# TanDEM-X – The First Bistatic SAR Formation in Space

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***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***

## I. INTRODUCTION

Existing SAR missions providing long time series of acquisitions allow for repeat-pass interferometry observing the target area at temporal baselines given by the orbit repeat-cycle. Temporal decorrelation, especially at higher frequencies over vegetation, is the major limitation of this technique restricting its application to long-term coherent targets (permanent scatterer) which can be found in sufficient density only over urban areas. Generation of digital elevation models (DEMs) has been demonstrated with repeat-pass interferometry, but the achievable accuracy is limited by too low coherence even for interferometric pairs with temporal baselines of only one day.

SRTM (Shuttle Radar Topography Mission) [1], the first space borne single-pass interferometer was built by supplementing the Shuttle Imaging Radar-C/X-Synthetic Aperture Radar system by second receive antennas mounted at the tip of a 60m deployable mast structure. Within a ten day mission SRTM collected interferometric data for a near global DTED-2 (see specification in Table 1) DEM, covering the Earth’s surface between -56° and +60° latitude. Beyond DEM generation, SRTM also demonstrated along-track interferometry at a fixed 7m baseline for measuring ocean currents and vehicle velocities.

A bistatic SAR system like TanDEM-X with reconfigurable cross-track and along-track baselines does not only provide a flexible single-pass interferometer for the generation of precise high-resolution DEMs and acquisition of bistatic and super resolution images but also allows to perform along-track interferometry to measure object velocities at different scales (e.g. ocean currents, sea ice drift, road traffic). Based on an advanced SAR sensor like TerraSAR-X featuring up to 300MHz bandwidth, dual phase center (split antenna) mode and quad-pol operation promising new techniques like multiple phase center moving target indication, polarimetric interferometry, and digital beamforming can be investigated and demonstrated.

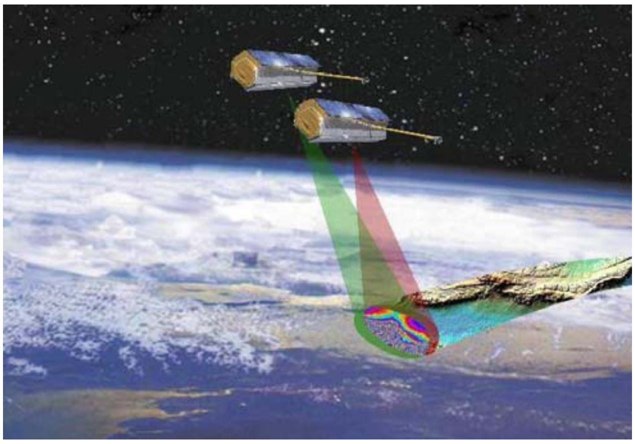

Figure 1. The TanDEM-X satellite formation.

## II. THE TANDEM-X SYSTEM

The TanDEM-X formation (see Fig. 1) is build by adding a second spacecraft (TDX) to TerraSAR-X (TSX) and flying the two satellites in a closely controlled formation [2]. 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.

### *A. 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 [3] shown in Fig. 2. 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 [4]. Cross- and along-track baselines ranging from 200m to 10km and from 0 to several 100km, respectively, can be accurately adjusted.

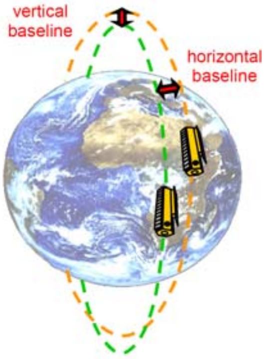

Figure 2. Artist’s view of the HELIX orbit concept used for TanDEM-X

### *B. TanDEM-X Operational Modes*

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

| | |
|---|---|
| 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 |

TABLE I. MAIN CHARACTERISTICS OF THE TERRASAR-X SAR SYSTEM

Interferometric data acquisition with the TanDEM-X satellite formation can be achieved in three different operational modes: Bistatic, Monostatic, and Alternating Bistatic Mode [5]. 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. 3), 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 [6] 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.

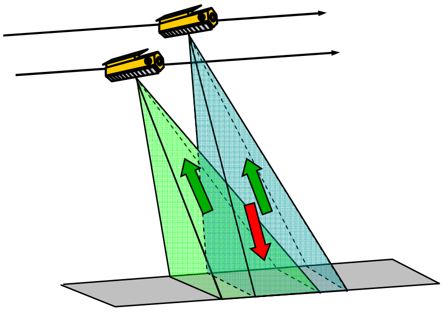

Figure 3. TanDEM-X in bistatic mode: one satellite transmits and both receive the echoes simlutaneously.

### *C. 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 10-20 Hz. For a SNR of 30 dB (a reasonable assumption for along-track displacements up to 1 km) the residual interferometric phase error can be reduced to below 1°.

## III. MISSION PRODUCTS

The collection of scientific and commercial user requirements for the TanDEM-X mission clearly demonstrates the need of a HRTI-3 DEM data set with global access (see comparison of DEM product specifications in Table II) for both scientific and commercial users. The majority of the geo-science 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 topographic maps are also a prerequisite for reliable navigation, and the improvements in their precision needs to keep step with advances in the performance of global positioning systems. For commercial exploitation, DEMs and ortho-rectified images are the most important products for a growing Earth observation market.

Besides this primary goal of the mission, several secondary mission objectives are based on along-track interferometry or new techniques with bistatic SAR.

From a comprehensive user survey, three standard data products have been derived: standard HRTI-3 DEMs, Customised DEMs (CDEMs) with even higher height resolution or improved horizontal spacing and Radar Data Products (RDPs) acquired by along-track interferometry or new SAR techniques. For RDPs the user has to provide specific data acquisition parameters like e.g. interferometric baselines and imaging geometry, SAR operation modes, instrument settings, etc. TanDEM-X will then acquire the desired SAR data during the available time slots.

## IV. PREDICTED DEM GENERATION PERFORMANCE

A detailed height performance model has been developed for the Bistatic Mode covering the relative height error estimates, the calibration concept and the absolute error predictions.

### A. *Relative Height Error Estimation*

The performance prediction for the relative height error is based on the following random error contributions [5]:

- 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.
- 3-D baseline estimation errors causing primarily a systematic phase/height ramp in the cross-track direction (~0.3 cm/km for a height of ambiguity of 35 m and a baseline estimation error in line of sight of 1 mm).

A combination of all these error sources yields the predicted relative height accuracy as shown in Fig. 4. The predicted point-to-point height errors are below 2 m for the full performance range of TSX (and TDX) which ranges from 20° incidence angle up to 45° incidence angle.

### B. *Height Calibration Concept*

The absolute height accuracy is mainly driven by the distribution and accuracy of reference height information, the calibration and mosaicking concept and the data acquisition strategy. Long continuous data takes up to 1000 km length are preferred to avoid additional errors from scene concatenation. The current calibration concept foresees the following steps:

- The generation of "raw" DEMs using SRTM heights or even lower-resolution DEMs as reference (absolute accuracy of the reference data has to be sufficient to resolve the height of ambiguity interval).
- Evaluation of swath overlaps in these raw DEMs for consistency checks between acquisitions, along-track error reduction and across-track tilt correction.

| 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%)<br>15 m (slope > 20%) | 2 m (slope < 20%)<br>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) | 12 m (0.4 arc sec) |

TABLE II. COMPARISION OF DTED-2 AND HRTI-3 DEM SPECIFICATIONS

- A bundle adjustment based on the analysis of relative deviations between raw DEMs and absolute calibration references over large areas, up to continental size.

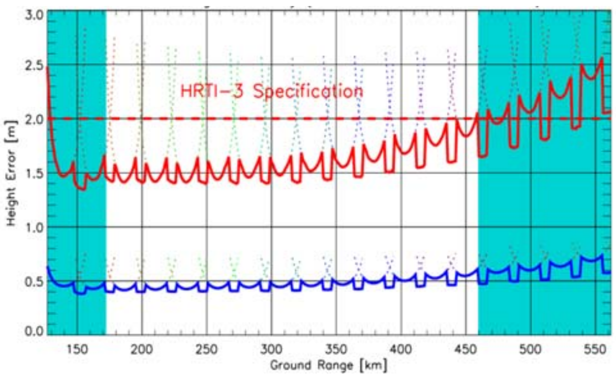

Figure 4. Predicted relative height errors for a height of ambiguity of 35 m. The red curve shows the predicted point-to-point height errors at a 90% confidence level, the blue curve the rel. height error standard deviation.

### C. *Absolute Height Error Estimation*

The HRTI-3 standard requires for the absolute height accuracy a value of 10 m at a 90% confidence level. On top of the above presented relative height errors, which contribute as a random component, the following error sources have to be considered in predicting the absolute height error:

- Accuracy of the interferometric baseline (between the SAR antenna phase centers) with contributions from the GPS differential carrier phase measurements. The Phase A study confirmed that the relative vector between the spacecraft's centers of mass can be determined to within 1 mm.
- 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.
- Uncompensated long-term instrument phase errors due to temperature drift in the internal calibration network and the synchronization link.
- Residual errors in the bundle adjustment process and quality of the reference height information.

The Phase A estimate of the various error contributions results in an absolute height accuracy of 6.6 m demonstrating that TanDEM-X allows for the derivation of highly accurate digital elevation models based on the HRTI-3 standard and even beyond in Stripmap mode.

## V. 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. 5). 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.

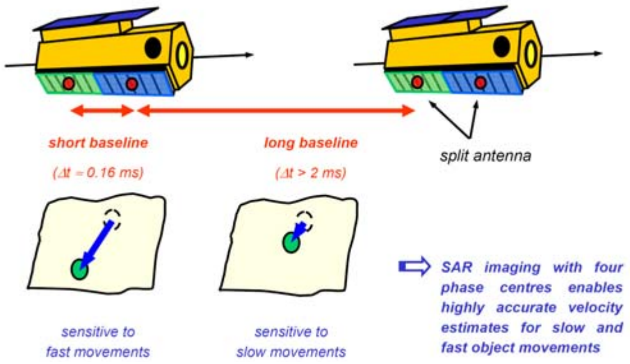

Figure 5. Along-track interferometry modes in TanDEM-X.

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. 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. 6). 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.

Polarimetric SAR interferometry [7] 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.

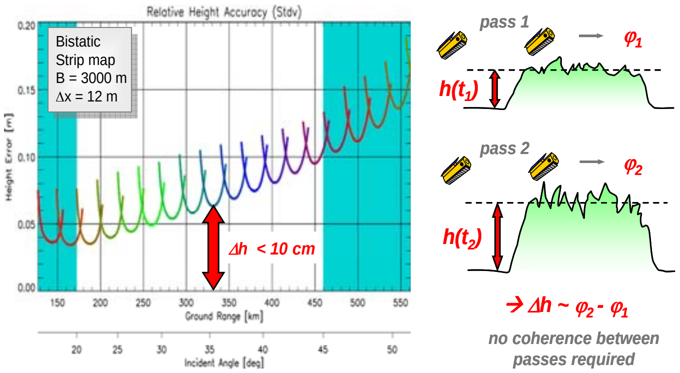

Figure 6. Performance example for double differential SAR interferometry with TanDEM-X (cross-track baseline = 3000 m, posting = 12 m). A relative height accuracy (standard deviation) better than 10 cm is achieved.

Bistatic SAR imaging provides additional observables for the extraction of important scene and target parameters [8]. 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 [9]. TanDEM-X will be the first configuration which demonstrates this highly innovative technique from space.

## VI. 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.

## REFERENCES

[1] M. Werner, “Shuttle Radar Topography Mission (SRTM): Mission Overview”, *Journ. Telecommunication (Frequenz)*, Vol. 55, No. 3-4, pp. 75-79, 2001.

[2] Moreira, A., et.al., “TanDEM-X: TerraSAR-X Add-on for Digital Elevation Measurements”, Mission Proposal, Doc. No. 2003-3472739, 2003.

[3] Fiedler, H., Krieger, G., Werner, M., Hajnsek, I., Moreira, A., “TanDEM-X: Mission Concept and Performance Analysis,” CEOS SAR CAL/VAL Workshop, Adelaide, Australien, 2005.

[4] H. Fiedler, G. Krieger, Close Formation of Passive Receiving Micro-satellites, 18th Int. Symp. Space Flight Dynamics, Germany, 2004

[5] Krieger, G., Moreira, A., Fiedler, H., Hajnsek, I., Eineder, M., Zink, M., Werner, M., “TanDEM-X: A Satellite Formation for High Resolution SAR Interferometry,” ESA Fringe Workshop, Frascati, Italy, 2005.

[6] M. Eineder, N. Adam, 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, 2005.

[7] K. P. Papathanassiou and S. R. Cloude, “Single-baseline polarimetric SAR interferometry,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 39, pp. 2352-2363, 2001.

[8] G. Krieger and A. Moreira, “Spaceborne Bi- and Multistatic SAR: Potential and Challenges,” *IEE Proceedings - Radar, Sonar and Navigation*, vol. 153, pp. 184-198, 2006.

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