Tandem-L: An Innovative Interferometric and Polarimetric SAR Mission to Monitor Earth System Dynamics with High Resolution

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Abstract

Tandem-L is a proposal for an innovative interferometric and polarimetric radar mission that enables the systematic monitoring of dynamic processes on the Earth surface. Important mission objectives are global forest height and biomass inventories, large scale measurements of millimetric displacements due to tectonic shifts, and systematic observations of glacier movements. The innovative mission concept and the high data acquisition capacity of Tandem-L provide a unique data source to observe, analyze and quantify the dynamics of a wide range of mutually interacting processes in the bio-, litho-, hydro- and cryosphere. By this, Tandem-L will be an essential step to advance our understanding of the Earth system and its intricate dynamics.

1 Introduction

Tandem-L is a German proposal for an innovative interferometric radar mission to monitor the Earth system and its intricate dynamics. Important mission objectives are global inventories of forest height and above-ground biomass, large-scale measurements of Earth surface deformations due to plate tectonics, erosion and anthropogenic activities, observations of glacier movements and 3-D structure changes in land and sea ice, and the monitoring of ocean surface currents. The Tandem-L mission concept is based on co-flying two fully-polarimetric L-band SAR satellites in a close formation. The synergistic use of two satellites enables highly accurate interferometric measurements to derive contiguous 3-D structure profiles and their spatiotemporal evolution. The advanced imaging capabilities and the systematic data acquisition strategy make Tandem-L a unique observatory to significantly advance our scientific understanding of environmental processes in the bio-, geo-, cryo-, and hydrosphere. A detailed description of the mission goals can be found in [1][2]. The German Tandem-L mission proposal has in its primary science objectives several commonalities with the DESDynI mission [3] suggested by the US National Research Council in its Decadal Survey for Earth Science. DLR and NASA/JPL are currently investigating in the scope of a pre-phase A study the feasibility of a joint mission that meets or even exceeds the science requirements of both proposals and provides at the same time a significant cost reduction for each partner.

Tandem-L employs many innovative techniques and technologies to achieve its ambitious mission goals. One example is the use of advanced digital beamforming techniques to provide wide swath coverage and short revisit time without sacrificing fine geometric resolution. This innovation enables a frequent monitoring of 2-D and 3-D structure changes with high precision. The systematic acquisition of wide-area single-pass and repeat-pass interferograms with high revisit frequency will open a new era in radar remote sensing and it can be expected that besides the primary mission objectives a wealth of new applications will emerge from the unique Tandem-L observatory. This paper gives an overview of the Tandem-L mission concept. Special emphasis is put on the innovative SAR imaging techniques.

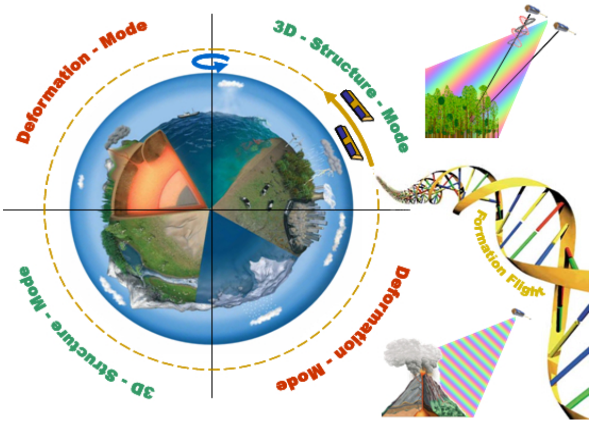

Figure 1: The Tandem-L mission concept relies on a systematic data acquisition strategy using a pair of L-band SAR satellites flying in close formation. The satellite system is operated in two basic data acquisition modes: 3-D structure mode and deformation mode. New SAR imaging techniques enable frequent coverage with high geometric resolution. (Credit for the Living Planet Image: "ESA/AOES Medialab").

2 Science Requirements

The science requirements for Tandem-L have been elaborated during several international workshops that brought together representatives from multiple geoscience disciplines. It turned out that Tandem-L has exceptional capabilities to acquire a worldwide unique data set that enables a wealth of innovative remote sensing applications and provides fundamental information to resolve urgent scientific questions related to climate research, geophysics, hydrology, glaciology, and vegetation monitoring. Leading scientists specified the observational requirements of their respective disciplines (cf. Table 1).

TABLE I. TANDEM-L USER REQUIREMENTS (EXCERPT)

	Science Product	Coverage	Resolution	Accuracy
Biosphere	Forest Height	all forest areas	50 m (global) 20 m (local)	~ 10 %
	Above Ground Biomass		100 m (global) 50 m (regional)	~ 20 % (or 20 t/ha)
	Vertical Forest Structure		50 m (global) 20 m (local)	3 layers
	Underlying Topo.		50 m	< 4 m
Geo-/Lithosphere	Plate Tectonics	all risk areas	100 m (global) < 20 m (fault)	1 mm/year (after 5 y)
	Volcanoes	all land volcanoes	20 – 50 m	5 mm/week
	Landslides	risk areas	5 – 20 m	5 mm/week
	Subsidence	urban areas	5 – 20 m	1 mm/year
Cryo- & Hydrosphere	Glacier Flow	main glaciers	100 – 500 m	5 – 50 m/year
	Soil Moisture	selected areas	50 m	5 – 10 %
	Water Level Change	regional	50 m	10 cm
	Snow Water Equiv.	local (exp.)	100 – 500 m	10 – 20 %
	Ice Structure Chng.	local (exp.)	100 m	> 1 layer
	Ocean Currents	prio. areas	~ 100 m	< 1 m/s
All	Digital Terrain & Surface Model	global	~ 20 m (bare) ~ 50 m (forest)	2 m (bare) 4 m (veg.)

The primary Tandem-L mission goals can be grouped by the following target areas and applications:

- Biosphere (3-D vegetation monitoring):
  - measurement of forest height and structure
  - global inventory of above ground forest biomass
  - detecting vegetation disturbances and biomass changes
- Geo-/Lithosphere (deformation measurements):
  - understanding earthquake and volcano eruption cycles
  - quantifying the magnitude of events
  - determination and forecasting the probability of events
- Hydro- & Cryosphere (structure & deformation):
  - measurements of ice structure and its changes
  - monitoring soil moisture and surface water changes
  - observation of ocean currents and wave field dynamics

The reader is referred to [1][2] for a more detailed description of the Tandem-L science objectives. Table 1 provides a short excerpt of the collected requirements.

3 Mission Concept

The Tandem-L mission concept relies on a systematic data acquisition strategy using a pair of co-operating L-band SAR satellites flying in close formation. The satellite system operates in two basic measurement modes:

- The ***3-D structure mode*** employs fully-polarimetric single-pass SAR interferometry to acquire structural parameters and quasi-tomographic images of semi-transparent volume scatterers like vegetation, sand, and ice (cf. Figure 2).

- The ***deformation mode*** employs repeat-pass interferometry in an ultra-wide swath mode to measure small shifts on the Earth surface with millimetric accuracy and short repetition intervals.

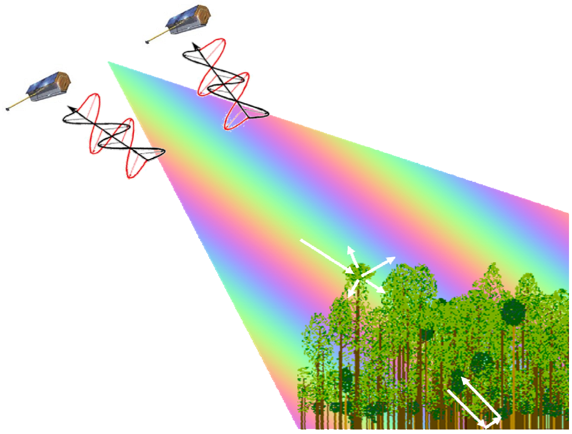

Figure 2: The 3-D structure mode employs polarimetric SAR interferometry to measure tree heights and vertical vegetation profiles. The individual contributions from ground and canopy are separated via their polarimetric signatures and the corresponding heights are measured by cross-track interferometry.

Figure 3 shows the predicted accuracy of 1-D line-of-sight displacements in the deformation mode. Here, a linear deformation model with parameters provided in the figure caption has been assumed. It becomes clear that, for a large number of images, contributions from SNR decorrelation can be neglected while temporal decorrelation and atmospheric phase errors become the main limiting factors. Errors from temporal decorrelation can be reduced by increasing the number of independent looks, while the highly correlated atmospheric errors ask for an increased number of acquisitions[1]. Anyway, a large number of high-resolution SAR images will be necessary to achieve the desired accuracy of 1mm/year after a 5 to 7-year mission time. 2-D deformation measurements require in addition observations from ascending and descending orbits. Tandem-L improves the deformation measurements via innovative SAR modes that enable frequent coverage with high geometric resolution (cf. Sect. 4).

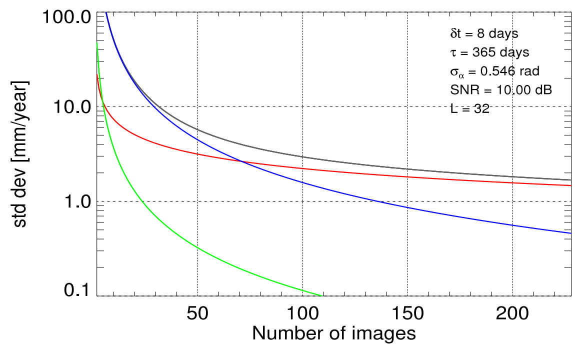

Figure 3: Performance prediction example for the deformation mode. The coloured curves show the individual error contributions from SNR decorrelation (green), atmosphere (blue), and temporal decorrelation (red). The overall error is shown in grey. The model in [7] has been used assuming a repeat orbit of δt=8 days, an exponential coherence decay with τ=365 days, an atmospheric phase error standard deviation of 0.546 rad (~ 10 mm @ L-band), an SNR of 10 dB, and L=32 independent looks.

[1] Contributions from the ionosphere can also be reduced by advanced calibration techniques while contributions from the troposphere could be reduced and/or filtered via external (e.g. meteorological) information.

Figure 4 shows an example of the predicted accuracy of forest height measurements using the Pol-InSAR structure mode [5][6]. The performance depends on both the forest height and the length of the cross-track baseline (expressed in terms of the vertical wavenumber k_z). Accuracies below 10% can be achieved by combining multiple acquisitions with different vertical wavenumbers.

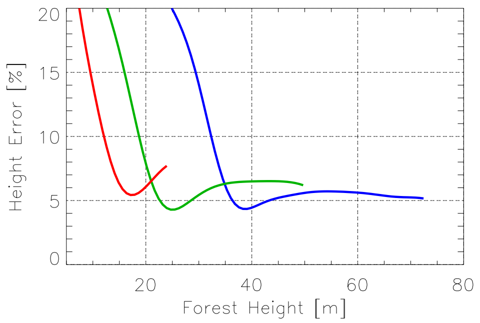

Figure 4: Performance prediction for the 3-D structure mode. The coloured curves show the expected accuracy of vegetation height measurements for different vertical wavenumbers (blue: k_z=0.05rad/m, green: k_z=0.1rad/m, red: k_z=0.2rad/m) and n=30 looks. A random volume over ground model has been assumed with an extinction of 0.3 dB/m. System errors (mainly limited SNR) have been modeled by a decorrelation factor of γ_{sys} = 0.9. The domain of the individual curves is limited to those forest heights that can be measured without ambiguities.

The Tandem-L acquisition plan foresees a systematic variation of the cross-track baselines to optimize forest height and vegetation profile measurements in the 3-D structure mode. At least three acquisitions with vertical wavenumbers kz ranging from 0.05 rad/m to 0.2 rad/m are planned for each season. Figure 5 shows the correspondence between kz and the lengths of the perpendicular baselines assuming an interferometric acquisition in bistatic mode. For an orbital altitude of 700 km and incident angles ranging from 30° to 45°, the required perpendicular baselines vary between 750 m and 5 km. At the equator, this corresponds to horizontal baselines between 850 m and 6.6 km in case of using a Helix formation [4] with no radial orbit separation at zero latitude.

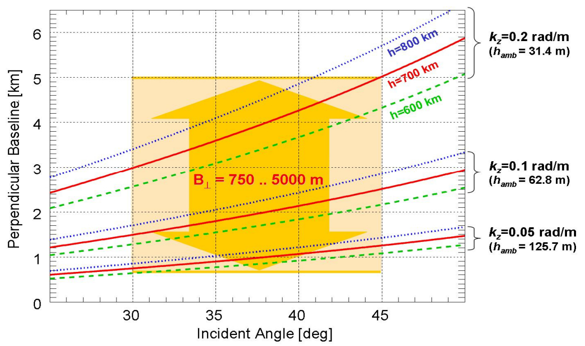

Figure 5: Correspondence between vertical wavenumbers and perpendicular baselines as a function of incident angle and orbit height.

An elegant technique to provide the wide range of cross-track baselines exploits the naturally occurring differential secular variations of the right ascension of the ascending nodes in response to slightly different inclinations. Figure 6 shows the evolution of the horizontal baselines at the equator for different inclination offsets (expressed as horizontal baselines at orbit turns).

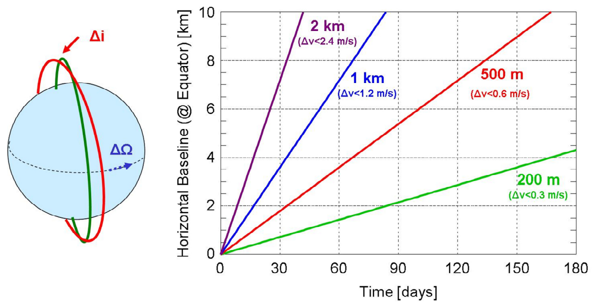

Figure 6: A systematic variation of the equatorial cross-track baselines can be achieved by using orbits with slightly different inclinations. The inclination offset causes a relative drift of the ascending nodes.

A further challenge for Tandem-L is the adjustment of large cross-track baselines at higher latitudes. One opportunity is the use of a large eccentricity offset to provide a sufficient radial orbit separation at high latitudes, but a significant amount of fuel will be required to compensate the resulting motion of libration for longer time periods. Another opportunity is the use of an even larger separation of the ascending nodes, which may then provide sufficient baselines for accurate forest height retrievals in the mid latitudes. Boreal forests at higher latitudes can moreover be imaged in the alternating bistatic mode [4] which doubles the phase to height scaling, thereby increasing the effective baseline by a factor of two. An optimized data acquisition concept is currently under development.

4 SAR Instrument Innovation

Tandem-L foresees an 8-day repeat orbit with an altitude of 760 km. Hence, a minimum swath width of 350 km is required to provide full spatial coverage at the equator. The imaging of such wide swaths with reasonable range and azimuth resolutions requires an extremely capable SAR instrument. To meet this challenge, Tandem-L will employ a highly innovative SAR instrument architecture which combines the advantages of digital beamforming with the large aperture provided by an unfurlable reflector [8][9]. The parabolic reflector is illuminated by a digital feed array where each feed element has its own T/R module and A/D converter as schematically illustrated in Figure 7.

In this innovative SAR instrument architecture, the simultaneous activation of all feed elements generates a broad transmit beam as desired for wide swath illumination. On the other hand, radar echoes arriving as plane waves from a given direction activate typically only a small number of feed elements if the feed array is located close to the focal plane. The systematic correspondence between beam direction and activated feed array elements is well suited to significantly enhance the imaging performance of Tandem-L without an undue increase of the implementation complexity and the costs of the radar instrument. For example, a significant improvement in NESZ and range ambiguity suppression is achieved via a time variant combination of a small number of individual feed signals. The combination corresponds to real-time digital beamforming where a narrow antenna beam with high gain is steered in synchrony with the systematic variation of the swath echoes' direction of arrival. The increased performance relaxes thermal, power and energy demands and allows for longer operation times as desired for a systematic Earth monitoring mission.

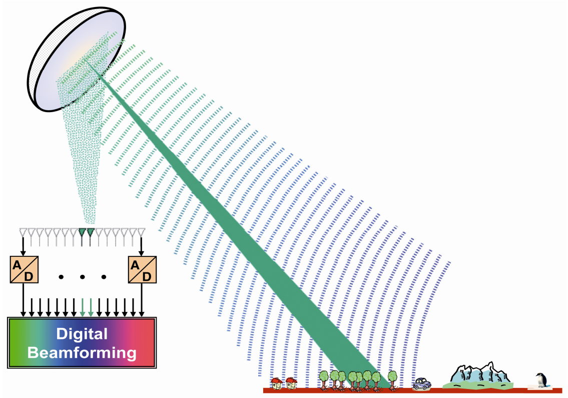

Figure 7: Digital beamforming with large reflector antennas.

The digital beamforming architecture of Tandem-L can moreover improve the spatial coverage without reducing the geometric resolution. One example is the simultaneous imaging of multiple swaths, each with full stripmap resolution, thereby overcoming the limitations of the ScanSAR mode [8]. For a reflector antenna, multiple Rx beams are easily formed by combining displaced subsets of activated feed element signals. The different swaths are separated by "blind ranges", as the radar cannot receive radar echoes while transmitting. The gaps can be made rather small due to the high receiver gain and by varying the PRF, it is even possible to fill in the gaps at the cost of a slightly increased ISLR [8]. Figure 8 shows a performance example for the imaging of a 350 km wide swath in full polarization using a stripmap mode with four beams.

Parameter	Value	Parameter	Value
Orbit Height	760 km	Reflector Size	15 m (∅)
Repeat Cycle	8 days	Focal Length	10 m
Incident Angle	26.3° - 46.6°	Feed Location	centre
Look Angle	23.3° - 40.5°	Feed Elements	24
Swath Width	349 km	Feed Length	3.43 m
Ground Range	331 – 680 km	Tilt Angle	31.9°
Tx Power (avg.)	96 W	System Loss	1 dB
Duty Cycle	4 %	Rx Noise Tmp.	420 K
Bandwidth	85 MHz	PRF	2365 Hz
Polarization	Quad (linear)	Az. Resolution	10 m

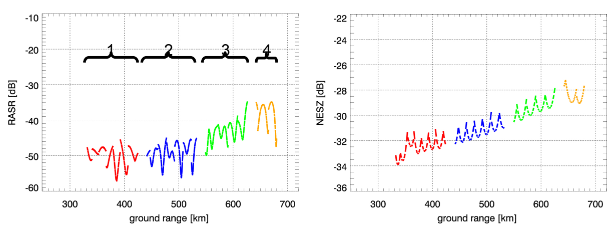

Figure 8: Performance prediction for a 350 km quad-pol stripmap acquisition with 4 beams. Shown are the system parameters (upper table), the range ambiguities (lower left), and the NESZ (lower right).

5 Conclusions

This paper introduced the Tandem-L mission concept and showed its great capabilities to monitor the Earth system and its intricate dynamics. Tandem-L builds up on the know-how and experience gained from TanDEM-X. Innovative SAR imaging techniques have been developed to support a systematic data acquisition with high spatial resolution and short repeat intervals.

The advanced mapping capabilities of Tandem-L provide a unique data base for new Earth observation applications. One example is the quasi-tomographic mapping of internal 3-D structure changes of semi-transparent volume scatterers via the repeated acquisition of single-pass SAR interferograms. This will provide important information about structural processes in vegetation, ice, permafrost soils, etc. and we expect a range of novel applications emerging from the advanced interferometric measurement capabilities. Tandem-L can be regarded as a first step towards a global monitoring system for the quasi-continuous observation of natural and anthropogenic processes that continuously restructure the Earth surface. Radar is the optimum sensor for continuous Earth system monitoring since it provides high resolution images independent of weather conditions at day and night. Together with its unique ability to measure subtle changes with millimetric accuracy and its even more unique ability to obtain quasi-tomographic images from space, radar will likely become the most important sensor for a huge amount of remote sensing applications, most of which we are currently even not thinking about. It is our responsibility to develop the best tools and techniques to be able to deal with the upcoming challenges in a rapidly changing world and environment. Tandem-L is an important step into this direction.

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