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The Operations Concept for Tandem-L – From Mission Goals to Spacecraft Requirements

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Abstract

Tandem-L is a highly innovative L-band SAR mission for the global observation of dynamic processes on the Earth's surface with unprecedented quality and resolution. Two identical satellites of ~3000 kg will fly in a variable formation with separations between 500 meters and 20 kilometers. Thanks to a Large Deployable Reflector and digital beam forming techniques Tandem-L will support the science community with unique data in the areas of the biosphere, geosphere, cryosphere, and hydrosphere.

The mission was proposed by the DLR Microwaves and Radar Institute and is currently in the requirements definition phase. The German Space Operations Center (GSOC) has participated since the early phase of the project during the development of the mission operations concept and by reviewing the studies from industrial partners. As DLR is responsible for contracting the space segment supplier, the recent goal has been to derive satellite system requirements from the mission requirements as well as from operational strategies. New technical opportunities and standards were analyzed and considered in the operations approach. Simultaneously, a working group was established to collect lessons learnt from previous missions operated at GSOC.

This paper presents the mission operations concept and the new challenges compared to the precursor missions TerraSAR-X and TanDEM-X. Drivers are amongst others the volume of generated mission data of more than 8 terabytes per day, the highly variable formation, and the effects of the radar reflector on the orbit determination accuracy. Additionally, the derived satellite system requirements are discussed with a focus on the propulsion system, mutual radar illumination, the AOCS safe-mode, GNSS performance, the Ka-band downlink, and the on-board schedule.

1. Introduction

Tandem-L will comprise two satellites flying in sun-synchronous orbits of 750 km altitude with a target launch date in 2025. The goal of this mission is to image the entire landmass of the Earth up to twice per week. Each spacecraft will operate a Synthetic Aperture Radar (SAR) instrument in the L-band at 23.6 cm wavelength, which allows observing the Earth independent of weather conditions like clouds and daylight. Two satellites are necessary for bistatic observations where radar signals transmitted by one satellite are recorded in two places in space at the same time. For these interferometric acquisitions the intensity as well the phase information of the electro-magnetic waves has to be measured. Furthermore, the vector between the satellites, which is also referred to as baseline, has to be known with millimeter accuracy. Together, the two satellites form a unique single-pass SAR interferometer, which offers the opportunity for flexible baseline selection. Key technologies used to achieve bistatic radar operation are the time synchronization of the radar satellites to an accuracy of a picosecond (10^{-12} s) and the precise determination of the interferometric baseline. Similar technical challenges were addressed and solved first by the TanDEM-X satellite formation, which has been operated by DLR successfully since 2010, see [1] and [2]. Nevertheless Tandem-L is confronted with numerous new challenges, which are addressed in chapter 3.

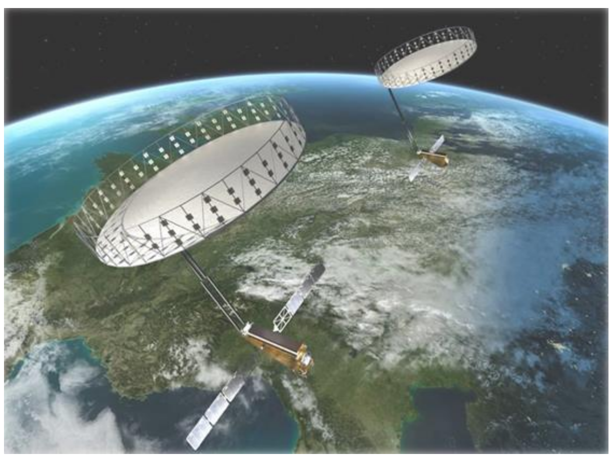

Fig. 1: Tandem-L formation with deployed reflector

The longer wavelength of L-band (23.6 cm) compared to X-band (3.1 cm) and C-band (5.6 cm) exhibits a much larger penetration depth into volume scatterers, such as vegetation and ice. This allows measuring the three-dimensional structure of vegetation and ice regions. Another benefit of using long wavelength radar signals is the better temporal coherence when measuring deformations on the Earth and glacial motion. Thus, Tandem-L permits motion measurements of the Earth's surface with centimeter down to millimeter accuracy over very long periods [3].
The enormous imaging capability of Tandem-L is realized by the use of a large deployable antenna reflector (LDR) combined with a two-dimensional digital feed array. The deployed LDR will have a diameter of 15 meters and is positioned 13.5 meters above the SAR instrument on the satellite main body. It will redirect the radar beam towards the Earth and subsequently reflect the scattered signal back to the SAR instrument which is placed in the focal point of the reflector (Fig. 2). The digital architecture of the feed array will permit a flexible beam forming whereby the radar echo received by different antenna elements are digitised in parallel and forwarded to further processing [4].

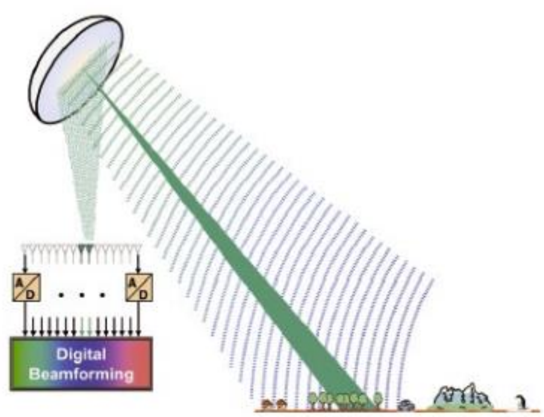

Fig. 2: Use of innovative digital beamforming

Tandem-L will be the first radar mission to implement the new technology of digital beamforming in combination with a reflector antenna. The use of the LDR increases the sensitivity and leads to a considerable reduction of transmit power. Because of this, the SAR instrument can be operated virtually continuously.

1.1. Scientific goals

Thanks to the novel imaging techniques and immense recording capacity, Tandem-L will provide urgently needed information for answering scientific questions in the fields of the biosphere, geosphere, cryosphere, and hydrosphere. It will make vital contributions towards a better understanding of the Earth and its dynamic processes. Important mission objectives are:

- global measurement of 3-D forest structure and biomass for a better understanding of ecosystem dynamics and the carbon cycle,
- systematic recording of deformations of the Earth's surface with millimeter accuracy for earthquake research and risk analysis,
- quantification of glacier movements and melting processes in the polar regions for improved predictions of sea level rise,
- high resolution measurement of variations in soil moisture close to the surface for advanced water cycle research,
- systematic acquisition and monitoring of coastal zones and sea ice for environmental monitoring and ship routing, as well as
- monitoring of agricultural fields for crop and rice yield forecasts.

These objectives are of great importance for society and encompass a spectrum that ranges from basic Earth system research to environmental monitoring and disaster mitigation. Moreover, in a time of intense scientific and public debate on the extent and influence of climate change, Tandem-L can provide important and currently missing information for improved scientific forecasts upon which socio-political decisions can be based.
Beyond the primary mission objectives, the data set recorded with Tandem-L represents a tremendous opportunity for the development of novel scientific applications and commercial services.
Tandem-L will be operated over a timespan of at least ten years. The utilization phase will greatly exceed this operational timespan, as the data obtained can still be used intensively for science and research after the end of the mission.

2. Mission Operations Concept

2.1. Observation Concept

The Tandem-L satellites will operate in three different configurations [5]:

- Close Formation (cross-track separation < 20 km)
- Constellation (separated by a few 1000 km in along-track direction within the same orbit)
- Pursuit Formation (separated by a few hundred km in along-track direction)

The observation concept foresees a fixed sequence of these configurations to be repeated on a two-year basis. This is necessary to fulfil the needs of the different scientific applications. Acquisitions for forest structure estimation and global digital elevation models (DEM) will be made in the *Close Formation* phase. Altering of the horizontal baselines between 800 m and 20 km is required for tomography applications to distinguish the different layers of forests and thereby understand its structure.

In *Constellation* phase the satellites will be separated by about 2800 km (resulting in a revisit of the same ground track with the second satellite after seven days, i.e. a phasing of 7+9 days) or even 5600 km (resulting in a revisit of the same ground track with the second satellite after two days, i.e. a phasing of 2+14 days) in along-track direction. This significantly reduces the revisit time and thereby enables applications in the fields of agriculture or soil moisture mapping and deformation.

Acquisitions to determine ice structure require along-track distances of several hundred kilometres at higher latitudes. Due to the fixed radial baseline at the poles, a *Pursuit Formation* phase is required to realize this, where the respective data is acquired mono-statically by each satellite and then combined to a bi-static image pair in the processing.

All configurations are based on the Tandem-L reference orbit which has a 16 day repeat cycle with 231 revolutions. It is generated by GSOC Flight Dynamics according to the optimization process described in [6]. The orbit parameters are given in Table 1.

Table 1: Reference Orbit

Orbit Parameter	Value
Mean orbit height	740.482 km
Mean semi-major axis (a)	7118.619 km
Mean inclination (i)	98.377 deg
Mean eccentricity (e)	0.00117
Mean Local Time of the Ascending Node (MLTAN)	18:00h ±15 min

The formation configuration is driven by the cross-track interferometry requirements, and will be implemented by a helix geometry. An illustration is given in Fig. 3. It is achieved by the separation of the relative eccentricity and inclination vectors [7]. The normal separation is largest at the equator crossings and decreases with the cosine of the argument of latitude. Over the poles the maximum radial separation is reached, which assures that radial and normal separation never become zero at the same time and thus a collision free satellite formation.

The helix parameters in terms of radial, along-track and cross-track separation were calculated to meet the requirements for the different products to be generated in the close formation phase, i.e. forest structure and height, digital elevation model and ice structure. The TDL acquisition plan foresees a systematic decrease of the horizontal baseline (see Fig. 4) over a period of 6 months from ~20 km to ~800 m and a corresponding increase over another period of approximately 6 months (not necessarily directly after the first period).

Fig. 3: Formation Flight of the Tandem-L satellites

The vertical baseline is kept constant at 600 m. The different horizontal baselines are generated by installing an inclination difference (Δi). This results in a natural drift of one satellite's RAAN (**Ω**) being different from the sun-synchronous drift of the RAAN of the other satellite. The drift can be stopped (Δi = 0) or inverted (change of sign of Δi) by means of inclination control maneuvers. The maximum of vertical baseline at the polar crossings results from a small eccentricity difference (Δe).

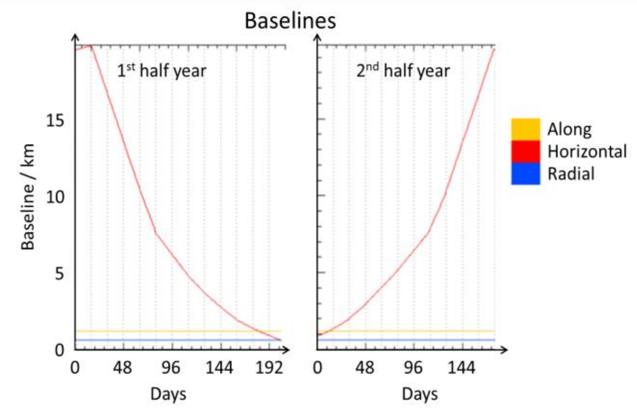

Fig. 4: Variations of the baselines during the close formation phases

The satellites will be operated in two different attitude configurations, which are referred to as *Right-Looking* or *Left-Looking* depending on whether the LDR will reflect the beam to the right or to the left side of the ground track. A transition between the modes is achieved by a 180 degree yaw-slew around the nadir pointing axis. The Right-Looking mode is used for the majority of SAR acquisitions. The Left-Looking mode is needed on the one hand for data takes of central Antarctica, which would not be possible otherwise for orbits of 98° inclination. On the other hand, only with Left-Looking it is possible to acquire a third observation geometry, which is essential for the generation of the 3D-deformation maps. There, ascending, descending and the Left-Looking acquisitions are combined to derive the deformation of the Earth's surface in north/south, east/west, and height direction.

2.2. Operations Concept

Ground Stations Network

During the Launch and Early Orbit Phase (LEOP) S-band will be used for control and monitoring of the satellites. The S-band Ground Station Network will consist of the following stations:

- Weilheim (Germany)
- Neustrelitz (Germany)
- Inuvik (INU) (Canada)
- O'Higgins (Antarctica)
- Svalbard (Norway)

The S-band ground station network will be reduced to Weilheim and Neustrelitz after the LEOP. Svalbard and O'Higgins can still be requested in case of need such as software updates or critical operations.

With the start of the commissioning phase the generation of payload data will increase in turn. The collected SAR data will be downlinked in the Ka-band. This permits much higher data rates than the S-band or X-band, which are commonly used for data downlink of satellites in low earth orbit. Designated Ka-band ground stations for Tandem-L are:

- Neustrelitz (Germany)
- Weilheim (Germany)
- Inuvik (Canada)
- O'Higgins (Antarctica)
- Awarua (New Zealand)
- Svalbard (Norway)

In the routine mission phase on average three Ka-band passes will be used by both Tandem-L satellites combined per orbit.

Dual Satellite Operations

Both satellites are operated from the same team located in one control room at GSOC. For passes over Weilheim and Neustrelitz the possibility of simultaneous S-band uplink/downlink will be given. To reduce the risk of confusion with concurrent dual satellite operations during the LEOP, the following rules will apply:

1. The focus during each ground station contact is on one satellite. Activities are therefore planned only on one satellite at a time.
2. On the second satellite only health monitoring is performed, preferably using automatic configuration checks.
3. Commands to the second satellite are limited to contingency responses or data retrieval.

The same approach was used at GSOC in the LEOP of two satellites from the GRACE Follow-on Mission. Simultaneous S-band passes will be made possible with Weilheim and Neustrelitz for the uplink of the timeline during the routine operations phase. An automation system is supporting the command operator in order to reduce costs and minimize human errors in periods of peak workload. It can perform different pre-pass, in-pass and post-pass activities and was initially developed for the TanDEM-X Mission [8].

Contingency Handling

The monitoring of the satellites in the routine phase will be supported by GSOC's Multi-Mission Flight Support Team also during non-office hours, weekends and holidays. In case of anomalies the Flight Director on duty will be called. Depending on the anomaly, actions will be taken immediately or postponed to office hours. Further on-call support is available from Flight Dynamics incl. collision avoidance and Ground Data Systems. The ground stations Svalbard and O'Higgins can be requested additionally on short notice for anomaly resolution. Although on-call personnel should be able to reach the control center within one hour also the possibility is given to react from outside GSOC. Telemetry is available in realtime in the tool Satmon@Home developed by Heavens Above GmbH. Commanding input can be issued by referring to or instantiating flight procedures. For the latter a password protected process is started which allows full traceability and visibility in a web-based tool. The described process is the standard approach for missions operated at GSOC.

Orbit and Formation Control

The Tandem-L formation control is based on the concept from the TanDEM-X mission. One satellite is considered the master satellite whose orbit is monitored and controlled against an Earth-fixed repeat ground-track reference orbit during all mission phases. Inclination control maneuvers are planned in case the ±0.0015 deg control band is violated, which occurs 3-5 times per year. Drag make-up maneuvers are planned to raise the semi-major axis and correct the eccentricity vector at same time. The maneuver planning process maximizes the period between two maneuvers while maintaining the radial-normal-separation between master satellite and reference Orbit below 250 m (2D, 3-sigma). In constellation phases the slave satellite is also controlled against the Earth-fixed reference orbit, but at a different constellation slot than the master satellite, e.g. about 2800 km behind. In all other phases, the slave satellite is controlled against the master orbit. Small differences in eccentricity ($a\Delta e \cong 600$ m during Close Formation phases), right ascension of the ascending node ($a\Delta\Omega \cong 800$m … 20km) as well as in inclination are implemented in order to yield an ellipsoidal or helix-shaped relative motion of the two satellites. The novelty w.r.t. TanDEM-X lies in the frequent and large changes in the formation geometries. The underlying control concept and budget is outlined in [5].

Debris Collision Avoidance

Tandem-L will be operated in an altitude of 740 km, which is inside the orbital region of the peak debris population. It is estimated that between 7 and 24 critical events will occur per year with a collision probability higher than 10^{-4}. Not every critical event must necessarily result in a collision avoidance maneuver however. The regularly planned orbit and formation control maneuvers can partially be used for the purpose of collision avoidance. This can be done by executing a planned in-plane maneuver earlier or later in time, to achieve an increased debris-satellite separation at moment of closest approach and hence reduced collision probability. Dedicated collision avoidance maneuvers are less flexible as compared to the routine orbit and formation maintenance maneuvers, and will result in an interruption of SAR operations.

Reactive Mission Planning

The Mission Planning System generates a command timeline for platform and payload operations taking into account all spacecraft and ground related constraints and resources. Tandem-L will make use of a new generic framework for automated planning and scheduling. The approach of the so-called Reactive Planning framework differs from the rolling planning approach as used in previous planning system. Received acquisition requests trigger an immediate planning run in contrast to being collected and processed only a short time before the timeline uplink pass [9]. This way the outcome of all currently known information and acquisition requests is immediately available and potential conflicts can be identified and resolved earlier.

3. Space Segment Requirements

DLR as the mission customer is responsible for contracting the space segment supplier of Tandem-L. A Space Segment System Requirements Document was generated based on the mission requirements, the observations concept and the mission operations concept. Also the experience from previous missions contributed to the specification of the satellites. For this, lessons learnt were collected from previous missions operated at GSOC, such as TerraSAR-X, TanDEM-X, GRACE, GRACE Follow-on, TET-1, Biros and Eu:CROPIS. The following chapter will focus on requirements for the satellite platform not including those of the SAR instrument.

3.1. Attitude and Orbit Control

The architecture of the Attitude and Orbit Control System (AOCS) for Tandem-L is driven by the large deployable reflector. For a Tandem-L satellite the moment of inertia is estimated of being up to 50 000 kg m^2 around the roll-axis. The support of thrusters is inevitable for acquiring and maintaining a stable attitude in safe-mode. Furthermore, a collision-free operation of the satellite formation can only be guaranteed when the on-board autonomy does not change the orbit. Although this may drive the costs for the space segment, it will reduce costs on the ground segment as less ground station contacts are necessary for monitoring the formation. For Tandem-L an upper limit of admissible delta-v was specified for a period of 72 hours in safe-mode. A suitable accommodation of the thrusters has to be implemented, which allows attitude control without imposing a remaining force on the satellite's center of gravity. Additionally, the disturbing torques during orbit control maneuvers must be compensable by the attitude control system. The performance of the propulsion system is required to allow for:

- formation keeping along-track maneuvers in positive and negative direction in the range of 0.5 mm/s to 50 mm/s with an accuracy of better than 0.25 mm/s

- formation reconfiguration along-track maneuvers in positive and negative direction of up to 0.15 m/s (EOL) within a maximum burn duration of 10 minutes and with an accuracy of better than 4 mm/s
- out-of-plane maneuvers of up to 0.3 m/s within a maximum burn duration of 10 minutes and with an accuracy of better than 8 mm/s.

The propulsion budget is required in terms of delta-v. It adds up to 105 m/s for orbit and formation control including collision avoidance. The value is based on the calculations from the observation concept for 12 years of operation. Additional propellant will be provided for initial orbit acquisition, attitude control in safe-mode and the de-orbiting.

Performance requirements for the AOCS are implicitly given through the radar beam pointing accuracy (0.04° in elevation and azimuth) and stability (0.01°/s in elevation and azimuth). These include also thermal deformations of the LDR as well as the interaction between the large reflector antenna structure and the attitude control system. The transition between Right-Looking and Left-Looking – the two AOCS modes dedicated for SAR acquisitions – is described by a 180 degrees yaw-slew which shall be completed within 45 minutes.

The AOCS is required to support a continuous attitude steering independently in all three axis based on the spacecraft's argument of latitude. This is necessary to compensate the Doppler shift of the radar echo, which depends on the rotation speed of the Earth and therefore on the argument of latitude. An update of the steering angles is necessary any time the formation was changed or has drifted a notable step.

3.2. Orbit determination and navigation

The requirements for Global Navigation Satellite System (GNSS) capabilities are broken down from the mission requirements: The orbit of a single satellite shall be reconstructed with an accuracy of 8 cm (1D, 1-sigma), and the baseline, i.e. the vector between the reference points of the two SAR antennas, shall be determined with an accuracy of 10 mm (1D, 1-sigma). Although the requirements for the precursor mission TanDEM-X are even stricter, the technical challenges for Tandem-L must be considered higher in comparison: First, the effect of the large reflector caused by the air drag and the solar radiation pressure is difficult to model. Second, the placing of the GNSS antennas imposes inevitable negative effects. If mounted on the main satellite body, a portion of the field of view of the antennas is obstructed by the reflector. If placed on top of the reflector, thermal deformations of the boom will change the relative position between the center of mass (CoM) and the GNSS antenna. This in turn directly impairs the orbit determination accuracy. Another challenge for Tandem-L arises from the circumstance that SAR transmissions in the L-band will interfere with GNSS measurements in one or more frequency bands of the GNSS constellations.

The spacecraft requirements derived from the mentioned challenges are:

- The antenna accommodation shall ensure unobstructed visibility of at least 75% of a hemisphere of the sky.
- The GNSS receiver shall support GPS and Galileo measurements in two frequency bands with a minimum of 18 tracking channels. Raw observation data like pseudo-range observations, carrier-phase observations, Doppler observations and carrier-to-noise ratio shall be provided.
- A Laser Ranging Array shall be accommodated on the nadir side of the spacecraft. It will be used to validate the orbit determination products.
- The spacecraft shall support the regular determination on ground of the center of mass (CoM) location with an accuracy of better than 3 mm in radial and cross-track direction and 5 mm in along-track direction.

The latter implies that not only the remaining amount of propellant must be known at any time, but also the mass distribution within the tank must be predictable to a certain degree.

3.3. Operability Capabilities

Most operability requirements for Tandem-L are formulated as reference to services described in the Telemetry and Telecommand Packet Utilization Standard (PUS) of the European Cooperation for Space Standardization (ECSS). They cover most of the operational requirements to control and monitor a spacecraft and its payloads, e.g. telecommand verification, data storage and retrieval, memory management and event reporting. The services are specified from a functional and semantical perspective including the structure and contents of the associated service requests (telecommand packets) and service reports (telemetry packets). The selection of services to be implemented – the PUS tailoring – is an ongoing task which is not yet finished in detail. The task became particularly important after the publication of a new version of the Packet Utilization Standard in 2016 (ECSS-E-ST-70-41C; also referred to as "PUS-C"). Whereas most of the satellites operated by GSOC are based on PUS version A, the decision was made that PUS-C should be applied for Tandem-L. PUS-C introduces a number of new service and subservice types and follows in general a more explicit specification. The compatibility of PUS-C to the existing monitoring and control systems has to be checked however, which calls for special caution in the tailoring task.

The majority of lesson learnt from previous missions lie in the field of operability services which are partially not covered by the Packet Utilization Standard. Therefore several mission specific services were required for Tandem-L. Examples are:

- The capability to store and request all medium and high severity on-board events in a system log. It shall be available for failure analysis even after a reconfiguration of the on-board computer.
- The capability to save the operational configuration in a non-volatile memory persistent even after a reconfiguration of the on-board computer.
- The capability to update the operational timeline in the on-board schedule only after the reception of the whole timeline update is verified. This ensures a safe update of the on-board schedule in case of problems with the communication link during a ground station contact.
- The capability to update the attitude steering table via regular telecommands. This function is a recommended improvement from a previous mission where an update had to be done directly in the RAM. This was considered an operation of high potential risk in particular because the memory address may differ between spacecraft simulator, Flight Model and different versions of the on-board S/W. Patching a wrong memory address would have unpredictable effects reaching from a reboot of the on-board computer to malfunctions in essential S/W routines.

The implementation of new PUS services for Tandem-L is still under discussion. It involves primarily file based operations as well as a position based on-board schedule. The latter permits to pre-program the operations based on the spacecraft position in parallel to the conventional time controlled execution of telecommands. File based operations include the transfer and management of files containing for instance timeline updates or software patches.

A driving factor for Tandem-L originates from the digital architecture of the SAR feed array. This leads to the need to update the receive beam coefficients once per second to follow the terrain change in the acquired swath. In order to uplink a data volume of seven megabytes per day several performance requirements have been derived:

- The S-band uplink data rate shall be 128 kbps.
- SAR operations shall be pre-programmed for up to 48 hours. This means that the on-board schedule shall provide sufficient space, e.g. for up to 64000 telecommands with an application data size of 200 bytes per telecommand.
- The command and data handling system shall support the execution of up to 30 telecommands of any service type and subtype per second independently of the source like ground, on-board schedule or on-board autonomy.

The total number of telecommands given is exemplary and depends on the maximum agreed size of the application data per telecommand.

3.4. Payload data handling and downlink

A major challenge for Tandem-L is the large amount of generated payload data. Analyses from the observation concept show that per day up to eight terabytes of SAR data are to be downlinked by the satellites. The designated frequency band to be used is the Ka-band between 25.5 and 27 GHz. The coding scheme will be adapted with the elevation angle of the satellite as seen by the ground station. The data rate will be varied between 2292 and 3388 Mbps. This procedure is needed to account for rain attenuation, which the Ka-band is subject to. For the link budget calculations the availability of 99% is assumed, meaning that 99% of transmitted data shall available at the receiving end. The Ka-band antenna assembly will be equipped with a steering mechanism that permits continuous pointing to the ground station. The pointing trajectory will be computed on-board and shall not be constrained by ongoing orbit maneuvers or attitude slews around the yaw axis. The coordinates of up to 16 ground stations shall be stored on-board for this purpose. The Ka-band antenna assembly is foreseen to support a total of 135000 downlink cycles over the operational lifetime.

3.5. Comparision to TanDEM-X

The precursor mission TanDEM-X is equipped with the feature of an Inter Satellite Link (ISL), which transfers selected GNSS, AOCS and status information directly from one satellite to the other via the S-band system. It serves two prime functions:

1. In case of a safe-mode the companion satellite is informed via the ISL and both spacecraft will immediately switch off their radar instruments. This is necessary because thruster activities of the satellite in safe-mode might maneuver it into the radar beam of the other satellite, which consequently could damage the sensitive electronics.
2. GNSS data from the companion satellite are fed into the TanDEM-X Autonomous Formation Flight System (TAFF). If the relative position is above the configured threshold a formation keeping maneuver can be issued on-board autonomously.

Both features, TAFF and ISL, were considered not critical for Tandem-L and are therefore not required from the space segment. As described in 3.1, the orbit for Tandem-L may be changed only minimally by the on-board autonomy. Thus there is no risk of mutual illumination as consequence from a safe-mode and no notification to the partner satellite is needed. TAFF on the other hand was designed to meet in particular the high control accuracy requirements for along-track interferometry with TanDEM-X (along-track separation of 50 ± 10 m) necessary for measuring ocean currents [10]. As the demands for Tandem-L are relaxed in comparison (along-track separation ± 300 m), formation keeping manoeuvers can be issued from ground with a planning interval of 24 hours.

The risk of mutual illumination is in principle given twice per orbit resulting from the helix formation. For TanDEM-X special care is taken on ground at the generation of the SAR operations timeline. So-called exclusion zones are defined where no acquisitions are scheduled on one satellite when the other one is crossing in front of it [11]. Additionally, a Fault Detection, Isolation and Recovery (FDIR) function is in place on-board that would detect and stop an active radar transmission. It is based on the satellite's argument of latitude which is in turn correlated to the exclusion zone. Both mechanisms, the FDIR and the exclusion zone definition on ground, have to be adapted whenever the formation is changed. Considering that the radar signal strength of Tandem-L will be much lower than the one of TanDEM-X and the distance between both will be higher, it was investigated if the mentioned safety measures are necessary for the successor mission as well. The implementation of the following requirement seemed to be achievable without sophisticated provisions on the space segment: No danger shall exist by illumination from the partner satellite if the SAR instrument is operated at a distance greater than 400 m. It will mitigate the issue of mutual illumination for any nominal formation as the observation concept only foresees inter-satellite distances above 500 m. With a safe-mode that does not significantly change the orbit, the only illumination risk left is during formation reconfigurations. In some cases the satellite distance might be reduced here below 400 m in order to minimize the need of propellant. The mission planning system will ensure that SAR operations are stopped during these periods.

4. Conclusion

Tandem-L is an Earth observation mission of outstanding scientific importance and relevance to our society. The German Aerospace Center has released a system requirements document for the space segment as derived from the mission requirements and the operations concept. Lessons Learned from previous missions contributed considerably to identifying and defining required functions. Despite the ambitious mission goals and technical challenges, Tandem-L can be realized without two key features from the precursor mission TanDEM-X, namely the inter-satellite link and the TAFF system for autonomous formation flight.

An early dialogue with the industry partners has turned out to be an effective measure to get a common understanding on required functions. One example is the performance of the propulsion system. Maneuvers with the largest delta-v are needed primarily in out of plane direction, whereas the highest accuracy is required for in-plane maneuvers for formation keeping. Specifying the performance for different use cases can open the way for a reasonable and cost efficient design. Further iteration of the space segment system requirements also in the context of implementation costs is an ongoing task in the current stage of the mission.

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