Extending the TerraSAR-X Ground Segment for TanDEM-X

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Abstract

This paper describes selected areas in which the TerraSAR-X ground segment had to be extended in order to incorporate the TanDEM-X mission, namely flight dynamics, instrument operations and receiving stations and addresses their testing.

1 TerraSAR-X Mission and Ground Segment

Major goal of the TerraSAR-X mission is the provision of high-resolution synthetic aperture radar data. Both science and commercial users may choose from a variety of SAR imaging and polarisation modes to individually image their region of interest. It is the TerraSAR-X Ground Segment built up and operated by the German Aerospace Center (DLR) which is in charge of controlling and operating the TerraSAR-X satellite (TSX), for commanding and calibrating its SAR instrument, for receiving, processing and archiving its X-Band data and for generating and delivering the final user products [1]. Its major achievement is the provision of high-quality SAR products to the user community based on a reliable service since the TerraSAR-X mission entered its routine operation phase end of 2007 while maintaining a remarkable SAR system performance [2], [3]

2 TanDEM-X - A Challenging Mission On Top

By adding a second satellite (TDX), a challenging second mission is defined on top of TerraSAR-X, the **T**erraSAR-X **a**dd-o**n** for **D**igital **E**levation **M**easurement abbreviated by TanDEM-X. It realizes a single-pass space-borne radar interferometer by flying the two satellites TSX and TDX in a close formation. Primary TanDEM-X mission goal is the consistent generation of a world-wide global digital elevation model with high accuracy. Both satellites are used in parallel (one in receive-only configuration) for bi-static TanDEM data acquisitions [4]. To counterbalance the interferometric usage of TSX, TerraSAR-X mission data are acquired by both satellites TSX and TDX whereby the appropriate one to fulfil a given user acquisition request is chosen by the GS.

The TanDEM-X mission profile is particularly challenging from a flight dynamics point of view and poses new needs for spacecraft navigation and control. These comprise the formation design, the ground-controlled formation maintenance and reconfiguration, as well as the high precision reconstruction of the interferometric baseline. Furthermore, unforeseen events (e.g. abortion of manoeuvre execution) must not imply any danger of collision.
Even if the satellites TSX and TDX are regarded as twins and are built up in an identical way as far as possible, they still provide two active and independent SAR instruments which are to be combined in order to form a bi-static SAR interferometer. Specifically the two ultra-stable local oscillators which may run at slightly different frequencies require specific counter-measures both in instrument commanding and on-ground processing to compensate for relative phase errors and to account for time annotation differences. Flying the two instruments in spitting distance in a helix formation also calls for precaution measures to prevent mutual illumination.

3 Ground Segment Extension

The TanDEM-X mission requires a major extension of the existing TerraSAR-X GS. Complex new subsystems to specifically fulfil the TanDEM-X requirements have to be added, e.g. for the definition of the global TanDEM data acquisition plan and for the systematic reception, archiving and processing of bi-static SAR acquisitions into individual "raw" DEMs [5], [6] and their final mosaicking into the global DEM product. A new missing planning system being in charge of generating combined TerraSAR-X and TanDEM-X mission timelines for both satellites TSX and TDX has to replace the current operational one. Selected GS upgrade areas are described in the following sections.

4 Flight Dynamics System

4.1 Orbit Control

In accordance with the TerraSAR-X mission requirements, the TSX satellite has to be controlled in a predefined Earth-fixed tube of 250 m radius that enables highly repeatable data take conditions. Orbit manoeuvres at daily to weekly intervals (depending on solar activity) are conducted to adjust the TSX orbit to the reference trajectory.
The TSX ground-in-the-loop orbit control starts with the reception of AOCS housekeeping and GPS telemetry dumps, an input to the TSX orbit determination (OD). The resulting orbit parameters are predicted, orbit control maneuvers are planned and commanded keeping the satellite precisely within its Earth-fixed 250 m tube.
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) TDX has to compensate the natural deviation of the relative eccentricity/inclination vectors and additionally must replicate the TSX orbit keeping manoeuvres. 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 towards flight-direction. In case a pre-defined 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 TSX-TDX relative motion is monitored and predicted to the point, where control dead-bands are violated. In most cases this is due to the Earths gravity field (mainly J2) reshaping the TDX-TSX formation ellipse in the plane perpendicular to flight direction and hence the SAR interferometric baseline. Because of the tight formation control accuracy requirements - 20 m (1-sigma) vertical and horizontal displacement - the planning process for the formation maintenance maneuvers, which are exclusively executed by TDX, is triggered daily. Besides formation maintenance the software has to plan formation reconfiguration maneuvers as well to change the formation over larger time scales.

In order to verify the new developed software modules and further to validate the operational interaction with the existing TSX FDS a software simulation was set up within the real TSX system. Because of the lack of TDX telemetry the relevant GPS navigation data has to be simulated too. The TDX S-Band dumps are modeled to occur daily at 5:00, 7:00, 16:00 and 18:00 UTC providing 6 hours of data which is based on the latest available TDX OD and maneuver planning information. Uncertainties in the drag coefficient and 2-3% maneuver 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 quick-look and predicted orbit products which are used as auxiliary products for SAR data processing. To cancel common errors in the OD of TSX and TDX a synchronized orbit determination (SOD) process follows yielding time-synchronous TSX and TDX orbit data sets that are exclusively used for all FD functionalities related to formation flight. For example, this is used to determine SAR transmit exclusion products for instrument timeline generation within mission planning and on-ground exclusion zone check prior to timeline upload (for usage of these products see sec. 5). 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 GS wide testing activities.
The simulation set up was finished in June 2009 and operation is running since 9 months and will continue until some weeks before TDX launch. 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 [7], (b) the FD engineers already gathered several months of formation (pre-)flight experience and became well trained in nominal and contingency operations, and (c) the FDS with most of the operational interfaces was successfully validated.

4.2 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 the generation of DEMs. Errors in the line-of-sight component result in a scene-dependent vertical and, more importantly, 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 a 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 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 [8] for the DLR/GSOC baseline determination process and [9] for the pre-flight verification performed with actual flight data from the GRACE formation and the stand-alone TSX.

5 Bi-Static Radar Instrument Operations

Operating the two independent SAR instruments in a synchronous manner leads to significant data take commanding concept updates compared to the TerraSAR-X case [10]. One satellite takes the active role by transmitting and receiving radar pulses while the other takes the passive role by receiving the scattered echoes only. Since both instruments use their own local oscillator, the passive receive echo windows exhibit a time shift and thus an echo window shift with respect to the active one. As a countermeasure, selected pulse repetition intervals (PRI) of the passive instrument are shortened or enlarged to provoke either a hastening or retarding effect. Furthermore, a larger echo window is chosen for the passive instrument than the active one.

Since bi-static focusing [11] requires an accurate knowledge of the echo window timing, specific synchronization pulses are sent directly from one satellite to the other and vice versa using one out of six sync horn antennas mounted at both satellites. The activation of the appropriate sync horn antenna is part of the data take commanding and the received sync pulses are embedded into the data takes and evaluated during on-ground SAR data screening. This SAR data screening is performed directly after data reception to provide a fast feedback on the data quality without performing the time-consuming interferometric processing itself [5], [12]. Specifically the sync pulse evaluation results are used to estimate the oscillator frequency differences and will be used as input for the commanding of future data takes.

A further complexity arises from the fact, that TSX and TDX are flying in spitting distance in a helix formation and thus a precaution algorithm is implemented which prevents radar transmission of the first satellite when the second could be in its antenna main lobe. Orbital sections where transmission is prohibited are called exclusion zones (EZ). These EZ are established and observed during data take planning in dependence of the formation flight parameters assuming a nominal satellite position and antenna pointing including safety margins. Therefore, an in-orbit confirmation check is implanted using the sync horns and pairs of so-called sync warning data takes. Over suitable orbital sections (typically twice per orbit), one satellite transmits a pulse via the pre-selected sync horn which is in turn received by a pre-selected horn of the second satellite and evaluated. In case, the received signal exceeds the pre-defined signal to noise level threshold a positive on-board event is generated allowing continuation of SAR operation, otherwise a negative event is generated disabling radar transmission. The same mechanism is performed in the reverse way.

6 Ground Station Network

A network of ground station located at appropriate geographical locations was established for the downlink of the TanDEM-X data volume which is about 3.5 times higher than the current TerraSAR-X. This TanDEM-X ground station network consists of

- DLR's German Antarctica Receiving Station (GARS) O'Higgins on Antarctic Peninsula
- DLR's Inuvik Satellite Station in Canada (INU)
- DLR's ERIS Chetumal Station in Mexico and (CHM)
- the partner ground station SSC ESRANGE Kiruna in Sweden (KIR)

Apart from CHM, all stations provide S-band and TT&C services as well. For a further description, refer to [13].

Since October 2008, GARS operationally performs X-band data reception for TerraSAR-X background missions taking a huge data volume. Since November 2008, GARS also provides routine 24h/7d TT&C support during the Antarctic summer. It has been chosen many times since then for a reliable software upload, e.g., to upgrade the TSX onboard software for the TanDEM-X mission or to enable new sophisticated instrument modes. First engineering tests for optimized XDA downlink operations were done with GARS before being operationally released for the other TerraSAR-X ground stations.

The on-site acceptance test for INU was performed in September 2009 covering X-Band downlink and S-Band TT&C activities as well as high bandwidth SAR interference testing incorporating the real TSX spacecraft. In December 2009 quasi operational X-Band data reception was successfully demonstrated. The upcoming experimental TSX dual receive mode campaign will make maximum usage of INU too.

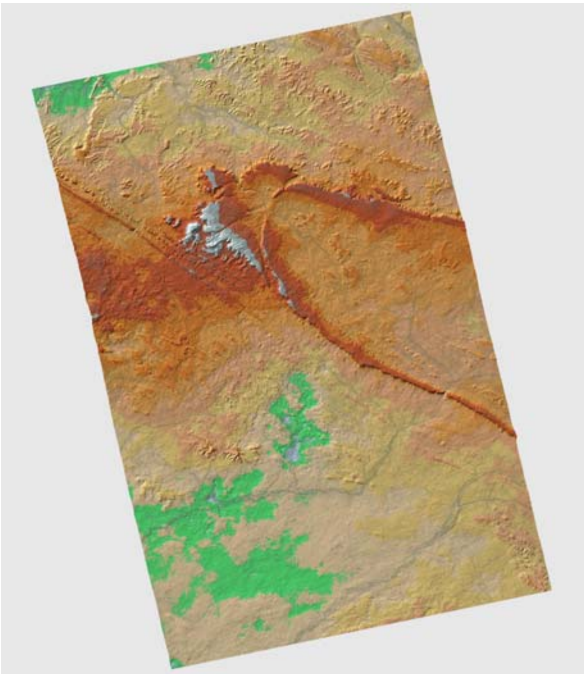
In August 2009 DLR's partner ground station KIR underwent an extensive test series with all antenna systems possibly used for TanDEM-X. Again the tests

used the real TSX spacecraft to demonstrate most realistic TanDEM-X conditions.
Currently, the CHM ground station is upgraded to be in place for absorbing TanDEM-X peak loads [12].

7 Ground Segment Verification and Validation Testing

The ground segment integration and test program followed the principles established and successfully exercised for TerraSAR-X [1]. Full GS workflows were tested comprising the ordering of both TerraSAR and TanDEM data takes, the generation of combined timelines for both TSX and TDX and their execution using the on-ground integrated TDX followed by the processing of the recorded data takes.
In December 2009, the GS setup for the commissioning phase was successfully tested in a 3-day validation test along with the on-going nominal TerraSAR-X operations whereby the TDX spacecraft simulator replaced the TDX in orbit. This operational test specifically included successful data reception at the GSN stations O'Higgins, Inuvik and Kiruna.

The completion of both the GS setup and the TSX on-board configuration for TanDEM-X, set the base to test TanDEM-X data take commanding, acquisition and processing under the most realistic SAR condition achievable before the TDX launch. A selection of test sites is imaged in 11-day repeat cycles using the later TanDEM data take commanding. This enables testing of the TanDEM SAR processing system which uses two TSX repeat channels to derive a raw DEM.



The sample DEM shown is from a Western Australia test site as seen by TSX with the Stripmap beam "tanDEM_a1_020R" on February 25 and March 07, 2010 (incidence angle 33.7°, effective. baseline 75 m).

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