TanDEM-X: Mission Concept, Product Definition and Performance Prediction

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Abstract

This paper gives a short overview of the TanDEM-X mission concept, summarizes the basic products, illustrates the achievable performance, and gives some examples for new imaging modes.

1 Introduction

TanDEM-X is a mission proposal for an innovative spaceborne radar interferometer which has successfully been evaluated in a phase A study by a joint DLR and EADS/Astrium team. The main goal of the TanDEM-X mission is the generation of a world-wide, consistent, timely, and high-precision digital elevation model according to the emerging HRTI-3 standard as the basis for a wide range of scientific research, as well as for operational, commercial DEM production [1]. Secondary mission goals of TanDEM-X are moving target indication with a distributed four aperture displaced phase centre system, the measurement of ocean currents and the detection of ice drift by along-track interferometry, high resolution SAR imaging based on a baseline induced shift of the Doppler and range spectra (super-resolution), the derivation of vegetation parameters with polarimetric SAR interferometry, large baseline bistatic SAR imaging for improved scene classification, as well as regional very high resolution DEM generation based on spotlight and large baseline interferometry.

TABLE I DEM SPECIFICATION FOR HRTI LEVEL -3 STANDARD

Requirement	Definition	HRTI-3
Relative Vertical Accuracy	90% linear point-to-point error	2m (slope < 20%)
Absolute Vertical Accuracy	90% linear error	10 m
Horizontal Accuracy	90% circular error	10 m
Spatial Resolution	independent pixels	12 m (1 arc sec)

2 Mission Concept

The TanDEM-X mission concept is based on an extension of the TerraSAR-X mission [2] by a second TerraSAR-X like satellite. Both satellites will fly in close formation and will be operated as a flexible single-pass SAR interferometer where the baseline can be selected according to the specific needs of the application (cf. Figure 1). 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. The TanDEM-X satellite (TDX) will be designed for a nominal lifetime of 5 years and has a nominal overlap with TerraSAR-X (TSX) of 3 years. A prolongation of the mission overlap is possible by means of an extension of TSX operation which is compatible with the TSX consumables and resources.

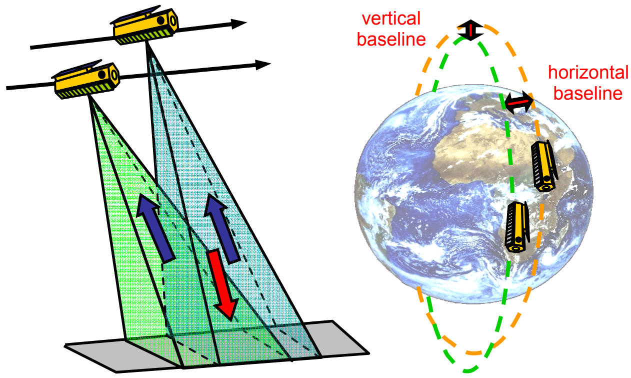

Figure 1 Bistatic InSAR operation (left) and HELIX orbit (right).

Interferometric data acquisition can be performed in (1) the pursuit monostatic mode where both satellites are operated independently, (2) the bistatic mode where one satellite serves as a transmitter and both satellites record the scattered signal simultaneously, and (3) the alternating bistatic mode where the transmitter changes from pulse to pulse. Current baseline for operational DEM generation is the bistatic mode which minimizes temporal decorrelation and makes efficient use of the transmit power. The alternating bistatic mode can be used for phase synchronization, system calibration, and to acquire interferograms with two different phase-to-height sensitivities, but the simultaneously acquired monostatic interferogram has a higher susceptibility to ambiguities especially at high incident angles [3]. Monostatic data takes are planned during the commissioning phase and at the end of the mission where the satellite formation is flown with a sufficient along-track separation between the satellites to avoid potential RF interferences.

The TanDEM-X operational scenario requires a coordinated operation of two satellites flying in close formation. Several options have been investigated and the HELIX satellite formation has finally been selected (Figure 1, right). This formation combines an out-of-plane 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, it is now possible to arbitrarily shift the satellites along their orbits, e.g. to adjust very small along-track baselines at predefined latitudes and to allow safe spacecraft operation without autonomous control. The HELIX formation enables a complete coverage of the Earth with a stable height of ambiguity by using a small number of formations ($a\cdot\Delta\Omega$={300m,400m,500m}, $a\cdot\Delta e$={300m,500m}, [4]). Baseline fine tuning can be achieved by taking advantage of the natural rotation of the eccentricity vectors due to secular disturbances and fixating the eccentricity vectors at different relative phasings. An appropriate reference scenario has been derived which enables one complete coverage of the Earth with baselines corresponding to a height of ambiguity of ca. 35m (see Sect. 3) within somewhat more than 1 year assuming a bistatic acquisition in strip map mode with an average acquisition time of 140s per orbit [4].

3 Product Definition

Two basic product classes have been defined for TanDEM-X in close cooperation with both the scientific and the commercial users [5].

3.1 Digital Elevation Models (DEM)

This product class comprises all DEM data products. The DEM class is divided into two subclasses: standard and customized DEMs. The standard DEMs will be available globally after all interferometric data from the TanDEM-X mission are processed. The specification for standard DEMs is aligned with the emerging HRTI-3 standard (cf. TABLE I), but some modifications have been made to take into account the different user requirements. The major modification concerns the availability of different trade-offs between horizontal and vertical resolution. Other modifications concern e.g. the vertical datum where it was decided to use the WGS 84 ellipsoid instead of the Mean Sea Level. Standard DEMs will be available at the resolutions shown in TABLE II (high spatial resolution (HSR) DEMs are only available on special request).

TABLE II TanDEM-X DEMs

	DSM 50	DSM 25	HRTI-3	HSR
Post Spacing	50 m	25 m	12 m	6 m
Relative Height Accuracy	0.5 m	1 m	2 m	4 m

It is assumed that all these DEM products can be derived from one and the same TanDEM-X SAR data acquisition by applying different multilooking windows during the interferometric processing. DEM data may be accompanied by the following supporting data: (1) geocoded amplitude SAR images, (2) coherence maps, and (3) height error maps. Moreover, TanDEM-X will be able to produce customized DEMs on a local basis. Customized DEM acquisition takes into account specific user demands regarding imaging geometry, DEM accuracy, and acquisition time. The performance goal for improved DEM generation is 0.8 meter relative height accuracy for an independent post spacing of 6 meter, as required by the emerging HRTI-4 standard.

3.2 Radar Data Products (RDP)

This product class comprises all TanDEM-X data products which are not covered by the DEM class. Examples are SAR data products for along-track interferometry, polarimetric SAR interferometry, four phase centre moving target indication, bistatic SAR imaging, and digital beamforming. The user/customer has to provide specific data acquisition parameters like e.g. imaging geometry, SAR operation modes, instrument settings, and so on. TanDEM-X will then acquire the desired SAR data during the available time slots. The following data will be available: (1) single look complex (SLC) SAR images, (2) SLC quality flags, (3) SAR interferograms (if applicable), (4) auxiliary data (baseline, precise orbit, calibration data, system errors, accuracy, etc.), and for some special applications SAR raw data. It is then the responsibility of each customer/scientist to derive higher level products from the Radar Data Products offered by TanDEM-X.

4 Performance Analysis

This section investigates the DEM performance of TanDEM-X. For this, an interferometric data acquisition in bistatic strip map mode is assumed. Table 1 summarizes the main instrument, orbit, and processing parameters which have been used in the performance analysis.

TABLE III TanDEM-X System Parameters

Parameter	Value	Parameter	Value
Satellite Height (nom.)	514 km	Antenna Length	4,8 m
Nominal Swath Width	30 km	Antenna Width	0,7 m
Swath Overlap	6 km	Antenna Elements	32 x 12
Carrier Frequency	9,65 GHz	Antenna Tapering	linear phase
Chirp Bandwidth	<= 150 MHz	Antenna Mounting	33.8°
Peak Tx Power	2260 W	Quantization	4 bits/sample
Duty Cycle	18 %	Proc. Az. Bandwidth	2266 Hz
Noise Figure TRM	4.3 dB	Misregistration	0.1 pixel
Losses (proc., atm., taper, degrad., …)	4.1 dB	Sigma Nought Model (Ulaby, 90%, X-band)	Soil and Rock, VV
Indep. Post Spacing	12 m x 12 m	Along-Track Baseline	< 1 km

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. Figure 2 shows the predicted total coherence assuming the 50% (dotted) and 90% (solid) occurrence levels of the scattering coefficients (cf. TABLE III).

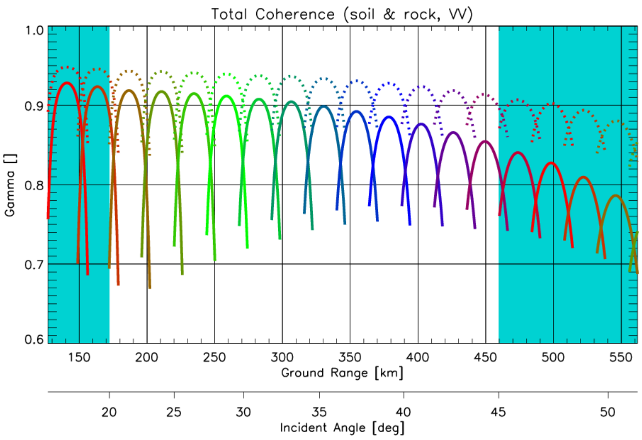

Figure 2 Total coherence in bistatic strip map mode.

To calculate the height accuracy, the interferometric phase errors have first been estimated from the total coherence taking into account the number of independent looks obtained after spectral filtering in range and azimuth. Figure 3 shows the predicted point-to-point height errors for the 90% confidence interval assuming fixed heights of ambiguity of 50m (top), 35m (middle), and 20m (bottom). Note that the derivation of the height accuracy assumes a maximum likelihood combination of the interferometric data from overlapping swath segments. The impacts of slopes, volume decorrelation, etc. have been analyzed in

[3], where it is shown that e.g. a variation of the slopes by ±20% may cause a maximum increase of the height errors by a factor of <1.1 for medium incident angles and 1.2 for either very steep or very shallow incident angles.

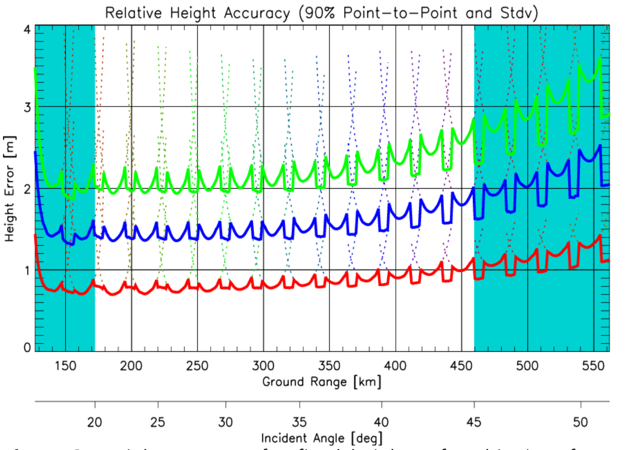

Figure 3 Height accuracy for fixed heights of ambiguity of 50m (top, green), 35m (middle, blue) and 20m (bottom, red) in strip map mode after combining adjacent swaths. Shown are point-to-point height errors for a 90% confidence interval.

Figure 3 shows that the acquisition of DEMs with 2m relative height accuracy (point-to-point errors at 90% occurrence level according to HRTI-3 standard) will require a height of ambiguity which is in the order of 35m. This height of ambiguity corresponds to perpendicular baselines of $B_\perp$=260m and $B_\perp$=439m at incident angles of 30° and 45°, respectively. It is clear that unambiguous DEM generation in mountainous areas will require additional data takes with different baselines to support phase unwrapping, e.g., by employing an appropriate adaptation of the maximum likelihood technique suggested in [6]. The current TanDEM-X mission concept assumes 1-2 additional acquisitions for areas with moderate slopes and tall vegetation and 3-4 additional acquisitions for mountainous terrain with steep slopes. Phase unwrapping in forested areas may also be improved by evaluating the coherence loss due to volume decorrelation. Difficult terrain can furthermore be imaged in the alternating bistatic mode, which enables the acquisition of two interferograms with an effective baseline ratio of two in one single pass.

Up to now, we have neglected 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 HRTI-3 standard is much less stringent and requires an accuracy of 10m at a 90% confidence level.

Baseline estimation errors can be divided into along-track, cross-track, and radial errors. Along-track errors will be sufficiently resolved during the co-registration and are hence regarded as uncritical. Cross-track and radial errors may cause errors in both the line of sight ($\Delta B_{||}$) and perpendicular ($\Delta B_\perp$) to the line of sight. Baseline errors perpendicular to the line of sight will cause a bias in the phase to height scaling. The resulting height error is given by $\Delta h = h * \Delta B_\perp / B_\perp$, where h is the topographic height, $\Delta B_\perp$ is the error of the baseline estimate perpendicular to the line of sight, and $B_\perp$ is the length of the perpendicular baseline. Assuming a maximum topographic height of h=9000m and baselines corresponding to a height of ambiguity of h_{amb}=35m ($B_\perp$=260m for θ_i=30° and $B_\perp$=439m for θ_i=45°), a baseline estimation error of $\Delta B_\perp$=±1mm will result in height errors of ±3.5cm and ±2.1cm for incident angles of θ_i=30° and θ_i=45°, respectively.

Errors in the relative position estimates of the antenna phase centres parallel to the line of sight ($\Delta B_{||}$) will primarily cause a rotation of the reconstructed DEM about the (master) satellite position. As a result, the DEM will be vertically displaced by $\Delta h = \Delta B_{||} / B_\perp * r * \sin(\theta_i) = \Delta B_{||} * h_{amb} / \lambda$ 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=±1.1m for $\Delta B_{||}$=±1mm and h_{amb}=35m. A parallel baseline error of one satellite will furthermore cause a tilt of the DEM which is given by $\varphi_{tilt} = \Delta h / \Delta s = \Delta B_{||} / B_\perp$ where Δs is the ground range distance from the selected reference point. The resulting tilt will be 3.8mm/km and 2.3mm/km for incident angles of θ_i=30° and θ_i=45°, respectively ($\Delta B_{||}$=1mm and h_{amb}=35m). Table 4 summarizes the predicted height errors resulting from $\Delta B_{||}$=1mm and $\Delta B_\perp$=1mm.

TABLE IV HEIGHT ERRORS FOR 1MM BASELINE UNCERTAINTY

Incident Angle	Normal Baseline (h_{amb}=35m)	Height Errors (for h_{amb}=35m)		
		$\Delta B_{\|\|}$ = 1mm		$\Delta B_\perp$ = 1mm
		Δh	Δh/Δs (tilt)	Δh (h=9km)
30°	260 m	1.1 m	3.8 mm/km	3.5 cm
45°	439 m		2.3 mm/km	2.1 cm

The current mission concept assumes precise baseline determination by a direct evaluation of GPS carrier phase measurements. Analyses indicate an achievable accuracy for the estimation of relative satellite positions in the order of 1-2mm [7]. The additional impact of satellite attitude errors and uncertainties in both the GPS and the RF antenna phase centre positions are being investigated. Note in this context that both satellites experience almost the same gravity field and are exposed to highly correlated orbital perturbations. Residual (i.e. unmodelled) variations of the baseline vector will hence show a high degree of temporal correlation. Even in case of a large differential acceleration of $\Delta a = 100 * 10^{-9} m/s^2$ (e.g. due to unmodelled differential drag between the two satellites, etc.), the resulting differential error after a 100km data take will be in the order of only 10µm. Noting furthermore, that such an acceleration will mainly affect estimates of the along-track baseline (which are uncritical for cross-track interferometry), we may conclude that residual orbit fluctuations can be neglected in the computation of relative height errors (the area for relative point-to-point height errors in HRTI-3 is approx. 100km x 100km).

Not neglected for the computation of relative height errors can, however, be the DEM tilt resulting from initial estimation errors of the relative RF antenna phase centre position. For example, an initial error in the estimate of the RF relative phase centre position of $\Delta B_{||}$=±1cm can in the worst case result in a relative height error of ±3.8m for Δs=100km (assuming an ideal mosaicking of equally tilted swaths). Such a tilt can be reduced by additional calibration data takes from crossing orbits by applying an appropriate bundle block adjustment in either radar or DEM geometry. Calibration data takes could also profit from larger baselines and/or different interferometric (e.g. pursuit monostatic or alternating bistatic) and/or different SAR (e.g. ScanSAR) modes. Absolute DEM calibration requires a final height accuracy of 10m and will be based on a combination of (1) a sparse net of calibration targets, (2) GPS tracks, and (3) ocean data takes with short along-track baselines. Further calibration strategies are currently under investigation.

The impact of oscillator phase noise in bistatic mode has been analyzed in [8] where it is shown that oscillator noise may cause errors in both the interferometric phase and SAR focusing. The stringent requirements for interferometric phase stability in the bistatic mode will require an appropriate relative phase referencing or an operation in the alternating bistatic mode. Direct transmission and reception of radar pulses is foreseen on both the TerraSAR-X and the TanDEM-X satellites. Assuming a height of ambiguity of 35m, the sensitivity to phase errors will be $h_{amb}/360° = 0.097$m/deg. The maximum allowed phase error for a height error of ±1m is hence ±10.3°. The required update frequency in the direct transmission mode is in the order of 1-10Hz depending on (1) the tolerable height errors, (2) the exact specification of the phase spectra of the two local oscillators, and (3) the phase noise on the 'synchronization' link.

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 parameter retrieval.

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 measure 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 TSX and TDX to the desired value. The combination of both modes will provide a highly capable along-track interferometer with four phase centers. As outlined in Sect. 2, 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

The phase A study of TanDEM-X demonstrated the feasibility of the mission and of associated key technologies. The achievable height accuracy in TanDEM-X is mainly limited by the height of ambiguity that can finally be processed during phase unwrapping. A mission concept has been developed which enables the acquisition of a global DEM within three years. 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 an optimization of the mission scenario by redefining the standard TerraSAR-X beams to improve both the performance and the coverage, an in depth analysis of the synchronization link, the development of a detailed calibration plan, the development of a multibaseline processing concept, as well as performance investigations for the other innovative TanDEM-X imaging modes.

7 References

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