

# The Tandem-L Mission for Monitoring of Earth's Dynamics: Main Performance Results during Phase-B1

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## Abstract

Tandem-L is a German proposal for an innovative interferometric radar mission to systematically monitor the Earth and its intricate dynamics with unprecedented quality and resolution. Several are the mission objectives, among which the 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 are all of great importance. In this paper we show the expected performance that the Tandem-L mission will achieve for three of its main applications: (i) measurement of global deformation rate, (ii) forest height and vertical structure and (iii) topographic map. The unique products and performance achievable by Tandem-L open a new era for different strategic applications and services in the geosphere, cryosphere, biosphere and lithosphere of the Earth system.

## 1 Introduction

The Synthetic Aperture Radar (SAR) mission proposal Tandem-L is designated to represent a breakthrough remote sensing system to advance the understanding dynamic processes on the Earth's surface. The Tandem-L mission concept is based on two twin SAR satellites operating at L-band, with large deployable reflectors for increasing the swath width and imaging resolution, together with the use of digital beamforming techniques. The innovative radar mission concept will base on a flexible as well as highly optimized formation flight between the two cooperative radar satellites, with adjustable baselines, allowing for variable formation flight configurations, serving for highly innovative applications, such as polarimetric SAR interferometry, multi-pass coherence tomography, and single-pass interferometry.

Such an advanced interferometric and polarimetric radar mission concept together with the novel imaging techniques and the high data acquisition capacity of Tandem-L will offer a unique mean to observe, analyze and quantify the dynamics of a wide range of mutually interacting processes in the bio-, geo-, hydro- and cryosphere. More in detail, Tandem-L aims to achieve the following mission objectives: (i) to perform global measurement and monitoring of 3-D forest structure and biomass, (ii) to systematically record small and large scale deformations of the Earth's surface with millimeter accuracy, (iii) to quantify glacier movements, 3-D ice structure, and melting processes in the polar regions, (iv) to finely measure soil moisture and its variations close to the surface, (v) to systematically observe coastal zones and sea ice, (vi) to monitor agricultural fields, (vii) to generate highly accurate global digital terrain and surface models [1, 2].

During the phases A and B1 of the Tandem-L mission study, the performance has been estimated for some of the most important high-level products that the mission will provide. Accordingly the mission concept has been optimized, especially in terms of observation strategy (revisit time, frequency of acquisition, looking direction). This has been iteratively carried out in order to fully meet the mission requirements. After a short overview of the Tandem-L mission concept, the present paper shows the results of the analysis conducted during the phase B1 in terms of expected performance for three main applications of interest: (i) 3-D large scale deformation retrieval by means of repeat-pass differential interferometry (InSAR) (ii) 3-D forest structure and forest height determination by exploiting multibaseline polarimetric tomography (iii) Digital Elevation Model through single-pass across-track InSAR.

## 2 Tandem-L Mission Concept

The Tandem-L mission concept relies on a systematic data acquisition strategy using a pair of cooperating identical L-band SAR satellites. The satellite system operates in two basic modes [1]. The 3-D structure mode employs fully-polarimetric single-pass SAR interferometry to acquire structural parameters and quasi-tomographic images of semitransparent volume scatterers like vegetation, sand, and ice. On the other hand 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.

### 3 Methodology and Initial Settings

As already mentioned the mission performance analysis is conducted in order to not only assess the the expected Tandem-L performance, but also to optimize the mission design, especially in terms of geometry and baselines, number of acquisitions, operational modes reaching, however, trade-offs for a moderate data volume. In order to compute global performance considering the Tandem-L mission capabilities and requirements, a mission simulator tool has been developed. It uses different inputs, among the others, the SAR performance for the operational modes and the acquisition timeline (as the one shown in **Figure 1**). Accordingly the mission simulator provides, for each point on the ground, a set of parameters which drive the final performance. They consist in number of available acquisitions in a certain time span, satellites formation and image performance figures associated to each data take: incidence angle, acquisition mode, polarizations, range and azimuth resolutions, noise equivalent sigma zero (NESZ), ambiguities, etc.

### 4 Large Scale Deformations

The Tandem-L mission proposal has a high potential for deformation-monitoring applications, that is the most demanding application of the geosphere with respect to accuracy. With a short revisit time at L-band, high coherence is expected over a variety of artificial and natural structures. Its wide swath will enable geological applications that are concerned with small motions over large distances. The main limiting factors to the estimation accuracy are orbital errors and refractive effects caused by atmospheric turbulences and by the ionosphere. Therefore short satellite revisit times are required in order to quickly build up long series of images and reduce the impact of the atmospheric related noise by temporal averaging.

#### 4.1 Performance Model

Assuming that we are interested in some slow and continuous motion that can be modeled by a constant velocity, the performance model for deformations bases on the Hybrid Cramer-Rao [4] bound. It provides the performance limit achievable by maximum-likelihood estimation for a linear velocity and is applied to give the performance for each line-of-sight (LoS), as a function of the sampling times, the number of looks, the coherence matrix and the atmospheric noise power. After the accuracy is computed for each geometry, the different LoS are combined to derive the performance of the 3-D motion reconstruction, following the analysis in [5, 6]. The interferometric performance strongly depends on the coherence matrix ( $\Gamma$ ) of the data and the phase disturbance characterization. Concerning the coherence, the combined contribution of thermal noise and ambiguities can

be considered:

$$\gamma_{system} = \frac{1}{1 + SNR^{-1} + RASR + AASR} \quad (1)$$

where  $SNR$ ,  $RASR$  and  $AASR$  are respectively the signal-to-noise ratio and the range and azimuth ambiguity-to-signal ratios of the two identical Tandem-L satellites. Additionally, the temporal decorrelation has to be considered. It is of particular importance since it affects time series of interferometric SAR images as a function of the time separation of the image pairs. An exponential model can assumed for it:

$$\gamma_{temp}(\Delta_n) = (\gamma_0 - \gamma_{inf} \cdot e^{-|\Delta_n|/\tau} + \gamma_{inf}) \quad (2)$$

in which  $\gamma_0$  is the coherence at short time lags (a few days),  $\gamma_{inf}$  is the level for long time lags (i.e., 10 years of Tandem-L mission),  $\tau$  describes the transition velocity and  $\Delta_n$  is the temporal separation in repeat-pass intervals. For an L-band system, it can be supposed  $\tau = 60$ ,  $\gamma_0 = 0.95$  and  $\gamma_{inf} = 0.1$ , basing on real ALOS PALSAR data. After different studies conducted to assess the role of the atmosphere, in the statistical analysis carried out to assess the mission performance, a phase delay corresponding to a standard deviation of 1 cm or 4 cm (worst case scenario) has been considered for the tropospheric propagation disturbances. For the uncorrected ionospheric disturbance also a standard deviation of 1 cm has been assessed as a reasonable value to be taken into account.

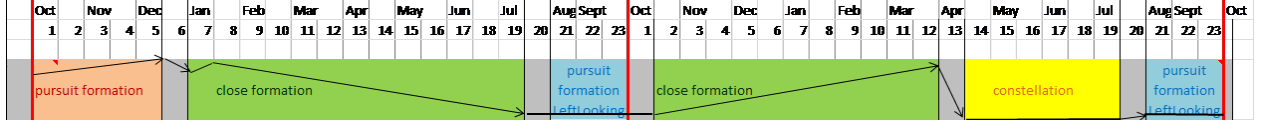
#### 4.2 Achievable Mission Performance

In order to estimate the full 3-D displacement vector, i.e., to decompose a detected deformation in the East-West, Up-Down and North-South components, it is necessary to observe the area of interest under at least three different geometries. Thus, it has been investigated the possibility of adding to the ascending and descending passes, also squinted or left-looking acquisitions to ensure the multiple observation geometries. At the end of the phase-A study, the left-looking has been chosen as the acquisition mode to enable the retrieval of the full 3-D deformation vector.

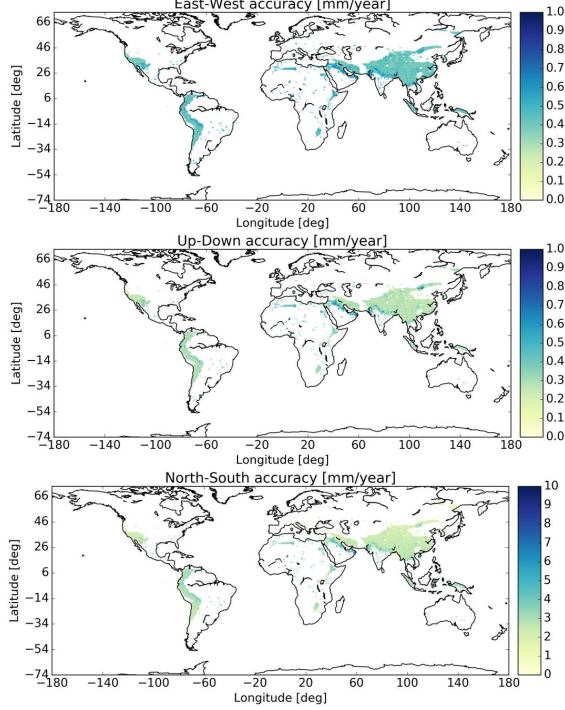
In **Figure 2** the mission performances are shown. They represent the capability of measuring 3-D deformations with a degree of accuracy, expressed in millimeters/year, better than 1 mm/year in the East-West and Up-Down direction, and better than 10 mm/year for the North-South component. This is in line with the mission requirements and assesses the strong potential of the Tandem-L mission for such a fundamental application for the geosphere.

### 5 Forest Height and Structure

Tandem-L has the potential to initialize a new era for forest applications providing products that allow a systematic monitoring with a high spatial resolution of natural and anthropogenic forest change processes. In particular, Tandem-L will be able to provide:



**Figure 1:** Diagram of the different mission phases. A base scenario of 2 years will repeat in the following years.



**Figure 2:** Global mission performance for large scale deformation. The performance represents the achievable accuracy in retrieving 3-D deformation rate (in mm/year). The error contributions are: orbit inaccuracy phase error of 10 cm, residual tropospheric delay is 1 cm and residual ionospheric delay of 1 cm

- annual global forest height mapping with accuracy better than 10% on  $50 \times 50 \text{ m}^2$  grid. Forest height is one of the most important parameters for forest stand characterization and allows observing the successional state of the forest, particularly important for forest dynamics description.
- global forest 3-D mapping with a voxel size of  $10 \times 50 \times 50 \text{ m}^3$  twice a year in order to monitor annual and seasonal forest structure changes. The knowledge of the vertical forest structure allows to assess the spatial heterogeneity of the forests and to map biodiversity.

This will enable to map for the first time the (vertical) complexity and diversity of Earth's forest ecosystems and to assess the extent and intensity of forest structural disturbances [7]. Forest height and vertical structure can be used to constrain model estimates of above-ground biomass and associated carbon flux components between the vegetation and the atmosphere. The knowledge of forest height and vertical structure changes can

be directly used to characterize forest growth, mortality and deforestation and to conclude about the associated carbon fluxes, as well as type and the intensity of forest disturbance and seasonal and annual forest cycle variation.

## 5.1 Acquisition Requirements

In the frame of the Tandem-L Phase-B1, the forest data takes have been planned considering all three forest types, i.e. boreal, temperate and tropical forests. Due to their different nature and distribution, each forest type has different acquisition requirements, which have been summarized in **Table 1**. The number of baselines is a trade-off with respect to the data volume (8 terabytes/ day). Directly related to the across-track baseline, the  $k_z$  is the vertical wavenumber and provides an indication of the height sensitivity of the system. The forest acquisitions have to be accomplished with  $k_z = 0.05, 0.1, 0.15 \text{ rad/m}$  in order to ensure a 10% accuracy in the estimation of forest height.

Forest type	Latitudes	Baselines	Max $k_z$
Boreal	$\mp[60^\circ, 75^\circ]$	4	$> 0.4$
Temperate	$\mp[25^\circ, 60^\circ]$	5	$> 0.5$
Tropical	$[-25^\circ, +25^\circ]$	6	$> 0.6$

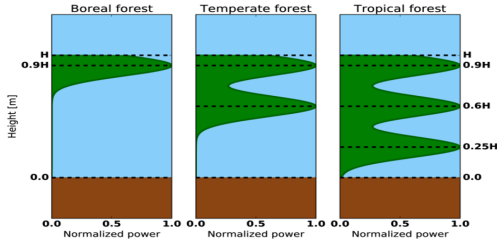
**Table 1:** Acquisition requirements for the three different forest types, considering one year of acquisitions. The  $k_z$  values are expressed in [rad/m]

## 5.2 Performance Model and Achievable Mission Performance

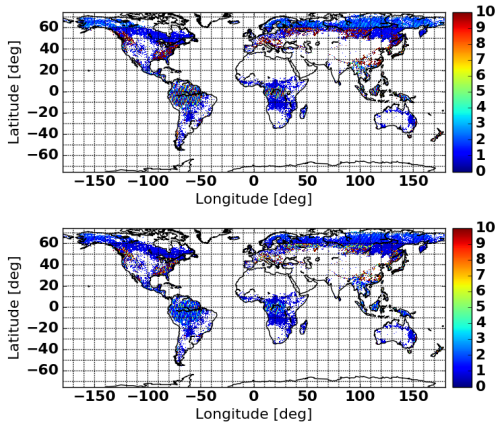
In order to compute performance figures related to 3-D forest structure is necessary to define volume power profiles. The vertical structure has been modeled with  $M = 1, 2, 3$  volume layers within a height interval  $H$  representative of a boreal, temperate and tropical forest, respectively. The layer locations have been arranged relative to  $H$ , their normalized power depend on the assumed mean forest extinction coefficient  $\sigma$ , and the layer widths have been set equal to 2.5 m. The case of  $\sigma = 0 \text{ dB/m}$  (i.e. all layers to be distinguished are equally strong) is assumed as a reference scenario. The employed volume power profiles are shown in **Figure 3**. Furthermore, according to real L-band SAR data, the following ground-to-volume ratios have been used respectively for boreal, temperate and tropical forest:  $\mu = [-11, -5.1, 1.0] \text{ dB}$ ,  $\mu = [-9, -4.25, 3.0] \text{ dB}$  and  $\mu = [-9, -4.25, -1.0] \text{ dB}$ . A global forest height map has been used (based on FAO

and lidar data) to receive as the forest height is an input parameter of the model.

In order to assess the mission performance the Cramer-Rao lower bound (CRB) has been exploited, that for the forest structure performance study, needs to assume a specific data model for the characterizations of the structure information of the multibaseline, polarimetric data stacks as detailed in [8, 9]. **Figure 4** shows the global average CRB values on the layer locations (in meters) both for the first and the second semester of a year. The presented performance assumes complete temporal decorrelation from pass to pass, which represents the worst case scenario. The case of residual coherence present until the last acquisition has also been analyzed and the results are summarized in **Table 2**. It is possible to observe that the worst performance (i.e. higher standard deviation values) on the forest layers location is provided in the first semester. This mainly happens because the maximum values of the vertical wavenumber  $k_z$  are different for both semesters, in particular due to orbit inclination.



**Figure 3:** Normalized power distributions of the three different forest types, considering a generic forest height  $H$ , a forest extinction of  $\sigma = 0$  dB/m and total decorrelation from pass to pass.



**Figure 4:** Averaged layer height standard deviation [m] for the reference scenario ( $N = 50$  looks,  $\sigma = 0$  dB/m) during the first semester (top) and during the second semester (bottom).

To better understand the results, we used an adaptive threshold which depends on the number of layers and the forest height to discriminate on which areas an acceptable performance can be met. The threshold has been set equal to the 20% of the (average) distance between two layers, in meters, which is a reasonable value for distin-

guishing the layers with a high probability. The obtained performance are summarized in **Table 2**.

In general, the worst performance (i.e. higher standard deviation values) occurs mainly on temperate forest. In a minority of cases, these poorer results over temperate forest are caused either because  $k_{z,max} < 0.5$  rad/m or the  $k_z$  values are not uniformly distributed over the  $k_z$  interval. However, a thorough investigation of the pixels with  $CRB > t$  have revealed that these correspond to temperate forest areas with  $H \approx 25.0$  m, where  $M = 2$  layers are required to be properly separated. According to our classification criterion, it arises that in such cases a threshold  $t = 1.66$  m, which is a rather restrictive value considering also the limited number of available acquisitions and the maximum  $k_z$  value. In fact, the improvement provided by relaxing the threshold to the 50% of the average distance between two layers, the performance significantly improves and meet the requirements.

Forest type	First Semester		Second Semester	
	$\gamma_T = 0$	$\gamma_T > 0$	$\gamma_T = 0$	$\gamma_T > 0$
Boreal	56.5%	100%	83.9%	100%
Temperate	67.2%	70.1%	69.1%	72.9%
Tropical	62.9%	85.9%	77.0%	96.3%

**Table 2:** Quantitative evaluation of the performance maps over a time span of six months for the reference scenario

A performance gain by a factor of  $\sqrt{2}$  can be achieved if we double the number of looks that means to consider a product resolution of 50 m x 50 m. Instead, the increase of the extinction  $\sigma$  will slightly worsen the final estimation performance. However, such worsening effect might be only noticeable if the assumed number of forest layers increases (i.e. tropical forest) and if total temporal decorrelation is expected.

## 6 Global Digital Elevation Model

Digital elevation models (DEMs) are of fundamental importance for a broad range of commercial and scientific applications. Many geoscience areas, like hydrology, glaciology, forestry, geology, oceanography, and land environment, require precise and up-to-date information about the Earth's surface and its topography. Digital maps are also a prerequisite for reliable navigation. Even more important, all the applications take advantage of a DEM acquired with the same wavelength. Tandem-L will provide a worldwide consistent, timely, and high precision DEM twice a year in order to establish a consistent global archive of bistatic interferometric data. The interferometric data acquired during the different mission phases will provide global digital elevation and terrain models (DEM and DTM) with a quality comparable to the final product being available by the TanDEM-X mission [3]. However, it is important to underline that compared to the TanDEM-X mission, that provides only a digital surface model with no updates of it, Tandem-L

will release also seasonal and yearly updates of the terrain and surface models with high accuracy and resolution.

## 6.1 Performance Model and Achievable Mission Performance

The global DEM generation requires bistatic global acquisitions that cover the entire land surface in descending, while only the areas that can be affected by shadows or layovers will be acquired in ascending, according to the acquisition plan. Nonetheless, if additional acquisitions that satisfies the acquisition mode, even if designed for different applications, are available, they could be exploited for the final DEM product, improving its accuracy. It is still under investigation the possibility of performing acquisitions in single or quad-pol mode for the generation of global DEM. With acquisitions in single-pol the swath-width is 350 km while with quad-pol the available swath-width reduces to 175 km and fewer acquisitions are consequently available. Furthermore, in single-pol the available range bandwidth is larger than that employed in the quad-pol case and this implies a lower number of looks for quad-pol acquisitions. However, in this case the final performance benefits from 4 more looks thanks to the four polarimetric channels.

The look number together with the total coherence are the key parameters driving the interferometric performance for DEMs. Knowing the probability density function of the phase difference between the two interferometric SAR channels  $p_\varphi(\varphi)$  [3], the standard deviation of the interferometric phase  $\sigma_\varphi$  can be derived as:

$$\sigma_\varphi = \sqrt{\int_{-\pi}^{\pi} \varphi^2 \cdot p_\varphi(\varphi) d\varphi} \quad (3)$$

and correspondingly the standard deviation of the height error:

$$\sigma_h = \frac{h_{amb}}{2\pi} \sigma_\varphi \quad (4)$$

$h_{amb} = 2\pi/k_z$  is the height of ambiguity, defined as the height difference equivalent to a complete  $2\pi$  phase cycle in the interferogram scaled with the perpendicular baseline between both satellites and is a measure of the system height sensitivity.

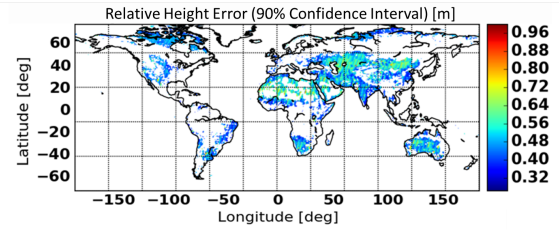
As an alternative, the height accuracy and determine the DEM performance, the 90% single point interferometric error can be computed. In case of homogeneous errors with independent Gaussian distributions, the 90% single point can be approximated with  $\Delta\varphi = 1.65 \cdot \sigma_\varphi$  where the factor 1.65 (sigma) is due to the assumption of a Gaussian error distribution, and consequently,

$$\Delta h = \frac{h_{amb}}{2\pi} \cdot \Delta\varphi \quad (5)$$

An improvement of DEM accuracy can be achieved by combining overlapping data segments from successive Tandem-L satellite passes. The redundant interferometric signals can be used to partially compensate the performance decay at the swath border and to improve, thereby, the overall interferometric height accuracy [3].

For the current analysis only interferometric performances for the DEM height accuracy over bare surfaces are provided. In fact, the ground topography underneath the forest covered area, is a specific product provided by a different type of processing exploiting polarimetric and tomographic data. Over snow-, ice- covered areas and sandy deserts areas, given the variation of the penetration depth, is not possible to predict mission performance and no operational DEM over such areas will be provided.

In **Figure 5** the global performance are provided for the case of single-pol acquisitions: the relative height accuracy is below 1 m for 12 m posting, which means an improvement of approximately a factor 2 compared to DEM generated during the TanDEM-X mission.



**Figure 5:** Global relative height accuracy for DEM products expressed as single-point 90% confidence interval.

## 7 Conclusions

In this paper, the Tandem-L performance estimated during the phase B1 have been shown for the main applications of interest of the mission. The study has been conducted exploiting the mission simulator tool, where the performance models are integrated and additional mission information need to be passed as inputs.

For long time deformation monitoring with Tandem-L it has been shown the high degree of accuracy with which the full 3-D deformation vector can be retrieved, given the possibility of exploiting ascending and descending passes both in right and left looking geometry. For 3-D imaging of forest volume by the use of TomoSAR acquisitions the results are also rather promising as well as for DEM products, for which the relative height accuracy shows an improvement of a factor 2 compared to current reference DEM product from TanDEM-X. The possibility of optimizing the formation and improve the performance is still a dynamic process of the Tandem-L mission design and will be address in the next phases of the mission study.

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