TanDEM-X: Key Features and Mission Status

Manfred, Zink, German Aerospace Center (DLR), manfred.zink@dlr.de, Germany

Abstract

TanDEM-X, 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. 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. Beyond this primary mission objective TanDEM-X is also an important pre-cursor for future SAR satellite formations allowing demonstrating novel SAR techniques, with focus on multistatic SAR, polarimetric SAR interferometry, digital beam forming and super resolution. In this paper the status of the global DEM generation and key features of the TanDEM-X mission will be presented in view of their importance for future missions.

1 Mission Objectives

The primary objective of the TanDEM-X mission [1] is the generation of a world-wide, consistent, and high-precision (see **Table 1**) digital elevation model (DEM) as the basis for a wide range of scientific research, as well as for serving commercial applications. Beyond the generation of the global TanDEM-X DEM, local DEMs of even higher accuracy level and applications based on Along-Track Interferometry (ATI) like measurements of ocean currents are important secondary mission objectives. Combining both, the so-called dual-receive antenna mode on each of the two satellites and adjustment of the along-track distance between TSX and TDX to the desired value, will provide a highly capable along-track interferometer with four phase centers for e.g. 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.

Parameter	Definition	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)

Table 1: Specification of the Global TanDEM-X DEM.

TanDEM-X has a tight time schedule to reach the main mission goal. The first four years are dedicated to the global DEM acquisitions using baseline geometries optimized for DEM performance. During periods of suitable baselines, a limited number of scientific acquisitions have been included since the beginning of the DEM acquisition phase. In a dedicated Science Phase planned after the DEM acquisitions have been completed even larger baselines can be adjusted for higher accuracy DEMs on local scales and for the exploration and demonstration of scientific experiments.

2 Key Mission Features

The TanDEM-X mission is an extension of the TerraSAR-X radar mission [2], co-flying a second satellite of nearly identical capability in a close formation. The TerraSAR-X satellite (TSX) is not only a high performance SAR system, but it has already built in all necessary features required for the implementation of the TanDEM-X mission. The second satellite (TDX) is as much as possible a rebuild of TSX with only minor modifications like an additional cold gas propulsion system for formation fine tuning or double-sized on-board solid-state memory for increased data recording capacity. The instruments on both satellites are advanced high-resolution X-band synthetic aperture radars based on active phased array technology, which can be operated in Spotlight, Stripmap, and ScanSAR mode with full polarization capability [3]. The TDX satellite is designed for a nominal lifetime of 5.5 years. Predictions for TSX based on the current status of system resources indicate at least five extra years (until the end of 2017) of lifetime, providing more than 5 years of joint operation.

2.1 Close Formation Flight

An orbit configuration based on a Helix geometry as shown in **Figure 1** 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

Figure 1: Orbit illustration of Helix satellite formation. Red: TSX, Green: TDX.

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 [1].

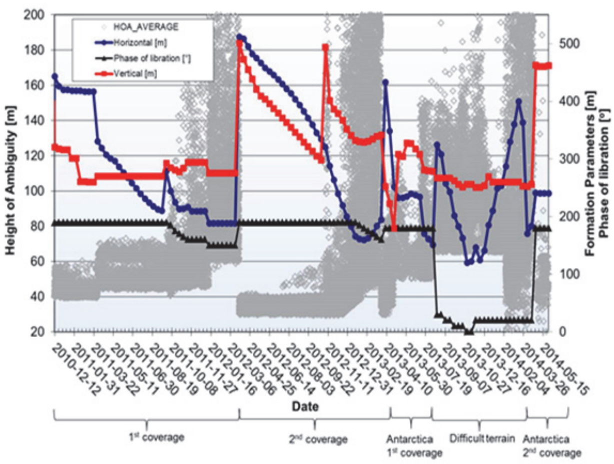

Figure 2: TanDEM-X formation parameters for global DEM acquisitions: horizontal (blue) and vertical (red) distance, phase of libration (black), and height of ambiguity per acquisition (grey).

The Helix formation enables a complete mapping of the Earth with a stable height of ambiguity by using a small number of formation settings shown in **Figure 2** [4]. Southern and northern latitudes are mapped with the same formation by using ascending orbits for one and descending orbits for the other hemisphere. A fine tuning of the cross-track baselines can moreover be achieved by taking advantage of the natural rotation of the eccentricity vectors due to secular disturbances, also called motion of libration. The phase of this libration can be kept in a fixed relative position with small maneuvers using the cold gas thrusters on a daily basis, while major formation changes as well as a duplication of the orbit keeping maneuvers required by TSX are performed by the hydrazin thruster system.

2.2 System Synchronization

TanDEM-X DEM generation combines one monostatic and one bistatic radar image in a joint SAR interferogram. A peculiarity of the bistatic data acquisition is the use of independent oscillators for the modulation and demodulation of the radar pulses. The impact of oscillator phase noise in bistatic SAR has been analyzed in [5] where it is shown that oscillator noise may cause significant errors in both the interferometric phase and SAR focusing. The stringent requirements for interferometric phase stability in the bistatic mode will hence require an appropriate relative phase referencing between the two SAR instruments. For TanDEM-X, a dedicated inter-satellite X-band synchronization link has been established: the nominal bistatic SAR data acquisition is shortly interrupted, and radar pulses are exchanged between the two satellites using the dedicated synchronization horn antennas. On ground, a correction signal can be derived from the recorded synchronization pulses to compensate the oscillator induced phase errors in the bistatic SAR signal. The performance of such a synchronization link has been investigated in [6] indicating that a phase error below 1° can be achieved. This prediction has been validated during the bistatic TanDEM-X commissioning phase [7].

In bistatic operation, short along-track distances are required to ensure sufficient overlap of the Doppler spectra. As a result, there is the danger that one satellite illuminates its partner by its radar antenna, which could cause interference, or, in the worst case, damage of sensitive electronic equipment. To mitigate the risk of mutual illumination, the transmission of radar signals has to be suppressed for one satellite at specific arguments of latitude, so-called exclusion zones. TanDEM-X ensures exclusion zone compliance by a double fail save approach including both a check on ground before command upload and an additional real-time check on the satellite which suppresses signal transmission within predefined latitude windows.

2.3 Calibration of the TanDEM-X Interferometer

Precise determination of the interferometric baseline is performed by a double differential evaluation of GPS carrier phase measurements with accuracies in the order of 1–2mm. However, primarily due to uncompensated offsets from the SAR antenna phase centers, the relative satellite positions derived from GPS measurements show a bias that can be estimated from interferometric acquisitions over well-known areas [8]. Correction of differential delays between TSX and TDX was necessary to facilitate the utilization of radargrammetry for resolving the 2π-ambiguity band. Additional systematic height error sources include the formation of the bistatic replica for both synchronization and bistatic imaging, as well as residual errors in the bistatic SAR processing, e.g. due to relativistic effects and Earth rotation.

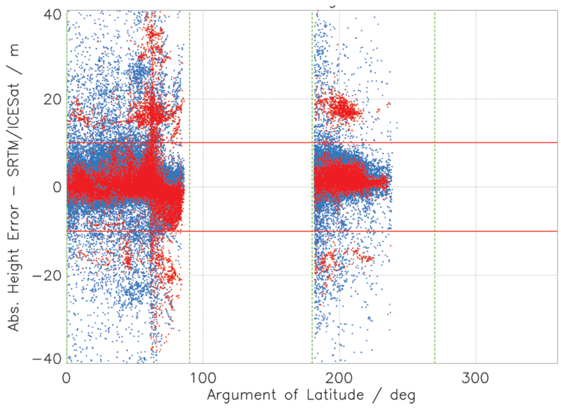

Figure 3: Absolute height error (in comparison to SRTM and ICESat) for the scene based Raw DEMs (i.e. before final calibration using ICESat data as reference heights); blue: first year coverage, red: second year coverage.

Early in the mission phase, delay and baseline calibration have been continuously improved and reached such an accuracy level , that more than 90% of all so-called Raw DEMs (scene-based DEMs as output from the first fully automated processing step [9]) are within ±10m of DEMs from SRTM/ICESat data (see **Figure 3**) already before the final calibration step using ICESat data as reference heights.

3 Mission Status

After the TanDEM-X launch in June 2010 and the commissioning phase, close formation was achieved mid October 2010 and the operations at typical distances between 120 and 500 m is running remarkably smooth and stable since then. Global DEM acquisitions have started in December 2010 and the first and second global coverage (except Antarctica) was completed in March 2012 and March 2013, respectively. After an acquisition period for gap filling, Antarctica was mapped during local winter conditions (for reasons of better SNR) and since early August 2013 the Helix formation has been re-adjusted to allow imaging of difficult mountainous terrain from the opposite viewing geometry [4]. After reversing the Helix formation in April 2014, a subsequent second coverage of Antarctica, and some further gap filling, it is anticipated to finalize data acquisitions for the global DEM in the second half of 2014.

A comprehensive system has been established for continuous performance monitoring and verification [10], [11], including feedback to the TanDEM-X acquisition planning for additional acquisitions. More than 350,000 Raw DEMs have been generated so far in a fully automated process employing multibaseline interferometric techniques [9].

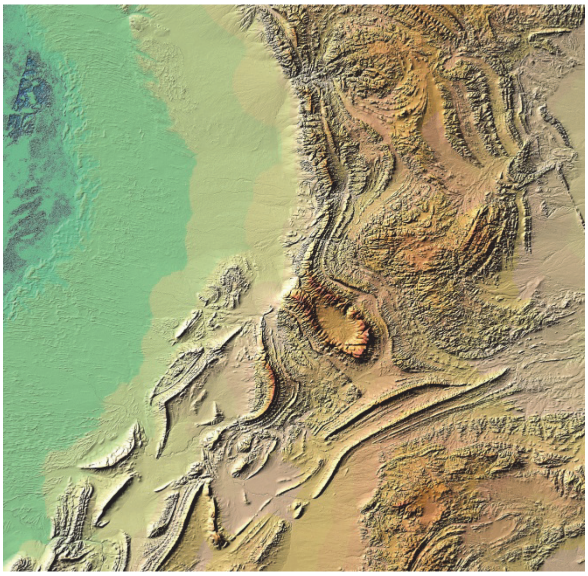

Figure 4: Final TanDEM-X DEM: Flinders Ranges, Australia.

The final calibration and mosaicking chain is fully operational since 2013 [12]. Based on the first global acquisition, so-called intermediate DEMs have been produced for larger regions. Currently all efforts are concentrated on the generation of final DEMs for areas requiring only first and second acquisitions. Up to now most of Australia (see example in **Figure 4**) and the rather flat areas of North America and Russia have been finished, areas in South Africa and South America are next in the production. The quality of the first final DEMs is well within specification for both the relative [13] and the absolute height error (see **Figure 5**) [12]. First examples for final DEMs over mountainous terrain will become available after the summer. It is expected to complete the global DEM by the end of 2015.

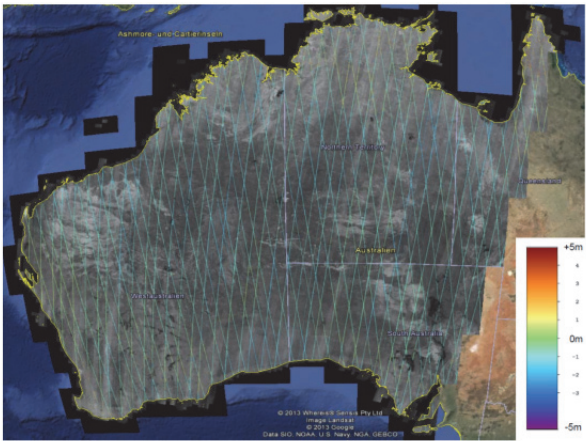

Figure 5: TanDEM-X amplitude mosaic of Australia overlayed with difference between the final TanDEM-X DEM and ICESat tracks (only a small subset of ICESat points is used for DEM calibration, all the others are used for validation as in this example).

4 Conclusions

TanDEM-X opens a new era in spaceborne radar remote sensing. Key technologies like close formation flying, bistatic SAR operation and synchronization, precise baseline estimation and calibration as well as sophisticated bistatic and interferometric processing chains have been implemented. The complete mission is fully operational since December 2010 and both satellites as well as the ground system perform remarkably well. Data acquisition for the global DEM will finish in the second half of 2014. The current focus is on the processing of the global DEM data. About 20% of the global land mass covering most of Australia and the rather flat areas of North America and Russia are already available as final DEMs. The global DEM will be available by the end of 2015 and is expected become a new reference for commercial and scientific applications since it is at least 30 times more accurate than the presently available global scale DEM data set.

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

References

[1] 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.

[2] R. Werninghaus and S. Buckreuss, “The TerraSAR-X Mission and System Design,” IEEE Transactions on Geoscience and Remote Sensing, vol. 48, no. 2, pp. 606–614, 2010.

[3] W. Pitz, D. Miller: *The TerraSAR-X Satellite*, IEEE Transactions on Geoscience and Remote Sensing, vol. 48, no. 2, pp. 615–622, Feb. 2010.

[4] D. Borla Tridon, et.al.: *TanDEM-X: DEM Acquisition in the third Year Era*, International Journal of Space Science and Engineering, pp 1-14, ISSN 2048-8459.

[5] G. Krieger and M. Younis: *Impact of Oscillator Noise in Bistatic and Multistatic SAR*, IEEE Geoscience and Remote Sensing Letters, vol. 3, pp. 424- 428, 2006.

[6] M. Younis, R. Metzig, G. Krieger: *Performance Prediction of a Phase Synchronization Link for Bistatic SAR*, IEEE Geoscience and Remote Sensing Letters, vol. 3, pp. 429- 433, 2006.

[7] P. Rizzoli et al.: *Interferometric Performance*, TanDEM-X science meeting, Oberpfaffenhofen, Germany, February 17, 2011, online link.

[8] J. Hueso González, et.al.: *Bistatic System and Baseline Calibration in TanDEM-X to Ensure the Global Digital Elevation Model Quality*, ISPRS Journal of Photogrammetry and Remote Sensing, Volume 73, September 2012, pp. 3–11.

[9] T. Fritz, et.al.: *Processing Strategies for Global Interferometric TanDEM-X DEM Generation,* European Conference on Synthetic Aperture Radar (EUSAR), Berlin, Germany, 2014.

[10] P. Rizzoli, et.al.: *Relative Height Error Analysis of TanDEM-X Elevation Data*, ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 73, pp. 30-38, 2012.

[11] M. Martone, et.al.: *Coherence Evaluation of TanDEM-X Interferometric Data*, ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 38, pp. 21-29, 2012.

[12] B. Wessel, et.al.: *Status of TanDEM-X DEM Calibration and Mosaicking towards the TanDEM-X DEM,* European Conference on Synthetic Aperture Radar (EUSAR), Berlin, Germany, 2014.

[13] D. Schulze, et.al.: *Status of TanDEM-X DEM Acquisition, Calibration and Performance*, European Conference on Synthetic Aperture Radar (EUSAR), Berlin, Germany, 2014.

TanDEM-X is partly funded by the German Federal Ministry for Economic Affairs and Energy (50 EE 1035).