EXTENDING THE TERRASAR-X FLIGHT DYNAMICS SYSTEM FOR TANDEM-X

Ralph Kahle [(1)] and Benjamin Schlepp [(1)]

[(1)] German Space Operations Center (DLR/GSOC), D-82234 Wessling (Germany), Email: Ralph.Kahle@dlr.de

ABSTRACT

This paper describes the current operational TerraSAR-X (TSX) flight dynamics system (FDS) and depicts its extensions needed to fulfil the requirements for TanDEM-X, which shall form a close formation with TSX. Operational constraints imposed by the instrument operation and the ground station network are explained and the impact on the FD operations concept is discussed. The paper specifically elaborates on the pre-launch qualification of the formation control function, which has been performed in a nine months simulation to verify the safe and robust maintenance of the satellite formation.

1. INTRODUCTION

TSX was launched on June 15, 2007 and is flying in a 514 km altitude sun-synchronous dusk-dawn orbit with frozen eccentricity. The Earth-fixed reference trajectory is repeated exactly every 167 orbits or 11 days [5]. Major goal of the TSX mission is the provision of high-resolution Synthetic Aperture Radar (SAR) data. Both science and commercial users may choose from a variety of SAR imaging and polarisation modes to individually image their region of interest. The ground segment was built up by the German Aerospace Center (DLR) which is in charge of controlling and operating TSX, commanding and calibrating its SAR instrument, receiving, processing and archiving its X-Band data and generating and delivering the final user products [3]. 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.

Like TSX, the TanDEM-X (TDX) project is being implemented by a Public-Private Partnership between DLR and Astrium GmbH. The primary goal of the TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) mission is to generate a global digital elevation model (DEM). To achieve this, two satellites – TDX and TSX – will form the first configurable SAR interferometer in space with a separation of only a few hundred metres. The satellites will fly in formation and operate in parallel for three years to cover the entire surface of the Earth.

DLR is responsible for the scientific exploitation of the TanDEM-X data as well as for planning and implementing the mission, controlling the two satellites and generating the digital elevation model. Astrium built the satellites and shares in the cost of its development and exploitation. As with TerraSAR-X, the responsibility for marketing the TanDEM-X data commercially lies in the hands of Infoterra GmbH, a subsidiary of Astrium.

2. THE TSX FLIGHT DYNAMICS SYSTEM

GSOC FD is responsible for rapid and precise orbit determination (ROD and POD, respectively), attitude determination and analysis, ground station tracking support, provision of orbit and attitude products for SAR processing, and orbit control. The ROD/POD and orbit control processes are briefly described.

The TOR-IGOR dual-frequency GPS receiver (or single-frequency MosaicGNSS receiver as backup) telemetry data is pre-processed to extract GPS navigation data for use in ROD and raw data for POD. The ROD performs a least-squares batch adjustment of the following estimation parameters: epoch state vector (position and velocity), drag coefficient, solar radiation coefficient, extended maneuvers, and measurement biases. As a result of ROD and orbit prediction, the following products are made available to the ground-segment: (a) Type 0 (Predicted) orbit product with 700 m required accuracy (along-track, 1-sigma); (b) Type 1 (Quicklook) orbit product with 10 m required accuracy (3D, 1 Sigma). The achieved accuracies are 70 m for Type 0 and 3 m for Type 1 when using the TOR-IGOR navigation data. The achievable accuracy for the 24h prediction is expected to degrade during periods of moderate and high solar activity. Based on the ROD results, orbit related products are regularly generated and distributed, e.g. pointing data and two-line elements for S-Band ground station support, input to mission operations sequence of event planning, and CCSDS orbit data messages [4] for laser tracking support.

The POD is performed based on GPS carrier phase and pseudo-range data. Auxiliary data such as the GPS orbit and clock products, Earth orientation parameters, and S/C attitude information are acquired prior to the generation of the precise orbits. The latency of the auxiliary data drives the availability of individual POD product types, i.e.: (c) Type 2 (Rapid) orbit product with 2 m required accuracy (3-D, 1-sigma); (d) Type 3 (Science) orbit product with 20 cm required accuracy (3D, 1 Sigma). The achieved 3D-accuracy is 10 cm for Type 2 and 5 cm for Type 3 orbit products [12].

The TSX satellite 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 reference trajectory. As illustrated in Fig. 1 for locations near the ascending node, the orbit raising maneuvers are conducted near the eastern (right-hand) boundary of the tube and induce a drift of the normal component in a westerly direction. This drift is ultimately reverted by atmospheric drag after which the satellite returns to the right-hand side (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. Currently (Apr. 2010) a moderate increase in solar activity causes higher drag and hence shorter maneuver cycle (about 1 week) and larger size (~1.5 cm/s). 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.

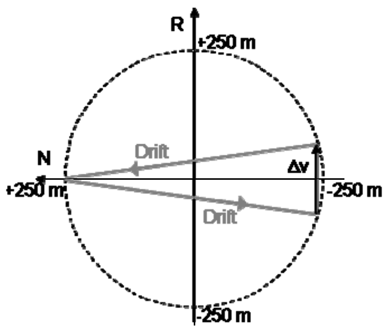


Figure 1. Schematic view of TSX motion relative to the predefined reference orbit at ascending node transits. R-T-N convention is used in all figures.

3. NEW FUNCTIONS IMPOSED BY TANDEM-X

The realization of the TanDEM-X mission required a major extension of the existing TSX FDS. This section introduces the most challenging new functions.

3.1. Formation Control

For the purpose of SAR interferometry, TDX must be kept in close proximity of TSX. In order to meet the tight relative control requirements (20 m perpendicular and 200 m parallel to flight-direction, 1-sigma) TDX has to (a) compensate the natural deviation of the relative eccentricity and inclination vectors (see e.g. [6] for definition of Keplerian relative elements), (b) control the along-track separation which is perturbed by relative drag and in-plane maneuver execution errors, and (c) replicate the TSX orbit keeping maneuvers. In case such a synchronous maneuver fails, the formation geometry becomes significantly disturbed, possibly implying a collision in the worst case – an unacceptable risk. Therefore, a maneuver planning post-processing is applied whereby the TDX-TSX relative motion is continuously analyzed considering all possible maneuver failure scenarios to estimate the minimum distance of the two satellites in the plane perpendicular to flight-direction. In case the 150 m threshold could become violated, the planned maneuvers are not released for commanding and the automated process stops and requires manual interaction by the FD on-call engineer instead. A cross-check of the results is performed and the maneuvers are possibly split to reduce their size and hence the collision risk.

In a subsequent step the TDX-TSX relative motion is monitored and predicted to the point, where control dead-bands are violated. Due to the Earth oblateness, the relative eccentricity and inclination vectors are subject to secular perturbations. In the latter case, a drift in the i_y direction occurs, which is proportional to the inclination difference of the two satellites (and thus the x-component of the relative inclination vector). When choosing identical inclinations, the TSX and TDX right ascension of ascending node (RAAN) rotate at the same angular velocity yielding stable horizontal baselines as foreseen for the TDX commissioning phase. However, for the DEM acquisition phase the horizontal baseline has to be adjusted frequently. Here, a small inclination offset in the TDX orbit is used to build up large horizontal baselines over time without the need for expensive RAAN adjustment maneuvers. The concept is demonstrated in sect. 5.3 (see Fig. 7 left).

The relative eccentricity vector, on the other hand, reflects the secular perigee variation of the individual satellites. It performs a rotation about the origin of the relative eccentricity vector plane with a period of roughly 100 days [6]. This drift needs to be compensated by suitable formation keeping maneuvers to maintain a stable configuration. The required daily along-track velocity increment is proportional to the adopted eccentricity vector difference and thus the desired peak separation of the orbits in radial direction. For example, a 300 m vertical separation demands every day two burns of approx. 0.5 cm/s each and separated by half a revolution [10]. These maneuvers are additionally used to adjust the along-track separation and to compensate possible differential drag effects. In order to reduce the total maneuver size and improve along-track control performance at the same time, the number of drift orbits in-between the maneuver pair has been introduced as a further variable in the maneuver planning process (see sect. 5.4 for an example).

All formation maintenance maneuvers are performed by the TDX satellite, which is equipped with a supplementary cold-gas propulsion system for fine-orbit control in the (anti)-along-track direction. Detailed performance results are presented in sections 5.2 and 5.3.

3.2. Transmit Exclusion Zone Determination

If one satellite is located in the area illuminated by the SAR antenna main lobe of the other satellite, damage of electronic units could result on the illuminated satellite. Therefore exclusion zones (EZ) have to be defined along the orbit for each satellite, in which the transmission by the SAR antenna is disabled.

As the control accuracy of the relative along-track distance between the satellites is relatively low, the definition of the EZ is neglecting the inherent along-track variations and the EZ location is defined only depending on the elevation angle in the cross-track plane. EZs are determined for both satellites and for both looking directions. For each case the corresponding envelope antenna pattern is used and specific security margins are applied. As a result, each of these four cases has its corresponding transmit exclusion zone product. This assures that the illumination risks are minimized for both satellites and for both looking modes.

FD generates the following products: (a) Transmit Exclusion Windows (TEW) for on-board timeline generation within Mission Planning System (MPS) and, (b) Transmit Exclusion Ephemeris (TEE) for a further on-ground check within the Monitoring and Control System (MCS).

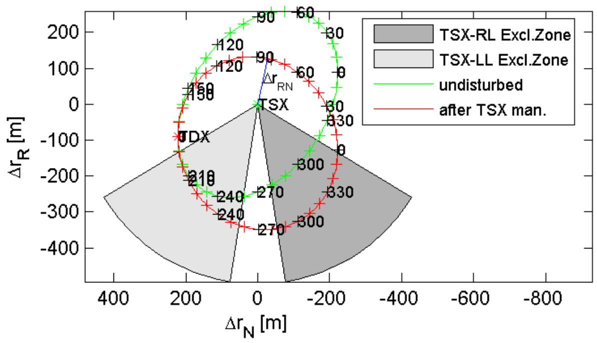


Figure 2. TDX-TSX undisturbed motion (green curve) and TSX right- and left-looking (RL, LL) exclusion zones (grey). At 180 deg argument of latitude (AOL) a maneuver is executed on TSX but fails on TDX. The perturbed relative motion and corresponding exclusion zone AOLs are shown in red (from [9]).

In order to avoid mutual illumination due to unforeseen formation geometry after non-execution of orbit maneuvers FD computes extended transmit exclusion products for a period starting after any hydrazine maneuver and lasting for a pre-defined interval. For example, if one planned TSX maneuver has to be replicated by TDX, four cases are considered in determine the TEWs. This is necessary because e.g. the non-execution of an 1 cm/s maneuver may cause the illuminated satellite to stay 100 seconds longer in the exclusion zone compared to the nominally computed TEW (Fig. 2). After reception of TEWs MPS checks in the first place whether or not requested data-takes fall into transmit exclusion windows. For data-take requests outside TEWs command sets are sent to the MCS. As these command sets might be manually modified by the operators, a second "Late Check" based on the TEE Product is performed in MCS before the actual data-take commands are uplinked on the satellites.

3.3. Precise Baseline Reconstruction

The baseline vector between the two satellites has to be determined with an accuracy of 1mm (1D RMS). In particular, an accurate determination of the line-of-sight component is considered critical for DEM generation. Errors in the line-of-sight component result in a scene-dependent vertical and lateral shift of the resulting DEM. For a direct matching of overlapping DEMs the lateral errors should be maintained to better than one pixel, which in turn limits the acceptable line-of-sight baseline error to typically 1mm.

Earlier research conducted in the context of the GRACE mission has indeed demonstrated the feasibility of achieving a 1 mm standard deviation for the along-track separation, where the GRACE K-band ranging system enables a direct evaluation of the baseline precision. However, slightly higher noise levels in the cross-track component of the baseline vector as well as biases between different processing strategies have been noted at the same time. In view of the highly challenging accuracy requirements, independent baseline solutions will be generated by expert teams at both DLR/GSOC and Geo-Forschungs-Zentrum Potsdam (GFZ). These will then be merged into a quality controlled combined product prior to use in the interferometric SAR processing. This merged solution will take care of bias calibrations performed through dedicated SAR calibration data-takes scheduled at semi-regular intervals throughout the mission. Refer to [10] for the DLR/GSOC baseline determination process and [11] for the pre-flight verification performed with actual flight data from the GRACE formation and the stand-alone TSX.

3.4. Autonomous Formation Flying Support

TAFF (TanDEM-X Autonomous Formation Flying) is a GPS-based software on-board TDX, which enables autonomous relative navigation and in-plane formation keeping. The TAFF algorithms were developed by GSOC's space flight technology department [10].

For sufficient operation TAFF needs several ground information inputs commanded by FDS, e.g. the required formation parameters and ground-planned maneuver information. Furthermore the operational mode of TAFF (there are navigation only, open loop, and closed loop modes) is set by FD and the received telemetry is firstly monitored and evaluated by FD to verify correct performance and secondly (if in closed loop) scanned for TAFF-executed maneuvers to be considered in further orbit determination.

Because of the fact that TAFF in-plane formation control is independent from the ground station network, a much better control accuracy is expected especially in along-track. Limiting factor is the necessary inter-satellite link from TSX to TDX which only works in close proximity. For more information on TAFF refer to [10].

4. OPERATIONAL CONSTRAINTS

The FD orbit control processes are to be coordinated with instrument activities and strongly depend upon the availability of data dumps and upload capability. These constraints are outlined in this section.

4.1. SAR Instrument Operation

The nominal TSX/TDX attitude is not exactly aligned with the orbit-defined roll-pitch-yaw coordinates and slightly differs in pitch and yaw depending on the orbit position (for details on the Total-Zero-Doppler-Steering refer to [7]). In order to maneuver with the hydrazine thrusters the attitude has to be changed disabling the acquisition of SAR data-takes for typically 10 minutes duration. Furthermore the acceleration of the four 1N thrusters would disturb focussing within on-ground SAR processing. The instrument timeline is planned twice a day by MPS typically at 10:15 and 22:15 UTC for upload at the evening and morning Weilheim and Neustrelitz contacts, respectively. To consider outage times during hydrazine maneuvers the maneuver information has to be available at MPS before the start of the planning run and hence minimum 8 hours before on-board execution.

On the contrary, no instrument interruption is required for the TDX in-plane formation maintenance maneuvers which are performed with the cold-gas thrusters pointing in (anti-)flight direction. Here cross-coupling of up to 6 % of the in-plane Δv (for maximum 3.7 deg yaw offset) in out-of-plane direction is tolerated. Although the acceleration caused by this maneuver type is too small to negatively affect SAR processing, it could affect the processing of bi-static data-takes acquired by both satellites if the reconstructed baseline experiences changes in its bias or drift. However, the common occurrence is generally avoided by the DEM acquisition strategy foreseeing bi-static data-takes at argument of latitudes of 0 to 90 and 180 to 270 deg while the in-plane formation control maneuvers are typically at 330 to 360 and 150 to 180 deg. This concept has been approved within the FD system validation simulation (sect. 5). Anticipating the results, Fig. 3 depicts the distribution of more than 60 simulated cold-gas maneuvers during 33 days within the bi-static configuration.

Thus cold-gas maneuvers can be planned and commanded on short notice while hydrazine maneuvers are to be prepared on a longer time scale.

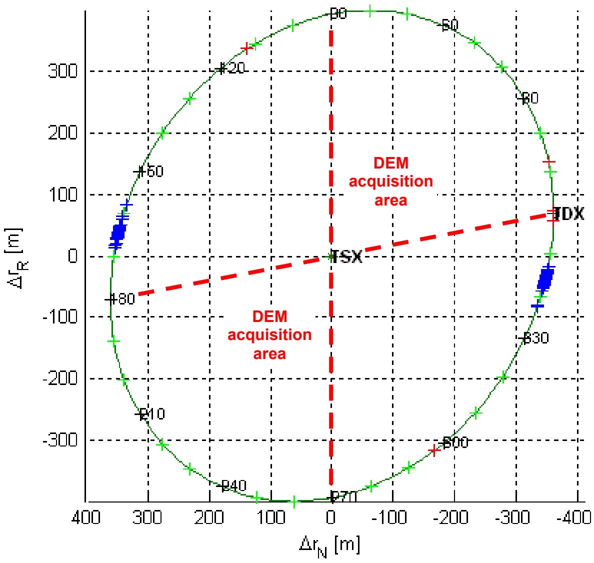


Figure 3. Cold-gas (blue) and hydrazine (red) maneuver distribution for simulated bi-static commissioning phase in the period from 2010/02/18 to 2010/03/23. Green crosses depict argument of latitude.

4.2. Ground-Station Network

Initially the TSX telemetry and telecommand (TMTC) network for routine operations only comprised of the Weilheim ground-station offering command and dump capacity typically twice in the morning from approx. 4:30 to 7:00 UTC and twice in the evening from approx. 15:30 to 18:00 UTC. The period between two contacts within successive orbits (i.e. 90 minutes) is too short for dump data transfer, pre-processing, orbit determination including maneuver calibration and new maneuver planning and command upload preparation. Furthermore, the amount of data that can be dumped within one contact is typically less than 6 hours. Considering the time for gathering all telemetry data necessary to calibrate an executed maneuver and for planning and uploading a new one, the minimum achievable maneuver cycle (i.e. the period between two independently planned maneuvers) is 24 hours for the single Weilheim station scenario. With the use of the Neustrelitz station for TDX, both the coverage and hence the maneuver cycle duration are not affected.

In nominal cases the formation control maneuvers would then take place not earlier than 24 hours after simultaneous execution of absolute TSX/TDX orbit control maneuvers. Given the fact that a 3 % relative execution error of a 5 cm/s along-track maneuver (as expected for high solar activity) changes the relative semi-major axis by almost 3 m and thus introduces a drift of 24 m per orbit or 370 m per day, it is evident that to achieve 200 m along-track accuracy a 1 day cycle is not sufficient.

Even though the achievable along-track formation control accuracy was the initial driver for a 6 hours TMTC interval, safety concerns that raised during the development phase became even more stringent. Major concerns are the risk of mutual radar illumination and the collision risk after AOCS safe mode drop with possible use of hydrazine thrusters for attitude control (for details refer to [8]). Thus the TMTC routine network was extended by O'Higgins (Antarctica) and Inuvik (Canada) to support midnight contacts and Kiruna as well as Svalbard to have contacts at noon.

5. SYSTEM VALIDATION

In order to verify the developed software modules and further to validate the operational interaction with the existing TSX FDS a TDX software simulation was set up within the operational TSX system.

5.1. Simulation Setup

Because of the lack of TDX telemetry the relevant GPS navigation data had to be simulated too. TDX data dumps are modelled to occur daily at 5:00, 7:00, 16:00 and 18:00 UTC (according to the Weilheim/Neustrelitz dump scenario), with each contact providing six hours of data which is simulated based on previous TDX ROD results and maneuver planning information. Uncertainties in the drag coefficient and up to 3% maneuver execution errors are introduced to yield non-ideal TDX navigation data. Thereafter the TSX-like processing is triggered comprising navigation data pre-processing, single satellite orbit determination and generation of orbit products for SAR data processing. To cancel common errors (that are mainly related to atmospheric drag modelling) in the ROD of TSX and TDX a synchronized orbit determination (SOD) process follows using common navigation data arcs and same auxiliary data (e.g. solar flux parameters) to yield time-synchronous TSX and TDX orbit data sets that are exclusively used for all functionalities related to formation flight, e.g. to determine SAR transmit exclusion zones (see sec. 3.2). The SOD results together with the formation target parameters are input to the formation monitoring and control system. The SOD and all following processes were simulated in exactly the same way as foreseen for real operations. On request individual FD products were exported to support ground-segment wide testing activities.

5.2. Commissioning Phase

After TDX launch it takes 3 to 4 weeks to acquire a first formation with TSX. The long duration comes from the fact that TDX has to drift up to 20,000 km (depending on the launch date) towards TSX with very limited maneuver budget. The final along track distance of 20 km is kept constant during the two-month mono-static commissioning phase (CP). To achieve a similar ground-track as TSX, the normal separation is set to 1305 m (Fig. 5) which corresponds to the equator surface motion within 2.6 sec of flight-time (or 20 km).

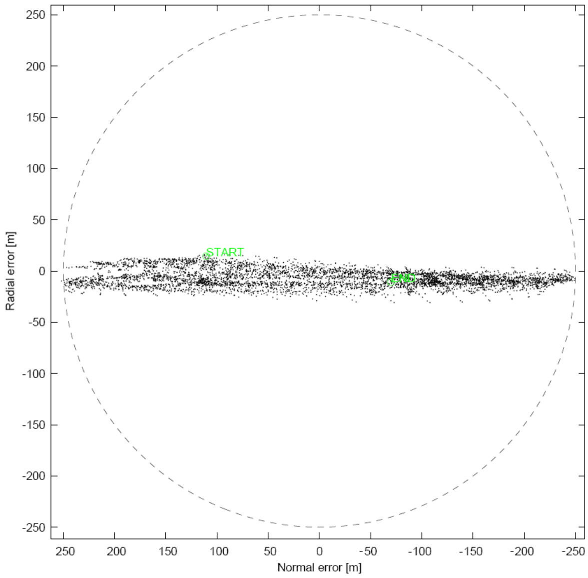


Figure 4. Real TSX orbit control performance in cycle 85 (2009/12/25 – 2010/01/05). Reference trajectory is at (0, 0). Dashed circle depicts 250 m radius control tube.

Since the target formation parameters, which are used in FDS are provided by the instrument operations team this simulation served as an interface test too. Fig. 4 and 6 depict the real TSX orbit control performance over an 11-days cycle and the simulated TDX orbit position w.r.t. the TSX reference orbit, respectively. The tolerable radial tube violation of TDX is caused by the target radial separation of 300 m, which was chosen for safety reasons, i.e. to ensure sufficient relative eccentricity / inclination vector separation in case of an unintended drift of the satellites towards each other.

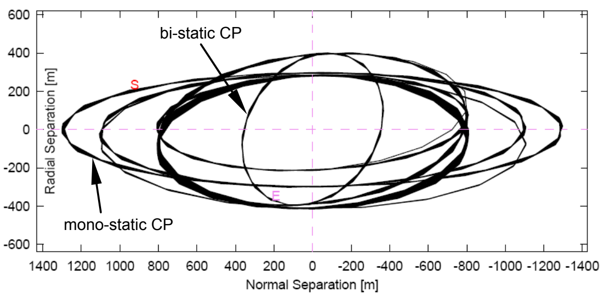


Figure 5. TDX-TSX relative motion during the reconfiguration from mono-static CP (300 m radial, 1305 m normal separation) to bi-static CP (400 m radial, 362 m normal). Not shown is the change of mean along-track separation from 20 km to 0 m.

After completion of the mono-static CP three days are foreseen to enter the first close formation as required for the 1-2 month bi-static commissioning phase. Here, the mean along track distance is decreased to 0 m, the normal separation is 362 m and the radial separation is 400 m. Contrary to the automated formation maintenance, the larger reconfiguration maneuvers are manually planned by means of the same software but using different setup parameters. The change in relative motion during the reconfiguration process is depicted in Fig. 5. The target formation is shown in Fig. 3 too.

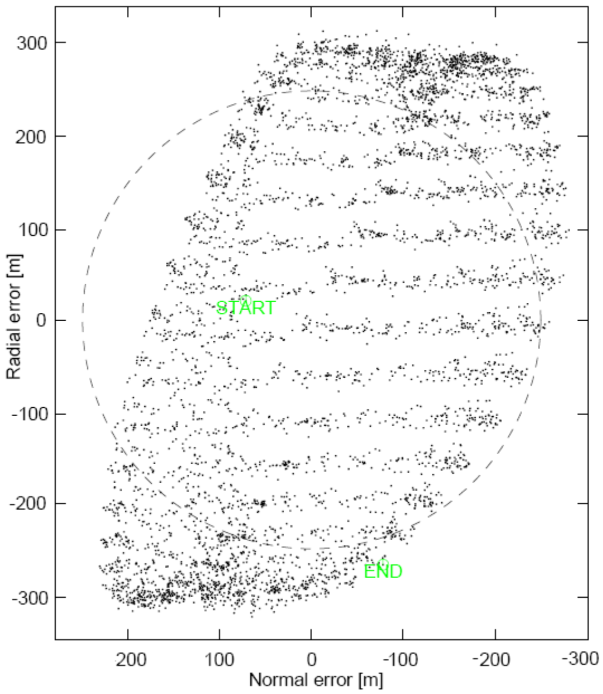


Figure 6. TDX orbit position w.r.t. TSX reference trajectory within mono-static CP. The same simulation period as in Fig. 4 applies.

5.3. DEM Acquisition Phase

For the purpose of global HRTI-3 DEM acquisition and to fulfil secondary mission objectives (e.g. along-track interferometry and demonstration of new SAR imaging techniques and applications) up to three years of TDX-TSX formation flight are necessary after completion of the CP. The simulation described in this section covers the beginning of the first year where acquisition with the smallest baselines is performed. This strategy is necessary to yield a large height of ambiguity that eases DEM derivation and supports phase unwrapping of large baseline acquisitions in succeeding mission phases. Within this year the acquisition plan foresees a continuously growing horizontal baseline which is realized by means of a natural relative ascending node drift (see sect. 3.1).

In Fig. 7 the simulated formation control performance for an 11-days period is shown. The targeted horizontal separation linearly drifts from 219 to 228 m (right top). The x-component of the relative inclination vector was set to 6.6 m (i.e. corresponding to TDX-TSX inclination difference of 5.5e-5 deg) to initiate a small drift of the relative RAAN and hence the horizontal separation at equator crossings (Fig. 7 left). Besides the drift initiation no additional out-of-plane maneuvers are needed. The following example illustrates the fuel saving capability: to change the horizontal baseline by 300 m over 11 months a stepwise adjustment of the TDX RAAN would demand for about 3.3 m/s of Δv compared to less than 0.1 m/s required to initiate the RAAN drift. Additional Δv to compensate for cross-couplings from in-plane control maneuvers has to be considered in both cases.

The achieved cross-track (i.e. combined radial and normal) and along-track control errors are summarized in Fig. 7 right middle and bottom, respectively. During the 11-days period TSX performed two regular in-plane maneuvers which were replicated by TDX (April 1: 1.6 cm/s, April 7: 1.8 cm/s; shown by green verticals in Fig. 7, index M-I). In both cases these maneuvers prevented the timely placing of formation maintenance maneuvers causing the relative eccentricity vector to drift for about 12 hours longer than nominal (i.e. 24 h) resulting in temporal violation of the allowed 20 m cross-track limit.

For the same reason the along-track control limit of +/-200 m became violated (Fig. 7 bottom). This is of particular interest for the purpose of cross-track interferometry that aims on along-track baselines which are as short as possible to ensure an optimum overlap of the Doppler spectra and to avoid temporal de-correlation in vegetated areas (e.g. due to wind). The problem will be solved by better phasing of absolute and relative orbit control maneuvers within the individual planning processes.

5.4. Debris Collision Avoidance

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 to re-asses the risk to both satellites. In case a significant risk (i.e. 10-4) remains the following precautions exist in principle. 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 (fuel-expensive), or

B.2 TDX remains passive and the formation has to be re-acquired afterwards (time-consuming).

Of course the risk assessment is to be repeated for every maneuver planned for TSX and/or TDX before command upload. If solely TDX is affected, TSX remains passive and TDX has to perform maneuvers for collision avoidance and formation re-acquisition.

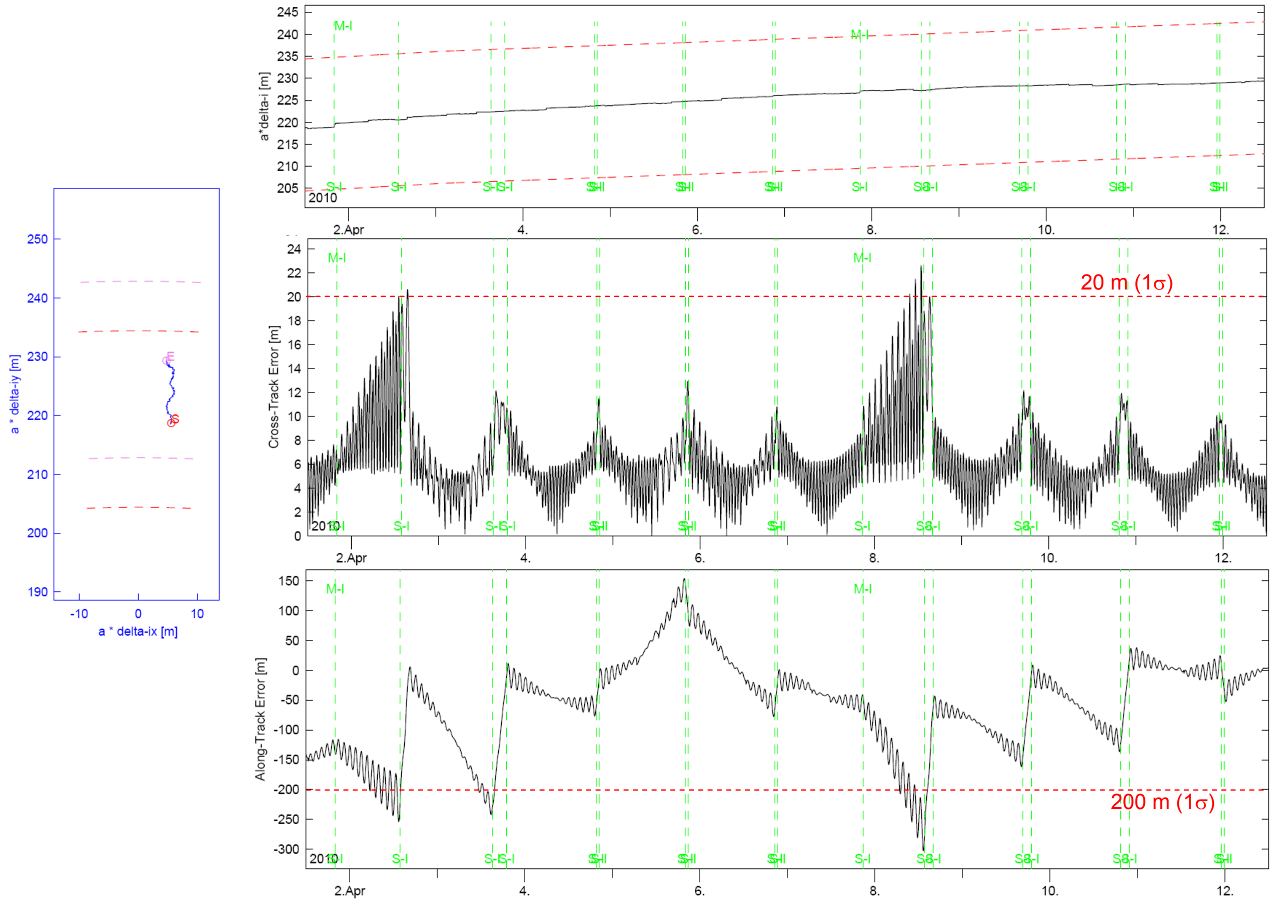


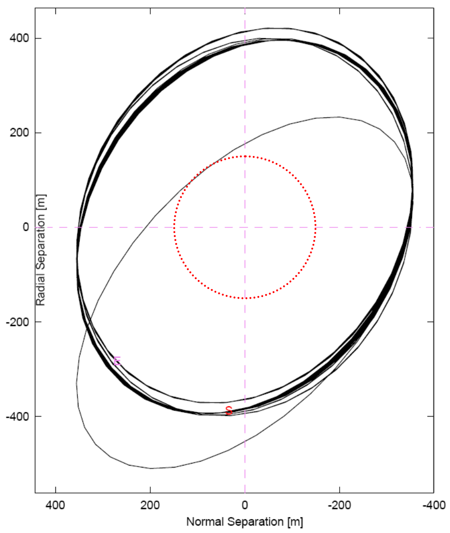
Figure 7. Left: Relative inclination vector drift (S: Apr. 1, E: Apr. 12) and sliding control window (red: start of interval, purple: end of interval). Right: Maneuver-free horizontal baseline adjustment by inclination offset (top), Relative control error in cross-track (i.e. combined radial and normal error) (middle) and along-track direction (bottom). Green lines indicate TSX (M-I) and TDX (S-I) in-plane maneuvers, red lines are 1-sigma control requirements.

The example given in Fig. 8 illustrates the scenario B.2. Here, TSX experienced a close approach with a COSMOS 2251 debris on 2009/11/27 5:39 UTC. Temporarily the TLE-based risk-estimate exceeded 10^{-4}. Because radar tracking is not yet operational a collision avoidance maneuver had to be performed at half orbital revolution before the event (at 4:51 UTC) to yield sufficient radial separation. Exactly one orbit later (at 6:26 UTC) a second maneuver was done to return to the 250 m reference orbit tube. The maneuver size was approx. 8 cm/s in each case. To safe fuel on-board the simulated satellite, TDX did not replicate the maneuver pair and an along-track drift resulted (Fig. 8 right). The TDX formation re-acquisition on Nov. 28 required two cold-gas maneuvers with Δv of 1.3 cm/s each. To decrease the along-track separation 4.5 drift orbits were selected between the maneuver pair. Worth mentioning here is the fact that the collision-check process showed a minimum cross-track distance of 148 m violating the 150 m threshold and therefore rejected the planned TSX maneuver. But a further manual analysis of the relative formation concluded sufficient safety distance between TSX and TDX (see Fig. 8 left). With the performance of this maneuver variant the saving compared to option B.1 amounts to about 13 cm/s of Δv on-board TDX.

6. CONCLUSION

The realization of the TanDEM-X mission required a major extension of the TSX FDS. The complete FD system design and implementation (incl. development of all software modules) was performed within GSOC's space flight technology department. A software simulation was set up in June 2009 and TDX pre-launch "operation" is running since 9 months and will continue until some weeks before TDX launch which is currently planned in June 2010. The considerable test effort clearly has been worth: (a) the entire FDS was stepwise improved (i.e. software bug-fixing and parameter adjustment) and especially the formation control concept was verified, (b) the FD engineers already gathered several months of formation (pre-)flight experience and became trained in nominal and contingency operations, and (c) the FDS with most of the operational interfaces was successfully validated.

Furthermore, the simulation proofed the correctness of fuel saving strategies for both debris collision avoidance and horizontal baseline adjustment. It also showed that an along-track control accuracy of about 200 m can be achieved throughout the entire TanDEM-X mission with ground based operations and 6-hourly station contacts. The relative motion perpendicular to the flight direction (i.e. 2D) is currently controlled to better than 20 m which is sufficient in terms of achievable height of ambiguity. Even better accuracy is expected when improving the phasing of absolute and relative orbit control maneuvers. This would be advantageous for the combined processing (i.e. phase unwrapping) of DEM acquisitions made in the first two years of formation flight.



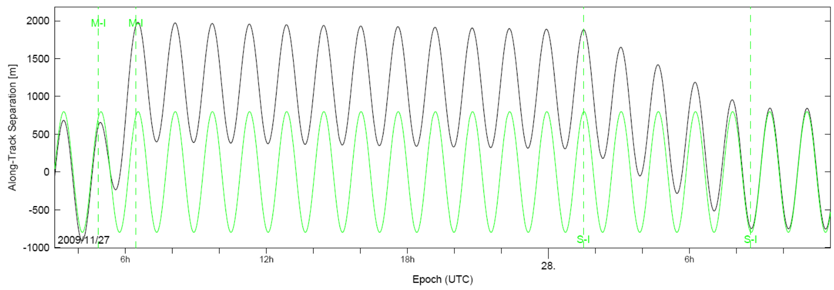


Figure 8. TDX-TSX relative motion during TSX collision avoidance.
Right: Achieved (black) and nominal (green) along-track separation over time. Vertical lines illustrate the TSX collision avoidance maneuvers (index M-I) and TDX formation reconfiguration maneuvers (index S-I).
Left: The semi-minor axis of the relative motion ellipse decreases in the period between the two TSX maneuvers (i.e. one orbit) causing a minimum 148 m cross-track distance shown as a tangent to the 150 m threshold (red circle).

7. ACKNOWLEDGMENT

The authors acknowledge the helpful comments by Reinhard Kiehling and Gerhard Krieger.

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.

8. REFERENCES

1. Aida S., Patzelt T., Leushacke L., Kirschner M. & Kiehling R. (2009). Monitoring and Mitigation of Close Proximities in Low Earth Orbit. In Proc. 21st ISSFD, Toulouse, France.

2. Arbinger Ch., D'Amico S. & Eineder M. (2004). Precise Ground-In-the-Loop Orbit Control for Low Earth Observation Satellites. In Proc. 18th ISSFD, Munich, Germany.

3. Buckreuss S. & Schättler B. (2010). The TerraSAR-X Ground Segment. IEEE Transaction on Geoscience and Remote Sensing **48**(2), 623-632.

4. Consultative Committee for Space Data Systems (CCSDS) - Orbit Data Messages. Blue Book. CCSDS 502.0-B-1.

5. D'Amico S., Arbinger Ch., Kirschner M. & Campagnola S. (2004). Generation of an Optimum Target Trajectory for the TerraSAR-X Repeat Observation Satellite. In Proc. 18th ISSFD, Munich, Germany.

6. D'Amico S. & Montenbruck O. (2006). Proximity Operations of Formation-Flying Spacecraft Using an Eccentricity/Inclination Vector Separation. *Journal of Guidance, Control and Dynamics* **29**(3), 554-563.

7. Fiedler H., Fritz Th. & Kahle R. (2008). Verification of the Total Zero Doppler Steering. In Proc. RADAR 2008, Adelaide, Australia.

8. Hofmann H. & Kahle R. (2010). The TanDEM-X Mission Operations Segment: Close formation flight: Preparation and First Experiences. In Proc. SpaceOps, Huntsville, Alabama, USA.

9. Kahle, R. (2008). TerraSAR-X/TanDEM-X Formation Collision and Illumination Aspects. Technical Note TD-MOS-TN-4060, GSOC, DLR.

10. Montenbruck O., Kahle R., D'Amico S. & Ardaens J.-S. (2008). Navigation and Control of the TanDEM-X Formation. *Journal of the Astronautical Sciences* **56**(3), 341-357.

11. Montenbruck O., Wermuth M., Kahle R., König R. & Moon Y. (2010). GPS Based Relative Navigation for the TanDEM-X Mission. In Proc. ION GNSS, Portland, Oregon, USA.

12. Wermuth M., Hauschild A., Montenbruck O., Jäggi A. (2009). TerraSAR-X Rapid and Precise Orbit Determination. In Proc. 21st ISSFD, Toulouse, France.