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 hydro-sphere. 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 DESDynl 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 inter-

![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").](image-url)

2 Science Requirements

The science requirements for Tandem-L have been elaborated during several international workshops that brought together representatives from multiple geo-science 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).
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.

#### Table I. TANDEM-L USER REQUIREMENTS (EXCERPT)

<table>
<thead>
<tr>
<th>Science Product</th>
<th>Coverage</th>
<th>Resolution</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest Height</td>
<td>all forest areas</td>
<td>50 m (global)</td>
<td>10 %</td>
</tr>
<tr>
<td>Above Ground Biomass</td>
<td>all forest areas</td>
<td>100 m (global)</td>
<td>20 %</td>
</tr>
<tr>
<td>Vertical Forest Structure</td>
<td>all forest areas</td>
<td>50 m (global)</td>
<td>3 layers</td>
</tr>
<tr>
<td>Underlying Topo.</td>
<td></td>
<td>50 m</td>
<td>&lt; 4 m</td>
</tr>
<tr>
<td>Plate Tectonics</td>
<td>all risk areas</td>
<td>100 m (global)</td>
<td>1 mm/year</td>
</tr>
<tr>
<td>Volcanoes</td>
<td>all land volcanoes</td>
<td>20 – 50 m</td>
<td>5 mm/week</td>
</tr>
<tr>
<td>Landslides</td>
<td>risk areas</td>
<td>5 – 20 m</td>
<td>5 mm/week</td>
</tr>
<tr>
<td>Subsidence</td>
<td>urban areas</td>
<td>5 – 20 m</td>
<td>1 mm/year</td>
</tr>
<tr>
<td>Glacier Flow</td>
<td>main glaciers</td>
<td>100 – 500 m</td>
<td>5 – 50 mm/year</td>
</tr>
<tr>
<td>Soil Moisture</td>
<td>selected areas</td>
<td>50 m</td>
<td>5 – 10 %</td>
</tr>
<tr>
<td>Water Level Change</td>
<td>regional</td>
<td>50 m</td>
<td>10 cm</td>
</tr>
<tr>
<td>Snow Water Eqiv.</td>
<td>local (exp.)</td>
<td>100 – 500 m</td>
<td>10 – 20 %</td>
</tr>
<tr>
<td>Ice Structure Chng.</td>
<td>local (exp.)</td>
<td>100 m</td>
<td>&gt; 1 layer</td>
</tr>
<tr>
<td>Ocean Currents</td>
<td>near areas</td>
<td>~ 100 m</td>
<td>&lt; 1 m/s</td>
</tr>
<tr>
<td>Digital Terrain &amp; Surface Model</td>
<td>global</td>
<td>~ 20 m (bare) – 50 m (forest)</td>
<td>2 m (bare) – 4 m (vegetation)</td>
</tr>
</tbody>
</table>

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 to improve the deformation measurements via innovative SAR modes that enable frequent coverage with high geometric resolution (cf. Sect. 4).

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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.

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 $k_z$ ranging from 0.05 rad/m to 0.2 rad/m are planned for each season. Figure 5 shows the correspondence between $k_z$ 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 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.

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.

References


