The TanDEM-X Mission

Manfred Zink, Gerhard Krieger, Hauke Fiedler, Irena Hajnsek, Alberto Moreira, Marian Werner

Microwaves and Radar Institute
German Aerospace Center (DLR)
82234 Oberpfaffenhofen, Germany
Phone: +49 8153 282356, email: manfred.zink@dlr.de

ABSTRACT

TanDEM-X opens a new era in space borne radar remote sensing. The first bistatic SAR mission, is formed by adding a second, almost identical spacecraft, to TerraSAR-X and flying the two satellites in a closely controlled formation with typical distances between 250 and 500 m. Primary mission objective is the generation of a consistent global digital elevation model with an unprecedented accuracy according to the HRTI-3 specifications. Beyond that, TanDEM-X provides a highly reconfigurable platform for the demonstration of new SAR techniques and applications. This paper gives an overview of the TanDEM-X mission concept, summarizes the capabilities of the system, illustrates the achievable performance, and provides some examples for new imaging modes and applications. The mission has been approved for full implementation by the German Space Agency with a planned launch in spring 2009.

Keywords: Bistatic SAR formation, single-pass interferometry, HRTI-3 DEM, new SAR techniques, TerraSAR-X

1. INTRODUCTION

Digital elevation models (DEMs) are of fundamental importance for a broad range of commercial and scientific applications [1]. For example, many geoscience areas like hydrology, glaciology, forestry, geology, oceanography and land environment require precise and up-to-date information about the Earth's surface and its topography. Digital maps are also a prerequisite for reliable navigation, and improvements in their precision need to keep step with the advances in global positioning systems, like GPS and Galileo. In principle, DEMs can be derived from a variety of air- and spaceborne sensors. However, the resulting mosaic of data from different sources with a multitude of horizontal and vertical data, accuracies, formats, map projections, time differences and resolutions is hardly a uniform and reliable data set. The Shuttle Radar Topography Mission (SRTM, [2]) had hence the challenging goal to meet the requirements for a homogeneous and reliable DEM fulfilling the DTED-2 specification. The coverage of this DEM is, however, principally limited to a latitude range from 56° S to 60° N due to the inclined orbit of the space shuttle and its mapping geometry. Further restrictions apply to the X-band DEM with its wide gaps at lower latitudes and the C-band DEM where the data are available to the public only at an artificially impaired spatial resolution.

A user survey among a wide range of scientists and commercial customers has clearly shown that many applications require both an extended latitudinal coverage and an improved accuracy corresponding to the emerging HRTI-3 standard and comparable to DEMs generated by high-resolution airborne SAR systems [1]. Here, the acronym HRTI stands for High Resolution Terrain Information and relates to a DEM standard which uses a fixed latitude and variable longitude grid to represent the elevation data on a global scale [3]. The specifications of the DTED-2 and HRTI-3 DEM standards are summarised in Tab. 1. A coverage comparison with existing DEM products is presented in Fig. 1.

Table 1. Comparison of DTED-2 and HRTI-3 DEM Specifications

Requirement	Specification	DTED-2	HRTI-3
Relative Vertical Accuracy	90% linear point-to-point error over a 1° x 1° cell	12 m (slope < 20%) 15 m (slope > 20%)	2 m (slope < 20%) 4 m (slope > 20%)
Absolute Vertical Accuracy	90% linear error	18 m	10 m
Relative Horizontal Accuracy	90% circular error	15 m	3 m
Horizontal Accuracy	90% circular error	23 m	10 m
Spatial Resolution	independent pixels	30 m (1 arc sec @ equator)	12 m (0.4 arc sec @ equator)

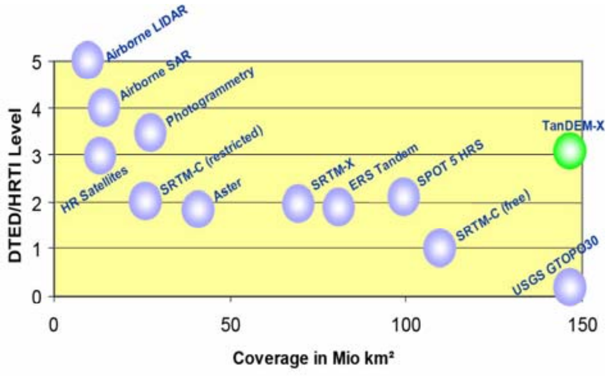

Figure 1. DEM-level versus coverage indicating the uniqueness of the global TanDEM-X HRTI-3 product

The primary objective of the TanDEM-X (TerraSAR-X add on for Digital Elevation Measurements) mission is the generation of a world-wide, consistent, timely, and high precision digital elevation model aligned with the HRTI-3 specification as the basis for a wide range of scientific research, as well as for operational, commercial DEM production. This goal will be achieved by means of a second, TerraSAR-X like satellite flying in close orbit configuration with TerraSAR-X. Both satellites will then act as a large single-pass SAR interferometer with the opportunity for flexible baseline selection. This enables 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.

Besides the primary goal of the mission, several secondary mission objectives based on along-track interferometry as well as new techniques with bistatic SAR have been defined which represent an important and innovative asset of the mission. TanDEM-X was approved for full implementation by the German Space Agency and will be realized in the framework of a public-private partnership between the German Aerospace Center (DLR) and EADS Astrium GmbH, as for TerraSAR-X. With a planned launch in spring 2009, TanDEM-X opens a new era in the German space programme providing a major push for the R&D activities and associated techniques and technologies of high resolution X-band Synthetic Aperture Radar (SAR).

The following chapters present the TanDEM-X system and its orbit formation and operational modes, provide a summary of the predicted DEM generation performance and give an overview of new SAR techniques and applications which will be demonstrated with this first bi-static SAR formation in space.

2. THE TANDEM-X SYSTEM

The TanDEM-X formation (see Fig. 2) is build by adding a second spacecraft (TDX) to TerraSAR-X (TSX) and flying the two satellites in a closely controlled formation [4]. The TDX satellite will be as much as possible a re-build of TSX with only minor modifications like an additional cold gas propulsion system for constellation fine tuning and an additional S-band receiver to enable a reception of status and GPS position information broadcast by TSX. This guarantees a low development risk and it offers the possibility for a flexible share of operational functions for both the TerraSAR-X and TanDEM-X missions among the two satellites. The TDX satellite will be designed for a nominal lifetime of 5 years and has a nominal overlap with TSX of 3 years. TSX holds consumables and resources for up to seven years of operation, allowing for a potential prolongation of the overlap and the TanDEM-X mission duration.

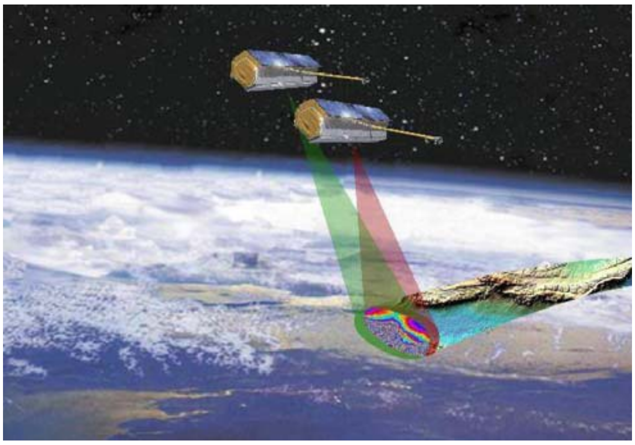

Figure 2. The TanDEM-X satellite formation

2.1 The HELIX Orbit Concept

The TanDEM-X mission concept is based on the coordinated operation of two spacecraft flying in close formation. Using two independent spacecraft provides the highly flexible and reconfigurable imaging geometry required for the different mission objectives. For example, the primary goal of generating a highly precise HRTI-3 DEM requires variable cross-track baselines in the order of 300 to 500 m.

In this close formation flight collision avoidance becomes a major issue and a minimum safety distance of 150 m perpendicular to the flight direction is to be observed around the orbit at any time. A formation, which fulfills these requirements, is the Helix formation [5] shown in Fig. 3. By applying an adequate eccentricity/inclination-vector separation, the two satellites perform a helix-like motion around each other ensuring the minimum safety distance. 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 [6]. Cross- and along-track baselines ranging from 200m to 10km and from 0 to several 100km, respectively, can be accurately adjusted.

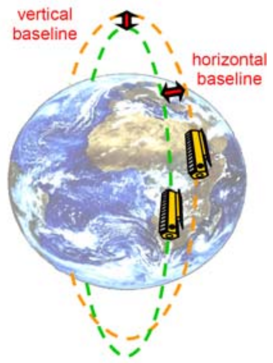

Figure 3. Artist's view fo the HELIX orbit concept used for TanDEM-X

2.2 TanDEM-X Operational Modes

The main parameters of the SAR sensor on TDX are fully compatible with those of TSX (see Table 2) allowing not only independent operation from TSX in a mono-static mode, but also synchronized operation (e.g. in a bistatic mode).

Table 2. Main Characteristics of the TerraSAR-X SAR System

RF center frequency:	9,65 GHz
Bandwidth:	up to 300MHz
Incidence angle range:	20° to 55°
Polarisation:	single, dual, quad
SAR modes	Stripmap, ScanSAR, Spotlight, Dual-phase (split-antenna) center mode

Interferometric data acquisition with the TanDEM-X satellite formation can be achieved in three different operational modes: Bistatic, Monostatic, and Alternating Bistatic Mode [7]. Operational DEM generation is planned to be performed using bistatic interferometry (Bistatic Mode), which is characterized by the illumination of a scene by one transmitter and the simultaneous measurement of the same scene with two receivers (see Fig. 4), thereby avoiding temporal decorrelation. To provide sufficient overlap of the Doppler spectra, less than 2 km along-track baselines are required while the effective across-track baselines for high resolution DEMs have to be in the order of 300 m. Over moderate terrain one complete coverage with such across-track baselines would be sufficient, but for mountainous areas (about 10% of the Earth's land surface) additional data acquisitions with different baselines and viewing geometry are required. To increase redundancy and robustness and to facilitate multi-baseline phase unwrapping [8] two global data sets at different heights of ambiguity (approx. 25-30m and 35-40m) will be acquired. Over rough terrain up to four acquisitions are foreseen.

The Radar Data Mode has been introduced as a synonym for the demonstration of innovative SAR modes and applications, offering a large variety of geometric constellations and of radar instrument settings (all SAR modes including 2 + 2 receive phase centers). The instruments will be commanded according to the parameters selected by the scientists for Along-Track Interferometry (ATI) applications and for demonstration of new SAR techniques.

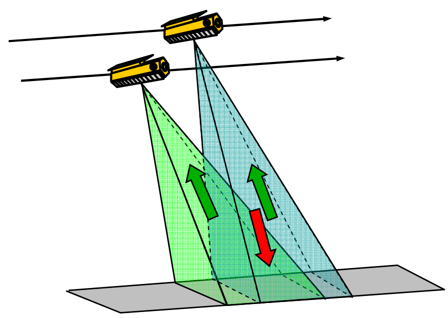

Figure 4. TanDEM-X in bistatic mode: one satellite transmits and both receive the echoes simultaneously.

2.3 Synchronisation (Relative Phase Referencing)

In Bistatic Mode the TanDEM-X interferometer is operated with two independent oscillators. Uncompensated oscillator noise will cause a slight deterioration of the bistatic impulse response, a significant shift of the bistatic SAR impulse response, and substantial interferometric phase errors. To correct for these phase errors and also to enable pulse repetition interval (PRI) synchronization, the TanDEM-specific SAR instrument features provide a scheme for transmission and reception of USO phase information between the SARs with adequate SNR. On both the TDX and TSX spacecraft six synchronization horn antennas are added at selected positions to ensure full solid-angle coverage with low phase disturbance. The required precise phase referencing for DEM generation in bistatic interferometry mode can be achieved using synchronization pulses with a PRF in the order of 5-10 Hz. For a SNR of at least 25 dB (which can be achieved for all HELIX formations in the DEM acquisition phase) the residual interferometric phase error can be reduced below 1° [7].

3. PREDICTED DEM GENERATION PERFORMANCE

A detailed height performance model has been developed for the Bistatic Mode, the main mode for DEM generation. The performance prediction for the height error is based on the following error contributions [7]:

- Noise due to the limited SNR during SAR data acquisition and interferogram generation, quantization errors from block adaptive quantization, limited co-registration accuracy and processing errors, as well as range and azimuth ambiguities. Decorrelation due to thermal noise in the instruments dominates this error contribution.
- Interferometric phase errors caused by the residual errors in the phase referencing via the noisy synchronization link.
- Random contributions from the TSX and TDX internal calibrations and uncompensated phase drifts along a data take also affecting the synchronization link.
- Accuracy of the interferometric baseline (between the SAR antenna phase centers) with contributions from the GPS differential carrier phase measurements. 3-D baseline estimation errors causing primarily a systematic phase/height ramp in the cross-track direction.
- The knowledge of the satellite's attitude and the SAR antenna phase center, and the accuracy of the transformation from the spacecraft to the Earth fixed coordinate systems.
- Residual errors in the DEM mosaicking process and quality of the reference height information.

Fig. 5 shows the predicted point-to-point height errors for the 90% confidence interval assuming two sets of DEM data acquisitions with two fixed heights of ambiguity of 30 m and 45 m. Note that the two acquisition sets use mutually displaced beams to further improve the performance. The height error from the combination of all acquisitions is shown in solid style yielding an almost constant performance with an accuracy which is well below the 2 m requirement for HRTI-3.

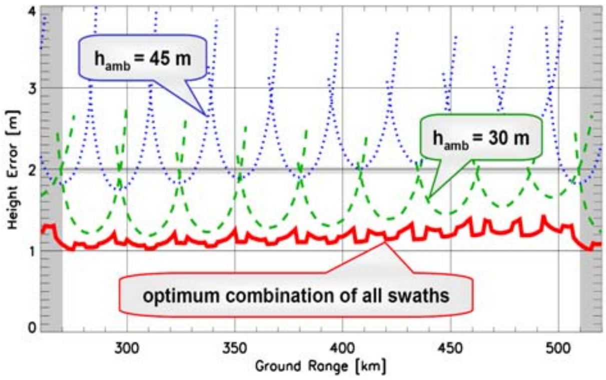

Figure 5. Height accuracy for a height of ambiguity of 45 m and 30 m. The solid curve shows the error resulting from the combination of multiple swaths. All errors are point-to-point height errors for a 90% confidence interval.

The impact of volume decorrelation on the achievable performance is shown in Fig. 6 for vegetation heights of 5 m, 10 m, and 20 m for an extinction of 1 dB/m. It is clear, that volume scattering will impact the performance for all incident angles, but this effect is mitigated by the availability of two interferometric baselines.

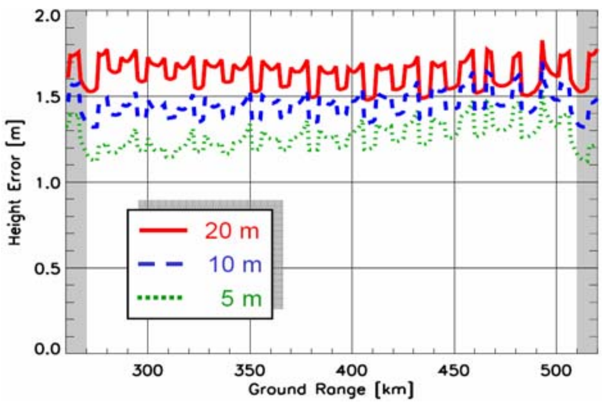

Figure 6. Impact of volume scattering on the 90% point-to-point height errors. Height accuracy for volume heights of 5 m, 10 m, and 20 m.

4. NEW SAR TECHNIQUES – RADAR DATA MODE

The TanDEM-X mission will provide the remote sensing scientific community with a first opportunity to exploit the capability of bistatic space borne radar and to apply these innovative concept for developing advanced parameter retrieval algorithms and new information products.

Along-track SAR interferometry can either be performed by the so-called dual receive antenna mode with a baseline of 2.4 m from each of the satellites or by adjusting the along-track distance of the two satellites to the desired size (see Fig. 7). The HELIX orbit concept allows this along-track baseline to be adjusted from zero to several kilometers. This technical feature is essential as this application requires velocity measurements of different fast and slow objects. Mainly four scientific application areas are identified to explore the innovative along-track mode: oceanography, traffic monitoring, glaciology and hydrology. Of scientific interest is the identification of moving objects as well as the estimation and the validation of different velocity estimates. In all three application areas the knowledge of the velocity will improve model predictions for environmental, economical, as well as social aspects.

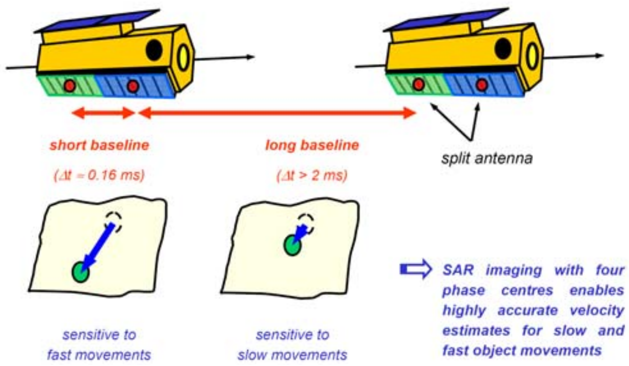

Figure 7. Along-track interferometry modes with TanDEM-X

Very large baseline interferometry takes advantage of the high RF bandwidth of the TSX and TDX satellites which allows for coherent data acquisitions with baselines of up to 5 km and more [7]. By this, it becomes possible to derive DEMs with HRTI-4 like accuracy on a local or even regional scale.

Comparison of multiple large baseline TanDEM-X interferograms acquired during different passes of the satellite formation provides a very sensitive measure for vertical scene and structure changes (see Fig. 8). Potential applications are a detection of the grounding line which separates the shelf from the inland ice in polar regions, monitoring of vegetation growth, mapping of atmospheric water vapour with high spatial resolution, measurement of snow accumulation or the detection of anthropogenic changes of the environment, e.g. due to deforestation. TanDEM-X enables hence the entry into a new age of interferometric (and tomographic) processing techniques as it was ERS-1/2 for the development of classical repeat-pass SAR interferometry.

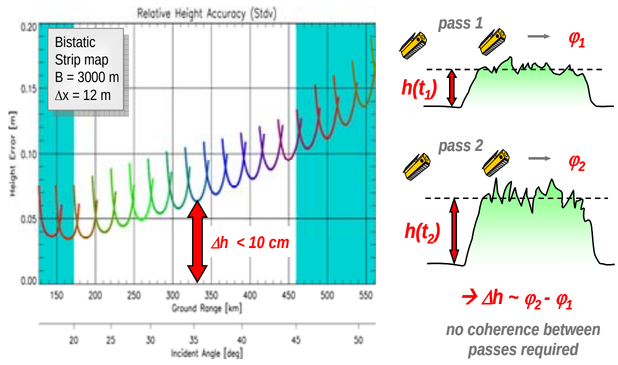

Figure 8. Performance example for double differential SAR interferometry with TanDEM-X (cross-track baseline = 3000 m, posting = 12 m). A relative height accuracy (standard deviation) better than 10 cm is achieved.

Polarimetric SAR interferometry [9] combines interferometric with polarimetric measurements to gain additional information from semi-transparent volume scatterers. This allows e.g. for the extraction of important biophysical parameters like vegetation density and vegetation height. TanDEM-X will be the first mission to demonstrate this technique in a single-pass data acquisition mode

Bistatic SAR imaging provides additional observables for the extraction of important scene and target parameters [10]. TanDEM-X allows for the simultaneous acquisition of bistatic and monostatic images in a single data take to obtain a highly informative set of multi-angle observations. A quantitative evaluation of the bistatic radar cross-section (RCS) and a comparison with its monostatic equivalents facilitates the detection and recognition of targets. The segmentation and classification in radar images is expected to be substantially improved by comparing the spatial statistics of mono- and bistatic scattering coefficients. Data takes with large bistatic angles are planned at the beginning and at the end of the TanDEM-X mission where the satellites are separated from each other by several tenths of kilometers

Digital beamforming combines the RF signals from a set of small non-directional antennas to simulate a large directional antenna. Due to the split antennas and dual receiver channels of TSX and TDX, four phase centers can be obtained in a tandem mode. An appropriate combination of the multiple Rx signals enables then an efficient suppression of azimuth ambiguities. By this, it is possible to demonstrate the capabilities of high resolution wide swath SAR imaging [11]. TanDEM-X will be the first configuration which demonstrates this highly innovative technique from space.

5. SUMMARY

The TanDEM-X mission encompasses scientific and technological excellence in a number of aspects, including the first demonstration of a bistatic interferometric satellite formation in space, as well as the first close formation flight in operational mode. Several new SAR techniques will also be demonstrated for the first time, such as digital beamforming with two satellites, single-pass polarimetric SAR interferometry, as well as single-pass along-track interferometry with varying baseline

6. REFERENCES

1. I. Hajnsek and A. Moreira (2006), "TanDEM-X: Mission and Science Exploration," *in Proc. EUSAR*, Dresden, Germany.

2. M. Werner (2001), "Shuttle Radar Topography Mission (SRTM): Mission Overview," *Journ. Telecommuni-cation (Frequenz)*, vol. 55, no. 3-4, pp. 75-79.

3. National Imagery and Mapping Agency (NIMA) (2000), "High Resolution Terrain Information (HRTI): Performance Specification", *MIL-PRF-89048.*

4. Moreira, A., et.al. (2003), "TanDEM-X: TerraSAR-X Add-on for Digital Elevation Measurements", *Mission Proposal*, Doc. No. 2003-3472739.

5. Fiedler, H., Krieger, G., Werner, M., Hajnsek, I., Moreira, A. (2005), "TanDEM-X: Mission Concept and Performance Analysis," *CEOS SAR CAL/VAL Workshop*, Adelaide, Australien.

6. H. Fiedler, G. Krieger (2004), Close Formation of Passive Receiving Micro-satellites, *18th Int. Symp. Space Flight Dynamics*, Germany.

7. G. Krieger, et.al. (2007), TanDEM-X: A Satellite Formation for High Resolution SAR Interferometry, *IEEE-TGARS*, to be published.

8. M. Eineder, N. Adam (2005), A maximum-likelihood estimator to simultaneously unwrap, geocode, and fuse SAR interferograms from different viewing geometries into one digital elevation model. IEEE Trans. Geosci. Remote Sens., Vol. 43, No. 1, pp. 24-36.

9. K. P. Papathanassiou and S. R. Cloude (2001), "Single-baseline polarimetric SAR interferometry," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 39, pp. 2352-2363.

10. G. Krieger and A. Moreira (2006), "Spaceborne Bi- and Multistatic SAR: Potential and Challenges," *IEE Proceedings - Radar, Sonar and Navigation*, vol. 153, pp. 184-198.

11. M. Süss, B. Grafmüller, and R. Zahn (2001), "A novel high resolution, wide swath SAR system," IEEE Geoscience and Remote Sensing Symposium (IGARSS), Sydney, Australia, (see also M. Süss and W. Wiesbeck (2001), "Side-looking synthetic aperture system," EP 1 241 487 A 1, 2001).