Tandem-L

Satellite Mission Proposal for
Monitoring Dynamic Processes
on the Earth's Surface

DLR

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Address
Microwaves and Radar Institute
Oberpfaffenhofen
D-82234 Weßling
Germany

Editors
Alberto Moreira
Gerhard Krieger

Authors
Michael Eineder
Irena Hajnsek
Gerhard Krieger
Alberto Moreira
Kostas Papathanassiou

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Tandem-L:
A Highly Innovative Radar Mission

Tandem-L is a proposal for a highly innovative satellite mission for the global observation of dynamic processes on the Earth's surface with hitherto unknown quality and resolution. Thanks to the novel imaging techniques and the vast recording capacity, Tandem-L will provide urgently needed information for solving pressing scientific questions in the areas of the biosphere, geosphere, cryosphere and hydrosphere. Tandem-L will make a vital contribution towards a better understanding of the Earth system and its dynamics.

Important mission goals are:

- the global measurement of forest biomass and its dynamics for a better understanding of the carbon cycle,
- the systematic recording of deformations of the Earth's surface with millimeter accuracy for earthquake research and risk analysis,
- the fine-scale measurement of surface moisture for water cycle research,
- the quantification of glacial shifts and melting processes in the polar regions for improved predictions of the sea level rise.

Hence, in a time of intensive scientific and public debate on the extent and influence of climate change, Tandem-L will deliver vital missing information for improved scientific predictions upon which socio-political decisions can be based.

The Tandem-L mission concept is based on the use of two radar satellites operating in L-band (24 cm wavelength). The utilisation of the special synthetic aperture radar technique (SAR) enables high resolution imaging of the Earth's surface independent of weather and time of day. It therefore offers the ideal basis for the continuous observation of dynamic processes on the Earth's surface. Moreover, the long wavelength compared to X-band (3.1 cm) fulfills the requirements for a tomographic measurement of the three-dimensional structure of vegetation and ice regions, as well as for large scale surveying of deformations with millimeter accuracy.

The goal of Tandem-L is to image the land mass interferometrically once a week. Above and beyond the primary mission goals, the data set generated by Tandem-L has immense potential for developing new scientific and commercial applications.

Beside the scientific component, the distinguishing feature of Tandem-L is the high degree of innovation with respect to the methodology and technology. Examples are polarimetric SAR interferometry for measuring forest height, multiple-pass coherence tomography for determining the vertical structure of vegetation and ice, utilisation of the latest beamforming techniques for increasing the swath width and imaging resolution and close formation flying of two cooperative radar satellites with adjustable spacing.

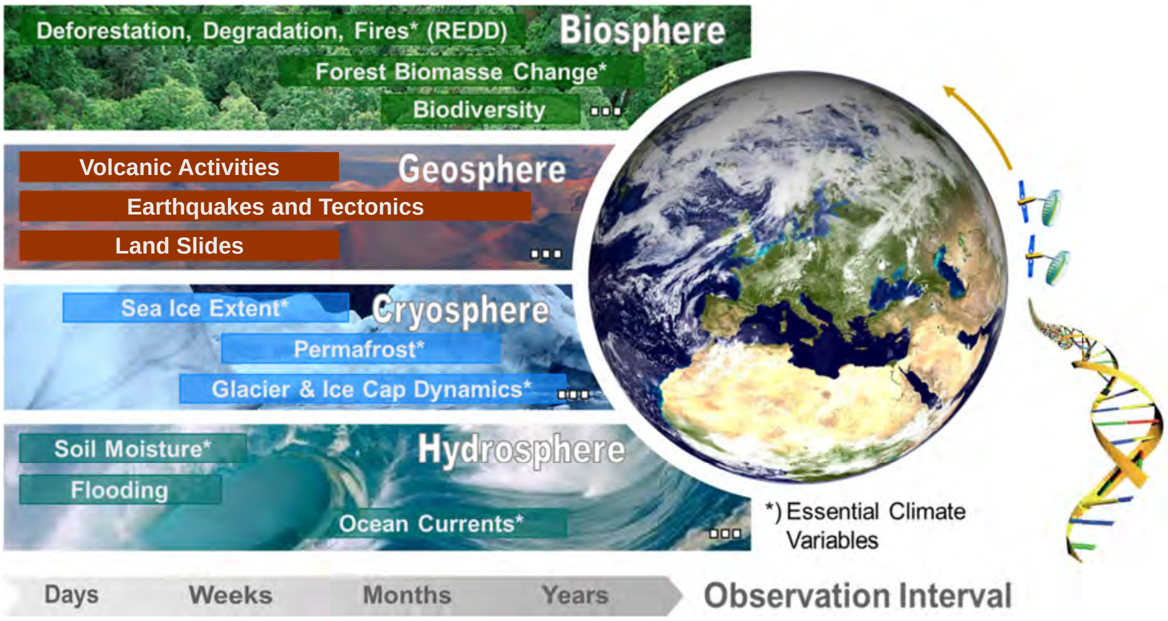
Tandem-L will further establish Germany's international leadership in the area of spaceborne radar and even extend it. Thanks to the unique data products, the mission will be a milestone in remote sensing, and the revolutionary techniques and technologies used in Tandem-L will form the basis for future generations of satellite SAR systems.

The mission concept was developed in detail in a phase A study. Tandem-L can either be realised in an international cooperation or as a purely national project. With the implementation of Tandem-L, a unique global Earth observatory will be created that will exceed the performance of existing systems by at least one order of magnitude. According to the current plans, the launch of the Tandem-L satellites could take place in 2024.

Tandem-L offers a unique opportunity to closely mesh the multifarious activities of the Helmholtz Association, spanning the different research areas, in a joint interdisciplinary project. The expertise of the relevant HGF research centers with their specific modelling techniques is imperative for producing highly aggregated information products. The exploitation of Tandem-L data and the integration of Tandem-L products and measurements into environmental models are already being prepared in the framework of the HGF alliance "Remote Sensing and Earth System Dynamics".

Because of the partially complementary expertise in data utilisation and modelling, the cooperation with international scientific teams promises great synergetic potential. Tandem-L is therefore predestined to set a historic milestone in international Earth system research and make an important contribution to a better understanding and preservation of the Earth and its environment.

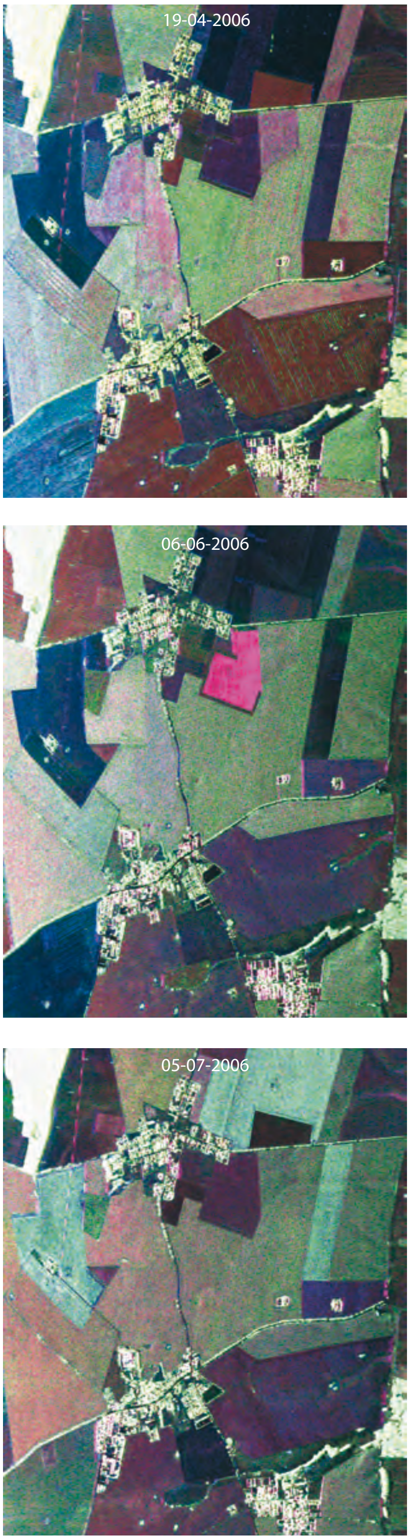
The Tandem-L mission will open the door to a future global remote sensing configuration for the continuous observation of the Earth's surface, as it currently exists for weather prediction, where a network of geostationary satellites is used.



Tandem-L enables the systematic observation of a multitude of dynamic processes on the Earth's surface. Using modern radar technologies, the stringent scientific requirements for observation interval, resolution and data quality can be optimally fulfilled.

Scientific Goals and Applications

Dynamic Processes on the Earth



The Earth system comprises a multitude of components and processes, which are intimately meshed through complex interactions. For example, variations in the biosphere, geosphere/lithosphere, hydrosphere and cryosphere can not only permanently change their equilibrium but also the physics and chemistry of the atmosphere. Changes in the atmosphere subsequently affect the weather and climate, which in turn influence a number of processes in the biosphere, geosphere, hydrosphere and cryosphere.

Many of these complex interactions are currently either insufficient understood or are inadequately quantified.
An important reason for this is that processes from several Earth spheres and different spatial and temporal scales are interlinked, while suitable observation data for analysing the many interactions are unavailable or only available locally or for a limited time range.

The measurement of dynamic processes requires a continuous, extended and systematically planned observation strategy in order to detect changes promptly and quantify them with sufficient accuracy. Depending on the phenomena to be observed, changes have to be measured on different spatial and temporal scales and then related to one another. This, in turn, requires a broad spectrum of observation intervals. With the advent of satellite-based Earth observation, our understanding of changes in Earth system has increased markedly. However, the imaging performance, measurement accuracy and recording capacity of existing systems are inadequate to quantify the dynamics of large-scale processes and to allow reliable conclusions.

Hence, an essential requirement of the Tandem-L mission is to image large areas regularly with high temporal and spatial resolution. This, together with a systematic acquisition scenario will allow to monitor in a consistent way the evolution of natural and/or anthropogenic processes. Only thus can the dynamics of the different changes in the Earth's surface be measured with sufficient accuracy and resolution. The combination of short revisit times and data recording periods extending over several years allows the monitoring of rapidly developing, highly-dynamic processes, such as the relaxation following an earthquake, as well as slowly developing processes, like the variation of forest biomass, with the necessary precision and resolution.

A vital scientific goal of Tandem-L is the quantitative recording of dynamic processes on the Earth's surface both systematically and on a global scale.

Using modern radar technology, changes in the Earth's surface can be monitored systematically, independent of weather and daylight conditions. The three polarimetric radar images document the strong seasonal changes of agricultural areas (image sub-sections 3 km x 6 km).

Contribution to a Better Understanding of Climate Change

Tandem-L will decisively contribute to a better understanding of processes which are recognised as drivers of local and global climate change.

Carbon Cycle

The increase in the concentration of greenhouse gases in the atmosphere and the associated climate change today make the carbon cycle a core part of climate research. In addition to the atmosphere, the oceans and the biosphere are the main carbon stores, which are in an active interchange with the atmosphere. The rise in the atmospheric CO_2 concentration can only be partially compensated for by the absorption of CO_2 in the biosphere and the oceans.

Forests store approximately half of the terrestrially bound carbon. As forests grow they are enriched with biomass and thereby act as CO_2 sinks. The importance of tropical forests is manifested in the fact that tropical forests can store about 50% more carbon than forests outside the tropics. The clearing and destruction of forests causes that a large amount of bound carbon becomes extracted from the forest. Parts of the extracted carbon will be either immediately (e.g. slash-and-burn) or with a significant delay (wood use) released into the atmosphere. The emissions due to global loss of forest are today the second largest source of CO_2. The uncertainties in the carbon flows between the land and the atmosphere are very large in comparison with the other components of the carbon cycle. The main reasons for this are the incomplete monitoring and the lack of knowledge about the biomass in the disturbed and deforested regions.

For the first time, Tandem-L will measure biomass and its seasonal and yearly variation with unprecedented accuracy on a global scale. This will be a key contribution to drastically reducing the uncertainties in the terrestrial components of the carbon cycle.

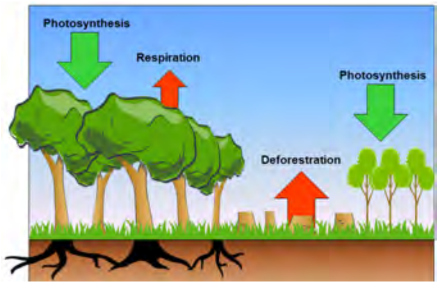
Water Cycle

The water exchange between land, ocean and atmosphere is one of the most important factors determining weather and climate. Even though the ultimate proof is still missing, a scientific consensus is growing that man-made climate change will influence the water cycle and water availability. There is a close relationship between the water cycle and the climate; hence, the accuracy of regional and global climate predictions is strongly dependent on the uncertainties in the dynamics of the water cycle.

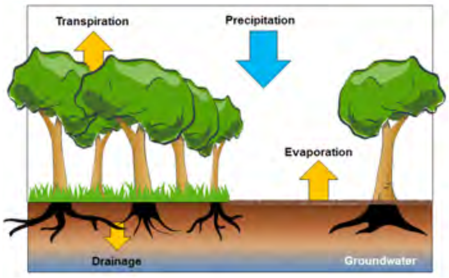
In climate models, soil moisture is a core parameter for characterising the land surface, because it directly influences the heat and water transport between the land surface and the atmosphere. Even small variations in the water content have a large influence on the thermal characteristics of the land. Due to the strong temporal and spatial variability, measurement of soil moisture and its dynamics is practically impossible.

Today, we can observe changes in the water cycle, such as the accelerated melting of snow, ice and glaciers or the increased rain and reduced snowfall due to the raise of temperatures. Often, positive feedback can occur, e.g., less snow and longer melting periods can lead to an additional increase in the temperature.

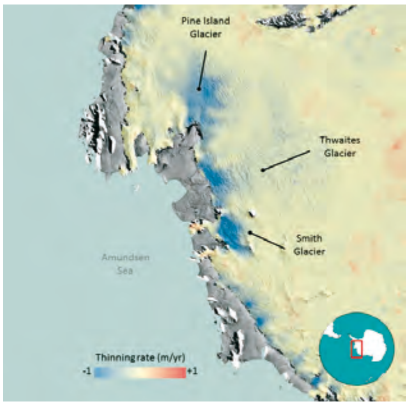
For the first time, Tandem-L will record the critical components of the water cycle, such as soil moisture, and the dynamics of flow and melting processes in the cryosphere on a global scale with high temporal and spatial resolution.



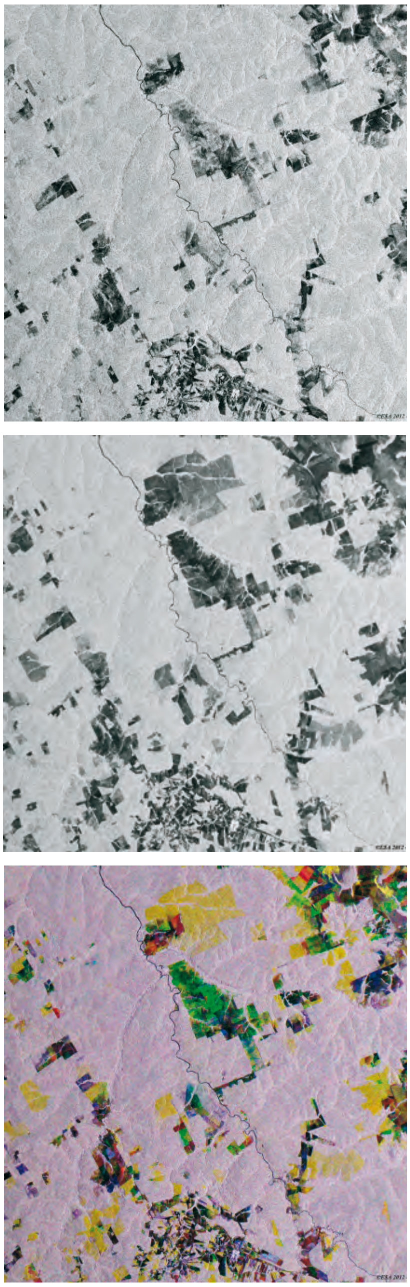
Today, the knowledge of the terrestrial components of the carbon cycle is very inaccurate. These components are directly related to the global forest conditions.



The moisture content of the soil controls important components of the local water cycle.



Between 2011 and 2013, the western antarctic ice shield lost more than 150 cubic km of ice yearly. The figure shows changes in the ice height measured by the ESA altimeter CryoSat. Tandem-L will permit continuous monitoring of the ice shield with high spatial and temporal resolution.



ERS Image over Mato Grosso, Brazil
Top: June 07, 1992
Center: September 08, 1999
Bottom: RGB Composition:
September 08, 1999
June 27, 1993
June 07, 1992

Biosphere

Forests belong to the most important terrestrial ecosystems and are an integral component of the Earth system. They are habitat and/or livelihood for a quarter of the world population. At the same time, forests (particularly tropical forests) are the most biodiverse habitats of our planet: two thirds of all animal and plant species live in forests.

As a source of timber and an increasing number of non-timber products, forests are not only of great economic value but most important natural resources, too. Forests produce oxygen and store carbon dioxide and water. In this way, they regulate the biochemical circulation between the biosphere and atmosphere and influence the local and global climate. They protect the ground from erosion and prevent flooding.

In spite of their importance, forests are today more than ever before under the threat of a growing world population and climate change. Mankind has already destroyed more than half of the forests. A large part of the remaining forests is disturbed. Only a third of the global forest area consists of primary forest. A large part of that is regarded as being seriously endangered. Driven by the expansion of agriculture and increasing wood use, a further 10 to 15 million hectares of forest are destroyed every year, due to conversion into agricultural land, forest clearance or illegal logging.

This damage not only destroys important resources and the habitat of many plants and animals, but it also releases a large amount of CO_2.

Consistent global monitoring of the condition of the forests and the influence due to human activity and climate therefore becomes an urgent necessity.

Forest Biomass

Biomass is significant because of its direct relationship to the carbon content and as a measure of forest and ecosystem productivity. The UNFCCC (United Nations Framework Convention on Climate Change) identified biomass as an essential climate variable, whose measurement is of great importance today. In the commercial exploitation of forests, forest biomass represents the amount of useful wood, information that is essential for the sustainable management of forests.

Estimation of biomass is very inaccurate on local, regional and supra-regional scales. Ground measurements of biomass in natural forests often exhibit errors much greater than 20%. Particularly large are the deviations in tropical and natural forests due to their spatial heretogeneity. Global and national estimations of forest biomass often lack a spatial reference, because they are derived from the generalisation of forest inventory data. Accordingly, they are affected by different definitions and computation methods. The lack of accurate spatial forest biomass data was recognised as one of the greatest uncertainties in the global carbon budget by the Intergovernmental Panel on Climate Change, IPCC.

Dynamic changes of biomass and their spatial distribution are a direct measure of the exchange of carbon between the terrestrial ecosystem and the atmosphere. At the same time they characterise the variation of forest growth and productivity induced by water or climate stress.

Tandem-L will enable a global inventory of biomass with an accuracy of 20%, as well as measurements of seasonal and yearly variations.

Forest Degradation

Selective logging, the conversion of natural to plantation forests, forest segmentation and the structural degradation of the forests disturb important forest functions without the area of forest being necessarily reduced. This reduction in the quality of the forest, known as forest degradation, not only leads to carbon emissions, but also to an often dramatic loss of biological diversity.

The lack of suitable remote sensing systems with the ability to estimate the vertical structure of forests and its spatial variability makes accurate monitoring of the disturbed and degraded forests impossible. Hence, the degree of forest disturbance and the ecological consequences remain unknown.

An important and unique contribution of Tandem-L lies in the mapping of the complexity and diversity of vertical forest structures, as well as their variation.

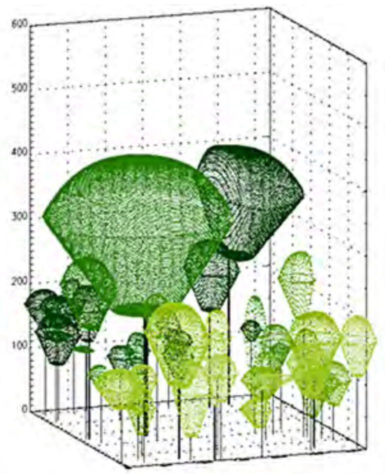
This will enable the extent and intensity of forest disturbance to be determined and their yearly variation documented.

REDD+

In 2007, recognition of the relevance of forests for the global climate led to the introduction of a forest protection mechanism into the UN follow-up climate treaty. This mechanism is known as REDD+ (Reducing Emissions from Deforestation and Forest Degradation). REDD+ creates a legal framework within which the emerging and developing countries, particularly in the tropics, can be supported by the international community to protect their forests. REDD+ has the potential to be a core instrument in stopping large scale forest destruction.

Accurate determination of emissions from the elimination, disturbance and degradation of forests is a prerequisite for the sustained success of REDD+. Only a monitoring system based on globally available remote sensing data can deliver meaningful data everywhere.

Tandem-L will pioneer remote sensing methods and technologies to build monitoring systems for supporting the implementation and verification of environmental policies.



3D representation of a primary tropical forest having a natural structure using the example of a dipterocarpaceen forest in Borneo, Indonesia. Tandem-L will measure the vertical forest structure on a global scale.

Today, tropical rain forests are most endangered, and therefore of particular importance. They play a central role in the terrestrial carbon cycle, influence the regional water budget and are hotspots of biodiversity.

Deformation of the Earth's Surface

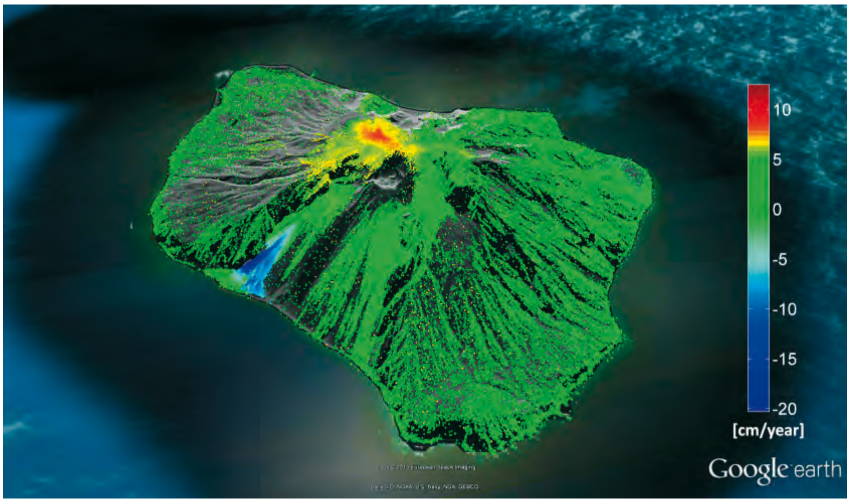
The topography of the solid Earth is constantly changing due to continental drift and more localised magmatic, climatic and anthropogenic processes. The results are earthquakes, volcanic eruptions, landslides or subsidence. Earthquakes are amongst the most fatal and expensive geo-risks; according to the reinsurance company 'Munich Re', they cost more than 540 billion US dollars between 1994 and 2012.

Even if we can't reliably predict earthquakes and volcanic eruptions today, understanding of the geological processes has improved greatly in recent years, not least due to modern technologies such as seismic arrays, GPS, differential radar interferometry (D-InSAR) and Very Long Baseline Interferometry (VLBI), but also thanks to more precise numeric modelling. The improved sensors and methods mean, for example, that networks of German seismographs can now locate the epicenter of an earthquake on the coast of Sumatra with a precision of 100 km, and the global tectonics can be measured with millimeter accuracy using coarsely distributed GPS systems and VLBI.

With Tandem-L, these coarse GPS data will be augmented by high-resolution deformation maps.

These maps will globally and systematically record the inter-seismic and co-seismic changes in areas of risk, such as fault zones, and magmatic processes of volcanoes with far greater accuracy than ever could be achieved with GPS. Expected are significant improvements in the numeric models, leading to improved estimation of the location and time of future tectonic and volcanic events.

Also, in the deformation mode of Tandem-L, local events, like unstable hillsides and landslides, possibly caused by climate changes, e.g., thawing of permafrost regions, can be monitored with centimeter, and even millimeter accuracy. In the same way, anthropogenic processes, like land subsidence after water extraction or mining, can also be measured. Existing satellite systems have only so far yielded good results for urban areas.



Deformation of the volcano Stromboli in Italy in cm/year. The use of both point targets and distributed targets yields a particularly high information density.

Limitations of Current Systems and New Solutions

For radar measurements in the deformation mode, mainly the ESA satellites ERS-1, ERS-2 and Envisat were used in the past. Their imaging parameters, wavelength, orbit, fixed viewing angle and repeat cycle (35 days), were originally intended for oceanic applications and are only of limited suitability for the deformation mode.

The short wavelength of 5.6 cm (C-band) causes temporal decorrelation. C-band microwaves are reflected by the topmost layers of the vegetation. Random and comparatively fast movement of leaves and small branches leads to strong decorrelation and masks the measurement of slow ground motion in forest areas. In a similar manner, changes in the surface structure between images on a sub-wavelength scale (e.g. due to ground erosion) lead to distortion of the phase signal and even to its complete cancellation.

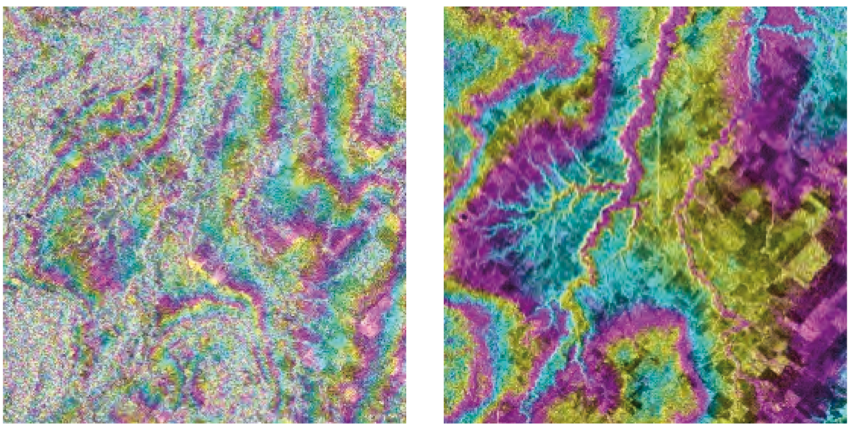
The D-InSAR analyses published so far are impressive, but always with positive results. Unsuccessful analyses are seldom published and normally only known to experts. Tandem-L is much less sensitive to changes in the surface structure. Therefore, motion measurements of the Earth's surface are possible everywhere and over very long time periods.

The 35-day repeat cycle of past systems is too long to detect fast movements. Thanks to the Tandem-L wide swath (up to 350 km), the repeat cycle can be reduced to 8 days. Large swath width and wave length are a prerequisite for recording fast motion and recognising future dangers. Thus, combined with geophysical models, the predictability of these events will be greatly improved.

Up to now, the systems only measure one component of the three-dimensional motion vector. By combining different observation geometries, Tandem-L will enable the reconstruction of three-dimensional motion vectors. These are essential for selecting the optimum model for earthquakes and for quantitative analysis.

The mission scenarios of previous satellites didn't allow local systematic monitoring of risk areas. Tandem-L will facilitate this for the first time.

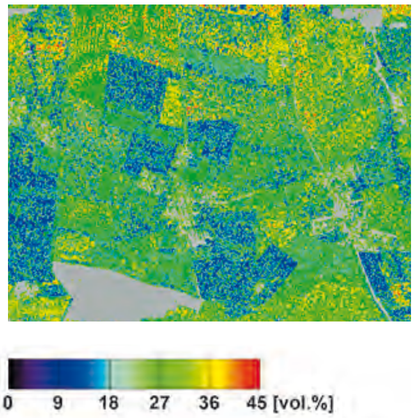
Thanks to the improvements described above, Tandem-L will be the first system optimised for a deformation mode without compromise. Like the SRTM and TanDEM-X missions, it will represent a milestone in the history of radar remote sensing.



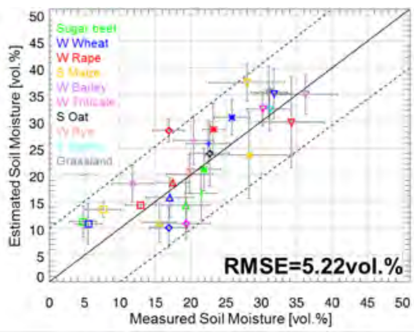
Phase interferograms from the SIR-C/X-SAR mission, 1994. After only one day, the C-band interferogram (left) shows strong decorrelation (phase noise) in areas of thick vegetation, while the L-band interferogram (right) exhibits high and uniform quality.

Hydrosphere

SAR image in L-band



Surface layer soil moisture over an agricultural area in Northern Germany



Validation of soil moisture estimates for different vegetation types

The hydrosphere comprises Earth's surface and subterranean water resources. Seen from space, the Earth is a blue planet, as three quarters of its surface is covered with water.

Due to climate changes and anthropogenic influence, the hydrological conditions are changing more and more. This has extensive consequences, ranging from changed energy fluxes to reduced water quality and availability. The former can influence the global, regional and local climate, while the latter are prerequisites for sustainable ecological development. Studies of climate change predict a rise of the global air temperature over the next decades. This is expected to enhance the variability of precipitation patterns. Also, an increase in the occurrence and intensity of hydrological extreme events, such as flooding and drought, is expected. The ability to model and predict such changes and their impact on the water cycle is of great importance for the development of appropriate prevention and survival strategies, in order to limit the potential negative consequences for society and economy.

In order to understand the influence of anthropogenic and climate changes on the hydrosphere, it is necessary to know the key hydrological processes and their spatial and temporal patterns with sufficient accuracy. An essential parameter, thereby, is the soil moisture, because it determines both the water fluxes and the energy fluxes at the boundary between the land surface and atmosphere. Accurate knowledge of the spatial distribution and the variation over time of soil moisture is fundamental for improving prediction models. For evaporation of water, large amounts of energy are required. Hence, the moisture of the surface layer is a key parameter for the exchange of water and energy between the land and the atmosphere. It follows that spatial and temporal fluctuations of soil moisture inside the unsaturated zone influence the weather and climate from a local to regional scale. The simulation of the effect of greenhouse gases on the water cycle and energy processes using current climate models is limited by the large uncertainty in the prediction of moisture variations close to the surface. The fact that soil moisture changes depend on the soil composition, the vegetation cover and the variations in precipitation and evaporation (which are also influenced by the vegetation) compromises not only the modeling, but also the extrapolation/interpolation of the measurements. A high temporal and spatial resolution when determining the level, distribution and variation of soil moisture can considerably improve hydrological river basin models, weather forecast models and seasonally dependent climate models.

Over the last ten years, soil moisture measurements derived from remote sensing data have been used in data assimilation models to tune prediction approaches. Although this allowed to demonstrate the potential of remote sensing, today no sensor exists which can comprehensively monitor the Earth's surface with adequate temporal and spatial resolution. Space missions, such as SMOS (Soil Moisture and Ocean Salinity), SMAP (Soil Moisture Active/Passive) and GRACE (Gravity Recovery and Climate Experiment) give an important insight into the global water cycle. However, their poor spatial resolution is insufficient for a large number of applications.

With Tandem-L the soil moisture will be able to be measured over large areas with a resolution less than 50 m and at short time intervals for the first time.

Cryosphere

The Earth's snow and ice masses form the cryosphere and play an important role in Earth's climate system, due to feedback mechanisms with the atmosphere and the oceans.

These mechanisms have the tendency to amplify climate changes. The processes that regulate the dynamics and mass balance of the individual components of the cryosphere are still not adequately known. For this reason, the coupling of processes in the cryosphere is a weakness of current climate models and one of the largest sources of inaccuracy in climate predictions and climate scenarios. With better and more systematic observations one can expect large advances in Earth system modeling incorporating the cryosphere.

The importance of satellite measurements for this purpose is emphasised in the IGOS Cryosphere Theme Report of the World Climate Research Programme. In addition to the influence of the atmosphere and the oceans, the changes in the cryosphere directly affect the environment, the ecology and the economy of polar and subpolar regions. Disappearing water resources due to the retreat of winter snow and glaciers degrade water supply, agriculture and biodiversity in many mountainous regions. The rise in sea level due to the melting of glaciers and the polar ice masses endangers coastal regions worldwide. The melting of the arctic sea ice cover, which is proceeding far more quickly than predicted, creates new geopolitical and ecological situations at high latitudes in the northern hemisphere.

Satellite remote sensing configurations are the most important elements for comprehensive, consistent and global observations of the snow and ice reserves. Satellite measurements deliver comprehensive data upon which our current knowledge of the various components of the cryosphere is based. However, there are many open questions on the mass balance and dynamics of snow and ice, and on the interaction of the cryosphere with the atmosphere and the oceans. The clarification of the following scientific questions is regarded as being paramount:

1. What contributions do glaciers, ice caps and polar ice shields make to the rise in sea level? In what way are climate changes influenced by their mass balance and dynamics?

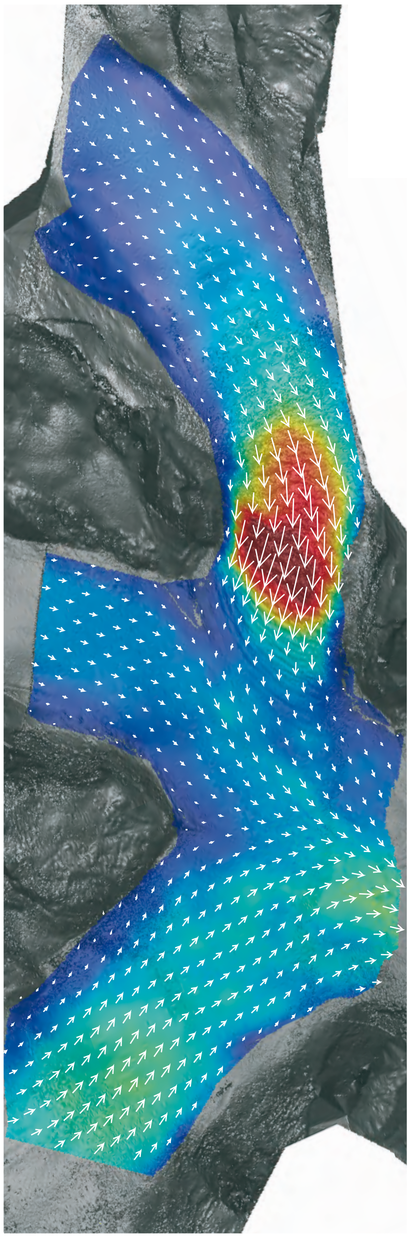
2. What is the impact of natural and anthropogenic environmental changes on the spatial distribution of sea ice characteristics and the seasonal variation of sea ice extent?

3. How do changes in the snow and ice masses affect the circulation in the atmosphere and in the oceans?

4. What spatial and temporal changes in the snow and ice reserves are to be expected in future decades, and how will these changes influence the water supply, the ecology and the biodiversity?

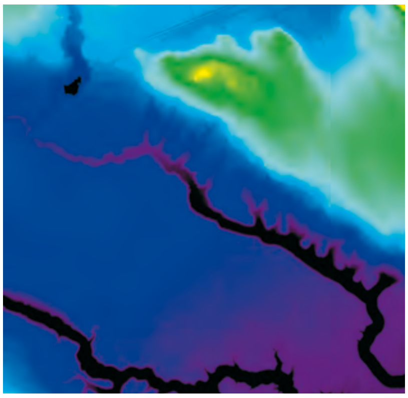
5. Can changes in the cryosphere trigger abrupt or critical changes to the global climate system?

Tandem-L will deliver vital information on ice motion, ice topography, and, therefore, on ice mass balance.

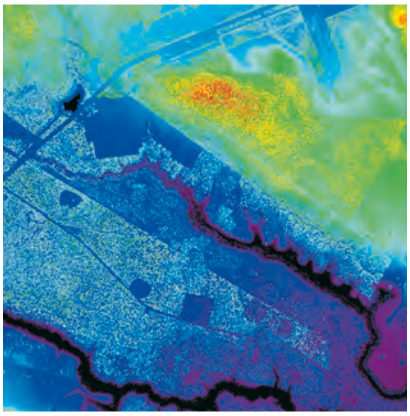


Measurement of glacial velocities using the Aletsch glacier (Switzerland) as an example. The information was derived from airborne L-band data.

Digital Elevation Model



Digital terrain model (L-band DEM)



Digital surface model (X-band DEM)

Until 2016, only coarse, inconsistent or incomplete elevation models existed for parts of the Earth, assembled from a multitude of different data sources using different data compilation methods. In 2016, TanDEM-X closed these gaps and provided a homogeneous global elevation model as an indispensable basis for many scientific and commercial applications.

The TanDEM-X DEM is specified with a spatial resolution of 12 m x 12 m and a relative vertical accuracy of 2 m and has been completely available since September 2016. For acquiring the data TanDEM-X utilises an interferometric radar system operating in X-band, which only penetrates the vegetation by a short distance due to the short wavelength of 3.1 cm. Thus, the TanDEM-X mission is delivering a digital elevation model, which, to a first approximation, represents the Earth's upper surface, i.e., the upper surface of strongly vegetated areas (e.g. forest) and the top surface of urban areas (roofs of buildings). In contrast, a digital terrain model describes the topographic variation beneath the vegetated area.

With a wavelength of 24 cm, Tandem-L penetrates the vegetation and can determine not only the surface topography, but also the topography under the vegetation by using polarimetric SAR interferometry. Therefore, complementary to TanDEM-X, Tandem-L will provide urgently needed information on the topography of the Earth's surface.

Assuming a launch of Tandem-L in 2024, the first digital terrain and surface models could be made available in 2025. These will be an ideal extension of the surface model from the TanDEM-X mission. Over the duration of the Tandem-L mission, it is also possible to produce regular updates of the terrain and surface models.

Furthermore, in X-band it can be seen that the digital surface model is influenced by vegetation. From previous investigations on the X-band DEM generated by the Shuttle Radar Topography Mission (SRTM) we know that the digital surface model doesn't represent the topmost forest layer but lies approximately 10% to 20% lower, due to penetration into the forest (dependent on the nature of the forest).

This problem is also observed for thickly vegetated agricultural crops. In the first two mission phases, TanDEM-X has imaged the whole of the Earth twice with different baselines, but each region always at the same time of the year. Because of this, it wasn't possible to record a digital surface model of agricultural areas once with and once without vegetation cover. Tandem-L doesn't have this restriction because, thanks to the penetration capability and the concept of multi-temporal imaging, it can compensate these effects. Digital terrain models have fundamental significance for a broad spectrum of commercial and scientific applications (geo-scientific research areas: hydrology, glaciology, geology, permafrost, forestry, environmental research, etc.).

The Tandem-L science team has formulated the requirements on a global digital terrain model with a spatial resolution of 12 m x 12 m and a relative vertical accuracy of ~2 m. With this resolution, the global digital terrain model generated by Tandem-L will be unique and the basis for uniform and universal map material.

Mission Concept and Technical Realisation

Measurement Principle

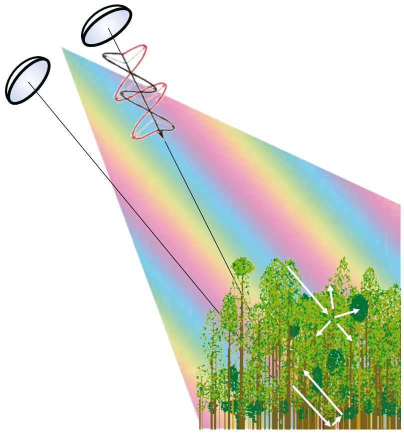
For the Tandem-L mission, an innovative concept for data acquisition has been developed. It consists of two complementary measurement techniques:

3D-Structure Mode for the three-dimensional surveying and tomographic imaging of volume scatterers, such as vegetation, ice, snow and dry soil. This imaging mode is necessary to collect unambiguous data on volume scatterers (height, density, structure, etc.). The 3D-structure mode optimally fulfills the requirements of applications pertaining to the biosphere, hydrosphere and cryosphere. The basis of the 3D-structure mode is the polarimetric SAR interferometry (POL-InSAR) technique developed by DLR. Tandem-L will be the first radar mission that will perform global 3D-structure measurements with the innovative Pol-InSAR technique.

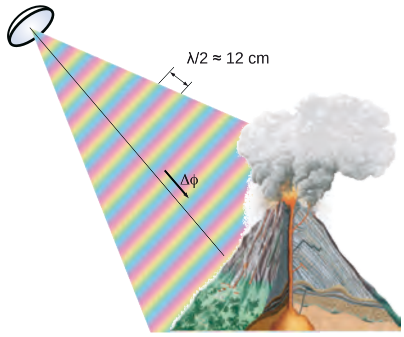
Deformation Mode for monitoring topographic changes in the Earth's surface with accuracies down to centimeters and millimeters. In this mode, the largest possible swath width up to 350 km will be imaged. In this way, temporal spacing between the images is minimised. The deformation mode is optimum for applications in the geosphere and lithosphere research fields.

Both measurement techniques permit systematic and global imaging of the Earth with a spatial resolution down to 5 m x 7 m. While deformation mode requires a repeat measurement cycle of one to two weeks, for the 3D-structure mode a repeat cycle of one to two months is sufficient, because of the slower fluctuations of volume scatterers.

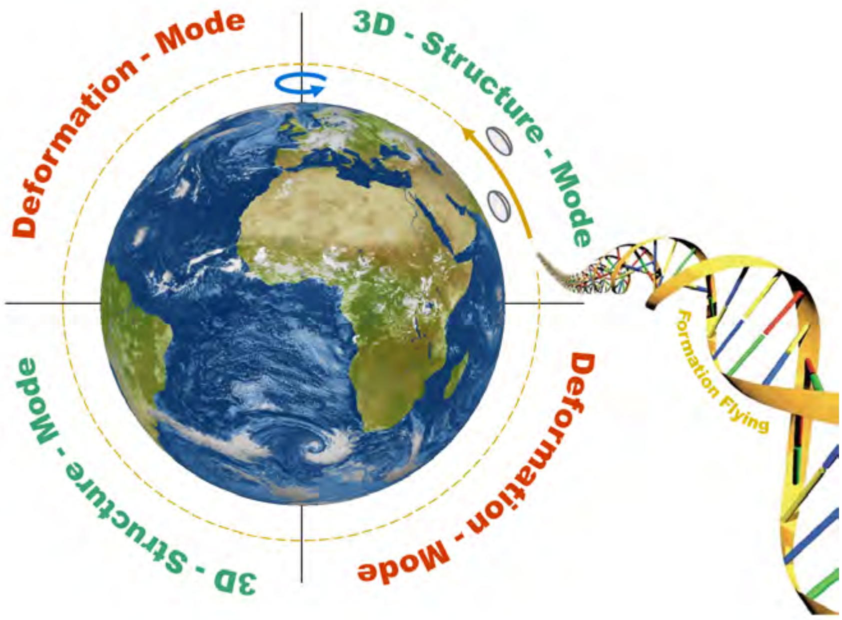
Thanks to the weather independence of the radar instrument, in the case of a crisis (earthquakes, floods, volcanic eruption, dam or forest damage, etc.) any area on the Earth's surface can be imaged within one to two days with high resolution by performing suitable satellite manoeuvers.



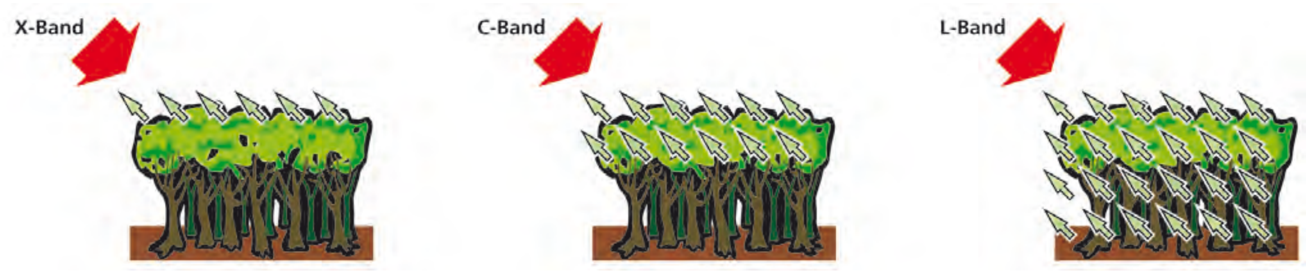
3D-Structure Mode



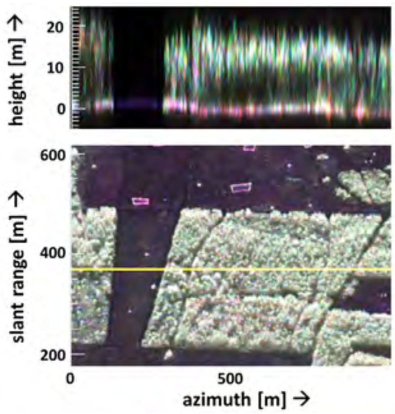
Deformation Mode



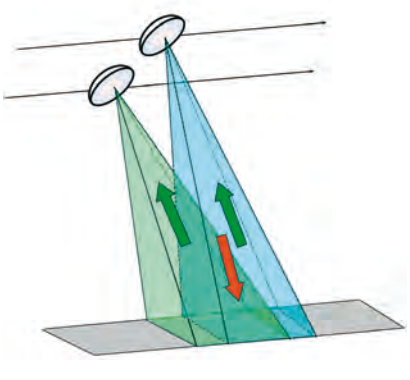
Tandem-L uses two complementary imaging modes in combination with a systematic data acquisition strategy to fulfill the many mission requirements.



Comparison of the penetration depth in vegetation for X, C and L-band with 3 cm, 5 cm and 24 cm wavelength. While radar waves in X-band are only reflected from the upper canopy, L-band penetrates down to the ground. Only L-band radar systems can receive signals from all vegetation layers.



Demonstration of tomographic imaging of a group of trees in L-band. In this example, the radar data were recorded using DLR's airborne SAR system by making several passes at intervals of a few minutes.


The simultaneous data acquisition with two fully polarimetric radar satellites in L-band allows the generation of unique data products for a wide spectrum of scientific uses.

Why L-band?

Radar systems can be operated over a broad frequency spectrum. The selection of the frequency greatly influences the radar images and therefore the information that can be derived from them. Several national and international publications and studies with major participation by German scientists show that the frequency range in L-band has the greatest potential for applications in scientific fields pertaining to the Earth and its environment.

L-band corresponds to a wavelength of 24 cm and, compared to the shorter wavelengths in C-band (5.6 cm) and X-band (3.1 cm), exhibits a much greater penetration depth of volume scatterers, such as vegetation, ice, dry soil and sand. Only by using long wavelength L-band signals it is possible to penetrate thick vegetation down to the ground and therefore measure their vertical structure.

Another key advantage of the use of long wavelength radar signals is the much improved temporal coherence when measuring deformations on the Earth and glacial motion. Thus, Tandem-L permits motion measurements of the Earth's surface with centimeter down to millimeter accuracy over very long periods.

Radar Satellites in Formation Flight

Only the use of two radar satellites in an innovative tandem formation does allow the three-dimensional imaging of the Earth's surface. Thanks to the penetration depth in L-band, Tandem-L can probe the vertical profile of a volume tomographically, as well as image the surface.

This not only allows the generation of a highly accurate digital terrain model without the influence of the vegetation, but also the global measurement of forest height and the determination of the associated biomass using allometric relationships. The tandem formation offers a number of other advantages.

Examples are the observation of the same area from different viewing angles for improved registration of the deformations, the doubling of the swath width to simultaneously image large areas, the measurement of wave height and sea currents, the determination of ice structure and its variations, the measurement of seasonal ice gain and loss, the determination of sea ice thickness, the detection of wetland and water level measurements beneath vegetation, the monitoring of reforestation and logging, the detection of forest degradation (storms, fire, etc.) and many more.

3D representation of the Stadtwald forest in Traunstein, Germany. The forest height was derived from radar data using polarimetric SAR interferometry.

Measurement of Biomass

The determination of forest biomass is performed indirectly via the measurement of the vertical forest structure. A decisive structure parameter is thereby the forest height.

In order to record the forest height globally one has to use

- a long wavelength radar signal that penetrates the forest down to the ground,

and

- polarimetric SAR interferometry for determining the height.

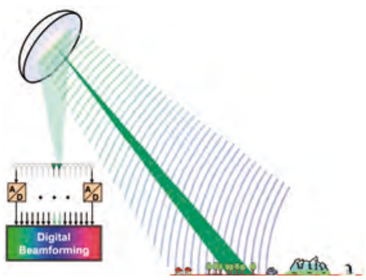
The ground breaking polarimetric SAR interferometry technique was developed in DLR Microwaves and Radar Institute in collaboration with diverse partners in Germany and Europe, and was repeatedly demonstrated successfully with DLR's airborne SAR system on different forest types.

The method is based on a simplified forest model and on the fact that with SAR polarimetry the ground, trunk and canopy can be resolved separately. With aid of SAR interferometry the scattering as a function of height can be determined. From these, the forest height can be computed with great accuracy.

With Tandem-L, additional vertical structure profiles are produced by combining several images using a new tomographic technique. With the aid of allometric equations the biomass can be calculated. This unique technology has already been demonstrated on boreal and tropical forests, as well as in temperate latitudes, and it has been shown that forest height can be measured with an accuracy of 10%; from this, the biomass can be derived with an accuracy of 20%.

Technology and Innovations

Tandem-L satellite with reflector antenna



Use of innovative technology on Tandem-L. The digital beamforming technology for high resolution radar systems was developed and patented in a close collaboration between DLR and German industry.

Digital beamforming demonstrator on a DLR helicopter

Next Generation of High-Resolution Radar Satellites

A particular challenge of the Tandem-L mission is the development of two inexpensive yet capable SAR instruments for operation in space, and meeting the stringent mission requirements.

Besides the innovative mission concept, a new technology is required to meet the call for greater swath width and higher resolution. The key with Tandem-L lies in the use of a deployable antenna reflector and shifting the digital interface to the antenna.

This technical revolution makes digital beamforming possible, whereby the scattered radar signals received by sub-arrays are digitised and fed in parallel to the processor. Tandem-L will be the first radar mission to implement the new technology of digital beamforming in combination with a reflector antenna. The use of a large reflector increases the sensitivity and leads to a considerable reduction in transmit power. Because of this, the SAR instrument can be operated virtually continuously.

Digital antenna synthesis using digital beamforming technology increases the flexibility of the radar imaging enormously and permits the implementation of very powerful operating modes that can be optimally tailored to the differing requirements of the 3D-structure mode and the deformation mode.

By implementing the latest radar technologies, Tandem-L will be able to image a swath width of 350 km with a resolution better than 7 m in a single/dual polarimetric mode and a swath width of 175 km in a fully polarimetric mode for the first time. Compared to TerraSAR-X and TanDEM-X, this corresponds to an increase in the imaging performance by more than an order of magnitude. If the quasi-continuous imaging capability is also taken into account, the imaging capacity is more than two orders of magnitude greater than with TanDEM-X. This performance improvement is based on the use of a deployable reflector antenna with a diameter of 15 m.

The combination of reflector antennas and the latest digital beamforming technology exhibits a much improved performance over satellite radars with conventional phased array antennas and also has a much lower mass, leading to a noticeable reduction in mission costs.

As far back as 1999, DLR Microwaves and Radar Institute built a first prototype of a radar with digital beamforming and used it to demonstrate new applications on a helicopter. Following on from that, a technology development programme at the (then) Astrium GmbH company was initiated with the goal of developing the hardware for a space qualified radar using digital beamforming. Important aspects of digital beamforming were also able to be demonstrated using the split antenna of TerraSAR-X. The current maturity of the hardware and algorithm development means that the use of this highly innovative technology will be ready in time for Tandem-L.

Bistatic Radar Operation

The 3D measurement of vegetation and ice structures, as well as the generation of other products requires simultaneous imaging with two radar satellites.
This technology, using two closely linked radar satellites for the production of high-value information products, was exploited for the first time on the TanDEM-X mission.

In this way, it was possible to produce a unique digital elevation model of the Earth. Two key technologies used to achieve bistatic radar operation were the synchronisation of the radar satellites to an accuracy of a picosecond (10^{-12} s) and the precise determination of the interferometric baseline to within 1 mm. Tandem-L also uses this unique technology and develops it a step further.

Formation Flight

For tomographic measurements of 3D structures, Tandem-L requires several interferometric image sets with satellite spacings in the range of one to ten kilometers. To meet this requirement, a new concept similar to the helix formation used by TanDEM-X was developed, whereby, by clever use of natural drift motion, a periodic variation of the baselines can be achieved with minimum fuel consumption. During specific mission phases, the second satellite can also be used to improve imaging performance by further reducing the time delay between images. This is very useful, for example, for tailoring the data acquisition according to the needs following earthquakes or other natural disasters.

Data Transmission to the Ground

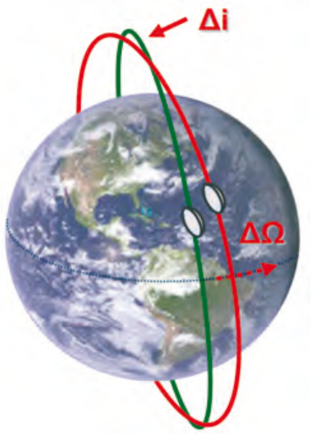
Tandem-L data acquisition not only sets new standards on product availability and quality, but also results in new challenges because of the data volume that has to be transmitted to the ground. Current planning foresees that the two Tandem-L satellites will acquire 8 terabyte of data every day. To transfer this amount of data to the ground the latest transmission technology in Ka-band will be employed together with an international network of ground stations.

Real-time Data Products

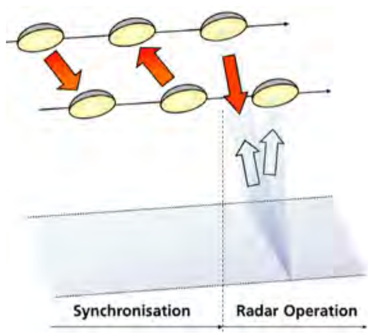
To provide users with up-to-date products, on-line processing will be performed keeping in step with the image generation. To limit the processing load, these products may not at first possess the highest possible accuracy, which can often only be achieved in combination with other image and product data. However, they still serve as useful indicators for early warning.

Application-specific Product Generation and Archiving

High-quality products will be delivered to the users on demand. Depending on the type of user these can be sensor-specific products (e.g. SAR images), intermediate products or refined geo-information products, such as biomass maps. For a selection of products, users can request specific processing parameters. Product generation and distribution take place via the internet. As far as possible, only intermediate products will be archived. From these, the appropriate final products can be generated as needed in accordance with the user requirements.

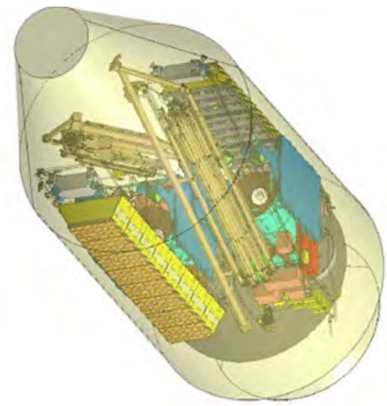


The formation flight of the Tandem-L satellites is fundamental for tomographic imaging in the 3D-structure mode.



To synchronise the radar systems, short pulses are exchanged between the satellites. This permits a synchronisation at picosecond accuracies.

Integration of TerraSAR-X at Airbus Defence and Space (previously EADS Astrium GmbH) in Friedrichshafen, Germany



Two Tandem-L satellites in the fairing of a Falcon 9 aircraft

Implementation and Schedule

Status of Tandem-L

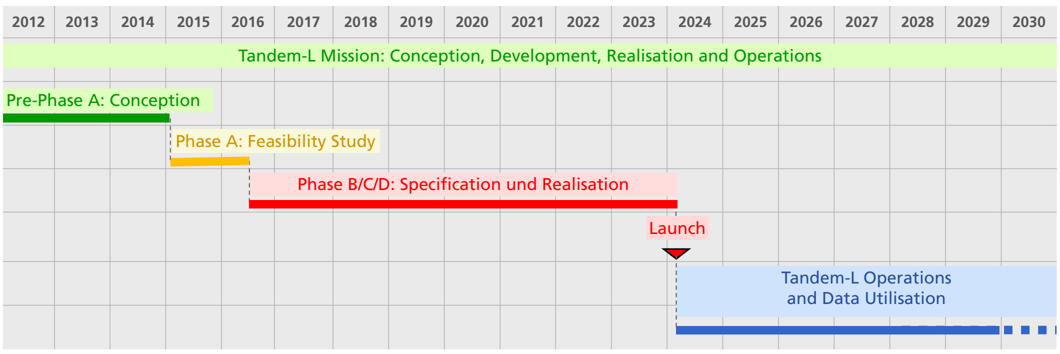
The mission concept was developed in detail in a several-year pre-phase A study. Tandem-L can either be realised within an international cooperation or as a purely national project. With the implementation of Tandem-L, a unique global Earth observatory will be created that will exceed the performance of existing systems by at least one order of magnitude. According to the current planning, the launch of the Tandem-L satellites could take place in 2024. The mission lifetime is planned to be at least ten years. However, the satellite consumables will allow further operation for two to three years.

Ground Segment

The Tandem-L mission is based on the existing DLR infrastructure, which is capable of exploiting the technical possibilities of the radar satellites to the maximum. This is facilitated by the so-called ground segment, which will be provided by DLR Oberpfaffenhofen. The ground segment consists of the planning, operation and control of the satellites according to the data acquisition plan. It controls the orbits of the satellites in formation flight, operates and calibrates the radar instruments, processes the radar data into images and higher-value information products, e.g., tree height, biomass or deformation maps, archives the products and delivers them to the users. Hence, the ground segment represents the interface between the satellites and the scientific and commercial users. As part of the ground segment activities, DLR will also be responsible for the coordination of the science data utilisation. Because of the high degree of scientific and technological innovation, Tandem-L requires a maximum of technical competence and a wide system engineering know-how in the radar field. Both of these have been repeatedly demonstrated by the great success of TerraSAR-X and TanDEM-X.

Space Segment

Since the successful space shuttle radar missions (SIR-C/X-SAR and SRTM), DLR has been cooperating with the German space industry, which has achieved a leading position in the development and construction of highly innovative radar satellites for Earth remote sensing. TerraSAR-X and TanDEM-X are today the most modern radar systems and have a price/performance ratio that is beyond the capabilities of other manufacturers worldwide. Tandem-L builds on the experience with TanDEM-X and will continue its success.



Schedule for the realisation of Tandem-L

Overview and Summary

Tandem-L Key Facts

Mission Profile

The main goal of the Tandem-L mission is the systematic global monitoring of dynamic processes on the Earth's surface with an unprecedented accuracy and resolution. Tandem-L will give answers to highly topical scientific problems pertaining to the biosphere, geosphere, hydrosphere and cryosphere, and it will close gaps in climate research.

In addition to the scientific aspects, Tandem-L will stand out for its highly innovative technology and measurement methods (digital beamforming for greater simultaneous swath width and spatial resolution, and polarimetric SAR interferometry for measuring forest biomass). The unique products generated by Tandem-L will be a milestone in remote sensing. It will stablish and extend Germany's lead in the radar sector.

Scientific Goals

Climate:

- Global measurement of forest biomass and its fluctuation
- Contribution to a better understanding of the carbon cycle (CO_2 sinks and sources)
- Monitoring of melting processes in snow and ice regions
- Quantification of variations in the soil moisture of the surface region
- Measurement of ocean currents
- Measurement of the growth and seasonal change of wetlands and permafrost areas

Biodiversity:

- Global monitoring of the forest structure (e.g. height and vertical profile)
- Quantification of the biodiversity (indirectly derived from the spatial distribution of forest height and biomass)

Earth Dynamics:

- Measurement of topographic changes (e.g. due to earthquakes, volcanoes, etc.)
- Better understanding of earthquake and volcanic activity as a contribution to their prediction
- Monitoring of risk areas contributing to relief measures after catastrophes

Scientific Requirements

- Systematic monitoring of the total land surface with high spatial and temporal resolution
- Utilisation of complementary imaging techniques for the systematic recording of numerous dynamic processes in the different Earth spheres
- Polarimetric SAR interferometry and tomography for the model-based determination of structural and environmental parameters
- Differential SAR interferometry to measure deformations on the land surface with millimeter accuracy
- Minimisation of the temporal decorrelation by the use of single-pass interferometry and a suitable wavelength (L-band)
- Multiple coverage of the Earth's surface according to an optimised imaging schedule to monitor both short and long term variations of biophysical and geophysical parameters

Satellites & Instrument

- Two satellites in formation flight both equipped with a fully-polarimetric L-band synthetic aperture radar (SAR)
- Polar orbit with an altitude of 745 km and approx. 97° inclination (16 day repeat cycle)
- 350 km swath width at a resolution down to 5 m x 7 m
- Global coverage of land surface within 8 days (possible through the use of highly innovative digital beamforming techniques)
- Two-frequency GPS receiver for precise orbit and baseline determination
- Data transmission to the ground of up to 8 terabyte/day using a network of ground stations in Ka-band
- Joint launch of the two satellites, e.g., with the Falcon-9 launcher

Operation and Scientific Use

- Mission operations (control of the satellites and the radar instruments) by DLR
- Optimised systematic imaging plan (formulated by a team of experts according to the scientific requirements and available resources)
- Fully automatic processing chain from raw data up to Level-3/4 products for timely delivery of the high-value geo-information
- Additional generation of co-registered interferometric SAR data sets (Level-1b) for developing new methods and products
- Preparation for the exploitation of the scientific data for a wide-range of applications within the framework of the HGF projects TERENO and ACROSS, as well as the HGF Alliance "Remote Sensing and Earth System Dynamics"

Data Products and Scientific Utilisation

Tandem-L will deliver a unique global data set for numerous scientific applications in the fields of climate research, geodynamics, glaciology, oceanography and hydrology, as well as for communal and statutory duties. Due to the innovative imaging techniques of Tandem-L, it can be expected that many new information products and promising applications will be created.

At the moment, the Tandem-L science team comprises approx. 180 national and international members. The HGF centers AWI, DLR, HZG, GEOMAR, GFZ, HMGU, FZJ, KIT and UFZ form the core of the Tandem-L science team. The scientific mission requirements and products were iterated and refined in cooperation with further partners and in further research programmes (e.g. network EOS, the geo-technology programme Exupery, TERENO and ACROSS).

The optimum exploitation of the Tandem-L data is being actively prepared within the framework of the Helmholtz Alliance "Remote Sensing and Earth System Dynamics". This research network was established in 2012 with a budget of 20 million Euros and comprises 18 partners (9 HGF centers, several universities, as well as MPI and Leibniz institutes), 10 associated partners and more than 30 members of the Tandem-L science team.

With the HGF Alliance, an innovative platform for the education of young scientists has been established and approx. 35 PhD students have been employed.

Thanks to the unique product list of Tandem-L, which includes the measurement of 7 essential climate variables, and to the expertise gained through the HGF Alliance, a quantum leap can be expected in the modelling and extraction of biophysical/geophysical parameters using radar data for monitoring the environment and climate research.

Cooperation with international partners also promises to increase the usefulness of the Tandem-L mission, due to synergy effects.

	Applications/Products	Coverage	Resolution	Accuracy	Repetition Rate
Biosphere	Forest Height	all forest areas	50 m (global) 20 m (regional) 10 m (local)	~ 10 %	every 16 days up to seasonal acquisitions and seasonal to annual product delivery
	Above Ground Biomass		100 m (global) 50 m (regional)	~ 20 % (or 20 t/ha)	
	Vertical Forest Structure		50 m (global) 30 m (regional)	3 layers	
Geo-/ Lithosphere	Tectonics (3D Deformation Rate map)	high strain areas	50 m (global)	1 mm/year (after 10 years)	weekly acquisition; seasonal to annual product delivery
	Volcanoes (Displacement map)	>1500 land volcanos 50 x 50 km	50 m	10 mm	
	Landslides (PSI)	risk areas	7 m	1 mm/year (after 10 years)	
	Subsidence (PSI)	urban areas	7 m	1 mm/year (after 10 years)	
Cryo-/ Hydrosphere	Glacier Flow	worldwide	50 - 500 m	cm - m/year	seasonal
	Ice Structure Change	Greenland	100 m	> 1 layer	annual
	Ice Sheet Elevation	worldwide	50 m	0.5 - 1 m	half a yearly
	Sea Ice	Arctic/Antarctic	5 - 50 km	Thickness <0.5 - 1m Type 5 - 20%	every 16 days up to monthly
	Permafrost regions	selected areas	10 - 20 m	1 cm per season	every 16 days (summer/autumn)
	Agricultural mapping	selected areas	5 - 10m	-	weekly during the growing season
	Soil Moisture	selected areas	50 - 100 m	5 - 10 %	weekly
	Ocean Currents	selected areas	4 - 20 km	5 cm/s	weekly
	Wind Speed Velocity	selected areas	4 - 20 km	2 m/s	weekly
	Ocean Surface Waves	selected areas	5 km	0.1 - 0.25 m / 10°	weekly
Global	Digital Terrain & Surface Models	global/local	12 m	2 m (bare) 4 m (vegetation)	global: annual local: on demand
Emergency	Risk areas	local	-	-	on demand

Summary of important scientific products of Tandem-L

Unique Features of Tandem-L

High Degree of Innovation (Technology and Methodology)

- Tandem-L will generate a high resolution image of the whole of the Earth's surface every 8 days thanks to the latest digital beamforming techniques.
- Tandem-L will exceed the imaging performance of all existing SAR satellites by more than a factor of ten and therefore lead the SAR development by at least 7 years.
- For the first time, Tandem-L will determine the vertical structure of vegetation and ice over the whole globe by using SAR interferometry and tomography techniques, which were developed in Germany.
- Nine Helmholtz centers and numerous associated facilities are already active in an HGF alliance to prepare comprehensive and systematic exploitation of the Tandem-L data.
- Already more than 100 research institutes have expressed great interest in using Tandem-L data and are members of the Tandem-L science team.
- Tandem-L has unparalleled potential for monitoring the environment, increasingly required today.
  An example is the REDD+ programme for protecting the forests.

Programmatics

- Tandem-L will extend Germany's leading role in the field of synthetic aperture radar (SAR). Tandem-L builds on the know-how from past German SAR missions.
- Tandem-L will demonstrate a strong commitment to climate protection and open up new avenues to international cooperation.
- Tandem-L lays the foundation for a unique spaceborne Earth observatory for continuous monitoring of the Earth and its environment, analogous to the existing network of weather satellites.

Combining X & L-band

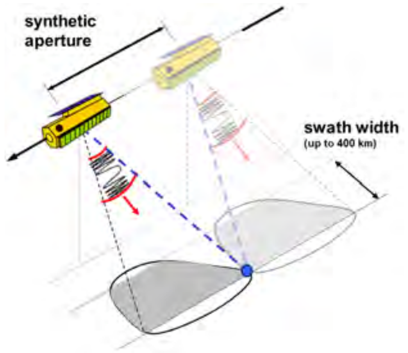
- One of the most important discoveries from the SIR-C/X-SAR space shuttle missions was that L-band and X-band are the optimum frequency combination for the overwhelming majority of applications. The continuity of the German X-band development line has very high priority and a new L-band line is the ideal extension.

Scientific Excellence

- For the first time, with Tandem-L it will be possible to measure seven essential climate variables within the scope of a single satellite mission.
- Tandem-L is the first mission for the systematic high-resolution monitoring of dynamic processes in the bio-sphere, geosphere, cryosphere and hydrosphere.
- Tandem-L will help Germany to attain a leading position in Earth system, climate and environmental research.

Numerous national and international facilities are affiliated to the Tandem-L science team. The scientific data exploitation from Tandem-L is being prepared as part of the Helmholtz Alliance „Remote Sensing and Earth System Dynamics", in which already more than 130 scientists from Helmholtz centres (AWI, DLR, HZG, GEOMAR, GFZ, HMGU, FZJ, KIT and UFZ), Max-Planck and Leibniz institutes and other national and international universities and research institutes are involved.

Synthetic Aperture Radar (SAR)



Synthetic aperture radar (SAR).
The formation of a synthetic aperture several kilometers long enables a high-resolution independent of the range distance.

Because of their independence of weather and daylight conditions, SAR instruments are an indispensable source of Earth observation data and enable numerous powerful applications.

The spectrum of scientific and commercial applications is widening continuously and comprises the following fields:

- Climate research: observation of vegetation parameters like biomass
- Solid Earth physics: monitoring of plate tectonics, volcanism, earth-quakes, landsides and subsidence
- Hydrology: measurement of soil moisture and modelling of precipitation run-off regions
- Oceanography: monitoring of currents and ocean floor topography, measurement of wind and wave fields
- Glaciology: monitoring of glaciers and the polar ice masses

SAR data products are also essential for performing communal and statutory duties: examples are the provision of digital terrain models and topographic maps for regional planning, environmental monitoring, air traffic control and mobile telecommunication services, as well as high-resolution SAR images for disaster relief and intelligence, independent of the optical visibility.

SAR is the only sensor that can provide global, high-resolution and wide-scale imaging of the Earth's surface. For this reason, spaceborne SAR instruments are predestined to generate geo-information and to do this rapidly, universally and continuously.

River mouth at Balikpapan, Indonesia. The shrimp breeding grounds enclosed by the mangrove forests can be clearly seen. The fully polarimetric L-band radar image was taken in November 2004 with DLR's airborne SAR system.

Germany's Leading Position in Radar Technology

Together with German industry, DLR has achieved a leading position amongst its worldwide competitors in the field of high-resolution radar.

Why is DLR so successful in the field of radar remote sensing?

- Overall system competence was strived for from the outset, i.e., covering all stages from the image generation up to data interpretation and researching new technologies and methods.
- A strategy and roadmap for future radar missions was developed in close collaboration with DLR Execuctive Board, Space Administration, Programme Directorate, research institutes and German industry.
- All the German missions were logical steps in the radar development line.
- German industry has a leading position in highly innovative radar technology with an excellent price-performance ratio and cooperates closely with DLR.
- The strategic long-term planning of the radar Earth observation development line has been systematically realised as a core activity by DLR Executive Board, the Space Administration and Programme Directorate. Consequently, with the TerraSAR-X and TanDEM-X missions, an international leading role has been attained in high-resolution radar remote sensing.

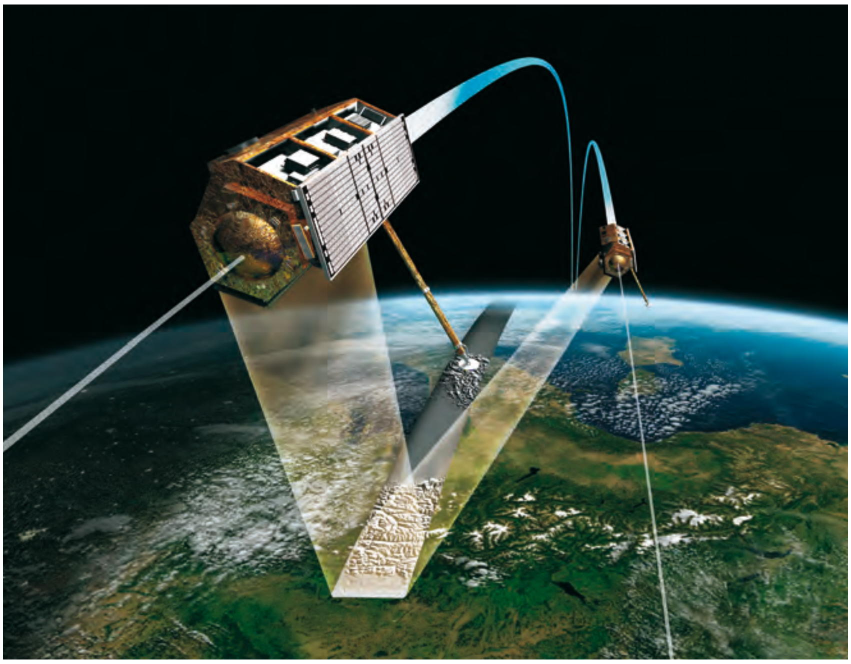
Why does Germany need a radar mission following TanDEM-X?

- If the successful radar development line isn't to be interrupted, the way has to be prepared for a follow-on mission after TanDEM-X. Preliminary studies, approval and realisation of a space mission take approximately six to seven years. Hence, the launch of a new mission cannot take place before 2024.
- With radar missions, increasingly strong competition can be expected. The current leading international position is quickly lost unless we develop innovative radar concepts and turn them into missions.

The mission proposal as a follow-on of TanDEM-X has to be technologically highly innovative to maintain or even extend Germany's leading position in the radar field.

It also has to complement the programmatic radar development line.

In this context, it is essential that the mission provides answers to urgent scientific problems pertaining to dynamic processes on the Earth's surface. Tandem-L can therefore be regarded as the next logical step in the radar development line.



The TanDEM-X mission is the first radar interferometer in space with the controlled formation flight of two radar satellites.

Roadmap for Earth Observation

The current radar roadmap of the German Space Administration foresees a sustained X-band development line.

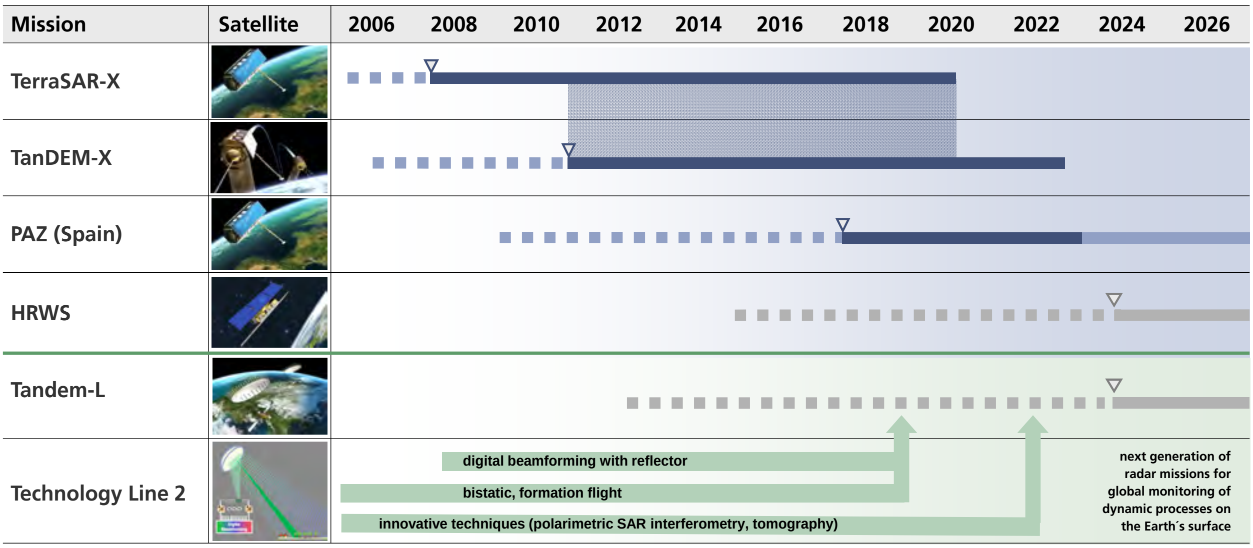
The launch of TanDEM-X in June 2010 clearly extended Germany's lead in high-resolution radar remote sensing and technology. The successful development of radar technology in X-band was achieved by systematically following a programmatic development line in the national space programme, supported by technology funding since the 1980s.

The DLR roadmap for future X-band radar missions foresees a new-generation SAR (HRWS) mission with digital beamforming. Because the instrument design of TerraSAR-X and follow-on missions is centered on achieving high-resolution, commercial exploitation and product services (e.g. Copernicus) will take precedence in the future, although scientists will still be greatly interested in utilising the radar data.

Tandem-L is a unique opportunity to closely connect diverse activities in the participating Helmholtz centres, Max-Planck institutes and universities across different areas of research within a single interdisciplinary project (Helmholtz Alliance "Remote Sensing und Earth System Dynamics").

The expertise of the respective research centers in terms of particular modelling techniques is of central importance to the generation of highly aggregated information products. In addition, Tandem-L offers fresh opportunities for international cooperation with worldrenowned research groups, and highly fruitful collaborations as well as synergetic effects are to be expected given the complementary expertise in data exploitation and modelling. According to the current schedule, the Tandem-L satellites are to be launched in 2024 and operated for at least 10 years thereafter.

Radar development line — German radar missions

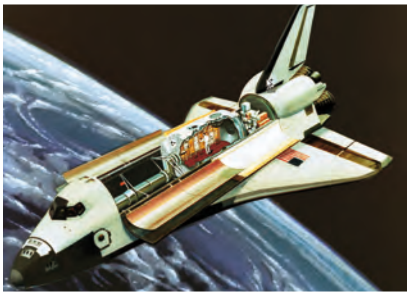


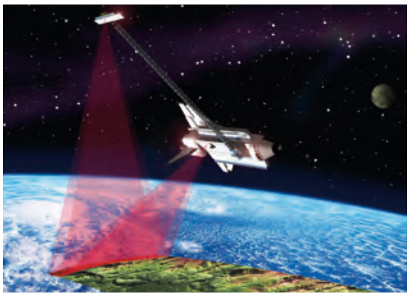
German Radar Missions

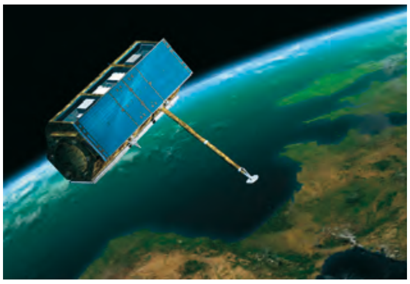
MRSE (**M**icrowave **R**emote **S**ensing **E**xperiment) comprised a compact X-band microwave sensor, which flew with the SPACELAB on the space shuttle in 1983. There were three operating modes: SAR, radiometer and scatterometer. Due to a short-circuit in the transmit TWT, the SAR and scatterometer only operated for a few seconds. In spite of this fault, this experiment was decisive for the future radar development in Germany.

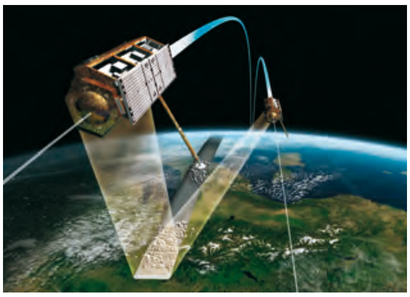
SIR-C/X-SAR – The **S**huttle **I**maging **R**adar missons consisted of two flights in April and September 1994. It had the goal to demonstrate the potential of a polarimetric radar system with three different frequencies for a variety of applications. Germany developed the X-band radar system in cooperation with Italy, and the C-band and L-band systems were developed by the USA. The two SIR-C/X-SAR missions set new standards in scientific remote sensing with multi-frequency, multiple-polarisation SAR systems. The combination of L-band, C-band and X-band data sets with different polarisations are unrivalled to this day.

SRTM (**S**huttle **R**adar **T**opography **M**ission) was a highlight of the radar activities in Germany and was realised in a cooperation with NASA/JPL.
On the 11th February 2000, SRTM was launched on the space shuttle Endeavour and is unique in mapping the Earth's topography with two radar systems. Within only 11 days, a total of 3600 gigabytes of X-SAR/SRTM data were recorded. With the aid of secondary antennas mounted on a 60 m long mast, it was possible to map approx. 80% of the land surface with a height accuracy of 10 m. Germany contributed an interferometric X-band radar system (X-SAR) that additionally mapped 40% of the land surface with an increased accuracy of 6 m.









TerraSAR-X is the latest generation of radar satellites and was launched on the 15th June 2007 from Baikonur/ Kazakhstan. Since then, the satellite has been orbiting the Earth at an altitude of 514 km in a polar orbit. With its active radar antenna, it generates images with a maximum resolution of one meter. TerraSAR-X is Germany's first radar satellite and was realised in a public-private partnership between DLR and Airbus Defence and Space.

TanDEM-X (**T**erraSAR-X **a**dd-o**n** for **D**igital **E**levation **M**easurement) has generated a global digital elevation model with an unsurpassed accuracy from space (2 m height accuracy with 12 m spacing). The TanDEM-X satellite was launched in June 2010 and is since then in tandem formation with its twin TerraSAR-X.
The two satellites form a large radar interferometer in space. TanDEM-X was implemented in a continuation of the public-private partnership established for TerraSAR-X between DLR and Airbus Defence and Space.

DLR at a Glance

DLR is the national aeronautics and space research center of the Federal Republic of Germany. Its extensive research and development work in aeronautics, space, energy, transport and security is integrated into national and international cooperative ventures. In addition to its own research, as Germany's space agency, DLR has been given responsibility by the federal government for the planning and implementation of the German space programme. DLR is also the umbrella organisation for the nation's largest project management agency.

DLR has approximately 8000 employees at 20 locations in Germany: Cologne (headquarters), Augsburg, Berlin, Bonn, Braunschweig, Bremen, Bremerhaven, Dresden, Goettingen, Hamburg, Jena, Juelich, Lampoldshausen, Neustrelitz, Oldenburg, Oberpfaffenhofen, Stade, Stuttgart, Trauen, and Weilheim. DLR also has offices in Brussels, Paris, Tokyo and Washington D.C.

DLR's mission comprises the exploration of Earth and the Solar System and research for protecting the environment. This includes the development of environment-friendly technologies for energy supply and future mobility, as well as for communications and security. DLR's research portfolio ranges from fundamental research to the development of products for tomorrow. In this way, DLR contributes the scientific and technical expertise that it has acquired to the enhancement of Germany as a location for industry and technology. DLR operates major research facilities for its own projects and as a service for clients and partners. It also fosters the development of the next generation of researchers, provides expert advisory services to government and is a driving force in the regions where its facilities are located.

DLR **Deutsches Zentrum für Luft- und Raumfahrt**

Microwaves and Radar Institute

Oberpfaffenhofen
D-82234 Weßling

www.DLR.de/HR