TerraSAR-X/TanDEM-X Mission Planning

Handling Satellites in Close Formation

Dr. Michael P. Geyer, Dr. Falk Mrowka, Christoph Lenzen

German Space Operations Center, DLR Oberpfaffenhofen,

82234 Wessling, Germany

I. Introduction – The TanDEM-X Mission

The TanDEM-X project is implemented by a Public-Private Partnership (PPP) between the German Aerospace Center (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, TanDEM-X and TerraSAR-X, form the first configurable SAR (Synthetic Aperture Radar) interferometer in space with a separation of only a few hundred meters. TerraSAR-X is of almost identical construction as TanDEM-X and has been in orbit since 2007. A powerful ground segment which is closely interfaced with that of TerraSAR-X completes the TanDEM-X system. The TanDEM-X satellite has been launched on June, 21st, 2010. The original primary goal of the TerraSAR-X satellite is the TerraSAR-X mission, which is to supply the commercial and scientific users with radar image data on request.

The satellites will fly in formation and operate in parallel for three years to cover the entire surface of the Earth. The radar instruments on both satellites may be used synchronously in a bi-static mode: One or both satellites actively transmit radar pulses; the echo is received by both satellites. This configuration gives a stereoscopic view such that information comprising all three dimensions can be retrieved from the data.

Shortly after the launch, the two satellites have been brought into a formation with a distance of about 20km in flight direction. This configuration has been the baseline for the first part of the commissioning phase. After successful space segment and ground segment validation, a dedicated review has given their go for the close formation. Since October, 13th, 2010, the two satellites are now flying with horizontal distances of about 360m and vertical distances of about 400m [8]. The formation parameters will be changed throughout the mission to match the requirements of the global DEM acquisition plan. The second part of the commissioning phase, concentrating on close formation aspects, will end in December 2010.

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 satellite 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.

As TanDEM-X is considered to be an add-on, the original TerraSAR-X mission and its mission goals are still performed, such that a combined TanDEM-X/TerraSAR-X mission is achieved. Beginning with the second part of the TanDEM-X commissioning phase, nominal delivery of single satellite TerraSAR-X products has been restarted for scientific and commercial customers.

The German Space Operations Center (GSOC) designed the operations concept, implemented the necessary facilities and software and will operate the two-satellite mission throughout its lifetime [6]. This paper concentrates on the mission planning aspects. The combined TerraSAR-X / TanDEM-X mission planning system handles the two satellites as well as two completely different missions with their different mission goals. As a consequence, the new combined TerraSAR-X / TanDEM-X mission planning system not only has to support two satellites with their mutual constraints, but also handles two different missions at the same time: the long-term mapping approach of the TanDEM-X mission and the short-term on-demand approach of the TerraSAR-X mission. The original TerraSAR-X mission planning system has been retired by the end of the first part of the TanDEM-X commissioning phase. Is has been successfully used to perform two planning runs per day starting shortly after the TerraSAR-X launch. It has been described in various papers [1, 2, 3]. With the retirement of the old system, the commissioning of the new TanDEM-X mission planning system started. The new system is now shortly before nominal operations, which is planned to start end of December 2010.

The following sections start with a high level description of the changes with respect to the existing TerraSAR-X system, which are necessary to operate the TanDEM-X mission, with special focus in mission planning aspects. The following section gives detailed information on the implementation and integration of the new combined TerraSAR-X/TanDEM-X mission planning system. The paper ends with a wrap up of the integration phase of the new system, the launch and the commissioning phases.

II. Requirement for Two-Satellites-Two-Missions

The combined TerraSAR-X/TanDEM-X mission planning system can handle the two satellites as well as the two different missions with different mission goals.

The old TerraSAR-X mission goal, which up to now has been fulfilled using the TSX satellite, is to operate the satellite in such a way that the users, the scientific and commercial partners, are satisfied. This is accomplished by a highly flexible, automated system.

For example, the TerraSAR-X mission planning system may cope with more than 500 imaging requests per day, obey the given priority rules and consider late order input as late as 6 hours (nominal) or 45 minutes (short notice planning) before the last possible up-link [5]. In consequence, the schedule of the TSX satellite, and with that the commands to be up-linked to the satellite, are only known with short notice.

On the other hand, the new goal of the TanDEM-X mission is to generate a global high-resolution digital elevation model by performing acquisitions completely covering the Earth's land surface [4]. This implicates the need for a schedule which is available a long time in advance and which is stable for several planning cycles. Whereas TerraSAR-X orders are ordered incoherently and the failure to execute one or the other order is not essential for the TerraSAR-X mission goal from a global perspective, the complete fulfillment of TanDEM-X acquisition plan, with its approximately 10000 to 15000 imaging request per year, is essential for the success of the TanDEM-X mission.

The mission planning system has to consider both satellites and both missions at the same time in order to create one combined schedule [Fig. 1]. This implies that the mission planning system has distinct interfaces which cover the different missions, e.g. the ordering interface, or covering the different satellites, like the command interface to the satellites' mission control systems [Fig. 5 and 6].

Besides that, the extension of a one-satellite mission to a two-satellite mission not only means there is one additional satellite to cope with. During the design of the space and ground segment, it became obvious that several important inter-satellite constraints have to be obeyed in order to guarantee a safe combined mission. The following lists give the major requirements that have to be dealt with in the two satellite close formation mission planning system for the combined TerraSAR-X/TanDEM-X mission.

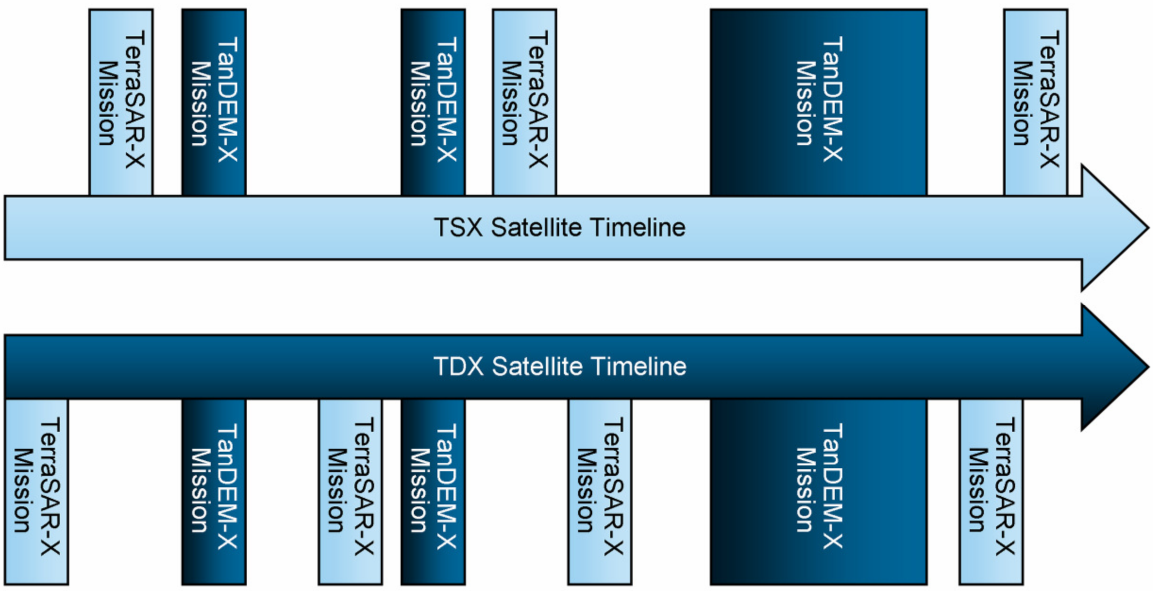

Fig. 1 Two missions on two satellites

The dark blue blocks represent TanDEM-X mission data-takes; the light blue blocks represent TerraSAR-X mission data-takes. TerraSAR-X mission data-takes are distributed and executed on one or the other satellite. TanDEM-X data-takes are executed on both satellites at the same time.

The following requirements have been derived from the need to continue to support the TerraSAR-X mission:

- The original TerraSAR-X mission image request shall be performed using both satellites.
- It shall be possible to perform short notice planning on both satellites.

The next set of requirements has been derived mainly from the need to support the future TanDEM-X mission:

- The additional TanDEM-X global imaging mission requires the use of both satellites simultaneously to perform its imaging requests.
- The enlarged ground station network for data down-link has to be supported.
- Satellite and mission specific enhancements which allow to increase the imaging capability per time:
  - better memory management on board
  - power/thermal model in the scheduling algorithm
  - data-take splitting
- Security Requirements regarding TanDEM-X image data (German legislation, "Satellitendatensicherheitsgesetz", SatDSiG) have to be obeyed.
- The provision of a long-term timeline will be foreseen. It will cover especially the TanDEM-X images to allow pre-planning at customer's site. TerraSAR-X images are included as far as the orders are available.

The following major requirements have been derived from the technical needs of a close-formation two-satellite mission:

- Safety measurements have to be implemented in order to avoid mutual exposure to instrument radiation.
- Command Up-link to satellites as well as telemetry and house keeping downlinks from both satellites may be performed at the same time using two distinct satellite dishes.
- Data downlink must not be performed at the same time.

Some requirements, e.g. safety requirements to avoid mutual exposure or the requirement to perform the TerraSAR-X mission on both satellites, are only valid or possible if the two satellites are in close formation with distances of a few hundred meters. In intermediate phases, where the satellites are positioned in formations with greater distances, not all of the given requirements are applicable or different requirements will be needed. For detailed background information, especially on the security issues, see [6].

Besides the new requirements, it is obvious that it is challenging, not only for mission planning but for the whole ground segment, to integrate the upgraded systems into the fully operational, existing TerraSAR-X ground segment. The goal is to affect the on-going TerraSAR-X mission as little as possible.

In the following, the implications of these new constraints for the design and operations of the new combined TerraSAR-X/TanDEM-X mission planning system are discussed.

III. TanDEM-X Mission Planning

This section starts with a brief presentation of the existing TerraSAR-X mission planning system and then concentrates on the enhancements which are necessary to successfully operate the combined TerraSAR-X/TanDEM-X missions in a secure and safe way. The section ends with the description of the integration concept, which allows phasing in the new ground segment, including the mission planning system, in the running TerraSAR-X environment.

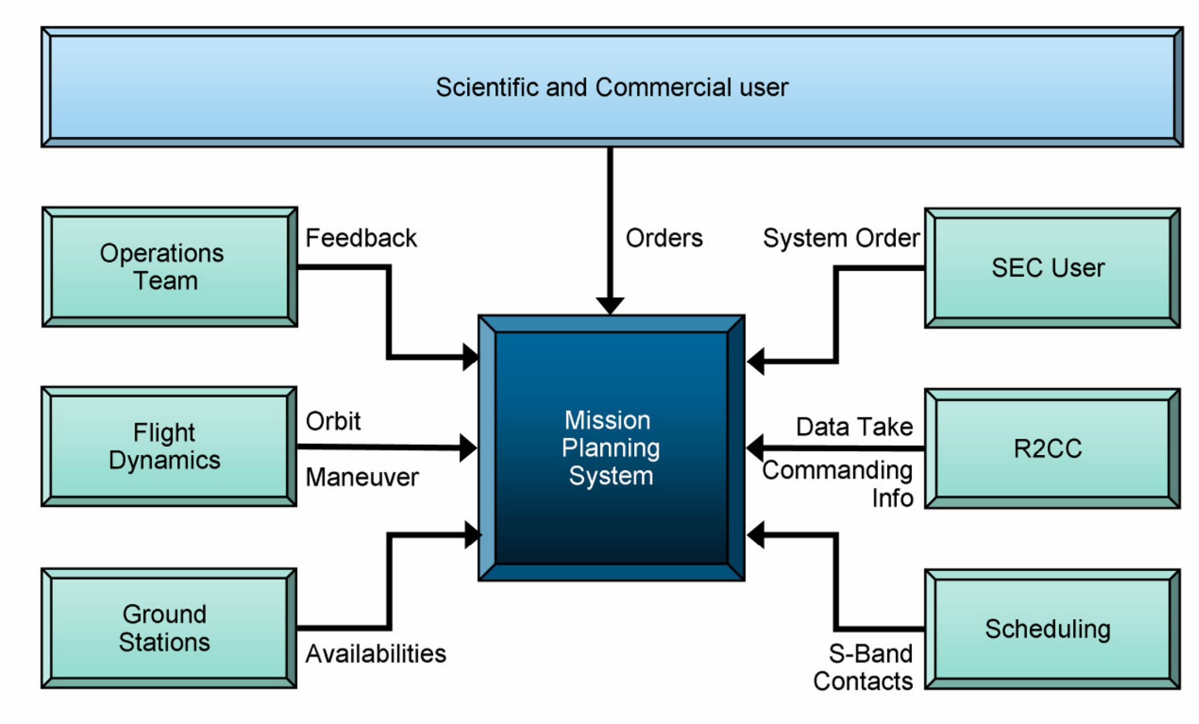

Fig. 2

Information flux from the ground segment to the TerraSAR-X Mission Planning System

Interface partners are displayed in rectangles with light green, whereas MPS is shown in dark blue. The extended bar on top represents the wide TSX SAR user community. For non standard order request an interface to the System Engineering and Calibration (SEC) user has been established. Arrows indicate the information flow towards Mission Planning. The interface content is briefly described next to the arrows. The Data Information and Management System (DIMS) in between the user and MPS is not displayed for simplicity. [1]

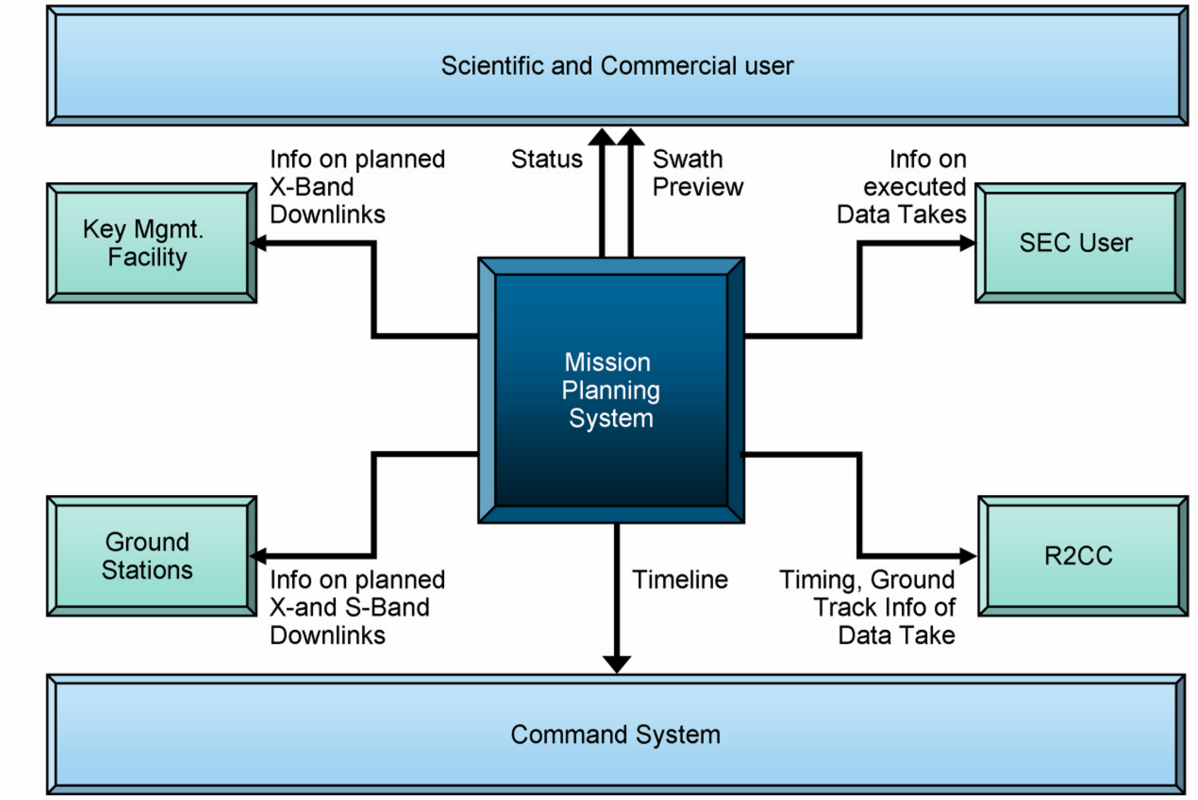

Fig. 3 Information flux from TerraSAR-X Mission Planning to the ground segment and the spacecraft

Interface partners are displayed in light green. The extended bar on top represents the user community. The principal output of Mission Planning, the timeline, is sent via the Command System to the spacecraft. For each interface the direction is symbolized by arrows and the content is briefly described next to the arrow. System Engineering and Calibration is abbreviated by "SEC" [1].

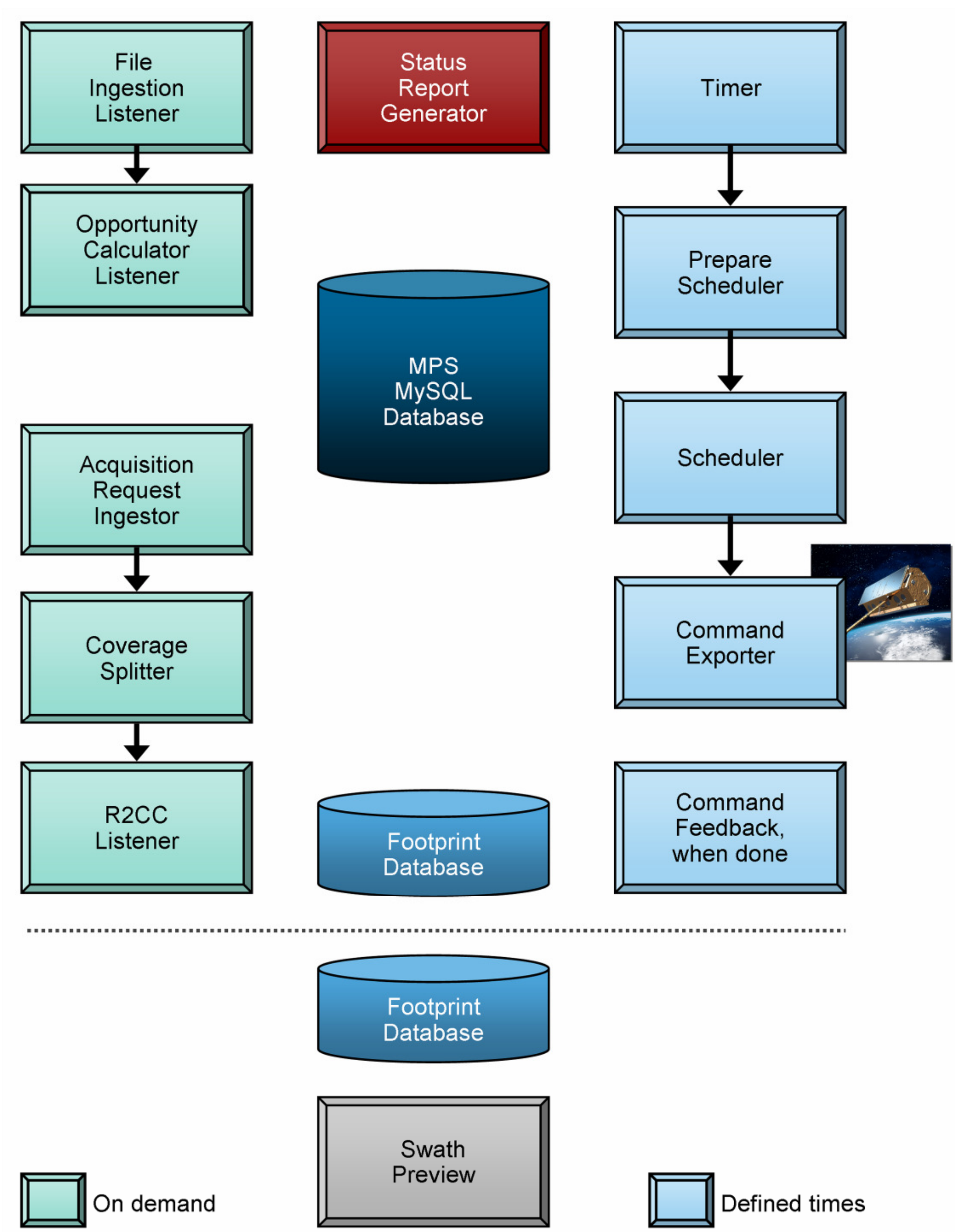

Fig. 4 Simplified Mission Planning System Architecture

Software Modules are represented by rectangles. Databases are displayed with cylindrical shapes. Mission Planning items are hosted in two different network environments. The division is indicated by the dashed line. The upper part is, compared to the lower one, situated in a more protected and safer environment. Green applications on the left hand side *are part of the input preprocessing chain. The modules are triggered if the corresponding input has been received (on demand). The MPS MySQL Database is the heart of the Mission Planning System. All modules in the same network read from and write into the database. The footprint database is a static collection of all possible swathes for SAR acquisitions on Earth. One copy of the footprint database is located in each network environment. The Swath Preview Service is called by users prior to SAR image ordering [1].*

III. A. Summary of TerraSAR-X Mission Planning Design

The design of the TerraSAR-X mission planning system has been presented in various papers [1, 2, 3, 4, 5].

Fig. 2 and 3 [1] show the TerraSAR-X mission planning's basic data flow concept with respect to external interface partners:

- Orders from the scientific and commercial customers as well as from system engineering and calibration (SEC)
- Feedback on commands that have been up-linked to the satellite from the operations team
- Orbit information from the flight dynamics segment
- Availability information from all considered ground stations
- The scheduled up-link contacts from the scheduling department
- Data-take commanding and planning information provided by the request to command converter (R2CC)

The mission planning system considers all available information, creates a schedule for on-board and on-ground activities and delivers the following main products to its interface partners:

- The execution timeline to the command system
- Information on the scheduled imaging data down-links to the ground stations

- Information on the planned encrypted downlinks to the key management facility
- Information on the executed data-takes to the R2CC and SEC
- Information on possible swaths that may be acquired are provided to the users

III. B. TanDEM-X Mission Planning System Design

The combined TerraSAR-X/TanDEM-X mission planning system is a development based on the TerraSAR-X mission planning system and the gained operational experiences. The basic TerraSAR-X mission planning decomposition as outlined in Fig. 4 is also valid for the new TerraSAR-X/TanDEM-X system.

Besides the new TanDEM-X requirements, all requirements originally derived from the TerrSAR-X mission are still valid and have to be fulfilled.

The following section describes the changes and enhancement to the TerraSAR-X system to support the TerraSAR-X/TanDEM-X functionalities.

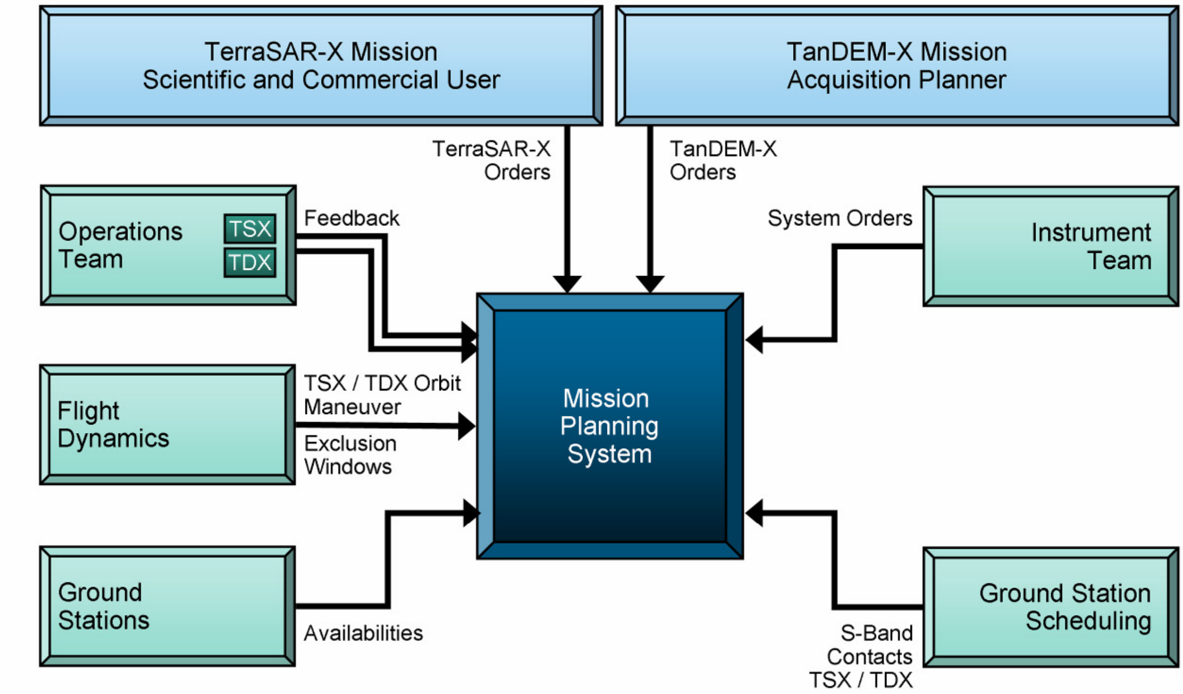

Fig. 5 Information flux from the ground segment to the

TerraSAR-X/TanDEM-X Mission Planning System

Interface partners are displayed in rectangles with light green, whereas MPS is shown in dark blue. The extended bars on top represent the TerraSAR-X user community and the TanDEM-X acquisition planner, which provides the TanDEM-X global acquisition plan. For non standard order an interface to the System Engineering and Calibration (SEC) user has been established. Arrows indicate the information flow towards Mission Planning. The interface content is briefly described next to the arrows. The Data Information and Management System (DIMS) in between the user and MPS is not displayed for simplicity.

Of course the most prominent change to the mission planning system in order to support a two-satellite system is the necessity to create a schedule for two instead of one satellite and to submit the according commands to the two individual command systems. Fig. 5 and 6 show the input and output, respectively. A detailed technical description of the scheduling engine developed at DLR is presented in [7].

Changes to the mission planning input data:

- Feedback on up-linked commands is provided separately for the two satellites by the satellites' command operators.
- Flight dynamics delivers manoeuvre information for two satellites.
- Flight dynamics delivers the exclusion windows where the satellites' radar instruments are not allowed to transmit due to mutual interference.
- TanDEM-X mission orders are posted by the TanDEM-X acquisition planner.
- The schedule for S-band up-link contacts will comprise TSX and TDX satellite passes.
- Other input, like ground station availabilities, data-take commanding info or system orders have been extended to support two missions and two satellites.

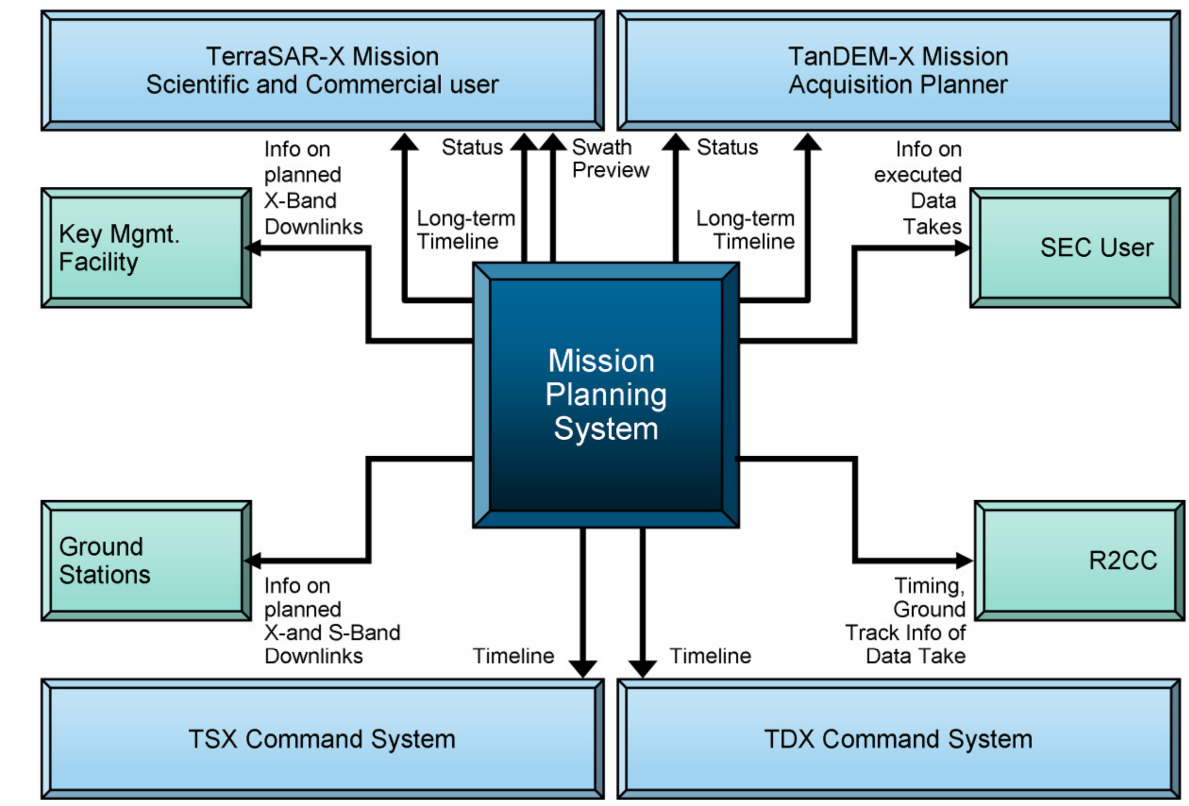

Fig. 6 Information flux from TerraSAR-X/TanDEM-X Mission Planning

to the ground segment and the spacecraft

Interface partners are displayed in light green. The extended bars on top represent the TerraSAR-X user community and the TanDEM-X acquisition planner, which gets information on the long-term timeline of the TanDEM-X acquisition plan. The principal output of Mission Planning, the timeline, is sent via the two Command Systems to the spacecrafts. For each interface the direction is symbolized by arrows and the content is briefly described next to the arrow. System Engineering and Calibration is abbreviated by "SEC".

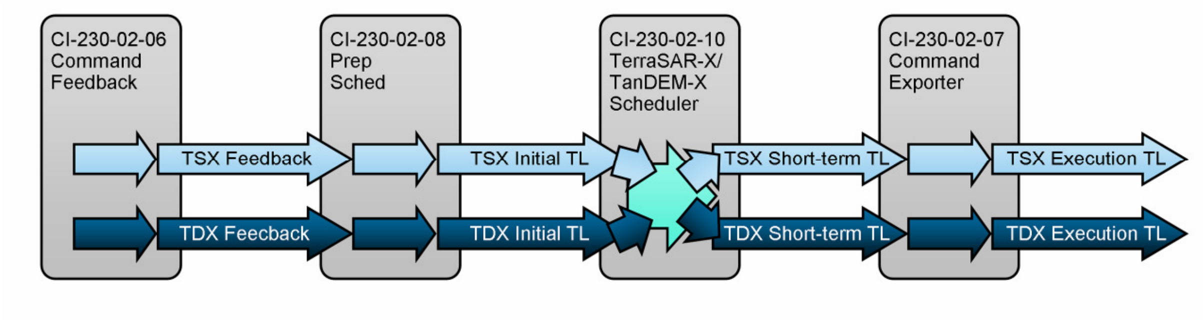

Fig. 7 Internal data flow with respect to two satellites

Modules are the same as in Fig. 4. Whereas command feedback, prepare schedule and command exporter module are able to handle input and output for two satellites separately, the scheduler module has to consider also inter-satellite constraints.

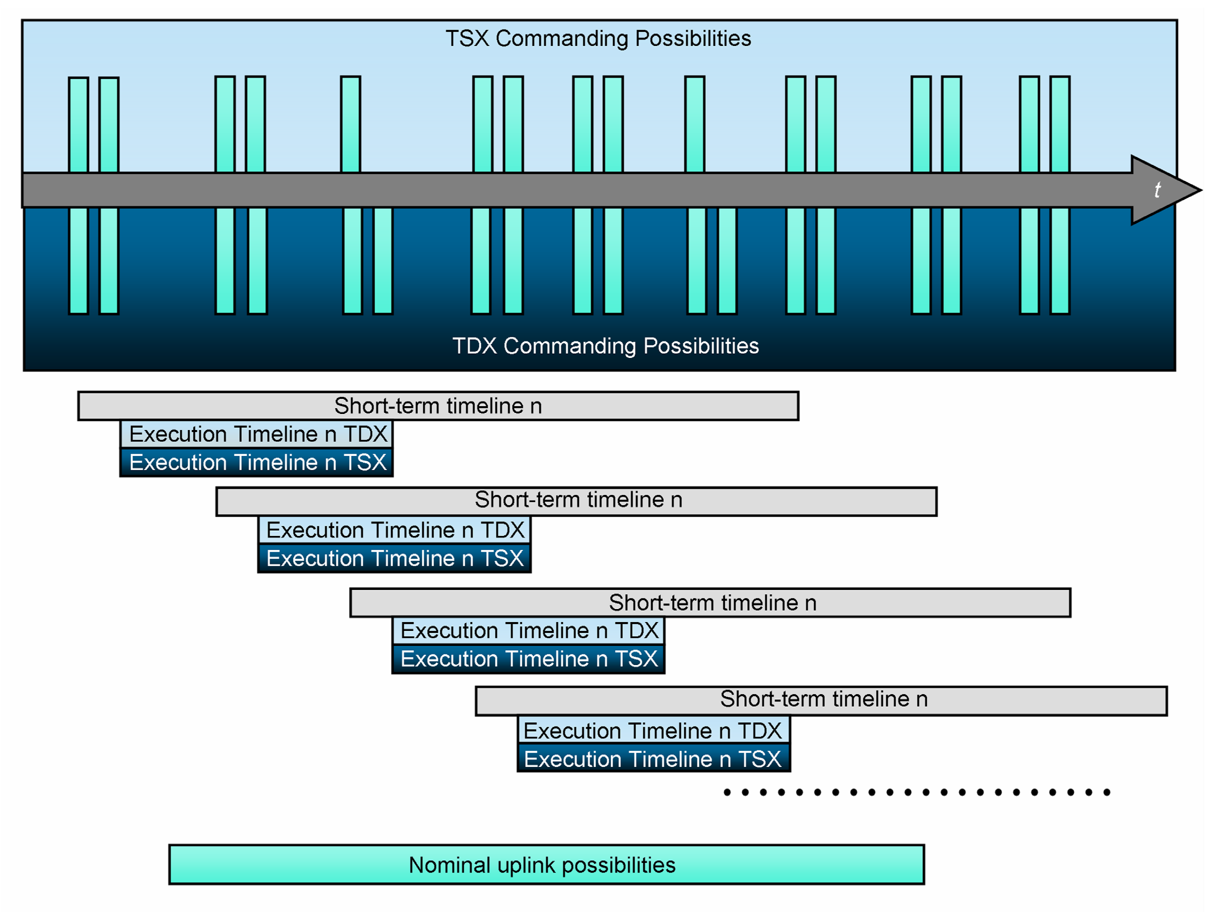

Fig. 8 Timing of scheduling and execution timeline generation

On the top time arrow, possible commanding opportunities / up-link ground station passes are shown. Below, the two-satellite schedule, the short-term timeline and the individual execution timelines, one for each satellite, are indicated.

Changes to the mission planning output data:

- Two execution timelines are sent to the TSX and the TDX command system and are up-linked to the satellites.
- Information on the long-term timelines is sent to the scientific and commercial users as well as to the tandem acquisition planner.
- The actual statuses of imaging requests are sent to the scientific and commercial users as well as to the tandem acquisition planner.
- Other output, like information on planned down-links etc. have been extended to support two missions and two satellites
- The swath preview is solely applicable to the TerraSAR-X mission. It will be delivered to the TerraSAR-X customers only.

Fig. 7 shows the coarse internal flow of data inside the mission planning system's most important modules. It can be seen that, even in the mission planning system, most modules handle the timeline for the two satellites separately. It is only the combined TerraSAR-X/TanDEM-X scheduling module which considers the two satellites and the two missions as one single system [7]. The feedback on the up-linked commands triggers the prepare schedule module which initializes the timelines in the central database. The timelines itself are established by the scheduler and afterwards exported to the different command systems by the command exporter.

The timing of the planning concept for the two satellites is shown in Fig. 8. The primary up-link stations are Weilheim and Neustrelitz. Each day there a two up-link "sessions" for each satellite. One up-link session comprises at least one ground station pass for each satellite; one ground station will be used for one satellite. For each session, the mission planning system has to provide two execution timelines, one for the TerraSAR, one for the TanDEM satellite.

III. C. Overview TanDEM-X / TerraSAR-X Mission Planning System Extensions

This section lists and explains the most important additional functionalities which had to be implemented as enhancements to the mission planning system in order to support the combined TerraSAR-X/TanDEM-X operations. The description starts with functionalities derived from more technical aspects, like guaranteeing the satellite safety during close formation flight, and ends with functionalities needed to solve management-like problems like supporting two mission goals and their priorities.

Safety Requirements to avoid mutual exposure to instrument radiation

Due to the close distances of a few hundred meters between the two satellites and the considerable radar power, one of the satellites might be harmed if it crosses the illumination cone of the other satellite's active antenna during radar operations.

This implies that there are, depending on the orbit geometry, certain exclusion zones, where the instrument on one satellite may not be used for active radar operations. The consequences for TerraSAR-X and TanDEM-X are:

- Regarding TanDEM bi-static images, where two satellites are involved, this satellite may only be used in receive mode.
- TerraSAR-X images, where the imaging satellite in any case needs an active radar instrument, are not allowed at all in exclusion zones.

Flight dynamics delivers information on the exclusion zone time intervals to the mission planning system. Mission planning assures that there is no active radar operation for the according satellite during these exclusion zones. Effort has been spent in the design to treat off-nominal cases, like interface communication problems, such as exclusion zones which are not delivered or planned maneuvers that are not executed and thus orbit deviations from the planned scenario occur.

Other off nominal cases might occur if one of the satellites deviates from its orbit or is not operational for a certain time period. The measurements taken are described in detail in [6]. The sync warning functionality assures that radar operation is stopped in case of such anomalies: sync warnings make use of the fact that during bi-static data-takes information is exchanged using the satellites' sync horns. For a sync warning, a short data-take without radar transmission is executed on-board of both satellites. If satellite B is not "in sync" during this test, an exception is triggered on satellite A and radar operation is stopped. Mission planning is responsible for scheduling these sync warning data-takes in given time slots about once per orbit.

Support of enlarged ground station network for data down-link

The TerraSAR-X mission ground station network for data-downlink comprises of Neustrelitz, Germany, as the main DLR station and O'Higgins, a DLR station located on the Antarctic continent. In addition, several ground stations are provided by the commercial user. To handle the large volume of data that will be created for the TanDEM-X global coverage images, further ground station passes in Inuvik, Chetumal and Kiruna will be used.

The majority of TerraSAR-X mission imaging requests that are actually performed on the TSX satellite are small enough in size, such that during one down-link opportunity to a ground station a group of data-takes may be down-linked. In case of large data volumes, one data-take down-link may be split, so that the data can be transmitted in two subsequent passes of a ground station. This behavior is sufficient in case of TerraSAR-X data, as e.g. local customers need their data at their local station, and only at their local station.

For TanDEM-X, all data-takes, including split downlinks, shall be sent to Earth as fast as possible, no matter which one of the additional TanDEM-X ground stations is used. The TanDEM-X mission planning system has been extended with the functionality to freely distribute downlinks within defined ground station pools. The scheduler may decide to send data to any of the stations inside the pool and may split up individual data-takes to the different stations. This functionality optimizes the usage of the available down-link resources.

Command Up-link, telemetry and house keeping downlink in parallel

The up-link concept for the two-satellite formation (see Fig. 8) comprises of one dedicate up-link station for one satellite, e.g. Weilheim ground station for the TDX satellite, Neustrelitz ground station for the TSX satellite. The mission planning system has to support the S-band transmitter switching for both satellites as well as parallel scheduling of H/K data to these and additional, dedicated H/K-dump stations.

Power/Thermal Model

The TerraSAR-X scheduler uses a simplified model, specified by the satellite manufacturer, to ensure that power and thermal constraints for the TSX satellite are obeyed: the maximum time which can be used for radar imaging, is restricted to a maximum of 170s per orbit. The maximum time is decreased during eclipses. However, the TanDEM-X mission relies on an increased orbit usage: first, TanDEM-X mission data-takes itself may have a length of up to 250s in order to cover long tracks along the continents. Second, the total number of images needed for the global coverage exceeds the simplified model.

Together with Astrium and DLR’s Microwaves and Radar Institute, mission planning developed a thermal model which allows increased usage for imaging: The scheduler makes use of gliding windows. A gliding window defines how long the radar instrument may be in operation during a given time period. In the complete model, 15 gliding windows for each satellite are defined, ranging from 1 orbit to 15 orbits.

In addition to the thermal model, a power model is used: the scheduler propagates the state of charge of the battery using a static approximation of the consumers and suppliers. Static in this sense means, that the value of modification is not dependent on the current state of charge.

Inter-satellite-constraints

The close formation flight of the two satellites implies certain technical inter-satellite constraints which have to be considered by the mission planning system:

- TerraSAR-X data-takes may not be scheduled in parallel on both satellites due to radar interference.
- TanDEM-X data-takes have to be schedule in parallel on both satellites.
- The sync horns, which allow the satellites to synchronize with each other, have to be selected according to the actual orbital geometry.

Data downlink must not be performed at the same time

In close formation it is not allowed that both satellites perform a data downlink in parallel: The X-band transmitters use the same frequency and the transmissions would interfere. In consequence, mission planning has to treat down-links as an inter-satellite constraint. The majority of TerraSAR-X mission data is down-linked in Germany/Neustrelitz. To minimize the conflicts, for TanDEM-X stations outside the visibility circle of Neustrelitz, e.g. O'Higgins/Antarctica and Inuvik/Canada will be used. Kiruna also will be used for the TanDEM-X mission, but the usage will be restricted to regions not overlapping with the Neustrelitz visibility circle.

However, the TerraSAR-X mission also makes use of an increasing number of international stations which will compete with already established TerraSAR-X stations as well as the new stations used for TanDEM-X. It was necessary to introduce a completely new flexible X-band handling: Until now, if a ground station contact is used for down-link, the transmitter has been switched on and off at a given elevation above the horizon of the ground station. Additionally, X-band down-link model did not have a restriction and thus ground station contacts had to be pre-selected in orbits where too many ground station opportunities would cause an overload of the satellite's downlink equipment. Last, the traveling wave tube of the X-band transmitter only allows a limited number of on-off-cycles, which needs to be minimized due to the increased number of downlink opportunities.

The new TanDEM-X mission planning system implements the X-band resource handling:

- The X-band transmitter is included in the power model.
- A standby functionality of the X-band transmitter has been introduced on-board and will be used by mission planning to minimize the on-off-cycles.
- The X-band transmitter is switched on and off with respect to data down-link itself. This means that e.g. for a station receiving only one single data-take with transmission times of some seconds, the X-band transmitter will be switched on or off only seconds before or after the transmission starts or ends. In case a conflict on the X-band transmitter model would occur, a different downlink opportunity will be used.
- Mission planning will schedule down-links such that two satellites may share one ground station pass: down-links will be performed sequentially first with the one, then with the other satellite. The ground station has to be able to synchronize with the second satellite in a given time. This feature ensures that data is down-linked as soon as possible, freeing on-board memory.

Two missions, two satellites

As elaborated in Section II, the two-satellite system will be used to fulfill the two missions, TerraSAR-X and TanDEM-X. The mission planning scheduler ensures that the TerraSAR-X mission imaging requests are distributed to the two satellites and that the TanDEM-X imaging requests are scheduled on both satellites at the same time.

This new concept implies that there will be restrictions but also advantages for the on-going TerraSAR-X mission. On the one hand, two satellites give the possibility of an increased number of images in one region and a backup if one of the satellites is temporary not operational or in maintenance. The project also led to technical improvements, including a power/thermal concept, where both missions, TanDEM-X and TerraSAR-X will benefit from.

On the other hand, the TanDEM-X mission obviously imposes new restrictions on the TerraSAR-X mission: There are technical restrictions, like the exclusion zones mentioned above or additional sync warning data-takes which constrain the available resources. In addition, there will be a competition between the two different missions. Especially the highly prioritized short-term TerraSAR-X images will get into conflict with TanDEM-X images. Due to the asymmetric Earth's land distribution, there will be peak orbits with increased number of TanDEM-X images which cannot be shifted in time without prolonging the complete mission. Also, TanDEM-X data-takes have to be executed in certain formation configurations, which means they have to be performed in a given, restricted time interval. Whenever a high-priority TerraSAR-X data-take overrules a TanDEM-X one, the TanDEM-X mission may be prolonged.

To minimize these influences, a new priority concept has been elaborated between the three parties, the scientific TerraSAR-X users, the commercial TerraSAR-X user and the TanDEM-X user. It has been agreed that the TanDEM-X images will be given a scheduling priority high enough to ensure that the global coverage of the Earth may be reached in time. The parties also agreed in order to minimize scheduling conflicts, that the coarse TanDEM-X acquisition plan, as submitted to mission planning (see Fig. 5) will be published to all parties so that TerraSAR-X imaging may take it into account these pre-planned acquisitions. Also other resources, like the usage of ground station opportunities with overlapping contact times have to be negotiated between the involved parties.

The next two new functionalities, provision of a long-term timeline and implementation of data-take splitting, support the priority concept.

Provision of a long-term timeline

One of the principal main problems is the contradiction between the envisaged long-term stable TanDEM-X acquisition plan and the need for short-notice updates caused by high-priority TerraSAR-X orders as denoted above. In consequence, besides the nominal schedules established by mission planning twice a day, TanDEM-X mission planning will provide a long-term timeline at least every third day (see Fig. 6). This long-term timeline will cover time intervals of at least three months and will include TerraSAR-X and TanDEM-x orders. This long-term timeline allows

- to check the feasibility of the TanDEM-X global coverage in general,
- the TerraSAR-X users to consider and respect imaging times already planned for TanDEM-X and
- to detect possible conflicts months ahead.

Data-take splitting

Data-take splitting is a compromise between assuring a stable long-term acquisition plan for TanDEM-X requests and the need for reflecting high-priority TerraSAR-X orders in the schedule.

The commercial and scientific TerraSAR-X customers are allowed to overrule a limited amount of TanDEM-X global acquisition data-takes by ordering with high priority. If a large TanDEM-X data-take, e.g. crossing a whole continent, may not be scheduled anymore, mission planning will split this TanDEM-X data-take such that the high-priority TerraSAR-X images may be performed as well as the remaining parts of the TanDEM-X image. On the same time, the still to be performed parts of the TanDEM-X data-take are shifted to higher priorities to assure their execution shortly in the future, i.e. during a time where the formation configuration parameters are still in-line with the order.

Support of short notice planning on both satellites

The TerraSAR-X mission includes a concept for short notice planning [5]. Defined ground stations are used to up-link short-notice changes to already commanded imaging requests. This service is locally restricted.

Due to the nature of the service, it will remain restricted to TerraSAR-X mission images. However, the service will be updated such that it will be possible to choose between both satellites, either TSX or TDX, the one which shall support the short notice planning commanding for the given pass. This avoids outages due to radar transmission exclusion zones or maintenance phases on one of the two satellites.

Security Requirements regarding TanDEM-X image data (German legislation, "Satellitendatensicherheitsgesetz", SatDSiG)

German legislation has defined the security requirements on earth-observing satellite missions. Already implemented within the TerraSAR-X mission, sufficient security measurements, like encryption of the down-linked imaging data, are integrated. Mission planning administrates the decryption keys to be sent to the receiving ground stations by sending key requests to the key management facility (see Fig. 3 and 6). For the high-resolution TanDEM-X images, the law requires that the down-linked data may not be decrypted outside Germany. This means, no decryption keys may be sent to the ground stations receiving TanDEM-X data with a too high resolution. The combined TanDEM-X/TerraSAR.-X mission planning system will ensure that these data are down-linked in separately encrypted chunks and that the encryption keys are withheld in Germany. The received data may only be encrypted after being transferred to Germany to the main processing center in Neustrelitz.

III. D. Integration into the Operational TerraSAR-X System

The combined TanDEM-X/TerraSAR-X mission planning system had to be integrated into the fully operational TSX satellite ground segment. This integration, like the other updated parts of the ground segment, had to be performed with special care as to not disturb the on-going scientific and commercial imaging more than absolutely needed.

The following measurements have been taken:

- Verification and validation tests have been executed for the new mission planning system for use with the TSX/TDX two-satellite space segment with respect to the combined TanDEM-X/TerraSAR-X mission
- Validation of the new combined TanDEM-X/TerraSAR-X mission planning system with respect to the single satellite TerraSAR-X mission has taken place during the first half of the TanDEM-X satellite's commissioning phase. This means the new system fully supports all features of the original TerraSAR-X system
- A high value was and is set on the establishment of the mission planning procedures to upgrade and operate the mission planning systems.
- Stepwise integration: The new mission planning system has been put into operations in two steps: The first step was the upgrade to an intermediate system that was used during the so-called mono-static commissioning phase, where the two satellites are in a formation with ca. 20km distance. Here, no inter-satellite constraints besides X-band downlink had to be considered and the satellites could be operated like two single-satellite systems. This step allowed to operate the TSX satellite using the established old mission planning system, guaranteeing that there will be no additional down-times. The TDX satellite was operated with the new mission planning system, allowing extensive testing and in-orbit validation. After successful validation and after the two satellites have been positioned in a close formation with few hundred meters distance in October 2010, the bi-static

commissioning phase started. Beginning with this second phase, bi-static TanDEM-X imaging requests could be performed. From then on, the new combined TanDEM-X / TerraSAR-X mission planning system has been in operation

.

IV. LEOP and Commissioning Phase

The following paragraphs give a wrap up of the now successfully finished launch and early operation phase (LEOP) and the mono-static commissioning phase, as well as the nearly finished bi-static commissioning phase.

Launch and Early Operation

At the time of the TDX satellite launch, the ground segment and the mission planning system was set up as the intermediate system described in chapter III.D: one dedicated mission planning system for the new satellite TDX. Launch and early operations was completely successfully. Already 86 hours after the launch the first image had been available on ground [9]. For ordering, scheduling, commanding and processing the whole ground segment chain, including the mission planning system, had been involved. Of course, during this phase of operation, the procedure steps needed manual interaction.

Mono-static Commissioning

Since the execution of the first image acquisitions, the new mission planning system has been operated two times per day to establish the required timelines and to create the commands to be up-linked to the spacecraft.

The mono-static commissioning phase proved that the two-step mission planning integration approach allowed operating the old TSX satellite without any interference, while at the same time checking out the new TDX satellite and the new ground segment.

From two to one system and bi-static Commissioning

At the end of the mono-static commissioning phase, the whole ground segment, together with the commercial customers, set up detailed switch over procedures and schedules to guarantee that all ground segment interfaces could be shut down and re-connected without any loss of data. The mission planning central data-base had to be updated to the new structure; each already present order had to be reprocessed in order to be used in the now dual satellite environment.

As anticipated, increased number of personnel has been needed to guarantee a short hand-over time. Only during this time period of four weeks, execution of commercial and scientific imaging requests had been stopped.

With the start of the bi-static commissioning phase, TerraSAR-X mission scientific and commercial image requests execution has been re-started and since then performed with only minor impacts from the TanDEM-X bi-static checkout.

During the whole commissioning phase, mono-static and bi-static, the mission planning runs have been done in a semi-automatic way: The output products have been closely monitored by the mission planning operators to allow manual interference whenever it was necessary.

At the end of the bi-static commissioning phase, the mission planning system will be operated fully automatic.

V. Summary

The development of the combined TerraSAR-X/TanDEM-X mission planning system with its new functionalities showed that it had to be categorized rather as a new development in spite of an “add-on”. Of course, the basis TSX satellite’s mission planning system gave valuable experience for implementation, testing and operations. Without the already achieved

TSX satellite knowledge, it would not have been possible to establish the new combined TanDEM-X/TerraSAR-X mission planning system in the given time.

It has been shown that the requirements for the TerraSAR-X/TanDEM-X mission planning system can be divided into three main categories:

- TerraSAR-X mission requirements which are still applicable to the new combined mission
- Management and technical requirements derived from the TanDEM-X mission requirements
- Technical requirements derived from a close formation satellite mission

The new combined TerraSAR-X/TanDEM-X mission planning system reflects and fulfills the competing goals of the two missions: Commercial and scientific success by supporting individual imaging requests as well as Commercial and scientific success by supporting a long-term acquisition strategy that will lead to a complete global digital elevation model.

By end of 2009, the TanDEM-X/TerraSAR-X ground segment, including the new planning system, had been successfully validated to be able to support the mono-static commissioning phase. The TanDEM-X satellite was launched successfully on June, 21st, 2010. The functionalities which are the basis for the close formation flight have been integrated into the system before October 2010, when the second part of the commissioning phase with its bi-static operations started. The mission planning system successfully supports TerraSAR-X single satellite data-take execution using both satellites TSX and TDX since October 2010. It also successfully supports the bi-static commissioning, which will end in December 2010. The ground segment and its mission planning system are looking forward for the operational phase.

Glossary

GSOC	=	German Space Operations Center
DLR	=	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
TanDEM-X	=	TerraSAR-X add-on for Digital Elevation Measurement
Satellite – mission	=	The paper distinguishes between the satellites ("TSX satellite", "TDM satellite") and the missions which are performed using both satellites ("TerraSAR-X mission", "TanDEM-X mission")
TDX	=	the TanDEM-X satellite
TSX	=	the TerraSAR-X satellite
TerraSAR-X mission	=	the TerraSAR-X mission comprises of active radar imaging requests performed on one single satellite. It does not matter which of the two satellites is used.
TanDEM-X mission	=	the TanDEM-X mission comprises of radar imaging requests performed on the two satellites at the same time. One satellite actively transmits radar signals; the second may be passive, that means it is only receiving data, or may also be active.

Acknowledgments

We would like to thank Dr. Edith Maurer and Gary Alastair Morfill for the valuable comments improving our original manuscript, Juliane von Geisau for the overall layout and the preparation of the figures.

References

[1] Maurer E., Mrowka, F, Braun A., Geyer M. P., Lenzen C., Wasser Y., Wickler M., "TerraSAR-X Mission Planning System: Automated Command Generation for Spacecraft Operations", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 48, No. 2, 2010, pp. 642-648

[2] Braun, A., Geyer, M.P., Wickler, M., Foussal, C.I., "Autonomous End-to-End Planning System for TerraSAR-X," *AIAA Space Ops 2004*

[3] Geyer, M. P., Braun, A., Foussal, C.I., Lenzen, C. and Köhler, A., "Tailoring the TerraSAR-X Mission Planning System to PPP needs," *AIAA Space Ops 2006*

[4] Krieger, G., Moreira, A., Fiedler, H., Hajnsek, I.,Werner, M., Younis, M., Zink, M., "Satellite Formation for High Resolution SAR Interferometry," *IEEE Transactions on Geoscience and Remote Sensing,* 45 (11), 2007

[5] Maurer, E., Geyer, M., Braun, A., Mrowka, F., Lenzen, C.. Wasser, Y., Köhler, A., "TerraSAR-X Short Notice Planning", *AIAA Space Ops 2008*

[6] Hofmann, H, Zimmermann, S., "The TanDEM- X Mission Operations Segment: Close Formation Flight, Preparation and First Experiences", *AIAA Space Ops 2010,* submitted

[7] Lenzen, C., Mrowka, F., Spörl, A., Klaehn, R., "Pinta-Plato Scheduling Complex System Resources", *AIAA Space Ops 2010,* submitted

[8] Kahle, R., TanDEM-X Blog October, 15th, 2010, "Blickkontakt der Satelliten", http://www.dlr.de/blogs/desktopdefault.aspx/tabid-5919/9754_read-268/

[9] Schättler, B., TanDEM-X Blog June 25th, 2010, „Erster Blick auf die Erde: ‚Einfach phantastisch'", http://www.dlr.de/blogs/desktopdefault.aspx/tabid-5919/9754_read-186/