PERFORMANCE ASSESSMENT OF THE FINAL TANDEM-X DEM

Johannes Böer, Carolina Gonzalez, Christopher Wecklich, Benjamin Bräutigam, Daniel Schulze, Markus Bachmann, Manfred Zink

German Aerospace Center (DLR), Microwaves and Radar Institute
Oberpfaffenhofen, Germany, E-Mail: Johannes.Boeer@dlr.de

ABSTRACT

The TanDEM-X system is an innovative radar mission, which is comprised of two formation flying satellites, with the primary goal of generating a global Digital Elevation Model (DEM) of unprecedented accuracy. TanDEM-X, being a large single-pass radar interferometer, achieves this accuracy through a flexible baseline selection enabling the acquisition of highly accurate cross-track interferograms that are not impacted by temporal decorrelation or atmospheric disturbances. At least two global coverages (at least four in the case of difficult terrain) are combined into a homogenous global DEM mosaic consisting of 1° by 1° geocells. With the DEM data production of the Earths continents almost completed, apart from Antarctica, this paper provides a quality summary of the currently available part of the TanDEM-X global DEM with respect to the DEM absolute and relative height accuracy as well as to void density.

1. INTRODUCTION

Digital Elevation Models (DEMs) are raster-based digital datasets of the topography of a terrain surface and are of fundamental importance for a wide range of scientific and commercial applications, e.g. in navigation systems, hydrology and geology applications. In the realm of global DEMs, spaceborne remote sensing is the most efficient way to acquire a global DEM and, within the ±60º latitude band, data from the Shuttle Radar Topography Mission (SRTM) has been the primary source of elevation information [1]. Above 60º latitude and for Antarctica only lower resolution data are available on a large scale.

Since 2010 the German Aerospace Center (DLR) has been operating the first two formation flying Synthetic Aperture Radar (SAR) satellites, TerraSAR-X and TanDEM-X, with the objective to generate an updated global DEM which exceeds the presently available global data sets in terms of resolution, coverage, and quality by orders of magnitude. The baseline between the two SAR sensors can be flexibly adjusted for single-pass SAR interferometry which provides the opportunity for accurate cross-track and along-track interferograms overcoming the limitations of atmospheric disturbance and temporal decorrelation in multi-pass data [2].

The primary mission of TanDEM-X is the generation of a world-wide, consistent, current, and high-precision DEM, with a spatial resolution of 0.4 arcseconds (12 m at the equator) and according to the specifications listed in Table 1.

Parameter	Specification	Requirement
Absolute Height Accuracy	90% linear error (globally)	≤ 10 meters
Relative Height Accuracy	90% linear point-to-point error (in 1º x 1 º geocell)	≤ 2 meters (slope ≤ 20%)
		≤ 4 meters (slope > 20%)
Data Coverage	Percentage of valid DEM data over land (globally)	≥ 97

Table 1. Global DEM Height Accuracy Performance Parameters

This paper presents a general introduction into how the TanDEM-X global DEMs are generated as well as the latest quality status (Section 2). This is followed by a section each dedicated to the evaluation of absolute and relative height accuracy of the already finalized part of global DEM products (Sections 3 and 4, respectively). Finally the paper is concluded with an evaluation of the TanDEM-X data coverage or void density (Section 5).

2. TANDEM-X GLOBAL DEM

2.1. DEM Generation

SAR interferometry is based on the evaluation of the phase difference between two coherent radar signals acquired from slightly different spatial and/or temporal positions. Using this principle, TanDEM-X is able to measure the range difference between the two satellites and a given scatterer on the ground with millimeter accuracy. The height of the scatterer is then inferred from this range difference by geometric triangulation. As the TanDEM-X radar operates in the X-band, the resulting height represents the reflecting surface of the radar backscatter.

The mapping strategy is to cover all land masses at least twice [3]. The first coverage is acquired at small baselines which facilitates the unwrapping process of the interferometric phase into absolute height values and minimizes decorrelation effects between the two

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interferometric channels. The second coverage is acquired with large baselines providing improved relative height accuracy. Difficult terrain is covered at least four times. Examples of difficult terrain are mountains, which require an opposite viewing geometry to compensate radar shadowing and layover effects; forests, which require small baselines to minimize volume scattering decorrelation; and deserts, which require a steep viewing angle for an improved backscatter return [4].

The generation of a DEM product out of the raw SAR data starts with the synchronization [5] and focusing of the images from the two satellites. This delivers co-registered scenes of 50 km by 30 km in size. These scenes are interferometrically processed, phase unwrapped [6] and converted to geocoded RawDEMs. A pre-requisite to DEM processing is the precise calibration of the interferometric system [7].

When all the input data of a larger region (i.e. several thousands of square kilometers) are available, the tilts and offsets are calibrated out against ICESat data (a small subset of selected ICESat points) and difference between overlapping TanDEM-X acquisitions. The ICESat dataset was selected because of the global coverage, consistency, and precision of this laser altimeter mission [8]. Finally, the mosaicking processor combines all elevation data and produces the output DEM tiles of 1° by 1° size (ca. 110 km by 110 km at equator) [9]. The DEM product also contains add-on layers such as a relative height accuracy map and a water indication mask [10].

2.2. DEM Status

The TanDEM-X global DEM acquisition started in December 2010 and the first global coverage (except Antarctica) was completed in January 2012. By the end of 2014, the Earth’s entire land masses had been mapped at least twice (four times in the case of difficult terrain) with varying baselines, and with different imaging geometries in order to overcome the difficulties posed by e.g. mountains or deserts.

Two dedicated campaigns have been performed to acquire Antarctica in the local winter for high SNR. The interferometric processing and the generation of raw DEM products have been taking place parallel to the data acquisition. In total around 500,000 single scenes are being processed into RawDEMs for the subsequent calibration and mosaicking steps. Of the nearly 20,000 final DEM tiles to be produced, approximately 82 percent are available as of April 2016. Delivery of DEM products commenced in 2014 and the complete global DEM is expected to be available in autumn 2016.

3. ABSOLUTE HEIGHT ACCURACY

Table 1 shows that the final DEM product generated by the TanDEM-X system is specified with an absolute height accuracy of at most 10 meter with a 90% linear error. The absolute height accuracy of the TanDEM-X data will be globally validated using the majority of ICESat points that have not already been utilized in the calibration process. When evaluating the absolute height accuracy, only the first 1,000 points with the lowest height variation between DEM pixels within an ICESat

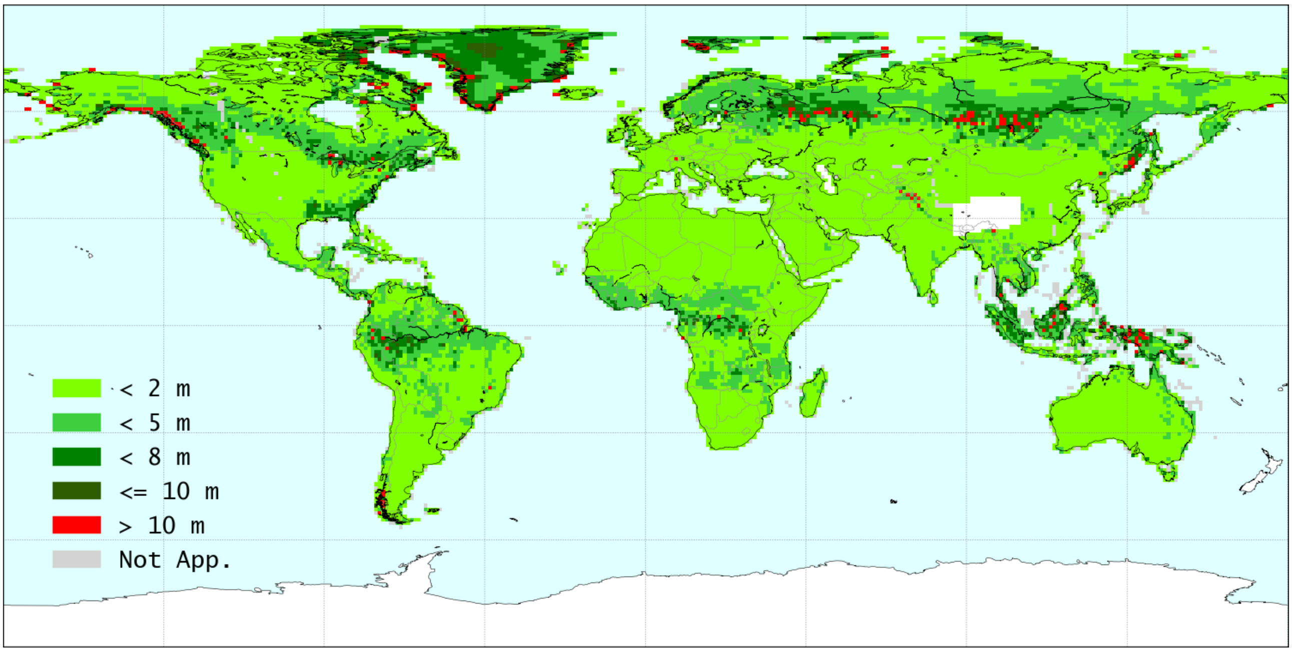

Figure 1. Available TanDEM-X Final DEMs absolute height accuracy per DEM Tile, “Not Applicable” represents tiles where no validation points are available.

footprint are considered. This approach was taken so that tiles with fewer validation points (e.g. coastal regions) are evaluated with similar weight as tiles with more copious validation points. As the ICESat data is laser-based, there can be an offset to the radar-based TanDEM-X measured height, especially over vegetation or ice where the signal penetration of the two systems can differ [11]. Thus the quality of DEMs over other icy as well as mountainous terrain will impact the global statistics.

The most current height statistics, as of April 2016, of the available DEMs is shown in Table 2. Of all the ICESat data points that overlap with the available TanDEM-X data (around 93 Million), over 13 million are within the top 1,000 points of thus generated DEMs. The mean of the height deviation between these validation points and the DEM data is quite small, only 5 centimeters. The linear accuracy level of the validation points for 10 meters is very high at 99.65%. The system specification of an absolute global height accuracy of at most 10 meters with a 90% linear error is met and far exceeded with an accuracy of 1.31 meters.

In addition to the *global* specification, the absolute height accuracy is also monitored on a *DEM tile basis* for all validation points within a tile. Figure 1 shows a per tile overview of the absolute height error. The majority (over 10,000) of the 15,947 produced tiles have an absolute height accuracy of less than 2 m, 3,411 tiles are between 2 and 5 m and 1,055 are between 5 and 10 m. 203 tiles have an absolute height accuracy greater than 10 m, however most of these tiles are over dense forest or floating ice sheets, cover (coastal) regions with strong topography, or suffer from too few available ICESat validation points.

4. RELATIVE HEIGHT ACCURACY

The DEM relative height accuracy is important for derivative products that make use of the local differences between adjacent elevation values, such as slope, aspect calculations, and drainage networks. As the system is very well calibrated and tilts and trends are negligible, the relative height accuracy is well described solely by the random errors in the system. It can be calculated after suppressing the systematic errors and anomalies.

Number of DEM Tiles	15,947
Accumulated Number of Validation Points	13,017,297
Mean Height Deviation of Validation Points (m)	0.05
Accumulated Absolute Height Accuracy of 10 m (Linear Error)	99.65%
Accumulated Absolute Height Accuracy with 90% Linear Error (m)	1.31

Table 2. Absolute Height Accuracy statistics of the TanDEM-X DEM data available as of April 2016

The relative height accuracy specification describes the point-to-point error within a 1° x 1° tile and it states that the confidence level in each tile shall be above 90% with a height accuracy of 2 m for flat terrain and 4 m for steep terrain (see Table 1).

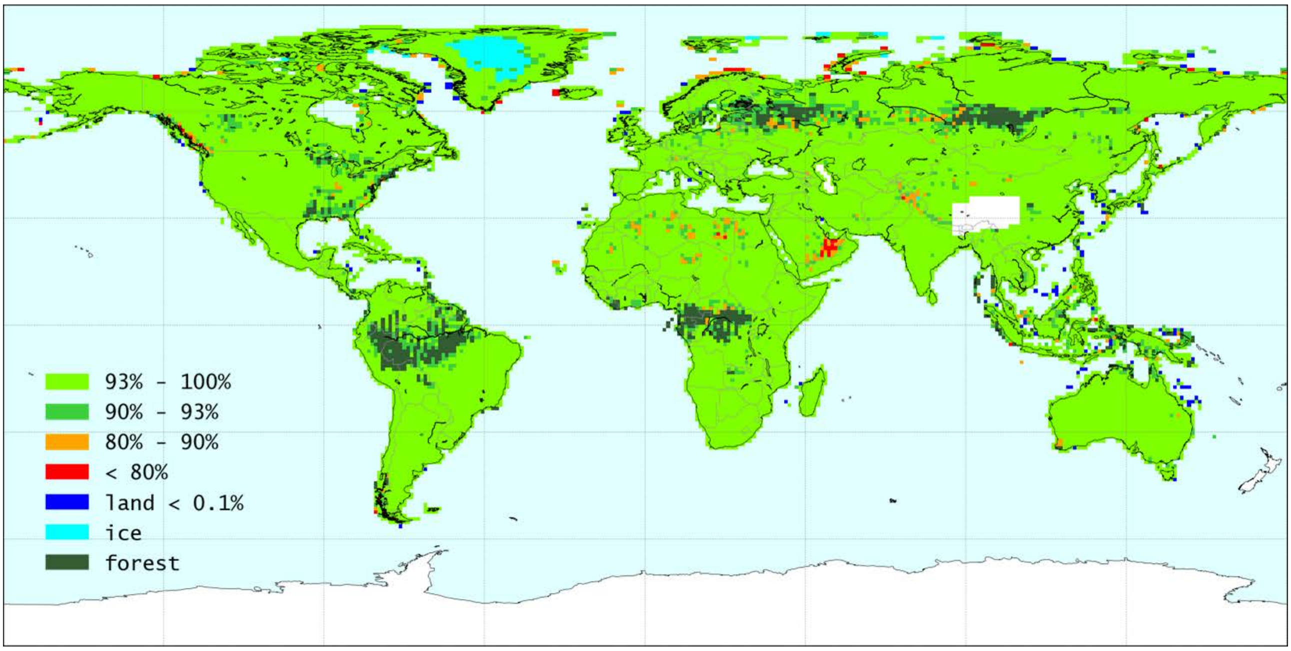

Figure 2. Relative height accuracy in % confidence level for the TanDEM-X global DEM Tiles, considering an accuracy specification of 2 meters in flat terrain regions (slopes up to 20%) and 4 meters in steep regions (slopes higher than 20%).

For InSAR-based DEMs the relative height accuracy *per pixel* can be computed from the respective phase error and the height of ambiguity (HoA). The phase error, in turn, can be analytically derived from the coherence between the two SAR channels of the interferogram (and the number of looks) [12]. The coherence is a measure for the amount of noise in the interferogram. The respective relative height accuracy is given as the standard deviation (σ) of the corresponding error. The *single point* height accuracy per pixel is saved as a height error map (HEM) inside the TanDEM-X product. In case a DEM pixel is derived from more than one interferometric SAR image, which is almost always the case in order to improve DEM quality, this is taken into account in the HEM computation by application of an appropriate weighting of the source pixel's height accuracies.

The error distributions of the pixels are assumed to have a Gaussian form. By this, the transformation from *single-point* accuracy to *point-to-point* accuracy can be performed by a multiplication of the standard deviation (σ) by $\sqrt{2}$ [2].

The confidence level for the relative height accuracy Δh over a DEM tile can be computed by first summing the Gaussian error distribution functions of all m pixels into a sum probability density $sP(\Delta h)$, taking into account the additional factor $\sqrt{2}$, and separated by flat and steep terrain, as follows:

$$sP(\Delta h) = \sum_{i=1}^{m} \frac{1}{\sigma_i \cdot 2 \cdot \sqrt{\pi}} e^{-\frac{\Delta h^2}{4 \cdot \sigma_i^2}} \qquad (1)$$

The confidence level of the height accuracy in meters is then calculated based on the sum of the areas under the sum probability densities $sP(\Delta h)$ [13].

About 15,000 out of 15,947 DEM Tiles have a relative height accuracy of more than 90% for the specified 2 m (4 m) of flat (steep) terrain or are not evaluated due to too few data points (e.g. small islands) or sea ice coverage. Furthermore, 691 tiles with lower relative height accuracy are dominated by highly forested areas. Due to volume decorrelation, the coherence estimation is artificially deteriorated and consequently the height accuracy is also artificially deteriorated [14]. Hence, up to now only 227, or 1.42% of the produced tiles, do not meet the relative height accuracy specification. Figure 2 shows a global plot of the relative height accuracy confidence level for the final TanDEM-X DEMs.

5. DATA COMPLETENESS

Voids, i.e. invalid pixels, in DEM data arise when a pixel's height cannot be determined during processing and can occur for various reasons, including phase unwrapping anomalies, low return signal power, shadow/layover effects or lack of raw DEM data.

As specified in Table 1, TanDEM-X aims at a data completeness of at least 97% for the global DEM product, to be verified after masking out of all areas that are covered by water. Thus, an accurate analysis requires an accurate global water mask. Within the latitude band covered by SRTM the SRTM Water Body Dataset (SWBD) can be used, which has been created as a by-product of the SRTM DEM data.

An extensive evaluation of TanDEM-X voids based on the SWBD and a set of 11,714 finalized DEM tiles has been carried out. It yielded excellent results and showed the high quality of the TanDEM-X data. Globally less than 0.1% of DEM pixels over land in this dataset are invalid. Figure 3 shows the results on a *DEM tile basis.* Out of the 11,714 analyzed tiles only 754, or 6.4% of the total tiles, contain more than one percent of invalid pixels over land.

6. CONCLUSION

The TanDEM-X mission is an innovative system for spaceborne radar remote sensing, enabling the systematic acquisition of a global, highly accurate digital elevation model (DEM) with unprecedented resolution and accuracy. First parts of the global TanDEM-X DEM became available in 2014 and as of April 2016, 15,947 DEM Tiles are available covering 88% of the Earth's land mass.

The final DEM product will have an absolute height accuracy of no more than 10 meter with a 90% linear error when evaluated against ICESat data. It has been shown in this paper that the cumulated absolute height accuracy is with 1.31m outstanding and one order of magnitude below the 10m requirement.

The relative height accuracy of full-resolution DEMs from TanDEM-X are specified to meet a linear point-to-point accuracy of 2 m (4 m) with a 90% confidence level for flat (steep) terrain within a tile. About 15,000 out of 15,947 DEM Tiles fulfill the relative height accuracy specification.

The percentage of void/invalid pixels over land per tile in the TanDEM-X DEM data is extremely low with less than 0.1% of invalid pixels within the thus far produced tiles.

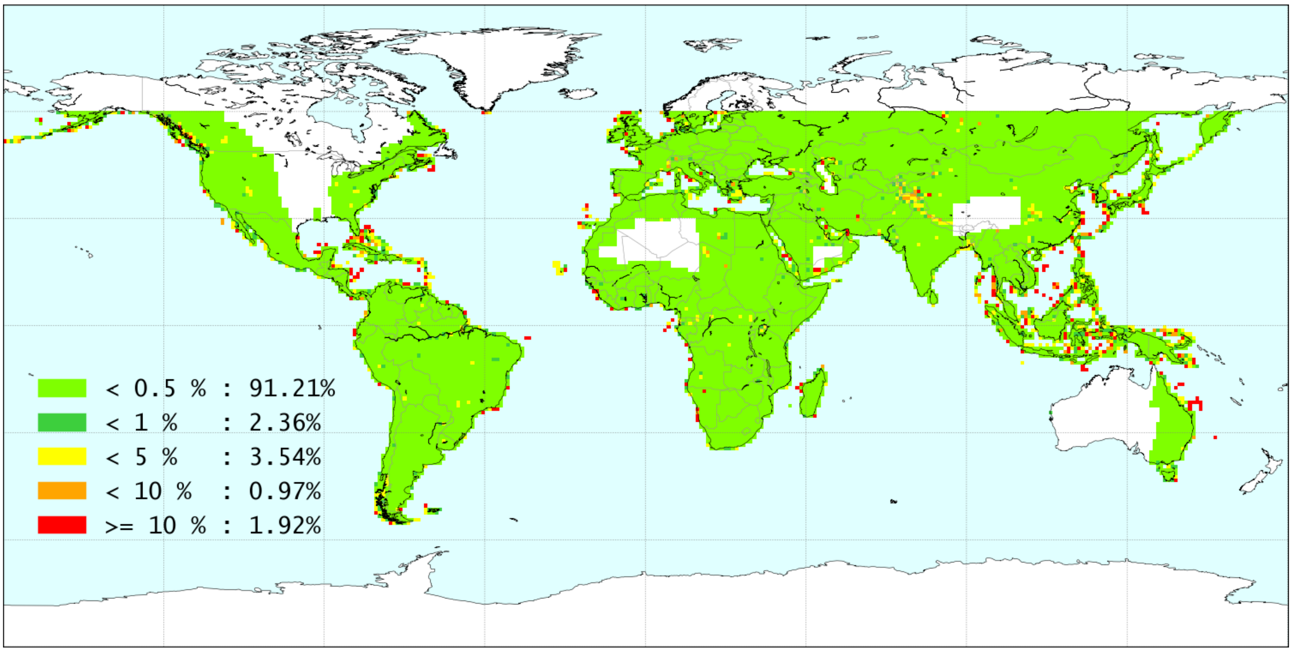

Figure 3. Percentage of “voids over land” based on the evaluation of 11,714 TanDEM-X global DEM Tiles. For each quality class the percentage of contained tiles is given.

In conclusion, the results presented in this paper for theabsolute and relative height accuracy as well as void count of the TanDEM-X DEM data demonstrates the exceptional quality of this global Digital Elevation Model.

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