

TANDEM-L: MONITORING THE EARTH'S DYNAMICS WITH INSAR AND POL-INSAR

Alberto Moreira⁽¹⁾, Irena Hajnsek⁽¹⁾, Gerhard Krieger⁽¹⁾, Kostas Papathanassiou⁽¹⁾, Michael Eineder⁽²⁾,
Francesco De Zan⁽¹⁾, Marwan Younis⁽¹⁾ and Marian Werner⁽¹⁾

(1) *Microwaves and Radar Institute, German Aerospace Center, PO BOX 1116, 82234 Wessling, Germany, e-mail: alberto.moreira@dlr.de, gerhard.krieger@dlr.de, irena.hajnsek@dlr.de; kostas.papathanassiou@dlr.de; francesco.dezan@dlr.de; marwan.younis@dlr.de; marian.werner@dlr.de*

(2) *Remote Sensing Technology Institute, German Aerospace Center, PO BOX 1116, 82234 Wessling, Germany, e-mail: michael.eineder@dlr.de*

ABSTRACT

Tandem-L is a German mission proposal for an innovative interferometric L-band radar mission that enables the systematic monitoring of dynamic Earth processes using advanced techniques and technologies. The mission is science driven aiming to provide a unique data set for climate and environmental research, geodynamics, hydrology and oceanography. Important application examples are global forest height and biomass inventories, measurements of Earth deformation due to tectonic processes and/or anthropogenic factors, observations of ice/glacier velocity field and 3-D structure changes, and the monitoring of ocean surface currents. The Tandem-L mission concept consists of two cooperating satellites flying in close formation. The Pol-InSAR and repeat-pass acquisition modes provide a unique data source to observe, analyse and quantify a wide range of mutually interacting processes in the bio-, litho-, hydro- and cryosphere. The systematic observation of these processes benefits from the high data acquisition capacity and the novel high-resolution wide-swath SAR imaging modes that combine digital beamforming with a large reflector antenna. This paper provides an overview of the Tandem-L mission concept and its main application areas.

1. INTRODUCTION

Tandem-L is a German proposal for an interferometric and polarimetric SAR mission at L-band for mapping dynamic Earth processes. The motivation for this mission proposal comes from the increasing science requirements for a continuous and global monitoring of climate and environmental variables with high resolution and on a reliable way. Examples of the essential variables to be measured by Tandem-L in a systematic way are:

- Above ground forest biomass and its 3-D vertical structure distribution. Observation of changes in forest height and biomass (e.g. due to deforestation or afforestation), changes in biodiversity, etc.

- Earth surface deformation (e.g. due to seismic movements, volcano eruptions, land slides, subsidence, uplift, etc.).
- Retreat and accumulation in ice and snow covered regions, velocity field estimation of land ice movement within a high velocity range variation.
- Changes in surface soil moisture and land use (high resolution maps).
- Measurements of ocean surface currents.

In order to achieve the ultimate goal to estimate these essential variables in a systematic and reliable way, the following requirements are posed on the SAR mission concept:

- Single-pass interferometry for estimation of forest height, biomass and 3-D structure by means of multi-baseline Pol-InSAR.
- Repeat-pass acquisition mode for estimation of surface deformation with differential interferometry.
- L-Band as the most appropriate frequency for Pol-InSAR and D-InSAR acquisition modes due to the following reasons:
 - high bandwidth of the available frequency allocation (85 MHz).
 - penetration capability in vegetated areas allowing the forest biomass estimation up to 500 tons/ha.
 - high coherence values in repeat-pass mode.
 - low RF interference and ionospheric perturbations when compared to lower frequency bands.
- Short revisit cycle for small temporal decorrelation.
- High data rate acquisition and downlink capability to allow a systematic acquisition of dynamic processes (acquired data volume larger than 1 TB/day).

In section 3 the measurement and mission concept will be presented based on these requirements. Due to the need of having Pol-InSAR and D-InSAR modes in the mission concept, one satellite should have a nearly circular and polar orbit within a narrow tube of a few hundred meters for D-InSAR operation, while the second satellite should have an

orbit which provides the required baselines for Pol-InSAR. The same helix orbit concept as in the TanDEM-X mission is adopted for the second satellite where a small eccentricity offset and a shift of the ascending node allows for a flexible adjustment of the desired baselines [1].

2. SCIENCE EXPLORATION

The estimation of dynamic processes on Earth surfaces requires systematic, long term and continuous observation strategies in order to detect short and long term changes with a sufficient accuracy. Depending on the environmental and/or anthropogenic process to be observed there is a need for having different time intervals in the acquisition plan.

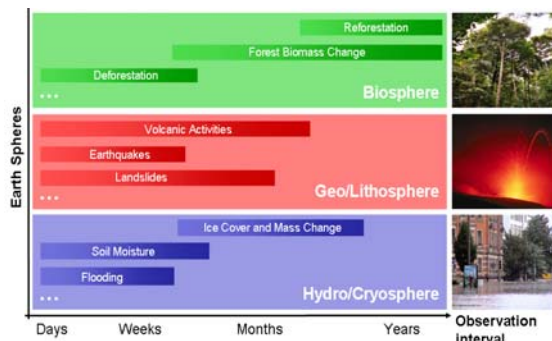


Figure 1: Dynamics of different Earth spheres and the requested interval for sampling the corresponding process in an unambiguous way.

Existing SAR sensors could already demonstrate that radar plays an important role in the parameter estimation related to essential environmental, climate and anthropogenic processes. Today, SAR sensors are mostly covering only small and selected areas and do not acquire data in a long term and systematic way in order to make reliable statements about Earth's processes changes. In some cases large areas are being acquired, but the required sampling interval as shown in fig. 1 is not fulfilled.

One important feature of Tandem-L is therefore to achieve observation intervals of weeks to several months on a global scale with an appropriate sampling to characterise dynamic processes. A second important feature is a systematic acquisition strategy with a global coverage that allows generating consistent time series over at least 5-7 years of mission lifetime. The combination of short observation intervals and systematic data acquisition will enable to observe short term highly dynamic processes like seismic movements as well as long term processes with yearly cycle change like forest biomass growth changes.

The main scientific focus of Tandem-L is placed on two application areas, the biosphere and geosphere. However, with the requirements for a systematic and global mapping with short repeat times Tandem-L will be also very useful for other application areas in hydro- and cryosphere. The Tandem-L mission will provide a new insight and will increase the information content in bio- and geo-sciences and represents therefore a unique concept that will provide a step forward towards a holistic view of global land processes.

a. 3-D Forest Structure

26% of the land surfaces are covered with forest corresponding to an area of 40 Mio km². Forests play an important role in storing natural resources (ecological and economical aspect) and in the storage of carbon content (climate aspect). The relation between carbon content and biomass is given by the dry matter of the wood; 50 % of the plant dry matter consists of carbon. The role of biomass in the global carbon cycle is determined by two components, the static and the dynamic one. The static is describing the amount of biomass currently existing worldwide. The dynamic one is defined through the biomass change occurring due to forest structure change or forest areas extent change. The dynamic component is the most unknown one, although the estimation uncertainty of the static component has the highest influence in the whole carbon cycle budget error. The dynamic processes of the biomass can be seen as carbon sources and sinks and are also essentially influencing the carbon cycle.

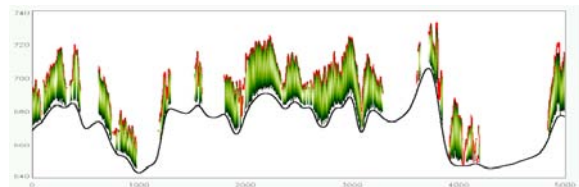


Figure 2: 3-D forest structure profile derived from the Pol-InSAR technique at L-band with DLR's E-SAR airborne system.

Tandem-L will be the first mission that will measure biomass with an accuracy of 20% on a global scale and in addition estimate its yearly change throughout the mission lifetime. With this information the uncertainty in the terrestrial stored above ground biomass will be drastically reduced. Biomass will be derived from the direct estimate of the forest height and 3-D forest structure that will be measured by Tandem-L.

b. Surface Deformation

The topography of the solid Earth is continuously changing due to several processes like continental drift, magma movement on smaller spatial scales, water level changes and also other processes with anthropogenic influence. The results of these

movements may be disastrous events as earthquake, volcano eruption, land slides or surface up and down lifting.

Even if today no predictions for earthquakes or volcanic eruption are possible on a reliable way the understanding of the involved processes has increased in the last years, mainly due to new technologies as for example seismic measurement arrays, GPS, differential SAR interferometry and very long baseline approaches but also due to more accurate numerical models with data assimilation. With these techniques a coarse-mesh network for deformation measurements can be established with accuracies of the surface deformation in the order of millimetres.

Tandem-L aims to substitute the irregular coarse-mesh grid with a homogenous high resolution deformation map with wide coverage. These accurate deformation maps are on the one side needed for inter and co-seismic change detection especially at fault zones and on the other side they will map world wide and consistently seismic and volcanic areas with an accuracy and coverage that cannot be achieved with GPS. In addition, small scale deformation areas like land slides will be detectable due to the high resolution. Not only anthropogenic factors like water level lowering can lead to land slides and deformation. These can also be initiated through climate change where the permafrost soil is thawing.

Tandem-L will be very well suited for deformation measurements. The main advantages will be the short repeat cycle that allows reducing atmospheric propagation delay errors by data stacking and the long wavelength in L-band with 23 cm that provides long time phase coherence and can penetrate through vegetation cover in order to be sensitive to the deformation beneath. By means of the combination of different incident angles of the SAR observations the three-dimensional displacement field can be derived.

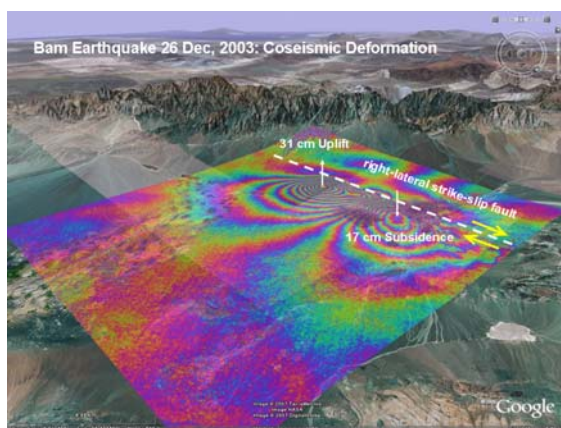


Figure 3: Bam Earthquake deformation map (Dec. 2003) derived with C-band ENVISAT/ASAR data

c. Cryo-, Hydrosphere and Oceanography

Processes occurring in the cryo- and hydrosphere are indicators for climate change and have an inevitable impact on the stability of the Earth system. The already observed dramatic changes such as the worldwide melting of the inland glaciers and of the Greenland ice sheets, the thawing of the permafrost, the diminishing of the Arctic sea ice and so forth are calling considerable attention from the climate science community, national and international policy makers as well as the media and the general public.

The cryosphere is the largest potential source for sea-level fluctuations and contains 90% of the Earth's freshwater. The prediction of future sea-level rise is therefore difficult. Estimates of the rise during the 21st century vary from 20 to 60 cm (IPCC 2007). This spans a range of modest coastlines migration to changes with profound political and economical consequences. The largest uncertainties are associated with the ice sheets, but all sources of sea level rise require an improved measurement.

The observation of changes over huge areas of the polar regions can efficiently be carried out using a longer wavelength SAR instrument, which provides sustained, consistent observations over a longer time and with a certain penetration depth. In order to monitor parameters that are important for detecting environmental changes affecting the Earth's climate, whereby sea-level fluctuations are only one component, a consistent observation with sufficient temporal and spatial resolution as well as wide coverage is needed. Again, this is the same requirement described in section 1 of this paper that is needed for mapping dynamic processes in the different Earth spheres.

The main objective for the cryosphere can be summarized as the measurement of sea-ice and land-ice extent and mass changes, the determination of the grounding line position, as well as glacier ice velocity field estimation.

Hydrology, which is also affected by changes of snow cover and ice extent, contributes also to the understanding of Earth surface processes. Several other current and future missions are dedicated to hydrology and oceanography. Tandem-L with its systematic mapping concept will provide important information about surface soil moisture over the main Earth's agricultural regions. Other contributions are ocean current measurements (close to the shoreline and partly in the deep ocean).

3. Measurement Concept

For the data acquisition an innovative concept has been worked out. The satellite system as it is planned up to now will operate in two basic data acquisition modes:

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

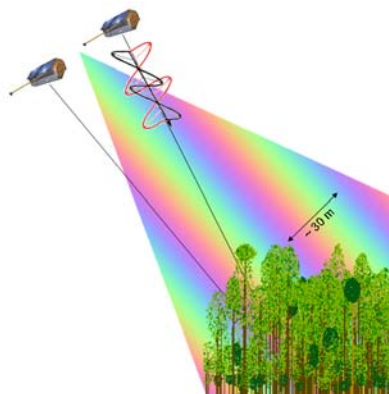


Figure 4: 3-D structure mode using single-pass SAR interferometry

2) The *deformation mode* employs repeat-pass interferometry (InSAR) in an ultra-wide swath mode in order to measure small shifts on the Earth surface with millimeter accuracy in short repetition intervals.

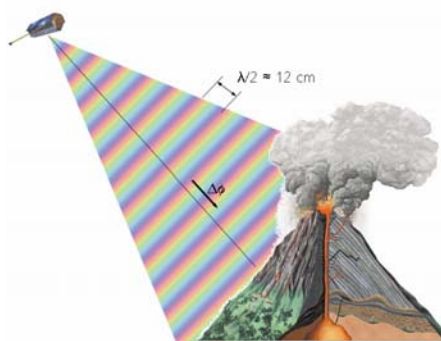


Figure 5: Deformation mode using repeat-pass SAR interferometry

Both acquisition modes enable a systematic and global mapping of the Earth with a high spatial resolution due to the use of digital beamforming techniques. The deformation mode requests a short orbital repeat cycle, whereas the 3-D structure mode needs only a repeat pass time of one month due to slower changes in the vegetation cover.

In case of critical events and hazards (earthquakes, flooding, volcano eruption, dike breaks etc.) it will be possible to adapt the satellite acquisition plan to

a certain area of interest that can then typically be mapped within one or two days.

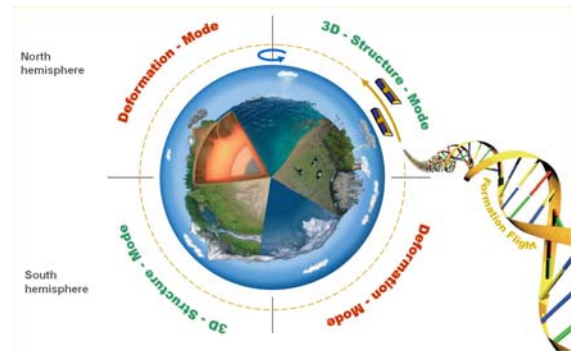


Figure 6: Tandem-L mission concept with two acquisition modes.

The deformation mode can be operated in any position of the orbit cycle, while the 3-D structure mode requires adequate interferometric baselines that are only present within two quadrants of each orbit cycle (assuming a fixed right looking direction). Hybrid operation modes in connection with digital beamforming will allow resolving the conflicts in the acquisition mode due to different user requirements [5].

4. Implementation Plan

One most challenging task in the Tandem-L realisation is the development of two identical satellites with a cost effective implementation approach and at the same time having a high performance in order to fulfil the demanding scientific needs. However, besides an innovative mission concept also new imaging techniques and technologies are needed for fulfilling the science requirements.



Figure 7: Artistic view of a Tandem-L formation with two satellites (preliminary design achieved during a joint DLR and NASA/JPL pre-phase A study).

One key technology of Tandem-L is the use of a large reflector antenna and the use of digital beamforming in the feed array that illuminates the reflector. While all feed elements are used during transmission, allowing the illumination of a large image swath, 2-3 feed elements are activated during

the receive window. The feed element positions are periodically shifted in synchrony with the systematic variation of the direction of arrival from the swath echoes. The advantages of this concept are manifold. First, the use of a large reflector antenna in connection with digital beamforming allows the reduction of the transmit power by a factor of 3-4 in comparison to the traditional SAR concept for the same imaging parameters. Second, it allows the mapping of a much wider swath (ca. 350 km) in high resolution stripmap mode [4], [5]. The fully polarimetric acquisition in stripmap mode with a wide swath is possible without the constraints of conventional SAR systems. This leads, however, to a large data rate and requires the implementation of advanced technologies for high data rate downlink. The downlink requirements can however be alleviated by employing new hybrid SAR modes suggested in [5]. These modes enable variable resolutions within a single scene and allow by this for an optimum adaptation to the non-homogeneous resolution requirements from the different science disciplines.

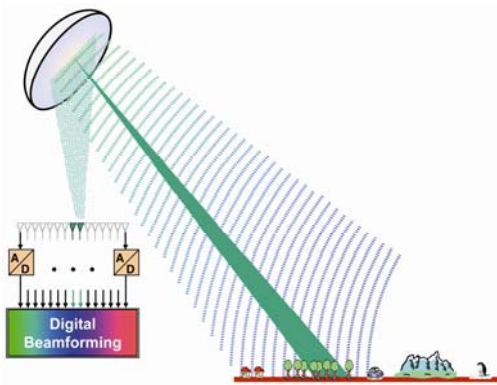


Figure 8: Concept of digital beamforming for high resolution, wide-swath radar systems.

The Tandem-L mission is currently in the pre-phase A study and is being performed in cooperation with NASA/JPL. The study shall demonstrate a concept for a joint realisation of a Tandem-L/DESDynI type of mission. Currently, the mission proposal is scheduled for a mission operation time of five to seven years with a launch in 2015.

Table 1: Tandem-L Time Schedule

Year	Planning
2008-2009	Pre-Phase A (1 Year)
2009-2010	Phase A (1 Year)
2010-2011	Phase B (1 Year)
2011-2014	Phase C/D (3 Years)
2015	Launch of Satellites
2015-2020	Nominal mission duration
2021-2022	Optional prolongation of mission duration

5. Summary

Tandem-L is an innovative mission proposal for mapping Earth dynamics with an unprecedented accuracy and capability. Advanced measurement techniques like single-pass Pol-InSAR allow the estimation of new essential environmental and climate variables. The instrument concept includes the innovative technology of digital beamforming in connection with a large reflector antenna which allows fulfilling the so far contradicting user requirements for a fully polarimetric imaging mode with wide swath and high resolution.

In addition to the science objectives described in this paper, Tandem-L has the potential for allowing many other applications and products due to its global and systematic acquisition plan. As an example, single-pass Pol-InSAR can also be used to estimate the bare soil topography as complementary information to the surface DEM that will be provided with the TanDEM-X mission with HRTI-3 standard.

6. Acknowledgement

We like to thank the Tandem-L science and project team for their contributions to the pre-phase A study. In addition we like also to thank the DESDynI science team for sharing their expertise in ecology and geo-sciences and the NASA/JPL research/engineering team for the constructive discussions.

7. References

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