Height Accuracy for the First Part of the Global TanDEM-X DEM Data

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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 (four in the case of difficult terrain) are combining into a homogenous global DEM mosaic consisting of 1° by 1° geocells. 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 per geocell.**

***Index Terms*—Synthetic Aperture Radar (SAR), Interferometry, bistatic SAR, Digital Elevation Model (DEM), Spaceborne SAR, absolute/relative height accuracy, voids.**

I. INTRODUCTION

Digital Elevation Models (DEMs) are raster-based digital datasets representing the partial or complete topography of a planetary body and are of fundamental importance for a wide range of scientific and commercial 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 Germany's 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].

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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 height accuracy specifications listed in Table 1. This paper presents a general introduction into how the TanDEM-X global DEMs are generated as well as the latest quality status (Section II). This is followed by a section each dedicated to the evaluation of absolute and relative height accuracy of the first part of global DEM products (Sections III and IV, respectively). Finally a summary comparison between SRTM and TanDEM-X data in regard to void density is presented.

II. TANDEM-X GLOBAL DEM

A. 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 interferometric channels. The second coverage is acquired with large baselines providing an improved relative height accuracy. Difficult terrain is covered

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TABLE 1: Global DEM Height Accuracy Performance Parameters

Parameter	Specification	Requirement
Absolute Height Accuracy	90% linear error - globally	≤ 10 meters
Relative Height Accuracy	90% linear point-to-point error in 1° x 1 ° geocell	≤ 2 meters (slope ≤ 20%)
		≤ 4 meters (slope > 20%)

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].

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 its global coverage, consistency, and precision [5]. Finally, the mosaicking processor combines all elevation data and produces the output DEM geocells of 1° by 1° size (ca. 110 km by 110 km at equator) [6].

B. 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 July 2014, the Earth's entire land masses had been mapped at least twice (four times in the case of difficult terrain) with varying baselines. Of the nearly 20,000 final DEM geocells to be produced, approximately 50 percent are available as of April 2015. Delivery of DEM products commenced in 2014 and the complete global DEM is expected to be available in late 2016.

III. 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 footprint are considered. This approach was taken so that geocells with fewer validation points (e.g. coastal regions) are evaluated with similar weight as geocells with more copious comparison 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 [7].

The most current height statistics, as of April 2015, of the available DEMs is shown in Table 2. Of all the ICESat data points that overlap with the available TanDEM-X data (on the order of 35 million), over 8.7 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 15 centimeters. The linear accuracy level of the validation points for 10 meters is very high at 99.77%. 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 1.07 meters.

In addition to the global specification, the absolute height accuracy is also monitored on a geocell basis for all validation points in the geocell. Only twelve out of 9,691 geocells have an absolute height accuracy greater than 10 m, however all of these geocells suffer from volume decorrelation (forest), floating ice sheets, or too few ICESat validation points. The top plot in Figure 1 shows a per geocell overview of the absolute height error for the continent of Africa and the Middle East which was finalized at the start of April 2015. The vast majority of these geocells (over 3,000) have an absolute height accuracy of less than 2 m, 247 geocells are between 2 and 5 m and only 22 are between 5 and 8 m. It is expected that the quality of DEMs over more mountainous terrain will impact the global statistics.

IV. 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

TABLE 2: Absolute height accuracy statistics of the TanDEM-X DEM data available as of April 2015

Number of DEM Geocells	9,691
Accumulated Number of Validation Points	8,741,165
Mean Height Deviation of Validation Points (m)	0.15
Accumulated Absolute Height Accuracy of 10 m (linear error)	99.77%
Accumulated Absolute Height Accuracy with 90% Linear Error (m)	1.07

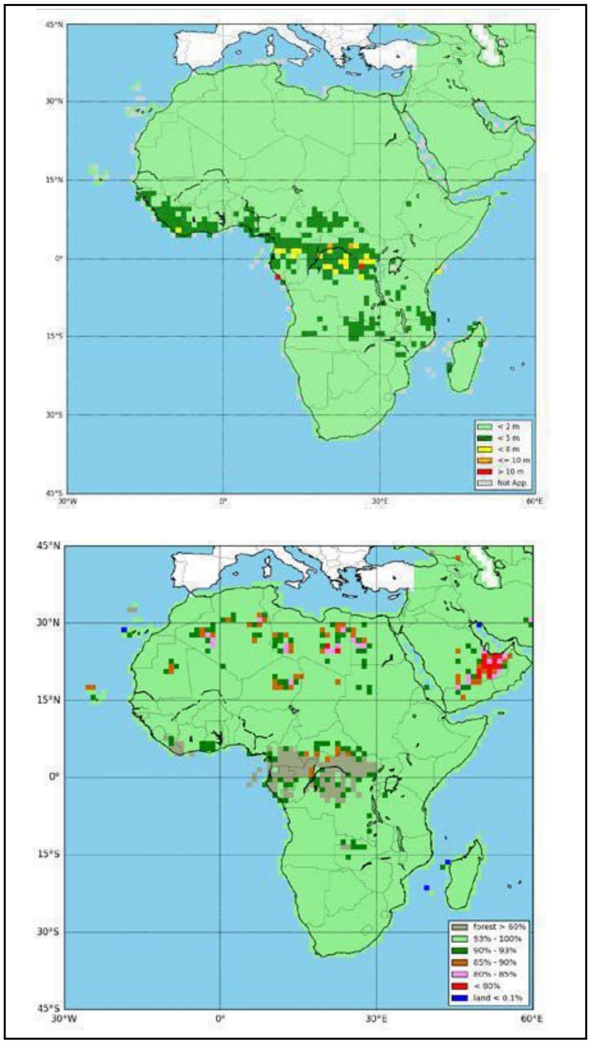

Figure 1: Available TanDEM-X Final DEMs absolute (top) and relative (bottom) height accuracy over Africa and the Middle East per geocell.

in the system, and can be calculated after suppressing the systematic errors and anomalies.

The relative height accuracy per pixel can be estimated from the coherence (and number of looks) between the two SAR channels of the interferogram [2]. As 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 into a height error map inside the TanDEM-X product.

The relative height accuracy specification describes the point-to-point error within a 1° x 1° geocell and it states that the confidence level in each geocell shall be above 90% with a height accuracy of 2 m for flat terrain and 4 m for steep terrain. 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 height accuracy Δh over a geocell can be computed by first summing the Gaussian error distribution functions of all m pixels, separated by flat and steep terrain as follows:

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

The combined confidence level is calculated based on the sum of the areas under the sum probability densities, $sP(\Delta h)$ [8].

9,099 out of 9,691 geocells 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, 514 geocells 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 [2]. Hence, up to now only 143 geocells, or 1.5% of the produced geocells, do not meet the relative height accuracy specification. As an example, the bottom plot in Figure 1 shows the relative height accuracy confidence level for the final TanDEM-X DEMs in Africa and the Middle East.

V. DEM Voids Summary

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, or shadow/layover effects.

The most up-to-date TanDEM-X statistics show that out of the 9,691 geocells produced thus far, only 175 or 1.8 %, of the geocells contain more than 1 percent of invalid pixels over land. In comparison, over 20% of the geocells in the SRTM version 1.0 data have over 1 percent pixels that are invalid.

Figure 2 shows a comparison of the void percentage per geocell for both the SRTM and TanDEM-X data in Africa and the Middle East. The difference in percent of voids per geocell demonstrates the highly improved quality of the TanDEM-X data. This is especially true in the desert areas of the Sahara and Saudi Arabia, where, a mentioned above, TanDEM-X

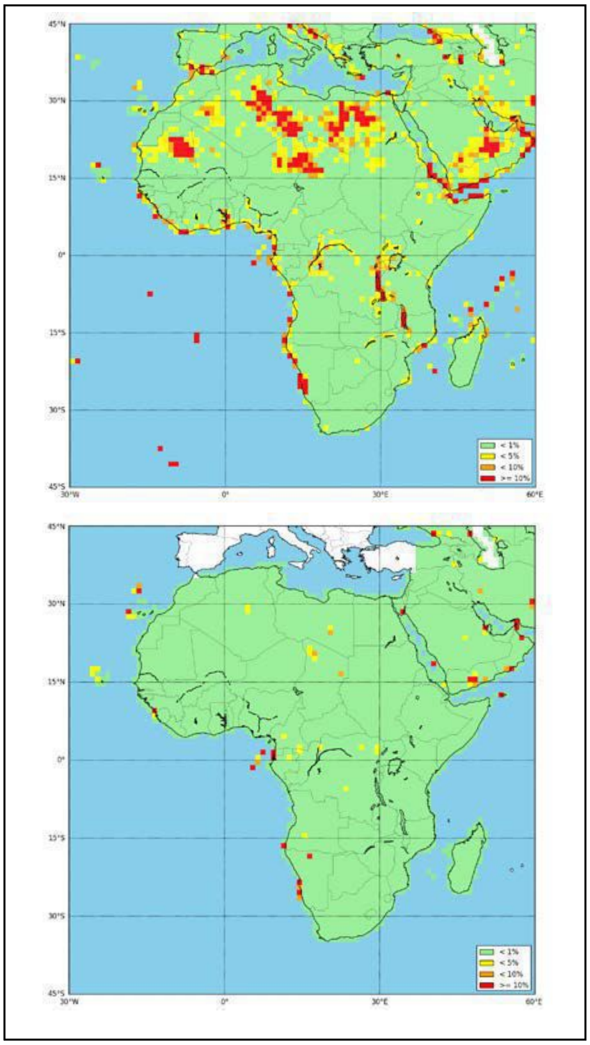

Figure 2: Void Percentage per geocell for SRTM (top) and available TanDEM-X (bottom) data.

performed at least two additional coverages with a steep viewing angle for an improved backscatter return [4].

VI. 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 2015, 9,691 geocells are available covering 58% of the Earth's land mass.

The final DEM product shall demonstrate 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 first available part DEMs has reached a level of absolute height accuracy on the order of one meter using almost 8.7 million validation points.

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 geocell. 9,548 out of 9,691 geocells fulfill the relative height accuracy specification.

The percentage of void/invalid pixels over land per geocell in the TanDEM-X DEM data is extremely low with less than 2% of the thus far produced geocells containing over 1% of invalid pixels.

In conclusion, the results presented in this paper for the absolute 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.

REFERENCES

[1] T.G. Farr, P. Rosen, E. Caro, R. Crippen, R. Duren,S. Hensley, M. Kobrick, M. Paller, E. Rodriguez, L. Roth, D. Seal, S. Shaffer, J. Shimada, J. Umland, M. Werner, M. Oskin, D. Burbank, D. Alsdorf, "The Shuttle Radar Topography Mission," Reviews of Geophysics, Vol. 45, 2007.

[2] G. Krieger, A. Moreira, H. Fiedler, I. Hajnsek, M. Werner, M. Younis, M. Zink, "TanDEM-X: A Satellite Formation for High Resolution SAR Interferometry," IEEE Transactions on Geoscience and Remote Sensing, vol. 45, no. 11, pp. 3317-3341, 2007.

[3] D. B. Tridon, M. Bachmann, D. Schulze, C. Ortega-Mìguez, M. D. Polimeni, M. Martone, J. Böer, and M. Zink, "TanDEM-X: DEM acquisition in the third year era," Int. J. of Space Science and Engineering, vol. 1, no. 4, pp. 367–381, 2014.

[4] M. Martone, P. Rizzoli, B. Bräutigam, and G. Krieger, "First two years of TanDEM-X mission: interferometric performance overview," Radio Science, vol. 48, pp. 617–627, October 2013.

[5] J. Hueso Gonzalez, M. Bachmann, R. Scheiber, G. Krieger, "Definition of ICESat Selection Criteria for their use as Height References for TanDEM-X," IEEE Transactions on Geoscience and Remote Sensing, vol. 48, no. 6, pp. 2750-2757, 2006.

[6] B. Wessel, A. Gruber, A. Wendleder, M. Huber, M. Breunig, U. Marschalk, D. Kosmann, A. Roth, "Production Chain towards First Calibrated and Mosaicked TanDEM-X DEMs," IEEE International Geoscience And Remote Sensing Symposium (IGARSS), Vancouver, Canada, 2011

[7] M. Huber, B. Wessel, D. Kosmann, A. Felbier, V. Schwieger, M. Habermeyer, A. Wendleder, A. Roth: "Ensuring Globally the TanDEM-X Height Accuracy: Analysis of the Reference data sets ICESat, SRTM and KGPS-Tracks" IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Cape Town, South Africa, 2009

[8] C. Gonzalez, B. Bräutigam, M. Martone, P. Rizzoli, "Relative Height Error Estimation Method for TanDEM-X DEM Products", European Conference on Synthetic Aperture Radar, Berlin, Germany, 2014