# TanDEM-X: A Global Mapping Mission

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**Abstract.** TanDEM-X (TerraSAR-X Add-on for Digital Elevation Measurements) is a bistatic SAR interferometry mission which is currently implemented as a national Earth observation mission by the German Aerospace Center (DLR) and EADS Astrium GmbH. This paper provides an overview of the mission with main focus on the primary mission goal, the generation of a global digital elevation model (DEM), and the data acquisition concept for the interferometric radar data.

## 1. Introduction

The TanDEM-X system [1] is a synchronized SAR satellite formation consisting of the TerraSAR-X satellite (TSX) and another new TerraSAR-X like add-on satellite (TDX) which, in combination, allow single-pass SAR interferometry with variable across-track baselines of typically 250…500 m. 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 [2]. The center frequency of the instruments is 9.65 GHz with a selectable SAR chirp bandwidth of up to 300 MHz. The active phased array antenna, which has an overall aperture size of 4.8 m x 0.7 m, is fixed mounted to the spacecraft body and incorporates 12 panels with 32 dual-pol waveguide sub-arrays each. This enables agile beam pointing and flexible beam shaping.

Primary mission goal is the production of a global digital elevation model (DEM) with an accuracy which is currently available only on a local scale. Secondary mission goals are along-track interferometry (ATI) for measuring the velocity of moving objects with a high accuracy, digital beam-forming, bi-static experiments and local DEMs with increased accuracy for suitable terrain (local areas with high reflectivity, low noise, high correlation, suitable observation conditions).

The launch of TDX, which is designed for a nominal lifetime of 5½ years, is planned for October 2009. It will therefore have a nominal overlap of 3 years with TSX, which is already in space since June 2007. A prolongation of the mission overlap might be possible by means of an extension of TSX operation which is compatible with the TSX consumables and resources.

## 2. Acquisition Modes

Interferometric data acquisition with the TanDEM-X satellite formation can be achieved in different operational modes: Examples are bistatic, monostatic, and alternating bistatic operation, which are illustrated in Fig. 1. The three interferometric configurations may further be combined with different TSX and TDX SAR imaging modes like Stripmap, ScanSAR, Spotlight, and Sliding Spotlight.

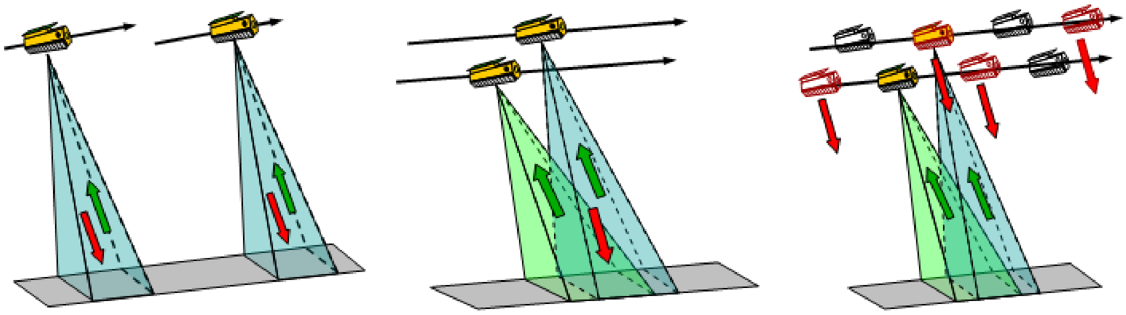

**Fig. 1: Main data acquisition modes for TanDEM-X: Pursuit monostatic mode (left), bistatic mode (middle), and alternating bistatic mode (right).**

Operational DEM generation is planned to be performed using the bistatic InSAR Stripmap mode shown in Fig. 1 in the center. This mode uses one satellite as a transmitter to illuminate a common radar footprint on the Earth's surface. The scattered signal is then recorded by both satellites simultaneously. This simultaneous data acquisition makes dual use of the available transmit power and is mandatory to avoid potential errors from temporal decorrelation and atmospheric disturbances.

## 3. Satellite Formation

The TanDEM-X operational scenario requires the coordinated operation of two satellites flying in close formation. The adjustment parameters for the formation are the orbits node line angle, the angle between the perigees, the orbit eccentricities and the phasing between the satellites. With these parameters, several options have been investigated during the phase A study, and the HELIX satellite formation shown in Fig. 2 has finally been selected for operational DEM generation.

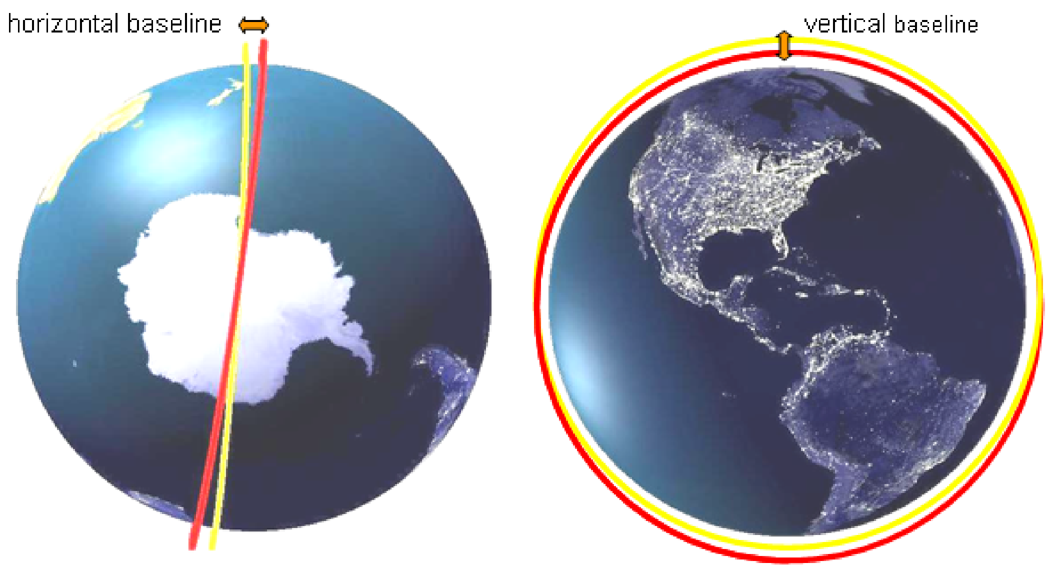


**Fig. 2: HELIX satellite formation for TanDEM-X with maximum of horizontal baseline at the equator (left) and maximum of vertical baseline near the poles (right)**

This formation combines an out-of-plane (horizontal) orbital displacement by different ascending nodes with a radial (vertical) separation by different eccentricity vectors resulting in a helix-like relative movement of the satellites along the orbit. Since there exists no crossing of the satellite orbits, arbitrary shifts of the satellites along their orbits are allowed. This enables a safe spacecraft operation without the necessity for autonomous control.

It is furthermore possible to optimize the along-track displacement at predefined latitudes for different applications: cross-track interferometry will aim at along-track baselines which are as short as possible to ensure an optimum overlap of the Doppler spectra and to avoid temporal decorrelation in vegetated areas, while other applications like along-track interferometry or super resolution require selectable along-track baselines in the range from hundred meters up to several kilometers.

The HELIX formation allows a complete mapping of the Earth with a small number of formation settings. Southern and northern latitudes can be mapped with the same formation setting by using ascending orbits for one and descending orbits for the other hemisphere. A fine tuning of the cross-track baselines can be achieved by taking advantage of the natural rotation of the eccentricity vectors due to secular disturbances, also called motion of libration. The phases of this libration can be kept in a fixed relative position by scheduling small manoeuvres using the cold gas thrusters on a daily basis, while major formation changes as well as a duplication of the orbit keeping manoeuvres required by TSX will be performed by the hot gas thrusters.

## 4. Acquisition Concept

As the TanDEM-X mission is based on the TerraSAR-X mission, it must be ensured that both missions will achieve their mission goals. Therefore all TerraSAR-X data takes will be distributed almost homogenously onto the two satellites. This will leave enough satellite resources free to fulfill the TanDEM-X mission goals.

For data acquisition a Joint TerraSAR-X & TanDEM-X Acquisition Concept has been developed which is capable of handling acquisition requests of both missions based on a simple priority concept as it is already established for the TerraSAR-X mission. According to this concept, the TanDEM-X data takes for global DEM generation are planned well in advance for a long time span (e.g. one year) and are set to high priority. Nonetheless a DEM acquisition can still be overruled by another high-priority acquisition, but it is ensured by the ground segment ordering chain that the skipped acquisition is shifted automatically to one of the following orbit repeat cycles, where it is scheduled with highest priority. The same re-ordering concept applies for the case of unexpected data loss.

The generation of a global acquisition plan follows a fundamental mapping strategy which ensures that the satellite formation is suitable for each individual acquisition. In this context ‘suitable’ means that in order to get a consistent HRTI-3 quality DEM, the height of ambiguity of the interferometric acquisition should be as homogeneous as possible for all datatakes. Therefore the satellite formation is not kept fixed but permanently and slowly drifting, with the two satellite’s horizontal separation at the ascending node (see Fig. 2) starting from a small value (~230m) and increasing over mission time. As a consequence, the height of ambiguity is changing slowly for a given beam and latitude. Acquisitions are now planned starting from geographical positions with lower latitudes and finally reaching polar regions.

Apart from the satellite formation settings, the final mapping pattern also accounts for a number of other constraints:

- **On-board mass memory.** Due to different storage capacity (384 GBit for TSX, 768 GBit for TDX) TSX data is dumped first as a general rule.
- **Data rate.** For local fine-tuning of the acquisition timeline the data rate of the radar system can be influenced by several radar parameters like pulse repetition frequency (PRF), transmit duty cycle or raw data compression factor (BAQ).
- **Ground station network and downlink capacity.** Apart from the nominal G/S network additional downlink opportunities are available for individual peak load orbits (e.g. Chetumal, Mexico).
- **Thermal constraints** are respected by limiting mean orbit usage to ~180s. Nonetheless, peak orbit usage may be considerably higher.
- **Ground coverage** of the available radar elevation beams. With increasing latitude a smaller number of swaths must be recorded, but additional acquisitions in left-looking geometry are required for a complete mapping of Antarctica.

- **Access time.** DEM acquisitions shall not block the same geographical position for many adjacent repeat cycles. This is eased by the restriction to ascending orbits only or descending orbits only for any geographical location.
- **Long datatakes.** The DEM Calibration concept favours long DEM acquisitions which can be assembled into continental DEMs with better quality. In peak orbits single DEM acquisitions exceed 300s, while the mean duration of DEM acquisitions is somewhere around 70s.

With a complete DEM acquisition timeline, the whole Earth can be recorded within somewhat less than one year. Because the complete mission time is three years, it is possible to map the Earth for a second time with different satellite formation settings. Mapping the Earth twice will facilitate phase unwrapping of the interferometric data sets and will make it possible to achieve the specified DEM accuracy.

Of course, there are some regions which lie in the radar shadow within the first two years, or are distorted by layover/foreshortening due to the imaging geometry of the side-looking radar system. These (mountainous) regions will be mapped again in a subsequent, separate mission phase. Also recording of the so-called crossing orbits, which are extra long data takes at an almost fixed equator spacing to allow for additional calibration of the final DEM, shall be done in this mission phase.

At the end of this mission phase, the satellites will be separated in along track, e.g. such that their respective ground tracks on the Earth's surface will be separated by one day. Then, repeat pass interferometry with one day time interval will be possible. During the process of along-track separation experiments with large bistatic angles might be performed.

## 5. Synchronization

The bistatic data acquisitions are based on the use of two independent oscillators for modulation and demodulation of the radar pulses. The impact of oscillator phase noise in bistatic SAR has been analyzed in [3] 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 or an operation in the alternating bistatic mode. For TanDEM-X, a dedicated inter-satellite X-band synchronization link will be established by a mutual exchange of radar pulses between the two satellites. For this, the nominal bistatic SAR data acquisition is shortly interrupted, and a radar pulse is redirected from the main SAR antenna to one of six dedicated synchronization antennas mounted on each spacecraft. The pulse is then recorded by the other satellite which in turn transmits a short synchronization pulse. By this, mutual phase referencing can be achieved without exact knowledge of the actual distance between the satellites. On ground, a correction signal can then be derived from the recorded synchronization pulses, which compensates the oscillator induced phase errors in the bistatic SAR signal.

In addition, synchronization is also required for data take commanding. TSX and TDX trigger the start of a data take via GPS, but the radar pulse timing is then derived internally from the Ultra Stable Oscillators (USO). A deviation of the two USO frequencies will hence lead to a drift of the receiving window of one satellite with respect to the transmit event of the other satellite and may by this prevent a proper recording of the echo signal. TanDEM-X accounts for this by introducing leap pulse repetition intervals (leap PRIs), which readjust the position of the receiving window.

## 6. DEM Calibration

A detailed height performance model was developed for the Bistatic Mode, the main mode for DEM generation [4,5]. It showed that very precise knowledge of interferometric baseline is required in order to achieve the terrain height accuracy that the mission is aiming at. Examples of systematic slow changing errors for baseline determination are inaccuracies in the relative orbit and attitude determination of the TanDEM-X HELIX formation and variations in the SAR antenna phase centre. On instrument side, slow errors occur due to remaining interpolation errors after internal calibration and phase drifts during synchronization pulse sequences in the amplifiers not compensated by the internal calibration. When a data take is acquired, these phase errors lead to a height error in the resulting raw DEM.

Absolute height calibration of the final DEM requires accurate height references. The references have to be adequately distributed. Coverage on all significant isolated land masses and a known accuracy which fulfils the requirements are pursued, with the aim of guaranteeing the correct adjustment of the elevation models by the TanDEM-X Mosaicing and Calibration Processor (MCP). Several suitable sources of height reference data have been identified, including global data sets (e.g. ICESat radar altimeter data), GPS tracks, ground targets (corner reflectors, transponders) and local highly accurate DEMs from airborne LIDAR, photogrammetry and SAR.

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