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Evolving the Operations of the TerraSAR-X/TanDEM-X Mission Planning System during the TanDEM-X Science Phase

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After the successful Global Coverage of the Digital Elevation Model, the TanDEM-X Science phase was initiated in September of 2014, dedicated to the demonstration of innovative techniques and experiments. The TanDEM-X Science phase had a large impact on the TerraSAR-X/TanDEM-X Mission Planning System. The two main challenges were the formation flying changes and the activation of a new acquisition mode, the so called Dual Receive Antenna (DRA) acquisition mode. This paper describes all actions and quantitative analyses performed in order to achieve the twofold target of the Mission Planning System: a) support the new TanDEM-X mission's requirements, while b) proceed seamlessly with the TerraSAR-X mission fulfilling both its scientific and commercial demands. Regarding the first objective, several system reconfigurations are presented which were executed either due to the new flying formations or due to enabling the new DRA acquisition mode. In parallel, various analyses are included for the ground station visibilities of each formation and the distribution of the S- and X-Band contacts. For the second objective, it is presented how, via new concepts and mechanisms, it was possible to continue the TerraSAR-X mission undisturbed. Statistical analyses depict their successful integration and performance in the operational system. As a heritage of the TanDEM-X Science phase, the statistical analyses have become a very useful tool for the daily operations of both satellites and missions.

Nomenclature

DLR	=	German Aerospace Center
MPS	=	Mission Planning System
SAR	=	Synthetic Aperture Radar
DEM	=	Digital Elevation Model
TerraSAR-X	=	TerraSAR-X mission
TanDEM-X	=	TerraSAR-X add-on for Digital Elevation Measurements mission
TSX	=	TerraSAR-X satellite
TDX	=	TanDEM-X satellite
SRA	=	Single Receive Antenna
DRA	=	Dual Receive Antenna

I. Introduction

Since the beginning of the parallel routine operations of the TerraSAR-X and TanDEM-X missions, the TSX and TDX satellites were flying in Bistatic Close formation, building a single-pass space-born radar interferometer[1].

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The primary objective of the TanDEM-X mission was the generation of a consistent global Digital Elevation Model (DEM)[2]. At that time, the joint TerraSAR-X/TanDEM-X Mission Planning System was rolled-out, switching from the "one mission one satellite" concept -TerraSAR-X mission on TSX satellite- to the "two missions two satellites" concept -TerraSAR-X/TanDEM-X missions on TSX/TDX satellites. Many novel concepts and mechanisms had been introduced at that time, creating the joint Mission Planning System in order to fulfill the requirements of both missions through an automated and unattended operational mode[3,4].

After the successful global coverage of DEM acquisitions, the primary goal of the TanDEM-X mission was reached in September 2014[5]. The next seventeen months were dedicated to the secondary objective of the TanDEM-X mission: the demonstration of innovative techniques and experiments, defined as the TanDEM-X Science phase. For the first time since the launch of the TDX satellite, the Mission Planning System needed to evolve extensively[6] in order to support a twofold target: a) support the new TanDEM-X mission's requirements, while b) seamlessly proceed with the TerraSAR-X mission fulfilling both its scientific and commercial demands.

Based on the milestones of the TanDEM-X Science phase, we present the operational evolution of the TerraSAR-X/TanDEM-X Mission Planning System. We describe the installation of new mechanisms and the ad-hoc reconfiguration of existing concepts in the system, together with the analyses performed and the countermeasures taken against any arisen implications. This paper is concluded with the end of the TanDEM-X Science phase, presenting the heritage of this campaign to the routine operations of the TerraSAR-X/TanDEM-X Mission Planning System.

II. TanDEM-X Science Phase Timeline

From the Mission Planning point of view, the TanDEM-X Science phase can be seen as three consecutive periods of different formation geometries, in parallel to the introduction of the Dual Receive Antenna configuration. The formation before the initiation of this phase was defined as Bistatic Close formation, where the inter satellite distance between the two satellites was up to a few hundred meters[1]. Below we present the chronological milestones of the TanDEM-X Science phase[5] (see Figure 1) and list the corresponding scientific applications[7]:

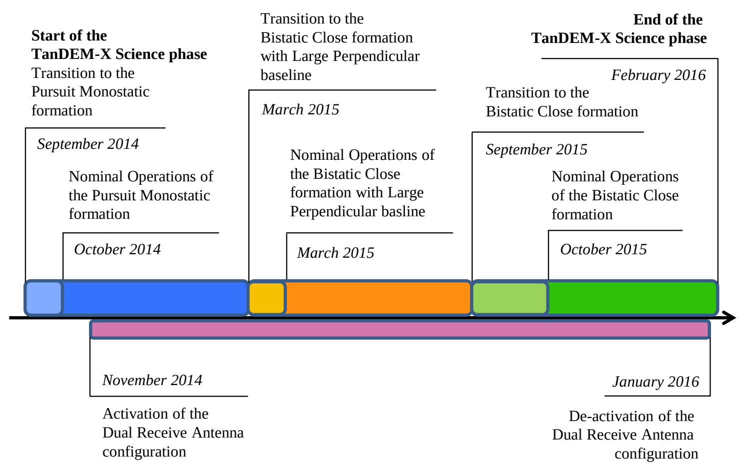

Figure 1. The TanDEM-X Science phase timeline.

- In September 2014, the formation geometry of the satellites switched to Pursuit Monostatic Far formation. The TDX satellite was flying on the same ground track as the TSX satellite, following the latter with an along-track separation of 76 km. This formation was kept until March 2015. The main application of this phase was the measurement of sea ice and glaciers.
- In November 2014, a new acquisition mode was introduced. The Dual Receive Antenna configuration was enabled on both satellites, giving the opportunity for quad-polarization acquisitions. This configuration was kept throughout the TanDEM-X Science phase. Its main applications are the ground moving target indication (i.e. traffic) as well as vegetation monitoring.
- In March 2015, the formation geometry was changed from Pursuit Monostatic Far formation to Bistatic Close formation with Large Perpendicular Baseline. The TSX satellite remained in its orbit, while the TDX satellite was close to its partner over the poles, but with a cross-track separation of 3600 m over the equator. This formation remained for six months, performing acquisitions of the full growing cycle of vegetation as well as high resolution DEMs.
- In September 2015, the TDX satellite slowly approached the TSX satellite's orbit, creating a pure Bistatic Close formation after one month. Four months after the end of this transition phase, performing acquisitions for research on forests and ocean-currents, the TanDEM-X Science phase was officially terminated, in February 2016.

We present the Operations of the Mission Planning System primarily in the three consecutive formation flying geometry periods (Chapters III, IV, V), leaving at last the installation of the new acquisition mode (Chapter VI).

III. Pursuit Monostatic Far Formation

In September 2014, the TanDEM-X Science phase was officially initiated with the Pursuit Monostatic Far formation, implying from the operational point of view its successful preparation and validation. Already in September 2014 the TDX satellite broke off the Bistatic Close formation, following the same ground track with the TSX satellite. Both satellites ended flying with a 76 km along-track baseline separation, translated to roughly 10 s difference in terms of timing. This formation opened up new applications and demonstrations in the areas of the geosphere, cryosphere and hydrosphere by generating data for elevation models with a height accuracy of a few tens of centimeters. These data are used in the investigation of volcanic eruptions, the melting of ice, and the tomographic imaging of cities[7].

A. Transition to the Pursuit Monostatic Far Formation

In September 2014, the transition to the new Pursuit Monostatic Far formation started. In the beginning of this maneuvers campaign, the formation was still considered as close, entailing the risk of SAR illumination to the partner satellite[1]. Therefore, no acquisitions were executed on any of the satellites in this timeframe. Twelve hours later the TDX satellite was considered far enough from its partner, giving the opportunity to start the TerraSAR-X mission only on the TSX satellite, minimizing the downtime of this mission. Four days later, the TDX satellite reached its target position and the check-out phase was ready to begin.

Since the TerraSAR-X mission was already operationally supported by the TSX satellite, the check-out phase was split into two periods: a) check-out of the TerraSAR-X mission on TDX satellite, and b) check-out of the TanDEM-X mission. Four days were assigned for validating the correct ordering, planning, execution, and processing of TerraSAR-X calibration acquisitions on the TDX satellite while carrying on with the routine operations of the TerraSAR-X mission exclusively on TSX. At last, a complete repeat orbit cycle[1] (i.e. 11 days) was reserved for the overall validation of the support of the mixed TerraSAR-X/TanDEM-X missions in the Pursuit Monostatic Far formation. In October 2014, the check-out phase of the Pursuit Monostatic Far formation was successfully declared as passed, leaving room for the nominal operations of both missions.

B. Mission Planning Operations during the Pursuit Monostatic Far Formation

The separation of the satellites of this formation geometry broke off the existing definition of the single-pass radar interferometer. The Mission Planning System had to adapt to this new configuration in terms of a) planning of monostatic TanDEM-X acquisitions, where both satellites transmit and receive radar pulses over the same scene, and b) assigning the ground station contacts to the satellites. The next paragraphs present the analyses and measures considered to cope with the new formation flying concept.

1. Acquisitions in Pursuit Monostatic Far Formation

The TerraSAR-X acquisitions were always described as monostatic acquisitions, meaning that only one of the two satellites is selected to transmit a radar beam and to receive the backscatter from the Earth's surface. Up to the initiation of the Pursuit Monostatic formation, the acquisitions of the TanDEM-X mission were characterized as bistatic, assigning the "active" and the "passive" role to the satellites[1]. Therefore, inside the Mission Planning System, all TerraSAR-X acquisitions were characterized as "active" for the satellite that they were planned to be executed, while for the TanDEM-X mission the acquisition recorded by the satellite that transmitted the radar beam was characterized as "active", and its pair acquisition that was only recorded by the other satellite was characterized as "passive". Respectively to the acquisitions, the satellites were also flagged: a) for TerraSAR-X acquisitions always as "active" satellite, and b) for TanDEM-X acquisitions one as the "active" satellite and the other as the "passive" satellite. Consequently, the separation of 76 km between the satellites changed the perception on the planning of a TanDEM-X acquisition, since it could not be performed simultaneously with a pair of acquisitions anymore (one "active" and one "passive"), but in two consecutive, individual acquisitions, both characterized as "active".

In parallel, the planning concept of the TanDEM-X acquisitions was switched through a configurable parameter, to be performed based on earth location of the acquisition and not on its timing. In the previous configuration, for bistatic TanDEM-X acquisitions, it was sufficient to switch on the instrument of the "passive" satellite at the same time as the one of the "active" satellite, with both of them receiving the same backscatter from Earth's surface. In the Pursuit Monostatic formation, the planning was performed primarily based on the relative position of the acquisition location to each satellite, and individually from the acquisition time of the partner satellite. Here we have to note that the new formation did not have any consequence on the planning of the TerraSAR-X acquisitions.

2. Downlink Distribution Concept

Due to the large along track separation of the satellites, the mission planning concept of the downlink distribution had to be adapted for both S- or X-Band contacts. In the previous Bistatic Close formation, both satellites were available for every ground station, and the Mission Planning System was assigning the contacts to the satellites, either completely to only one satellite or sharing their downlink time (assuming each ground station provides one antenna at a time). In the Pursuit Monostatic formation, the satellites were too far apart to be tracked in parallel and too close to be tracked one after the other. As a result, only one satellite was available per ground station.

Prior to the Pursuit Monostatic formation, we conducted several analyses in order to define the most efficient distribution of the S- and X-Band contacts of the ground station network for both missions and satellites over the 11 day repeat cycle[1]. The S- and X-Band contacts were assigned satellite specific and in a satellite alternated order matching the following constraints:

- overlapping X-Band contacts must be assigned to the same satellite,
- X-Band contacts in which a S-Band downlink is foreseen must be assigned to the same satellite,
- X-Band contacts must keep a balanced downlink time per mission, satellite and day.

During the routine operations, we performed statistics fortnightly to identify, monitor and report potential bottlenecks such as payload and/or downlink utilization, updating if needed the distribution of the downlinks on demand.

3. TerraSAR-X Parallel Downlink Feature

The conducted statistics demonstrated immediately a bottleneck in the downlinks of the TerraSAR-X mission compared to the ones of the TanDEM-X mission. The first measure taken was the utilization of a second antenna of the Neustrelitz station, the primary TerraSAR-X mission ground station[1]. The Mission Planning System had to be adapted in order to allow parallel X-Band downlinks from both satellites, only over this station. Its activation increased the total downlink time of the TerraSAR-X mission, and as a result it not only solved the existing downlink bottleneck, but also increased the total number of executed TerraSAR-X acquisitions.

4. TerraSAR-X Ground Station Pool Concept

The second countermeasure taken for the undisturbed continuation of the TerraSAR-X mission was the activation of the Ground Station Pool concept. This concept was already operational for the TanDEM-X mission downlinks. Under this configuration, the Mission Planning System considers a pool of ground stations for every downlink, instead of only one ground station, increasing the downlink availability for each acquisition. As a result, the downlink distribution was optimized and the on-board queuing time of the acquisitions was shortened. This concept was extended by creating various pools, containing different combinations of ground stations. The most significant pool is the Near Real Time pool, a concept restricted only on TerraSAR-X commercial orders that are flagged with a higher downlink priority[6].

C. Closing the Pursuit Monostatic Formation

The enhancement of the Mission Planning System for the Pursuit Monostatic Far formation allowed the validation of pursuit monostatic TanDEM-X acquisitions for the very first time while supporting seamlessly the TerraSAR-X mission. In March 2015, the first milestone of the TanDEM-X Science phase was accomplished.

IV. Bistatic Close Formation with Large Perpendicular Baseline

The Bistatic Close formation with Large Perpendicular Baseline was initiated in March 2015. During the following six months, the TSX and TDX satellites flew close to each other over the poles, but having a cross track separation up to 3600 m. Although they were flying in a close formation, their large separation over the equator made it impossible for some ground stations to consider them always as one flying object. Some SAR applications of this formation are: the execution of vegetation measurements, the demonstration of super resolution acquisitions, the demonstration of improved scene classification, and the demonstration of innovative multi baseline cross-track interferometry and tomography[2].

A. Transition to the Bistatic Close Formation with Large Perpendicular Baseline

The transition phase from the Pursuit Monostatic formation to the new formation lasted four days, plus a couple of days more for the check-out phase. At the starting point of the transition phase, the TDX satellite was roughly

76 km behind TSX satellite. During the first two days of the TDX maneuver campaign, the separation of the satellites was large enough to allow performing the TerraSAR-X mission on the TSX satellite, while the SAR instrument on TDX satellite was directly switched off. On the third day, we switched off the instrument also on TSX satellite, in order to ensure that TDX satellite would reach its final orbit without any SAR illumination problems. Another couple of days later, the maneuvers campaign was over: TDX satellite reached its new orbit, and the check-out phase for the new formation started.

During the check-out phase, we planned only specific calibration-acquisitions. Their successful execution validated that both missions were fully functional under the new formation, ensuring that the nominal operations during the new Bistatic Close formation with Large Perpendicular Baseline can be initiated.

B. Mission Planning Operations during the Bistatic Close Formation with Large Perpendicular Baseline

In order to ensure that the TerraSAR-X/TanDEM-X Mission Planning System met the requirements of both missions during this new formation, we needed to introduce new concepts, mechanisms and checks in the system. These entries comprise either novel concepts designed specifically for this formation geometry, or updated mechanisms already in-use beforehand.

1. Preferred Satellite Concept

The most significant modification in the Mission Planning System in this formation was the introduction of the Preferred Satellite Concept, specifically designed to compensate the impact of the new formation flying geometry on the TerraSAR-X mission. The root cause of introducing this concept was the amplitude variation of the perpendicular baseline of the TDX satellite orbit from the reference orbit of the TSX satellite. For a perpendicular baseline of the TDX satellite that was exceeding a (configurable) threshold value at the time of an acquisition, the acquisition was considered to be planned firstly on TSX satellite: the preferred satellite. Only after not being planned on TSX (i.e. due to mission/formation constraints), the acquisition was considered to be planned on TDX satellite. For baselines below the defined threshold, the acquisitions had an even probability to be firstly considered to be planned on any of the two satellites.

Obviously, the Preferred Satellite Concept applied only for TerraSAR-X acquisitions, due to the fact that the SAR signal of the TanDEM-X orders is received by both satellites (thus no differentiation exists). As a consequence, most of the TerraSAR-X orders were directed on TSX satellite, while both satellites worked equally for the TanDEM-X mission. This fact not only created a bottleneck on the execution of the acquisitions and on-board storing on TSX satellite, but also strained this satellite even more than its partner. Countermeasures were taken to cope with all consequences of the Preferred Satellite Concept, which are presented in the next paragraphs.

2. Balancing the Workload on both Satellites

The orbit of the TSX satellite, within this formation geometrically advantageous, drove this satellite to execute more tasks than its partner. We created various scripts in order to monitor, check and compare automatically the performance and the health of both satellites on a daily basis. As aforementioned, most of the TerraSAR-X acquisitions were unavoidably directed to TSX satellite, creating a bottleneck on the on-board memory that led some acquisitions not to be executed due to allocation constraints. The first countermeasure was to flag, while ordering (prior to an acquisition arriving at the Mission Planning System), the TanDEM-X orders “satellite-specific” on TDX satellite, considering only this satellite as ‘active’ during a TanDEM-X acquisition. Applying this rule, the active contribution of TSX satellite for the TanDEM-X mission was minimized, without any implications for the mission itself. The acquisitions on orbit sections, where the TDX satellite could not activate its instrument (i.e. due to exclusion zones[5]), were excluded by this rule and ordered on TSX satellite by the users, imposing some extra prior-to-ordering

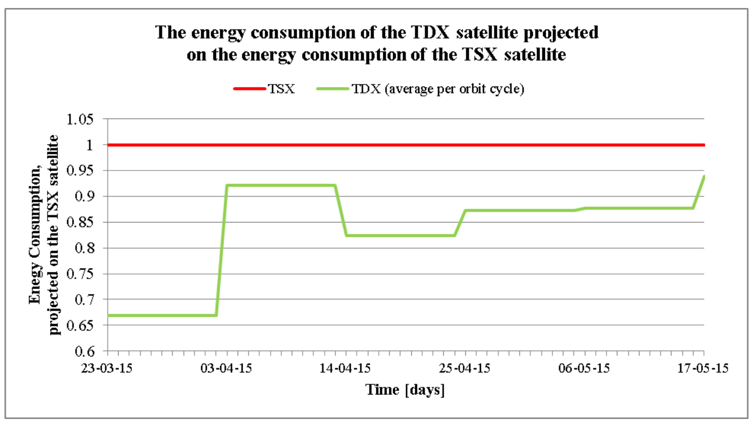

Figure 2. The energy consumption of TDX satellite projected on the energy consumption of TSX satellite. *After the measures taken, the TDX satellite was forced to execute more acquisitions, increasing its energy consumption and balancing its workload to the TSX satellite.*

analysis. This measure, as it is depicted in Figure 2, was successful for restraining the TSX satellite workload (i.e. energy consumption) but, on the other hand, it could not accelerate the free-memory process on the TSX satellite.

Regarding the downlinks, more sophisticated measures took place, considering a) the locations of the ground stations, and b) the orbit of the satellites. The fact that the formation was not homogeneous created three ground station groups based on their location:

- the ground stations close to the poles, that could track both satellites with the same antenna (sharing the downlink time),
- the ground stations closer to the equator, where one antenna could be assigned only to one satellite,
- the ground stations that could track both satellites with the same antenna during some orbits, while only one satellite could be supported for rest of the orbits.

Therefore, a detailed study was performed in order to balance the downlink opportunities between the satellites as well as between the missions, similar to the study of the previous formation phase. The results were monitored on a daily basis, and further updates of the downlink distribution among the stations per satellite and per mission were performed. At this point, the Ground Stations-Pools concept was very useful, providing more downlink-options per acquisition and minimizing the on-board waiting time of an acquisition. We reconfigured the Near-Real-Time pool, optimizing its internal ground station selection, in order to restrict the on-board waiting time of the acquisitions assigned to this pool to a few hours.

3. Sync Warning Mechanism

A critical reconfiguration in the Mission Planning System for the Bistatic Close formation, in comparison with the Pursuit Monostatic one, was to re-enable the sync warning mechanism. This mechanism is designed for the Bistatic Close formation, where both TSX and TDX satellites exchange a bi-directional 1 bit information before every SAR acquisition (partner ok or not ok), as a countermeasure to the risk of SAR illumination to the partner satellite during the SAR acquisition[1]. Obviously, this mechanism could not apply while the perpendicular baseline was so large that this bi-directional 1 bit information could not reach its target, the partner satellite. This limited the available periods, called Sync Warning opportunities, to the orbit sections over the poles (twice per orbit), where the formation was actually close. Nevertheless, in case that another activity with higher priority was planned during this period (i.e. attitude or orbit control activities, etc.), the Sync Warning mechanism could have been blocked. In order to cope with this fact, it was decided to increase the distance between a Sync Warning and the succeeding SAR acquisition to slightly longer than one orbit (100 min)[5], giving at least two Sync Warning opportunities for every SAR acquisition. In the meantime, the Mission Planning System, through automated scripts, was raising flags in case a) a complete Sync Warning opportunity was blocked, or b) an acquisition could not be scheduled because no Sync Warning was planned beforehand. All those cases were identified in advance, and ad-hoc operational measures were taken for each specific case before the corresponding timelines were uplinked to the satellites.

C. Closing the Bistatic Close Formation with Large Perpendicular Baseline

During the period of the Bistatic Close formation with Large Perpendicular Baseline, the TerraSAR-X/TanDEM-X Mission Planning System evolved successfully, facing not only direct challenges due to the formation re-configuration, but also issues implied by this new formation geometry, while supporting seamlessly both TerraSAR-X and TanDEM-X missions. In September 2015, the operations of this phase were successfully accomplished, and the transition to the last formation geometry of the TanDEM-X Science phase was initiated.

V. Bistatic Close Formation

The initiation of the Bistatic Close formation with a short across-track baseline marked the beginning of the last formation flight of the TanDEM-X Science phase. This is the same flying formation geometry as it was before the initiation of the TanDEM-X Science phase, and the satellites would keep this formation also after the end of this campaign. This formation was mostly suitable for height estimation experiments and for ocean applications in the Southern hemisphere[7].

A. Transition to the Bistatic Close Formation

In September 2015, the actual across-track baseline of 3600 m over the Earth’s equator was gradually reduced back to the initial separation of a few hundred meters[5]. The transition to the new formation was performed in three steps over three orbit repeat cycles (33 days). During the first two cycles of the transition phase, the TSX and TDX satellites flew in Bistatic Close formation over the poles but with a minimum separation of 1900 m over the equator. During this period, it was anticipated that the Sync Warning mechanism would have a similar behavior to the previous formation, restricting the Sync Warning opportunities only over the poles, but for larger periods. As a result, there was more time available for the planning of a Sync Warning, but still only twice per orbit. Therefore, the following strategy was followed: a) we decreased the distance between a Sync Warning and the succeeding SAR acquisition to the standard value of the Bistatic Close formation (53 min, slightly longer than half orbit)[5], while in parallel b) we introduced a script that forces the reservation of a short slot for the planning of the Sync Warning inside every Sync Warning opportunity. From the third cycle of this transition phase, the satellites were close enough to perform Sync Warnings also over the equator, providing more Sync Warning opportunities per orbit, thus it was decided to disable the aforementioned script for the Sync Warning slots reservation.

B. Mission Planning Operations during the Bistatic Close Formation

After the end of the transition period in October 2015, the nominal routine operations in Bistatic Close formation were initiated for both missions. Since this is a similar formation to the one before the initiation of the TanDEM-X Science phase, all ground segment features were already supported operationally, and the routine operations consisted mainly of monitoring closely the two satellites.

Repeating the same analysis regarding the workload of the satellites as during the previous formation, it was noticed that the TSX satellite started again executing more tasks than its partner, although there was no obvious indication for this new unbalancing of the workload. The ordering strategy of satellite-specific TanDEM-X acquisitions on the TDX satellite was resumed also in this formation, therefore we had to look for another root-cause. Searching more deeply in the system, we found out that many acquisitions were ordered for locations where the TDX satellite was in an exclusion zone, meaning that it could not activate its instrument for acquisitions[5]. Excluding those orders from the statistical analysis, the workload was again balanced, as it is shown in Figure 3. This workload of both satellites was monitored throughout the Bistatic Close formation.

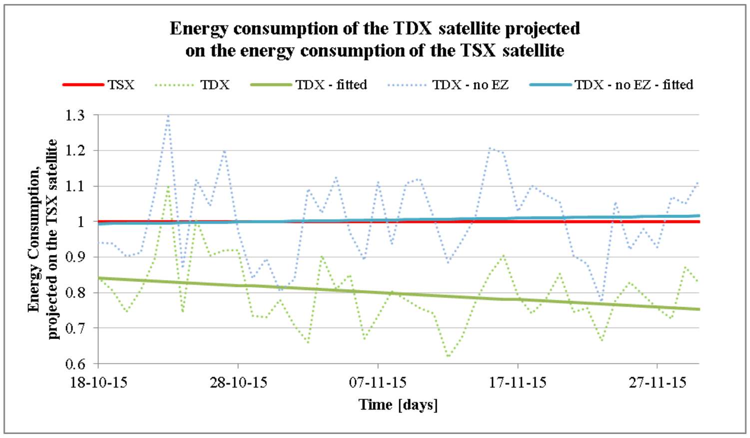

Figure 3. The energy consumption of TDX satellite projected on the energy consumption of TSX satellite. *After the transition to the Bistatic Close formation we observed a higher workload on the TSX satellite, which is only related to the fact that many acquisitions where in locations where the TDX satellite was in an exclusion zone.*

C. Closing the Bistatic Close Formation

During the period of the Bistatic Close formation, no specific evolvements needed to be introduced into the joint Mission Planning System and both TerraSAR-X and TanDEM-X missions were seamlessly supported. This was the last formation geometry of the TanDEM-X Science phase, and after February 2016, the satellites continued flying in the same geometry, the Bistatic Close formation.

VI. Dual Receive Antenna Configuration

The Dual Receive Antenna (DRA) configuration stands for the on-board configuration where both the prime and the backup SAR instruments of one satellite are switched-on during the execution of an acquisition: one of the two instruments (in our case the prime) transmits the radar signal for the acquisition (i.e. flagged as active), while both of them (prime and backup) receive back the signal, generating a Dual Receive Antenna acquisition, hereinafter DRA-acquisition. This configuration can be applied to one or to both satellites simultaneously, defining:

- the TerraSAR-X DRA-acquisitions (both instruments only on one satellite switched-on), and
- the TanDEM-X DRA-acquisitions (both instruments on both satellites switched-on; one of the four instruments is active, while all four receive the radar signal).

The DRA-acquisitions are intended to demonstrate the ability of moving object indication and traffic monitoring, as well as the demonstration of digital beamforming[2,8]. Although the DRA configuration was tested in a dedicated campaign on TSX satellite prior to the launch of TDX satellite, this configuration was never incorporated into the joint TerraSAR-X/TanDEM-X Mission Planning System. Configuring the Mission Planning System in a way to a) receive DRA-acquisition requests for both missions, b) plan them in the master timeline, and c) finally export the corresponding commands for each of the satellites in parallel with the already existing TerraSAR-X and TanDEM-X configuration, has been one of the biggest challenges for the Mission Planning team throughout the TanDEM-X Science phase.

A. Single Receive Antenna Configuration vs. Dual Receive Antenna Configuration

Under the DRA-configuration, both instruments have access to the on-board memory. Half of the memory is assigned to the prime instrument and the other half to the backup, dividing the available memory in half. On the other hand, the downlink of the DRA-acquisition pair is (obviously) serial, therefore performed always in SRA-configuration, independent of the instrument configuration during its acquisition. As a consequence, it was necessary to distinguish the two instrument modes inside the Mission Planning System, based on the two instrument configurations:

- The Single Receive Antenna mode (SRA-mode) for the default, already existing, on-board configuration. This mode is applied also for all the non-DRA-configuration activities of a DRA-acquisition, i.e. the downlinks.
- The Dual Receive Antenna mode (DRA-mode), representing the instrument configuration where both instruments of the same satellite record an acquisition.

B. Preparation of the Mission Planning System for the Dual Receive Antenna Configuration

The DRA-configuration was never validated in the joint TerraSAR-X/TanDEM-X Mission Planning System, after the launch of TDX satellite. Therefore, before the TanDEM-X Science phase, a test-day in February 2014 was dedicated for the validation of the Dual Receive Antenna configuration in the TerraSAR-X/TanDEM-X mission. During this test-day, the nominal operations were interrupted and a timeline containing only DRA-acquisitions was manually generated.

The successful ordering, processing, planning and execution of those first DRA-acquisitions gave the green light to incorporate the DRA-configuration in the TanDEM-X Science phase. From the Mission Planning point of view, the manual changes we performed, the problems we dealt with, and the observations we noticed during this test-day; were our guidelines for the evolution of the Mission Planning System to cope with two different instrument configurations, the Single- and the Dual Receive Antenna configurations.

Individual tests prior to the initiation of each formation geometry phase were performed[6]. Through those tests, we proved the smooth processing of the DRA-acquisition requests inside the Mission Planning System, in parallel with all the internal and external changes by the new formation geometries.

C. Mission Planning Operations during the Dual Receive Antenna Configuration

The DRA-configuration was operated in parallel with the three different formations of the TanDEM-X Science phase. It was enabled in November 2014, during the Pursuit Monostatic phase, and continued throughout the Bistatic Close formation with Large Perpendicular Baseline and the Bistatic Close formation. The DRA-configuration was disabled shortly before the official end of the TanDEM-X Science phase. In the following paragraphs, we describe the challenges we faced while operating under the DRA-configuration, and the countermeasures that were taken.

1. Receiving DRA-Acquisition Requests

The first differentiation in the Mission Planning System was during the ordering of the acquisition requests, where a new flag was introduced for defining the instrument mode (SRA- or DRA-mode) during the acquisition. Only Science users were able to order DRA acquisitions, while all other acquisition-requests were set to SRA-mode by default.

2. Planning the DRA-Acquisition Requests

The SRA-mode, as abovementioned, was decided to be the default mode. The SRA-/DRA-mode flag of the acquisition requests was considered during the planning of the timeline events. A new rule was added for the DRA-acquisition requests: to distinguish the tasks that should be performed on-board under the DRA configuration, switching to the DRA-mode, from the rest being performed in the default, SRA-mode. Therefore, two switches were introduced: SRAtoDRA and DRAtoSRA, enabling or turning off the backup instrument chain respectively.

It was obvious that conflicts might arise due to this switching between the two modes (i.e. blocking on-board memory activities). Having as default mode the SRA-mode, it was more probable for DRA-mode tasks to be blocked. Between the SRA- and the DRA-acquisitions, the nominal planning rules applied. Nevertheless, we introduced a new planning rule related only to the planning of the DRA-acquisitions. It could be possible that downlinks of a DRA-acquisition (as aforementioned, performed in SRA-mode) block an upcoming DRA-acquisition (in DRA-mode). In order to avoid this problem, the Mission Planning System considered the DRA-acquisitions in a reverse-chronological-execution order. Hence we achieved to consider always DRA-acquisitions with execution time earlier than the already scheduled downlinks of upcoming DRA-acquisitions, minimizing the probabilities of conflicts between the two instrument modes.

The DRA-acquisition consists of a pair of acquisition files stored in the memory, the first representing the sum of the signals recorded by the two instruments and the second representing their delta. The Mission Planning System was responsible to assign the corresponding naming to these files, in order to reflect to the same acquisition, but also to differentiate their instrument chain. This was a requirement not only for Mission Planning, but also for the ground stations, in order to distinguish the downlink files they were receiving, as well as for the recipients of the orders while processing the DRA-acquisitions.

As a consequence, for every DRA-acquisition, double on-board memory was reserved in comparison to a SRA-acquisition. In the TanDEM-X Science phase, a TanDEM-X DRA-acquisition required four times more memory than the respective TerraSAR-X SRA-acquisition. The more DRA-acquisitions were planned for a specific timeframe, the less on-board memory capacity was available. Through techniques to minimize the on-board queuing time of an acquisition until its downlink (as described in the previous chapters for each formation geometry), we succeeded to minimize the quantitative impact on the execution of other acquisitions.

Finally, the continuous fluctuation of the on-board memory usage, together with the consecutive instrument mode switches, forced a more frequent check between the Mission Planning on-board memory model and the actual on-board memory levels. Throughout the whole DRA configuration campaign, the Mission Planning memory model was proved perfectly accurate.

3. Mixed SRA-/DRA-Mode Timeline Export

The third part of the Mission Planning System that needed to be re-configured was the Master Timeline export. New Flight Procedures had to be released for the backup chain of the instrument for this new configuration. In parallel, old Flight Procedures (i.e. for downlinks) needed to be adapted to receive input for DRA-mode information. All the corresponding Flight Procedures were validated and tested extensively prior to their operational usage.

After the master timeline export and prior to its uplink to the satellites, a final check was implemented regarding the consecutive switching between the two modes and the tasks included in each mode. A script was developed to prove that the final planning was correct and the respective tasks were included in the correct (SRA- or DRA-) mode.

D. Closing the Dual Receive Antenna Configuration Campaign

The DRA configuration campaign was terminated in January of 2016, a shortly before the end of the TanDEM-X Science phase. After thousands of DRA-acquisitions, in parallel to the nominal operations of the TerraSAR-X and TanDEM-X missions, the DRA configuration was disabled in the Mission Planning System, through configurable parameters. Nevertheless, it proved that the Mission Planning System can cope with large internal changes, expanding the spectrum of the provided services to the users of the mission.

VII. Conclusion

The TanDEM-X Science phase was a challenging period for the Mission Planning System. Regardless of the numerous adaptations, reconfigurations, and new entries in the system, no large contingency was experienced, thanks to the extensive and thorough testing prior to their operational installation. The features introduced into the Mission Planning System were disabled through configurable parameters at the end of the TanDEM-X Science phase, together with the relevant documentation for future usage. A large amount of the described statistical analyses are kept and now automated, providing new aspects on the operations of both satellites and missions. The joint TerraSAR-X/TanDEM-X Mission Planning System has successfully evolved for the TanDEM-X Science phase, giving more operational flexibility and robustness, continuing at the same time its automated and unattended operations.

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