TanDEM-X Mission and DEM Accuracy

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***Abstract*—TanDEM-X (TerraSAR-X Add-on for Digital Elevation Measurements) is currently implemented as a national Earth observation mission by the German Aerospace (DLR) and EADS Astrium GmbH. This first bistatic satellite synthetic aperture radar (SAR) mission opens a new era in spaceborne radar remote sensing. The tandem configuration is formed by flying TanDEM-X and TerraSAR-X in a closely controlled helix formation. The primary mission goal is the derivation of a high-precision global Digital Elevation Model (DEM) with 12 m resolution, 10 m absolute height accuracy and 2 m relative height accuracy. This paper provides an overview of the mission with main focus on the data acquisition concept for the interferometric radar data and the derivation of the specified accurate global DEM.**

***Index Terms*—Digital elevation model, InSAR, satellite remote sensing, synthetic aperture radar, TanDEM-X.**

I. Introduction and Objectives

THE TanDEM-X system [1] is a synchronized SAR satellite formation consisting of the TerraSAR-X satellite (TSX) and its twin satellite TanDEM-X (TDX). Their combined operation allows single-pass SAR interferometry (InSAR) with variable cross-track baselines typically between 250 and 500 m. The instruments on both satellites are advanced high resolution X-band SAR systems 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 × 0.7 m, is mounted on one side of the hexagonal spacecraft body. It consists of 12 panels with 32 dual-polarization waveguide sub-arrays each. This enables extremely flexible beam steering and shaping options.

The primary mission goal is the derivation of a global DEM of the Earth surface within four years after launch. The aimed DEM resolution is 12 m (independent posting), and the DEM height requirements are 10 m absolute and 2 m relative accuracy in regions with 100 km × 100 km size [1]. This has been only achieved up to now by local scale DEM products.

To achieve these goals, around 3 years of combined satellite operations are required. TSX has been in orbit since June 2007, and the launch of TDX is planned for the first half of 2010. Considering the current TSX satellite resources status, it is expected that the satellite exceeds its nominal lifetime of 5½ years, so that the 3 years overlap with TDX are maintained. In addition, to achieve the demanding relative height accuracies, DEM systematic errors have to be corrected. Therefore, a robust DEM calibration concept has been implemented [3].

Secondary mission goals are the experimentation of several SAR techniques, like 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 selected terrain (local areas with high reflectivity, low noise, high correlation, suitable observation conditions).

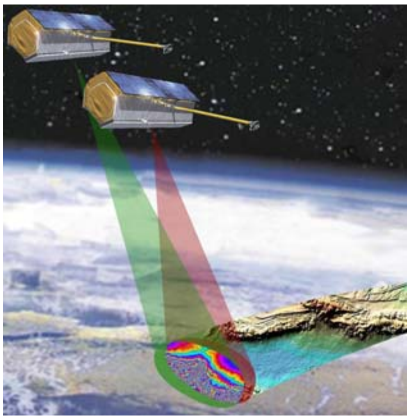

Fig. 1. Illustration of the TanDEM-X constellation. One of the satellites transmits the radar pulses, while the reflected signal from the Earth surface is received by both SAR antennas. On ground, an InSAR-derived DEM is generated.

II. Mission Description

A. 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. 2. The three interferometric configurations may further be combined with different TSX and TDX SAR imaging modes like Stripmap, ScanSAR, Spotlight, and Sliding Spotlight.

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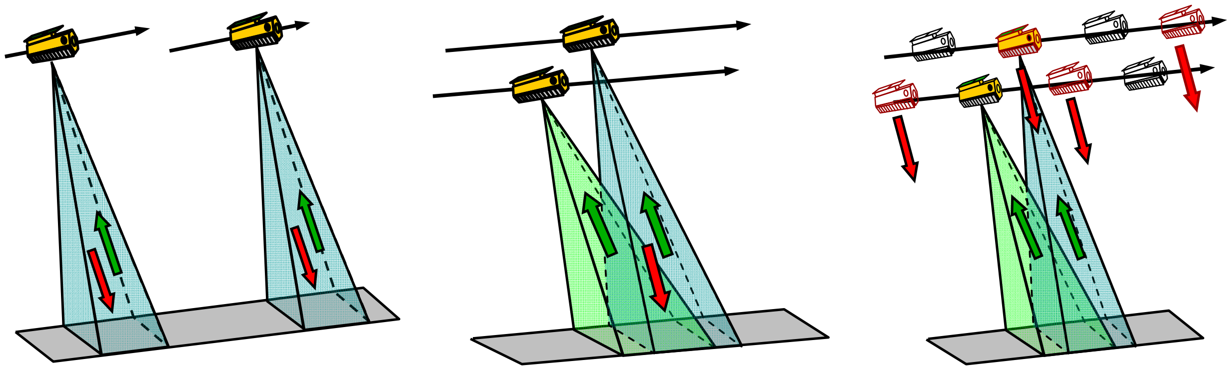

Fig. 2. Data acquisition modes for TanDEM-X: Pursuit monostatic mode (left), bistatic mode (middle), and alternating bistatic mode (right).

Operational DEM generation is planned to be performed using the bistatic InSAR Stripmap mode shown in the center of Fig. 2. 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.

B. *Satellite Formation*

The TanDEM-X operational scenario requires the coordinated operation of two satellites flying in close formation. A so-called "helix" satellite formation, shown in Fig. 3, has been chosen for the operational DEM generation.

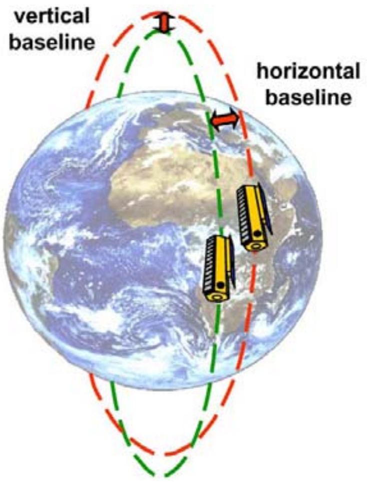

Fig. 3. Orbit planes of the TanDEM-X constellation. Horizontal separation in the equator; vertical separation in the poles. This results in a relative helix movement between the satellites with one orbit periodicity.

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.

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 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 will be performed by the hot gas thrusters. This flexibility in the baseline configuration permits the implementation of an robust acquisition strategy against phase unwrapping errors, as will be explained in the following Section II.C.

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

C. *DEM Acquisition Plan*

The TanDEM-X mission should not interfere in the fulfillment of the TerraSAR-X mission. To minimize conflicts, TerraSAR-X datatakes will be distributed on both satellites. This leaves sufficient satellite resources for the DEM acquisition. For coordinating the 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, already established for the TerraSAR-X mission. According to this concept, the TanDEM-X datatakes 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.

In order to achieve the required global DEM accuracy, the height of ambiguity of the interferometric acquisition should be as homogeneous as possible for all datatakes. Therefore the satellite formation is not kept fix, but permanently and slowly drifting. For example, the horizontal baseline at the ascending node (see Fig. 3) will drift from a starting value of ~230 m to higher values (~400 m) over mission time. As a consequence, the height of ambiguity is changing slowly for a given beam and latitude. Acquisitions are planned starting from geographical positions with lower latitudes and finally reaching polar regions. The whole Earth land surface can be recorded in less than a year.

According to this, in the first year of TanDEM-X mission the full Northern Hemisphere will be acquired during ascending orbits and the Southern Hemisphere during descending orbits, resulting in a complete mosaic of parallel adjacent datatakes. Relatively small effective baselines will be used, resulting in a large height of ambiguity of around 45 m. The consequences of a large height of ambiguity are a simplification of the phase unwrapping procedure of the interferograms and a low height accuracy (compared to requirements). Hence, a full coverage Earth DEM with a reduced accuracy could be derived already after the first year of TanDEM-X operation.

In the second year, it is foreseen to repeat the same first year acquisitions with a scaled helix formation. This will mean larger effective baselines and smaller heights of ambiguity (around 30 m). Such configuration has two advantages with respect to the first year: a better height resolution and a high robustness against phase unwrapping errors. The latter is achieved by combining the two overlapping acquisitions with different heights of ambiguity employing multi-baseline phase unwrapping methods (resulting height of ambiguity lies around 90 m).

In the third year, the acquisition will focus on difficult terrain. This comprises e.g. mountainous regions, which will be acquired with a third effective baseline and/or from crossing orbits. Along the equator, the acquisition of long crossing orbits at equally spaced intervals can aid in the DEM calibration. Additionally, datatakes from the first two years specially affected by shadowing, layover or foreshortening effects will be acquired again from different incidence angles.

All this should be accomplished in the first half of the third year. In the second half, the satellites will be separated in along track to perform ATI scientific experiments like traffic, ocean current or glacier monitoring. The process of along-track separation is suited for experiments that require large bistatic angles.

D. Global DEM Processing Chain

The DEM processing chain (see Fig. 4) is a key part of the TanDEM-X ground segment. Focusing on the upgrades with respect to the TerraSAR-X mission, the processing chain combines the two SAR images (one monostatic and the other bistatic) recorded by the satellites and generates the interferogram. It has to be noted that either TSX or TDX can act as active satellite in a DEM acquisition. The instrument calibration is responsible of correcting the instrument drifts at this early phase, as well as known phase trends originated, e.g. by the SAR antenna phase center or by its phase diagram. The phase errors originated by the relative frequency drifts between the two instrument oscillators are also corrected at this stage by evaluating the synchronization information recorded within the radar data (see also Section III.C).

The raw DEM can then be derived. However, and according to the acquisition strategy introduced in Section II.C, the TanDEM-X processor will wait until the end of the second year acquisitions to operationally generate the raw DEMs, in order to minimize phase unwrapping and typical side-looking geometry errors.

Once a whole stack of raw DEMs is available for a large region (e.g. a fraction of a continent) in the database, the DEM Mosaicking and Calibration Processor (MCP) [4] takes care of correcting the residual systematic height error contributions, aided by a precise height references database, and generate the accurate TanDEM-X global DEM (see [3]).

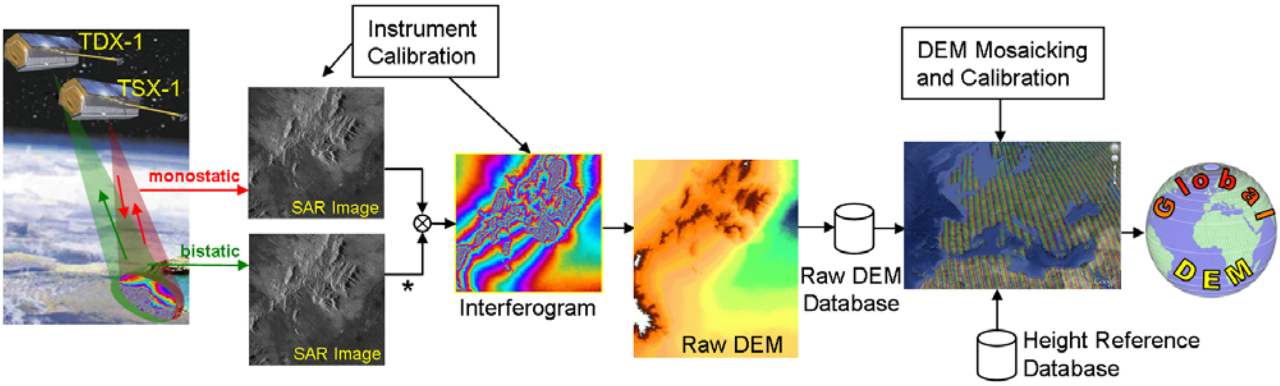

Fig. 4. TanDEM-X DEM processing chain.

III. CHALLENGES CONSTELLATION

A. *Collision Avoidance*

The absolute distance between the satellites in orbit oscillates between around 500 m to several kilometers, and their altitude over the Earth surface is around the 520 km. This gives an idea about the precision required to control the relative position between the satellites and to avoid any collision risk.

The helix formation described in Section II.B has a passive stability, as both orbit trajectories never cross. Nevertheless, several measures have been implemented to avoid uncontrolled thruster activities and constantly monitor the status of the satellites.

On the one hand, the ground operations and stations network have been adapted to ensure S-band telemetry contacts with a maximum separation of 6 hours. This allows the early detection of a potential event or anomaly in any of the satellites, and provides a sufficient reaction margin.

On the other hand, the Automatic Safe Mode (ASM) of the two satellites has been optimized. In the original design, in case of an event or anomaly in the satellite, the instruments entered in the so-called “safe mode”, in which most of the satellites electronics are cautiously shut down. In order to allow the maintenance of the orbit during an ASM, the thrusters started automatically regulating the satellite position. A potential error in the thrusters’ activity could not be detected on ground on time, which could cause a collision in the worst case. In order to avoid this, the thruster activity during safe mode has been now disabled, allowing only a slow magnet torquer attitude regulation of the satellites.

B. *Exclusion Zones*

Another challenge of the close flying formation of the TanDEM-X constellation is the risk of mutual SAR illumination. During certain orbit periods, one of the satellites might be located in the area illuminated by the SAR antenna main lobe of the other satellite (see Fig. 5), risking potential damage of electronic units on the irradiated satellite. Therefore, exclusion zones have to be defined along the orbit for each satellite, in which the transmission by the SAR antenna is disabled. Due to the helix formation, the exclusion zones are almost periodic with the orbit, and both satellites can never be simultaneously in an exclusion zone. Thus, TanDEM-X mission datatakes are never affected by them.

The exclusion zones are checked twice on ground before commanding the datatakes, and a third time on the satellite just before each acquisition starts. Additionally, two other techniques are used to allow the satellites to monitor the status of its neighbour and verify its nominal operation without needing the intervention of the ground. In case the opposite satellite does not respond or indicates an anomaly, its position is considered unknown, thus the requesting satellite automatically switches off its transmit capabilities to prevent radiation.

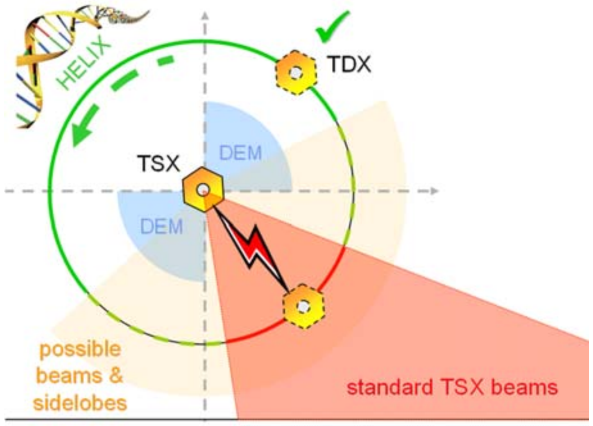

Fig. 5. View of the relative satellite movement (flight direction into the paper) and definition of an exclusion zone to avoid SAR illumination.

One of these methods is the inter-satellite link, through which house-keeping (HK) data are exchanged. The other procedure is the exchange of “sync warning” pulses through the synchronization link. This bi-directional check is possible after a software update on the satellites which allows for interpreting the sync pulses and setting an expected receive power threshold on board. If the received pulse is below the threshold or no pulse can be detected, it means that the neighbouring satellite is not in its nominal position, and could have traveled, in a worst case, towards the region of maximum SAR antenna radiation of the other satellite. The “sync warning” procedure quickly switches off transmission, and sets the satellite in standby. The problem is then analyzed and solved on ground, the current satellite positions are tracked again and commands are uploaded to resume nominal operations.

C. *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 [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 or an operation in the alternating bistatic mode.

In TanDEM-X, a dedicated inter-satellite X-band synchronization link has been established, through which special radar pulses are mutually exchanged (see Fig. 6). 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 horn 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.

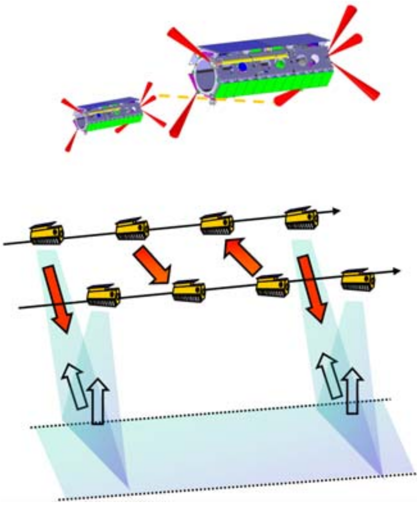

Fig. 6. On the top, sync horns (in red) ensure the constant communication in all directions regardless of the formation relative position.
On the bottom, the synchronization pulses sequence is shown.

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

IV. DEM CALIBRATION

A detailed height performance model was developed for the bistatic mode, the main mode for DEM generation [1]. It showed that very precise knowledge of interferometric baseline is required in order to achieve the specified height accuracy. Even so, residual baseline errors are present. In addition, and regardless of all the efforts along the DEM processing chain to eliminate height error sources, instrument error components will also remain [3].

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 datatake is acquired, these phase errors lead to a height error in the resulting raw DEM.

The DEM calibration strategy concentrates on eliminating the systematic components of these baseline and instrument residual errors, which is sufficient to accomplish the height error requirements. With the aim of guaranteeing the correct adjustment of the final DEM by the TanDEM-X MCP, height references are required.

On the one hand, they provide absolute height calibration. The references have to be adequately distributed, with coverage on all significant isolated land masses and a known accuracy that fulfils the requirements [3]. Several suitable sources of height reference data have been identified, including global data sets (e.g. ICESat laser altimetry data), GPS tracks, ground targets (corner reflectors, transponders) and local highly accurate DEMs from airborne LIDAR, photogrammetry and SAR [6].

On the other hand, the height references are used for the relative adjustment of the raw DEMs, aided by tie-points [3]. Tie-points are spots of a DEM with a high coherence and radar cross section, located in overlapping regions between adjacent datatakes.

A functional model based on the expected error behaviour has been developed to correct the systematic height error components. This model is a simple 2D polynomial function with up to 6 coefficients. The complete system of 2D polynomial functions in a full datatake scene is solved by a least-squares method, and the coefficients are determined by applying all high quality height references and tie-points available over the region.

This DEM calibration strategy ensures the generation of an accurate TanDEM-X global DEM.

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