ASTER GLOBAL DEM (GDEM) VERSION 3

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ABSTRACT:

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is a 14-channel imaging instrument operating on NASA's Terra satellite since 1999. ASTER's visible–near infrared (VNIR) instrument, with three bands and a 15 m Instantaneous field of view (IFOV), is accompanied by an additional VNIR band using a second, backward-looking telescope. Collecting along-track stereo pairs, the geometry produces a base-to-height ratio of 0.6. In 2009, the ASTER Science Team released Version 1 of the global DEM (GDEM) based on stereo correlation of 1.2 million ASTER scenes. The DEM has 1 arc-second latitude and longitude postings (~30 m) and employed cloud masking to avoid cloud-contaminated pixels. The GDEM covers all of the Earth's land surface from 83 degrees north to 83 degrees south latitude. Version 2 was released in 2011, with notable improvements in coverage and accuracy. In 2019, the final, Version 3, was released; again improving on coverage and removing almost all artifacts. Th GDEM is a unique, global high spatial resolution digital elevation dataset available to all users at no cost. In addition, a second unique dataset was produced and released. The raster-based ASTER Global Water Body Dataset (ASTWBD) identifies the presence of permanent water bodies, and marks them as ocean, lake, or river. An accompanying DEM file indicates the elevation for each water pixel. To date, over 110+ million 1x1 degree GDEM tiles have been distributed.

1. INTRODUCTION

A digital elevation model (DEM) depicts topography of the Earth's surface as a raster data set. As such, the DEM is a fundamental measure of topography, one of the primary attributes of the Earth. DEMs are used in numerous applications: water flow modelling for flood plains; glacier retreat and advance over time; geomorphology terrain analysis of slope, aspect and gradient; flight simulation; digital gaming; to name a few.

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is a 14-channel imaging instrument operating on NASA's Terra satellite (Yamaguchi et al., 1998). A joint project between the U.S. National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade, and Industry (METI), ASTER has been acquiring data for 22 years, since March 2000. ASTER has a VNIR instrument with three bands and a 15 m IFOV. One of those bands, at a wavelength of about 0.8 micrometers, is accompanied by an additional band using a second, backward-looking telescope. Collecting along-track stereo pairs, the geometry produces a base-to-height ratio of ~0.6. Each image covers an area of about 60 x 60 km with a resolution of 15 m. The archive now contains over 4 million scenes; for the vast majority of them, a stereo pair was collected using the nadir and backward telescopes. From this archive, three versions of Global DEMs (GDEM) have been produced over a period of 11 years.

Strictly speaking, the ASTER GDEM is a digital surface model (DSM) representing a three-dimensional elevation model of Earth's surface that includes objects, such as buildings, trees, shrubs, etc. Over bare areas, the DSM is the same as a true DEM, though the terms are used interchangeably. All optically-derived DEMs are DSMs. A radar topographic model, like SRTM, is closer to a bare earth model (Digital Terrain Model), or DTM, as the radar signal has partial penetration through foliage.

2. ASTER GDEMS

In June, 2009, the ASTER Science Team produced a global DEM (GDEM V1) based on stereo-correlation of 1.2 million ASTER scenes; the GDEM V1 was produced by the commercial company Sensor Information Laboratory Corporation (SILC) in Tokyo (Abrams et al., 2010; Fujisada et al., 2011; Fujisada et al., 2012).

The stereo images were acquired by ASTER's VNIR instrument, that has two telescopes. The nadir-looking telescope images in 3 spectral bands: green, red, and near infrared (NIR). A single NIR band is used for the backward-looking telescope. The viewing geometry for ASTER stereo data acquisition is shown in Figure 1. Sixty-four seconds after the nadir telescope acquires its image, the backward-looking telescope acquires an image of the same area, with an angle of 27.6 degrees. This geometry creates a base-to-height (B/H) ratio of about 0.6 (400km/705km).

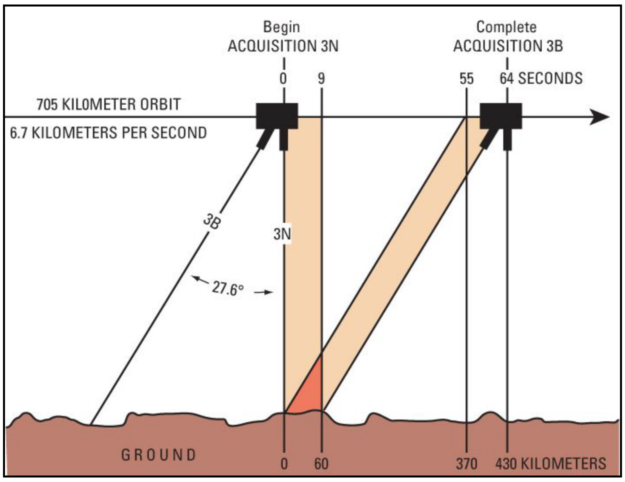

Figure 1. Viewing geometry for ASTER stereo data acquisition. Nadir- and backward-looking telescopes image the same area, 64 seconds apart.

The DEM had 30 m postings, and employed cloud masking to eliminate cloud-contaminated pixels. The GDEM covered all of the Earth's land surface between 83 degrees north and 83 degrees south latitudes. It was packaged into 22,000+ 1 x 1 degree latitude/longitude tiles. Each user order for GDEM tiles was accompanied with a summary of the validation report, describing the characteristics of the data set, anomalies discovered by the validation team, and caveats on use of the GDEM.

This was a unique, global, high-spatial resolution digital elevation data set available to all users at no cost. This data set was offered jointly by METI and NASA to the Group on Earth Observations (GEO) at the Summit of Ministers in Cape Town, as a contribution to the Global Earth Observing System of Systems (GEOSS) to serve societal needs. At this time, there were no other global high resolution DEMs freely available. The Shuttle Radar Topography Mission (SRTM) data set was released in 2013. Because of the Shuttle's orbit, the SRTM data covered the Earth from 54 degrees north to 53 degrees south latitudes, missing much of the northern hemisphere land mass. In addition, the data format was difficult to ingest. The U.S. National Geospatial Intelligence Agency (NGA) had a global high-resolution data set, but it was classified and unavailable to all except a few people with security clearance; and it remains classified to this day.

The methodology used to create the GDEM involved automatic processing of 1.2 million ASTER stereo scenes (Fujisada et al., 2011; Fujisada et al., 2012):

1) Each of the 1.2 million stereo pairs scenes was stereo correlated to produce individual scene-based DEMs with 30 m postings, using standard stereo photogrammetric techniques (Gangapurwala, 2021).
2) Individual scenes were cloud screened to eliminate cloud-contaminated pixels, using data from all ASTER bands, in the VNIR, SWIR, and TIR, to identify clouds.
3) For each pixel, all the good DEM values were stacked and averaged. Where only 1 or 2 ASTER pixels were available, the value was replaced by another existing DEM data set, such as SRTM; or left as a void if no other data were available.
4) Some elevation anomalies were replaced with substitute DEMs. For ocean areas, a value of 0 was inserted.
5) The mosaicked DEM values were cut into ~22,500 1x1 degree tiles, posted at 1 arc-second (about 30 m), and projected in rectangular (cylindrical equidistant projection) format on the WGS84 ellipsoid. GeoTIFF format was selected as being universally recognized by image processing software packages. The data set covers all the Earth surface from 83 degrees north to 83 degrees south latitudes.

In October, 2011, Version 2 of the GDEM was released, incorporating several improvements to Version 1: a smaller correlation window size was used, resulting in increased spatial resolution; reduction from a 9x9 window to a 5x5 window effectively increased the resolution by a factor of 2; improved cloud masking; this was performed when the individual scenes were stereo-correlated, and was done on a pixel-by-pixel basis; improved, more accurate water body mask; inland water bodies as small as 1 km^2 were identified, and the elevation value was flattened to match shoreline values; and reduction of holes in the data; during the two years between production of the two versions of the GDEM, ASTER acquired an additional 260,000 scenes, many of them targeted specifically to fill holes in ASTER's global coverage (caused primarily by the presence of persistent clouds).

In August 2019, the final version, Version 3 of the GDEM was released (Table 1) (Abrams et al., 2020). Rigorous re-processing of the stereo pairs, manual inspection of each of the ~23,000 1x1 degree tiles, and correction of anomalies, resulted in a data set with minimal errors and artifacts. Holes due to missing data were filled with SRTM data, other national data sets for high latitudes, interpolation, or left blank. The next paragraphs describe in detail the processes that were used to create the improved version. A colorized perspective view of part of a tile, over San Francisco, California, is shown in Figure 2, and a colorized version of the entire data set is shown in Figure 3.

Tile Size	3601 x 3601 (1 degree by 1 degree)
Posting interval	1 arc-second (30 m)
Geographic coordinates	Geographic latitude and longitude
DEM output format	DEM: GeoTiff, signed 16 bits, and 1m/DN for DEM; NUM: GeoTiff; unsigned 8-bit number of individual scenes used to compile each pixel (maxed at 50); and source of fill for missing ASTER data
Special DN values	-9999 for void pixels and 0 for sea-level water body
Ellipsoid/Geoid	Referenced to the WGS84/EGM96 geoid
Coverage	North 83 degrees to south 83 degrees, 22,912 tiles for GDEM

Table 1. Characteristics of ASTER GDEM Version 3

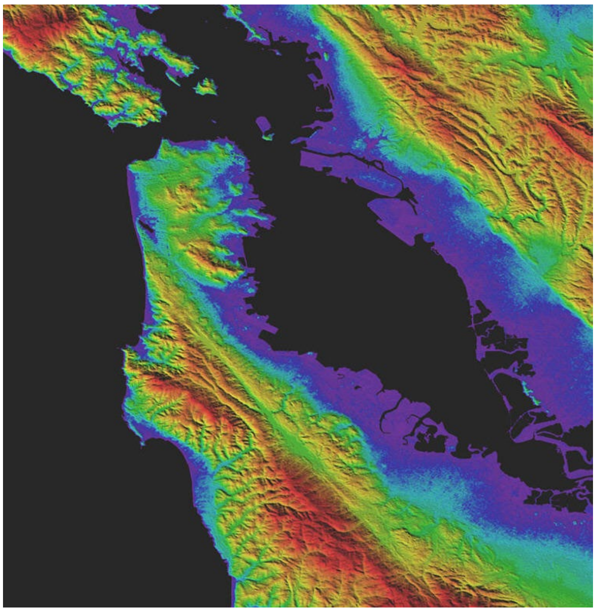

Figure 2. Colorized perspective view of San Francisco Bay from ASTER GDEM V3 data.

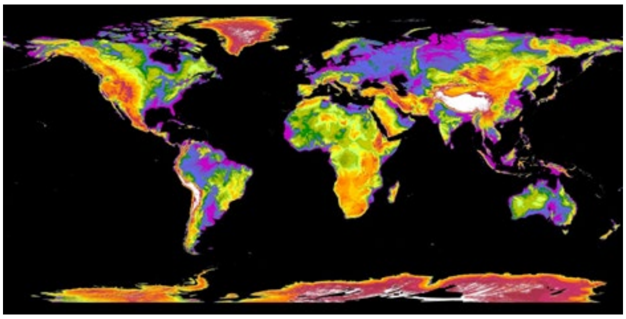

Figure 3. Colorized global mosaic of GDEM V3. White and red are highest elevations, black is ocean at 0 m elevation.

3. PROCESSING OF VERSION 3

3.1 Initial Corrections

Cloud masking was not 100% successful in removing contaminated pixels, particularly at cloud edges. Additionally, where there were 2 or fewer correlated pixels to average, that pixel had to be replaced with another source: SRTM1 V3, Alaska DEM (USGS, 2013), Canadian Digital Elevation Dataset (Natural Resources Canada, 2008), and Global Multi-resolution Terrain Elevation Data 2010 (USGS, 2010). Anomalies smaller than 1 km^2 were filled with interpolation.

3.2 Generating Error Mask

An error mask for the GDEM (described in the previous section) was constructed in three steps (Abrams et al., 2020). The first step involved comparing the GDEM to SRTM and ALOS (ALOS Global Digital Surface Model (AW3D30)); Tadono et al., 2016) DEMs. SRTM has no cloud errors, and ALOS cloud screening is more effective than that used for ASTER GDEM. GDEM pixels were rejected if they differed by more than 80 m from SRTM or ALOS data. An initial error mask was thus created. The mask was enlarged to the eight neighbour pixels to ensure problem areas were fully taken into account.

In the second step, the mask was further enlarged to any pixel that differed by more than 100-141 m from its neighbour (depending on direction). These values were determined after extensive trial-and-error and manual examination of the results.

The final step involved spatial filtering to identify anomalies at further distances or where the differences were smaller than previously accounted for, such as cloud edges and their interiors.

3.3 Void Filling

The error mask creates voids in the GDEM that must be filled. To be consistent, the first choice for void filling was GDEM V2, because errors were not always spatially the same in both data sets. The second choice was SRTM where available; however, at latitudes above 52 degrees, no SRTM data were available. The third choice, therefore, was to use PRISM ALOS World 3D-30m (AW3D30) to fill voids. Finally, where voids still existed because none of the three ancillary data sets were available or acceptable, an advanced interpolation method was used (Grohman, 2006). An example of the before and after results of the corrected GDEM is shown in Figure 4.

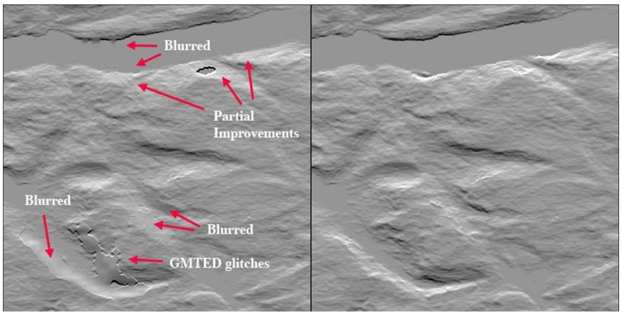

Figure 4. Global digital elevation model (GDEM) V3 tile N60E05; 400 by 400 pixel subarea. Left: Input GDEM with errors and artifacts, both original, and introduced in early attempt at correction. Right: Final GDEM tile after corrections.

4. VALIDATION OF GDEMS

GDEM Version 1 was subject to a rigorous validation process, conducted by the ASTER Science Team, NASA's Land Processes Distributed Active Archive Center, and the U.S. National Mapping Agency (ASTER GDEM Validation Team, 2009; Abrams et al., 2010; Hirt et al., 2010; Slater et al., 2010; Chrysoulakis et al., 2011). Comparison with high precision ground control points, and detailed comparisons with SRTM and GEODATA (to name a few of the many studies published) indicated that the GDEM vertical accuracy, expressed as RMSE, was 10.2 meters, versus 6.6 meters for an early version of SRTM data.

Satge et al. (2015) assessed GDEM V2 against SRTM V4 (90 m), over the Altiplano, Chile, using Icesat data. They found vertical accuracies, RMSE, of 9.0 m for ASTER GDEM V2, and 11.0 m RMSE for SRTM V4. Another study, by Morias et al. (2017), evaluated GDEM V2 and SRTM V3 (30 m) in an urban area in Brazil, using 25 cm LIDAR data as reference. They found that the RMSE accuracy values increased with slope gradient in both data sets. For smooth, flat terrain, the RMSEs were 5.5 m for ASTER, and 3.6 m for SRTM. This increased to 18.2 m for ASTER and 19.1 m for SRTM for the steepest terrain.

Gesch et al. (2016) evaluated a pre-release copy of the GDEM V3, using more than 23,000 reference geodetic ground control points over the conterminous US. They reported an RMSE error was 8.52 meters. This compared with 8.68 meters for GDEM V2. Similar accuracy values from other studies were summarized in the ASTER GDEM V3 User Guide (Abrams and Crippen, 2019), that accompanies every GDEM tile ordered from NASA. This included a detailed analysis of accuracy for flood modelling purposes (Guillaume et al., 2019). A detailed comparison of 30 m DEMs, over Nepal, was reported by Talchabhadel et al. (2021) using ASTER GDEM V3, SRTM, ALOS World 3D-DEM and Cartosat-1 DEM. Against 2900 control points, they found RMSE values for vertical accuracy of 10.3 m for ASTER, 5 m for SRTM, 3.6 m for ALOS, and 5.1 m for Cartosat. A similar study over a part of India by Mahesh et al. (2021) reported vertical error RMSEs of 8 m for ASTER GDEM V3, 3 m for SRTM, 2.5 m for ALOS, and 3.8 m for Cartosat, (Note that ALOS and Cartosat 30 m DEMs are resampled from original 5-10 m DEMS.)

A simple comparison of GDEM V3 versus SRTM (from the NASADEM product, (NASA JPL, 2020)) is shown in Figure 5. The area covered is the 1 x 1 degree tile whose lower left corner is 34 degrees north latitude, 119 degrees west longitude. Visually, the two DEMS are indistinguishable (Figures 5A and 5B). When we difference the two DEMs (SRTM minus ASTER, Figure 5C) and stretch the values, we find that the ocean has a value of 0, as expected. Differences between the two DEMs are more or less random. Figure 5D is a histogram of the differences: the mean is -5.9 meters, with a standard deviation of 7.0 meters. The minimum and maximum values are -106 and +100, highlighting a very few outliers that are anomalies in both data sets. ASTER elevations are overall higher, perhaps reflecting the difference between ASTER being a DSM (and measuring tree height), and SRTM being closer to a bare earth model, as discussed earlier.

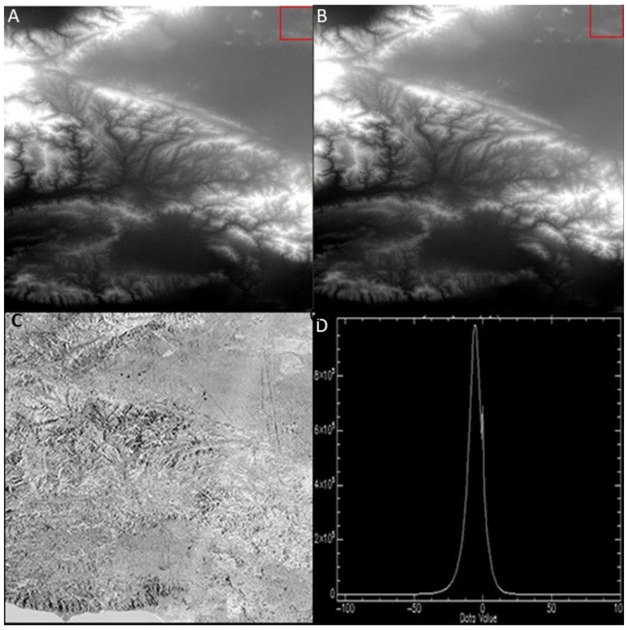

Figure 5. DEM tile N34W119 (lower left corner): A) ASTER GDEM 3; B) SRTM 3; C) SRTM-GDEM; D) Histogram of SRTM-minus-GDEM.

5. GDEM DATA PACKAGE AND DISTRIBUTION

For each of the 1x1 degree GDEM tiles, there are two files provided: the DEM data file with elevation values; and a “NUM” file with ancillary information. Each file is 3601 lines by 3601 samples, covering a 1 x 1 latitude/longitude area, with a slight overlap with adjacent tiles. The DEM file is in GeotTIFF format, elevation values are 16-bit integers, with -9999 assigned to pixels with no elevation value. In the NUM file, for each pixel, the number of scene-based DEMs used in the compilation is identified. Additionally, the source for replaced pixel values is identified, so a user can determine if the elevation values are ASTER-derived, or if they came from an external data source.

The GDEM data are distributed from two sources. In the U.S., NASA’s Land Processes Distributed Active Archive provides free data through the earthdata search web tool (https://search.earthdata.nasa.gov/search). The product is identified as AST14DEMv003. In Japan, the GDEM is distributed by Japan Spacesystems (https://gdemdl.aster.jspacesystems.or.jp/). Orders for the ASTER GDEM continue at a high rate; to date, over 110 million 1x1 degree GDEM tiles have been distributed (Figure 6).

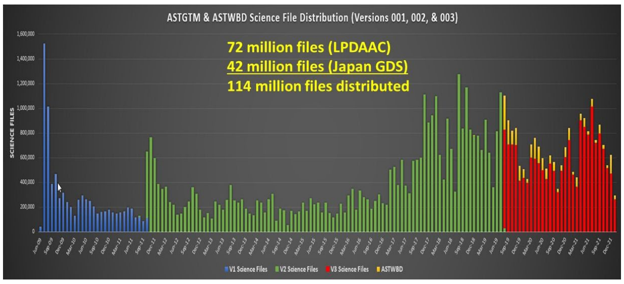

Figure 6. Distribution statistics for ASTER GDEMs Versions 1, 2, and 3. Version 3 numbers are in red.

6. ASTER GLOBAL WATER BODY DATASET (ASTWBD)

In addition to ASTER GDEM, the ASTER Global Water Body Database (ASTWBD) was generated as a by-product to correct elevation values of water body surfaces like oceans, rivers, and lakes. The ASTWBD was applied to GDEM such that it has a proper elevation value for all water body surfaces. The ocean and lakes have a flattened, constant elevation value. Rivers have a stepped-down elevation value from their upper reaches to where they join another river or reach the ocean.

The ASTWBD is the only near-global raster data set; it delineates water bodies smaller than 0.2 km². In addition, the data set defines which type of water body is delineated: ocean, lake or river. Two other, less complete, data sets are publicly available. 1.) The Shuttle Radar Topography Mission (SRTM) Water Body Dataset (SWBD) was created from the SRTM data and covers 60 degrees north to 54 degrees south at 30 m resolution. It is a binary vector, data set: water or no water (NASA JPL, 2013). 2.) The Landsat Global Surface Water Explorer, developed by the European Commission, is based on 32 years of Landsat data, and maps show change from 80 degrees north to 60 degrees south, at 30 m resolution and is available at https://global-surface-water.appspot.com (Pekel et al., 2016). The "occurrence" data set is a binary water/no-water raster data set, which does not identify the types of water bodies.

The ASTWBD was produced by the commercial company Sensor Information Laboratory Corporation (SILC) in Tokyo (Fujisada et al., 2018). Proprietary software was used to extract water bodies from the ASTER images used to produce the GDEM. Additional manual editing was done to improve the output. Generation of the ASTWBD was carried out in two steps: separation of waterbodies from land, and classification of waterbodies into ocean, lake or river. Lake elevations were calculated from their perimeters, and a single value was assigned to the entire lake. To separate rivers from lakes, visual inspection was needed. Rivers were assigned stepwise elevations with a one-meter step, using both automated methods and manual editing.

7. ASTWBD DATA PACKAGE AND DISTRIBUTION

The ASTWBD product is packaged as 1 x 1 degree tiles; for each GDEM V3 tile there is a corresponding ASTWBD tile. The ASTWBD tiles consist of two files: an attribute (*.att) file and an elevation (*.dem) file. The attribute file has four values: 0 for land, 1 for ocean, 2 for river, and 3 for lake, in GeoTIFF format. The *.dem file has elevation values for all non-land pixels.

Like the GDEM, the ASTWBD data are distributed from two sources. In the US, NASA's Land Processes Distributed Active Archive provides free data through the earthdata search web tool (https://search.earthdata.nasa.gov/search). In Japan, the GDEM is distributed by Japan Spacesystems (https://gdemdl.aster.jspacesystems.or.jp/).

8. CONCLUSIONS

The ASTER GDEM was the first, and the most complete high resolution global DEM data set, available free to all users. Version 3, released in August 2019, was produced using custom software and manual inspection of each of the 22,500+ tiles, creating an almost artifact-free dataset. Validation of the GDEM provided RMSE values for vertical accuracy of ~8 m. This is near the theoretical limit for optical stereo data, acquired at 15 m pixel size, and with a base-to-height ratio of 0.6. Higher resolution data sets are now available from commercial users, most at high cost. Orders for the ASTER GDEM continue at a high rate; to date, over 110 million 1x1 degree GDEM tiles have been distributed.

The ASTWBD is the only near-global raster data set; it delineates water bodies smaller than 0.2 km². In addition, the data set defines which type of water body is delineated: ocean, lake or river.

9. ACKNOWLEDGMENT

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