TanDEM-X: A Satellite Formation for High-Resolution Radar Interferometry

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Abstract

TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurements) is an innovative spaceborne radar interferometer mission that was approved for full implementation by the German Space Agency in spring 2006. This paper gives an overview of the TanDEM-X mission concept, summarizes the basic products, illustrates the achievable performance, and provides some examples for new imaging modes and applications. Two special aspects are pointed out which are the relative phase referencing and the mutual interference issue.

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 aligned with the HRTI-3 specification. This is the basis for a wide range of scientific research, as well as for operational, commercial DEM production [1]. 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 will be implemented in the framework of a public-private partnership between the German Aerospace Center (DLR) and EADS Astrium GmbH, as for TerraSAR-X. The launch of TanDEM-X is planned for spring 2009.

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, 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) will be 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 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 among the two satellites. The TDX satellite will be designed for a nominal lifetime of 5½ years and has a nominal overlap with TSX of 3 years. Note in this context that 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.

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

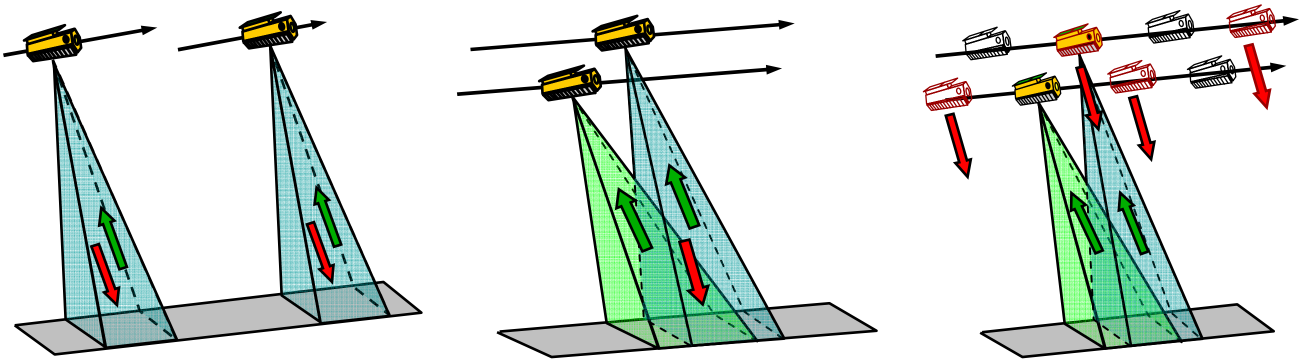

Figure 1: Data acquisition modes for TanDEM-X: Pursuit monostatic mode (left), bistatic mode (middle), and alternating bistatic mode (right).

incorporates 12 panels with 32 dual-pol waveguide sub-arrays each. This enables agile beam pointing and flexible beam shaping.

2.1 Interferometric Data Acquisition

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 1. 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.

2.2 Relative Phase Referencing

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 [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 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, a bidirectional link between the two radar instruments will be 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 which compensates the oscillator induced phase errors in the bistatic SAR signal. The performance of such a synchronization link has been investigated in [4].

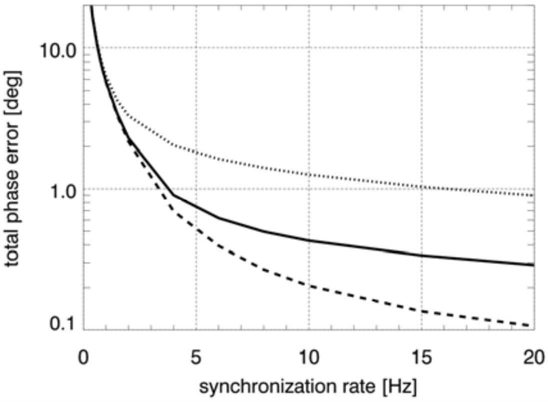

Figure 2: Standard deviation of the total synchronization link phase error as a function of the synchronization frequency. The three curves are for signal-to-noise ratios of 20 dB (dotted), 30 dB (solid), and 40 dB (dashed).

Figure 2 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 of 5 Hz.

2.3 Orbit Configuration and Formation Flying

The TanDEM-X operational scenario requires a 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 3 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, one may now allow for arbitrary shifts of the satellites along their orbits. 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.

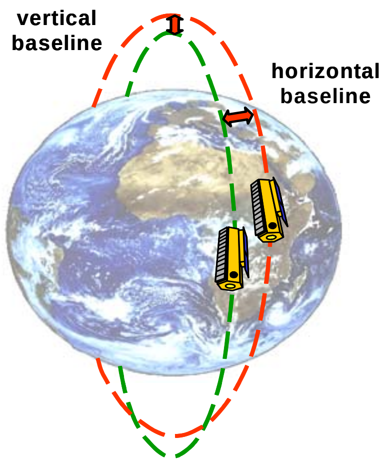

Figure 3: HELIX satellite formation for TanDEM-X showing the orbital arrangement.

The HELIX formation enables a complete coverage of the Earth with a stable height of ambiguity by using a small number of formation settings [5]. 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 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 thrusters.

2.3 Interference between the Two Satellites

An aspect that is new to spaceborne SAR systems is the mutual interference issue between the two satellites. Due to the close formation flying this aspect requires special consideration. Here we address the matter of the SAR antenna of one satellite illuminating the other. The approach is to define an exclusion zone for SAR operation. For this it is necessary to determine the angular range, with respect to one satellite, for which the electric field strength exceeds the critical value. The exclusion zone depends on the radiation pattern of the transmitting satellite and the relative position of the satellites. In addition the extend of the exclusion zone should considering the possible uncertainty in relative position determination.

The Equivalent Isotropic Radiated Power *EIRP* is used to represent the transmitted power. The *EIRP* includes the TRM peak output power, the cable losses, in addition to the element and array gains. Its peak value for TSX is as high as 82MWatt.

Then the field strength in Volt per meter at a point (r,ϑ,φ) from the antenna is:

$$E_{rms}(r,\vartheta,\varphi)=\frac{C(\vartheta,\varphi)}{r}\sqrt{\frac{EIRP\cdot Z_{F0}}{4\pi}}$$

with the free space wave impedance $Z_{F0}=120\pi$ and the normalized antenna pattern $C(\vartheta,\varphi)$. For the TanDEM-X mission various antenna beams may be used depending on the mode of operation and intended swath (see section 2.1). In the following a generalized radiation pattern is used which is determined by taking the maximum of all possible, mode dependent, transmit radiation patterns for each angle. The approach is to use the generalized pattern in order to determine the filed strength on a sphere centred at one satellites and radius equal to the minimum separation between the two satellites. Figure 4 shows the field strength on a section of this sphere as a function of azimuth and elevation angle. The contour lines indicate the extend of the exclusion zone for a critical field strength of 20 V/m and 50 V/m, respectively. Only a critical field strength of 50V/m results in an exclusion zone of ±30° in elevation, which is acceptable from an operational point of view. This

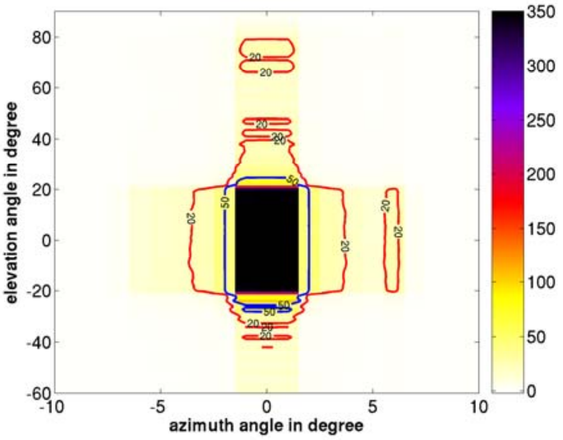

Figure 4: Field strength on a sphere of 130 m radius. The contour lines show the angular limits of the field strength exceeding the critical value of 20 V/m and 50 V/m, respectively**.**

4 Performance Analysis

This section investigates the interferometric performance of TanDEM-X. For this, an interferometric data acquisition in bistatic stripmap mode will be assumed. Major factors which affect the relative height accuracy are the radiometric sensitivity of each SAR instrument, range and azimuth ambiguities, quantization noise, processing and co-registration errors as well as surface and volume decorrelation, scaled by the baseline length [5]. The key quantity in estimating the interferometric performance is the coherence which has been computed by the product

$$\gamma_{tot} = \gamma_{SNR} \cdot \gamma_{Quant} \cdot \gamma_{Amb} \cdot \gamma_{Coreg} \cdot \gamma_{Geo} \cdot \gamma_{Az} \cdot \gamma_{Vol} \cdot \gamma_{Temp}$$

where the right hand side describes the different error contributions due to the limited SNR (γ_{SNR}), quantization (γ_{Quant}), ambiguities (γ_{Amb}), limited coregistration accuracy (γ_{Coreg}), baseline decorrelation (γ_{Geo}), relative shift of Doppler spectra (γ_{Az}), volume decorrelation (γ_{Vol}), and temporal decorrelation (γ_{Temp}). Each of these terms has been evaluated and Figure 5 shows the result of the interferometric performance analysis for two different ambiguous heights corresponding to different baseline lengths in the order of 300 m and 450 m, respectively.

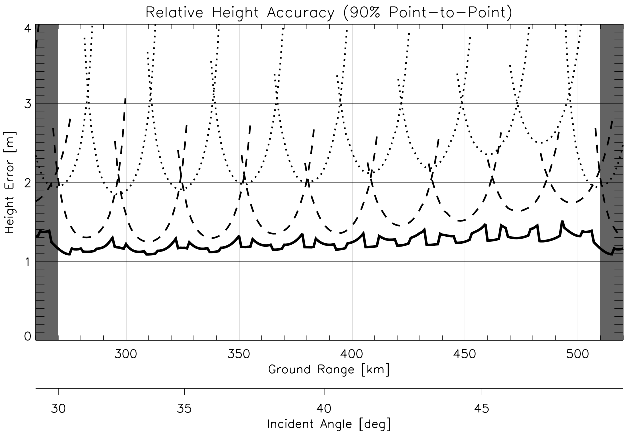

Figure 5: Height accuracy for a height of ambiguity of 45 m (dotted) and 30 m (solid). The lower solid curve shows the error resulting from the combination of multiple swaths. All errors are point-to-point height errors for a 90% confidence interval.

5 New Imaging Techniques

The TanDEM-X mission will provide the remote sensing scientific community with a unique data set to exploit the capability of new bistatic radar techniques and to apply these innovative techniques for enhanced geo- and biophysical parameter retrieval. In the following a short review is of these techniques is given.

Very Large Baseline Interferometry takes advantage of the large bandwidth of TerraSAR-X to significantly improve the height accuracy for local areas by combining multiple interferograms with different baseline lengths. This can e.g. be used to acquire DEMs with HRTI-4 like quality on a local or even regional scale. A temporal comparison of multiple large baseline TanDEM-X interferograms (either phase or coherence) provides furthermore a very sensitive measurable for vertical scene and structure changes. Potential applications are a detection of the grounding line which separates the shelf from the inland ice, monitoring of vegetation growth, measurement of snow accumulation or the detection of anthropogenic changes of the environment, e.g. due to deforestation.

Along-Track Interferometry can be performed by the so-called dual-receive antenna mode in each of the two tandem satellites and/or by adjusting the along-track distance between TerraSAR-X and TanDEM-X to the desired value. The combination of both modes will provide a highly capable along-track interferometer with four phase centers. As outlined in section 2.3 the along-track component can be adjusted from zero to several kilometers. Potential applications are Ground Moving Target Indication (GMTI), the measurement of ocean currents, and the monitoring of sea ice drift.

Polarimetric SAR Interferometry combines interferometric with polarimetric measurements. This allows e.g. for the extraction of vegetation density and vegetation height. Fully polarimetric operation uses the split antenna and is susceptible to ambiguities which limit the swath width. This could be avoided by a restriction to dual polarized measurements and/or an acquisition of multiple polarizations in successive passes.

Bistatic Imaging provides additional observables for the extraction of new scene and target parameters. A combination of bistatic and monostatic images can e.g. be used to improve segmentation, classification and detection. Data takes with large bistatic angles are planned at the beginning and end of the TanDEM-X mission.

Digital Beamforming and Super Resolution can be used to suppress ambiguities and to enhance the ground resolution. The combination of the four independent phase centers in TanDEM-X enables also a first demonstration of high resolution wide swath (HRWS) SAR imaging.

6 Conclusion

TanDEM-X is a highly innovative bistatic single-pass SAR interferometer which allows for the acquisition of unique remote sensing data products. The achievable height accuracy for global DEM generation with TanDEM-X is mainly limited by the height of ambiguity that can finally be processed during phase unwrapping. The standard HRTI-3 DEM is a reasonable compromise between performance, processing, and data acquisition effort. A mission scenario has been developed which enables the acquisition of a global HRTI-3 DEM within less than three years [5]. This concept includes several data takes with different baselines, different incident angles, and data takes from ascending and descending orbits to deal with difficult terrain like mountains, valleys, tall vegetation, etc. The TanDEM-X mission concept allocates also sufficient acquisition time and satellite resources to secondary mission goals like along-track interferometry or the demonstration of new bistatic radar techniques.

Current work includes the preparation of a detailed data acquisition plan which has also to take into account potential conflicts between the TerraSAR-X and the TanDEM-X mission, the development and analysis of a calibration concept, the design of a multibaseline InSAR processor, the compilation of a science plan as well as performance investigations for the other innovative TanDEM-X imaging modes.

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