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# Generation and performance assessment of the global TanDEM-X digital elevation model

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A B S T R A C T

The primary objective of the TanDEM-X mission is the generation of a global, consistent, and high-resolution digital elevation model (DEM) with unprecedented global accuracy. The goal is achieved by exploiting the interferometric capabilities of the two twin SAR satellites TerraSAR-X and TanDEM-X, which fly in a close orbit formation, acting as an X-band single-pass interferometer. Between December 2010 and early 2015 all land surfaces have been acquired at least twice, difficult terrain up to seven or eight times. The acquisition strategy, data processing, and DEM calibration and mosaicking have been systematically monitored and optimized throughout the entire mission duration, in order to fulfill the specification. The processing of all data has finally been completed in September 2016 and this paper reports on the final performance of the TanDEM-X global DEM and presents the acquisition and processing strategy which allowed to obtain the final DEM quality. The results confirm the outstanding global accuracy of the delivered product, which can be now utilized for both scientific and commercial applications.



## 1. Introduction

Digital elevation models are of fundamental importance for a large variety of scientific and commercial applications. For example, precise and up-to-date information about the Earth's topography is required in many geoscience areas, such as geology, forestry, glaciology, oceanography, and hydrology. Up to now, the primary source of elevation data on an almost global scale has been provided by the Shuttle Radar Topography Mission (SRTM), characterized by a spatial resolution of 30 m between 56° South latitude and 60° North latitude (Farr et al., 2007). Moreover, the ASTER and the AW3D30 DEMs are available with a 30 m posting: the first one covers latitudes between 83° South and 83° North (Meyer et al., 2011), while the second one presents numerous gaps in both Antarctica and arctic regions (Tadono et al., 2016). For higher latitudes and over Antarctica, only lower resolution (on the order of hundred meters to kilometers) DEMs are available, such as GTOPO (GTOPO, 2016), GLOBE (Hastings et al., 1999), RAMP (RAMP, 2016), and GLAS/ICESat (ICESat, 2016).

With the main goal of acquiring a global and consistent DEM with unprecedented accuracy, the TanDEM-X mission (TerraSAR-X add-on for Digital Elevation Measurements) opens a new era in spaceborne synthetic aperture radar (SAR) (Krieger et al., 2007, 2013). Developed in a public-private partnership between the German Aerospace Center (DLR) and Airbus Defence and Space, it is comprised of two almost identical satellites, TerraSAR-X and TanDEM-X, equipped with a synthetic aperture radar operating at X-band. Since October 2010, both satellites have been flying in a close orbit configuration at an altitude of around 500 km, as presented in Fig. 1, acting as a single-pass SAR interferometer and allowing for a flexible selection of baselines and acquisition geometries. Images have been nominally acquired in bistatic configuration, where one satellite transmits and both simultaneously receive the backscattered signal from the Earth's surface. This enables the acquisition of highly accurate interferograms, which do not suffer from temporal and atmospheric decorrelation.

A dedicated acquisition strategy has been developed and optimized throughout the years, in order to achieve the desired performance on a global scale. Both satellites have been flying in the so-called Helix orbit, which combines an out-of-plane orbital displacement with a radial (vertical) separation resulting in a

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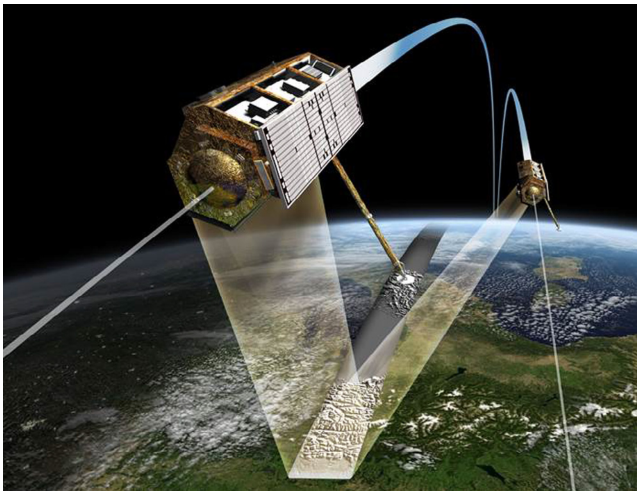

**Fig. 1.** Artist's view of TerraSAR-X and TanDEM-X satellites flying in close orbit formation.

helix-like relative movement of the satellites along the orbit, avoiding the collision risk at the poles (Moreira et al., 2003; Moreira et al., 2004). Driven by the DEM accuracy specifications the Helix formation has been continuously optimized during different mission acquisition phases.

Beyond the generation of a global DEM, the unique configuration of TanDEM-X also allows for the demonstration of innovative bistatic SAR techniques, such as multistatic SAR, polarimetry, interferometry, digital beam forming and superresolution. Hence, TanDEM-X also represents a milestone for the development of future spaceborne formation-flying SAR missions, such as Tandem-L, an L-band bistatic SAR mission proposed by DLR, with the goal of monitoring dynamic processes on the Earth surface with unprecedented accuracy and temporal coverage (Moreira et al., 2015).

The objective of this paper is to assess the final performance of the TanDEM-X global DEM. After an overview of the TanDEM-X mission and its specification, the error sources affecting the quality of the DEM are summarized, together with the developed acquisition strategy and processing chain. Finally, the global performance is then assessed in terms of vertical accuracy and coverage statistics. All specified performance parameters for the DEM accuracy have been achieved or even surpassed.

## 2. TanDEM-X mission overview

In this section, the TanDEM-X DEM specifications are reported, together with the interferometric processing chain for a single scene DEM. The error sources affecting the final performance are discussed as well, together with the implemented strategy for overcoming such limitations, in terms of acquisition planning optimization, calibration procedures, and DEM mosaicking. The presentation of the required steps for generating the final DEM is focusing on the most relevant approaches to ensure the final TanDEM-X DEM quality.

### 2.1. Mission performance specification

The global DEM delivered by TanDEM-X has been defined to meet or exceed the specification presented in Table 1, as in the TanDEM-X DEM product specification document (Wessel, 2016). The main parameters which are taken into account for assessing the final performance are summarized and explained in the following:

- The *DEM spatial resolution* (or independent spacing): For the global DEM interferometric data have been acquired in StripMap mode with a resolution of 3.3 m (Fritz and Eineder, 2013). Spatial multilooking is then applied in order to reduce the noise affecting the interferometric phase, which allows to generate a DEM with an independent ground pixel spacing of 12 m $\times$ 12 m at the Equator, referred to the WGS84 ellipsoid.
- The *absolute vertical height accuracy* is defined as the uncertainty in the height of a point with respect to the WGS84 ellipsoid caused by random and uncorrected systematic errors. The specified value is expressed as a linear error at a 90% confidence interval. The digital elevation information is defined with respect to the reflective surface of X-band interferometric SAR returns from the imaged Earth features, estimating therefore the location of the mean phase center resulting from a single or multiple backscattered signals within the same resolution cell. The data may hence include height offsets due to penetration into vegetation canopies or ice/snow-covered regions and possible seasonal variations. The specified absolute vertical accuracy of the global DEM shall be better than 10 m.
- The *relative vertical height accuracy* is defined as the uncertainty between two height estimates caused by random errors. The specified values are expressed as linear errors at a 90% confidence interval. The relative vertical accuracy shall be smaller than 2 m for low and medium relief terrain (predominant slope lower than 20%) and 4 m for high relief terrain (predominant slope greater than 20%), over a $1^\circ \times 1^\circ$ geocell in latitude/longitude.
- The *absolute horizontal accuracy* is defined as the uncertainty in the horizontal position of a point with respect to WGS84 caused by random and uncorrected systematic errors. The value is expressed as a circular error at the 90% confidence level. The absolute horizontal accuracy shall be better than 10 m.
- *Voids* or *Invalid Data*: areas in the DEM that are left void (i.e. no data) may occur for several reasons, including poor signal-to-noise ratio (SNR) over sandy desert areas, shadow and layover in mountains and canyons, DEM gaps which result from the absence of acquired data or input DEMs with satisfying quality, or decorrelated water areas such as lakes and oceans. According to the mission specification, at most 3% of all DEM pixels over land-covered areas (water bodies excluded) can be flagged as

**Table 1**
TanDEM-X DEM specification parameters.

| Requirement | Description | Specification |
|---|---|---|
| Relative vertical accuracy | 90% linear point-to-point error<br>over a $1^\circ \times 1^\circ$ cell | 2 m (slope <20%)<br>4 m (slope >20%) |
| Absolute vertical accuracy | 90% linear error | 10 m |
| Abolute horizontal accuracy | 90% circular error | 10 m |
| Spatial resolution | Independent pixels | 12 m<br>(0.4 arc sec @ equator) |
| Coverage | Percentage of land masses | 97% |