The TerraSAR-X / TanDEM-X Formation Flight: Challenges to Flight Dynamics and First Results

R. Kahle[1], M. Wermuth[1], B. Schlepp[1], S. Aida[1]
[1]*German Aerospace Center / German Space Operations Center (DLR/GSOC), Wessling, Germany, Email: ralph.kahle@dlr.de*

1 Introduction

The primary goal of the TerraSAR-X mission (launched on 15 June 2007) is the provision of high-resolution Synthetic Aperture Radar (SAR) data to both science and commercial users. At 21 June 2010 an almost identical satellite, TanDEM-X, was launched in order to form the first configurable SAR interferometer employing formation flying with TerraSAR-X. The primary objective of the common TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) mission is to generate a global digital elevation model (DEM) with unprecedented accuracy as the basis for a wide range of scientific research as well as for commercial DEM production. After finalization of the mono-static and bi-static radar instrument commissioning phases both satellites start routine operation as a large single-pass SAR interferometer in December 2010. Within three years of formation flying with flexible baselines ranging from 200 m to few kilometers the two satellites will image the terrain below them simultaneously, from different angles. These images will be processed into accurate elevation maps with a 12-metre resolution and a vertical accuracy better than 2 meters. Being entirely homogenous, the TanDEM-X digital elevation model will serve as a basis for maps that are globally consistent. Conventional maps are often fragmented along national borders, or difficult to reconcile as they are based on different survey methods or because of time lags between survey campaigns. Besides this primary goal, the mission has several secondary objectives based on new and innovative methods such as along-track interferometry, polarimetric synthetic aperture radar interferometry, digital beamforming and bistatic radar [8].

The TanDEM-X project is partly funded by the German Federal Ministry for Economics and Technology (Förderkennzeichen 50 EE 0601) and is realized in a public-private partnership (PPP) between German Aerospace Center (DLR) and Astrium GmbH. The entire ground segment was built up by DLR which is in charge of controlling and operating the two satellites, commanding and calibrating its SAR instruments, receiving, processing and archiving the X-Band data and generating and delivering the final user products. The major achievement is the provision of high-quality SAR products to the user community based on a reliable service since the TSX mission entered its routine operation phase end of 2007 while maintaining a remarkable SAR system performance (for an overview on the ground-segment refer to [9]).

The satellites were built by Astrium GmbH. The TanDEM-X satellite follows the TerraSAR-X design with minor modifications such as an additional cold gas propulsion system (powered by high-pressure nitrogen gas) to enable fine-tuning of its relative position during formation flying and an additional S-band receiver to receive status and position information sent by TerraSAR-X (see Tab. 1). This data is utilized within TanDEM-X Autonomous Formation Flying System (TAFF) for purpose of relative navigation and optionally closed loop in-plane formation maintenance. The TanDEM-X satellite has been designed for a nominal lifetime of five years and has a planned overlap with TerraSAR-X of three years. TerraSAR-X holds consumables and resources for up to seven years of operation however, potentially allowing for a prolongation of the overlap and the duration of the TanDEM-X mission.

Table 1. TerraSAR-X / TanDEM-X satellite characteristics (FD-relevant parameters only)

	TerraSAR-X	TanDEM-X
Launch date	2007-06-15	2010-06-21
Dimension	Height: 5 meters, Diameter: 2.4 meters	
Mass (2010-11-09)	1325 kg	1341 kg
Propulsion system	4 x 1N thrusters in anti-flight direction – 78 kg Hydrazine	4 x 1N thrusters in anti-flight direction – 78 kg Hydrazine, 2 x 40mN thrusters in each flight and anti-flight direction – 36 kg Cold-Gas (Nitrogen)
GPS receivers	MosaicGNSS single-frequency (EADS/Astrium), IGOR dual-frequency (BRE/JPL/GFZ Potsdam)	
Inter-satellite communication	S-Band transmitter	S-Band receiver
Other		TanDEM-X Autonomous Formation Flying System (TAFF)

The paper focuses on challenges to flight dynamics implied by the operation of the very first scientific Earth observation mission employing formation flying. In particular requirements, realization and results in the disciplines of a) formation acquisition, b) formation maintenance, c) precise baseline reconstruction, and d) space debris collision avoidance are discussed.

1.1 The TerraSAR-X Orbit

Before concentrating on the formation acquisition and maintenance aspects briefly the TSX orbit and its control concept are introduced. Since 2007 TSX is controlled within a tube of 250 m radius around a predefined Earth-fixed reference orbit that enables highly repeatable data-take conditions. Orbit keeping maneuvers are conducted on semi-regular basis to adjust the TSX orbit to the 11-days repeat reference trajectory (for details refer to [2]). Within the solar minimum period 2008-2009 in-plane control maneuvers with typically 1 cm/s Δv were performed every 10 to 14 days. Since end of 2010 an increased solar activity is causing higher drag, which results in a shorter maneuver cycle of about one week and larger maneuvers of about 2 cm/s size. For the period of solar maximum a two days maneuver cycle with 4-5 cm/s maneuver size is expected. To counteract luni-solar perturbations on the inclination, out-of-plane maneuvers are performed 3-4 times a year with up to 30 cm/s Δv.

2 Formation Acquisition

This section focuses on the in-flight realization of the TDX-TSX formation building. However, prior to TDX launch significant preparatory work was performed in the fields of launch injection collision assessment and target orbit acquisition analysis. Both topics were essential in the process of TDX launch day selection in order to minimize both the risk of collision and the maneuver budget (cf. [6] for details). Here risk of collision refers to the danger of close approach between TSX and the newly injected Dnepr upper-stage, the gas dynamic shield, and the TDX. Furthermore, the TDX total velocity increment required for the acquisition of the formation with TSX was analytically assessed as a function of launch day relative to the TSX 11-days cycle and launch injection accuracy. Based on the results a launch on cycle-day 3 with day 4 as backup was proposed to the spacecraft manufacturer for consideration within the launch arrangements. The TDX launch finally was scheduled and performed on June 21, 2010, i.e. on cycle-day 3.

As for TSX the TDX satellite was very accurately ingested by a DNEPR rocket launched from Baikonur. As expected, TDX was 15700 km behind of TSX at the moment of separation and about 4.8 km lower. During the first hours after separation TDX performed only few safe mode thruster firings resulting in a slight orbit raise of about 350 m. Later on the thrusters were also used to stabilize the spacecraft attitude during X-band boom deployment and reaction wheel check-out causing an additional 600 m altitude increase. Finally a safe mode drop after an on-board computer reboot on June 22 caused again a slight orbit raise of about 200 m. The total hydrazine fuel consumption for safe mode attitude control was only 580 gram and thus well within the limits. After commissioning of the main AOCS sensors and actuators, a first orbit maneuver could be performed within 1.5 days after launch to adjust the along-track drift rate towards TSX to about 630 km per day. As shown in Fig. 1 the maneuver also contributed to the correction of the relative eccentricity vector.

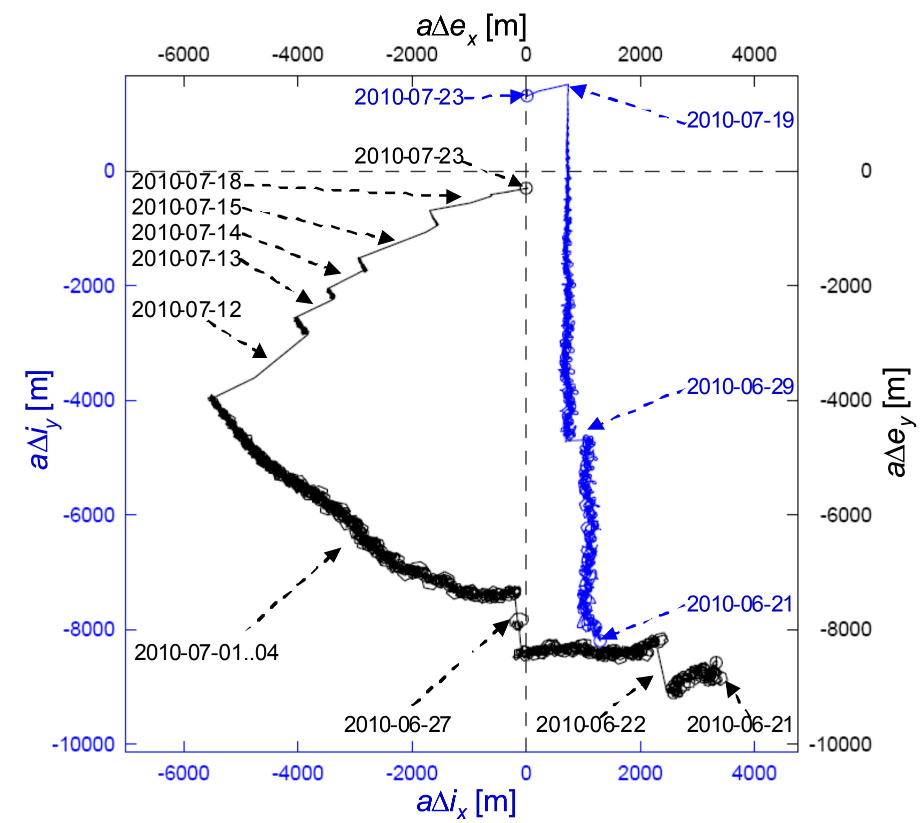

Figure 1: Evolution of TDX-TSX relative eccentricity (black) and relative inclination (blue) vectors in the period from June 21 to July 23, 2010. The labeled arrows indicate orbit maneuvers.

On June 27, 2010 TDX closely approached two space objects: a non-operational satellite (ERBS, launched 1984) and a TIMED space debris. Two collision avoidance maneuvers were performed: the first one raised the predicted radial separation during moment of closest debris approach from about 25 m to about 1 km. The second maneuver was executed in anti-flight direction to restore the along-track drift rate towards TSX and further to reduce the collision risk with ERBS from 1E-4 to 1E-6. Both maneuvers did not cause additional fuel consumption w.r.t. the nominal acquisition budget, because the maneuver locations were optimized to decrease the relative eccentricity vector deviation at the same time (cf. Fig. 1).

Thereafter, a long drift phase followed. Because only a few large hydrazine maneuvers were performed by then, the drift period was utilized to perform a total of 11 in-plane maneuvers with alternating direction and different sizes (i.e. ±1.0 … ±6 cm/s, July 1-4). After calibration of these maneuvers within the orbit determination process the maneuver command parameters were slightly adjusted to yield a better match of planned and executed performance, which was of high relevance for the period of formation fine acquisition and maintenance thereafter. The small maneuvers contributed to the relative eccentricity vector correction too (cf. Fig. 1).

In order to benefit in terms of ascending node drift the small injection offset in relative inclination (i.e. $a\Delta i_x \approx 1$ km) was kept constant for about one week and then was slightly reduced on June 29. The largest out-of-plane adjustment was a combined RAAN / inclination correction maneuver on July 19. In that way the initially huge relative inclination vector deviation (i.e. $a\delta\delta i \approx$ 6.5 km, cf. Fig. 1) was corrected by spending only 1.27 m/s. For comparison: without the drift of the TDX orbital plane a Δv of 7.2 m/s would have been necessary.

The along-track drift was step-wise reduced and finally stopped in the period from July 12 to 18. Similar to a rendezvous sequence the maneuver size was lowered towards smaller distances in order to reduce uncertainties from maneuver execution errors, too. Finally, the formation required for mono-static radar instrument commissioning phase was acquired accurately and on time. The total TDX velocity increment contained within 23 acquisition maneuvers (including debris collision avoidance and hydrazine calibration, too) performed in the period from June 22 to July 19 was only 6.5 m/s out of a maximum design budget of 18.5 m/s. The mono-static formation comprised of 20 km along-track, 300 m vertical (i.e. $a\delta e$) and 1305 m horizontal separation (i.e. $a\delta i$). The 1.3 km horizontal displacement at equator crossings was chosen to cancel the earth-fixed ground-track displacement resulting from the 2.6 seconds difference in flight-time. The pursuit mono-static commissioning phase was accomplished on October 10, 2010. In order to commission the bi-static capabilities of the constellation a first reconfiguration from wide into narrow formation was performed within three days comprising of four maneuvers with a total velocity increment of less than 1.2 m/s [6]. Since mid of October 2010 the satellites fly in a close formation with zero mean along-track separation and flexible baselines comprising of 260 to 400 m vertical separation (i.e. $a\delta e$) and 209 to 450 m horizontal separation (i.e. $a\delta i$).

3 Formation Maintenance

The formation monitoring process is based on synchronous orbit determination from navigation solution data obtained from the TSX / TDX dual frequency GPS receivers. The (relative) orbit determination process is dump-triggered and therefore automatically runs up to 10 times a day. The processing of equal data arcs with same environment model parameters cancels common errors which are mainly related to atmospheric drag modeling. Typically the relative navigation as used in the formation control process has a cross-track (2D) accuracy < 0.5 m (RMS) and the along-track accuracy is on the 1 m level, which is sufficient for the purpose of formation monitoring and control with specified 20 m and 200 m control accuracies in cross-track and along-track directions, respectively [7].

Since the original TerraSAR-X mission must not be affected by the TanDEM-X mission, the orbit control concept comprises of two steps: absolute and relative orbit control. Absolute control refers to the on-going orbit keeping of TSX within a 250 m radius tube around the TSX reference trajectory which exactly closes after an 11-days repeat cycle and the concept was introduced in sect. 1.1. On the other hand, the TDX-TSX relative orbit control concept is based on the relative eccentricity / inclination vector separation method (for details cf. [2]). In order to meet the relative control requirements imposed by SAR interferometry TDX must both replicate the TSX orbit keeping maneuvers and compensate the natural deviation of the relative eccentricity / inclination vectors. While the cm/s-level absolute orbit maintenance is performed with four 1 Newton hydrazine thrusters, two 40 milli-Newton cold-gas thrusters are used exclusively on-board TDX (cf. Tab. 1) to control the formation including counterbalancing of possible along-track drifts resulting from differential hydrazine maneuver execution errors.

The frequent maneuver planning process has to consider not only the ground-station network (implying the availability of command upload or navigation data availability) and the interaction with radar instrument operation. Also unforeseen events, e.g. maneuver failures or satellite safe mode drops, must not imply any danger of collision. A maneuver check has been implemented to analyze how the formation changes in consequence of all possible maneuver failure scenarios. For example, the planning of one common TSX / TDX maneuver and two additional TDX formation maintenance maneuvers yields 16 maneuver failure scenarios. If any of these scenarios implies a 150 m approach in the plane perpendicular to flight-direction the maneuver commanding is blocked and manual inspection becomes necessary. This is regularly the case for TSX out-of-plane maneuvers which can be up to 30 cm/s large, in the worst case resulting in a horizontal separation change of 270 m.

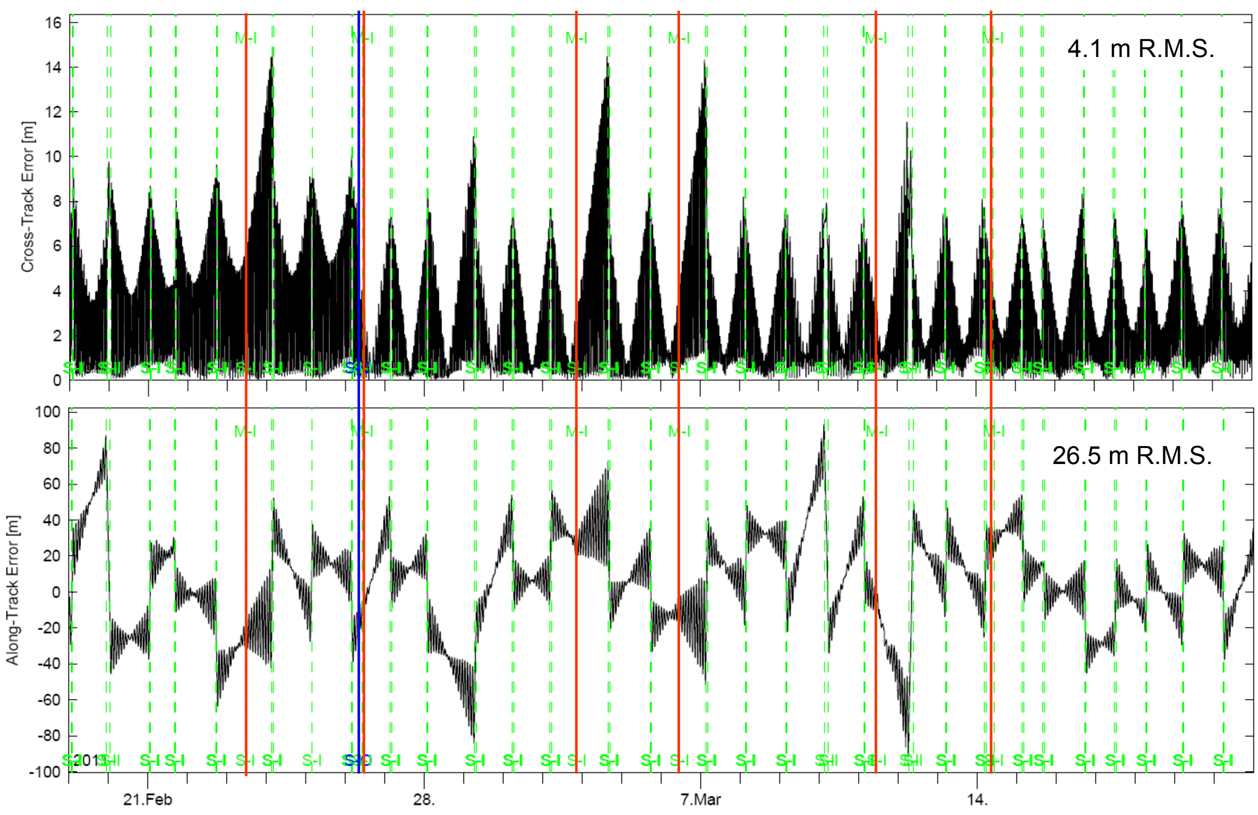

Figure 2: Formation control performance in the period from Feb. 19 to Mar 21. Top: the combined radial and normal error (i.e. cross-track error, 2D) is 4.1 m R.M.S. (requirement: 28.3 m). Bottom: the along-track error amounts to 26.5 m R.M.S. (requirement: 200 m). The vertical lines indicate common TSX/TDX maneuvers (red) and TDX formation maintenance maneuvers (green: in-plane, blue: out-of-plane).

As a result of an extensive ten-month formation control software simulation (for details cf. [5]), most of the FD system fine-adjustments were done and the ground processing parameters were almost finally configured before TDX launch. Thus the commissioning of the formation maintenance function at end of July 2010 went very smooth and fully validated the control and operations concept. Because of the achieved excellent control accuracy of 5 m RMS in cross-track (2D) and < 50 m RMS in along-track direction and in order to safe precious cold-gas for a likely mission extension, it was decided to make use of the TDX hydrazine propulsion system to control the 20 km along-track formation within the remaining time of the mono-static commissioning phase. The thereby achieved performance (i.e. < 20 m RMS in cross-track and < 300 m RMS in along-track direction) was fully sufficient for the purpose of calibrating the TDX radar instrument for mono-static operation and surprisingly accurate considering the fact that only two formation maintenance maneuver pairs were performed per week in order to minimize the impact on radar operations.

Shortly after acquiring the narrow formation in October 2010 the ground formation control process became fully automated. Daily formation maintenance maneuvers with the cold-gas propulsion are being performed especially in order to precisely control the along-track separation which is fundamental for purpose of SAR cross-track interferometry. Here, as short as possible along-track baselines ensure an optimum overlap of Doppler spectra and avoid temporal correlation in vegetated areas (e.g. due to wind). The biggest challenge as compared to previous experimental formation flying missions is the operational character demanding for continuously safe and robust operation with high control accuracy for at least three years. For example, Fig. 2 depicts the stable and precise control of the TDX-TSX cross-track and along-track separation over a 30-days period. Table 2 summarizes the formation control accuracies achieved during different mission phases and compares to mission requirements, which are clearly fulfilled.

Table 2. Formation control accuracy achieved during bi-static commissioning phase and first routine DEM acquisition cycle with large horizontal drift and mission requirements (right) [7].

[m]	Nov. 20 – Dec. 1, 2010			Dec. 12 – 23, 2010			Required
	Mean	STD	RMS	Mean	STD	RMS	RMS
Radial, ΔR	0.0	5.2	**5.2**	0.0	4.5	**4.5**	**20.0**
Along-Track, ΔT	-0.2	25.4	**25.4**	2.5	27.2	**27.3**	**200.0**
Normal, ΔN	0.0	0.9	**0.9**	0.0	7.8	**7.8**	**20.0**
Cross-Track, ΔC (2D)	4.2	3.2	**5.3**	8.6	2.7	**9.0**	**28.3**

4 Precise Baseline Reconstruction

In order to process the DEM data takes with highest accuracy, the baseline between the satellites has to be known with an accuracy of 1 mm (1D, RMS). The baseline is defined as the vector between the SAR antenna reference points of the two satellites. To achieve this goal, both satellites are equipped with high grade dual-frequency IGOR (Integrated GPS and Occultation Receiver) GPS receivers provided by GeoForschungszentrum Potsdam (GFZ).

The baseline is determined with the FRNS software (Filter for Relative Navigation of Spacecraft) developed at DLR/GSOC in cooperation with the TU Delft. It is based on an extended Kalman filter/smoother process. The underlying concept of the FRNS software is to achieve a higher accuracy for the relative orbit between two spacecraft by making use of differenced GPS observations, rather than by simply differencing two independent precise orbit determination results. The use of single-differenced code and carrier phase observations rigorously eliminates GPS clock offset uncertainties and largely reduces the impact of GPS satellite orbit and phase pattern errors. Double differences are used for the integer ambiguity resolution of the carrier phase observations and common error cancellation. One of the major error sources is ionospheric delay, which cancels out to a large degree due to the short distance between the two spacecraft.

Experience with relative navigation from the GRACE mission shows that a baseline accuracy of 1 mm 1D-standard deviation can be achieved with the given GPS receivers. But the comparison of solutions between independent software packages shows systematic offsets in the order of a few mm [4]. From internal quality assessments we conclude that the same level of accuracy as for the GRACE mission could be achieved: the differential GPS residuals for carrier phase observations show an RMS of about 1.0 mm for the L1 frequency and 0.6 mm for the L2 frequency (Fig 3).

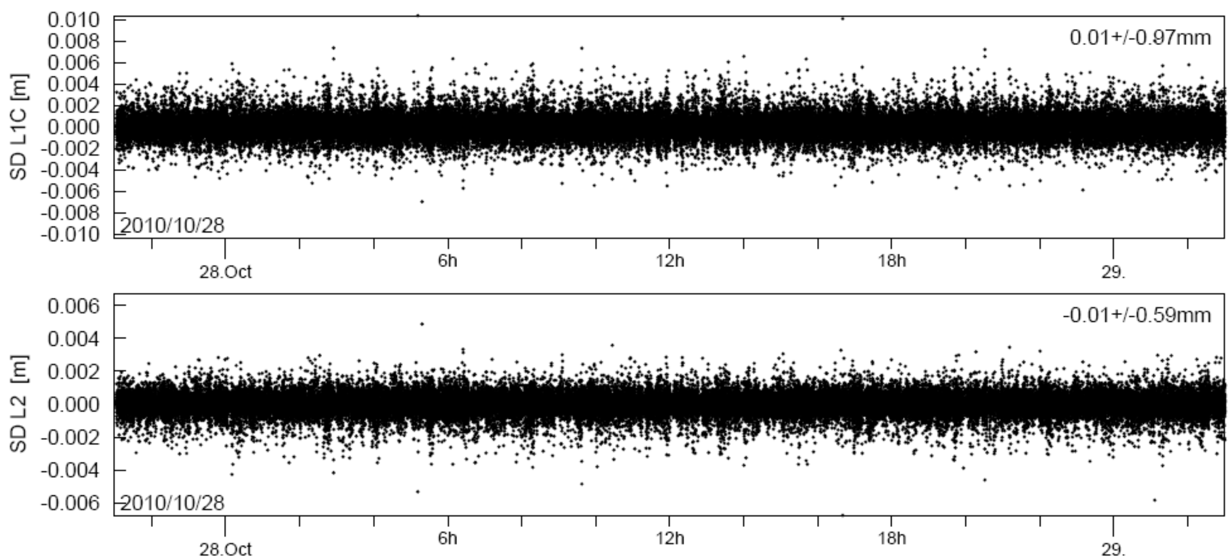

Figure 3: GPS differential carrier phase residuals for DOY 301/2010.

In order to asses the baseline accuracy by external means and further to quantify a possible systematic offset, the baseline products have to be calibrated by dedicated bi-static calibration radar data takes. These data takes are acquired over areas with a very well known DEM. In this way systematic offsets in the baseline solution can be detected and calibration parameters are derived. Current analysis confirms standard deviation in the line-of-sight vector below 1.5 mm [10]. Finally the calibrated solutions of different institutions and software packages (DLR/GSOC & GFZ) are merged to a calibrated baseline product for use within the DEM generation process.

5 Debris Collision Avoidance

Although the 514 km altitude sun-synchronous orbit implies only 3 to 5 critical space debris conjunctions per year on average, the operational handling of avoidance maneuvers to be performed by satellites flying in close formation can be quite challenging. In general, GSOC FD performs a daily collision risk assessment for all GSOC-operated satellites (for details refer to [1]). Depending on approach geometry and risk estimate a radar tracking campaign can be made for risk re-assesment. In case a significant risk remains (i.e. probability > 1E-4) the following precautions exist in principle for the TDX-TSX formation.

If the risk applies only to TSX there are three collision avoidance scenarios:

A. Change execution time and size of a regular TSX maneuver to take place before (or after) the event, TDX replicates the maneuver as usual, or
B. TSX performs two maneuvers: collision avoidance and re-acquisition of reference orbit, and
B.1 TDX replicates the maneuvers, which can be fuel-expensive, or
B.2 TDX remains passive and the formation has to be re-acquired by TDX afterwards, which can be time-consuming.
Clearly, in case B a trade-off has to be made when deciding about the avoidance strategy.
On the other hand, if solely TDX is affected TSX remains passive and TDX has to perform maneuvers for collision avoidance and formation re-acquisition.

Of course the risk assessment is to be repeated for every maneuver planned for TSX and/or TDX before command upload. Note that in our scenarios we have assumed that the debris orbit is known good enough to allow for precise approach geometry assessment. If that was not the case, the scenario B.1 will be used and both satellites perform avoidance maneuvers jointly.

The close approach of TDX to CZ-4 Debris (~15 cm diameter from radar cross section) at 2011/03/25 15:08:11 UTC was the first critical close approach and consequently lead to the first collision avoidance maneuver, since the close formation of TSX and TDX was achieved. Half a day before the time of closest approach (TCA), warnings for both satellites were received from the Joint Space Operation Center (JSpOC) specifying total/radial distances of 84/83 m (TDX) and 245/165 m (TSX). The event was re-assessed by FD using precise orbital elements of the satellites and orbit data of the debris provided by JSpOC. The updated results in Tab. 3 confirmed the critical proximity of the debris to both satellites, passing through their close formation (260 m radial separation) as shown in Fig. 4. Compared with the estimated orbit uncertainties (radial, 1-sigma: 6 m for TDX, and 20 m for debris), the small total/radial distance of 88/87 m for TDX was nearly in the 3-sigma region and thus considered as critical. In addition, radar measurement for debris orbit refinement was not available. Therefore seven hours before TCA a collision avoidance maneuver was decided for TDX. An additional radial separation of 40 m was planned to bring TDX to 50 % outside the 3-sigma uncertainty region. After the collision avoidance maneuver, a minimum total distance of 136 m was achieved, i.e. -125 m radial, 38 m along-track, and 38 m normal distance. Two maneuvers were performed in total; one was for the collision avoidance half an orbit before TCA and the other for the formation re-acquisition half an orbit after TCA.

Table 3: Prediction results before maneuver planning.

		TanDEM-X	TerraSAR-X
Source of primary object data		GSOC POD	GSOC POD
Source of secondary object data		JSpOC	JSpOC
TCA		2011/03/25 15:08:11 UTC	
Orbital plane angle	[deg]	90	
Relative velocity	[km/s]	10.8	
Collision probability	[-]	2.8E-05	6.8E-06
Minimum total distance	[m]	88	186
Relative position (R, T, N)	[m]	-87, -9, -9	173, -5, -5
1σ uncertainty (R, T, N), satellite	[m]	6, 191, 5	2, 69, 1
1σ uncertainty (R, T, N), debris	[m]	20, 876, 11	

Fig. 5 depicts the TDX-TSX relative motion (blue curve) in the plane perpendicular to the flight direction for March 25 during the period from 12:00 to 18:00 UTC. The pink error bars show the 20 m (1-sigma) radial and normal control requirement. Because of the avoidance maneuver, TDX was slightly outside the 1-sigma control band (upper blue curve). The maximum cross-track error was only 37 m with regard to the target formation parameters and therefore it can be concluded that the SAR instrument operation was not affected.

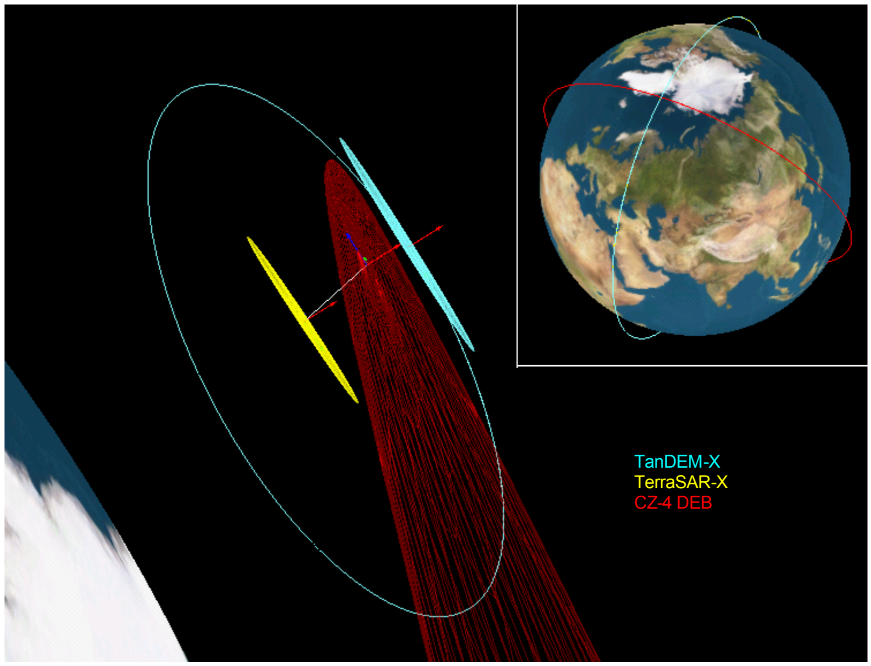

Figure 4: Close approach geometry at TCA, with 3-sigma orbit uncertainties.

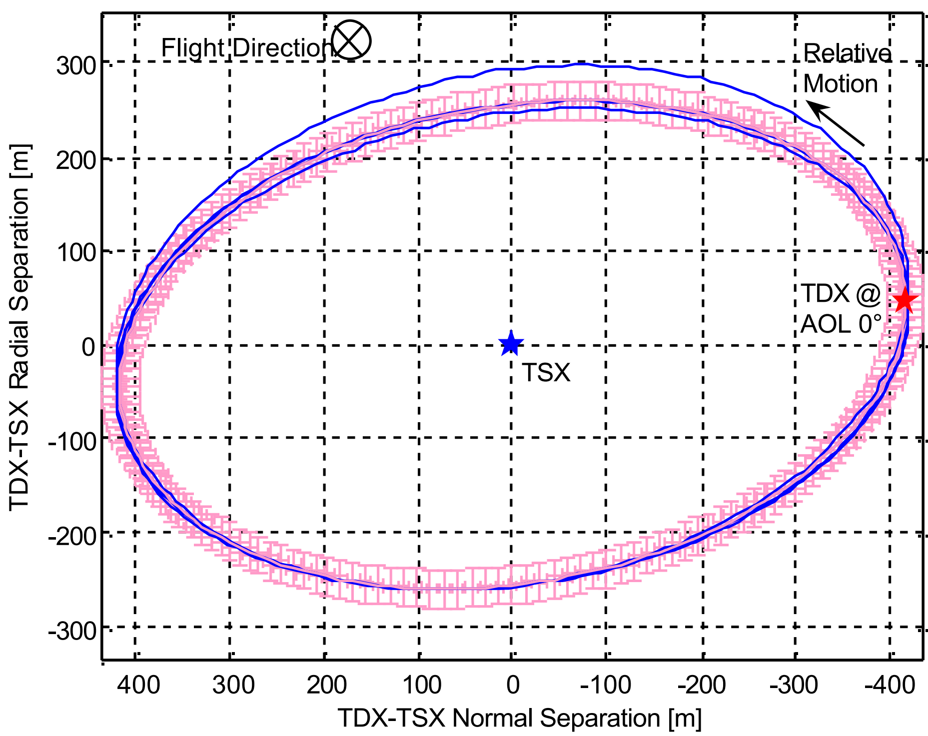

Figure 5: TDX-TSX relative motion (blue) in the plane perpendicular to flight direction during period March 25 from 12:00 to 18:00 UTC. Pink error bars indicate the 20 m 1-sigma control bands.

6 Conclusion

Within the first ten months after TDX launch remarkable results could be achieved by GSOC FD comprising the timely and fuel-efficient acquisition of the formation with TSX in July 2010, and the validation of safe and precise ground-in-the-loop formation control. Furthermore, the challenging 1-mm requirement in reconstructing the TDX-TSX baseline for DEM processing is almost achieved and is subject of ongoing analysis and development. Finally, we presented the realization of the very first debris collision avoidance maneuver performed in close formation.

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