TanDEM-X: Mission Overview and Status

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Abstract: TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurements) is an innovative formation flying radar mission that opens a new era in spaceborne radar remote sensing. Primary objective is the acquisition of a global DEM with unprecedented accuracy (12 m horizontal and 2 m vertical resolution). The mission was launched in June 2010 and started operational data acquisition in December 2010. This paper provides an overview of TanDEM-X and summarizes the actual mission status.

1 Introduction

The primary objective of the TanDEM-X mission is the generation of a world-wide, consistent, timely, and high precision digital elevation model (DEM) aligned with the HRTI-3 specification as the basis for a wide range of scientific research, as well as for commercial DEM production ([1], cf. Figure 1). This goal is achieved by enhancing the TerraSAR-X mission [2] by a second radar satellite flying in close formation with TerraSAR-X [3]. Both satellites 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 has been implemented in the framework of a public-private partnership between the German Aerospace Center (DLR) and EADS Astrium GmbH, as for TerraSAR-X. TanDEM-X was successfully launched on June 21, 2010.

Requirement	Specification	TanDEM-X DEM
Relative Vertical Accuracy	90% linear point-to-point error in 1° cell	2 m (slope < 20%) 4 m (slope > 20%)
Abs. Vertical Accuracy	90% linear error	10 m
Spatial Resolution	independent pixels	12 m (0.4 arc sec)

Figure 1: Primary objective of TanDEM-X is the acquisition of a global DEM with unprecedented accuracy.

2 Mission Concept

The TanDEM-X mission is an extension of the TerraSAR-X mission, co-flying a second satellite of nearly identical capability in a close formation. The TerraSAR-X satellite (TSX), as basis for TanDEM-X, was successfully launched into a sun-synchronous dusk-dawn orbit with 97.44° inclination on June 15, 2007. The nominal orbit height is 514.8 km and the orbit repeat cycle is 11 days. TSX is not only a high performance SAR system with respect to SAR image and operational features, but it has already built in all necessary features required for the implementation of the TanDEM-X mission. Examples are additional X-band horn antennas for inter-satellite phase synchronization, the availability of a dual-frequency GPS receiver for precise orbit determination, excellent RF phase stability of the SAR instrument, and PRF synchronization based on GPS as a common time reference. 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 and an additional S-band receiver to enable the reception of status and GPS position information broadcast by TSX. This guaranteed a low development risk and offers the possibility for a flexible share of operational functions among the two satellites.

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 [4]. 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 as required for the acquisition of a wide range of image products with varying resolutions and scene sizes.

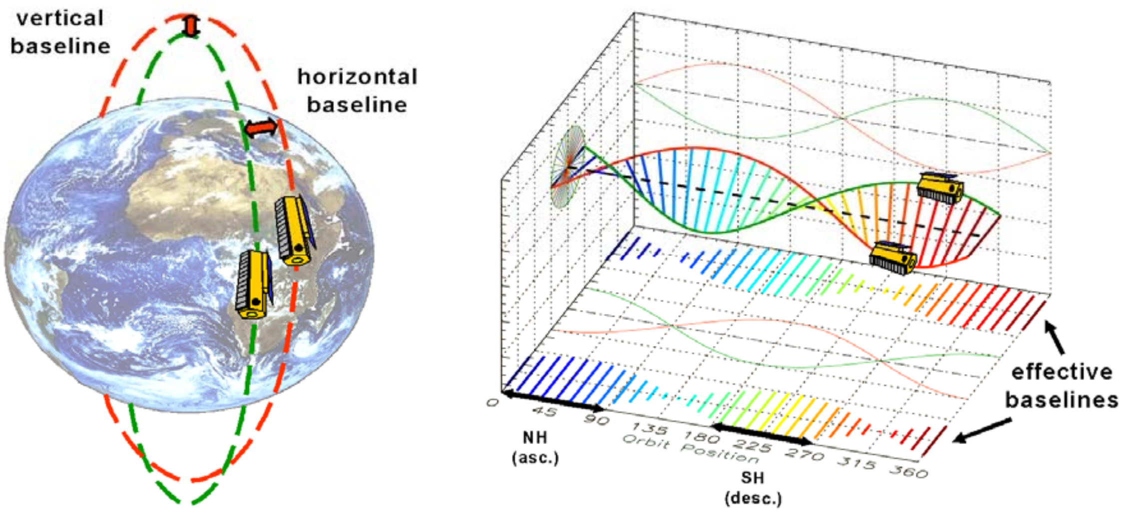

Figure 2: Helix satellite formation for TanDEM-X. Left: illustration of orbits. Right: cross-track and radial baselines as a function of the argument of latitude. The latitude positions correspond to one complete orbit.

2.1 Orbit Configuration and Formation Flying

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 Figure 2 has finally been selected for operational DEM generation. 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 aims 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. A fine tuning of the satellite formation is performed via the aforementioned cold gas propulsion system on TDX.

The Helix formation enables a complete mapping of the Earth with a stable height of ambiguity by using a small number of formation settings [3]. Southern and northern latitudes can be mapped with the same formation by using ascending orbits for one and descending orbits for the other hemisphere, as illustrated in Figure 2 on the right. 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 phases 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 will be performed by the hot gas thruster system.

2.2 Interferometric 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 Figure 3. The three interferometric configurations may further be combined with different TSX and TDX SAR imaging modes like Stripmap, ScanSAR, Spotlight, and Sliding Spotlight. Operational DEM generation is planned to be performed using the bistatic InSAR Stripmap mode shown in Figure 1 in the middle. This mode uses either TSX or TDX 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 possible errors from temporal decorrelation and atmospheric disturbances.

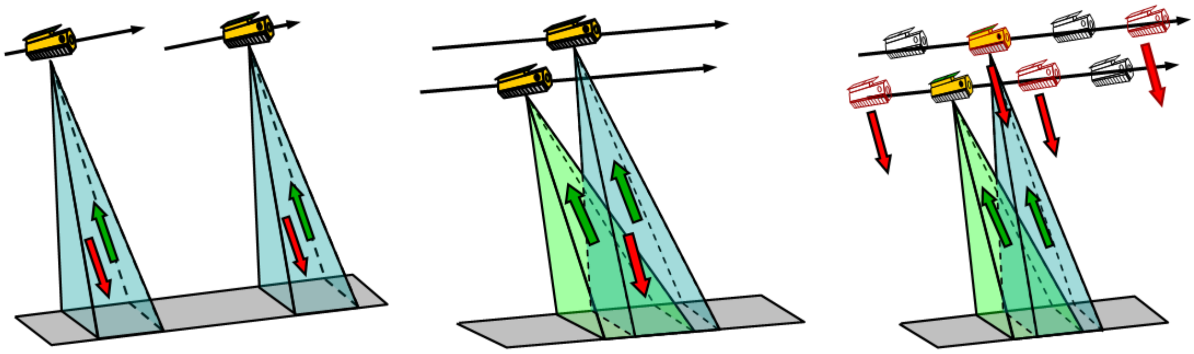

Figure 3: Data acquisition modes for TanDEM-X: Pursuit monostatic mode (left), bistatic mode (middle), and alternating bistatic mode (right).

2.3 Exclusion Zones

For DEM generation, TanDEM-X combines one monostatic and one bistatic radar image in a joint SAR interferogram. To ensure a sufficient overlap of the Doppler spectra, this requires a short along-track distance of typically less than 1 km between the two satellites, while the radial and cross-track baselines depend on the argument of latitude and vary between zero and a few hundred meters. 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 avoid this risk, the transmission of radar signals has to be suppressed for one satellite at specific arguments of latitude, which are known as exclusion zones (cf. Figure 4). TanDEM-X ensures exclusion zone compliance by a double fail save approach including both a check on ground before command uploading and an additional real-time check on the satellite which suppresses signal transmission within predefined latitude windows.

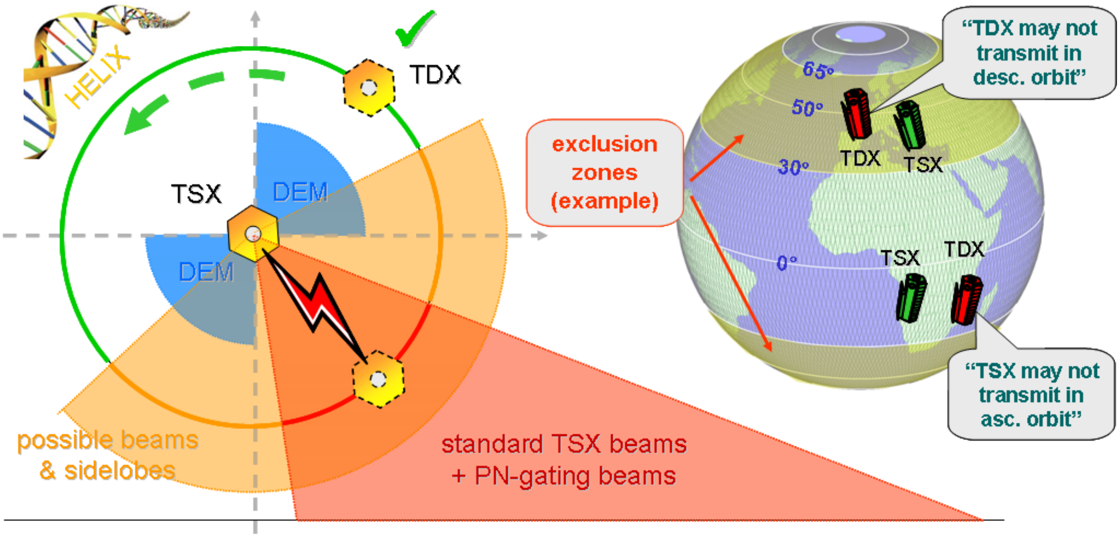

Figure 4: TanDEM-X exclusion zones.

2.4 System Synchronization

A peculiarity of the bistatic data acquisition is the use of independent oscillators for modulation and demodulation of the radar pulses. Any deviation between the two oscillators will hence cause a residual modulation of the recorded azimuth signal. 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. For TanDEM-X, a dedicated inter-satellite X-band synchronization link has been established via 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 horn antennas mounted on each spacecraft. The pulse is then recorded by the other satellite which in turn transmits a short synchronization pulse (cf. Figure 5, left). By this, a bidirectional link between the two radar instruments is established, which allows for mutual phase referencing without exact knowledge of the actual distance between the satellites. On ground, a correction signal can then be derived from the recorded synchronization pulses. This compensates the oscillator induced phase errors in the bistatic SAR signal. The performance of such a synchronization link has been investigated in [6]. The right hand side of Figure 5 shows the predicted standard deviation of the residual phase errors after synchronization as a function of the update frequency of the synchronization signals for different signal-to-noise ratios (SNR) of the bidirectional link. The actual SNR varies with the distance between the satellites as well as their relative attitude. For the typical DEM data acquisition mode with baselines below 1 km, the SNR will be in the order of 30 to 40 dB, and it becomes clear that a phase error below 1° can be achieved for synchronization frequencies above 5 Hz.

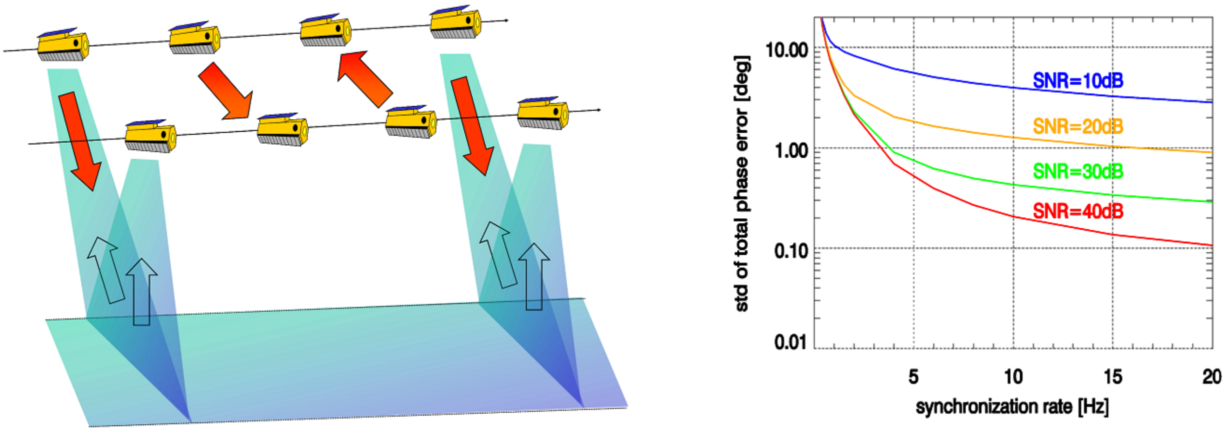

Figure 5: Synchronization of TanDEM-X satellites by exchange or radar pulses (left) and predicted performance (right). The performance is shown in terms of the standard deviation of the total synchronization link phase error as a function of the synchronization frequency with signal-to-noise ratio as a parameter.

The performance of the synchronization link has been validated during the bistatic TanDEM-X commissioning phase [7]. Note that the correct application of the sync-link signal during bistatic SAR processing has to take into account relativistic effects since bistatic SAR processing and bistatic radar synchronization are performed in different reference frames moving relative to each other. This introduces a notable non-simultaneity between transmit and receive events which depends on the along-track distance between the two satellites [8]. The effect can be approximated based on Einstein's special relativity by comparing the corresponding spacetime intervals

$$s^2 = \left(c \cdot t_m\right)^2 - \left|\vec{B}_{Tx-Rx}\right|^2 = \left(c \cdot \frac{r_{bi}}{c}\right)^2 - \left|\vec{B}_{Tx-Rx} + \vec{v}_{Rx}\frac{r_{bi}}{c}\right|^2 \quad \longrightarrow \quad r_{bi} \approx \vec{B}_{Tx-Rx}\frac{\vec{v}_{Rx}}{c} + c \cdot t_m \tag{1}$$

where s denotes the spacetime interval, c the velocity of light, t_m the radar pulse travelling time measured in the satellite reference frame, $\vec{B}_{Tx-Rx}$ the baseline vector connecting the master and slave satellites (length contraction can be neglected), r_{bi} the bistatic range, and $\vec{v}_{Rx}$ the velocity of the receiving satellite. This approximation neglects the effect of Earth rotation which introduces an accelerated reference frame and requires a more rigorous treatment using, e.g., tensorial calculus of general relativity.

2.5 Interferometric Performance and Global Data Acquisition Plan

Radar interferometry is based on the evaluation of the phase difference between two coherent radar signals acquired from slightly different spatial and/or temporal positions. By this, TanDEM-X is able to measure the range difference between the two satellites and a given scatterer with millimetric accuracy. The height of the scatterer is inferred from this range difference by geometric triangulation. The sensitivity of the phase-to-height scaling depends on the distance between the two satellites, where a larger baseline increases the sensitivity of the radar interferometer to small height variations. However, the conversion from phase to range and hence the conversion of phase differences to height is not unique, since the range difference measurement via phases is ambiguous with the wavelength. Radar interferometry expresses this ambiguity by the so called height of ambiguity

$$h_{amb} = \frac{\lambda r_0 \sin\left(\theta_i\right)}{B_\perp} \tag{2}$$

where λ is the wavelength, r_0 the slant range from the satellites to the scatterer under consideration, θ_i the local incident angle of the scattered electromagnetic wave, and $B_\perp$ is the perpendicular baseline. The scalar $B_\perp$ is obtained by projecting the vector connecting both satellites onto a plane normal to the satellite orbit and then again onto a plane perpendicular to the line of sight.

Figure 6 shows the predicted height accuracy as a function of ground range position and the height of ambiguity (cf. [3] for details). It becomes clear that a lower height of ambiguity (i.e. larger baseline $B_\perp$) improves the height accuracy. However, a lower height of ambiguity also increases the difficulties in selecting the correct ambiguity interval during DEM generation (phase unwrapping). To minimize such problems and to ensure a homogeneous performance, TanDEM-X combines acquisitions with different heights of ambiguity. This requires in turn frequent adjustments of the Helix formation parameters which are selected according to an optimized global data acquisition plan [3]. Important constraints in this challenging optimization procedure are besides the interferometric performance the available amount of fuel and thruster cycles, limitations in the onboard storage and downlink capacity in combination with the finite time for global DEM acquisition, as well as power and thermal constraints. Further challenges arise from the interleaved usage of both satellites to continue the TerraSAR-X mission.

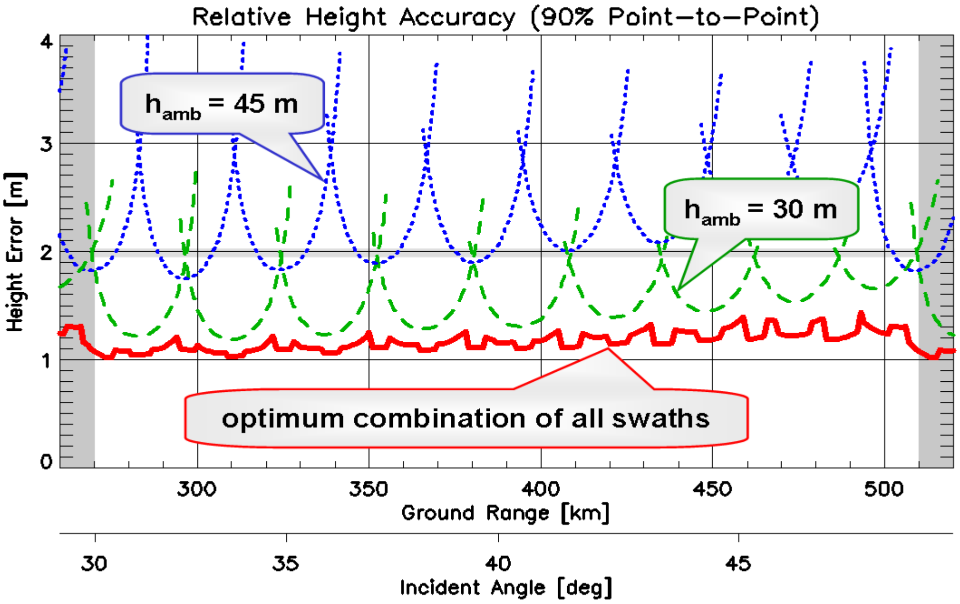

Figure 6: Predicted height accuracy for a height of ambiguity of 45 m (dotted) and 30 m (dashed). The lower solid curve shows the error resulting from the combination of multiple swaths. All errors are point-to-point height errors for a 90% confidence interval. First results from the TanDEM-X commissioning phase show a good agreement with the performance model (cf. [7]).

2.6 Baseline Estimation and DEM Calibration

Up to now, we have neglected errors due to the finite accuracy of relative baseline estimation. Such errors will mainly cause a low frequency modulation of the DEM, thereby contributing simultaneously to relative and absolute height errors. Most critical for TanDEM-X are baseline errors in the line of sight ($\Delta B_{//}$) which cause a rotation of the reconstructed DEM about the (master) satellite position. As a result, the DEM will be vertically displaced by

$$\Delta h = r \cdot \sin(\theta_i) \cdot \frac{\Delta B_{\parallel}}{B_{\perp}} = \frac{h_{amb}}{\lambda} \cdot \Delta B_{\parallel} \qquad (3)$$

where r and θ_i are the slant range distance and the incident angle of an appropriately selected reference point (e.g. at mid swath). This vertical displacement will be Δh = ±1.1

m for $\Delta B_{//} = \pm 1$ mm and $h_{amb} = 35$ m. A parallel baseline error will furthermore cause a tilt of the DEM which is given by

$$\varphi_{tilt} = \frac{\Delta h}{\Delta s} = \frac{\Delta B_{\parallel}}{B_{\perp}} \tag{4}$$

where Δs is the ground range distance from the selected reference point. The resulting tilt will be 3.8 mm/km and 2.3 mm/km for incident angles of $\theta_i = 30°$ and $\theta_i = 45°$, respectively ($\Delta B_{//} = 1$ mm and $h_{amb} = 35$ m).

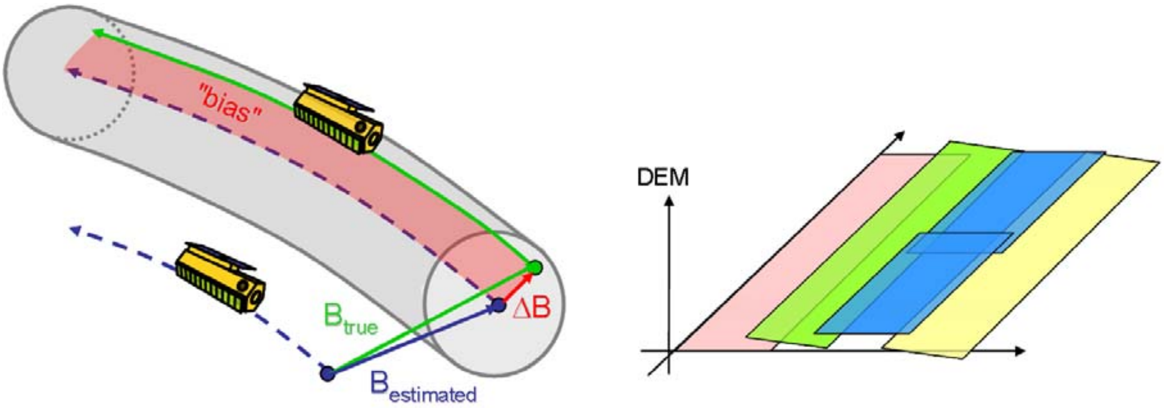

Figure 7: Illustration of the impact of baseline estimation errors. Left: unknown baseline offset during each data take. The baseline measurement accuracy of 1- 2 mm is indicated by the grey tube. Right: Vertical displacement and tilt of adjacent swaths as a result of different baseline offsets during the data takes.

Precise baseline determination is performed by a double differential evaluation of GPS carrier phase measurements. Experience from the GRACE mission and first results from the TanDEM-X mission indicate that the relative satellite positions can be estimated with accuracies in the order of 1-2 mm [9]. Additional systematic error sources include uncompensated offsets from the SAR antenna phase centers, uncompensated internal delays in the SAR instruments, the use of different synchronization horn antennas for different orbit positions, 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 (see also Section 2.5). The calibration of these offsets will be performed by evaluating the statistics over large data sets distributed all over the world, supported by systematic comparisons of the different interferograms obtained in the alternating bistatic mode. First results obtained from repeated acquisitions over the same test site indicate height offsets that vary within ± 10% of the height of ambiguity. This corresponds to interferometric baseline errors of ± 3 mm. While this accuracy is sufficient to start global DEM production, it is, however, expected that all systematic variations will still be reduced by the ongoing bistatic calibration process. The final calibration of the global DEM is based on a bundle block adjustment using all overlapping TanDEM-X DEM data takes in combination with an appropriately selected subset of height references which are primarily obtained from the ICESat mission [10].

3 Status Summary

TanDEM-X was successfully launched on June 21, 2010. The initial separation between TDX and TSX was 15700 km and after one month of drifting a formation with an along-track distance of 20 km was reached [11]. This formation was maintained for 3 months to calibrate the TanDEM-X radar instruments and to perform first bistatic and interferometric experiments employing large baselines. On October 14 both satellites were maneuvered into a close formation to start the bistatic commissioning phase. During this phase, the radial and cross-track baselines were kept constant at 360 and 400 m, respectively, and the mean along-track distance was set to 0 m. Results from both the mono- and the bistatic commissioning phase already demonstrate the unique interferometric performance of TanDEM-X [7]. Operational DEM acquisition was started on December 12, 2010, less than 6 months after satellite launch. Since then, about 50% of the total landmass of the Earth has been mapped with height of ambiguities ranging from 40 to 60 m. DEM data acquisition with varying baselines will continue until 2013, mapping difficult terrain like mountains, valleys, tall vegetation, etc., with at least two heights of ambiguity as well as from multiple incidence/aspect angles. The latter will be achieved by swapping the Helix formation. This allows for a shift of the DEM acquisition quadrants from ascending to descending orbits in the northern hemisphere and vice versa in the southern hemisphere. The fully mosaicked global DEM will become available in 2014. Figure 7 shows as an example the first bistatic DEM that has been acquired at the beginning of the bistatic commissioning phase in October 2010.

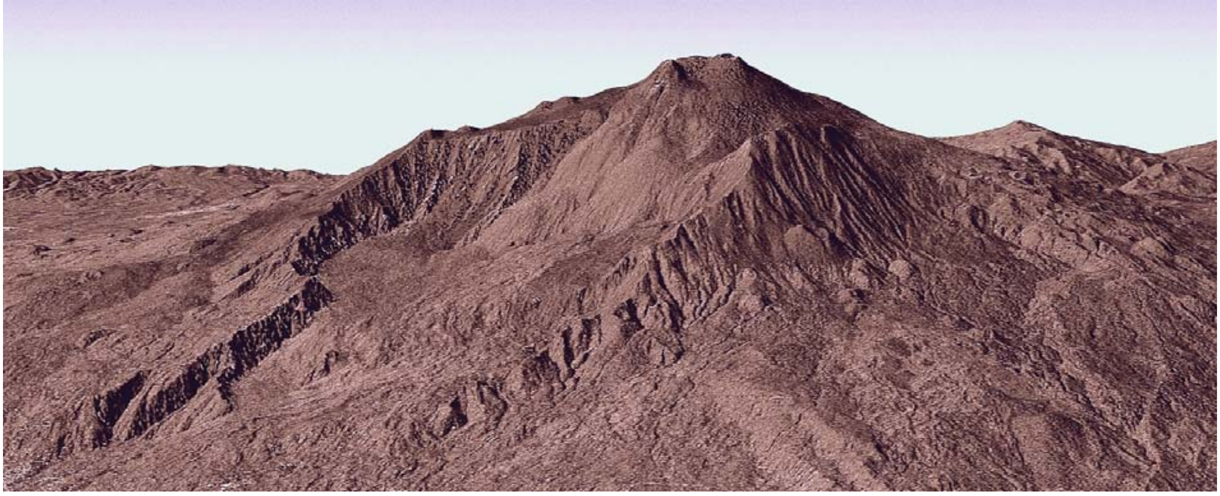

Figure 8: The “first” bistatic DEM acquired by TanDEM-X shows the Italian volcano Mount Etna, on the east coast of Sicily. This image was acquired while the satellites were orbiting at a distance of 350 meters from one another.

Current work includes the final calibration of the operational DEM processing chain, the test of the mosaicking and calibration processor, the optimization of the DEM acquisition plan for the second and third mission year, the conduction of interferometric radar experiments from the science service segment, as well as continuous performance monitoring and verification.

4 Conclusions

The TanDEM-X mission opens a new era in spaceborne radar remote sensing. A large single-pass SAR interferometer with adjustable baselines has been formed by adding a second, almost identical satellite to TerraSAR-X and flying both satellites in a closely controlled formation. This enables not only the acquisition of a global DEM with unprecedented accuracy, but also the demonstration of a broad spectrum of highly innovative bistatic and multistatic SAR techniques for future applications [12].

Acknowledgment

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