The Tandem-L Formation Flying Mission

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Abstract

Tandem-L is a challenging bi-static L-band SAR mission with the goal to provide substantial contributions to the better understanding of Earth system dynamics. Two identical 3-ton satellites proposed to launch in 2024 will be operated in close formation. Featuring latest digital beamforming techniques in combination with a large deployable reflector will enable SAR acquisitions with increased swath width and imaging resolution. Tandem-L will provide vital information for solving pressing scientific questions in the biosphere, geosphere, cryosphere, and hydrosphere [1]. This paper elaborates on the challenging navigation and formation control requirements as derived from the mission objectives. The focus is on the orbit control strategy foreseen to meet the large and frequent formation adjustments implied by the observation concept. The optimized formation geometries and schedule are presented proofing the feasibility of this ambitious formation-flying mission.

Keywords: Tandem-L, Formation flying, Mission analysis

Introduction

The Tandem-L mission will contribute significantly to a better understanding of the Earth system and its dynamics. The major scientific objectives are the global measurement of forest biomass and its variation in time for a deeper insight of carbon cycle processes, the systematic monitoring of deformations of the Earth's surface on a millimeter scale for the investigation of earthquakes, volcanos and risk analysis, the quantification of glacier motion and melting processes in the polar regions, the fine scale measurement of variations in the near-surface soil moisture as well as observations of the sea ice drift and ocean surface dynamics. Tandem-L will simultaneously measure seven essential climate variables in a single satellite mission [1].

The Tandem-L project has successfully passed the intermediate system requirements review. During the phase B1, the overall mission engineering has been further refined by the German Aerospace Center (DLR) and a thorough functional concept has been developed for the ground segment. With support by DLR two industry consortia, led by OHB and Airbus respectively, proposed different Tandem-L satellite and instrument concepts. A decision for the realization of Tandem-L as a German SAR mission is expected in 2019. Afterwards, the industrial prime will be selected for the space segment while the ground segment will be developed and operated by DLR. The two satellites could be launched in 2024 and operated for at least 10 years thereafter.

Orbit and Formation Requirements

The Tandem-L satellites will fly on a 741 km altitude, sun-synchronous (98.377° inclination) dusk-dawn orbit with 231 repeat orbits within a 16 days repeat cycle. The Master satellite

[*] Since Sep. 2018 with ALTEC S.p.A.

orbit will be controlled to stay within a 250 m radius tube surrounding the Earth-fixed reference orbit, which has been derived in [2]. The 18:00 mean local solar time at ascending node orbit is particularly suited for continuous radar observations due to steady illumination of the solar panels. Thus, it guarantees enough power except for short eclipse phases around summer solstice, in which the load lies entirely on the battery.

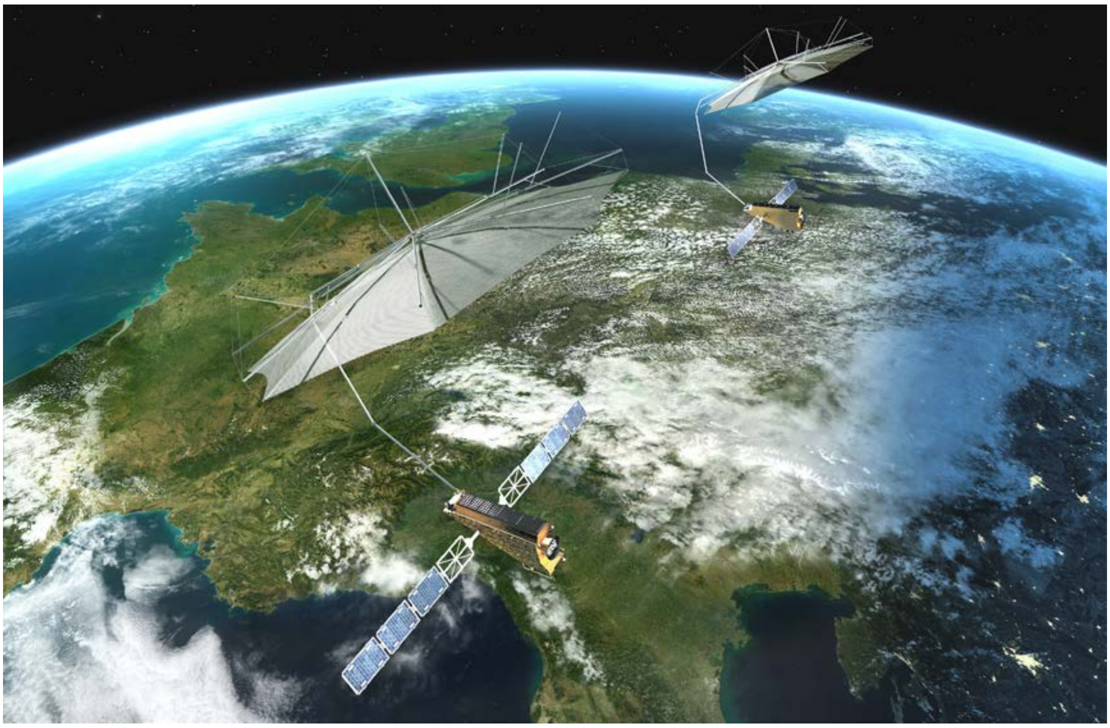

Fig. 1: Artistic view of the Tandem-L formation in 741 km altitude. Each spacecraft weighs about 3 tons and carries a deployable reflector antenna with a diameter of 15 m.

The Master-Slave formation geometries are optimized to best serve the observation scenarios, which are derived from the different scientific applications and the underlying requirements such as regions of interest, acquisition in monostatic or bi-static mode, resolution, acquisition frequency and polarization. In order to fulfil these requirements, the observation concept foresees acquisitions in four different phases repeated on a two-year basis as shown in Figure 4. The four formation regimes are mainly driven by the following applications:

- The required data for forest structure estimation and global digital elevation models (DEM) will be acquired in the Close Formation phases. With the constant altering of the across-track distance between 800 m and 20 km the various baselines required to enable tomography for forest structure estimation can be achieved.
- In Constellation phase the satellites will be separated by about 2,800 or even 5,600 km in along-track direction in order to significantly shorten the revisit time and thereby enable applications in the fields of agriculture or soil moisture mapping and deformation.
- Acquisitions to determine ice structure are performed during the Pursuit Monostatic phase as the need for a large baseline at higher latitudes can only be realized exploiting along-track distances of several hundred kilometres. The respective data is acquired mono-statically by each satellite and then combined to a bi-static image pair in the processing.

- The Left-Looking Pursuit Monostatic phases will be conducted during the local winter period to acquire central Antarctica, which is not visible in the routine right-looking geometry. .

Acquisitions for deformation applications like line-of-sight displacement and deformation rate map generation are acquired in all phases to provide the necessary amount of images to perform measurements in 3-D. Furthermore, agriculture and soil moisture measurements take place in every phase to provide constant time series. As an overview Figure 2 shows the regions of interest demanded by the scientific community for large-scale deformations on the left and forest structure determination on the right.

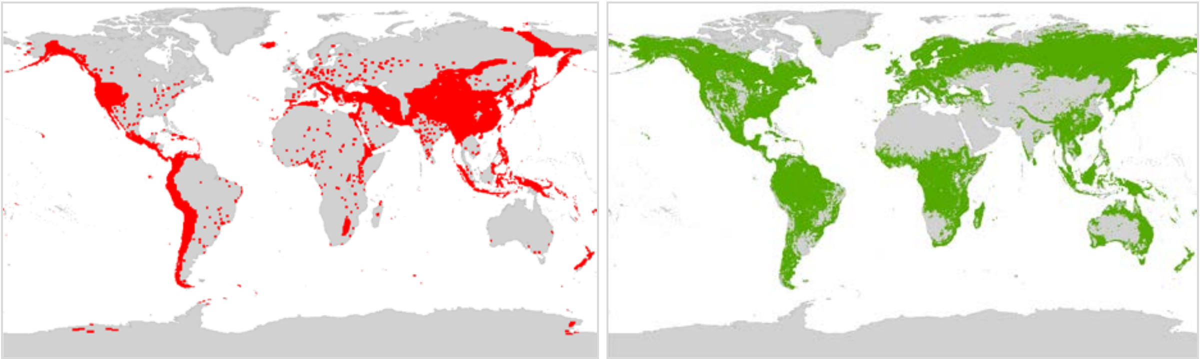

Fig. 2: Scientific required regions of interest for large-scale deformation measurements (left) and forest structure determination (right).

With a detailed acquisition planning the exploitation of both space- and ground-segment resources in these four phases are optimized. To perform an accurate planning the scientific requirements have to be translated into individual requirements for each acquisition. An important factor in this case is the height of ambiguity as it represents the acquisition geometry in terms of the perpendicular baseline and has a significant impact on the vertical accuracy. Further acquisition requirements comprise of polarization, acquisition frequency, if the acquisition is bi-static and if data should be acquired in ascending or descending orbit direction. These parameters are set in order to maximize the acquisition time, distribute the orbit usage as homogeneously as possible and combine together all the acquisitions. The result is a dedicated timeline for each phase including start and stop times of each acquisition as well as precise data volume, downlink and orbit usage estimation. For example, the downlink data volume must not exceed 8 terabyte per day. Figure 3 shows the data volume produced by an exemplary timeline for the Close Formation for one year. Different colours indicate the different applications. Eventually analyses are performed to determine the satisfaction of scientific as well as system requirements.

Orbit Control Concept

Absolute Orbit Control

The Tandem-L reference orbit forms the basis for both radar acquisition planning and orbit control. In contrast to traditional design considerations for sun-synchronous, frozen eccentricity repeat orbits, the reference orbit must be a closed orbit with matching states at the beginning and end of each 16-day repeat cycle comprising 231 orbits. Therefore, the reference orbit design has been formulated as an optimization problem [2]. The implemented reference orbit is expressed in an Earth-fixed frame and can be repeated in 16-day intervals throughout the entire mission.

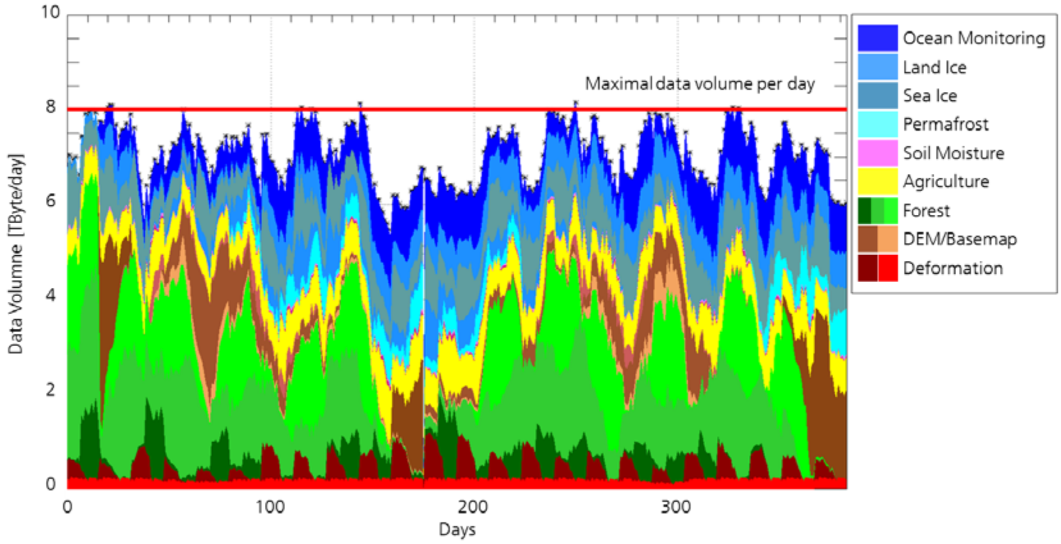

Fig. 3: Data volume of an exemplary timeline for the Close Formation for one year.

The repeat cycle allows to revisit targets within little time intervals (few days) and thus to monitor deformations on short time scales. This also brings the benefit of having fast access to targets in case of emergency observations. The Master satellite osculating orbit will be controlled within a “tube” defined about the Earth-fixed reference orbit. Similar to TerraSAR-X, the radius of the “tube” is set to 250 m, which corresponds to the maximum allowed deviation of the Master orbit from the reference orbit in the plane perpendicular to the flight direction. The implementation of the Tandem-L ground-control will be similar to the TerraSAR-X control concept [3], which in more than 10 years of operation has proved to work remarkably well, e.g. more than 99 % of the time TerraSAR-X was inside the 250 m control tube [4].

Thanks to the higher orbit (741 km mean altitude compared to 505 km for TerraSAR-X) less frequent drag make-up maneuvers are expected. However, because of the denser debris population in 741 km altitude in combination with the huge spacecraft cross-section (cf. Fig. 1) up to ten collision avoidance maneuvers may be necessary per year. In total the yearly Δv budget for absolute orbit maintenance is estimated as 2.3 m/s comprising collision avoidance, weekly to monthly drag make-up manoeuvers depending on the solar activity and about four inclination control maneuvers per year.

Relative Orbit Control

DLR benefits from a long history of operational formation-flying experience [5]. In particular, knowledge and system heritage from DLR’s TanDEM-X mission will be applied to Tandem-L since the relative motion concept is very similar. While the Master satellite is controlled against the reference orbit, the Slave satellite is controlled with respect to the Master orbit. Small differences in eccentricity ($a\Delta e \cong 600$ m during Close Formation phases), right ascension of the ascending node ($a\Delta\Omega \cong 800\text{m} \ldots 20\text{km}$) as well as in inclination are implemented in order to yield an ellipsoidal or helix-shaped relative motion of the two satellites. The underlying formation design and control concept is outlined in [6]. Furthermore, the operational experience from TanDEM-X and the hereby achieved very good control accuracy are discussed in [7]. In the following we will focus on the substantial differences implied by the Tandem-L mission.

Besides the scientific objectives Tandem-L will also be unique in terms of orbital variety. Significant effort has been made in designing formation sequences meeting the acquisition plan and minimizing the fuel expenditure at same time. During the Close Formation phases the horizontal separation will be varied between 800 m and 20 km. An elegant fuel-minimal technique for the realization of these large and also frequent changes in horizontal separation utilizes the Earth's oblateness perturbations. The RAAN rates $\dot{\Omega}$ of the Master and Slave orbits are particularly sensitive to changes in the inclination and the semi-major axis. In [8] we derive an analytical expression starting from the secular motion of the ascending node [9]

$$\dot{\Omega} = -\frac{3}{2}\frac{\sqrt{\mu}}{a^{3/2}} \cdot J_2 \cdot \frac{R_E^2}{a^2} \cdot \cos i \tag{1}$$

with J_2 = +1.083·10^{-3}, R_E = 6378.137 km and μ = 398600.4415 km^3/s^2. From the partial derivatives the differential RAAN rate is found as a function of differential semi-major axis $\Delta a = a - a_{ref}$ and differential inclination $\Delta i = i - i_{ref}$. The relative RAAN change during a period Δt can then be determined from [8]

$$\delta\Delta\Omega \approx -\dot{\Omega}_{ref} \cdot \left(3.5\,\Delta a / a_{ref} + \Delta i \cdot \tan i_{ref}\right) \cdot \Delta t \tag{2}$$

with $\dot{\Omega}_{ref}$ = 2π/365.256d being the natural (Sun-synchronous) RAAN drift rate, a_{ref} = 7118.619 km and i_{ref} = 98.377° being mean semi-major axis and mean inclination of the Tandem-L reference orbit [2]. The fuel-saving capability of this "natural" drift in horizontal separation is illustrated by the following example. From Gauss' variational equations the velocity budget for adjustment of inclination or RAAN at an optimal location is given by

$$\Delta v_N \cong n \cdot a \cdot \Delta i \quad \text{or} \quad \Delta v_N \cong n \cdot a \cdot \Delta\Omega \tag{3}$$

with n = 0.0010512 s^{-1} being the Tandem-L mean motion. An example 19.2 km change in the horizontal separation $a\Delta\Omega$ could be accomplished (almost) instantaneously by spending Δv_N = 20.18 m/s or instead by linearly growing over 11 repeat cycles (176 days) by installing an $a\Delta i$ = 933.5 m inclination offset at the cost of 0.98 m/s. Although the inclination offset has to be removed too, the resulting Δv_N = 1.96 m/s is remarkably lower compared to the pure RAAN control approach. The potential benefit strongly depends on the available drift time Δt. For Tandem-L different $a\Delta i$ increments will be applied resulting in a parabola-like variation of the horizontal separation over the two Close Formation phases (cf. Fig. 4). In total, less than 4 m/s Δv_N will be spent in each Close Formation phase (cf. Tab. 1).

For the design of Constellation and Left-Looking Pursuit Monostatic phases we are interested in the ground-track separation at ascending node crossing

$$d_{GT,AN} = \left(\Delta t \cdot \omega_E + \Delta\Omega\right) \cdot R_E \cdot \sin i' \tag{4}$$

with the flight time-offset Δt and ω_E = 2π/86164.1s. The "apparent inclination" i' in Eqn. 4 is defined as [10]:

$$i' = \operatorname{atan}\left(\frac{v_S \sin i}{-v_E + v_S \cos i}\right), \tag{5}$$

where i is the inertial inclination, v_S is the velocity of the satellite, and v_E is the velocity of the Earth at the equator and at the altitude of the satellite due to its rotation in inertial space.

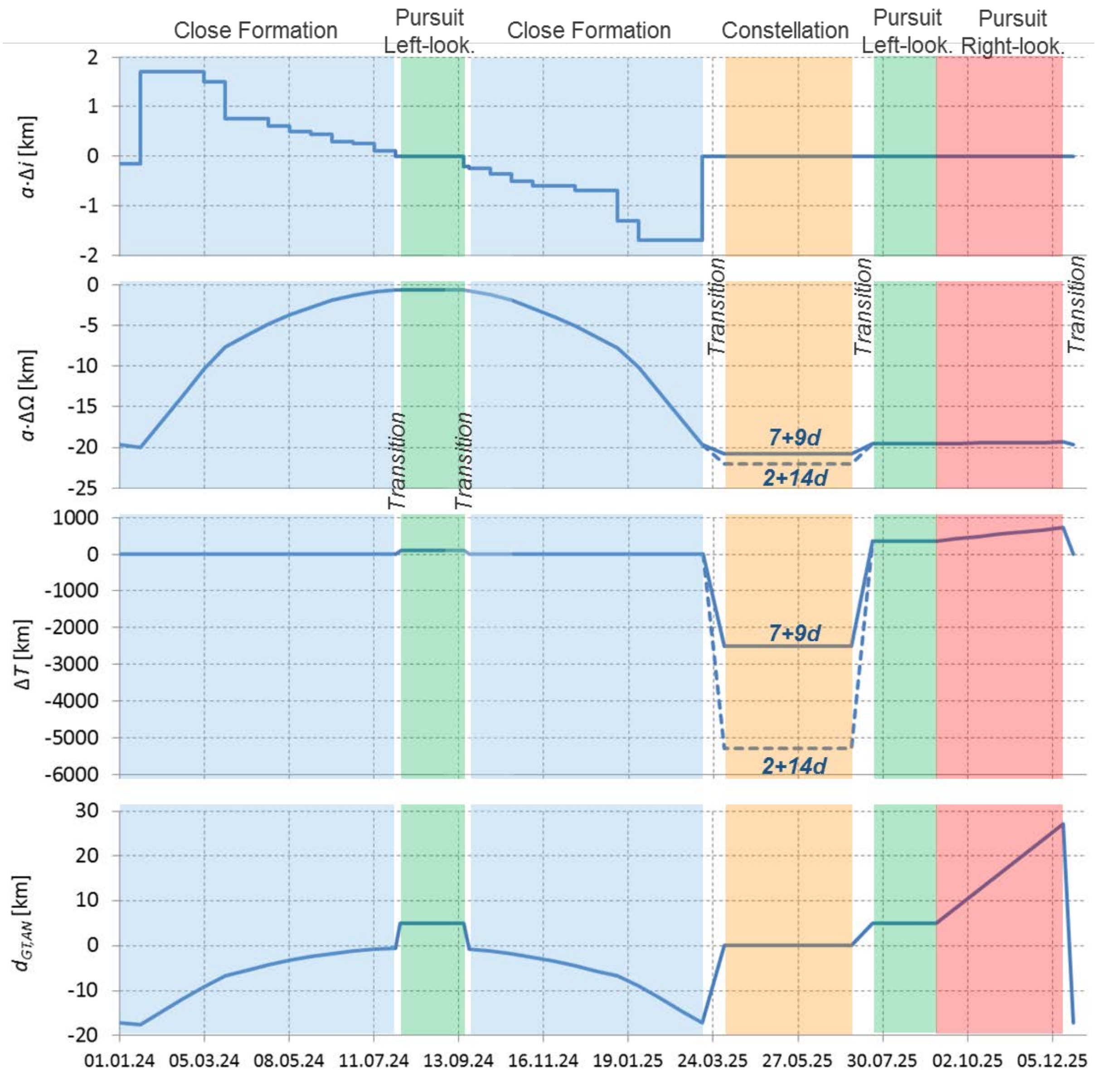

Fig. 4: Evolution of optimized formation parameters within a repeating two-year mission cycle. A constant vertical separation of 600 m applies to all Close Formation phases. Two options are depicted for the constellation phase, i.e. 7+9d and 2+14d constellations.

The analytical expression in Eqn. 4 is particularly helpful in designing the two Left-Looking Pursuit Monostatic (LLPM) phases, where the targeted ground-track separation $d_{GT,AN}$ shall be identical although the orbit geometries are very different. The first LLPM formation is entered shortly after the closest formation with $a\Delta\Omega = -700$ m and $\Delta T = 0$. Within a short 2-4 days transition phase the Slave satellite semi-major axis will be decreased by −343 m in order to start an along-track drift. This drift will be stopped at a distance of $\Delta T = +93.5$ km ahead of the Master satellite corresponding to a flight time-offset $\Delta t = \Delta T / v_S$ of 12.5 sec. During the drift phase the relative RAAN changes slightly (+41 m) resulting in a maximum ground-track separation of 5.1 km.

Contrary, the second LLPM follows the Constellation phase (in this example we refer to the 7+9d constellation) comprising significantly larger RAAN and along-track separations of $a\Delta\Omega = -20.8$ km and $\Delta T = -2498$ km, respectively. Here, a longer transition phase (14-16 days) is foreseen with significant semi-major axis reduction by $\Delta a = -1502$ m. During the drift phase the Slave will overtake the Master and will be stopped at a distance of $\Delta T = +366$ km being equivalent to 49 sec of flight-time. From the then achieved RAAN separation of $a\Delta\Omega = -19.5$ km a maximum ground-track separation of 5.1 km follows guaranteeing the same observation geometry as compared to the first LLPM phase.

Table 1: Tandem-L Δv budget for the two-year mission cycle (to be repeated 5-6 times)

Absolute Orbit Control by Master and Slave Satellites	**Δv [m/s]**	**Comments**
Reference orbit maintenance - Drag make-up - Inclination control	 1.6 2.0	Average values among one solar cycle including margins; confirmed by numerical simulation
Debris collision avoidance	1.0	
Total Δv for 2yrs Absolute Orbit Control	**4.6**	For each satellite

Formation Control by Slave Satellite	**Δv [m/s]**	**Comments**
Close Formation 1 - Formation maintenance in-plane - Rel. inclination adjustments	 3.5 3.9	Eccentricity vector maintenance for close formation with 600 m vertical separation requires 1.7 cm/s per day; 208 days
Transition to LLPM	0.8	2 days drift + 2 days operations margin
Left-Looking Pursuit Monostatic (LLPM)	0.0	No formation maintenance necessary
Transition to Close Formation 2	0.8	2 days drift + 2 days operations margin
Close Formation 2 - Formation maintenance in-plane - Rel. inclination adjustments	 3.0 3.6	Similar to 1st close formation phase but shorter, i.e. 176 days
Transition to Constellation	1.6	For 7+9d. 3.1 m/s for transition to 2+14d. 14 days drift + 2 days operations margin
Constellation	0.0	No formation maintenance necessary
Transition to LLPM	1.3	For 7+9d. 2.7 m/s for transition from 2+14d. 14 days drift + 2 days operations margin
Left-Looking Pursuit Monostatic (LLPM)	0.0	No formation maintenance necessary
Right-Looking Pursuit Monostatic	0.0	No formation maintenance necessary
Transition to Close Formation 1	1.0	6 days drift + 2 days operations margin
Total Δv for 2yrs Formation Control	**19.5**	For Slave satellite only. 22.4 for larger constellation

The formation parameters and schedule depicted in Fig. 4 have been optimized considering all acquisition objectives while minimizing the required Δv for acquisition as well as transition phases. During the mission, this two-year cycle will be repeated at least five times, i.e. the formation parameters at ending of the last transition phase in Fig. 4 (Dec. 2025) are identical to the starting parameters of the first Close Formation phase (Jan. 2024, 2026 and so on). The total Δv for each two-year cycle is estimated as 19.5 m/s including all formation maintenance and reconfiguration activities as summarized in Tab. 1. If the larger constellation (2+14d) will be realized, an additional 3 m/s will be necessary in order to accomplish the transfers to the more distant target constellation in the same transition period. The accumulated transition time (white areas in Fig. 4) has been minimized to 6.5% of mission time. These periods will be used for monostatic acquisitions and possibly experimental radar operations.

Table 1 summarizes the Δv budget for the two-year mission cycle depicted in Fig. 4. Because of the significantly larger budget associated to the Slave satellite for formation reconfiguration and maintenance (i.e. 19.5+4.6 m/s for Slave compared to 4.6 m/s for Master) an exchange of Master and Slave satellites after 6 years is foreseen. In summary, each satellite then has to provide a Δv of 86 m/s for 12 years mission operation plus a design margin and additional Δv needed for orbit acquisition after launch as well as for de-orbiting or re-entry after mission completion.

Navigation

Besides the advanced formation control ability, the precise determination of orbit and interferometric baseline are required too. In order to meet the scientific goals challenging accuracy requirements have been specified: (a) the orbit of a single satellite shall be reconstructed with an accuracy of 8 cm (1D, 1-sigma) which is driven by repeat pass interferometry requirements, and (b) for accurate DEM generation, the baseline vector between the SAR antenna reference points (ARPs) is required to be determined with an accuracy of 10 mm (1D, 1-sigma). Although both requirements have been fulfilled for the predecessor mission TanDEM-X [11, 12], the particular design of the Tandem-L mission poses new challenges.

Regarding the achievable orbit and baseline accuracy, there are two factors in favour of a better orbit modelling. Due to the higher orbit altitude of 741 km (compared to 505 km for TanDEM-X), the atmospheric drag is lower and the orbit modelling, in particular the along-track component, will be more precise. In addition the availability of two GNSS constellations, i.e. GPS and Galileo, should lead to more GNSS observations.

However, this is counteracted by several factors originating from the Tandem-L spacecraft design which have a negative effect on the orbit determination accuracy. The SAR reflector poses a large effective surface for both air drag and solar radiation pressure and makes the modelling of disturbing forces more challenging. For the placement of the GNSS antennas two options exist that both affect the orbit determination accuracy negatively: either the antennas are mounted on the boom or on the spacecraft body. In case of an antenna mounting on the boom vibrations and thermal deformations will cause a variation of the vector between centre-of-mass (CoM) and GNSS antenna, which directly impacts the orbit determination accuracy. Instead, if the GNSS antennas are mounted on the main satellite body, the large reflector will obstruct the field of view of the GNSS antennas. This can only be partially compensated by tracking two GNSS constellations. Furthermore, the main payload transmits in the L-band which may cause interferences with GNSS observations.

The baseline accuracy is additionally degraded. The baseline determined by reduced dynamic modelling [13] refers to the CoM of the spacecraft. Due to the necessary geometric transformation to the SAR ARPs which are located at the reflectors, attitude determination errors are amplified by the large distance (~15m) from the CoM to the ARP compared to more compact satellites (e.g. TanDEM-X).

Although a sufficient pre-flight validation of the relative orbit determination process cannot be performed, we are confident that the challenging requirements will be met. In order to counteract the aforementioned issues, the space-segment suppliers are working on design adaptations in order to improve the knowledge of the CoM position and reduce its variation. The impact of L-band interference will be mitigated by using the less perturbed E1/L1 and E5a/L5 frequencies (Galileo/GPS). Furthermore, the GNSS antenna positioning is subject to on-going optimization within the current phase B2.

Conclusion

Tandem-L is a proposal for a highly innovative satellite mission for the global observation of dynamic processes on the earth's surface with hitherto unknown quality and resolution. Thanks to the novel imaging techniques and the vast recording capacity, Tandem-L will provide urgently needed information for solving pressing scientific questions in the areas of the biosphere, geosphere, cryosphere, and hydrosphere. After the launch planned in 2024, Tandem-L will make a vital contribution towards a better understanding of the earth system and its dynamics.

The present paper elaborates on the challenging navigation and formation control requirements. Although the absolute and relative navigation demands are well accomplished by TerraSAR-X / TanDEM-X, the L-band instrument and the Tandem-L spacecraft design complicate the Tandem-L navigation performance. Miscellaneous mitigation measures are currently under investigation. The orbit control concept follows the flight-proven TerraSAR-X / TanDEM-X implementation. In order to meet the large and frequent formation adjustments implied by the Tandem-L observation plan a two-year formation timeline has been optimized with respect to acquisition needs, minimum fuel and minimum transition period. Thanks to the concept of inclination-induced drifting of the horizontal baseline significant fuel-savings could be achieved enabling a 12-year mission operation. The presented formation parameters and schedule and the corresponding Δv budget serve as basis for the on-going mission design phase.

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