The TanDEM-X Mission: Earth Observation in 3D

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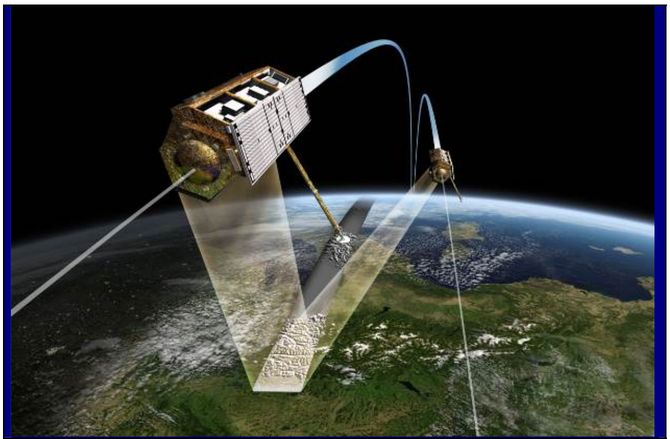
Abstract— **TanDEM-X is an innovative radar mission which encompasses two formation flying satellites. Its primary goal is the generation of a global Digital Elevation Model (DEM) of unprecedented accuracy. The baseline between the satellites can be flexibly adjusted for single-pass SAR interferometry. The DEMs are produced by cross-track interferometry. Their high performance will be achieved by combining at least two global coverages into a homogenous mosaic of a global DEM. The final DEM consists of geo cells with 1° by 1° size. Delivery of DEM products to registered scientific and commercial users will commence in 2014. Furthermore, the secondary mission goals of TanDEM-X exploit the versatility of the two SAR instruments. Along-track SAR interferometry as well as bistatic and multi-channel SAR techniques are possible, providing unique capabilities for scientific researches in the field of remote sensing. This paper gives a status summary of the TanDEM-X mission with respect to the DEM generation and actual performance, its output products, and an outlook on future mission steps.**

I. Introduction

Spaceborne remote sensing is the most efficient way to acquire global Digital Elevation Models (DEMs). Interferometric processing of synthetic aperture radar (SAR) acquisitions has already been used to form the SRTM product set, which provides DEM geo cells with up to 30 m horizontal resolution for latitudes between 58° South and 60° North [1]. Since 2010, Germany's SAR satellites TerraSAR-X and TanDEM-X are simultaneously operated by the German Aerospace Center (DLR) in order to acquire an updated DEM which exceeds the presently available global data sets in terms of resolution, coverage, and quality by orders of magnitude. Figure 1 shows the two satellites flying in close formation. The baseline between the two SAR sensors can be flexibly adjusted for single-pass SAR interferometry [2]. This provides the opportunity for accurate cross-track and along-track interferometry overcoming the limitations of atmospheric disturbance and temporal decorrelation in multi-pass data.

The primary mission goal is to cover the Earth's land masses at a spatial resolution of 12 m, and with relative/absolute height accuracies of down to 2 m/10 m, respectively (see Figure 1).

The DEM data will be the basis for a wide range of scientific research, as well as for commercial DEM production. Thanks to its unique capabilities, TanDEM X is furthermore well-suited to demonstrate novel bistatic and multistatic SAR techniques and Earth observation applications. This paper presents the general concept of how to acquire and to generate the TanDEM-X output products. The actual acquisition and performance status is given. At the end, an outlook on the future tasks and perspectives is provided.



Global Digital Elevation Model by TanDEM-X

Parameter	Specification	Requirement
Relative Vertical Accuracy	90% linear point-to-point error in 1° cell	2 m (slope < 20%) 4 m (slope > 20%)
Absolute Vertical Accuracy	90% linear error	10 m
Spatial Resolution	independent pixels	12 m (0.4 arc sec)

Figure 1. TerraSAR-X and TanDEM-X satellites flying in close orbit formation for the acquisition of a global Digital Elevation Model (DEM) with unprecedented resolution and accuracy.

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II. TANDEM-X DEM GENERATION CONCEPT

A. Acquisition Strategy

TanDEM-X follows a systematic acquisition scenario based on the coordinated operation of two SAR satellites flying in close formation. The mapping strategy is to cover the land masses at least twice. The first global coverage is performed at satellite baselines in the order of 300 m, the second coverage is acquired with larger baselines in the order of 400 m [4]. The driving factor for this is the interferogram's height of ambiguity, which is inversely proportional to the baseline

$$h_{amb} = \frac{\lambda r \sin\theta}{B} \quad (1)$$

where λ is the wavelength, r the slant range from the satellites to the illuminated ground target, θ the incident angle of the electromagnetic wave, and B is the perpendicular baseline component.

A lower height of ambiguity (i.e. larger baseline) improves the height accuracy, as the interferometric phase error is directly scaled by h_{amb}. On the other hand, a higher height of ambiguity increases the probability in selecting the correct ambiguity band during phase unwrapping. The correct ambiguity band contains the real elevation value, and its unambiguous determination is supported by radargrammetry [5]. To optimize the quality and to ensure a homogeneous performance, the acquisitions with larger height of ambiguity from the first coverage are used to support the phase unwrapping of the second acquisitions with lower height of ambiguity [6].

This requires in turn frequent adjustments of the orbit formation parameters which are selected according to an optimized global data acquisition plan [7]. During the mosaicking process of the final DEM, the multiple acquisitions can be combined in order to achieve a high and homogenous performance [2].

B. TanDEM-X Data Output

TanDEM-X features the flexibility to command several bistatic modes with the two satellites. The standard mode for DEM acquisition is the bistatic StripMap mode in single HH polarization. Furthermore, dual-polarized acquisitions or Spotlight imaging are possible. Interferometric acquisitions in alternating bistatic or even simultaneous bistatic mode can be supported, at selectable baselines [8]. Experimental data takes with these modes can be chosen by the scientific TanDEM-X users.

In a first step, the bistatic data are processed to co-registered SAR (CoSSC) products of about 50 km length [9], for which a sophisticated synchronization and calibration scheme is applied [10], [11]. These products contain the monostatic and bistatic SAR image plus additional metadata for post-processing, of e.g. the coherence between both images or the interferogram. CoSSCs can be ordered by scientific TanDEM-X users [12].

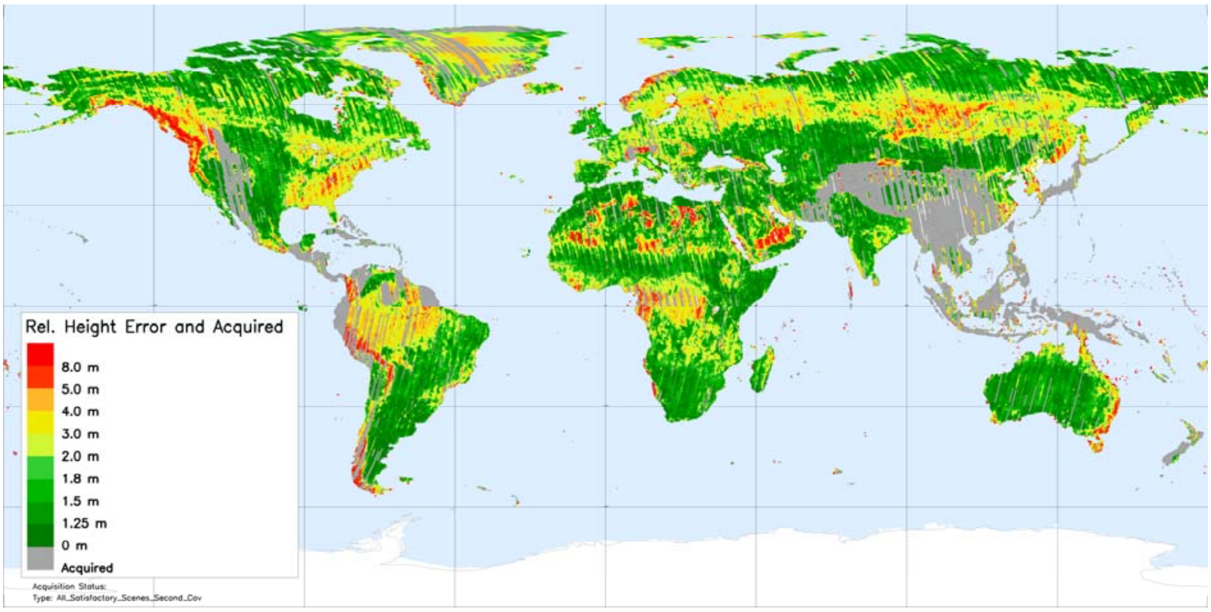

Figure 2. Mean relative height error per RawDEM acquired for the second global coverage (processing status August 2013). Green colors indicate areas where the height error is already within the 2 m requirement, yellow parts will be improved with the first coverage, red parts represent difficult terrain which requires additional acquisitions in the opposite viewing geometry. Grey parts have been acquired, but not processed yet.

For the DEM generation, each CoSSC is interferometrically processed and geocoded into a roughly calibrated "RawDEM" [5]. When all input data of a larger region (i.e. several thousands of square kilometers) are available, the tilts and offsets of the RawDEMs are calibrated against ICESat data. Finally, the mosaicking processor combines all elevation data and produces the output DEM geo cells of 1° by 1° size (ca. 110 km by 110 km at equator) [13]. The DEM products will also contain add-on layers like a height error map or a water indication mask. The detailed product and format specification can be found in [14]. Such output DEMs are provided to the commercial partner of DLR and are also available to the science community in the frame of dedicated TanDEM-X proposals.

III. DEM Acquisition and Performance Status

The global DEM acquisition started in December 2010 and the first global coverage (except Antarctica) was completed in January 2012. During processing of the first data sets it was analyzed that areas with strong topography variation, especially over forested regions, need an even larger height of ambiguity. Therefore, such areas have been re-acquired until April 2012 in order to have a robust basis for the DEM acquisitions of the second global coverage.

Up to July 2013, the Earth's land masses have been mapped at least twice (except Antarctica, which has been mapped once). In the meantime, phase, delay and baseline calibration have reached such an accuracy level, that more than 90% of all individual RawDEMs are within ±10 m accuracy compared to SRTM and ICESat data [11].

The mean coherence value derived from the CoSSCs is over 0.6 for 90% of all global DEM acquisitions and indicates the robustness of the SAR data [15]. The relative height error has been estimated from this coherence values and verified with sample repeat-pass DEMs [16]. Up to now, over 300,000 DEM scenes have been processed. A global status map of the relative height error only from the second year is depicted in Figure 2. A summary of the performance values from these acquisitions is given in Table I. The coherence and absolute height error percentages are derived from one value per scene. The relative height error percentage is evaluated on a 500 m pixel resolution. The final height performance will be achieved by combining the elevation measurements from several coverages in the mosaicking process.

Global DEM data acquisition with varying baselines will continue until mid 2014, concentrating on difficult terrain like mountains or valleys where shadowing and layover cause blind spots from a certain viewing angle. A change of the viewing angle is achieved by swapping the orbit formation, which has been performed in August 2013 [4]. First parts of the global TanDEM-X DEM will become available in 2014. Figure 3 shows an example TanDEM-X DEM at 12 m resolution compared to the SRTM DEM with 90 m resolution.

TABLE I. Quality of DEM scenes from single coverages processed until May 2013.

	Coverage	
	First Coverage	*Second Coverage*
Coherence > 0.6 (for land masses)	90.9%	90.1%
Relative Height Error (flat areas < 2 m / mountains < 4 m)	66.4% 79.4%	75.4% 84.9%
Absolute Height Error < 10 m (to SRTM / ICESat)	91.8%	89.0%

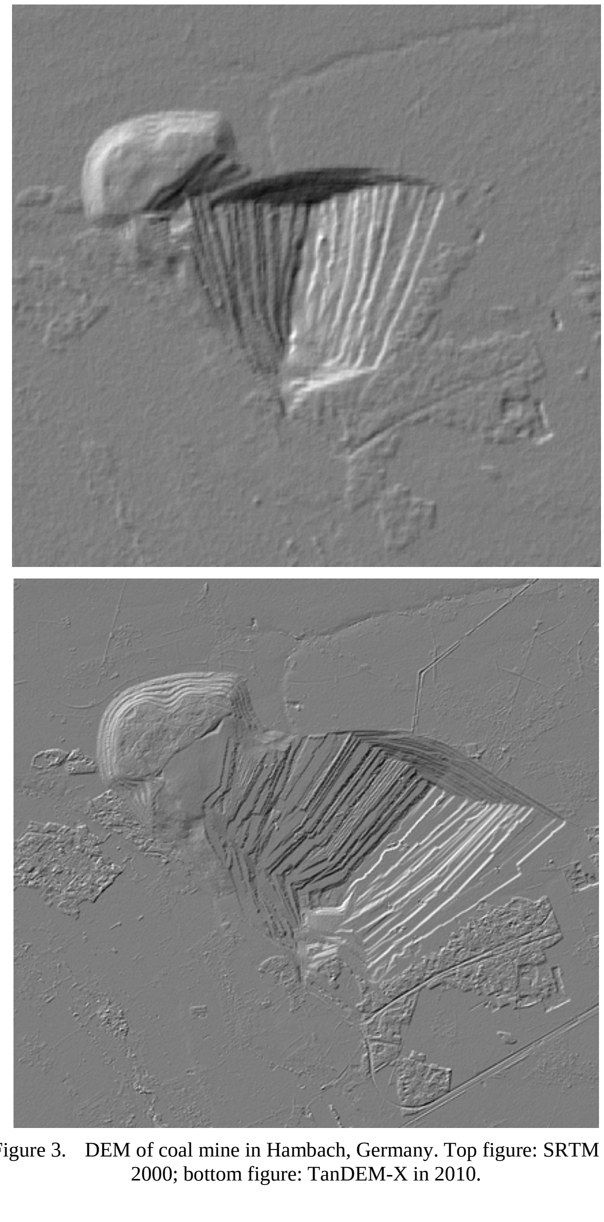

Figure 3. DEM of coal mine in Hambach, Germany. Top figure: SRTM in 2000; bottom figure: TanDEM-X in 2010.

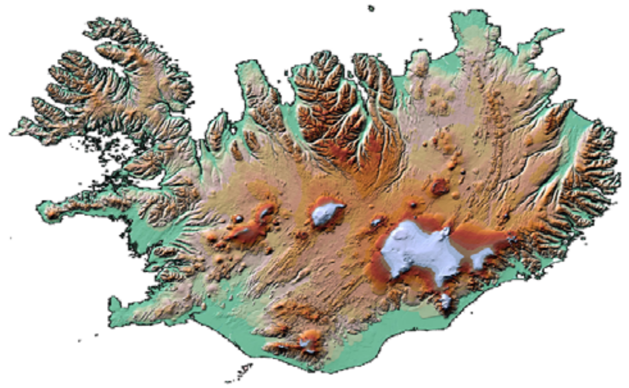

Figure 4. Mosaic of the intermediate DEM tiles of Iceland, provided by the Mosaicking and Calibration Processor [13]. Original resolution is 12 m.

IV. CONCLUSIONS AND OUTLOOK

The TanDEM-X mission is an innovative system for spaceborne radar remote sensing. A large single-pass SAR interferometer with adjustable baselines is realized by a close orbit formation. This enables the systematic acquisition of a global, highly accurate DEM. Furthermore, the demonstration of new bistatic and multistatic SAR techniques and applications is possible. Many innovative results have been obtained during the TanDEM-X commissioning phase [3], and CoSSC products are currently being investigated by scientific users around the world. Starting mid 2014, a dedicated scientific acquisition phase will be realized by TanDEM-X with the opportunity to acquire data at different baseline geometries and in different interferometric modes. The results and the experience from these experiments will be important for future formation flying SAR missions [18].

In 2013, DLR has started to calibrate the individual DEM acquisitions against ICESat data and mosaic the scenes into larger "tiles" of 1° by 1° size. These so-called intermediate DEMs have been generated on a regional basis, giving a first impression on the quality of the TanDEM-X data (see Figure 4). First parts of the global TanDEM-X DEM will become available in 2014. Scientific users can submit a TanDEM-X proposal in order to get CoSSCs, intermediate DEMs, and final DEMs. In parallel, the global DEM data are distributed to DLR's commercial partner.

ACKNOWLEDGMENTS

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