

The Shuttle Radar Topography Mission (SRTM) Collection User Guide

1.0 Introduction

The Shuttle Radar Topography Mission (SRTM) datasets result from a collaborative effort by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA – previously known as the National Imagery and Mapping Agency, or NIMA), as well as the participation of the German and Italian space agencies. Together, this international space collaboration generates a near-global digital elevation model (DEM) of the Earth using radar interferometry. The SRTM instrument consisted of the Spaceborne Imaging Radar-C (SIR-C) hardware set modified with a Space Station-derived mast and additional antennae to form an interferometer with a 60-meter (m) long baseline (Kobrick, 2006). A description of the SRTM mission can be found in Farr and Kobrick (2000) and Farr and others (2007). Radar interferometry is explained in Rosen and others. (2000).

Synthetic aperture radars are side-looking instruments that acquire data along continuous swaths. The SRTM swaths extend from about 30 degrees (°) off-nadir to about 58° off-nadir from an altitude of 233 kilometers (km), and thus are about 225 km wide. During the data flight, the instrument operated at all times the orbiter was over land and about 1,000 individual swaths were acquired over the ten days of mapping operations. The length of the acquired swaths ranged from a few hundred to several thousand km. Each individual data acquisition is referred to as a "data take."

SRTM was the primary, and virtually only, payload on the STS-99 mission of the Space Shuttle Endeavour, which launched February 11, 2000 and flew for 11 days. Following several hours for instrument deployment, activation, and checkout, systematic interferometric data were collected within a 222.4-hour period. The instrument operated almost flawlessly and imaged 99.96 percent (%) of the targeted landmass at least one time, 94.59% at least twice, and about 50% at least three or more times. The goal was to image each terrain segment at least twice from different angles (on ascending, or north-going, and descending, or south-going, orbit passes) to fill areas shadowed from the radar signal by terrain.

This 'targeted landmass' consisted of all land between 60° North and 56° South latitude, which comprises almost exactly 80% of the Earth's total landmass. The coverage reached somewhat further north than south because the side-looking radar looked toward the north side of the Shuttle.

NASA Version 3.0 SRTM (SRTM Plus) data includes topographic data from non-SRTM sources to fill the gaps ("voids") in earlier versions of SRTM data. The primary fill data are from the

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor on NASA's Terra satellite, which imaged Earth stereoscopically in near-infrared wavelengths since 1999 (Yamaguchi and others, 1998; Fujisada and others, 2011). The secondary fill are the USGS Global Multi-resolution Terrain Elevation Data (GMTED2010), which are lower resolution and derived from many sources (Danielson and Gesch, 2011). Researchers used the USGS National Elevation Dataset (NED) (Gesch and others, 2002) instead of GMTED2010 for the United States (except Alaska) and northern Mexico.

2.0 Dataset Characteristics

All SRTM data are divided into tiles extending over $1^\circ \times 1^\circ$ of latitude and longitude, in "geographic" projection.

Table 1: Dataset Characteristics for each product of the SRTM Global Collection

Short Name	Data Product	Rows/Columns	Spatial Resolution
SRTMGL1	Global 1 arc-second	3601/3601	1 arc-second
SRTMGL1N	Global 1 arc-second number	3601/3601	1 arc-second
SRTMGL3	Global 3 arc-second	1201/1201	3 arc-second
SRTMGL30	Global 30 arc-second	6000/4800	30 arc-second
SRTMGL3N	Global 3 arc-second number	1201/1201	3 arc-second
SRTMGL3S	Global 3 arc-second sub-sampled	1201/1201	3 arc-second
SRTMSWBD	Water Body Data Shapefiles & Raster files	3601/3601	1 arc-second
SRTMIMGR	Global SRTM Swath Image Data	3601/3601	1 arc-second
SRTMIMGM	Global SRTM Combined Image Data	3601/3601	1 arc-second

2.1 SRTM Topography

2.1.1 Versioning

SRTM data have undergone a sequence of processing steps resulting in data versions that have different characteristics. All processing occurred at 1 arc-second (about 30 m) postings. One (1) arc-second and 3 arc-second (about 90 m) are available with worldwide coverage.

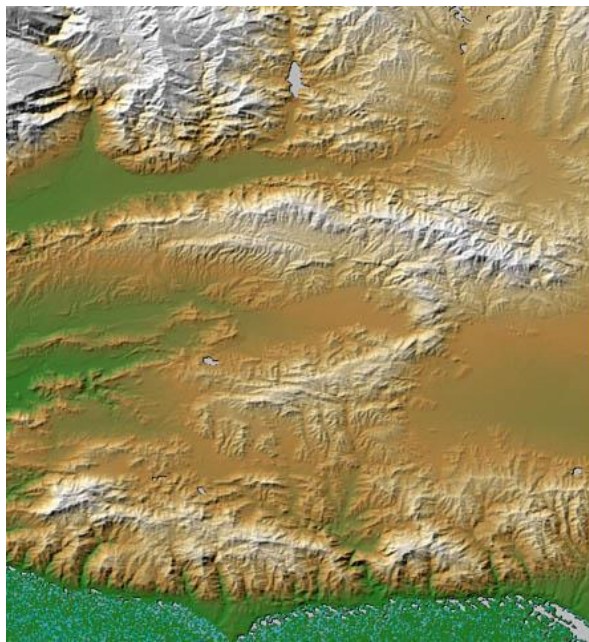
Version 1.0: SRTM radar echo data were processed in a systematic fashion using the SRTM Ground Data Processing System (GDPS) supercomputer system at the NASA Jet Propulsion Laboratory. This processor transformed the radar echoes into strips of digital elevation data – one strip for each of the 1,000 or so data swaths. These strips eventually were mosaicked into at least 14,549 - $1^\circ \times 1^\circ$ tiles. The data were processed continent-by-continent beginning with North America and proceeding through South America, Europe, Asia, Africa, Australia and Islands, with data from each continent undergoing a "block adjustment" to reduce residual

errors. The data were arranged in SRTM format, detailed in Section 3 below, and made available online from the U.S. Geological Survey (USGS) as Version 1.0.

Each SRTM data tile contains a mosaic and blending of elevations generated by averaging all “data takes” that fall within that tile. Since the primary error source in synthetic aperture radar data was speckle, which has the characteristics of random noise, combining data through averaging reduced the error by the square root of the number of data takes used. SRTM data takes ranged from a minimum of one (about 5% of the coverage) up to as many as 24 (very little of the coverage). Typical coverage was 2-to-3 data takes.

Version 2.1: Next, NGA applied several post-processing procedures to the SRTM data including editing, spike and pit removal, water body leveling, and coastline definition. Following these “finishing” steps, data were returned to NASA for distribution to a variety of user communities. These data are referred to as Version 2.0. Version 2.1 corrects some minor errors found in the original 3 arc-second Version 2.0 product.

Below, Figure 1 shows a portion of tile N34W119.hgt, demonstrating the difference between Malibu Coast and Simi Valley, California in the unedited (Version 1.0) and edited (Version 2.1) data. Ocean (bottom) and small lakes (e.g., center top) are flattened with shoreline elevations.



Version 1.0 – Unedited



Version 2.1 – Edited

Figure 1: Malibu Coast and Simi Valley, California

Version 3.0: The Version 3.0 dataset was created as a NASA Making Earth System Data Records

for Use in Research Environments (MEaSUREs) project. The primary goal of creating this version was to eliminate gaps, or voids, in the SRTM DEM. Ultimately, this goal was achieved by filling the voids with elevation data primarily from the Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2.0 (GDEM2) and secondarily from the USGS GMTED2010 elevation model or the USGS National Elevation Dataset (NED).

Below, Figure 2 shows the genealogy of all SRTM versions and demonstrates the different agencies and processing techniques that have been applied to the original SRTM Version 1.0 data.

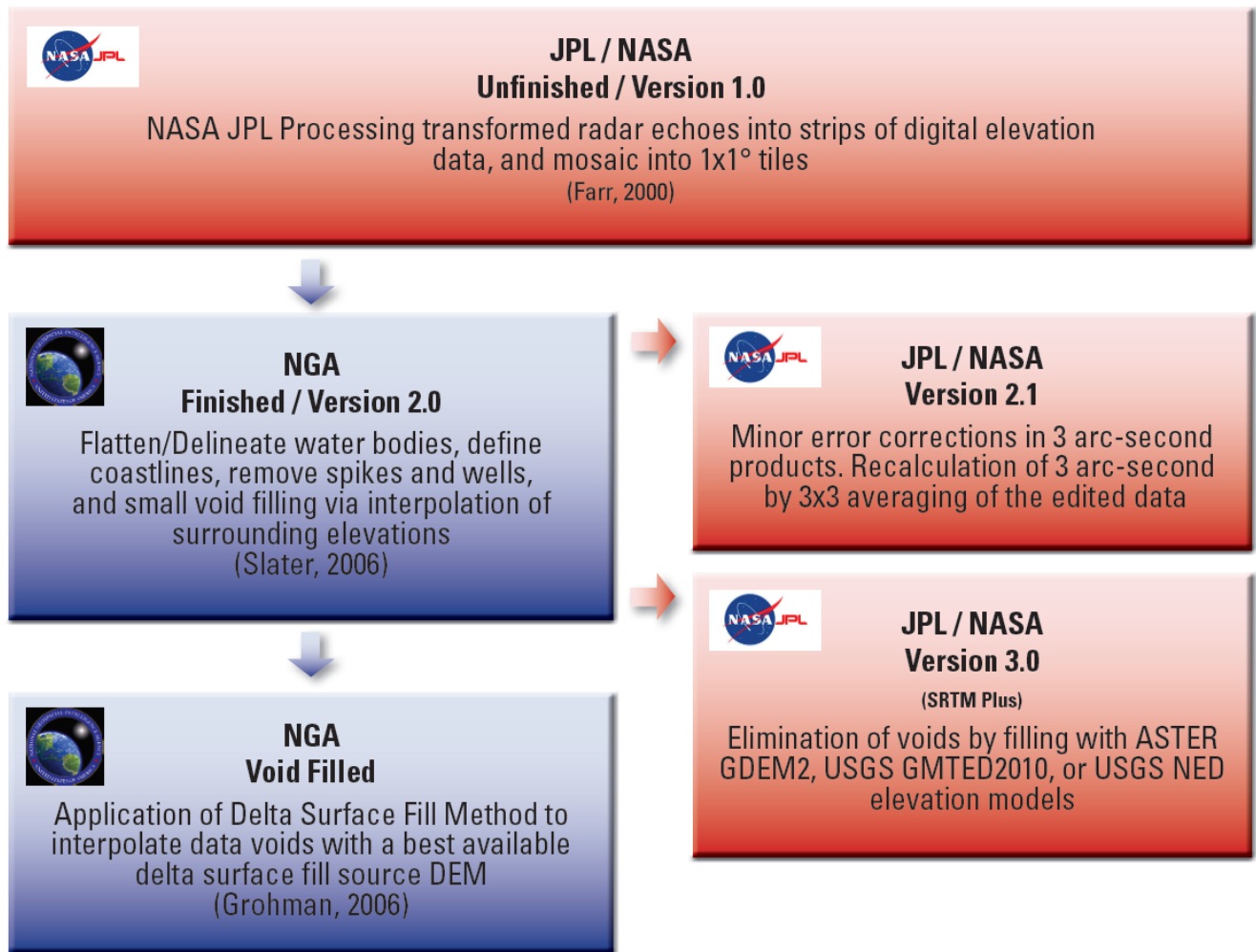


Figure 2: Genealogy of the SRTM versions

ASTER is a joint project of NASA and Japan’s Ministry of Economy, Trade and Industry, and now, Japan Space Systems. The Sensor Information Laboratory Corporation of Japan used more than one million ASTER scenes (stereo pairs) to produce ASTER GDEM2 (Fujisada et al., 2012). At its best, the ASTER

GDEM2 data are comparable to full resolution SRTM elevation data, but are much less consistent in quality. This is primarily due to ASTER being an optical system. Clouds can obscure ASTER's views but, SRTM is a radar system, which means it can look through clouds. Both ASTER and SRTM can have difficulty when collecting data in very steep and rugged terrain, but ASTER has some advantage due to its more nadir view (the stereo pair includes a nadir view). Thus, ASTER DEMs can generally fill SRTM voids in rugged terrain that are not often obscured by clouds. Elsewhere, both sensors have difficulty in smooth, flat terrain such as desert sand sheets, where little of the SRTM radar signal was reflected back to the Shuttle, and where ASTER stereoscopy is hindered by the lack of the Earth's surface patterns to correlate between the two views.

Voids in ASTER GDEM2 have been filled with American or Canadian national elevation data, SRTM 3 arc-second data, or NGA elevation data from undisclosed sources. Some GDEM2 ASTER elevations, where alternative sources were not available, are cloud tops that are hundreds (or even thousands) of meters above the ground.

Researchers merged ASTER GDEM2 data with SRTM data by retaining all of the SRTM Version 2.1 data and using a modified Delta Surface Fill algorithm (Grohman and others, 2006) to fill only the voids. This is essentially a "rubber sheet" methodology in which ASTER GDEM2 was matched to SRTM vertically and then gently warped to seamlessly meet the SRTM void edges. Researchers developed another technique to detect significant errors in ASTER GDEM2, based upon its inconsistency with SRTM, and to reintroduce voids at those locations. These new voids were then filled with GMTED2010 or NED data.

Scientists used GMTED2010 at its finest level of spatial detail, 7.5 arc-seconds, but interpolated to 1 arc-second postings, to blend with the SRTM DEM partially filled with ASTER GDEM2. Again, researchers used a modified Delta Surface Fill algorithm to fill the remaining voids with GMTED2010. Researchers used NED instead of GMTED2010 for the United States (except Alaska) plus northern Mexico (north of 25°N latitude).

Scientists produced an ancillary 1-byte (0 to 255) "NUM" (number) files was produced for each SRTM NASA Version 3.0 elevation file. The separate NUM file indicates the source of each DEM pixel, as well as the number of ASTER scenes used (up to 100), if ASTER GDEM2 was the pixel source, and the number of SRTM data takes (up to 24), if SRTM was the pixel source. The NUM file for both 3 arc-second products (whether sampled or averaged) references the 3x3 center pixel. Note that NUMs less than 6 are water and those greater than 10 are land. The NUM files have names corresponding to the elevation files, except with the extension ".NUM" (such as N37W105.NUM). The elevation files use the extension ".HGT", meaning height (such as N37W105.HGT).

Table 2: Fill Values of the “.NUM” files

Fill Value
1 = Water-masked SRTM void *
2 = Water-masked SRTM non-void *
5 = GDEM elevation = 0 in SRTM void (helped correct ocean masking)
11 = NGA-interpolated SRTM (were very small voids in SRTMv1) 21 = GMTED2010 oversampled from 7.5 arc-second postings
25 = SRTM within GDEM **
31 = NGA fill of SRTM via GDEM***
51 = USGS NED
52 = USGS NED via GDEM
53 = Alaska USGS NED via GDEM
72 = Canadian Digital Elevation Data (CDED) via GDEM 101-200 = ASTER scene count (count limited to 100)
201-224 = SRTM swath count (non-voided swaths) Actual maximum = 24

* Water-masked in SRTMv2 by the National Geospatial-Intelligence Agency (NGA) using its SRTM Water Body Database (SWBD).

** GDEM used SRTM 3 arc-second data, oversampled to 1 arc-second postings, as fill at some locations. Rarely some of these interpolations are at locations of void within the original 1 arc-second SRTM.

*** GDEM used a version of SRTM supplied by NGA that included elevation measurements from undisclosed sources.

2.1.2 Processing Steps

All SRTM Version 3.0 processing occurred at the original 1 arc-second postings. Products released with 3 arc-seconds were derived from the final 1 arc-second DEM. SRTM Version 3.0 processing steps are as follows:

1-2: GMTED2010 was prepared

(1) GMTED2010 included geo-location errors in much of Africa and parts of South America. These errors correspond to the SPOT DEM inputs to GMTED2010, and they consist of one full GMTED2010 pixel (7.5 arc-seconds) shift to the southwest (for Africa) or east (for South America) for some 1°x1° latitude-longitude quads. To correct these errors, those quads were shifted into proper position and the consequent pixel-wide gaps at the trailing edge were interpolated.

(2) GMTED2010 was resampled to 1 arc-second postings by bi-cubic interpolation to match the full-resolution SRTMV2.0 and ASTER GDEM2. Bi-cubic interpolation can introduce artifacts in some topographic features such as sea cliffs and mesas, including the introduction of some elevation values outside the range of the input pixel values (e.g., extrapolation). However, bi-cubic interpolation produced far fewer artifacts than bi-linear interpolation.

3: ASTER GDEM2 was used to edit the SRTM water mask

(3) SRTM voids were filled with an elevation of 0 meters if the pixel had an elevation of 0 meters in ASTER GDEM2. This significantly improved the topographic representation of shorelines, especially near sea cliffs by avoiding interpolations across voids that overlap steep coastal mountains (or high terraces) and flat offshore water, where a topographic inflection at the shoreline should occur.

4-6: A modified Delta Surface Fill method was applied to fill SRTM voids with ASTER GDEM2

(4) SRTM elevations were subtracted from ASTER GDEM2 elevations, but retain the SRTM voids (that remained after Step 3). This is the ASTER GDEM2-SRTM delta surface.

(5) GDEM2-SRTM delta surface voids were filled mostly via iterative edge-growing interpolation: In each iteration, each void pixel that bordered any non-void pixel was interpolated from the nearest non-void pixels in each of 16 different directions (north, south, east, west, northwest, southwest, northeast, southeast, and the eight directions intermediate to those eight: NNE, ENE, ESE, SSE, SSW, WSW, WNW, NNW). Each of the 16 reference pixels were weighted by the inverse square root of its distance. The effect of the inverse square root is to most heavily weight the closest pixels, but to also minimize the influence of distance variations for the more distant reference pixels. In other words, close pixels are most important in the interpolation and their relative closeness matters, while far pixels are less important in the interpolation and their relative distance does not matter (much). This edge-growing interpolation was applied in 50 iterations. The iterations greatly helped to smooth the interpolation because the reference pixels in each successive step were themselves interpolated during the previous step. It should be noted that delta surfaces of DEMs are entirely noise (errors of some sort) in either SRTM, ASTER GDEM2, or both. The goal was to characterize the broader systematic differences between the DEMs without being too subject to the higher spatial frequency random errors. Thus, smoothing was important for the interpolation. After 50 iterations, the smaller voids were already filled. Meanwhile, for the larger voids, the high spatial frequency random errors along the void edges largely were suppressed, such that any remaining voided pixels could be filled in the last step (no edge growing) via a final interpolation applied to all remaining voided pixels. The delta surface are now complete and considered void free.

(6) The delta surface from ASTER GDEM2 was subtracted. The result was the original SRTM DEM, where it already existed, with its voids filled by ASTER GDEM2, which had been adjusted in height and by gentle warping to merge seamlessly with SRTM.

SRTM Non-Void Areas $= \text{GDEM2} - (\text{GDEM2} - \text{SRTM})$
 $= \text{SRTM}$

SRTM Void Areas $= \text{GDEM2} - [\text{filled}(\text{GDEM2} - \text{SRTM})]$
 $= \text{GDEM2}$ with adjustments to fit SRTM

7: The Delta Surface itself was used as an error check for ASTER GDEM2 quality

(7) The DEM are complete spatially, but are they accurate? If it is assumed that the original

SRTM DEM are accurate, then the delta surface measures probable errors in the void fills. If ASTER GDEM2 exactly matched SRTM, then the delta surface would be all zeroes, and the interpolated voids would also be all zeroes. Any differences from 0 indicate an error that are assumed to be in ASTER GDEM2, but is not always the case. These errors do not affect the final DEM, where SRTM are not void since SRTM are used (unchanged) in the final DEM. However, large values in the delta surface (+/- differing from zero) indicated a significant inconsistency between SRTM and ASTER GDEM2, such as a cloud elevation in ASTER GDEM2.

Technicians experimented greatly to determine an optimum threshold to reject some void fills as errors. A threshold of 80 m caught most obvious errors while minimizing the rejection of apparently good elevation values. Using this threshold, voids were reintroduced to the ASTER GDEM2-filled SRTM DEM where the delta surface was equal to or outside +/-80 m. Note that this was only in the original SRTM voids and was often only part(s), if any, of each void.

8: Remaining voids were filled with GMTED2010 or NED

(8) Repeat Steps 4-6 (above) using GMTED2010 instead of ASTER GDEM2, and use the DEM from Step 7 (above) instead of SRTM. This was a (modified) Delta Surface Fill of the rejected parts of the ASTER GDEM2 fill of SRTM.

Scientists used NED, instead of GMTED2010, was used in the 48 conterminous United States and northern Mexico (N25-29W65-125) plus Hawaii (N19-23W154-161).

The final DEM are now complete: SRTM is filled with GDEM2, except where discordant and GMTED2010 or NED were used to fill those areas.

2.1.3 One (1) arc-second ("30 meter") and three (3) arc-second ("90 meter") postings

SRTM data are organized into individual rasterized tiles each covering 1°x1° of longitude. Sample spacing for individual data points is either 1 arc-second (United States and territories) or 3 arc-seconds (worldwide), referred to as SRTM1 or SRTM3, respectively. Since 1 arc-second at the equator corresponds to approximately 30 m in horizontal extent, the SRTM1 and SRTM3 are sometimes referred to as "30 meter" or "90 meter" data. (Note: a void-free 30 arc-second (about 1 kilometer) Version 1.0 product, referred to as SRTM*30 was also produced, with voids filled with the GTOPO30 elevation model.) With postings of 1, 3, and 30 arc-seconds, corresponding to nominal postings at 30, 90, and 1,000 m, and with versions numbering 1, 2, and 3, users should take care to reference these data specifically by "arc-seconds" or "meters" as well as by "version."

For Version 2.1, there is a difference between the data distributed via download from the NASA Land Processes Distributed Active Archive Center (LP DAAC), and those available from the NGA at the Earth Resources Observation and Science (EROS) Center through the Long Term Archive (LTA). Three arc-second sampled data from the NGA LTA have been generated from the 1 arc-second data by "sampling." In this method, each 3 arc-second data point is generated by selecting the center sample of the 3x3 array of 1 arc-second points that surround the post

location. For the NASA LP DAAC 3 arc-second data, each point is the average of the nine (3x3) 1 arc-second samples surrounding the post, as illustrated in Figure 3.

Many analysts feel that the averaging method produces a superior product by decreasing the high frequency “noise” characteristic of radar-derived elevation data. This is similar to the conventional technique of “taking looks,” or averaging pixels in radar images to decrease the effects of speckle and increase radiometric accuracy, although at some cost of horizontal resolution. The true spatial resolution of SRTM 1 arc-second data is generally estimated to be in the range of 50 to 80 m. Thus, the 1 arc-second postings beneficially oversample the data.

Three arc-second postings derived by sampling exclude some detail. Three arc-second postings derived by averaging use all the original postings but, in effect, blur them. The result is that the sampled 3 arc-second data has a slightly finer spatial resolution (about 100 m), but with more noise, in comparison to the averaged 3 arc-second data, which has a slightly coarser spatial resolution (about 112 m), but with less noise.

For SRTM Version 3.0, 3 arc-second data were derived using the sampling method and also the averaging method, and each is available for download.

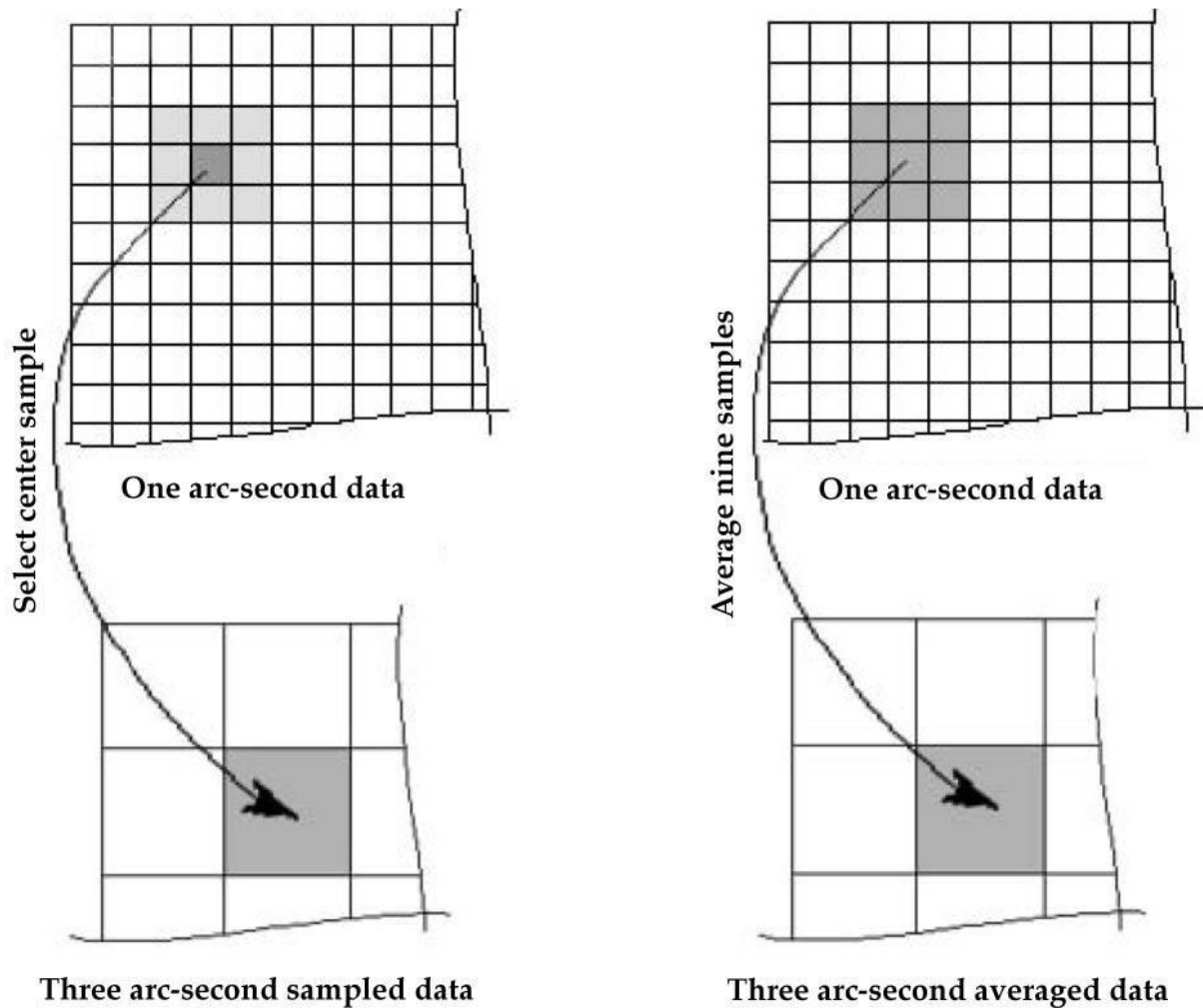


Figure 3: Deriving 3 arc-second data from 1 arc-second data: Sampling Method versus Averaging Method.

2.1.4 SRTM Topography Data Format

The names of individual data tiles refer to the latitude and longitude of the southwest (lower left) corner of the tile. For example, N37W105 has its lower left corner at 37°N latitude and 105° West (W) longitude and covers (slightly more than) the area 37-38°N and 104-105°W. To be more exact, the file name coordinates refer to the geometric center of the lower-left pixel, and all edge pixels of the tile are centered on whole-degree lines of latitude and/or longitude. The unit of elevation is meters as referenced to the WGS84/EGM96 geoid (NGA, 1997; Lemoine, 1998).

SRTM1 data are sampled at 1 arc-second of latitude and longitude and each file contains 3,601

lines and 3,601 samples. The rows at the north and south edges, as well as the columns at the east and west edges of each tile, overlap, and are identical to, the edge rows and columns in the adjacent tile. SRTM*3 data are sampled at 3 arc-seconds and contain 1,201 lines and 1,201 samples with similar overlapping rows and columns.

The SRTMGL30 data are sampled at 30 arc-seconds and extend from 90°N to 60°S latitude, and from 180°W to 180°E longitude. The SRTMGL30 data contains 27 tiles. Each tile has 6,000 rows and 4,800 columns. The tiles do not overlap, so the global dataset may be assembled by simply abutting the adjacent tiles.

The data are in "geographic" projection (also known as Equirectangular or Plate Carrée), which means the data is presented with respectively equal intervals of latitude and longitude in the vertical and horizontal dimensions. More technically, the projection maps meridians to vertical straight lines of constant spacing, and circles of latitude ("parallels") to horizontal straight lines of constant spacing. This might be thought of as no projection at all, but simply a latitude-longitude data array.

Height files have the extension .HGT, and the DEM is provided as two-byte (16-bit) binary signed integer raster data. Two-byte signed integers can range from -32,767 to 32,767 m and can encompass the range of the Earth's elevations. Header or trailer bytes are not embedded in the file. The data are stored in row major order, meaning all the data for the northernmost row, row 1, are followed by all the data for row 2, and so on.

The two-byte data are in Motorola "big-endian" order with the most significant byte first. Most personal computers, and Macintosh computers built after 2006 use Intel ("little-endian") order so byte swapping may be necessary. Some software programs perform the swapping during ingest.

Voids in Versions 1.0 and 2.1 are flagged with the value -32,768. There are no voids in Version 3.0.

2.2 SRTM IMAGE DATA

There are two types of SRTM data: DEMs and image swath data. For the DEMs, data from every acquisition that crossed a tile were mosaicked and combined, so there is only one data file for each 1° tile. However, for image data, 2 types of data are available:

- 1.) Swath Image Data – For this dataset, every data take that crossed a tile was saved as a separate file (no mosaicking or combining) so that some files may contain only partial data. In addition, because of the SCANSAR technique involved, each SRTM swath contained four overlapping sub-swaths. Data from each sub-swath was also included as a separate file, so every image pixel acquired by SRTM is included in

this dataset.

- 2.) Combined Image Data – This dataset was produced by averaging all image data in a $1^\circ \times 1^\circ$ tile, similar to the DEM. This produced a single, smoother, uncalibrated image for each tile.

Both types of SRTM image data are sampled at 1 arc-second of latitude and longitude and each file contains 3,601 lines and 3,601 samples. The rows at the north and south edges, as well as the columns at the east and west edges of each tile, overlap and are identical to the edge rows and columns in the adjacent tile.

This sampling scheme is sometimes called a "geographic projection," but it is not actually a projection in the mapping sense. It does not possess any of the characteristics usually present in true map projections. For example, it is not conformal, so that if it is displayed as an image, geographic features will be distorted. However, it is quite easy to handle mathematically, can be easily imported into most image processing and GIS software packages, and multiple tiles can be assembled easily into a larger mosaic (unlike the UTM projection, for example.)

2.2.1 SRTM Swath Image Data

There are two files for each sub-swath that passes through a tile:

- *.mag – radar sub-swath image data
- *.inc – local incidence angle for each sample in the corresponding *.mag file

The SRTM swath-image product provides the mean-surface backscatter coefficients of the mapped areas. This required the image processor to be radiometrically calibrated. For SRTM, the goals for absolute and relative radiometric calibration respectively were 3 decibel (dB) and 1 dB. The SRTM main antenna served as the major source of calibration error as it was a large, active-array antenna. In the spaceborne environment, both zero-gravity unloading and the large variation in temperature caused distortions in the phased array. Hundreds of phase shifters and transmit/receive modules populated the C-band antenna panels. Monitoring the performance of each module was very difficult, causing inaccuracies in the antenna pattern predictions, in particular in elevation, as the pulses were spoiled to obtain a wide swath. Therefore, antenna elevation pattern correction coefficients were derived with scientific methods using data taken over the Amazon rain forest. Since the Amazon rainforest is a homogeneous and isotropic area, the backscatter coefficient is almost independent of the look angle. Without compensation, a scalloping effect would have been visible in the sub-swath and full-swath images.

Speckle noise is present in the swath image data. This is a characteristic of coherent imaging systems and appears as a random, high-frequency, salt-and-pepper effect. Most imaging radar systems average many looks to reduce speckle, however SRTM was optimized for a wide swath and thus acquired only 1-2 looks per sub-swath causing a relatively high-speckle

noise level. This is one reason for the production of the combined image dataset, described later.

Because local incidence angle is so important for interpretation of radar images, a file containing that information is provided for each of the sub-swath image files. The values are calculated from the position of the Shuttle and the DEM. They represent the angle between the radar signal and the local normal to the surface at each pixel. Because this information could be used to “back-calculate” a full resolution DEM, the incidence-angle pixels were averaged 3x3 and sampled back to 1 arc-second to remain registered with the corresponding image file.

Figure 4, below, shows a portion of tile N34W119, demonstrating the characteristic of the swath image and incidence angle datasets and the difference with the topographic data.

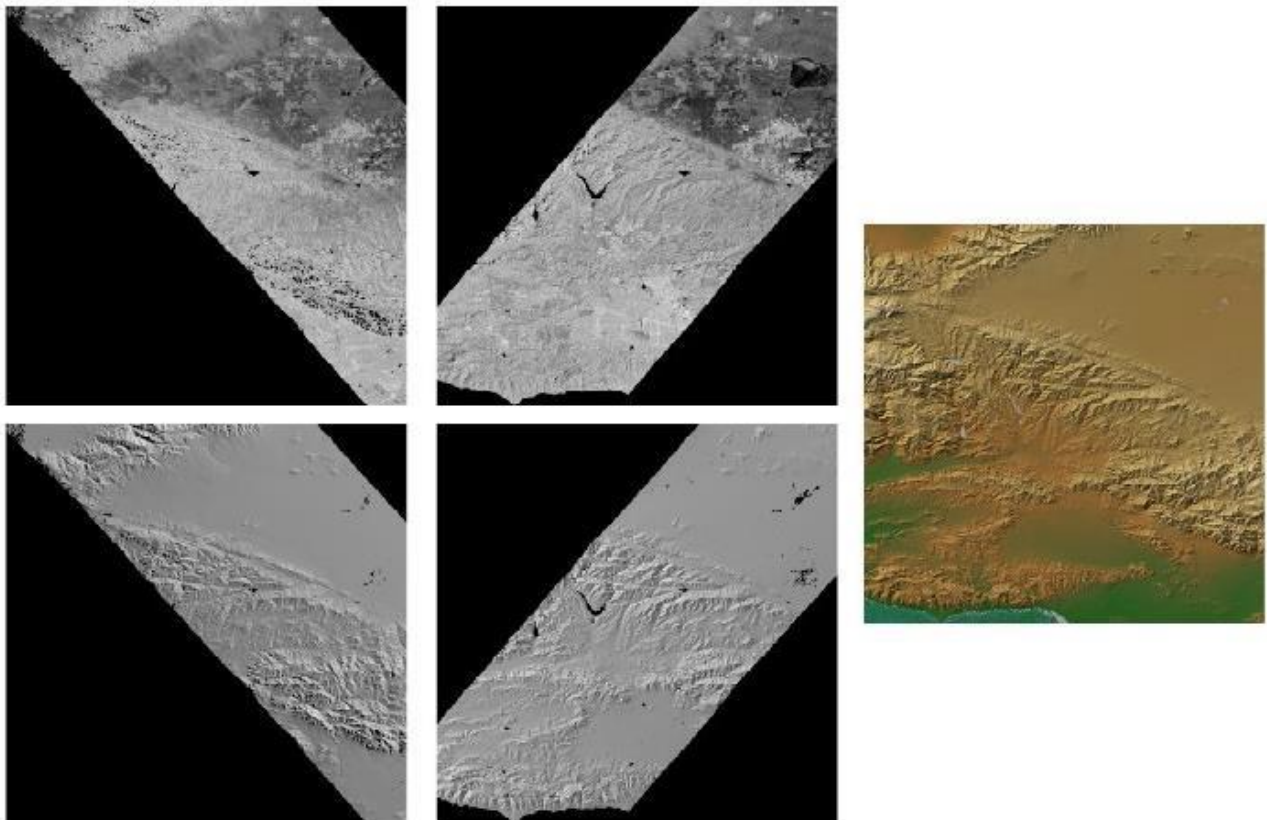


Figure 4: Comparison of SRTM swath image data and SRTM DEM for tile N34W119 (Los Angeles, CA). Left: Descending sub-swath N34W119_072_100_SS2_1_01. Upper left: Image file, Lower left: Incidence angle file. Center: Ascending sub-swath N34W119_114_030_SS4_1_01. Upper center: Image file, Lower center: Incidence angle file. Right: SRTM DEM for the same tile, shaded-relief and elevation color-coded. Voids in the DEM (shown in grey) correspond to black areas in the image and incidence angle file. The incidence angle files look like shaded-relief topography because they are calculated in a similar way. The rough, vegetated, mountains are bright in the images, while the smoother Mojave Desert tends to be dark.

As with the DEM files, the first 6 characters of each file name indicate the geographic coordinates of the center of the lower left (southwest) sample of each file. For swath image files, this is followed by 6 numbers that indicate the data take number, consisting of the orbit number followed by a serial number for that orbit. This is followed by a sub-swath number, which increases outward from the spacecraft nadir point, and also is the key to the polarization for that sub-swath. The remaining numbers were not used and are always the same. The polarization channels are vertical transmit and vertical receive (VV) and horizontal transmit and horizontal receive (HH).

- SS1 = sub-swath 1 HH polarization approx. 30° - 40° look angle
- SS1 = sub-swath 2 VV polarization approx. 41° - 48° look angle
- SS1 = sub-swath 3 VV polarization approx. 47° - 53° look angle
- SS1 = sub-swath 4 HH polarization approx. 52° - 59° look angle

For example, a file named "N34W119_072_100_SS2_1_01.mag" has its lower left sample centered on 34° N latitude, 119° W longitude, was the 100th data take on orbit 72, and includes data from sub-swath 2, indicating VV polarization.

Image brightness, or magnitude, in the swath image data is given as 8 bits/sample, with the values indicating radar cross section, scaled linearly between -50 dB and +40 dB. Data numbers (DN) can be converted to backscatter cross section in dB using the expression $\text{dB} = 0.3529 \cdot \text{DN} - 50$. The file does not have embedded header or trailer bytes. The data are stored in row major order (all the data for row 1, followed by all the data for row 2, etc.).

The local incidence angle is provided as 16-bit integer data in a simple binary raster. There are no header or trailer bytes embedded in the file. The data are stored in row major order (all the data for row 1, followed by all the data for row 2, etc.). The pixel values represent hundredths of a degree (e.g., -4,321 = 43.21 degrees).

Users must be aware of how the bytes are addressed on their computers because the incidence angle data are stored in a 2-byte binary format. The incidence-angle data are provided in Motorola or IEEE byte order, which stores the most significant byte first ("big endian"). Systems such as Sun SPARC and Silicon Graphics workstations and older Macintosh computers use the Motorola byte order. The Intel byte order, which stores the least significant byte first ("little endian"), is used on DEC Alpha systems and most personal computers. Users with systems that address bytes in the Intel byte order may have to "swap bytes" of the incidence angle data unless their application software performs the conversion during ingest.

2.2.2 SRTM Combined Image Dataset

The objective of the SRTM combined image dataset was to produce the smoothest mosaicked image data possible. Specifically, every pixel in the mosaic output is an average of all the image

pixels in that location. Pixels with a value of 0 (voids) were not counted. Because SRTM imaged a given location with two polarizations (VV and HH) and at a variety of look and azimuth angles, this means that quantitative scattering information has been lost as technicians sought to produce a smoother-image product. Quantitative scattering information is preserved in the SRTM swath image product, described earlier.

There are two combined image files for each tile:

- *.img is the SRTM image mosaic
- *.num gives the number of pixels averaged for each output pixel

As with the DEM files, the file name indicates the geographic coordinates of the center of the lower left (southwest) sample of each file. The combined image files are 8 bits/samples, with the values indicating uncalibrated radar brightness. The *.num file was also given as 8 bit/sample, with the value being the number of pixels averaged to create the output pixel. This value is typically 0 (for a void pixel) to 10 or more.

3.0 References

Campbell, B.A., 2002, *Radar Remote Sensing of Planetary Surfaces*, Cambridge Univ. Press, Cambridge, UK, 331 pp.

Danielson, J.J., and D.B. Gesch, 2011, *Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010)*, USGS Open-File Report 2011-1073, 26pp.

Elachi, C., 1988, *Spaceborne Radar Remote Sensing: Applications and Techniques*, IEEE Press, New York, 254 pp.

Farr, T.G., and M. Kobrick, 2000, Shuttle Radar Topography Mission produces a wealth of data, *American Geophysical Union Eos*, v. 81, p. 583-585.

Farr, T.G., E. Caro, R. Crippen, R. Duren, S. Hensley, M. Kobrick, M. Paller, E. Rodriguez, P. Rosen, L. Roth, D. Seal, S. Shaffer, J. Shimada, J. Umland, M. Werner, 2007, The Shuttle Radar Topography Mission. *Reviews of Geophysics*, volume 45, RG2004, doi:10.1029/2005RG000183.

Fujisada, H., M. Urai, and A. Iwasaki, 2011, Advanced methodology for ASTER DEM generation. *IEEE Transactions on Geoscience and Remote Sensing*, v. 49, no. 12, p. 5,080-5,091.

Fujisada, H., M. Urai, and A. Iwasaki, 2012, Technical methodology for ASTER Global DEM. *IEEE Transactions on Geoscience and Remote Sensing*, v. 50, no. 10, p. 3,725-3,736.

Gesch, D.B., M. Oimoen, S.K. Greenlee, C.A. Nelson, M. Steuck, and D. Tyler, 2002, The National

- Elevation Dataset. *Photogrammetric Engineering and Remote Sensing*, v. 68, no. 1, p. 5-11.
- Grohman, G., G. Kroenung, and J. Strebeck, 2006, Filling SRTM voids: The Delta Surface Fill method. *Photogrammetric Engineering and Remote Sensing*, v. 72, no. 3, p. 213-216.
- Henderson, F.M., A.J. Lewis, ed., 1998, Principles and Applications of Imaging Radar, Manual of Remote Sensing, v. 2, Wiley, NY, 866 pp.
- Kobrick, M., 2006, On the toes of giants: How SRTM was born. *Photogrammetric Engineering and Remote Sensing*, Vol. 72, Number 3, p.206-210.
- Lemoine, F.G., S. C. Kenyon, J. K. Factor, R.G. Trimmer, N. K. Pavlis, D. S. Chinn, C. M. Cox, S. M. Klosko, S. B. Luthcke, M. H. Torrence, Y. M. Wang, R. G. Williamson, E. C. Pavlis, R. H. Rapp and T. R. Olson, 1998, *The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96*. NASA/TP-1998-206861, NASA Goddard Space Flight Center, Greenbelt, MD 20771,U.S.A., July 1998.
<http://cdis.nasa.gov/926/egm96/nasatm.html>
- National Geospatial-Intelligence Agency (NGA), 1997, *Department of Defense World Geodetic System 1984, Its Definition and Relationships With Local Geodetic Systems*. NIMA Technical Report TR8350.2, Third Edition, 4 July 1997.
http://earth-info.nga.mil/GandG/publications/tr8350.2/tr8350_2.html
- Rosen, P.A., S. Hensley, I.R. Joughin, F.K. Li, S.N. Madsen, E. Rodriguez, R.M. Goldstein, 2000, Synthetic aperture radar interferometry, *Proceedings of the IEEE*, v. 88, no. 3, p. 333-382.
- Slater, J. A., G. Garvey, C. Johnston, J. Haase, B. Heady, G. Kroenung, and J. Little, 2006, The SRTM data 'finishing' process and products, *Photogramm. Eng. Remote Sens.*, v. 72, p. 237–247.
- Yamaguchi, Y., A.B. Kahle, H. Tsu, T. Kawakami, and M. Pniel, 1998, Overview of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). *IEEE Transactions on Geoscience and Remote Sensing*, v. 36, no. 4, p. 1,062-1,071.

4.0 Web sites of interest

NASA/JPL SRTM:

<http://www2.jpl.nasa.gov/srtm/>

U.S. Geological Survey:

<http://srtm.usgs.gov/>

ASTER Project:

<http://asterweb.jpl.nasa.gov/>

GMTED2010:

<https://lta.cr.usgs.gov/GMTED2010>

National Elevation Dataset (NED):

<http://ned.usgs.gov/>

LP DAAC Homepage:

<http://lpdaac.usgs.gov>