TanDEM-X: A TerraSAR-X Add-On Satellite for Single-Pass SAR Interferometry

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***Abstract* — TanDEM-X is a mission proposal for a TerraSAR-X add-on satellite for high-resolution single-pass SAR interferometry. This mission proposal has been selected for a Phase A study within the scope of a Call for Proposals for a next German Earth Observation Mission to be launched in 2008/2009. The mission has the goal of generating a global Digital Elevation Model (DEM) with an accuracy corresponding to the DTED-3 specifications (12 m posting, 2 m relative height accuracy for flat terrain). This goal will be achieved by means of a second, TerraSAR-X like satellite (TanDEM-X) flying in a close orbit configuration with TerraSAR-X. This paper describes the mission concept and requirements, including several innovative aspects like operation modes, orbit selection and maintenance as well as PRF and phase synchronization. Results from a detailed performance estimation show the achievable DEM accuracy. Finally, an overview of the potential of the TanDEM-X mission for several scientific applications is presented.**

Keywords - Synthetic Aperture Radar (SAR), Interferometry, Digital Elevation Model (DEM), Bi-static Radar, Moving Target Indication (MTI).

I. INTRODUCTION

Digital maps are a prerequisite for reliable navigation, and improvements in their precision needs to keep step with the advances in global positioning systems, like GNSS and Galileo. Exact information about the Earth's surface is also of fundamental importance in a variety of geoscience areas. DEMs can be derived from many spaceborne sensors. The resulting mosaic of data from different sources with a multitude of horizontal and vertical data, accuracies, formats, map projections, time differences and resolutions is hardly a uniform and reliable data set. The SRTM (Shuttle Radar Topography Mission) had the challenging goal to meet the requirements for a homogeneous, reliable DEM fulfilling the DTED-2 specifications. However, many scientific and commercial applications require improved accuracy, corresponding to the DTED-3 standard (12 m posting and < 2 m height accuracy), comparable to DEMs generated by high-resolution airborne SAR systems. Fig. 1 shows a comparison of DEMs with DTED-2 and DTED-3 standards. Currently there is only a draft specification for the HRTI-3 (High Resolution Terrain Information) standard which is very similar to the draft DTED-3 standard.

. The main goal of the TanDEM-X mission is the generation of world-wide, consistent, timely, high-precision Digital Elevation Models corresponding to the DTED-3 standard as the basis for a wide range of scientific research, as well as for operational, commercial DEM production. Besides the primary goal of the mission, several other secondary mission objectives based on along-track interferometry as well as new techniques with bi-static SAR have been defined which also represent an important and innovative asset of the mission.

The TanDEM-X satellite is designed for a nominal lifetime of 5 years and has a nominal overlap with TerraSAR-X (TSX-1) of 3 years. A prolongation of the mission overlap is possible by means of an extension of TSX-1 operation which is compatible with the TSX-1 consumables and resources.

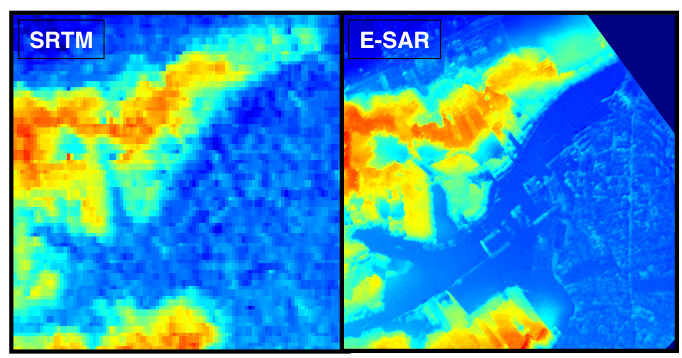


Figure 1. Comparison of DEM's with different DTED standards.
Left: DEM derived from SRTM corresponding to DTED-2.
Right: DEM derived from airborne E-SAR system, corresponding to DTED-3.

II. MISSION CONCEPT AND REQUIREMENTS

TanDEM-X has SAR system parameters which are fully compatible with TSX-1 [1], allowing not only an independent operation from TSX-1 in mono-static mode, but also a synchronized operation. Since TanDEM-X is based on TSX-1 technology and linked with the TSX-1 mission, the starting point of the mission requirements is the TSX-1 Space and Ground Segment Requirements [2]. With the user/data product requirements that have been derived from a questionnaire addressed to the science team of the TanDEM-X mission proposal, the mission specifications and the preliminary system requirements have been derived (see Table I).

The TSX-1 satellite, as a basis for TanDEM-X, is not only a high performance SAR system with respect to SAR image and operational features, but it is already built for repeat-pass interferometry. It provides several essential features for the TanDEM-X mission, like precise orbit control, dual frequency GPS for best localization knowledge, and very good RF phase stability. In the following, some of the required specifications for the mission realization will be described in more detail.

TABLE I. TANDEM-X MISSION AND SYSTEM REQUIREMENTS

Mission Requirements		Preliminary System Requirements	
Digital Elevation Models (DTED-3)		***Orbit, Constellation & Bus:***	
Vertical Accuracy:	2-4 m (relative)	Cross-Track Baseline:	300 m – 2 km (adjustable)
	10 m (absolute)	Along-Track Baseline:	< 2 km (for bi-static InSAR)
			200 m – 2 km (adjustable for ATI)
Horizontal Accuracy:	10 m	Baseline Measurement:	2-4 mm (without tie points)
DEM Post Spacing:	12 m	Orbit:	polar (i = 97.4°, h = 514 km)
Along-Track Interferometry (ATI)		Constellation Design:	reconfigurable (low fuel demand), stable baselines, close formation control, collision avoidance concept (compatible with TSX-1)
Accuracy:	0.01 m/s (sea ice drift)		
	0.1 m/s (ocean currents)	System Lifetime:	> 5 years
	1 m/s (traffic monitoring)	***Instrument & TTC:***	
Observation & Operation		SAR modes:	Strip-Map, ScanSAR as a min. (support of TSX-1 mission goals)
Coverage:	global	Wavelength:	X-Band (9.5 - 9.8 GHz)
Scenario:	mapping of 500 000 km^2 within:	Incident Angles:	25°-50°
		Radiometric Performance:	NESZ ≤ -19 dB (@ 100 MHz)
	a) 60 days (DTED-3)	Temporal Correlation:	> 0.9 (e.g. via bi-static InSAR)
	b) 30 days (~ DTED-2)	RF Phase Knowledge:	< 20°
		Resolution (Rg. & Az.):	< 6 m (for 4 interferometric looks)
Throughput:	100 000 km^2/day (avg.)	Pixel Localization Accuracy:	< 5 m
	200 000 km^2/day (peak)	Swath Width:	≥ 30 km
		Phase Centers:	4 (to resolve ATI ambiguities)
Calibration:	avoid reference points in target area	Downlink Capacity:	2 x 500 Gbit/day (e.g. via second ground station)
Duration:	> 5 years	Data Compression (BAQ):	2, 3 or 4 bit (or reduced BW)
		PRF:	synchronized (for bi-static mode)

A. *Spacecraft and Launch Vehicle*

Following the overall TanDEM-X concept, the spacecraft will be as much as possible a rebuild of TSX-1, i.e. the necessary modifications will already be implemented on TSX-1. This guarantees low development risks, the possibility to share operational functions and thus an inherent redundancy. The TSX-1 instrument is an advanced high resolution X-Band synthetic aperture radar based on active phased array technology which can be operated in Spotlight, Stripmap and ScanSAR mode with full polarization capability [1]. The TSX-1 instrument is operated at 9.65 GHz with a selectable SAR chirp bandwidth of up to 300 MHz. The active phased array antenna is fixed mounted to the spacecraft body and incorporates 12 tiles with 32 dual-pole waveguide sub-arrays each. The overall antenna aperture area is 4.8 m x 0.7 m, the overall instrument mass is less than 500 kg. The TSX-1 rebuilt has a total mass of 1100 kg and an average/peak power consumption of 800/5300 W.

The launch vehicle foreseen for the TanDEM-X satellite is either Rokot or DNEPR-1. The lift-off capability into TSX orbit is about 1350 kg. Launch site is Plesetzk in Siberia or Baikonour in Kasackstan.

B. *TanDEM-X Operation Mode*

Operational DEM generation will be performed using bi-static InSAR. Its principle, sketched in fig. 2.a, is characterized by the simultaneous measurement of the same scene and identical Doppler spectrum with 2 receivers, thereby avoiding temporal decorrelation. To provide sufficient overlap of the Doppler spectra, along-track baselines < 2 km are required while the effective across-track baselines for high resolution DEMs have to be in the order of 1 km. PRF synchronization and relative phase referencing between the satellites are mandatory. An alternating transmission mode (ping-pong mode) is also foreseen which allows the simultaneous generation of interferograms with single and double baseline as well as a direct phase synchronization of the radar systems.

A secondary DEM generation mode is the pursuit mono-static InSAR mode (cf. fig. 2.b), where two satellites are operated independently, avoiding the need for synchronization. The along-track distance is 30-50 km. The temporal de-correlation is still small for most terrain types except for water and vegetation at moderate to high wind speeds. The interferometric height sensitivity is doubled with respect to bi-static operation, meaning that the baseline determination has to be more accurate.

(a) bistatic mode

(b) pursuit monostatic mode

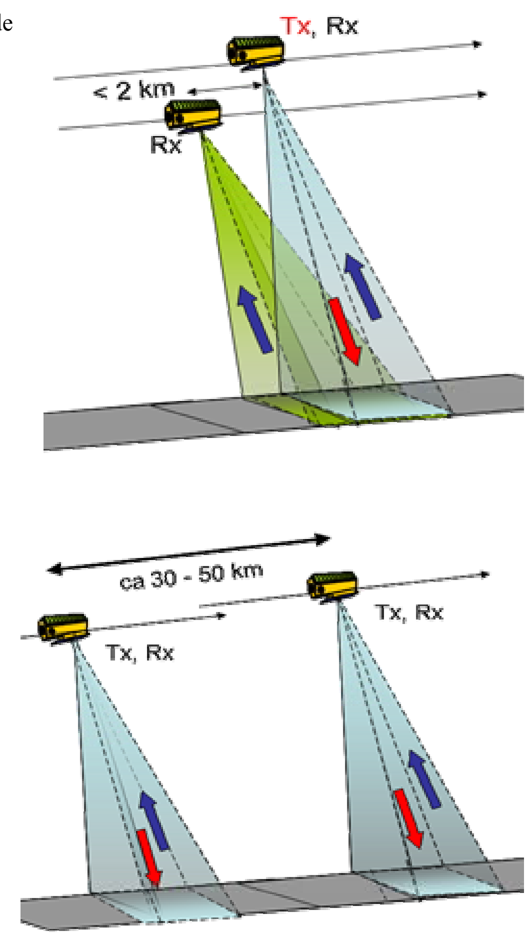


Figure 2. InSAR measurement configurations for TanDEM-X.

C. Orbit Configuration and Formation Flying

The TanDEM-X operational scenarios require selectable baselines at dedicated geographical locations. 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 stable orbit configurations (e.g. Pendulum and Helix) have been identified, capable of satisfying the mission requirements [4]. Optimum configurations will be established in the Phase A study work.

Coarse orbit control and maintenance of the tandem configuration will be done as part of the regular maintenance maneuvers using thrusters. Fine tuning of the orbit drag is proposed by canting of the satellites in non-operational phases.

The close formation flying requires a well defined collision avoidance concept working autonomously within 24 hours. Several promising concepts (w.r.t. schedule, technical feasibility and implementation effort), starting from simple, single satellite based systems to active S-Band inter-satellite link based systems, have been identified. Selection of the best suited concept is a priority task of the Phase A study.

D. Cross Referencing of On-board Time and Local Oscillator Phases

Knowledge of the RF oscillator phase drift between the two tandem satellites is mandatory to meet the absolute height accuracy requirements without tie points. Direct transmission of radar pulses is foreseen on TSX-1 within the field of view to the tandem satellite. This will be achieved by a new technique for precise phase referencing.

E. PRF Synchronization

PRF synchronization is best achieved through GPS based commanding of the start of the measurement. An alternative is the implementation of a triggering function for the receiving window.

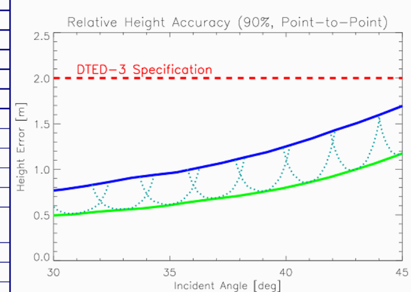
F. Baseline Vector Determination

The envisaged concept for precise interferometric baseline vector determination is based on dual frequency GPS data provided by the TOR (Tracking, Occultation and Ranging) instrument on TSX-1 and TanDEM-X. A study conducted by GFZ (GeoForschungsZentrum Potsdam) shows the feasibility of such a concept [6]. The analysis performed with GFZ's Earth Parameter and Orbit System (EPOS) utilizing an adapted GRACE configuration (altitude ca. 490 km, 30 s satellite separation) shows for different along-track separations (0 to 10s) that a relative position knowledge of 1 mm can be achieved in most cases.

III. PERFORMANCE ANALYSIS

The DTED specification differentiates between relative and absolute height errors. The emerging DTED-3 standard will require a relative height accuracy of 2 m and an independent horizontal post-spacing of 12 m. 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 de-correlation, scaled by the baseline length. A sensitivity analysis has been performed for TanDEM-X. The two columns on the left in Table II show the main instrument, orbit, and processing parameters. The expected height accuracy is illustrated in the figure on the right where the height errors are shown as a function of the incident angle. The dotted lines illustrate the variation of the height accuracy within a swath of 30 km. The height accuracy at the swath border and swath center is given by the upper and lower solid lines, respectively. In the performance analysis a stable effective baseline of 1km has been assumed. It is evident, that the expected TanDEM-X performance is always better than the DTED-3 specification with the possibility of further improvement by a coherent combination of multiple interferograms from ascending and descending orbits.

TABLE II. TANDEM-X SENSITIVITY ANALYSIS

Parameter	Value	Relative Height Accuracy
Wavelength	0.031 m	
Chirp Bandwidth	100 MHz	
Peak Transmit Power	2260 W	
Duty Cycle	18 %	
Noise Figure	4.5 dB	
Atmospheric Losses	0.5 dB	
Antenna Size (Tx , Rx)	4.8 m x 0.7 m	
PRF	3500 Hz	
Processed Bandwidth	2300 Hz	
Co-Registration Accuracy	1/10 pixel	
Quantization	3 bit (BAQ)	
Sigma Nought Model (90% occurrence levels)	Ulaby (X-Band, HH, Soil)	
Effective Baseline	1 km	
Along-Track Displacement	1 km	
Swath Width	30 km	
Post Spacing	12 m x 12 m	

The sensitivity analysis in Table II neglects errors due to the finite accuracy of relative baseline estimation and relative RF phase knowledge. Such errors will mainly cause a low frequency modulation of the DEM, thereby contributing simultaneously to relative and absolute height errors. For the latter, the DTED-3 standard is much less stringent and requires an accuracy of 10 m at a 90% confidence level.

Currently, it is not possible to quantify the relative allocation of the individual error budgets, since this will require a detailed specification of the baseline estimation and phase synchronization technique. Therefore, a conservative estimation for the necessary phase and baseline accuracy has been derived in Table III, assuming a maximum total height error of 1m. It is expected, that the requirements will be refined during the Phase A study, as soon as detailed models are available for the individual error sources. Note that the predicted GPS based baseline measurement accuracy of ~1 mm is already compliant with Table I, thereby allowing for a calibration of the DEM using the ocean surface before and after every coast crossing and avoiding the need to refer to a dense net of calibration targets.

TABLE III. REQUIRED ACCURACY FOR BASELINE ESTIMATION

Incident Angle	Phase Error (for 1m height error)	Required Baseline Accuracy (for 1m height error)		
		without tie points	one tie point	Two tie points
30°	±19,8°	3,4 mm	3 cm	34 cm (Δh = 3 km)
45°	±11,7°	2,0 mm		

IV. Scientific Applications

TanDEM-X has been designed to provide high quality data for commercial and scientific applications. As far as the scientific applications and corresponding geo-physical products are concerned, they have been endorsed with a questionnaire distributed to a large number of scientists. Many of the scientists represent end-users and have a long experience with the SRTM, SIR-C/X-SAR as well as ERS-1/2 data evaluation. The scientific applications can be summarized in three groups:

A. Across-Track Interferometry

A consistent and reliable DEM data set with global coverage and DTED-3 standard is an important information for a variety of on-going research areas and will allow new scientific applications to be developed. Examples are:

- *hydrology* (ice and snow, wetlands, morphology and flooding),
- *geology* (geological mapping, tectonics, volcanoes and land-slides),
- *land environment* (cartography, urban areas, disaster and crisis management, navigation, archaeology and change detection),
- *renewable resources* (land use mapping, agriculture, forestry and grassland),
- *oceanography* (wind and waves, ocean dynamics, sea-ice, ship detection, oil slicks and bathymetry). Some of these applications foresee the combined use of along- and across-track interferometry as well as polarimetry to enhance current products.

B. Along-Track Interferometry

Along-track interferometry will allow innovative applications to be explored. Along-track interferometry can be performed by the so-called dual-receive antenna mode (ca. 2.4 m along-track baseline) and/or by adjusting the along-track distance between TSX-1 and TanDEM-X to the desired value (up to 4 phase centers). By means of newly developed orbit concepts, the along-track component can be adjusted from 0 to several kilometers. The combination of the two different along-track baselines will be explored for moving target detection (MTI) and traffic monitoring applications. The following sub-groups have been defined for along-track interferometry:

- *Oceanography* (Ocean currents maps, ocean wave spectra),
- *Moving Target Detection* (Traffic flow monitoring maps - see also moving target techniques in application area *C*),
- *Glaciology* (Ice flow monitoring maps).

C. New Techniques with Bi-Static SAR

The TanDEM-X mission will provide the remote sensing scientific community with a unique data set to exploit the capability of the new bi-static radar techniques and to apply these innovative techniques for enhanced parameter retrieval:

- *Super Resolution* (high resolution maps, micro-topography enhancement maps, feature extraction algorithms)
- *Bi-static SAR* (new bi-static SAR processing algorithms, multi-angle SAR, enhanced scene feature extraction, combination of mono-static and bi-static signatures),
- *Moving Target Detection* (detection of ground moving targets and the estimation of their velocity, moving target relocation, isolation and target focusing),
- *Polarimetric SAR Interferometry* (DEM optimization using polarization diversity, vegetation bias and structure maps, crop biomass).

V. Discussion

In order to comply with the DTED-3 standard for DEM data, new technological skills will be developed in Phase A, such as:

- close formation flying to ensure suitable baselines for interferometric processing,
- baseline determination capability down to few millimetres,
- frequency/phase and time synchronization of the tandem instrument configuration,
- global scale, operational DEM generation with DTED-3 standard.

The experience gathered with the GRACE mission proves the feasibility and gives important background to adjust and maintain such a satellite formation. Furthermore, several strategies for failure recovery will be analyzed in phase A. As a fallback solution for the close distance formation flying, the pursuit mono-static mode can be used. In this case the two satellites acquire SAR data independently at an along-track displacement of several 10 km.

As far as the TSX-1 ground segment is concerned, it will be extended for TanDEM-X as follows: 1) to simultaneously operate two satellites in close formation (Mission Operations Segment, MOS), 2) to handle the increased data volume, to include a second receiving station and to adapt the processing chain for new data products (Payload Ground Segment, PGS), and 3) to calibrate and validate interferometric products (Instrument Operations and Calibration Segment, IOCS).

Acknowledgment

The authors would like to thank Prof. C. Reigber of GFZ as well as the members of the TanDEM-X science team for their contributions, support and advises which constitute a major component of the TanDEM-X mission proposal.

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