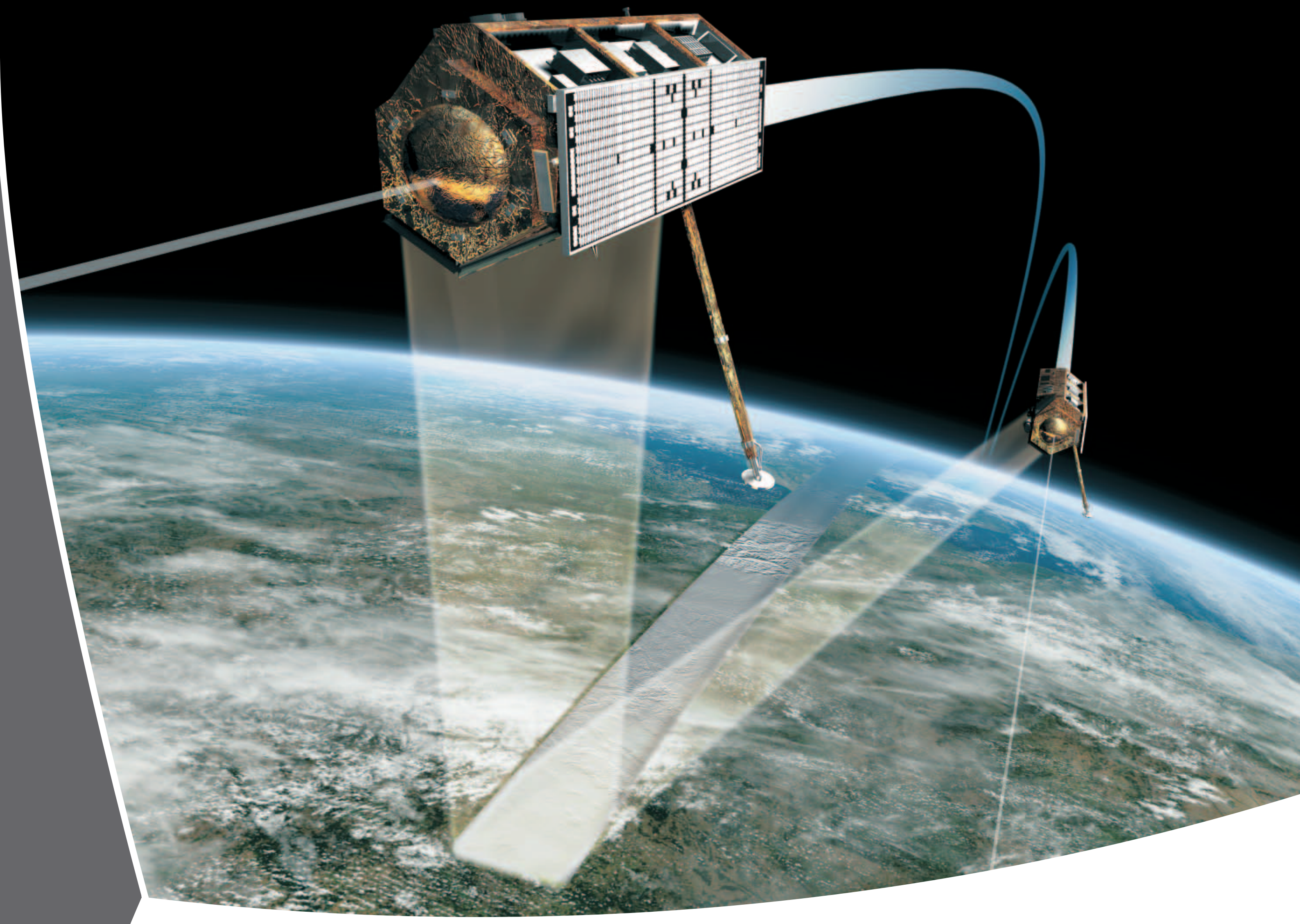

TanDEM-X

The Earth
in three dimensions

DLR

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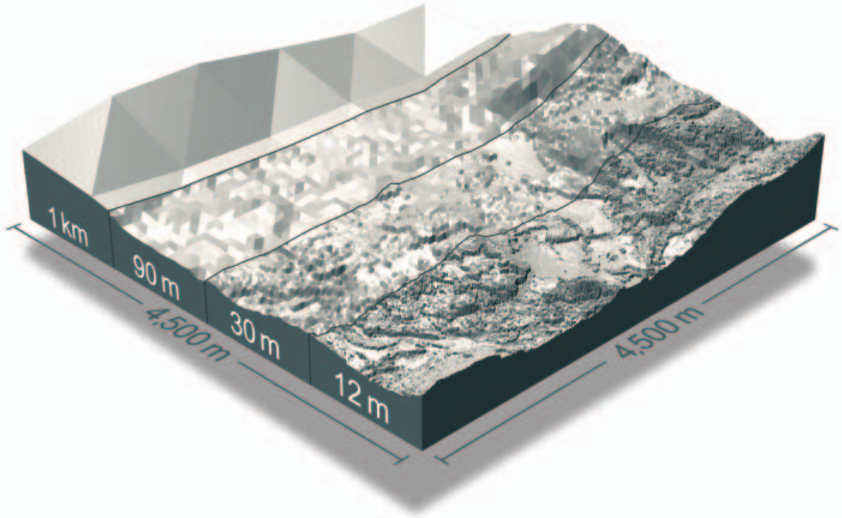
The Earth in three dimensions

The main objective of the TanDEM-X mission is to generate an accurate three-dimensional image of Earth that is homogeneous in quality and unprecedented in accuracy.

At present, the elevation models that are available for large parts of Earth are of low resolution, inconsistent or incomplete. In addition, they are commonly based on different data sources and survey methods. TanDEM-X, TerraSAR-X add-on for Digital Elevation Measurement, is designed to close these gaps and deliver a homogenous elevation model that should prove indispensable for many scientific and commercial applications. Orbiting Earth at an altitude of around 500 kilometres, two nearly identical radar satellites have begun mapping its surface. The first of the two, TerraSAR-X, has been operating since 2007. Three years on, TanDEM-X, its twin satellite, has joined it. Flying in close formation, only a few hundred metres apart, the two satellites are imaging the terrain below them simultaneously, from different angles. These images are processed into accurate elevation maps with a 12-metre resolution and a vertical accuracy better than 2 metres. The amount of data generated by the satellites will grow to 1.5 petabytes within three years, corresponding to a storage capacity of almost 200,000 DVDs. Like the TerraSAR-X mission, TanDEM-X is a project developed under a public-private partnership between the German Aerospace Center, DLR, and Astrium GmbH based in Friedrichshafen, Germany.



Horizontal resolution of elevation models; from top-left: 1 km – 90 m – 30 m – 12 m (TanDEM-X)

A German key project

Following in the footsteps of European radar satellites ERS-1, ERS-2, Envisat and TerraSAR-X, as well as the joint US-German-Italian Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR) that flew on the Space Shuttle and the US Shuttle Radar Topography Mission, TanDEM-X seeks to support scientific and commercial applications of radar-based Earth observation. Demonstrating Germany's expertise in satellite-based radar technology, the mission is the result of a long-term focus in Germany's national space programme. The German Federal Ministry of Economics and Technology has funded the project (code 50 EP 0603).

The TanDEM-X mission

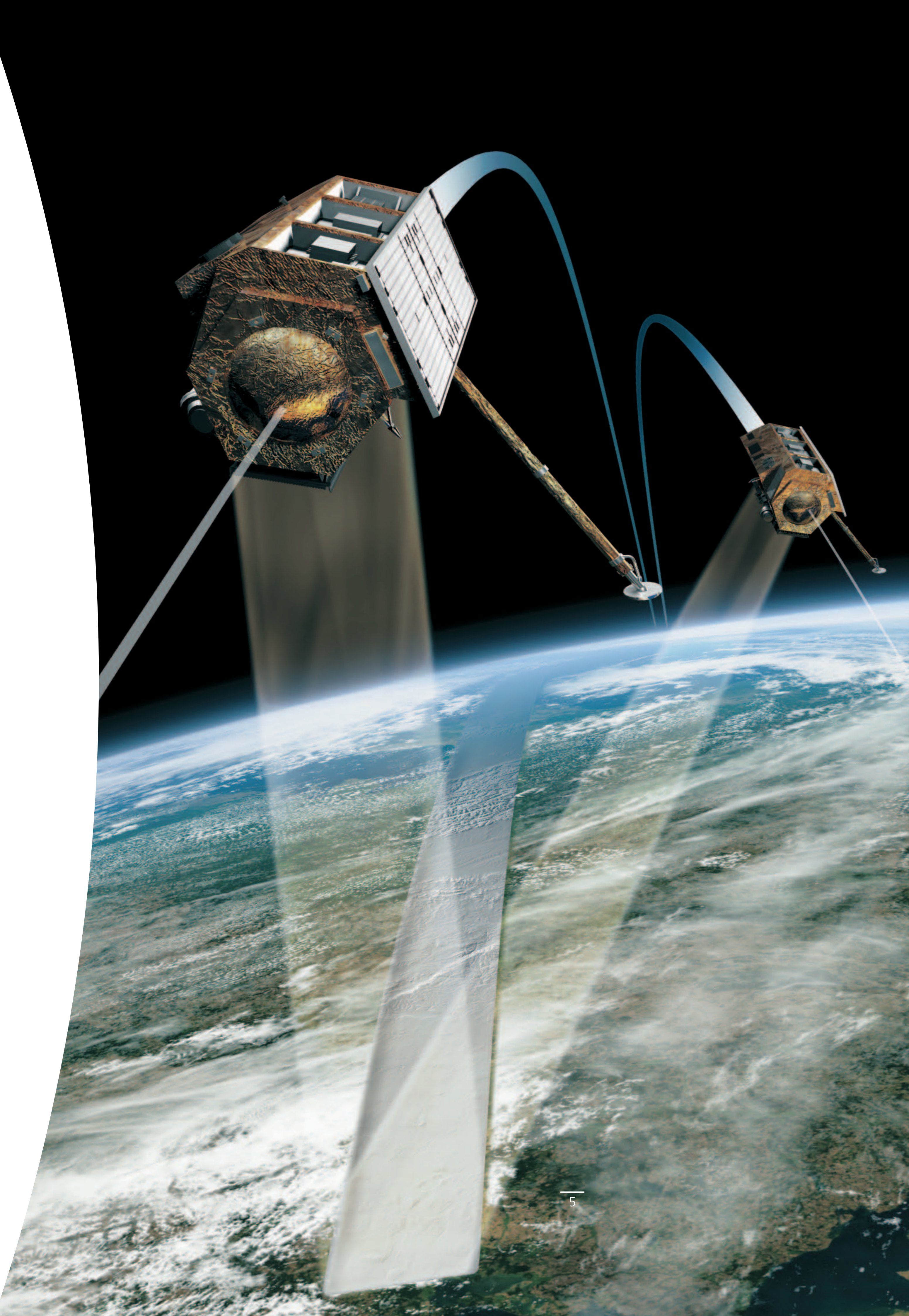
The TanDEM-X mission will survey all 150 million square kilometres of Earth's land surface several times over during its three-year mission. Apart from its high measuring-point density (a 12-metre grid) and high vertical accuracy (better than two metres), the elevation model generated by TanDEM-X will have another unrivalled advantage – being entirely homogenous, it will serve as a basis for maps that are globally consistent. Conventional maps are often fragmented along national borders, or difficult to reconcile as they are based on different survey methods or because of time lags between survey campaigns.

Together TanDEM-X and TerraSAR-X form the first configurable synthetic aperture radar interferometer in space.

Besides this primary goal, the mission has several secondary objectives based on new and innovative methods such as along-track interferometry, polarimetric synthetic aperture radar interferometry, digital beamforming and bistatic radar.

The TanDEM-X satellite follows the TerraSAR-X design with minor modifications such as an additional cold gas propulsion system (powered by high-pressure nitrogen gas) to enable fine-tuning of its relative position during formation flying and an additional S-band receiver to receive status and position information sent from TerraSAR-X. The TanDEM-X satellite has been designed for a nominal lifetime of five years and has a planned overlap with TerraSAR-X of three years. TerraSAR-X holds consumables and resources for up to seven years of operation, however, potentially allowing for a prolongation of the overlap and the duration of the TanDEM-X mission.

Flying in formation, TanDEM-X and TerraSAR-X will generate a precise global elevation model.



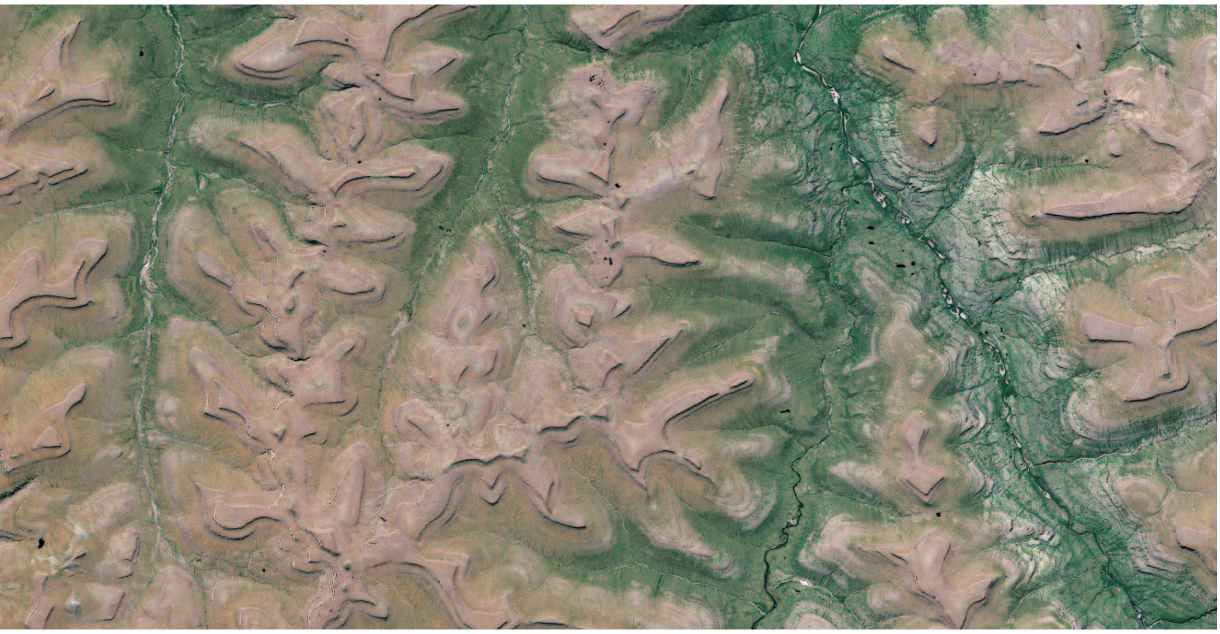
Public-private partnership

The TanDEM-X mission is financed and implemented as a public-private partnership between DLR and Astrium.

DLR is responsible for providing TanDEM-X data to the scientific community, mission planning and implementation, radar operation and calibration, control of the two satellites, and generation of the digital elevation model. To this end, DLR has developed the necessary ground-based facilities. The project's scientific coordination has been entrusted to the DLR Microwaves and Radar Institute in Oberpfaffenhofen, headed by Prof. Alberto Moreira.

Astrium has built the satellite and shares the cost of its development and use. Infoterra GmbH, a subsidiary of Astrium, is responsible for commercial marketing of the data from both missions, TerraSAR-X and TanDEM-X.

Because of the participation of industry, DLR and the Government in this public private partnership, high scientific and commercial yields can be generated at comparatively low cost.



Research institutes and industry are working in close cooperation on the TanDEM-X mission, developing a precise and homogenous survey of Earth's land surface.

TanDEM-X data for science

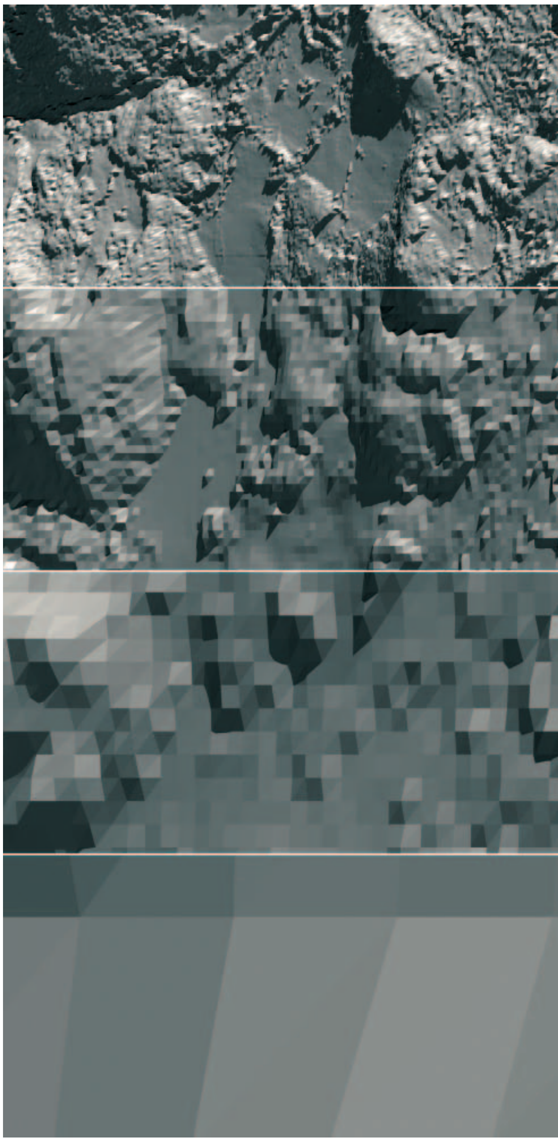
Digital elevation models are of fundamental importance across a wide range of commercial and scientific applications. Accurate and up-to-date information about Earth's surface and its topography is urgently needed for many geoscience research fields, including hydrology, glaciology, forestry, geology, oceanography and environmental research. Moreover, the accuracy of digital maps must keep step with the development of global positioning and navigation systems, such as GPS and the upcoming Galileo system. A wide-ranging user survey among scientists has clearly shown that many applications require both extended latitudinal coverage and improved accuracy, meeting the stricter specifications for a digital elevation model, such as those laid down by the US National Geospatial-Intelligence Agency.

Beyond its primary objective of generating a global digital elevation model, the TanDEM-X mission has a range of secondary objectives that involve testing new technologies. Most of these objectives are experimental and demonstrations are restricted to typical cases, given the satellite's limited resources.

Helix orbit

The TanDEM-X mission concept is based on the coordinated operation of two spacecraft flying in close formation. Using two independent spacecraft provides the flexible and reconfigurable imaging geometry required to meet the various mission objectives. For example, the primary goal of generating a precise digital elevation model requires variable cross-track 'baselines' – the distance between the satellites - of around 200 to 500 metres. At such short distances, collision avoidance becomes a major issue and a minimum safe distance of 150 metres perpendicular to the flight direction has to be maintained throughout the orbit.

The helix orbit fulfils these requirements. The helix-like relative motion of the satellites along the orbit is achieved by combining an out-of-plane (horizontal) orbital displacement imposed by different ascending nodes with a radial (vertical) separation imposed by the combination of different eccentricities and arguments of perigee. Since their orbits never cross, the satellites can be arbitrarily shifted along them. This enables safe spacecraft operation without the need for autonomous control. Cross-track baselines varying from 200 metres to 10 kilometres and along-track baselines from zero to several hundred kilometres can be achieved accurately. It is also possible to optimise the along-track displacement at predefined latitudes for different applications. Fine-tuning of the satellite formation will be performed with the cold gas propulsion system on TanDEM-X.



Digital terrain models provide the basis for many commercial and scientific applications. Horizontal resolution of elevation models, from top to bottom:
12 m (TanDEM-X) – 30 m – 90 m – 1 km

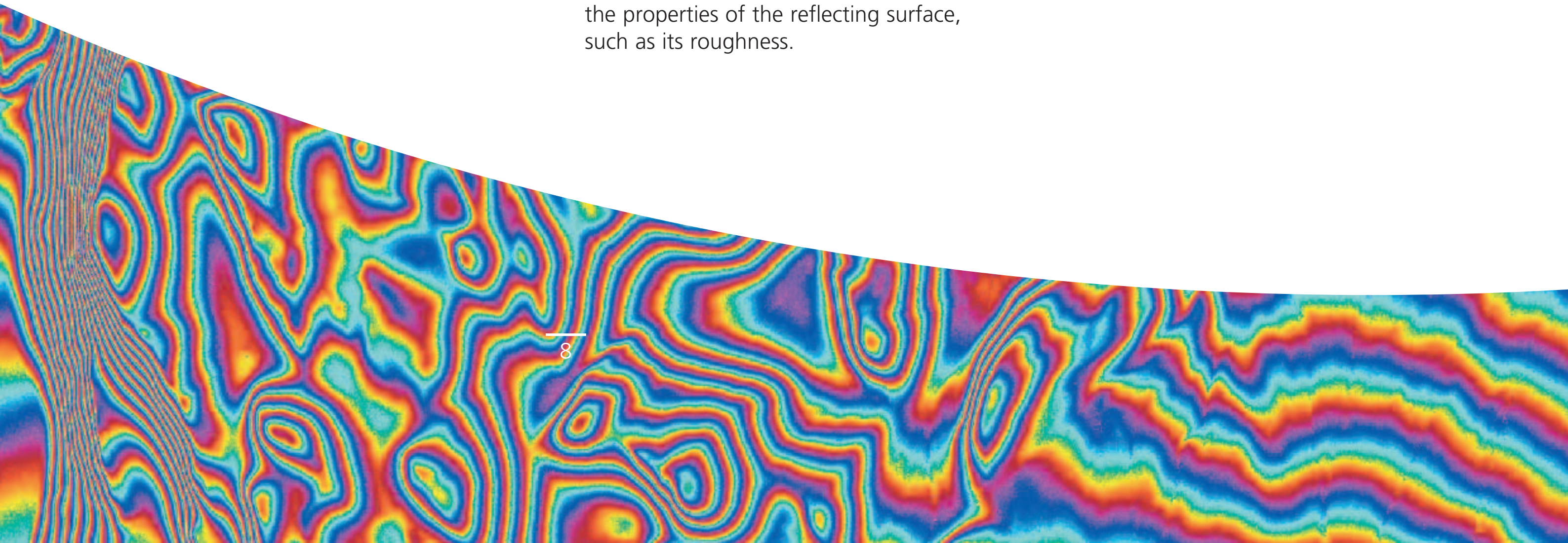
The helix orbit enables complete coverage of Earth with an adequate baseline geometry using a limited number of formation flight configurations. Southern and northern latitudes can be mapped with the same formation by using ascending orbits for one hemisphere and descending orbits for the other. Fine-tuning of the cross-track baselines can be achieved by taking advantage of the natural rotation of the eccentricity vectors due to secular disturbances, known as 'motion of libration'. The phases of this libration can be kept in a fixed relative position with small daily manoeuvres using the cold gas thrusters, while major formation changes, as well as a duplication of the orbit-keeping manoeuvres required by TerraSAR-X, will be performed using the hydrazine propulsion system.

Synthetic aperture radar interferometer

Conventional radar satellites operate using the principle of synthetic aperture radar. The radar transmits pulses of microwave energy and these are reflected from Earth ,s surface to be received again by the radar. From the round-trip transit time of the signals, the distance of the satellite from Earth's surface can be calculated. As the satellite orbits Earth, the radar illuminates a strip of ground beneath it and records the reflected signals sequentially. After intensive signal processing a two-dimensional image of the area is generated. The received echo signals also contain information about the properties of the reflecting surface, such as its roughness.

Synthetic aperture radar interferometry is a further development of this basic technique. The target land area is imaged from two different positions. The principle is similar to human stereoscopic vision, where depth perception – determining the distance of an object from the viewer – is achieved by viewing the object from slightly different angles with a pair of eyes. The 'radar eyes' are located on the satellites TerraSAR-X and TanDEM-X, which are orbiting Earth in close formation.

Because the satellites are a set distance or 'baseline' apart each other, the 'path length' that the signal travels as it is reflected back from each point on the ground will differ slightly for each of them – and by measuring these differences precisely enough elevation information can be derived. This is done by using the wave properties of the radar pulse and examining the relative time shifting of the waves due to the differing path lengths. This is also called 'phase difference measurement'. The result of performing these measurements for each point over an area of Earth's surface is an interference pattern called an interferogram. From the measured differences in path length, the desired height information is obtained, with interference 'fringes' that resemble contour lines on a conventional map.



Applications

The TanDEM-X mission design is flexible. In the course of the mission, imaging technologies may be selected from the available range as needed for use in various applications and experiments. In this context, a basic distinction must be made between across-track and along-track synthetic aperture radar interferometry. Both methods are based on measuring the path length difference when the same radar transmission is received separately by the antennas of the two satellites. With both satellites moving parallel to each other, such path differences in across-track direction can be used to compute elevation information needed in the applications described below.

Across-track synthetic aperture radar interferometry

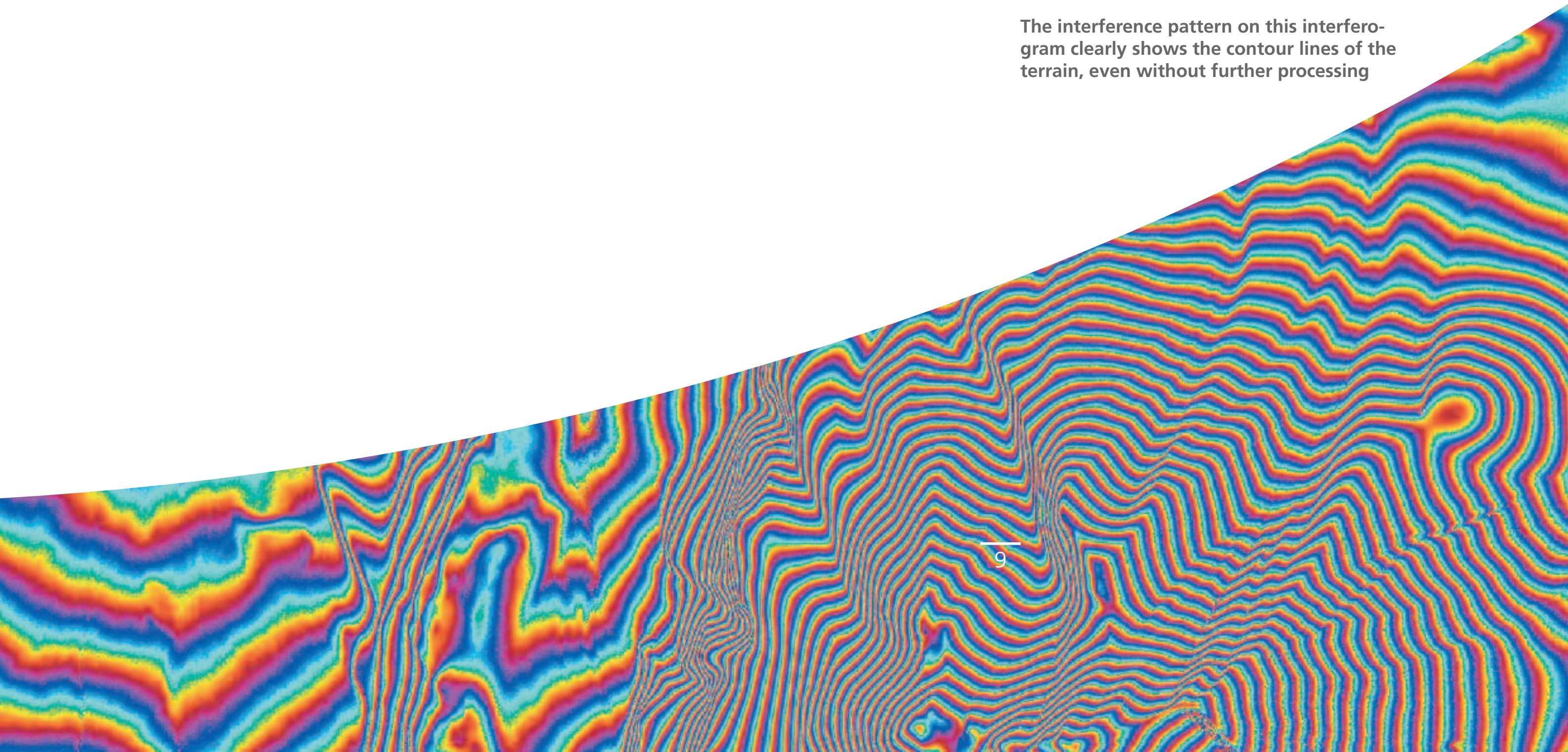
Topographical maps

Local topographical maps are generally available in industrialised regions. On a global scale, however, the information they provide is inadequate. The existing gaps can however be filled by a digital elevation model derived from synthetic aperture radar interferometry data. Current research focuses particularly on the development of algorithms for validating and calibrating elevation data. Another important aspect is the development of tools for visualising three-dimensional elevation maps.

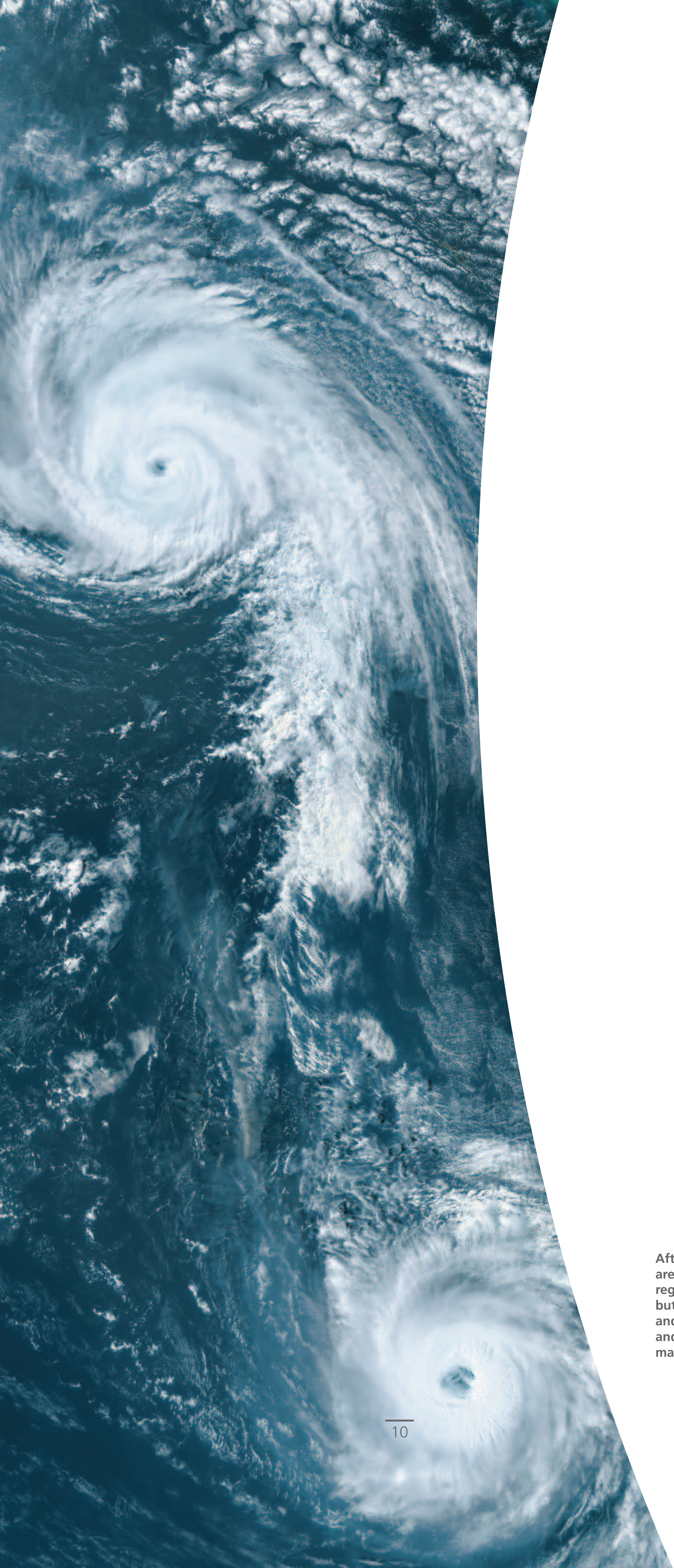
In addition, high-resolution elevation models are needed to eliminate distortions caused by surface relief from Earth observation images. 'Orthorectification' enables images to be superimposed and blended with geometrical precision. Terrain models subsequently integrated in geographical information systems may be linked to additional physical and socio-economic data for further evaluation. Municipalities, for instance, use geographical information system data for zoning.

Land use and vegetation

High-resolution synthetic aperture radar interferometry also makes it possible to survey vegetation in three dimensions. Such surveys reveal the size of treetops, their vertical distribution and gaps in the forest. Forest and fire protection services, as well as conservation efforts, stand to benefit from this information, which also improves the quality of land use and forest rehabilitation planning. Data supplied by observing forests and charting their growth phases improves our understanding of the global carbon cycle and assists in biodiversity research. The data provided by the TanDEM-X mission is unrivalled in its resolution and temporal coherence.



The interference pattern on this interferogram clearly shows the contour lines of the terrain, even without further processing



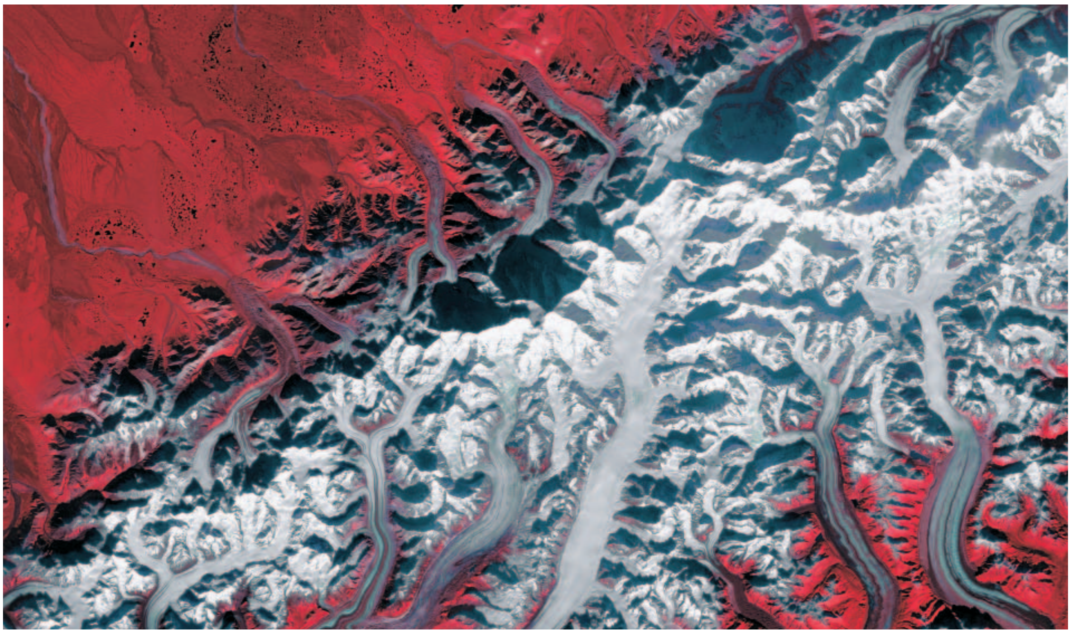
Navigation

The need for a high-quality, homogenous global terrain database is particularly urgent in safety-critical applications. Warning systems in aircraft cockpits are a case in point. One of these, the ground proximity warning system, gathers various flight data at low altitude and sounds the alarm if the aircraft's altitude falls below a critical limit. Precise terrain models would improve the reliability of these systems. The same holds true for synthetic vision systems that provide pilots with a three-dimensional view of their current environment, even in conditions of low visibility. The databases currently used by these systems are derived from various sources that conform to diverse specifications and standards. In future, terrain databases will have to adhere to reliable, validated and standardised quality parameters. The contribution made by the data from TanDEM-X will certainly be very important in this context.

Crisis management

Disaster management is another field in which terrain models are urgently needed. Whenever a disastrous flood or earthquake occurs, satellite images and three-dimensional terrain maps provide relief agencies with precise information about the situation on the ground, even before they reach the area. TerraSAR-X has become a vital part of satellite-based crisis management. Even when a location is under dense cloud cover, radar images can complement optical images, providing additional important information about the extent of the areas affected. TanDEM-X is increasing the effectiveness of these applications.

After earthquakes and volcanic eruptions, hurricanes are among the worst natural disasters in the Pacific region. People are threatened not only by high winds but also, and much more severely, by massive rainfall and the floods and landslides they cause. TerraSAR-X and TanDEM-X will provide important data for crisis management in the event of a catastrophe.



At 6,194 metres, Mount Denali (also known as Mount McKinley) is the highest peak on the North American continent. TerraSAR-X and TanDEM-X will permit continuous observations of inaccessible glaciers everywhere in the world.

Hydrology

High-resolution digital elevation models are also used to generate maps of areas at risk of flooding. These serve to assess risks and to identify hydrological and topographical characteristics. Information about drainage channels and soil moisture may be used as input parameters for weather and climate models set up on geographical scales of various sizes. Data from TanDEM-X may close the gaps in these hydrological models.

Another example is the transnational modelling of watershed yields that depends on reliable and consistent data and information about the local topography and vegetation. The option to monitor minor changes in topography or vegetation over space and time is a novelty in remote sensing. TanDEM-X will facilitate this even in the remotest regions.

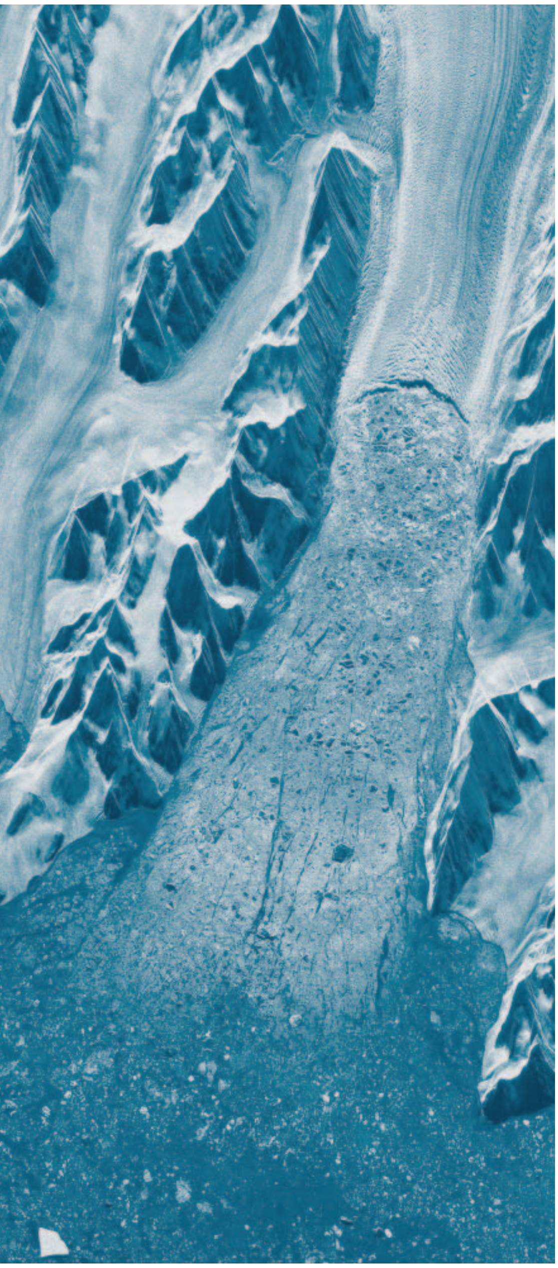
Geology

Terrain models form an essential basic element of geological research. Geological maps showing volcanic regions and earthquake zones are particularly interesting because, given a resolution of about one metre, they will show precisely what changes occur after an eruption or an earthquake. Unlike volcanic regions that are mostly well mapped, data of comparable quality are often lacking in regions threatened by earthquakes or ground subsidence. Similarly, the elevation data required to assess the tsunami risk across coastal areas is often incomplete. Here, TanDEM-X is a rich new source of information.

Glaciology

Changes in the mass of polar ice caps and glaciers represent evidence that the climate is changing. TanDEM-X is surveying the surface topography and size of these bodies of ice. Repeated measurements should permit scientists to measure ice losses and gains – important input parameters for climate models and forecasts that estimate global mass balances.

TanDEM-X may also help us understand the dynamics of the Antarctic ice sheet. One important parameter for the detection of ice sheet changes is its ‘grounding line’. Although this point of anchor on the ground is hidden under several hundred metres of ice, it can be identified by synthetic aperture radar interferometry. Differences in elevation that occur as the ice is raised and lowered by the tides can be measured by differential synthetic aperture radar interferometry so that the borderline between land and water concealed beneath the ice can be determined. So far, this method has been applied successfully only in a few locations. TanDEM-X will facilitate mapping of this marginal zone more systematically.



This TerraSAR-X radar image shows a region that was completely covered by an ice shelf five years ago. Under current conditions, calving glaciers drop ice directly into water that is largely covered by sea ice. The Larsen ice shelf has been shrinking at a rate of about one kilometre per year for the last 60 years.

Along-track synthetic aperture radar interferometry

Along-track synthetic aperture radar interferometry offers entirely new opportunities. This application uses two separate radar antennas arranged longitudinally along the direction of flight, a method that permits the measurement of the speed of moving objects as the two satellites image the same area successively, with a brief interval in between. The method is used particularly in oceanography, glaciology, and traffic research.

Oceanography

As TanDEM-X is capable of measuring water currents, its data will help to draw conclusions on several related features and processes, including the relief (bathymetry) of seafloors and riverbeds and silt deposition in navigation channels. Coastal current maps are also of great value in the planning of tidal power plants.

Only the combination of TanDEM-X and along-track synthetic aperture radar interferometry can permit, for example, measurement of the flow rates of otherwise inaccessible rivers so that their transport volume can be calculated. At present, radar altimeters can only measure water levels directly rather than flow.

Traffic monitoring

The ability to identify moving objects and measure their velocity is of great interest for traffic monitoring. TerraSAR-X can do this on its own but only for one direction of motion. With two satellites working in tandem it is now possible to monitor different speed velocity ranges – adjustable through shifting the distance between the satellites. In so doing, TanDEM-X may well be the precursor of a space-based system for assessing traffic flow.

Glaciology

Along with the topography of ice caps and glaciers and grounding line positions, flow rates are an important parameter for ice and climate researchers. To monitor the flow rate of fast-moving glaciers, images have to be taken at intervals of about one day or less. The high-resolution imaging mode of TanDEM-X will enable the determination of glacier flow rates with unprecedented precision.

Innovative new radar techniques and applications

TanDEM-X will also test innovative radar technologies such as polarimetric synthetic aperture radar interferometry. This is an innovative remote sensing technique that allows the investigation of the three-dimensional structure of natural volume scatterers. Interferometric observables are very sensitive to the spatial variability of vertical structure parameters and allow accurate three-dimensional localisation of the scattering centre. At the same time, scattering polarimetry is sensitive to the shape, orientation and dielectric properties of scatterers and allows the identification and/or separation of scattering mechanisms of natural media. In polarimetric synthetic aperture radar interferometry, both techniques are combined to provide sensitivity to the vertical distribution of scattering mechanisms. Hence, it becomes possible to investigate the three-dimensional structure of volume scatterers such as agricultural fields and to extract information about the underlying scattering processes. In addition, TanDEM-X will demonstrate a number of other innovative technologies such as bistatic observation and digital beam forming.

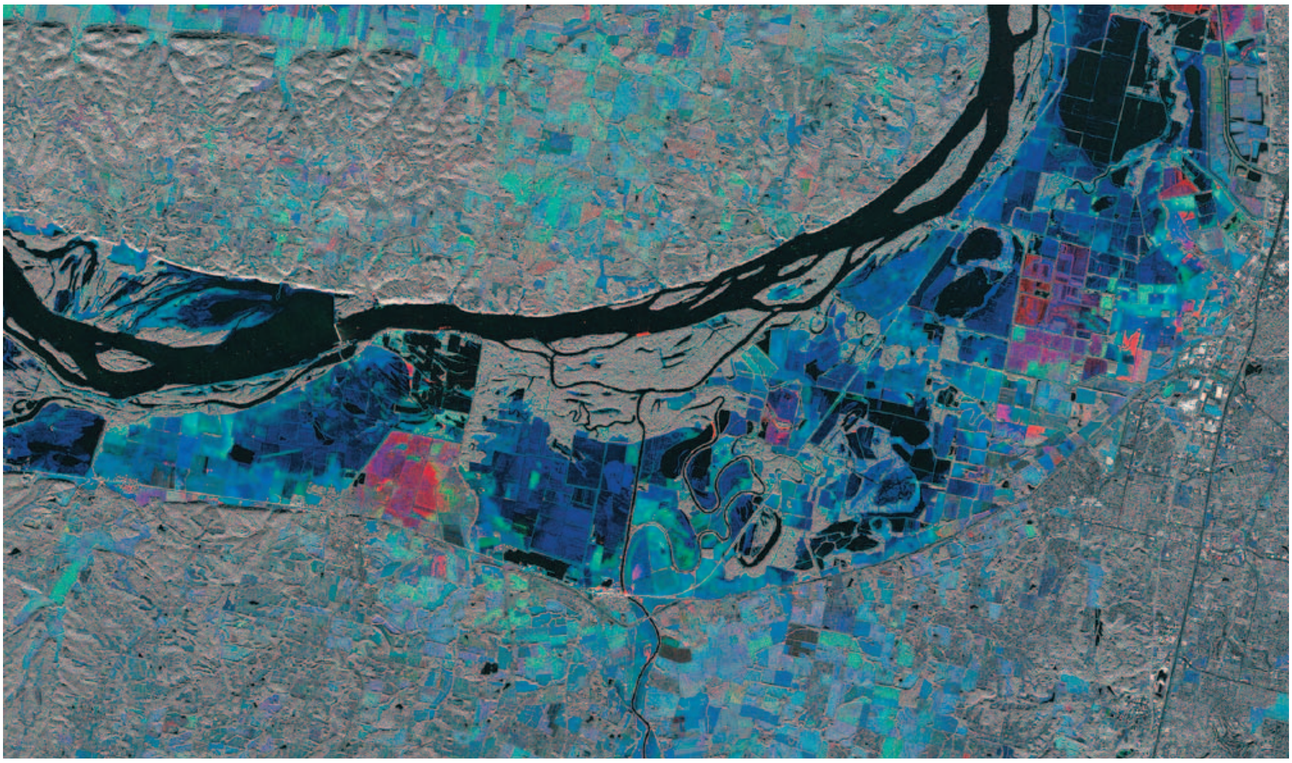
Commercial use

The public-private partnership agreement concluded between DLR and Astrium also deals with the commercial marketing of maps and data. Founded specifically to commercialise TerraSAR-X in 2001, Infoterra GmbH, a subsidiary of Astrium, will be responsible for supplying the elevation models delivered by TanDEM-X to customers all over the world.

Since TerraSAR-X entered operational service early in 2008, Infoterra has been setting up a distribution network with more than 50 partners in 33 countries. This broad commercial base serves to market TanDEM-X data and products with the maximum possible customer application flexibility.

Customers from both the private and the public sector are awaiting the TanDEM-X elevation model, whose quality, accuracy and coverage will be unique. Applications will be many and varied, ranging from enhancing the efficiency of oil, gas, or mineral extraction to improvements in the planning of crisis missions, predicting the aftereffects of disasters, and the preparation of defence and security missions. But first and foremost, leading cartographers all over the world are looking forward to receiving precise elevation data for their standard maps.

Today, radar images constitute an important source of information in crisis management. In future, maps showing potential flood areas will be generated on the basis of high-precision TanDEM-X elevation models. The illustration below shows a TerraSAR-X map of the area affected by the flood in Saint Louis in July 2008.



Technology

Safety and precision in orbit

A key feature of the mission is the close formation flight of TerraSAR-X and TanDEM-X, which allows reconfiguration of the imaging geometry as required to meet the differing mission objectives. Fine-tuning the satellite formation will be achieved with TanDEM-X's cold gas propulsion system, while major formation changes will be implemented through the hydrazine-powered propulsion units on both satellites.

Although the passive stability of the helix orbit will, in principle, prevent collisions, formation flying at such close distance calls for special measures to mitigate the risk of collision. Therefore, in addition, a safe mode based on the magnetorquers for attitude control has been introduced on both satellites. Magnetorquers are capable of stabilising the satellites in case of minor rotation. Unlike the hydrazine propulsion system, employing the magnetorquers for attitude control will avoid orbit perturbations. To complement this additional safety feature, the ground operations concept has been modified to ensure that the ground segment can respond swiftly to any problems with the space segment.

The TanDEM-X satellite without its protective outer cover

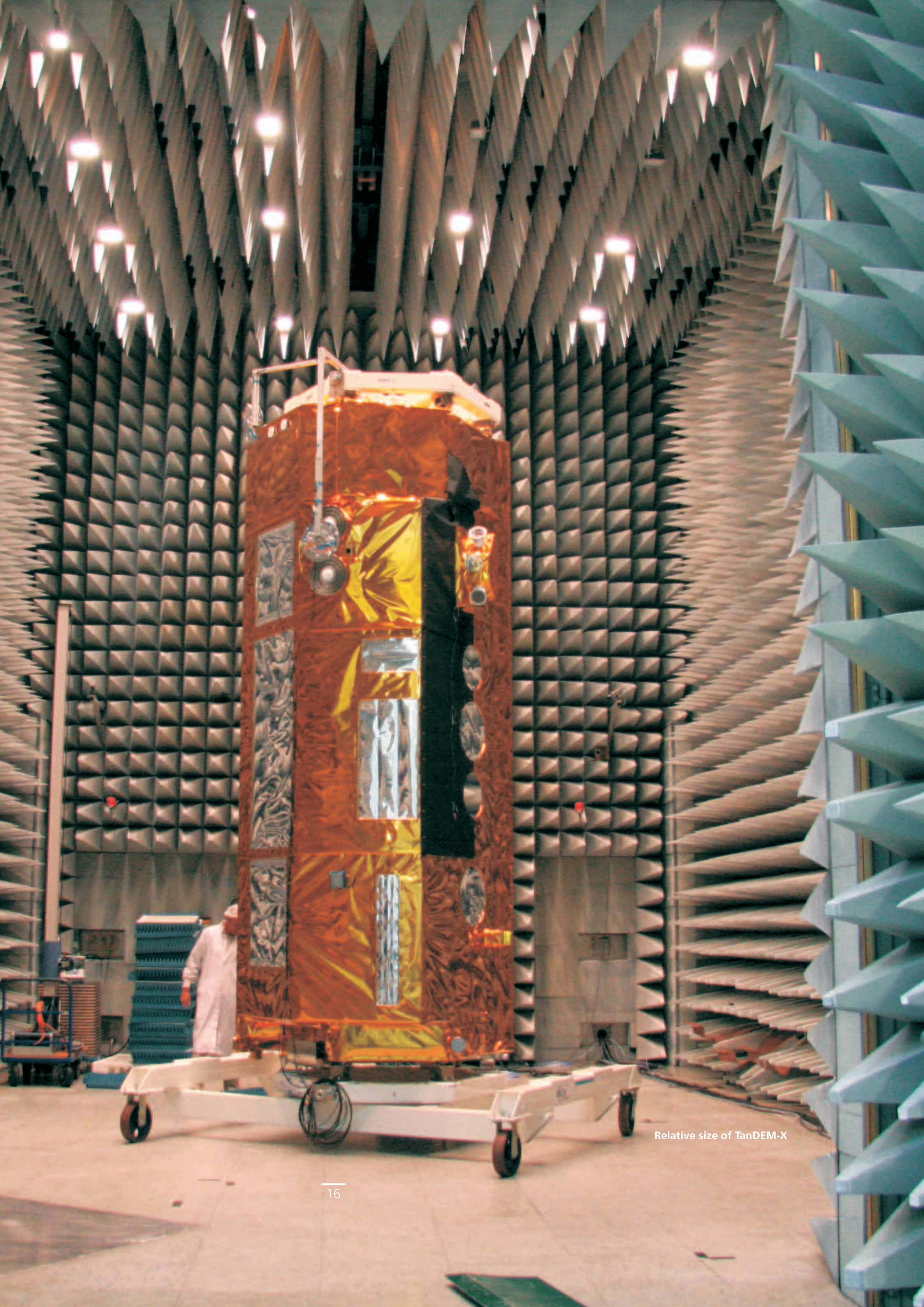
TanDEM-X being tested at IABG's Ottobrunn Space Test Centre

Not only must the two satellites be kept from colliding, they must also be prevented from moving into each other's radar beams, because the signal from a transmitter at such close range would interfere with the satellite electronics. This is why exclusion zones have been defined – these zones are segments of the orbit in which one of the two satellites is not allowed to transmit radar pulses. In addition, TanDEM-X is equipped to receive telemetry from TerraSAR-X and respond to any abnormal operating status. Lastly, both satellites can be commanded to check each other's technical status. If one of them experiences a problem, its radar pulses will be switched off immediately.

The distance between the two satellites must be known as accurately as possible so that the measurement data generated by the two operating in tandem can be converted to precise elevation data. As a rule of thumb, a one-millimetre error in the TanDEM-X baseline will lead to a one-metre error in elevation. This enormous level of navigational precision required is achieved in two ways. First, TanDEM-X, like TerraSAR-X, is equipped with a special GPS receiver called the Integrated GPS Occultation Receiver, which was provided by the German Research Centre for Geosciences in Potsdam. This device is responsible for monitoring the baseline precisely. Because the requirements are so strict, the baselines are also determined independently by DLR and calibrated by interferometric measurements. For that purpose, TanDEM-X regularly images areas whose elevation profile is known precisely. Any deviations from the reference elevation will result in the correction of the baseline. In addition to determining the baseline, the Integrated GPS Occultation Receiver is used for experimental radio-occultation measurements. This is performed by recording the signals transmitted through the atmosphere by GPS satellites rising or setting at Earth's horizon.

TanDEM-X operating modes

It is possible to operate TanDEM-X independently (monostatic mode), as well as in sync with TerraSAR-X (for example, in bistatic mode). Operational digital elevation model generation is planned to be performed using bistatic interferometry, which is characterised by the illumination of a scene by one transmitter and the simultaneous measurement of the same scene with two receivers. This avoids temporal variations of the ground surface characteristics between measurements, which would reduce the achievable height measurement performance. In the bistatic mode, the TanDEM-X interferometer is operated with two independent oscillators. Uncompensated oscillator noise will cause substantial interferometric phase, and consequently height, errors. To correct for these phase errors and also to enable synchronisation between the two synthetic aperture radar sensors, the TanDEM-X-specific synthetic aperture radar instrument features provide a scheme for exchanging synchronisation information through a dedicated link. This comprises a set of six horn antennas, optimally distributed to ensure full solid-angle coverage with low phase disturbance. The communication consists of a periodical exchange of synchronisation chirp pulses that are compressed as normal synthetic aperture radar pulses and provide, after proper evaluation, the differential phase behaviour of the satellite oscillators. This enables the phase correction of the interferometric system in the on-ground processing chain.



Relative size of TanDEM-X

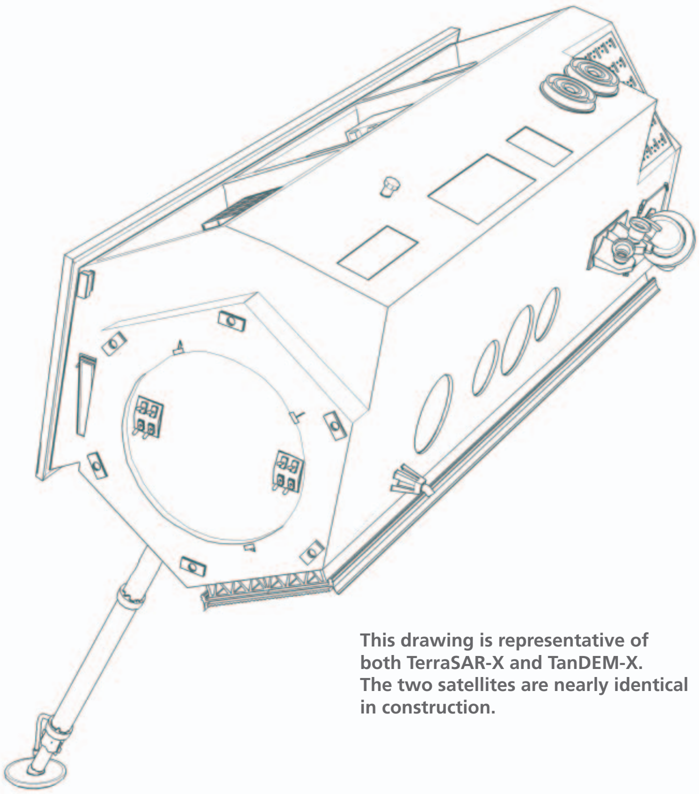
The satellite

The TanDEM-X satellite follows the TerraSAR-X template.

The idea of the TanDEM-X mission was conceived during the development of the TerraSAR-X satellite. To realise it, the design of the synthetic aperture radar on TerraSAR-X had to be modified slightly to support the synchronous operation of two radars. For the satellite bus, changes on TerraSAR-X were restricted to the software, whereas on TanDEM-X, the hardware was also modified to a limited extent to enable the two satellites to fly in formation.

The satellite measures 5 metres in length and 2.4 metres in diameter. Its hexagonal cross-section fits precisely under the fairing of the Dnepr launcher. The 80-cm-wide synthetic aperture radar antenna points towards Earth on the right-hand side of the satellite's ground track. Because its orbit is Sun-synchronous, TanDEM-X is equipped with a fixed solar panel installed on the left side to supply it with power. Synthetic aperture radar measurement data are transmitted to ground stations on the same frequency band as used by the radar. To avoid mutual interference, the antenna used for data transmission is mounted on a boom that was deployed when the satellite reached its orbit.

TanDEM-X is equipped with an additional propulsion system powered by high-pressure nitrogen gas. Delivering a weaker thrust than that of the hydrazine systems used by both satellites for orbit control, this cold gas system keeps TanDEM-X in formation by fine-tuning its orbit. Lastly, TanDEM-X features an additional receiver for obtaining information about the position and velocity of TerraSAR-X. The DLR algorithms for the TanDEM-X Autonomous Formation Flying (TAFF) experiment use this data.



This drawing is representative of both TerraSAR-X and TanDEM-X. The two satellites are nearly identical in construction.

Colour changes on this interferogram clearly indicate differences in the height of the buildings in the megacity of Tokyo.

The synthetic aperture radar

Radars operating at microwave frequencies are capable of imaging Earth's surface independently of the weather and local time of day. For this purpose, both TanDEM-X and TerraSAR-X use an active antenna consisting of an array of transmit and receive modules designed for rapid changes in the direction of the radar beam as well as programmable antenna characteristics. Electromagnetic wave polarisation and other radar parameters may even be varied from one pulse to the next. All this makes synthetic aperture radar technology flexible enough to be used for testing innovative, experimental operating modes.

The routing of the radar transmit and receive signals permits separating the two halves of each antenna electrically in the direction of flight and, consequently, separating radar signal reception by each half of the antenna. This facilitates gathering fully polarimetric data for classifying objects such as houses or trees, as well as along-track interferometry. Moreover, the architecture permits routing of calibration signals through the entire radar hardware chain except for the radiating waveguides, which consist of metallised, carbon-fibre reinforced plastic for inherent stability. The calibration signals are used to determine correction factors for optimising the stability of measurement data when they are processed on the ground.

The solid-state mass memory on TanDEM-X has a capacity of 768 gigabits, to cope with the enormous amount of data for the digital elevation model. This is twice the memory capacity of TerraSAR-X. In the last phase of the development of TerraSAR-X, the design of the synthetic aperture radar instrument was modified to permit the continuous exchange of synchronisation pulses in order to ensure the consistent operation of the two synthetic aperture radars in bistatic mode.

TanDEM-X quick facts

Launch	**Summer 2010**
Launch site	**Baikonur (Kazakhstan)**
Launcher	**Dnepr-1**
Orbit altitude	**514 kilometres**
Orbit inclination	**97.4 degrees**
Satellite mass	**1,330 kilograms**
Satellite dimensions	**Height: 5 metres** **Diameter: 2.4 metres**
Power consumption	**730 watts (average)**
Mission operation	**German Space Operations Center, Oberpfaffenhofen**
Satellite command	**Weilheim ground station**
Data reception	**Ground stations:** **- Inuvik, Canada** **- O'Higgins, Antarctic** **- Kiruna, Sweden**
Satellite lifetime	**5.5 years (6.5 years for consumables)**
Radar centre frequency	**9.65 gigahertz (X-band)**

The ground segment

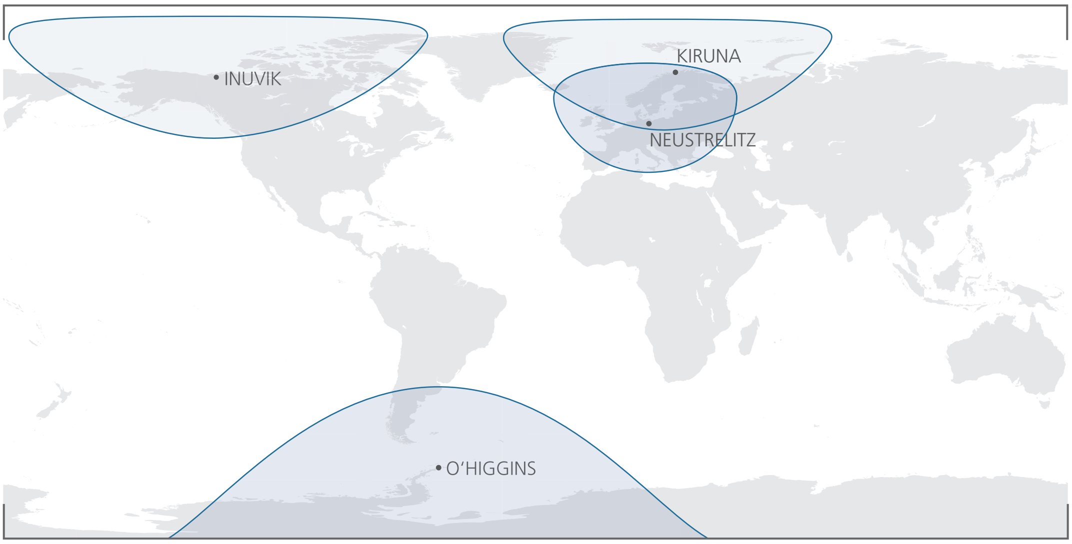
The radar data recorded by TerraSAR-X and TanDEM-X is downlinked from orbit to a global network of ground receiving stations. After reception it is forwarded to a data centre in Oberpfaffenhofen for processing into products such as elevation models. Finally it will be made available to customers worldwide. This complex data transfer and processing operation is handled by the ground segment that has been developed and is being operated by four DLR institutes: the Microwaves and Radar Institute, the Applied Remote Sensing Cluster, the German Remote Sensing Data Center and the German Space Operations Control Center (GSOC).

The ground segment originally developed by a DLR team for TerraSAR-X has been extended for the TanDEM-X mission to accommodate the operation of two satellites. It also has extensive new features such as safe formation flying, precise baseline determination, and a high-performance data reception and processing chain. Additional specific features have been added for TanDEM-X operations.

A key issue in operating the missions jointly is the different image acquisition scenarios. While TerraSAR-X requests are typically for single scenes that will be used by individual scientific and commercial customers, the global digital elevation model requires a global mapping strategy. This strategy has to also account for the formation geometry in use at any given time, which, in turn, depends on the helix parameters selected. This is because any given helix permits the acquisition of digital elevation model data only within a certain range of latitudes.

In addition, the two satellites have to be available for individual use during the three-year tandem phase. For this purpose, a reference mission scenario has been developed under which first priority is accorded to digital elevation model images. This scenario leaves enough space for planning TerraSAR-X images around those taken by TanDEM-X.

The two satellites will downlink their data to a network of three ground stations: Kiruna in Sweden, Inuvik in Canada and O‘Higgins in the Antarctic. The global acquisitions for digital elevation models alone will consume a data storage volume of more than 350 terabytes, which corresponds to the capacity of around 45,000 DVDs. After a brief quality check, the data will be recorded on tape and forwarded to the DLR Remote Sensing Data Center for processing and archiving.



Map showing the network of ground stations and regions where data reception is possible

The processing chain

The entire processing chain is a new TanDEM-X-specific development. However, it consists of individual modules that benefit greatly from the TerraSAR-X and Shuttle Radar Topography Mission heritage. Major design drivers result from the acquisition strategy, which requires the combination of several global-coverage acquisition cycles and the application of multi-baseline processing techniques based on supporting intermediate products. Another important constraint is the need for fast feedback on data quality for acquisition scheduling as well as rescheduling. Joint acquisitions are downlinked to different stations, and the arrival of the instrument data at the processing facility can take up to several weeks in case of the Antarctic station.

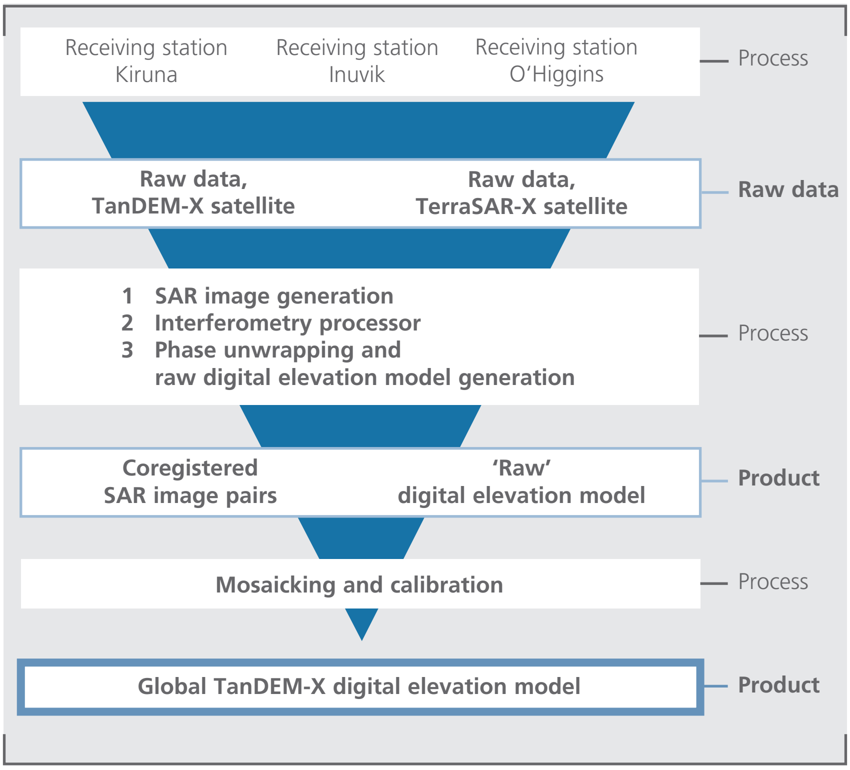
Synthetic aperture radar data processing for digital elevation model acquisition is divided into three major steps:

1. Screening of the downlinked data at the receiving station
2. Quality checking and assessment of the collected results from a combined acquisition at the processing centre in Oberpfaffenhofen
3. Processing of the data to scene-based raw digital elevation models

Finally, the digital elevation model mosaicking and calibration processor produces a global digital elevation model from the raw digital elevation models. The absolute orientation of thousands of raw digital elevation models is estimated and corrected by a continent-wise block adjustment. For absolute height calibration, globally distributed reference elevation data is needed. This is provided by the laser altimeter from the NASA ICESat mission that measures elevations with an absolute accuracy better than one metre. After the raw digital elevation models have been incorporated into a processed digital elevation model, the final output will be made available to scientific and commercial users.

In total, the TanDEM-X data will amount to 1.5 petabytes, which is being kept in the German Remote Sensing Data Center's archive. The global digital elevation model will amount to 15 terabytes and will become available four years from launch.

TanDEM-X processing chain



Taken by the German radar satellite TerraSAR-X, this picture shows the mangrove-covered islands surrounding the Bakassi peninsula (Cameroon) at the eastern edge of the Gulf of Guinea. TanDEM-X permits the generation of accurate maps of coastal regions that are essential for tsunami risk assessment, for example.

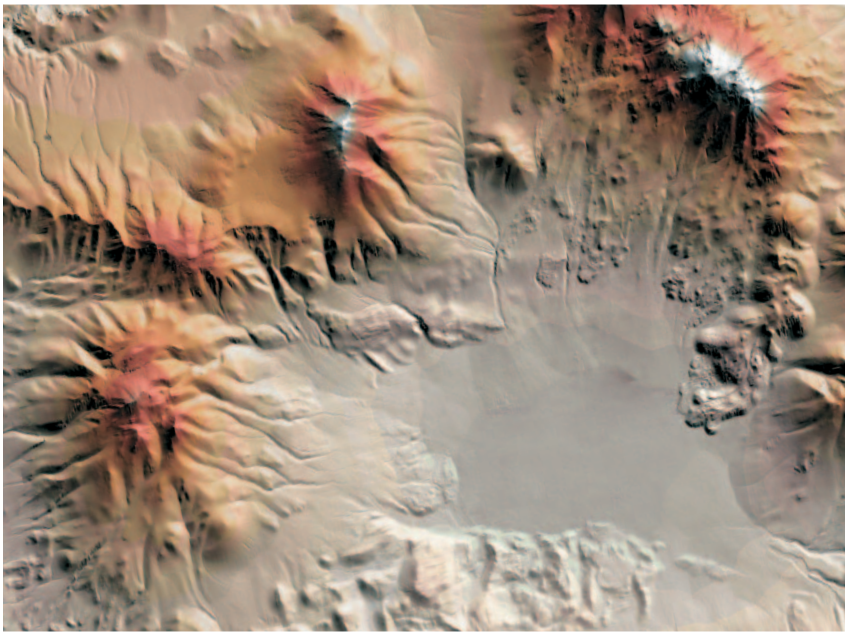
The future

Within Germany's national space programme, the development of radar technology focuses on continuing the X-band family of missions and transforming it into a self-sustaining business model. The length of radar waves in this band is around three centimetres (a frequency of 9.65 gigahertz), which makes them shorter than C- or L-band waves, producing higher-resolution imagery. In the public-private partnership agreement, the industrial partners are committed to reinvest the revenues and to finance and operate another TerraSAR-X satellite. At present, Infoterra GmbH is pursuing the definition of TerraSAR-X2, which is planned to replace the current TerraSAR-X mission in 2012 or 2013.

The promotion of the German national Earth observation programme implies that the foundations of future X-band radar satellites are being laid today. Therefore there are plans to improve experimental high-resolution measurement capabilities in the next generation and apply them to considerably wider observation swaths. Experts call this high-resolution wide-swath. Technologies such as digital beam forming will be used for this purpose. To this end, Astrium is currently developing an antenna demonstrator on behalf of DLR. In turn, DLR is developing methods and algorithms that permit the application of this technology to wide-swath imaging at a very high resolution.

The ultimate aim of all these developments is software-defined radar. This new generation of digital radar systems will revolutionise active microwave remote sensing and greatly increase the range of applications for it in Earth, environment and climate observation. Thus, for example, future radar satellites will be capable of being configured to suit various tasks and environmental conditions, and data acquisition will be optimised adaptively. To avoid conflicts in operation, it will be possible to use several imaging modes simultaneously, enabling providers to comply with increasingly stringent user requirements concerning product quality, operational availability and timeliness of data in an optimum way.

If a high-resolution wide-swath mission does follow TanDEM-X, it may also be implemented under the successful concept of public-private partnership in funding and commercial exploitation. Moreover, the high-resolution wide-swath technology may be a promising candidate for Sentinel radar missions being planned by the European Space Agency, because it may be capable of satisfying the requirements that are now emerging. The Sentinel programme involves a family of different satellites that are intended to perform all baseline Earth observation functions as routine operations. At the same time, DLR is looking for opportunities to add other frequencies to the established X-band line. Thus, it has begun, together with NASA's Jet Propulsion Laboratory, to explore mission concepts in the L-band (Tandem-L). In addition, both industry and DLR are involved in two of the European Space Agency's current Earth Explorer candidate missions in the P-band (BIOMASS) and the X/Ku-band (CoReH$_2$O). Another proposal that is currently being investigated for its potential is SIGNAL, a Ka-band synthetic aperture radar mission.



High-resolution elevation model generated from TerraSAR-X data

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DLR at a glance

DLR is Germany´s national research centre for aeronautics and space. Its extensive research and development work in Aeronautics, Space, Transportation and Energy is integrated into national and international cooperative ventures. As Germany´s space agency, DLR has been given responsibility for the forward planning and the implementation of the German space program by the German federal government as well as for the international representation of German interests. Furthermore, Germany's largest project-management agency is also part of DLR.

Approximately 6,500 people are employed at thirteen locations in Germany: Koeln (headquarters), Berlin, Bonn, Braunschweig, Bremen, Goettingen, Hamburg, Lampoldshausen, Neustrelitz, Oberpfaffenhofen, Stuttgart, Trauen, and Weilheim. DLR also operates offices in Brussels, Paris, and Washington D.C.

DLR's mission comprises the exploration of the Earth and the Solar System, research for protecting the environment, for environmentally-compatible technologies, and for promoting mobility, communication, and security. DLR's research portfolio ranges from basic research to innovative applications and products of tomorrow. In that way DLR contributes the scientific and technical know-how that it has gained to enhancing Germany's industrial and technological reputation. DLR operates large-scale research facilities for DLR's own projects and as a service provider for its clients and partners. It also promotes the next generation of scientists, provides competent advisory services to government, and is a driving force in the local regions of its field centres.

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