of very dynamic terrain.

The given vertical reference datum for GMTED is the EGM96 geoid, although several of the input data sets used to fill in the global product were originally published on geodetic datums other than EGM96. These products were not converted prior to mosaicking, but differences between the various datums are on the order of a few meters. Differences in horizontal reference datums between the various data sets were corrected [9].

A.4 ASTERv2

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is an instrument onboard the Terra satellite, launched in 1999. ASTER collects high-resolution images of the Earth on 15 bands of the electromagnetic spectrum. The images are used to create several data products, including the ASTER Global Digital Elevation Model (GDEM). ASTER GDEM provides elevations relative to the EGM96 geoid model between 83N/S at a nominal resolution of 1 arc-second (30 m). The GDEM is generated by compiling Visible and Near Infrared (VNIR) images using stereoscopic correlation techniques. The latest release (Version 2) of the ASTER GDEM used approximately 1.5 million stereo-pairs to construct the elevation data set [6]. Version 2 represents a significant improvement over the original GDEM release, with improved coverage and reduced artifacts. The horizontal and vertical accuracy are also greatly improved from the first version. Vertical accuracy of the GDEM is approximately 26 m at the 3-sigma confidence level [6].

Despite the improvements made to ASTER GDEM, several obstacles to using the data set for database generation remain. The method of data collection requires that the instrument see the ground on the visible spectrum and that there is a certain level of contrast between the geographic features. In areas under near-constant cloud cover, the data set shows significant voids. This is most prominent in the far northern latitudes, specifically in northern Russia and Scandinavia. In areas of low contrast, such as land ice or glaciers, the data set shows high levels of error. Some along-track artifacts can also be observed in the data set, and single pixel spikes and pits are prevalent. That the databases are constructed using extremes of elevation and relief makes it unadvisable in many circumstances to use ASTER GDEM as input for generating the DEM and DRM.

A.5 CDED

The Canadian Digital Elevation Database (CDED) digital elevation model is a gridded elevation data set provided by Natural Resources Canada. CDED provides complete coverage of all Canadian territory at postings ranging between 1:50,000 and 1:250,000; grid resolution varies with latitude. The elevations in CDED are recorded in meters relative to Mean Sea Level as defined by the Canadian Geodetic Vertical Datum of 1929 (CGVD29), and is horizontally referenced to the North American Datum 1983 (NAD83) [18]. CDED is well-validated, with mean errors measured at 0.34 m ± 6.22 m and 3-sigma accuracy better than 19 m [10]. The largest issue with using CDED as an input for database generation is its vertical datum, but differences between CGVD29 and EGM96 are small so the elevations can be converted to ellipsoid heights by assuming that the elevations are referenced to EGM96. The vertical datum does not play a role in the generation of the DRM as only relative differences between elevations are needed to calculate relief.

A.6 GIMP

The Greenland Ice Mapping Project (GIMP) elevation product is available from the Byrd Polar Research Center (BPRC). The data set is constructed from a combination of elevation products – ASTER and SPOT-5 for the ice sheet periphery and margin and AVHRR photoclinometry in the ice sheet interior and far north. The data is horizontally and vertically registered using ICESat mean elevations. The ice sheet wide RMSE validation error is ±10 m relative to ICESat, but errors range from ±1 m over most ice surfaces to ±30 m in areas of high relief. Elevations are provided in meters relative to the WGS84 ellipsoid. The DEM provides full coverage of Greenland at a nominal posting of 30 m, although the "true" resolution of the data set may vary from 40 m to 500 m depending on the collection method of the source data. A 90 m resolution elevation model produced using bilinear interpolation is also available. Caution must be taken when using the data set in areas of rapid change, i.e. major outlet glaciers. The product was released in 2012, but as the data is registered to ICESat elevations, the nominal age of the data set is 2007 [19].

A.7 BEDMAP2

Bedmap2 is a set of gridded products describing surface elevation, ice-thickness, and the seafloor and sub-glacial bed elevation of the Antarctic south of 60S at a resolution of 1 km. The surface elevation product is derived from a variety of elevation sources which are combined to exploit the strengths associated with each product. Bamber's 1 km Antarctic DEM is used for much of the ice sheet, and is highly accurate over areas of low surface slope, but less reliable in high slope areas and areas of mountainous terrain and widespread rock outcrops. A DEM developed Ohio State University using vector data is very accurate over rocky surfaces and is used to fill some rocky areas along the coasts and Transantarctic mountain range. Some coastal and mountainous areas are filled using data from an ICESat-derived gridded elevation model, which performs well in areas of dense ICESat coverage, and high-contrast areas on the Antarctic Peninsula are filled using data from ASTER and SPIRIT DEMs. The surface elevation product was quantitatively checked using airborne and ICESat laser altimetry data [12]. An illustration of the sources used in the construction of the surface elevation product is shown below in Figure A1.

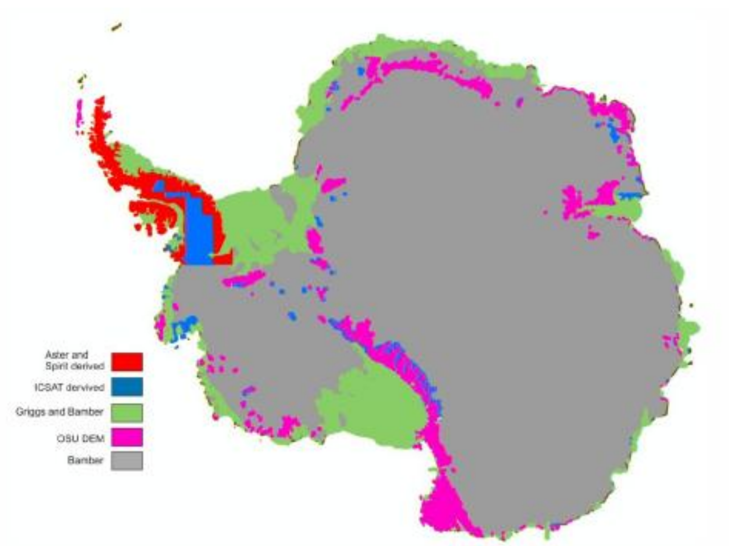


Figure A1: Map of Sources used in the production of Bedmap2 [12]

The estimated accuracy of the Bedmap2 product is ±30 m, although this could rise to ±130 m in mountainous regions [12]. The data set is provided on the GL04C geoid model, but a file is provided with the other Bedmap2 products that provides geoid heights to convert the elevations to the WGS84 vertical datum.

A.8 ASTER 100 M ANTARCTIC PENINSULA DEM

The 100 m Antarctic Peninsula DEM is a surface elevation model derived from ASTER GDEM elevation data. The raw GDEM product is of high quality over high contrast areas (e.g. rocky terrain, coastal regions), but shows large errors over ice-covered terrain as a consequence of the susceptibility of photogrammetry to errors over high-reflectance surfaces. Since the Antarctic Peninsula has significant areas of exposed rock, the developers of the DEM were able to improve the raw ASTER data and generate a new high resolution DEM for the region. The final product is distributed in a polar stereographic projection with elevations referenced to the EGM96 geoid model. Coverage of the product is limited to the Antarctic Peninsula north of 70S and does not include data over ice shelves. Accuracy of the product was evaluated using ICESat footprints, and the published RMSE is ±25 m [13]. This is a significant improvement over existing peninsular elevation products.

A.9 EGM2008 GEOID MODEL

The Earth Gravitational Model 2008 (EGM2008) geoid model is used to provide elevations for the DEM over ocean and sea ice regions. EGM2008 was developed by the National Geospatial-Intelligence Agency (NGA). This gravitational model is complete to spherical harmonic degree and order 2159, and contains additional coefficients up to degree 2190 and order 2159. The geoid model can be converted to geoid undulations relative to the WGS84 ellipsoid; NGA provides geoid undulations relative to latitude and longitude at 1x1-arc-minute and 2.5x2.5-arc-minute resolutions. Geoid heights relative to WGS84 range from -107 m to 86 m [23].

A.10 SIMARD'S VEGETATION HEIGHT MASK

A 1 km resolution canopy height model developed by Simard et al. at the Jet Propulsion Laboratory (JPL) is used to generate global maps of maximum vegetation height, which are then added to the DEM and DRM databases. ICESat waveforms were correlated with ancillary vegetation data, including forest type, tree cover, elevation, precipitation, and temperature, to enable estimation of canopy heights in areas where no ICESat footprints were available. The model estimates canopy heights using the GLAS waveform metric RH100, defined as the distance between signal beginning and the location of the lidar ground peak. Signal beginning is defined as the location at which the signal is 3.5 times above the standard deviation of the noise. The RMSE of the product is estimated as 6.1 m, but this may be a conservative value [14].

Glossary

ASTERv2 or ASTER GDEM – Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model, the second version of the elevation product from the ASTER instrument

ATLAS – Advanced Topographic Laser Altimeter System, the laser-ranging instrument to be carried onboard the ICESat-2 satellite

CDED – Canadian Digital Elevation Database, elevation model covering Canadian territory

Cell – a single elevation data point within an input DEM

Δ_E – The difference between elevations taken from a gridded input DEM and associated ICESat footprints

DEM – the onboard three-level grid digital elevation surface model created for the ATLAS receiver algorithm

DRM – the onboard two-grid digital relief surface model derived from the input DEMs for the ATLAS receiver algorithm

DRM-140 – the grid of the DRM associated with a 140m-long flight path segment

DRM-700 – the grid of the DRM associated with a 700m-long flight path segment

E_{ICESat} – An elevation value associated with a single ICESat measurement (footprint)

$E_{input\ DEM}$ – An elevation value from an input DEM associated with a specific ICESat geodetic measurement, value is obtained using bilinear interpolation to get elevation at exact location of ICESat footprint

EGM96 – Earth Gravitational Model 1996, a geopotential model of the Earth consisting of spherical harmonic coefficients complete to degree and order 360, datum for several elevation products

EGM2008 – Earth Gravitation Model 2008, a geopotential model of the Earth consisting of spherical harmonic coefficients complete to degree and order 2159, source for values of elevation over the oceans

GIMP – Greenland Ice Mapping Project, elevation model of Greenland from combination of several sources

GLA06 –ICESat/GLAS Level-1B Global elevation data, gives elevation of maximum peak in the waveform

GLAS – Geoscience Laser Altimeter System, the laser-ranging instrument onboard ICESat

GMTED2010 – Global Multi-Resolution Terrain Elevation Data 2010, global multi-product DEM available at three resolutions

Grid – a group of cell or tiles, i.e. an input grid of SRTM data an output grid of the DRM

ICESat – Ice, Cloud, and land Elevation Satellite

ICESat-2 – Ice, Cloud, and land Elevation Satellite-2, a follow-on laser altimetry satellite to ICESat

Input DEM or source DEM – A digital elevation model obtained from a third party for contribution to the global ICESat-2 DEM and DRM product production

Jason/TOPEX ellipsoid – reference ellipsoid used on the Jason and TOPEX satellites, ICESat data are given relative to this ellipsoid, which differs slightly from the WGS84 ellipsoid

Major frame – accumulation of 200 ATLAS laser shots, relative to the DRM-140 such that in 200 shots (0.02 seconds) the spacecraft will travel 140 m along-track (10 kHz laser repetition rate)

μ_E – The mean value of elevation difference (Δ_E) in a given quarter-degree tile

Overlap – The "buffer" that must be put on all DEM and DRM calculations, currently 2km

Relief –The difference between the maximum elevation and the minimum elevation seen in a group of cells, this is a general term describing a difference in elevation over some distance or area

RMSE – Root mean square error

SRTM – Shuttle Radar Topography Mission, elevation model available in mid-latitudes at 1 arc-second resolution (in US) or 3 arc-second resolution (between 60° N/S latitude) in other locations

SRTM-CGIAR – Void-filled SRTM product produced by the Consortium for Spatial Information, available at 3 arc-second resolution

Super frame - Accumulation of 1000 ATLAS laser shots, relative to the DRM-700 such that in 1000 shots (0.1 seconds) the spacecraft will travel 700 m along-track (10 kHz laser repetition rate)

Target cell – A cell over which the relief is being calculated, the center of a 140 m or 700 m long flight path segment is located within this cell. The target cell is a selected cell within an input DEM (maintaining consistent resolution)

σ_{DEM} – The accuracy value of the input DEM for a quarter-degree tile, taken to be the value for which 99.7% of elevation differences, Δ_E, are within the range $|\Delta_E - \mu_E| \leq \sigma_{DEM}$

σ_{DRM} – The accuracy value of the DRM produced from an input DEM, taken to be the accuracy of the input DEM for the same area, σ_{DEM}, scaled by a factor of $\sqrt{2}$

Tile – a single element of an output product

WGS84 – World Geodetic System 84, standard coordinate system and reference ellipsoid for the Earth.

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