# TANDEM-X MISSION:
# OVERVIEW, STATUS AND OUTLOOK

**U. Steinbrecher, M. Zink, G. Krieger, D. Schulze, J. Böer, M. Bachmann, A. Moreira**

*German Aerospace Center (DLR), Microwaves and Radar Institute, Oberpfaffenhofen, D-82234 Wessling*
*Ulrich.Steinbrecher@dlr.de*
*Manfred.Zink@dlr.de*
*Gerhard.Krieger@dlr.de*
*Daniel.Schulze@dlr.de*
*Johannes.Boeer@dlr.de*
*Markus.Bachmann@dlr.de*
*Alberto.Moreira@dlr.de*

ABSTRACT

TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) opens a new era in spaceborne radar remote sensing [1]-[3], [9], [12]. Realized in the framework of a public-private partnership between the German Aerospace Center (DLR) and EADS Astrium GmbH, a single-pass SAR interferometer with adjustable baselines in across- and in along-track directions was formed by adding a second (TDX), almost identical spacecraft to TerraSAR-X (TSX) and flying the two satellites in a closely controlled formation on average orbit height of 514 km. This allows the acquisition of highly accurate cross-track and along-track interferograms without the inherent accuracy limitations imposed by repeat-pass interferometry due to temporal decorrelation and atmospheric disturbances. With typical across-track baselines of 150 to 500 m a global Digital Elevation Model (DEM) with 2 m relative height accuracy at a 12 m posting is being generated.

## 1. TANDEM-X

### 1.1 Mission Objectives

Beyond the generation of a global TanDEM-X DEM as the primary mission goal, local DEMs of even higher accuracy level (posting of 6 m and relative vertical accuracy of 0.8 m) and applications based on Along-Track Interferometry (ATI) like measurements of ocean currents are important secondary mission objectives. Along-track interferometry also allows for innovative applications to be explored and can be performed by the so-called dual-receive antenna mode on each of the two satellites and/or by adjusting the along-track distance between TSX and TDX to the desired value. Combining both modes provides a highly capable along-track interferometer with four phase centers. The different ATI modes can e.g. be used for improved detection, localization and ambiguity resolution in ground moving target indication and traffic monitoring applications. Furthermore TanDEM-X supports the demonstration and application of new SAR techniques, with focus on multistatic SAR, polarimetric SAR interferometry, digital beam forming and super resolution.

TanDEM-X has an ambitious time schedule to reach the main mission goal. After the commissioning phase, the first three years are dedicated to the global DEM acquisitions. To facilitate dual-baseline phase unwrapping all land masses will be covered at least twice in the same looking direction but with different baselines. Difficult mountainous terrain requires additional acquisitions viewing from the opposite direction to allow filling gaps due to shadow and layover. The baseline geometry in these first years is optimized for DEM performance. A limited number of scientific acquisitions are being included during this mission phase depending on the available satellite resources and the suitability of the baseline values for fulfilling the scientific requirements.

### 1.2 The TanDEM-X Spacecraft

The TDX satellite is a rebuild of TSX with only minor modifications. This offers the possibility for a flexible share of operational functions for both the TerraSAR-X and TanDEM-X missions among the two satellites [4].

During the last phase of the TSX spacecraft development, the SAR instrument design was extended to allow exchange of synchronization pulses to support coherent operation of both SAR instruments during bistatic operation. Six sync horns on each satellite provide a quasi-omnidirectional coverage. An additional propulsion system based on high-pressure nitrogen gas is accommodated on TDX. This cold gas system provides smaller impulses than the hydrazine system on both satellites (which is used for orbit maintenance) and supports formation flying by fine orbit control of the TDX satellite. The TDX solid state mass memory capacity is 96 GB which is doubled compared with TSX to support the collection of the enormous amount of DEM data.

The TDX satellite is designed for a nominal lifetime of 5 years. Predictions for TSX based the current status of system resources indicate at least two extra years (until the end of 2014) of lifetime, providing a minimum of 4 years of joint operation.

### 1.3 The Ground Segment

The missions TerraSAR-X and TanDEM-X jointly share the same space segment consisting of the TSX and TDX satellites orbiting in close formation and are operated using a common ground segment, that was originally developed for TerraSAR-X and that has been extended for the TanDEM-X mission [5] – [8]. Specific new developments are described in the following.
The spatial baseline between the TSX and TDX is derived at millimeter accuracies from on-board GPS measurements taken by the two-frequency IGOR GPS receivers.

A key issue in operating both missions jointly is the different acquisition scenarios: whereas TerraSAR-X requests are typically single scenes for individual scientific and commercial customers, the global DEM requires a global mapping strategy. This strategy has also to account for the current formation flying geometry which, in turn, depends on the orbit parameters selected and for any given orbit configuration permits generating a digital elevation model only within a certain latitude range.

The two satellites downlink their data to a global network of ground stations: Kiruna in Sweden, Inuvik in Canada, and O'Higgins in the Antarctic. The global acquisitions for the digital elevation model alone absorb a data volume of more than 350 Terabytes. After a brief quality check, the data are recorded on tape and shipped to DLR in Oberpfaffenhofen for processing and archiving.

The entire processing chain is a new TanDEM-X specific development. Major design drivers result from the acquisition strategy which requires the combination of several (global) coverages and application of multi-baseline processing techniques based on supporting intermediate products. Absolute height calibration relies on a selected set of reference points of the globally distributed elevation data provided by the laser altimeter from NASA’s ICESat mission.

### 1.4 Close Formation Flight

An orbit configuration based on helix geometry has been selected for safe formation flying. The helix like relative movement of the satellites along the orbit is achieved by combination of an out-of-plane (horizontal) orbital displacement imposed by different ascending nodes with a radial (vertical) separation imposed by the combination of different eccentricities and arguments of perigee. Since the satellite orbits never cross, the satellites can be arbitrarily shifted along their orbits. This enables a safe spacecraft operation without the necessity for autonomous control. Cross- and along-track baselines ranging from 120 m to 10 km and from 0 to several 100 km, respectively, can be accurately adjusted depending on the measurement requirement [7].

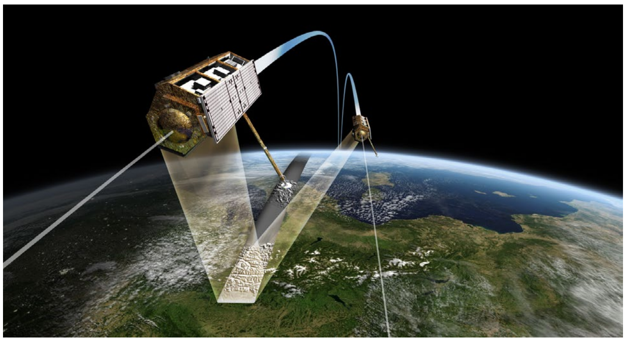

Figure 1: TSX and TDX satellites flying in close formation

### 1.5 Data Acquisition

The first challenge in developing a global DEM data acquisition plan is the fact, that the two participating satellites were originally designed to acquire images on a local scale, i.e. with limited coverage, and not to collect a global data set. Hence, the acquisition plan had to be designed such that limiting factors like on-board memory and downlink capacity, fuel, power limitations and the temporal behavior of the radar instrument are considered [10]. This also includes the requirement to carry on data acquisition for TerraSAR-X users.

The second challenge is the way how to acquire a global DEM with the high accuracy as it is the goal for the TanDEM-X DEM. There are two contradicting conditions due to the interferometric phase as the measurement source for the DEM [1]. The height accuracy mainly depends on the height of ambiguity (HoA). This height of ambiguity is the $2\pi$ interferometric phase cycle scaled with the perpendicular baseline between both satellites. The smaller the height of ambiguity is, the lower is the influence of errors caused by the instrument or the different decorrelation effects.

On the other hand an immediate jump in the real height on Earth can only be resolved if the height of ambiguity is larger than the jump. A vegetation change from bare ground to forest with tree heights of 30 m can only be unambiguously resolved with a height of ambiguity that is greater than this 30 m. Choosing a larger height of ambiguity will therefore reduce phase unwrapping errors in the generated DEMs.

The solution for this problem consists in the acquisition of two global coverage with different heights of ambiguity. This approach has two advantages. First, the combination of two acquisitions with a dual baseline phase unwrapping technique strongly reduces the number of phase unwrapping errors in the DEM. Second, the two acquisitions can be combined to reduce the noise like decorrelation errors. For this purpose the acquisitions of the second coverage are shifted by half a swath width compared to the first coverage. By this, the pattern regions with higher antenna gain, hence better SNR and thus lower height error are combined with the lower gain regions at the edges of the pattern main lobe from the other coverage. This enables a flatter gain distribution as would be achieved with one coverage only.

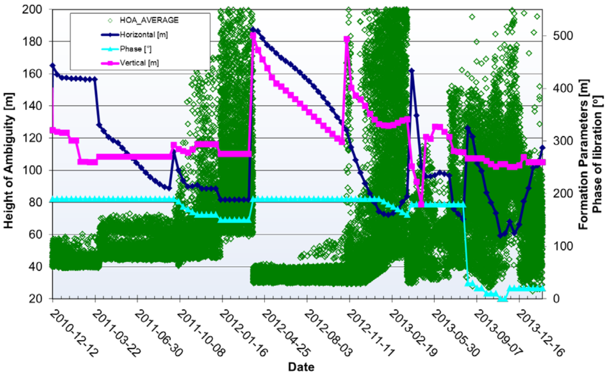

Figure 2: Height of ambiguity (HoA) and formation parameters (horizontal and vertical separations) for global DEM acquisition

Fig. 2 shows the evolution of the formation parameters and the resulting height of ambiguity for individual acquisitions, with similar patterns for first and second global coverage. The formation is designed such that the height of ambiguity is kept in a desired range around 50 m for the first coverage. As the height of ambiguity of an acquisition depends on the incidence angle and the latitude region on Earth, the formation has to change in order to keep a stable height of ambiguity. This can be seen by the decrease of the horizontal and vertical distance. In the second year the target height of ambiguity is in the order of 35 m in order to obtain an optimal ratio for unwrapping phase jumps by dual baseline phase unwrapping [18]. The trend of HoA from target value to larger values, observed in the HoA patterns of both, first and second year global coverage, is caused by a large number of extra acquisitions for already covered areas. Scenes are re-acquired with larger HoA in order to improve the phase unwrapping quality and thereby the quality of the final DEM.

The third year is dedicated to difficult terrain. To observe mountainous regions from a different side, the northern hemisphere will be acquired in descending orbits, the southern in ascending orbits respectively. The first acquisition of Antarctica has been performed before the third year formation parameters were set.

## 1.6 Interferometric Calibration

The calibration of the bistatic interferometer [11] is an important task in deriving the absolute height of the processed DEM acquisitions. In the mosaicking and calibration process, the processed DEMs will be calibrated and mosaicked to larger DEM tiles. However, for geocoding reasons and also to reduce the effort in the mosaicking and calibration processor, the processed DEMs have to be as close to their real height as possible. The three main components described in the following are involved in this interferometric calibration.

One major issue has been the calibration of baseline data. A stable baseline is a prerequisite for accurate interferometric imaging. An error in line of sight direction of the baseline directly contributes to a height offset of the DEM, only scaled by the height of ambiguity. In order to derive the final baseline, three different baseline solutions, based on different algorithms, are combined into the calibrated baseline. This approach enables the detection of outliers and averaging over the solutions.

The results of repeated acquisitions over baseline calibration test sites are depicted in Fig. 3 [16]. There, the baseline is decomposed into the radial and the cross track baseline which are the two relevant directions for the bistatic acquisition. The results show the high stability of the calibrated baseline with a standard deviation in the order of 1 mm.

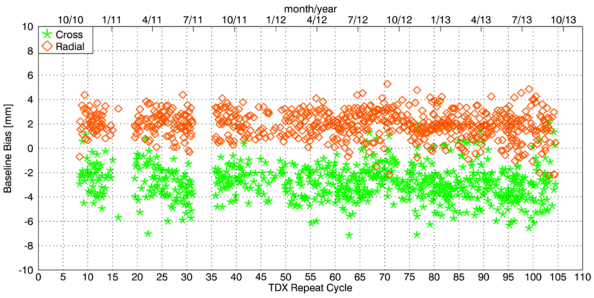

Figure 3: Baseline calibration results over time. Red: radial component, green: cross track component.

As a second component of interferometric calibration, radargrammetry is used to correctly derive the height of ambiguity band of the scene. It determines the approximate height of the acquisitions derived by the travel times of the radar signal. Hence, the technique is very sensitive to delays in the instrument caused by different instrument settings and by the two different instruments themselves. To calibrate these internal delays, statistical analyses were performed on the hitherto acquired data sets. Dependencies on the receiver gain setting, the bandwidth, the chosen sync horn combination, and the transmitting satellite were found and could be compensated providing correction values for the interferometric processor. In addition, radargrammetry is used to resolve a pi-ambiguity in the processing of the sync link signal used to compensate the oscillator drift between the two instruments.

Third component of interferometric calibration has been the analysis of phase errors. For accurate height derivation radar phase is the key parameter. The phase behavior of the instrument was thoroughly characterized on ground. Hence, in orbit mainly formation dependent effects based on the along track distance between both satellites or on different reference frames for timing and coordinate calculations had to be compensated. In addition, the differential troposphere had to be considered [13]. As well, the correct compensation of temperature effects in the instrument and the correct constant phase relation between both satellites have been adjusted.

To obtain an overview about the absolute height error of the TanDEM-X DEMs, the deviation of the DEM scenes from SRTM or ICESat data, where the latter are the main absolute height reference for TanDEM-X, is derived and analysed. Fig. 4 shows the results of this comparison: 90% of the acquired scenes (50 km × 30 km acquisition parts) are within ±10 m versus SRTM and ICESat. The outlying scenes are caused by the mentioned pi-ambiguity. They can be reprocessed with the correct ambiguity band information and will then also touch down into the correct band. After DEM calibration, the first tests [14] already showed that the vertical height error requirement of 2 m can be fulfilled.

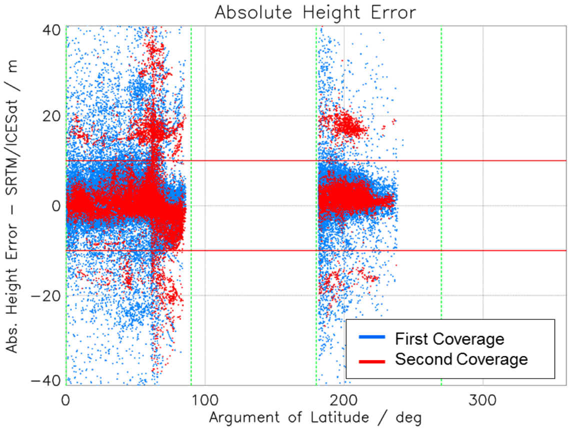

Figure 4: Height error monitoring and detection of outliers

## 1.7 Mission Status and Outlook

After the launch in June 2010 a monostatic commissioning phase was dedicated to calibration and performance verification and revealed calibration accuracies and overall performance of the TDX SAR system and its products as good as for TSX. After comprehensive testing of the various safety measures close formation was achieved mid October 2010 and the operations at typical distances between 150 and 500 m is running remarkably smooth and stable since then. The subsequent bistatic commissioning phase of the TanDEM-X mission concentrated on checking out the complete bistatic chains from acquisition planning to bistatic and interferometric processing and generation of so-called raw DEMs.

Global DEM acquisitions have started in December 2010 and the first global coverage (except Antarctica) was completed in January 2012. Parallel to the first months of operational data acquisition the team concentrated its efforts on the calibration of the bistatic interferometer as summarized in the previous section.

A comprehensive monitoring system has been established to evaluate the performance of each individual data take and provide feedback to the TanDEM-X acquisition planning for additional acquisitions. Ongoing work includes continuous performance monitoring and verification, and the acquisition for the remaining DEM data takes with optimized imaging geometries. Fig. 5 shows the color-coded relative height error derived from the coherence of the first and second global acquisitions, including the improvements by the already processed additional acquisitions. The regions with pastel colors are currently acquired with different geometry compared to the first and second year.
The DEM calibration and mosaicking chain is now fully operational. Based on the first global acquisition, so-called intermediate DEMs are being produced for larger regions. One example is the 1° DEM-tile mosaic of Bavaria shown in Fig. 6. The second global coverage has been completed in the first quarter of 2013. Acquisitions for the third or even fourth coverage over difficult terrain are ongoing. In addition Antarctica was acquired during local winter conditions in the mid of 2013. It is anticipated to finalize planned data acquisitions by the end of 2013. Gap filling and a second Antarctica period is planned until mid of 2014, again during local winter conditions. First parts of the global TanDEM-X DEM will become available in early 2014. Additional effort goes into the planning and conduction of bistatic and multistatic radar experiments within the science service segment [17].

## 1.8 Conclusions

Accurate calibration of radar system delay, phase synchronisation between the TSX and TDX radar systems as well as the interferometric baselines have been successfully carried out showing excellent system performance. The first global interferometric acquisition has been completed in 2012 and the second one in April 2013. After that, Antarctica was acquired followed by additional interferometric acquisitions with formation parameters optimised for difficult terrain. The results achieved so far are compliant with the expected performance for a global DEM with 2 m height accuracy.

After the standard DEM acquisitions, DEMs of even higher accuracy will be produced for selected areas. In addition, interferometric acquisitions with even larger baselines can be adjusted for the exploration and demonstration of scientific experiments.

TanDEM-X has demonstrated the feasibility of an interferometric radar mission with close formation flight and delivers an important contribution for the concept and design of future SAR missions. One example is Tandem-L [15], a mission proposal for monitoring dynamic processes on the Earth surface with unprecedented accuracy.

The complete mission is fully operational since December 2010 and both satellites as well as the ground system perform remarkably well. Current fuel consumption and battery degradation on the TerraSAR-X satellite is well below specification and will probably allow for life time extensions of two to three years. The prolonged mission time will allow for additional DEM acquisitions with improved accuracy and resolution as well as the conduction of advanced bistatic and multistatic SAR experiments in unique configurations, modes and geometries.

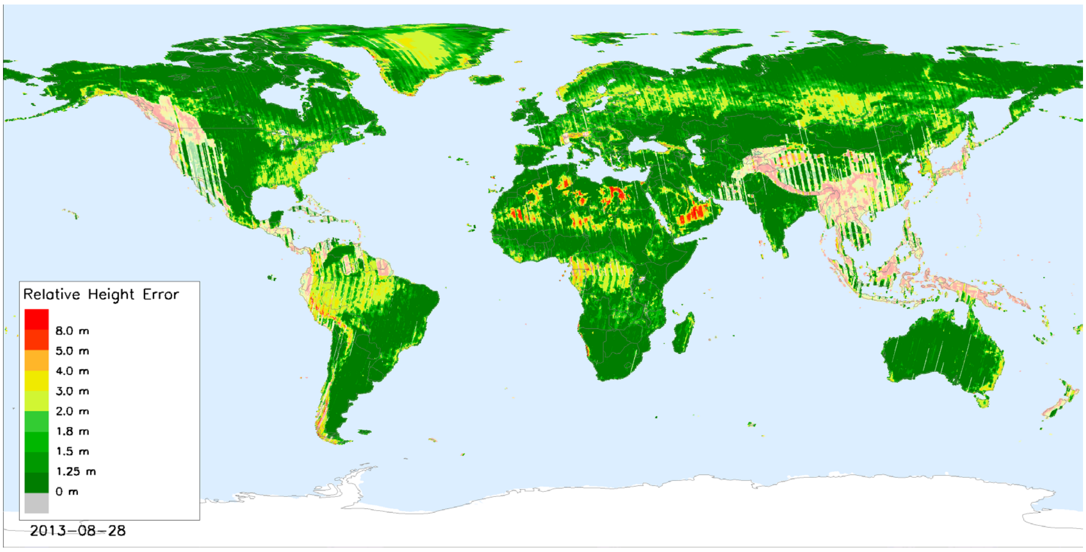

Figure 5: Global height error map of TanDEM-X data takes acquired during the two years, plus some additional acquisitions between Dec. 2010 and Apr. 2013. The pastel coloured areas will be currently acquired additionally from different orbit positions to minimize the height errors.

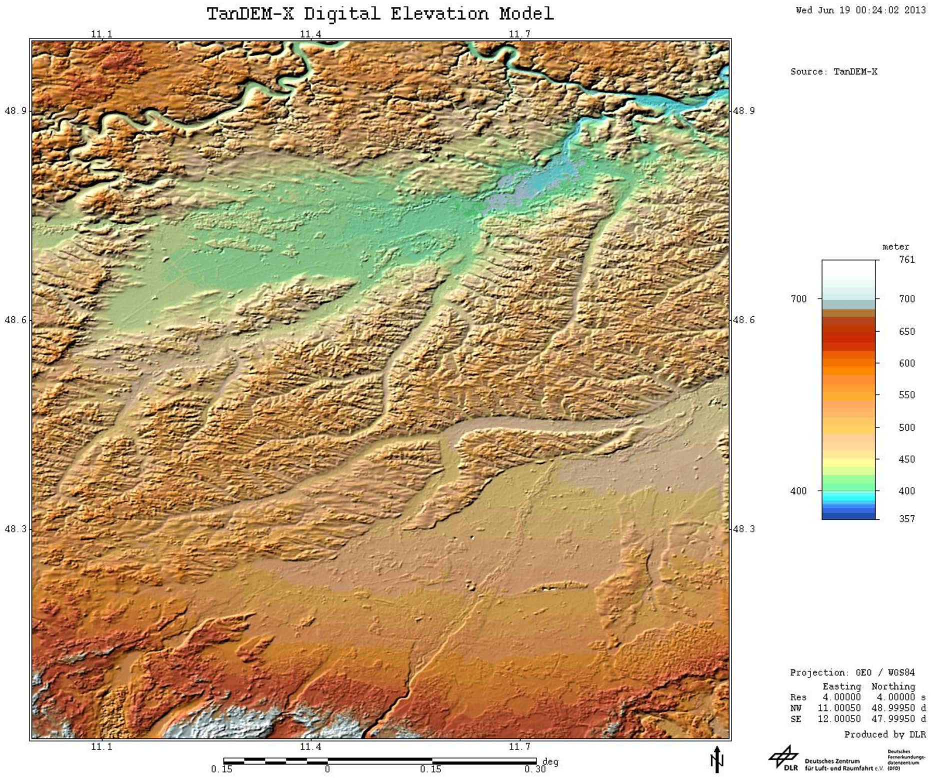

Figure 6: TanDEM-X DEM-Tile of Munich area, with 1° extent in both dimensions

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