The TanDEM-X Mission Design and Data Acquisition Plan

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Abstract

This paper gives an overview of the TanDEM-X mission design. A preliminary mission concept is proposed and a reference mission scenario introduced. It is shown that this reference scenario fulfils the requirements of deriving a global DEM according to the emerging HRTI-3 standard within the three year mission time and leaves enough spare time for secondary mission goals.

1 The TanDEM-X Mission

The primary goal of the TerraSAR-X/TanDEM-X (TDX) mission is the derivation of a global digital elevation model (DEM) in less than three years with accuracy according to the HRTI-3 standard [1]. The main specifications of this standard are given in Tab.1.

For setting up the mission concept, assumptions and constraints are analysed. Then, a preliminary reference scenario is introduced, for which the feasibility with respect to fuel consumption is proven. Data dump and a subsequent processing chain complete the proposed scenario.

Table 1 HRTI-3 specifications

Requirement	Specification	HRTI-3
Relative vertical accuracy	90% linear point-to-point error	2m (slope <20%) 4m (slope >20%)
Absolute vertical accuracy	90% linear error	10m
Horiz. accuracy	90% circular error	10m
Spat. Resolution	Indep. pixels	12m

2 The Mission Concept

2.1 Assumptions and Constraints

For gathering assumptions and constraints to derive a mission concept, the following aspects have been analysed in detail.

Collision Avoidance. For avoiding a collision within the formation, the separation of the two satellites should always be larger than 150m perpendicular to flight direction for safety reasons. Several formations have been investigated and the HELIX satellite formation has finally been selected. This formation combines an out-of-plane orbital displacement by different ascending nodes (i-vector) with a radial separation by different eccentricity vectors resulting in a helix like relative movement of the satellites along the orbit. The two orbits are spatially separated, allowing a ground-in-the-loop control.

Height of Ambiguity. For deriving a DEM, the satellites should monitor the same scene with slightly different incident angles and a very small time difference between the image acquisitions. One parameter, which determines the height accuracy of an interferometric image, is the effective baseline. The effective baseline is defined as the effective distance of the two receiving satellites orthogonal to the line of sight of one receiving satellite. There are two major aspects concerning this effective baseline: a larger effective baseline will result in a better height accuracy of the desired scene. On the other hand, problems will arise as soon as the phase difference between consecutive image pixels becomes as large as π, since it is then possible to assign different heights to a given phase value. These ambiguities are defined by the so-called height of ambiguity which decreases with increasing baseline length. As a consequence, also small baselines will be required for an unambiguous retrieval of the height information in scenes with steep terrain gradients. Another possibility would be the use of a priori information like an already derived DEM from former missions like the SRTM-mission [2] or another approach like the combination of two slightly differing heights of ambiguities [3].

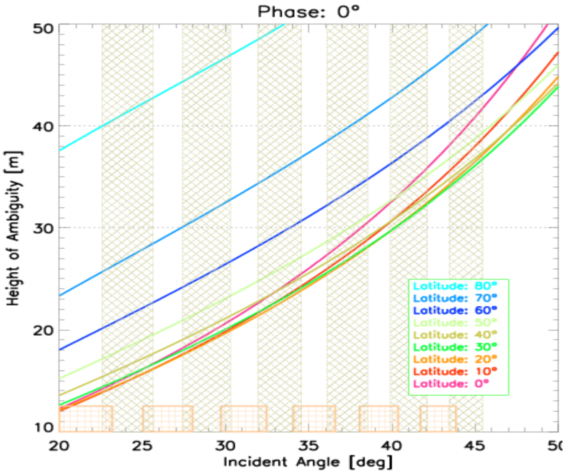

Fig. 1 Height of ambiguity for HELIX 300/500/0. The abscissa marks the incident angle and the ordinate the height of ambiguity. Shaded areas represent TerraSAR-X beams. The coloured lines represent the height of ambiguity for different latitudes.

For deriving a DEM according to HRTI-3 standard, performance predictions show that the height of ambiguity shall range between ~30m and ~40m [4]. As the height of ambiguity depends not only on the effective baseline but also on the incident angle, for a chosen HELIX not all swaths may be suitable for monitoring (cf. Fig 1). As shown in Fig. 1, the HELIX at the libration phase 0° is able to monitor the Earth from 0°…50° with a restriction to incident angles between 40°…45° with the required height of ambiguity. Due to the motion of libration, the HELIX will change in time, leading to different baselines at different libration phases – and hence to other heights of ambiguities. This suggests the derivation of the global DEM by a swath and latitude dependent monitoring.

Orbit geometry. Due to the natural orbits, ground tracks of the satellite will approach each other with increasing latitude. This implies that for higher latitudes fewer sub-swaths will be required. This indicates the advantage of a latitude based derivation of the DEM.

Monitoring Time. To estimate the mean joint monitoring time, we assume that the nominal monitoring time for one satellite is 170s as defined by the TerraSAR-X specifications. As the TerraSAR-X mission should not be impaired, this time is allocated on each satellite with 85s respectively. During receive the thermal and power constraints are not so critical so that 10s transmit correspond to 75s receive-only. Thus, the remaining 85s monitoring time can be regarded as 75s (receive-only) plus 75s (transmit and receive), resulting in a mean joint monitoring time of 150s. This time will be cut into 140s effective mean monitoring time including 10s margin for data loss and/or calibration etc.

Mission Time. The mission time is set to three years or 1095days. With a mean monitoring time of 140s per orbit, a global DEM may be derived in ~one year. It can be shown that ~65% of the Earth's landmass may be assumed rather flat, leaving ~35% of landmass which may require more than one mapping. Analyses show that with a conservative approach 50% of the landmass requires one monitoring, 30% requires additional 1-2 mappings and the remaining 20% additional 2-3 mapping, resulting in a total of 300 Mil. km² to be mapped. This will require at least 2 years, demanding a minimization of overlap between the swaths. This may be achieved by mapping the northern hemisphere with ascending orbits only and the southern hemisphere with descending ones (or vice versa). Due to the inherent symmetry in the HELIX formation, the adequate heights of ambiguity are supported for southern and northern latitudes simultaneously. Again, this will support a latitude dependent mapping.

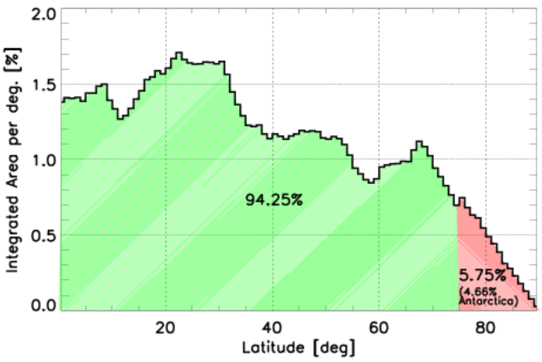

Fig. 2 Landmass distribution by latitude. Southern and northern landmasses are added.

Landmass distribution. An analysis shows that the landmass is almost uniformly distributed by latitude. This is valid for latitudes below ±75°, which cover ~ 95% of the global land mass (cf. Fig. 2) and supports a latitude dependent mapping.

Fuel. The TerraSAR-X mission is already planned and may not be changed. This means that the second satellite shall perform all formation keeping and formation change manoeuvres. As an e-vector separation must be stabilized, this vertical displacement is chosen as small as possible. Analyses show that 300m at the northern/southern turns is sufficient. Furthermore, the number of formations for deriving the DEM should be kept as small as possible to leave the flexibility as high as possible.

Radar limitations. It might be necessary to monitor the same scene with different incident angles, e.g. due to foreshortening, shadowing or steep terrain. This can be achieved by 'exchanging' the satellites, i.e. a libration phase shift of 180°. On the other hand, after the exchange the regions mapped prior with an ascending orbit may now be mapped with a descending one. This will allow for e.g. bundle adjustment and an enhancement of the DEM.

Performance: The TerraSAR-X beams fulfill the requirements of deriving the required DEM with its specifications from the performance point of view [4]. The definition of TerraSAR-X 30km wide Stripmap swaths with an overlap of 6km (SS05-SS14), corresponding to an incident angle range of [20°; 45,5°] may be found in [5].

Based on the assumptions and constraints above, it is now possible to derive a preliminary reference scenario.

2.2 Preliminary Reference Scenario

M-A – 1day: Launch of the satellite. In this mission phase, no radar monitoring is possible. The mean along-track separation of the two satellites is assumed to be in the order of 3000km for safety reasons.

M-B – 20days: Approach of the two satellites to 20km for commissioning. In this mission phase, it is possible to acquire data for e.g. calibration and other Radar data products.

M-C – 70days: Commissioning and calibration phase. Data will be acquired for DEM and system calibration and acquisition of raw data products. Testing of safe formation flight and ground control.

M-D – 462days: Global DEM acquisition and some secondary mission goals (e.g. along-track interferometry)

M-E – 11days: Change of the formation phase by 180°. For a safe manoeuvre, an along-track separation of 20km should suffice. This mission phase is also well suited for secondary mission goals.

M-F – 462days: Finalising the global DEM according to HRTI-3 standard. Again, secondary mission goals may be achieved in this mission phase.

M-G – 66days or more: In this phase, the satellites may be separated in cross-track for e.g. super-resolution techniques or in along-track for one-day-repeat pass interferometry. This phase is mainly for new modes.

Table 2 Preliminary detailed reference scenario. For each mission phase the corresponding HELIX, length of duration and mapping parameters are given. The last column represents the mission timeline.

Mission Phase	Vertical	Horizontal	Phase	Nominal along track	Time	Latitude	Swath	Timeline
M-A	-	-	-	3000km	1^d	-	-	**-91^d**
M-B	300m	1000m	0°	3000km-20km	20^d	0°-90°	03-14	**-90^d--70^d**
M-C	300m	1000m	0°	20km	70^d	0°-90°	03-14	**-70^d-0^d**
M-D1	300m	300m	345°-30°	0m	27.9^d	0°-10°	05-11	**0^d-165^d**
			345°-30°		25.8^d	10°-20°	06-12	
			345°-30°		32.6^d	20°-30°	06-13	
			345°-30°		27.6^d	30°-40°	06-13	
			345°-30°		19.3^d	40°-50°	06-11	
			345°-30°		14.1^d	50°-60°	05-09	
			345°-30°		13.4^d	60°-70°	04-06	
M-D2	300m	400m	345°-15°	0m	23.9^d	0°-10°	07-12	**165^d-297^d**
			345°-15°		22.1^d	10°-20°	08-13	
			345°-15°		24.5^d	20°-30°	08-13	
			345°-15°		17.2^d	30°-40°	09-13	
			345°-15°		16.1^d	40°-50°	08-12	
			345°-20°		14.1^d	50°-60°	07-11	
			345°-20°		13.4^d	60°-70°	06-08	
M-D3	300m	500m	345°-0°	0m	20.0^d	0°-10°	10-14	**297^d-418^d**
			345°-0°		18.4^d	10°-20°	10-14	
			345°-0°		16.3^d	20°-30°	11-14	
			345°-0°		13.8^d	30°-40°	11-14	
			345°-0°		16.1^d	40°-50°	10-14	
			345°-15°		16.9^d	50°-60°	09-14	
			345°-15°		17.9^d	60°-70°	07-10	
M-D4	500m	300m	345°-0°	0m	44^d	70°-90°	06-12	**418^d-462^d**
E	-	-	-	20km	11^d	-	-	**462^d-473^d**
M-F1 – M-F4	Same scenario as in mission phase **M-D1 – M-D4** with exchanged satellites. This means, that the same hemisphere is monitored with ascending and descending orbits. The same time, latitude, and swath parameters apply.							**473^d-935^d**
M-G1	500m	500m	210°-150°	0m	11^d	0°-90°	03-14	**935^d-946^d**
M-G2	500m	1000m	210°-150°	0m	11^d	0°-90°	03-14	**946^d-957^d**
M-G3	500m	2000m	210°-150°	0m	11^d	0°-90°	03-14	**957^d-968^d**
M-G4	500m	3000m	210°-150°	0m	11^d	0°-90°	03-14	**968^d-979^d**
M-G5	500m	4000m	210°-150°	0m	11^d	0°-90°	03-14	**979^d-990^d**
M-G6	300m	8000m	210°-150°	130km	11^d	0°-90°	03-14	**990^d-1001^d**
M-H1	0m	8000m	210°-150°	130km-7850km	X	0°-90°	03-14	**1001^d-end**

It is seen that for high latitude the HELIX is changed to a radial separation of 500m. This is necessary to supply the required height of ambiguity. The horizontal separation is set to 300m, which allows for mapping a large range of latitudes. The time in this mission phase is limited because the large radial separation requires more fuel.

2.3 Fuel Consumption

In order to estimate the fuel consumption, it is assumed that the TanDEM satellite will replicate all manoeuvres of the TerraSAR-X satellite. In addition, manoeuvres have to be executed by TanDEM-X to maintain and reconfigure the formation. In particular the following additional manoeuvres are taken into account: approach of TerraSAR-TanDEM to TerraSAR-X satellite after in orbit injection, manoeuvres to keep the formations stable for three years mission time, one manoeuvre to exchange the two satellites (this is necessary to monitor the same hemisphere with descending/ascending orbit), one separation manoeuvre almost at the end of the TanDEM mission to ~8000km for secondary mission goals. Detailed analyses show that for the formation keeping manoeuvres a second thrusters system is required with cold gas, requiring ~38kg fuel which is well within the mass budgets [6].

2.4 Data Reception Concept

For dumping the radar data to ground stations, adequate coverage of the ground stations is prerequisite. By assuming a minimum look angle of 5° from the ground station to the satellites, it can be demonstrated that 2-3 ground stations located at high latitudes suffice to dump all data within one orbit. Under certain conditions the two satellites will downlink their data to different stations. Since both satellites form one interferometric instrument, an instance has to be foreseen where both downlinks are compiled and synchronized for further processing.

2.5 Data Processing System

Processing of the bistatic TanDEM-X data to precise DEMs is a challenging task for a number of reasons. Alone the amount of data acquired within two years is on the order of 290 Terabytes compared to 10 Terabytes recorded during the Shuttle Radar Topography Mission (SRTM). The processing system and algorithms will be based on the SAR processor of the TerraSAR-X payload ground segment [7] and on the interferometry processor that has been developed for SRTM [8]. Due to the bistatic operation of the SAR, the mission duration of 3 years and the increased accuracy requirements significant changes have to be made on the existing systems. In the following some major aspects are shortly listed.

a) The bistatic operation with independent local oscillators will cause slight PRF asynchrony and echo window drifts over longer time spans, significant range mis-registration over shorter time spans and enormous interferometric phase drifts [9]. In the TanDEM-X satellites a special inter-satellite communication link is foreseen to measure such phase drifts. In the SAR processor a stepwise approach will be implemented to estimate and compensate the timing differences of both oscillators down to small fractions of a wavelength.

b) In order to achieve high accuracy, TanDEM-X will operate with effective baselines in the order of 200m resulting in height ambiguities of ~40m. Phase unwrapping of such data will be difficult if the terrain is steep and also shadow and layover problems must be solved in this case. Therefore multi baseline, multi incidence and multi aspect angle techniques are required to generate a homogeneous global DEM [10].

c) A further challenge is the final mosaicking of the single DEMs to continental scale. Bundle adjustment techniques and external references will be used to reduce the residual instrument errors down to the specified tolerances.

d) Finally a semi-automatic DEM editing process will be performed to mask or interpolate erroneous height values and to set water bodies to a constant height value. The overall processing system from the satellite raw data to the global DEM will be modular with intermediate data storage points so that critical steps can be repeated with improved processing parameters or with additional satellite acquisitions.

3 Conclusion

The investigations during the Phase A study have shown that the TanDEM-X mission is capable of the derivation of highly accurate digital elevation models of the Earth’s landmass according to the HRTI-3 standard. A reference mission scenario for deriving such a DEM has been developed which enables the acquisition of all required data takes within three years. There are enough resources and time in the TanDEM-X mission to arrange baseline constellations which allow for secondary mission goals like e.g. along-track interferometry, moving target indication, measurement of ocean currents, and digital beam-forming. In a Phase B, further analyses will optimise the above scenario, e.g. taking into account the possibility to create new swaths and/or increase the mean monitoring time.

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