The TerraSAR-X/TanDEM-X Mission Planning System: Realizing new Customer Visions by Applying new Upgrade Strategies

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The history of the TerraSAR-X and TanDEM-X mission planning system is briefly presented. In addition to the not trivial demands of the first years, special attention is given to the challenges of recent years. Here the TanDEM-X science phase, conducted between 2014 and 2016, is the most prominent feature. It is shown how agile software engineering methods can help to keep the already achieved system robustness, and how further enhancements can easily be incorporated.

Nomenclature

TerraSAR-X	=	The TerraSAR-X Mission
TanDEM-X	=	The TerraSAR-X add-on for Digital Elevation Measurement Mission
TSTD	=	TerraSAR-X & TanDEM-X
TSX-1	=	The TSX-1 Satellite
TDX-1	=	The TDX-1 Satellite
DRA	=	Dual Receive Antenna
SSMM	=	Solid State Mass Memory
MPS	=	Mission Planning System
GSOC	=	German Space Operations Center, a German Aerospace Center (DLR) institution
PLATO	=	PLAnning TOol – GSOCs automatic planning and scheduling library
SCOTA	=	SpaceCraft Orbit and groundTrack Analysis tool

I. Introduction

The successful launch of the TDX-1 satellite on June 21st, 2010 marked the beginning of the challenging TerraSAR-X add-on for Digital Elevation Measurement mission (TanDEM-X). Its primary mission goal is the generation of a high-accuracy world-wide global digital elevation model[1]. The satellites TSX-1 and TDX-1 were therefore flown for about four years in a close configuration to form a single-pass (bistatic) spaceborne radar interferometer in a stable baseline configuration. Since the acquisition of TanDEM-X data required both satellites, the ongoing TerraSAR-X mission also had to be distributed over both satellites to counterbalance the interferometric usage.

As the original TerraSAR-X mission already led to some complex solutions within its ground segment to fulfill its demanding requirements, the TanDEM-X mission required just as many new ideas and solutions for the acquisition of the DEM data within the TerraSAR-X/TanDEM-X ground segment[2].

In 2014, the DEM data acquisition was successfully completed. Since then, mainly the secondary TanDEM-X mission goal is supported by acquiring and generating radar data products for a number of science and new technology related applications. This phase is hereinafter called the *science phase*.

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In parallel to the DEM data acquisition and the science phase, the TerraSAR-X mission is still ongoing. As the TerraSAR-X mission is also breaking into new grounds with every further year of operation, the number of new features that are implemented on TerraSAR-X side and their complexity is comparable to the one on the TanDEM-X side.

The next chapters will highlight different aspects of achieving the challenging goal to smoothly operate a combined TerraSAR-X/TanDEM-X mission planning system (TSTD MPS) in parallel to a continuous upgrade process that improves the system dependability and increase its complexity, while minimizing the impact on the two missions[3].

A brief overview of the main system enhancements will be given. Two novel key features of the TerraSAR-X mission are selected: First the introduction of new radar imaging modes, which caused the need to upgrade the whole swath preview service, starting from the user's scene selection up to the spacecraft command preparation; second the near-real-time downlink scheduling strategy, which makes use of ground station pools. In this context, the specifics of a two-satellite scheduling problem are illustrated.

For the TanDEM-X mission two system enhancements that are needed during the science phase are described as well. First, the *preferred satellite* concept enabling the possibility to minimize a special effect on the TerraSAR-X mission while having the two satellites in an unfavorable constellation with respect to special orbit requirements; Second, as the most prominent feature enhancement for the science phase, the *dual receive antenna* configuration[4,5] is described from the Mission Planning point of view. While all other already mentioned add-ons already required clever solutions, this upgrade was the most complex one for the combined TerraSAR-X/TanDEM-X MPS since the launch of the TDX-1 satellite.

This paper explains the process of designing, implementing, testing and deploying those new features into an operational system via an agile software development process. Particular emphasis is put on the support tools for continuous software maintenance that allows for collaboration of multiple developers on the project.

At the end, the integration and validation process of the Mission Planning System into the whole ground segment is described, including the configuration management. Furthermore the maintenance and monitoring tasks that allow for unattended operation of the two interwoven missions side-by-side will be presented.

II. History of the TerraSAR-X/TanDEM-X Mission Planning System

A. The TerraSAR-X only MPS

The TerraSAR-X mission started in 2002 with the first ideas, how the mission can look like, with the definition of the Mission Requirements and the Mission Planning Concept[6-8]. In the subsequent years the TerraSAR-X mission planning system was specified, designed, implemented and tested[9] in accordance with the ECSS phase model. Very early, in 2006 due to changing customer requirements, the system engineering of the TerraSAR-X Mission Planning obtained an agile touch[10]. Even though not followed in detail, the development approach of the TerraSAR-X mission planning system became SCRUM-like, as already introduced in 1986 by Hirotaka Takeuchi and Ikujiro Nonaka[§,11] as "a flexible, holistic product development strategy where a development team works as a unit to reach a common goal", in contrast to a "traditional, sequential approach".

The main driver for changing the software engineering approach from sequential to agile was the modification of the whole mission planning workflow for the so called *short notice planning*[12], which implemented a feature to decrease the time interval between the latest order submission time and the earliest possible delivery of the processed radar data product from about 18h to a minimum of about one hour for selected applications.

B. The TanDEM-X Mission planning system

The mission planning team at GSOC implemented the first version of the TanDEM-X MPS in the years 2007 to 2010, already having the experience of regularly changing boundary conditions within the TerraSAR-X mission. This experience could be used to improve the system engineering methods applied during this phase. For the TanDEM-X mission not only a second satellite was introduced, but also several new features, e.g. formation flight, safety measures against mutual radiation (exclusion zones and so-called *deadman's control*), ground station pools were introduced[13,14].

As many parts of the ground segment for both missions were implemented and operated in parallel, a combined TerraSAR-X and TanDEM-X Mission Planning System had to be designed, implemented, tested and especially put into operation taking into account the demands of both missions[15]. One major challenge within the new mission planning system for the two missions was the reconcilement of their different mission goals. Examples are the

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[§] https://en.wikipedia.org/wiki/Scrum_%28software_development%29 [cited 30 March 2016] contrary temporality needs of both, on the one hand the near-real-time applications of TerraSAR-X, having late order submission and earliest downlink demands, on the other hand, the long term prediction need for TanDEM-X, to ensure the complete coverage of the land mass for the final global DEM to be generated.

C. Extensions to the combined TerraSAR-X/TanDEM-X Mission Planning System in the last years

From a simplified point of view, one could argue that mission planning is based on a collection of tasks, resources, constraints and algorithms; and the system shall by its nature be easily adaptable to any new operational requirement. Therefore the TSTD-MPS is already easily adaptable to many new operational requirements. However, reality is a bit more complex, as the mission planning system in many cases is embedded in a complex ground segment. The changes to be performed can range from the adaption of the mission planning model and algorithms, to the mission planning internal interfaces and workflows, over the complete revision of established ground segment internal workflows and last but not least to the adaption of external interfaces from and to the customer.

In this chapter, some important extensions of the combined TerraSAR-X and TanDEM-X mission planning system are outlined.

1. New Radar-Modes for TerraSAR-X

In the years 2012 and 2013, the whole TerraSAR-X ground segment was extended to support two new radar modes, the *Staring Spotlight* and the *Wide ScanSAR*[16]. The challenge was to integrate the functionality needed for them into various components, mainly in the acquisition request processing workflow. It was decided to have a new approach in contrast to the well-established modes w.r.t. swath preview and planning information.

Originally, the TerraSAR-X swath preview functionality, provided by mission planning as a fast and reliable service with a repetitious accuracy, was based on a pre-calculated data set, also known as *footprint database*[9]. This pre-calculation was necessary, as the calculation time was not sufficient for the on the fly processing. The swath preview and the planning information for scheduling and commanding of the new modes are now calculated on the fly, based on the sensor geometry (looking angles, dimensions), the satellite properties (attitude steering table), and the elevation model of the Earth surface. This approach became feasible not only due to improvements in the computer performance over the recent years, but also due to newly developed calculation and search algorithms within our generic event calculation library SCOTA, embedded in the mission planning system allowing a real-time processing. In case of additional new radar modes in the future only the configuration of the mission planning system needs to be adapted, rather than extending the footprint database again and again.

2. TanDEM-X science phase

After the successful global DEM data acquisition, and thus the completion of an important milestone for fulfilling the primary mission goal of the TanDEM-X mission in 2014, the so called TanDEM-X science phase was launched to enable new SAR applications for the science community, the secondary mission goal. This science phase posed again new challenges onto the mission planning system.

Operational support to a number of different flight formation constellations (pursuit monostatic, bistatic with large horizontal baseline) had to be given[17].

When executing TerraSAR-X mission acquisitions the respective satellite has to fulfill certain performance requirements, depending in particular on the actual orbit position on its reference orbit. While the TSX-1 satellite is flying this reference orbit, the TDX-1 satellite constantly revolves around it (once per orbit). Therefore these performance requirements are hard to fulfill by the TDX-1 satellite, if depending of the current formation the distance between the current TDX-1 orbit position and the TSX-1 reference orbit is increasing. Even with additional roll-steering on TDX-1, depending on its current orbit position, the geometrical deviation between the reference scenario and the current situation is too large to meet the performance requirements in general.

To take this fact into account, the *preferred satellite* concept was introduced. Based on the current orbit position of the satellite and its deviation from the TSX-1 reference orbit therefore the so-called *perpendicular baseline* is calculated. If this value exceeds a certain limit, the satellite with the smaller perpendicular baseline is preferentially selected for scheduling[18].The other, even more complex extension of the TerraSAR-X/TanDEM-X mission planning system for the TanDEM-X science phase is the support of the *dual receive antenna* (DRA) configuration[19, 20]. In this configuration, both the primary and the redundant on-board receiver chain are used to enable the acquisition of fully polarized or along-track interferometric SAR data. Even if this DRA is considered an experimental instrument mode, a full operational support of its handling by the mission planning systems is required. TanDEM-X DRA acquisition requests are interspersed with standard single-receive ones in one timeline. They have to be planned and executed simultaneously on both satellites. The redundant instrument chain needs to be activated on both satellites accordingly, the on-board Solid-State Mass Memory (SSMM) has to be enabled for DRA data storage which differs from the single-receive configuration. Specific downlink constraints are to be observed. Thus, the DRA support meant a considerable mission planning system update w.r.t. scheduling algorithms, commanding, on-board memory modelling, and downlink planning.

For the mission planning system, in particular the planning model and algorithm, and the correct commanding of the satellite, this extension was the dominant topic of the recent years, and will be highlighted in the next chapter from the system engineering point of view in some detail.

3. Further extensions

TerraSAR-X near-real-time downlink planning: As in the recent years the demand for near-real-time applications for the TerraSAR-X mission has increased significantly, the relevant temporality constraints have been improved at many facilities within the TerraSAR-X ground segment. One of the temporality parameters that can be influenced by mission planning to a certain extent is the time between data acquisition and data downlink. Therefore, the near real time downlink planning algorithm was implemented, scheduling the downlink of a near real time application at its earliest possible opportunity.

TerraSAR-X ground station pools: Having started in 2007 with the Neustrelitz downlink station only, the TerraSAR-X ground station network has been extended gradually. Although stations were added for local applications only at the beginning of their usage, over the years the need for additional stations as well for global applications was increasing. Soon, the downlink capacity of Neustrelitz was exhausted the ground station pool feature was implemented within the TerraSAR-X ground segment and the additional stations could be added on demand, to increase the downlink capacity. The benefit of the near-real-time downlink planning feature could be improved by combining it with a ground station pool such; that the time to the next earliest downlink opportunity can be further minimized.

III. System Engineering of the TerraSAR-X / TanDEM-X Mission Planning System

The overall ground segment system engineering process within the TerraSAR-X and TanDEM-X mission follows the ECSS standards[**]. The change management process is based on a dedicated configuration management plan, which was originally put in place for TerraSAR-X and later accordingly extended for the TanDEM-X mission. The processing of changes within the missions follows a top down approach on four hierarchical levels: The top level is the system or mission level, the second one the segment level consisting of space, ground, commercial service, and science service segment. The third level under the ground segment is formed by the three sub-segments. On fourth level follow the individual systems comprising a sub-segment. The TSTD MPS (fourth level) is thus embedded in the mission operations segment (MOS) on third level. Just for completeness, the TSTD MPS itself is composed of five components (level five) and 44 configuration items, all of the lowest level six. Most of the change requests for the TSTD MPS originate directly from the second level, and occasionally they are originated directly by the mission.

As the changes to apply on ground segment or mission level are by nature rather complex and usually require a coordinated implementation plan throughout all levels, a (purely) agile system engineering process is in general not applicable. It was however found to be appropriate for the evolving TSTD MPS to realize the numerous extensions and modification within the given tight schedule. The software development style guide of the TSTD MPS team describes how the activities for the MPS have to be derived from the overall implementation plan on system or segment level. Such, it is embedded tightly in the overall ground segment change process, but enables the MPS development team to make use of an agile software development process.

In the next paragraphs a more detailed insight into the principles of the MSP development approach is given by addressing the following aspects:

A. issue tracking, change management and release planning,
B. software configuration management and version control,
C. code collaboration and peer review, and
D. continuous integration

All of the methods were introduced and applied by the mission planning team in the recent years. With the experiences gained not only from TerraSAR-X and TanDEM-X now and in the future, these methods are permanently improved and adapted.

[**] http://www.ecss.nl/ [cited 30 March 2016]

A. Issue tracking and release planning

Having only two developers working on the TerraSAR-X mission planning system at the beginning in 2002, a simple Excel sheet was absolutely sufficient for tracking the tasks to be done. With more and more developers working in parallel dealing with an increasing number of issues a bug and change request database (called BCR tool) was developed mission planning internally in 2005. It consisted of a small bunch of PHP scripts, a MS Access database and was running on a Windows Desktop. It allowed an easy submission of new change requests to the TerraSAR-X mission planning system. With the increasing number of collaborating MPS developers being also involved in other projects in parallel, consequently the number of change requests to the change request tool itself increased as well, concerning for example the user management, the ability to reference more than one project, component and version tracking, etc. Thus it was time for the evaluation of several solutions. Finally the Jira™ issue tracking software was chosen.

In the following, several workflows supported by Jira were defined in the mission planning style guides for TSTD, and GSOC in general. Above all, the roadmap/release planning workflow has to be mentioned, as this is one of the anchors for the short term and long term planning within our team. Having the possibility to link issues to (future) versions of the Jira *components* (== *configuration items* in the ECSS world) a short and long term roadmap can be compiled. Using finally the release workflow, the automatic generation of the release notes and the deployment of a new component (configuration item) version is standardized.

Just as an example, for the dual receive antenna support about 200 Jira issues for sub-tasks to be implemented were generated for 12 Jira components and about 25 versions were released.

B. Version Control

Together with the issue tracking an effective version control system is the basis of any software project. Here the mission planning team was using the MS Visual Source Safe software for many years. Although this software had some limitations, like inefficient branching and merging capabilities and the exclusive checkout functionality, the version control based on VSS still delivered a valuable service.

After a successful pilot phase in 2010, however the GSOC mission planning team decided to migrate to the distributed version control system Git[21], with the following prominent features: intuitive branching and merging functionalities, allowing for working offline or working in parallel on the same file, cherry-picking between branches, flexibility to define own workflows and its robustness.

Together with Jira, Git has become part of one of the basic rules of our software development style guide, the 'No Jira-Issue, No Git-Commit' policy. This rule allows not only a transparent release planning for each component and each configuration item; it enables also the team to trace back any code change to an originating observation and purpose, not only to the local component domain, where it is already done within the code documentation, but also within the global view, up to the original customer request.

For the already mentioned 200 Jira issues for the implementation of the dual receive antenna mode over 500 Git commits were submitted. The lines of software code associated to these commits are difficult to count, but amount to several thousand, including code documentation.

C. Code collaboration

Distributing up-to-date knowledge about our development methods in general, and in particular ensuring the compliance with the agreed development style guide are other basic rules during the development of a software project. In addition, keeping in mind that software products for space projects have to be maintained for the upcoming years and sometimes decades, sharing the knowledge of the current enhancements other developers made to the software is essential

Beneath having automatic style checkers and static code analysis for the common programming languages available, formal code review processes or regular training sessions are possibilities to ensure these rules. However, using intuitive tools for code collaboration has proven to be another very effective method within the agile software development process.

For this purpose a BitBucket server was set-up at GSOC, as it provides a fully integrated Git server as basis. The big beneficial feature it provides is enabling code review via the so-called *Pull Request* workflow. As soon as a developer is ready to merge his code changes into a higher level software development branch, he is creating a *Pull Request* and is assigning this to at least one developer within the team who can include comments and improvement suggestions. If a change in the code or its documentation is necessary, a new commit is included in the Pull Request. As soon as the Pull Request is accepted, the new code can be merged.

D. Continuous integration

In spite of all precautions taken in the definition of the previously mentioned workflows, it cannot be completely ensured, that a code change necessary in a shared library for a specific functionality in component A has no influence to the functionality of a component B in which it is also used. The reasons why this situation can happen are manifold; bug-fixing of base functionalities and re-engineering of APIs for better code maintenance are just two prominent examples.

In former times, developers were very reserved doing this, because the potential implications were not directly observable. Alternatively, bugs in base libraries were worked around in the calling application. With the help of the continuous integration functionality, these dilemmas could be minimized.

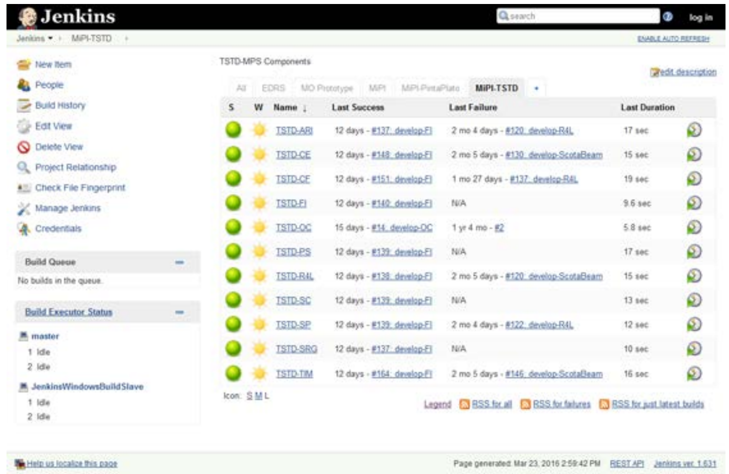

Figure 1. Build and test status of the TSTD-MPS Components within Jenkins, after a commit to the component develop-branch of the FI (FileIngestion) on the 11th of March.

A Jenkins Continuous Integration Server was introduced, that works the following way: For each change on any of the code-branches under supervision, all predefined components are re-compiled and all associated unit and regression tests are executed. Thus, for example, having a commit on the development branch of component A, automatically component B is re-built as well and all its unit and regression tests are executed. Depending on the complexity of the component this can take just seconds up to several days. Since for the two anchor applications TSTD Scheduler and TSTD Command Exporter the test set is huge and includes several gigabytes as test input and consequently several gigabytes as output, the Jenkins Continuous Integration Server here is only used for automatic re-build and basic test execution. The overall test-suite for both applications is executed only on demand, usually just before the release of a new version.

Figure 1 shows an example for the status information provided by Jenkins.

In case a Jenkins run for a specific component fails, currently an email is sent to the lead developer of the affected component and the lead of the component that caused the failure. The reason for the failure is analyzed and appropriate countermeasures are taken. In case of build failures usually just only a minor change in path specifications within libraries, project specifications or component solution setup files is necessary. In case of test failures, usually a more complicated root cause exists. A prominent example is the already mentioned 'supposed behavior pattern'. With Jenkins such failure cases can be discovered very easily already on base library test level (with unit tests defined) and immediately analyzed and solved.

If the Jenkins run is successful, a new version of a component of the TSTD MPS can be deployed.

E. Deployment and operational release

Since the presented agile workflows allow for doing a deployment of a new version of a component of the TSTD MPS at any time, the subsequent steps to finally release a new feature / software version are straight forward and well-established based on the applicable standards.

Once it has been decided to make a deployment, the respective system tests are executed and the test results are documented in the regular form of the TerraSAR-X/TanDEM-X mission. If during this tests nonconformities are detected, nonconformance reports are raised against the mission planning system and the presented agile workflow is triggered again. The same applies, if errors are detected within the verification or validation tests on ground segment level.

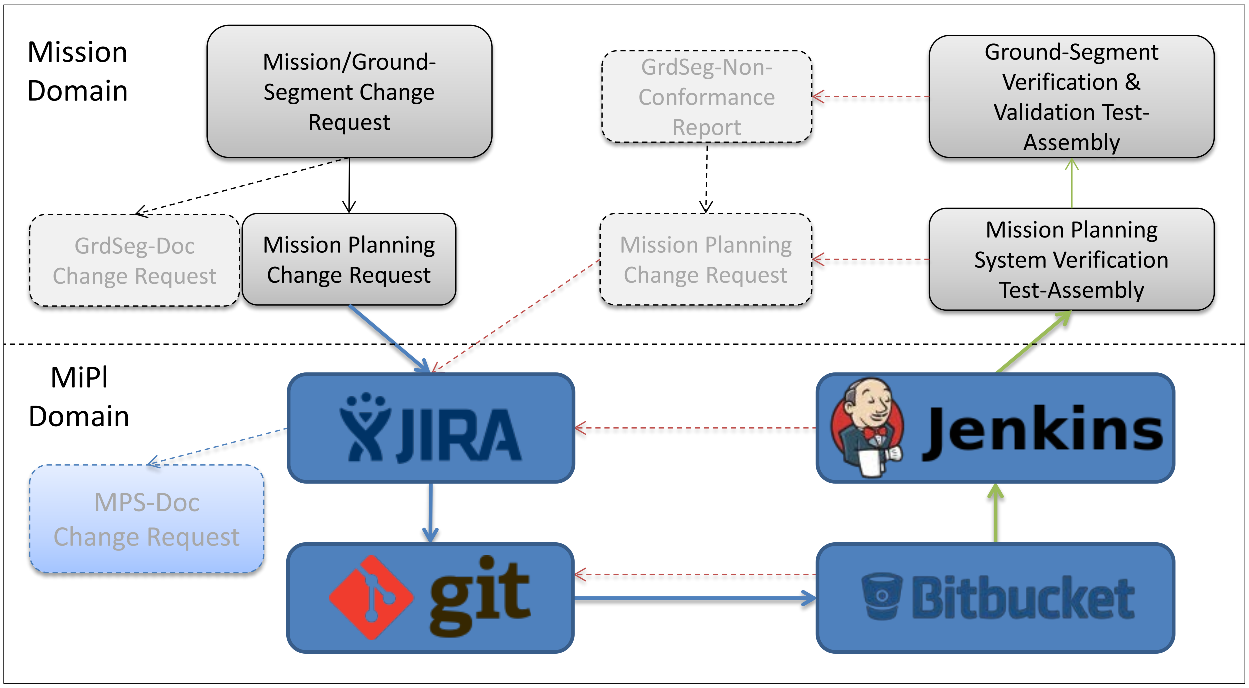

Figure 2. The overall workflow of change requests originated by the TSTD mission and affecting its Planning System. In the upper part the traditional system engineering workflow is sketched. The lower part is showing the interaction between the agile software development tools used by mission planning. The shaded boxes and arrows are illustrating the optional steps and workflows, by default they are not passed through. As some steps can finish with a positive or a negative result, the subsequent workflow is depicted with green or red arrows respectively.

The operational release of the software and its validation can be one of the trickiest steps within the software development process of a mission planning software. Especially, in case certain operational constraints are only assumptions and can only be finally verified in space. Again, the validation of the dual receive antenna configuration support and its operational release can serve as an example. Since this mode was implemented in some onboard software components for experimental purposes only, the related operational constraints of the spacecraft were only available to a certain extent, so a proper in-orbit validation of all implemented constraints at mission planning level was essential. These steps were included in a detailed plan to validate all ground segment and space segment aspects of the DRA configuration. As its operational release and validation could have had a major impact on the ongoing TerraSAR-X and TanDEM-X missions, it was decided to pause these missions for a short time frame and not allow the parallel operation with the DRA mode before the successful validation. However, with only three mission planning relevant observations during this validation, all of them hard or even impossible to find during the previous steps in the software engineering process, the release of the dual receive antenna mode in parallel to the TerraSAR-X and TanDEM-X mission could be done without any delay and 14 months of operations then did also not show any other anomaly in space or on-ground.

IV. Feedback of the TSTD mission planning operations into system engineering

Last but not least, some remarks should be given how the TSTD MPS is operated and monitored. As the special operation and monitoring activities during the TanDEM-X science phase is described in detail in Ref. [17], here only the feedback from the operations back to the system engineering is shown based on a current example.

Monitoring various parameters within the mission planning system is essential to recognize unusual behavior. If undetected it can have a negative impact to the mission, as for example an unplanned outage due to wrong scheduled and/or commanded spacecraft activities, or the excessive usage of a resource like the satellites due to a unbalanced distribution of the load between the TSX-1 and TDX-1. In Ref. 17 is shown that the various flight formations between the two satellites and the increased effect of the *perpendicular baseline* concept can lead to such an unequal distribution. In figure 3 the load distribution between the TSX-1 and TDX-1 satellites is shown. It can be easily recognized, that the TSX-1 satellite has always a higher load, than the TDX-1, with a maximum of about 185% in comparison to the TDX-1 satellite. Deeper analysis has shown, there are several reasons for having this imbalance. Beside the already mentioned effect of the perpendicular baseline, the pre-selection of the TerraSAR-X satellite for some specific applications, or the current positions of the exclusion zones are further reasons. As the last two cannot be bypassed, different options were discussed, inclusive a modification of the *perpendicular baseline* concept. First of all the pseudo random distribution between TSX-1 and TDX-1 acquisitions, realized by using a reproducible hash code algorithm during scheduling[13], was adapted such, that the current uniform distribution can be weighted to one of the two satellites, depending of the current needs. Even this change was affecting one of the core functionalities of the TSTD MPS, the workflow from the mission change request (the idea) to the successful completion of the mission planning system verification test could be done within two weeks. The validation test of the new feature is still in preparation, but with our long experience of placing new software in operation, this is only a question of days.

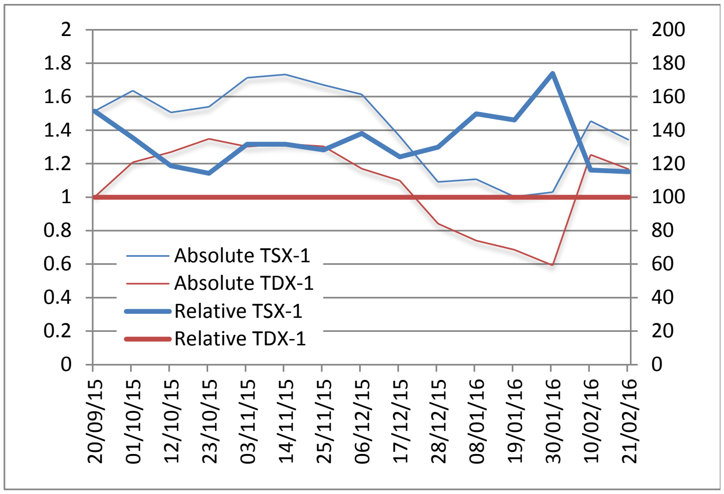

Figure 3. The Load Distribution between TSX-1 & TDX-1 over time. Left Axis: The absolute load normalized to the value on the 2015-09-20 is plotted; Right Axis: The relative load, normalized to the current value of TDX-1

V. Conclusion

The mission planning system for the TerraSAR-X and TanDEM-X missions has experienced several major updates within the recent years. Having the need to be able to implement the respective changes in short consecutive sequences or even in parallel, the traditional software engineering methods are hard to apply. During the implementation of the TerraSAR-X MPS, the GSOC mission planning team has started to use modern agile software development methods and tools. Over the years these methods were improved and the agile software engineering tool family was extended.

The agile system engineering methods can be very easily combined with the well proven software engineering standards for space products, as shown on the example of implementing support of the *dual receive antenna* configuration in the mission planning system on one hand and integrating it in the TanDEM-X ground segment. This enables the TerraSAR-X and TanDEM-X mission and its mission planning system to be responsive on new customer needs.

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