TANDEM-L: MAIN RESULTS OF THE PHASE A FEASIBILITY STUDY

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ABSTRACT

Tandem-L is a highly innovative SAR satellite mission for the global observation of dynamic processes on the Earth's surface with hitherto unknown quality and resolution. Thanks to its novel imaging techniques and its unprecedented acquisition capacity, Tandem-L will deliver urgently needed information for the solution of pressing scientific questions in the areas of the biosphere, geosphere, cryosphere and hydrosphere. The feasibility of Tandem-L has been analyzed and confirmed in the scope of a phase A study, which has been conducted in close cooperation between the German Aerospace Center (DLR) and the German space industry. This paper provides an overview of the Tandem-L mission concept and summarizes the actual development status.

Index Terms— Earth system, dynamic processes, SAR interferometry, tomography, polarimetry, digital beamforming, high-resolution wide-swath SAR imaging

1. INTRODUCTION

Tandem-L is a proposal for a highly innovative radar satellite mission to monitor dynamic processes on the Earth's surface with hitherto unknown quality and resolution [1], [2]. Important mission goals are the global measurement of forest biomass and its temporal variation for a better understanding of the carbon cycle, the systematic monitoring of deformations of the Earth's surface on a millimetre scale for the investigation of earthquakes 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 dynamics of ocean surfaces and ice drift.

The Tandem-L mission concept builds upon the success of TanDEM-X [3], [4] and utilises two formation-flying radar satellites operating in L-band (cf. Figure 1). The use of the synthetic aperture radar (SAR) technique enables the systematic acquisition of high-resolution radar images independent of weather and daylight and constitutes therefore an ideal basis for the continuous monitoring of dynamic processes on Earth's surface. Furthermore, the wavelength of Tandem-L (23.6 cm) optimally fulfils the requirements for a tomographic imaging of the three-dimensional structure of vegetation and ice bodies, as well as for a systematic measurement of wide-area deformations with millimetre precision. To ensure regular observations with short repeat intervals, Tandem-L will employ cutting-edge radar technology based on the latest digital beamforming techniques which allow for the mapping of ultra-wide image swaths with high azimuth resolution [4], [6], [7], [8]. The goal of Tandem-L is to interferometrically map large parts of the Earth's landmass up to two times per week. 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.

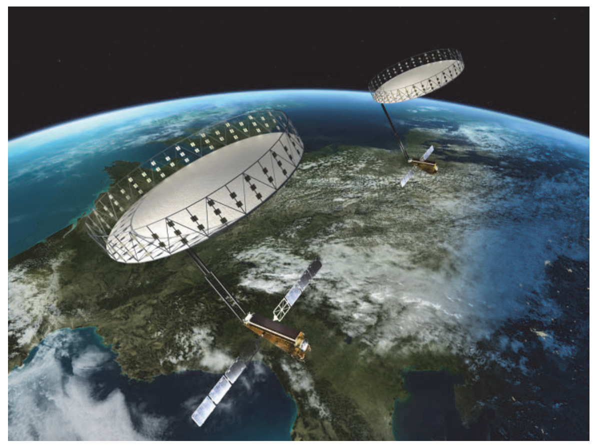

Figure 1: Artist's view of the Tandem-L satellites.

The feasibility of Tandem-L has been analyzed and confirmed in the scope of a phase A study, which has been conducted in close cooperation between the German Aerospace Center (DLR) and the German space industry. This paper summarizes the results of the phase A study and provides an overview of the mission objectives and requirements, the mission concept and the major innovations in the radar instrument.

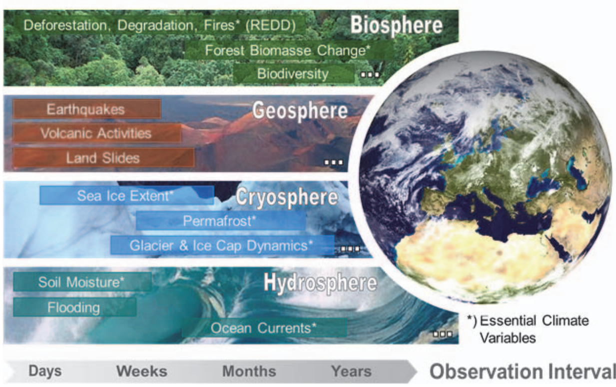

Figure 2: Examples of dynamic processes within the bio-, geo-, cryo- and hydrosphere and the observation intervals required for their systematic monitoring. The processes denoted by a star represent essential climate variables.

2. USER AND MISSION REQUIREMENTS

The Tandem-L user requirements have been defined and elaborated in close cooperation with a large international science community [9]. Important mission objectives are:

- global measurement and monitoring of 3-D forest structure and biomass for a better understanding of ecosystem dynamics and the carbon cycle,
- systematic recording of small and large scale deformations of the Earth's surface with millimeter accuracy for earthquake, volcano and landslides research as well as risk analysis and mitigation,
- quantification of glacier movements, 3-D ice structure and melting processes in the polar regions for improved predictions of future sea level rise,
- fine scale measurements of soil moisture and its variations close to the surface for a better understanding of the water cycle and its dynamics,
- systematic observation of coastal zones and sea ice for environmental monitoring and ship routing,
- monitoring of agricultural fields for crop yield forecasts, as well as
- generation of highly accurate global digital terrain and surface models which form the basis for a wide range of further remote sensing applications.

These objectives address subjects of great societal importance and encompass a broad science and application spectrum that ranges from basic Earth system research to environmental monitoring and disaster mitigation. Tandem-L will moreover contribute to the measurement of 7 essential climate variables (cf. Figure 2). The unique Tandem-L observations will therefore provide also important and currently missing information about the extent and influence of climate change, based on which improved scientific forecasts and socio-political decisions can be made.

Based on the user requirements, a set of 26 preliminary geophysical products have been defined during Phase A and summarized within the Mission Requirements Document [10]. Table 1 provides an excerpt of the most important products and their main parameters. Most of the products are unique in terms of their quality, quantity, resolution and coverage and rely on special data acquisition modes such as single-pass polarimetric SAR interferometry (PolInSAR) and multi-baseline coherence tomography. Implicit to most products is moreover the demand for high-resolution SAR acquisitions with short repeat intervals. Due to the limitations of current spaceborne SAR systems, such radar data can only be provided by a new generation of multi-channel SAR instruments (cf. Section 4).

	Products	Coverage	Resolution	Accuracy	Repetition Rate
Biosphere	Forest Height	all forest areas	50 m (global) 30 m (regional)	~ 10 %	seasonal (bi-weekly acquisitions)
	Vertical Forest Structure		50 m (global) 30 m (regional)	~ 20 % for 10 m layers	
	Forest Structure Change		50 m (global) 30 m (regional)	~ 15 % (goal) for each layer	
	Above Ground Biomass		100 m (global) 50 m (regional)	~ 20 % (or 20 t/ha)	
	Biomass Change		100 m (global) 50 m (regional)	~ 10 % (goal) (or 10 t/ha)	
Geo-/Lithosphere	LOS Deformation (Tectonics)	high strain areas	50 m	1 mm/year (E/V) 10 mm/year (N) (after 10 years)	weekly acquisitions from multiple angles
	3-D Deformation (Tectonics)				
	Subsidence & Landslides (PSI)	urban & risk areas	7 m	1 mm/year (after 10 years)	
	LOS Displacement (Volcanoes)	>1500 land volcanos	50 m	10 mm	
Cryosphere	Glacier Velocity Maps	most glaciers	50 – 500 m	1 – 50 m / year	4 / year
	Sea Ice Type and Thickness	Arctic and Antarctic	5 km – 50 km	5% – 20% / 0.5 m – 1 m	bi-weekly to monthly
	3-D Ice Structure	Greenland & selected areas	100 m	10 m vertical resolution	yearly
	Ice Sheet Elevation Change	ice sheets worldwide	50 m	0.5 m – 1 m	seasonal
	Permafrost	selected Arctic regions	10 m (quad)	1 cm LOS displ./season	bi-weekly
Hydrosphere	Soil Moisture	selected areas	50 m	0.05 – 0.1 m^3/m^3	weekly
	Agriculture Mapping	selected areas	20 m (16 looks, quad pol)	1 dB rad. res., NESZ $\lesssim$ -28dB	weekly
	Wind Speed & Wave Height	coastal regions	4 km	speed: 2 m/s height: 0.1 m	weekly
	Ocean Currents	selected areas	4 km	0.05 m/s	weekly
DEM	Digital Terrain & Surface Model	global	~ 12 m (bare) ~ 25 m (forest)	2 m (bare) 4 m (vegetated)	annual
	Global Basemap and Landcover	all land surfaces	10 – 20 m	single (2/year) quad (2/year)	4 / year
	Emergency	local	1 m	single/dual/quad	on demand

Table 1: Main geophysical products of Tandem-L.

Parameter	Value	Comments
Orbit height	745 km	231 cycles / 16 days
Orbital tube ∅	500 m (3σ)	refers to master satellite
Horizontal baselines	1 km … 18 km	variable horizontal baselines for tomography
Radial baselines	0 m … 600 m	radial baselines for passive safety (Helix concept)
Local time	6 h / 18 h	dawn/dusk
Inclination	98.4°	sun synchronous orbit
Revisit time	16 days	enables up to 4 global data acquisitions from different directions every 16 days
Downlink capacity	~ 8 Terabyte/day	Ka-band downlink and ground station network
Mission time	> 10 years	consumables for 12 years

Table 2: Key parameters and performance figures of the Tandem-L satellites.

3. MISSION CONCEPT

To satisfy the challenging user and mission requirements, a dedicated data acquisition concept has been developed which consists of two basic measurement modes:

- the ***3-D structure mode*** employs fully-polarimetric single-pass SAR interferometry to acquire structural parameters of semitransparent volume scatterers. By combining multiple interferometric acquisitions with varying cross-track baselines (cf. Figure 3), it becomes moreover possible to derive tomographic images with fine vertical and horizontal resolutions as required for the accurate measurement of 3-D forest and ice structure as well as for the generation of digital terrain and surface models.
- the ***deformation mode*** employs repeat-pass interferometry to measure small displacements on the Earth surface with accuracies down to centimeters or even millimeters. To minimize errors from atmospheric disturbances and temporal decorrelation, special attention has been paid to maximize the number of image acquisitions. For this, a special SAR imaging mode has been developed which allows for the systematic mapping of 350 km wide swaths with an azimuth resolution of 7 m.

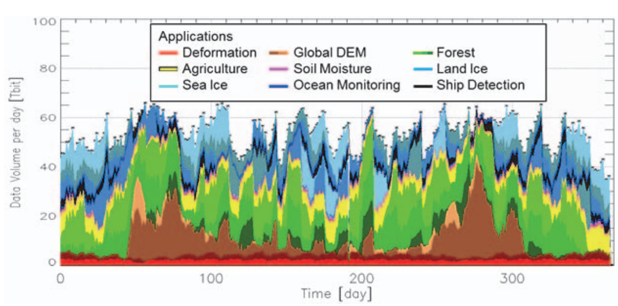

Figure 4: Daily data volume acquired for the different application areas over one year (cf. [12]). Note that most data acquisitions serve not only one but multiple applications.

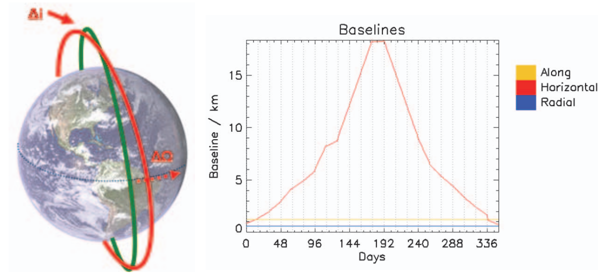

Figure 3: Left: The formation flight of the two Tandem-L satellites exploits the naturally occurring differential secular variations of the right ascension of the ascending nodes in response to slightly different inclinations. Right: Evolution of the equatorial baseline over the course of one year.

The Tandem-L satellites will fly on a sun-synchronous dawn-dusk orbit with a repeat cycle of 16 days (cf. Table 2). During each repeat cycle, up to four global data acquisitions can be performed from different viewing directions in single- and dual-pol mode. Deformation measurements are further supported by flying the master satellite in a closely controlled orbital tube with a radius of 250 m (3 σ). To obtain the required cross-track baselines for single-pass interferometry and tomography, the inclination of the slave satellite will be periodically adjusted. This results in a natural drift of the ascending node and allows for large periodic baseline variations with a minimum amount of fuel [11]. A challenge in Tandem-L is the large amount of data that has to be transferred to the ground. For this, a highly performant Ka-band downlink with a net data rate of up to 2.6 Gbit/s will be employed. Together with an appropriate ground station network, 8 Terabyte can be downlinked every day. To show the mission feasibility, a first data acquisition plan has been developed and Figure 4 shows how the available data volume is distributed among the different applications (cf. [12] for more details). The systematic observation of dynamic processes will be further supported by the long mission lifetime of 10 years, which may even be extended as all consumables are planned for 12 years. At the end of the mission, the satellites will be deorbited via dedicated thrusters.

4. SAR INSTRUMENT

A particular challenge of the Tandem-L mission is the development of two extremely capable but at the same time also cost-efficient SAR instruments that shall map a 350 km wide swath in single/dual pol mode and a 175 km wide swath in quad-pol mode, both with an azimuth resolution of 7 m and a range bandwidth of up to 84 MHz (cf. Table 3). Moreover, the noise equivalent sigma zero (NESZ) shall be better than -25 dB and the ambiguity-to-signal-ratio (ASR) shall be better than -25 dB in single/dual pol mode (-22 dB in quad-pol mode). These requirements exceed by far the capabilities of current spaceborne SAR systems. Therefore, a new instrument concept has been developed that combines a large unfurlable mesh reflector with a digital feed that is composed of 32 patch elements in elevation and 6 patch

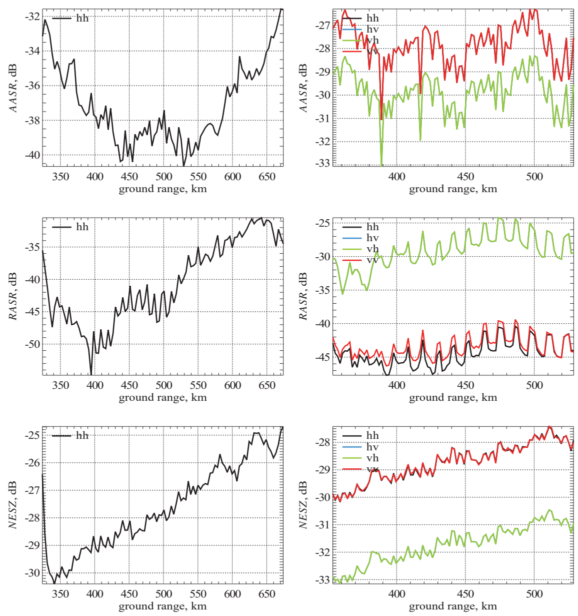

Figure 5: Top: azimuth ambiguity-to-signal ratio (AASR) for single-pol (left) and quad-pol mode (right). Middle: range ambiguity-to-signal ratio (RASR) for single-pol (left) and quad-pol mode (right). Bottom: noise equivalent sigma zero (NESZ) for single-pol (left) and quad-pol mode (right).

elements in azimuth. The 6 azimuth patches are connected to a single T/R module via fixed power dividers to obtain, for each elevation direction, an optimized azimuth antenna pattern. The outputs of the T/R modules are then individually digitized and combined in real-time to form multiple elevation beams that follow the simultaneously arriving radar echoes from subsequent transmit pulses. By this, it becomes possible to map a very wide swath with high azimuth resolution [5], [6], [7]. The emergence of blind ranges is moreover avoided by a systematic variation of the pulse repetition interval [8]. Figure 5 demonstrates that such a staggered SAR mode provides an excellent performance that can meet the demanding science requirements for both the fully polarimetric 3-D structure mode and the ultra-wide swath deformation mode [13]. As the staggered SAR mode is associated with a notable oversampling of the SAR signal, a new onboard data reduction technique will be employed to keep the data rate even below that of a conventional SAR system [14]. This will maximize the science output for a given downlink budget.

5. CONCLUSIONS

The phase A study of Tandem-L has confirmed both the feasibility and the unique opportunities of this highly innovative SAR mission. At the time of this writing, Tandem-L is proceeding to Phase B1 which will last until the mid of 2017. According to the current planning, and subject to timely financial approval, the Tandem-L satellites could be launched at the end of 2022.

Parameter	Value	Parameter	Value
Frequency	L-band	**Reflector ∅**	15 m
Bandwidth	≤ 84 MHz	**Focal length**	13.5 m
NESZ	< -25 dB	**Feed offset**	9 m
Azimuth res.	7 m (1 m spot)	**Feed size**	5.2 m x 0.86 m
Swath width	350 km	**Patches**	32 x 6
Swath (quad)	175 km	**Channels**	32 x 1
Incident ang.	26.3° - 47.0°	**T/R modules**	2 x 32
Inc. (quad)	28.4° - 39.5°	**TRM power**	56.6 W
ASR	< -25 dB	**Total losses**	3.6 dB
ASR (quad)	< -22 dB	**Noise figure**	3.5 dB
Look direction	right & left	**Duty cycle**	4% (8% quad)

Table 3: Key parameters of the SAR instrument.

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