A Tandem TerraSAR-X Configuration for Single-Pass SAR Interferometry

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Abstract: TanDEM-X is a mission proposal for a TerraSAR-X add-on satellite to enable high-resolution single-pass SAR interferometry. The TanDEM-X 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 paper describes the mission concept and requirements, including several innovative aspects like operational modes, orbit selection and maintenance as well as PRF and phase synchronization. Results from a 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).

1. Introduction

Digital elevations models (DEMs) are of fundamental importance for a broad range of scientific and commercial applications. For example, many geoscience areas like hydrology, glaciology, forestry, geology, oceanography and land environment require precise and up-to-date information about the Earth's surface and its topography [1]. Digital maps are also 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. In principle, DEMs can be derived from a variety of spaceborne sensors. However, 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 Shuttle Radar Topography Mission (SRTM, [1][3]) had hence the challenging goal to meet the requirements for a homogeneous and reliable DEM fulfilling the DTED-2 specification (cf. third column of Table 1). However, many scientific and commercial applications require improved accuracy, corresponding to the emerging DTED-3 standard (12 m posting and 2 m height accuracy, cf. right column of Table 1) which is comparable to DEMs generated by high-resolution airborne SAR systems.

The main goal of the TanDEM-X mission is the generation of world-wide, consistent, timely, and high-precision digital elevation models according to the DTED-3 standard as the basis for a wide range of scientific research, as well as for operational, commercial DEM production [4][5]. 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. Both satellites will then act as a single-pass SAR interferometer with the opportunity for flexible baseline selection. This enables the acquisition of high-resolution interferograms without the inherent accuracy limitations of repeat-pass interferometry due to temporal decorrelation and atmospheric disturbances [1]. 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 mission proposal for TanDEM-X [4] 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 TanDEM-X satellite will be 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.

Table 1: Comparison of DTED levels

Requirement	Specification	DTED-2	DTED-3
Relative Vertical Accuracy	90% linear point-to-point error over 1° x 1°	< 12 m (slope < 20%) < 15 m (slope > 20%)	< 2 m (slope < 20%) < 4 m (slope > 20%)
Absolute Vertical Accuracy	90% linear error	< 18 m	< 10 m
Relative Horizontal Accuracy	90% circular error	< 15 m	< 3 m
Absolute Horizontal Accuracy	90% circular error	< 23 m	< 10 m
Spatial Resolution	independent pixels	30 m (1 arc sec)	12 m (1 arc sec)

Table 2: TanDEM-X mission and system requirements

Mission Requirements		Preliminary System Requirements	
Digital Elevation Models (DTED-3)		***Orbit, Constellation & Bus:***	
Vertical Accuracy:	2-4 m (rel.)	Cross-Track Baseline:	300 m – 2 km (adjustable)
	10 m (abs.)	Along-Track Baseline:	< 2 km (for bistatic 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)	System Lifetime:	> 5 years
	0.1 m/s (ocean currents)	***Instrument & TTC:***	
	1 m/s (traffic monitoring)	SAR modes:	Strip-Map, ScanSAR as a min. (support of TSX-1 mission goals)
Observation & Operation		Wavelength:	X-Band (9.5 - 9.8 GHz)
Coverage:	global	Incident Angles:	25°-50°
Scenario:	mapping of 500 000 km^2 within:	Radiometric Perf.:	NESZ ≤ -19 dB (@ 100 MHz)
	a) 60 days (DTED-3)	Temporal Correlation:	> 0.9 (e.g. via bistatic InSAR)
	b) 30 days (DTED-2)	RF Phase Knowledge:	< 20°
Throughput:	1*10^5 km^2/day (avg.)	Resolution (Rg. & Az.):	< 6 m (for 4 interferometric looks)
	2*10^5 km^2/day (peak)	Pixel Localisation:	< 5 m
Calibration:	avoid reference points in target area	Swath Width:	≥ 30 km
Duration:	> 5 years	Phase Centres:	4 (to resolve ATI ambiguities)
		Downlink Capacity:	2 x 500 Gbit/day (e.g. via second ground station)
		Data Comp. (BAQ):	2, 3 or 4 bit (or reduced BW)
		PRF:	synchronised (for bistatic mode)

2. Mission concept and requirements

TanDEM-X has SAR system parameters which are fully compatible with TSX-1 [6], 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 [7]. 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 2).

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.

2.1 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 a 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 [6]. 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.

2.2 TanDEM-X Operational Mode

Operational DEM generation will be performed using bi-static InSAR. Its principle, sketched in Fig. 1.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 (cf. [8]).

(a) bistatic mode

(b) pursuit monostatic mode

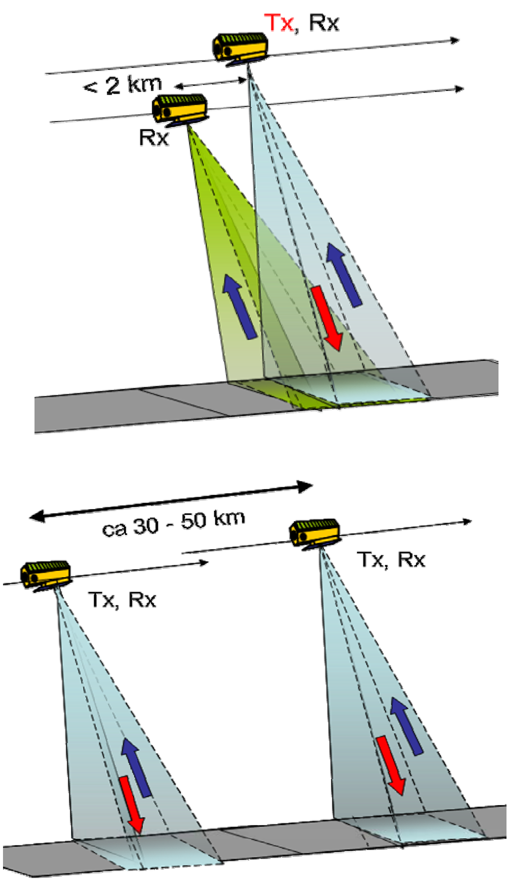

Figure 1: InSAR measurement configurations for TanDEM-X.

A secondary DEM generation mode is the pursuit mono-static InSAR mode (cf. Fig. 1.b), where two satellites are operated independently, avoiding the need for synchronization. The along-track distance is 30-50 km to exclude any interference between the radar instruments. The temporal decorrelation 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.

2.3 Orbit Configuration and Formation Flying

The TanDEM-X operational scenarios require 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 stable orbit configurations have been identified to provide the required baselines at dedicated geographical locations [9]. Fig. 2 shows an example which combines a horizontal cross-track displacement (e.g. by different ascending nodes) with a small vertical (radial) satellite separation (e.g. by slightly different eccentricities). Such a formation has the advantage that the satellite trajectories will never cross, thereby enabling a safe operation which minimizes the collision risk. The satellites may furthermore be shifted arbitrarily along their individual orbits. This enables an optimisation of the along-track displacement 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 will require selectable along-track baselines in the range from several hundred metres to several kilometres.

The selection of optimised orbits is furthermore closely related to requirements on the operational flexibility regarding the derivation of data products from different regions on the Earth within a specified time-interval. For example, interferometric phase ambiguities in mountainous terrain and steep slopes may require multiple passes with a slightly reconfigured satellite formation to achieve the DTED level 3 height accuracy. Several user scenarios will be defined and the major consequences of each of them on the orbit/formation selection will be analysed. This investigation includes a detailed coverage analysis for the different mission scenarios in combination with the identification of appropriate data acquisition strategies.

Coarse orbit control and maintenance of the tandem configuration will be done as part of the regular maintenance manoeuvres using thrusters. Several options for fine tuning the along-track displacement will be investigated in the Phase A study. The close formation flying requires also 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.

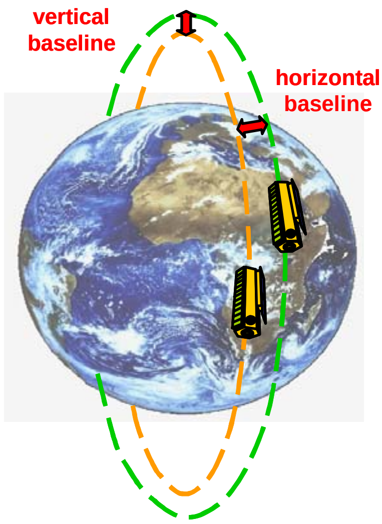

Figure 2: Orbit for TanDEM-X

2.4 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 enable a new technique for precise phase referencing.

2.5 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.

2.6 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. In case of close formations, the required accuracy can be provided by a direct evaluation of GPS carrier phase observations [10]. A study conducted by GFZ (Geo-Forschungs-Zentrum Potsdam) shows the feasibility of such a concept [11]. 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.

3. Performance analysis

The DTED specification in Table 1 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 decorrelation, scaled by the baseline length [12].

A sensitivity analysis has been performed for TanDEM-X. Table 3 shows the main instrument, orbit, and processing parameters. The expected height accuracy is illustrated in Figure 3 where the height errors are shown as a function of the incident angle. The dotted lines show 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 this analysis, a stable effective baseline of 1 km 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. Note that large baselines may cause ambiguities in the phase to height conversion. Hence, appropriate a priori information from a coarse DEM and/or multiple data acquisitions with different interferometric baselines will be required for reliable phase unwrapping.

Table 3: TanDEM-X system parameters for performance analysis

Parameter	Value
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
Quantisation	3 bit (BAQ)
Sigma Nought Model (90%)	Ulaby (HH, Soil & Rock)
Effective Baseline (bistatic)	1 km
Along-Track Displacement	1 km
Swath Width	30 km
Post Spacing	12 m x 12 m

The sensitivity analysis in Figure 3 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.

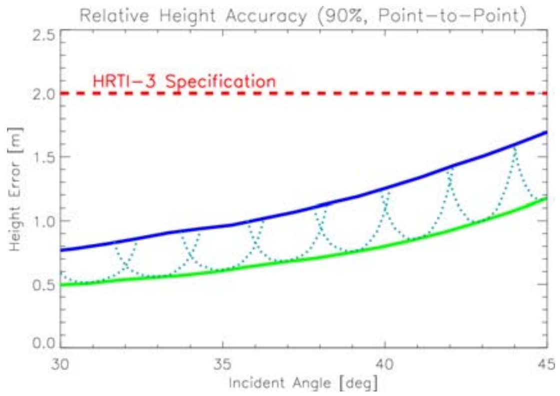

Figure 3: Predicted TanDEM-X height accuracy for an interferometric baseline of 1km.

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 4, assuming a maximum total height error of 1 m for an interferometric baseline of 1 km. 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. The predicted GPS based baseline measurement accuracy of ~1 mm (cf. Section 2.6) is already compliant with Table 4, 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. Note that such a calibration will require short along-track baselines to avoid any bias and temporal decorrelation induced by the ocean surface (cf. Sect. 2.3).

Table 4: Required phase and baseline accuracies for a height error of 1m and an effective baseline of 1 km.

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		

Oscillator noise may cause errors in both the interferometric phase and bistatic focusing. Such errors can be estimated from a linear systems model that weights the power spectral density of the oscillator phase noise. For example, errors from bistatic SAR focusing are modelled by an appropriate bandpass filter which accounts for the integration of the oscillator noise within the synthetic aperture time. A first evaluation yields an ISLR below -20 dB for coherent integration times of up to 5 s, a value which fits also quite well to the results from a joint DLR/ONERA bistatic airborne radar experiment. The stringent requirements for interferometric phase stability in the bistatic mode will require an appropriate relative phase referencing (Sect. 2.4) or an operation in the ping-pong alternating transmission mode (Sect. 2.2).

4. 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 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:

4.1 Across-Track Interferometry

A consistent and reliable DEM data set with global coverage and DTED-3 standard provides 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.

4.2 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 in each of the two tandem satellites (ca. 2.4 m along-track baseline, cf. [13]) and/or by adjusting the along-track distance between TSX-1 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 0 to several kilometers. The combination of the different along-track baselines will e.g. be used for improved detection, localisation and ambiguity resolution in ground moving target indication (GMTI) 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 Section 4.3),
- *Glaciology* (Ice flow monitoring maps).

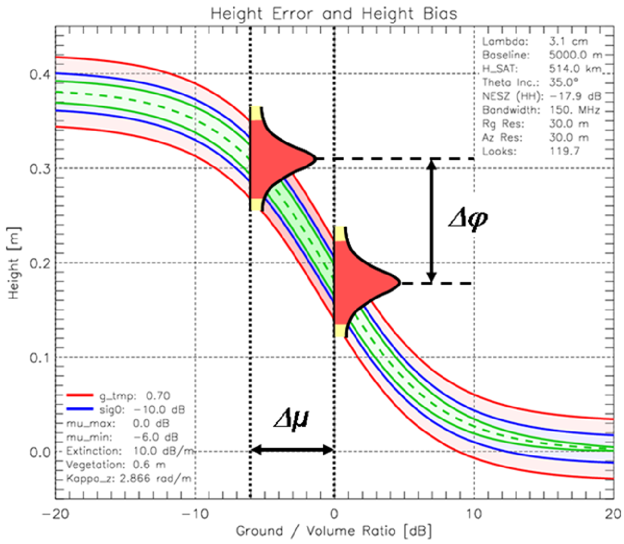

Figure 4: Vertical separation of interferometric phase centres in TanDEM-X as a function of the ground-to-volume scattering ratios μ.

4.3 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). Figure 4 shows an example for the achievable performance. This analysis is based on the Random Volume over Ground (RVoG) model [14] assuming a vegetation layer with a height of 0,6 m and an extinction coefficient of 10 dB/m. The dashed line indicates the height variation of the interferometric phase centre with different polarisations (corresponding to a variation of μ on the abscissa). The green tube shows the height errors due to volume decorrelation for an effective baseline of 5 km and an independent post-spacing of 30m x 30m. The blue tube shows additional errors due to the limited system accuracy and the red tube indicates potential errors in case of temporal decorrelation caused by a possible along-track separation between the two satellites (here: γ_{tmp} = 0.7). The performance analysis predicts a sufficient phase centre separation to enable a successful retrieval of important vegetation parameters like volume height, extinction, etc.

5. 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).

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8. Glossary

ATI:	Along-Track Interferometry
DEM:	Digital Elevation Model
DTED:	Digital Terrain Elevation Data
GFZ:	Geo-Forschungs-Zentrum, Potsdam
GMTI:	Ground Moving Target Indication
GRACE:	Gravity Recovery and Climate Experiment
HRTI:	High Resolution Terrain Information (NIMA will probably use HRTI instead of DTED)
InSAR:	Interferometric SAR
ISLR:	Integrated Sidelobe Ratio
NIMA:	National Imagery and Mapping Agency, United States of America
PolInSAR:	Polarimetric SAR Interferometry
PRF:	Pulse Repetition Frequency
RF:	Radio Frequency
SAR:	Synthetic Aperture Radar
SRTM:	Shuttle Radar Topography Mission
TSX-1:	TerraSAR-X 1