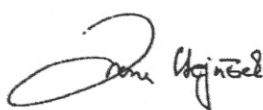

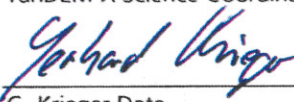
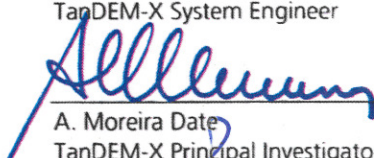


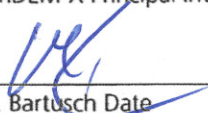


TanDEM-X
Ground Segment
TD-PD-PL-0069 TanDEM-X Science Plan
Microwaves and Radar Institute

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1 Introduction

1.1 Purpose

The purpose of this document is to provide background about the TanDEM-X mission to scientists who are interested to use TanDEM-X data for only scientific intent. It describes the mission and scientific objectives, the Science Service Segment, the proposal submission, the communication between the science coordinator and the scientists, the data products, and the data ordering and tracking. The document is structured into four parts. Chapter 4 provides a short overview of the TanDEM-X mission objectives and the mission schedule, chapter 5 deals with the science team and their suggested application research areas, chapter 6 summarizes the science products and chapter 7 is dedicated to science user coordination including the description of the Science Service Segment, data ordering, data products etc.

1.2 Scope

This document is dedicated to all science users of the TanDEM-X mission and as such it is accessible to the public.

1.3 Position within Project Framework

The TanDEM-X science coordination belongs to the supporting team of the TanDEM-X project management. The science coordination activities are part of the Instrument Operation & Calibration Segment (IOCS) within the TanDEM-X Ground Segment and the Science Service Segment. The Science Service Segment consists of the Science Service System, the Online Order & Delivery via EOWEB and the Science Coordinator & Order Desk, which interacts with the Ground Segment and the science user.

1.4 Executive Mission Summary

TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) opens a new era in spaceborne radar remote sensing. A single-pass SAR-interferometer with adjustable baselines in across- and in along-track directions is formed by adding a second (TDX), almost identical spacecraft to TerraSAR-X (TSX) and flying the two satellites in a closely controlled formation. TDX has SAR system parameters which are fully compatible with TSX, allowing not only independent operation from TSX in a mono-static mode, but also synchronized operation (e.g. in a bi-static mode). With typical across-track baselines of 200-600 m DEMs with a spatial resolution of 12 m and relative vertical accuracy of 2 m will be generated. The Helix concept provides a save solution for the close formation flight by combining a vertical separation of the two satellites over the poles with adjustable horizontal baselines at the ascending/descending node crossings.

Beyond the generation of a global TanDEM-X DEM as the primary mission goal, local DEMs of even higher accuracy level (spatial resolution of 6 m and relative vertical accuracy of 0.8 m) and applications based on Along-Track Interferometry (ATI) like measurements of ocean currents are important secondary mission objectives. Along-track interferometry will also allow for innovative applications to be explored and can be performed by the so-called dual-receive antenna mode on each of the two satellites and/or by adjusting the along-track distance between TSX and TDX to the desired value. Combining both modes will provide a highly capable along-track interferometer with four phase centers. The different ATI modes will e.g. be used for improved detection, localisation and ambiguity resolution in ground moving target indication and traffic monitoring applications. Furthermore,

TanDEM-X supports the demonstration and application of new SAR techniques, with focus on multi-static SAR, polarimetric SAR interferometry, digital beam forming and super resolution.

TanDEM-X has an ambitious time schedule to reach the main goals. The two first years after launch are dedicated to the global DEM data take acquisition, followed by 6 months of data take acquisition to cover critical areas, as high mountainous terrain and the remaining time is dedicated to the exploration and demonstration of scientific experiments.

The science proposal submission for data requests is available over the TanDEM-X Science Service System following the basic structure of the TerraSAR-X Science Service System. Some additional features were implemented to alleviate the handling and the use of the web-based interface. The main difference is the procedure for the data ordering. TanDEM-X is following a systematic data acquisition due to its high requirement on the DEM performance and this provides minor flexibility to other mission configurations for science proposals during a specific time. This means the science data takes are placed in the gaps between the DEM acquisitions. For a controlled handling the scientists cannot order the data takes autonomously as in the case of TerraSAR-X, but the science coordinator is translating the science requests and placing the data take orders according to the best possible acquisition timeline.

2 References

2.1 Applicable References

The following documents are fully applicable together with this document.

	Document ID	Document Title	Issue
R5	TDX-RD-DLR-1201	I. Hajnsek, M. Weber, "TanDEM-X User Requirements Document (URD)," , 20.06.2005 (project internal)	1.2
R9	TDX-PD-RS-0001	M. Bartusch, et al. "TanDEM-X Mission Requirements Document (MRD)," , 03.08.2009 (project internal)	2.1

2.2 Normative References

The following standards have been used for preparing the plan on hand.

	Document ID	Document Title	Issue
	None	None	

2.3 Informative References

The following documents, though not formally part of this document, amplify or clarify its content.

	Document ID	Document Title	Issue
R1		Krieger, Gerhard; Moreira, Alberto; Fiedler, Hauke; Hajnsek, Irena; Werner, Marian; Younis, Marwan; Zink, Manfred, TanDEM-X: A Satellite Formation for High Resolution SAR Interferometry . IEEE Transactions on Geoscience and Remote Sensing, vol. 45, no.11, pp. 3317–3341, 2010	
R2		M. Stangl, R. Werninghaus, B. Schweizer, C. Fischer, M. Brandfass, J. Mittermayer, and H. Breit, "TerraSAR-X technologies and first results," IEE Proceedings - Radar, Sonar and Navigation, vol. 153, pp. 86-95, 2006.	
R3		R. Werninghaus, S. Buckreuss, TerraSAR-X System and Mission Design, IEEE Transactions on Geoscience and Remote Sensing, vol 48, no 2, pp. 606-614, 2010.	
R4	TD-PD-RP-0012	G. Krieger, H. Fiedler, "TanDEM-X Mission Analysis Report" (project internal)	1.1
R6	TX-PGS-PL-4001	A. Roth, "TerraSAR-X Science Plan"	1.0
R7	TD-GS-PS-0021	B. Wessel, "DEM Products Specification Document"	1.6
R8	TD-GS-PS-3028	T. Fritz, " TanDEM-X Experimental Product Description"	1.0

3 Terms, Definitions and Abbreviations

3.1 Terms and Definitions

Term	Definition
None	None

3.2 Abbreviations

Abbreviation	Meaning
ATI	Along-track SAR Interferometry
COFUR	Cost of fulfilling user requests
DEM	Digital Elevation Model
DTED	Digital Terrain Elevation Data
EOWEB	Earth Observation WEB Interface
IOCS	Instrument Operation & Calibration Segment
MOS	Mission Operation Segment
PGS	Payload Ground Segment
PI	Principle Investigator
PRF	Pulse Repetition Frequency
RF	Radio Frequency
SRTM	Shuttle Radar Topography Mission
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurements
TDX	TanDEM-X Satellite
TD-X	TanDEM-X Mission
TSX	TerraSAR-X Satellite
TS-X	TerraSAR-X Mission
XTI	Across-track SAR Interferometry

4 The TanDEM-X Mission

4.1 Introduction to the Mission and its Connection to TerraSAR-X

TanDEM-X stands for *TerraSAR-X add-on for Digital Elevation Measurements* and its mission concept is essentially based on an extension of the TerraSAR-X mission by a second TerraSAR-X like satellite [R1] (figure 4.1). The mission is realized in the framework of a Public Private Partnership (PPP) between the German Aerospace Center (DLR) and EADS Astrium GmbH, as for TerraSAR-X.



Figure 4.1: Artist's View of the TanDEM-X Satellite Formation

The TerraSAR-X satellite (TSX), as basis for TanDEM-X, is not only a high performance SAR system with respect to SAR image and operational features, but it has already built in all necessary features required for the implementation of the TanDEM-X mission [R2, R3]. Examples are additional X-band horn antennas for inter-satellite phase synchronization, the availability of a dual-frequency GPS receiver for precise orbit determination, the excellent RF phase stability of the SAR instrument, and PRF synchronization based on GPS as a common time reference.

The second satellite (TDX) is a rebuild of TSX with only minor modifications like an additional cold gas propulsion system for constellation fine tuning and an additional S-band receiver to enable a reception of status and GPS position information broadcast by TSX. This guarantees a low development risk and offers the possibility for a flexible share of operational functions among the two satellites. Both systems can also be employed for monostatic data takes which is necessary to fulfil the data requirements of the TerraSAR-X mission together with the TanDEM-X mission goals.

The TDX satellite is designed for a nominal lifetime of 5 years with a planned overlap with TSX of 3 years. Note in this context that TSX holds consumables and resources for up to seven years of operation, allowing for a potential prolongation of the overlap and the TanDEM-X mission duration.

The instruments on both satellites are advanced high resolution X-band synthetic aperture radars based on active phased array technology which can be operated in different imaging modes like Spotlight, Stripmap, and ScanSAR with multi-polarization capability, respectively [R2, R3]. The centre frequency of the instruments is 9.65 GHz with a selectable SAR chirp bandwidth of up to 300 MHz. The active phased array antenna, which has an overall aperture size of 4.8 m x 0.7 m, is fixed mounted to the spacecraft body and incorporates 12 panels with 32 waveguide sub-arrays for both H and V polarization. This enables agile beam pointing and flexible beam shaping.

4.2 Mission Objectives

The primary objective of the TanDEM-X mission is the generation of a worldwide, consistent, timely, and high precision Digital Elevation Model (DEM) as the basis for a wide range of scientific research, as well as for operational and commercial DEM generation. Further, TanDEM-X will also exploit and demonstrate a wide range of advanced and innovative SAR techniques for the first time in space. These experiments are assigned as secondary mission objectives with less acquisition time, but they are regarded as an integral part of the mission [R5, R9].

4.2.1 Primary Mission Goals

Digital elevation models (DEMs) are of fundamental importance for a broad range of scientific and commercial applications. For example, many geoscience areas, like hydrology, glaciology, forestry, geology, oceanography, and land environment, require precise and up-to-date information about the Earth's surface and its topography. Digital maps are also a prerequisite for reliable navigation, and improvements in their precision need to keep step with the advances in global positioning systems, like GPS and Galileo. In principle, DEMs can be derived from a variety of air- and spaceborne sensors. However, the resulting mosaic of data from different sources with a multitude of horizontal and vertical data, accuracies, formats, map projections, time differences, and resolutions is hardly a uniform and reliable data set. The Shuttle Radar Topography Mission (SRTM) had the challenging goal to meet the requirements for a homogeneous and reliable DEM fulfilling the DTED-2 specification. The coverage of this DEM is, however, principally limited to a latitude range from 56° S to 60° N due to the inclined orbit of the Space Shuttle and its mapping geometry. Further restrictions apply to the X-band DEM with its wide gaps at lower latitudes and the C-band DEM where the data are available to the public only at an artificially impaired spatial resolution corresponding to the DTED-1 specification. A user survey among a wide range of scientists and potential customers has clearly shown that many applications require both an extended latitudinal coverage and an improved accuracy corresponding to higher class digital elevation models and comparable to DEMs generated by high resolution airborne radar systems [R5, R9].

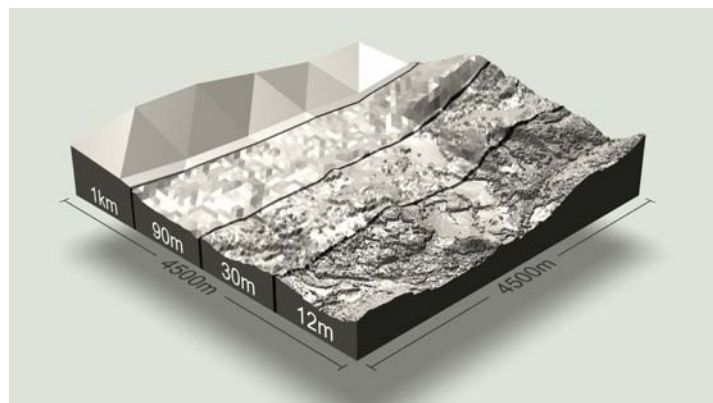


Figure 4.2: Simulation of digital elevation models with varying spatial and vertical resolution. The new class of DEMs is introduced with 12 m spatial resolution and a relative vertical accuracy of 2 m.

An outcome from the user survey is the specification of the digital elevation model named as TanDEM-X DEM. In table 4.1 a comparison between the SRTM DTED-2 and the TanDEM-X DEM is given. The TanDEM-X DEM specification will be achieved by means of the acquisition of highly accurate across- and along-track interferograms without the inherent accuracy limitations is imposed by repeat-pass interferometry due to temporal decorrelation and atmospheric disturbances.

Requirements	Specification	DTED-2	TanDEM-X DEM
Relative Vertical Accuracy	90 % linear point-to-point error over a 1° by 1° cell	12 m (slope < 20 %) 15 m (slope > 20 %)	2 m (slope < 20 %) 4 m (slope > 20 %)
Absolute Vertical Accuracy	90 % linear error	18 m	10 m
Relative Horizontal Accuracy	90 % circular error	15 m	3 m
Absolute Horizontal Accuracy	90 % circular error	23 m	10 m
Spatial Resolution	Independent pixels	30 m (1 arc sec @ equator)	12 m (0,4 arc sec @ equator)

Table 4.1. Comparison of DTED-2 and TanDEM-X DEM specifications

4.2.2 Secondary Mission Goals

Besides the primary goal of the mission, several secondary mission objectives based on new and innovative SAR techniques as for example along-track interferometry (ATI), polarimetric SAR interferometry (PolInSAR), digital beamforming, and bistatic radar have been defined which represent an important asset of the mission. The secondary mission goals have in general an experimental character and they are constrained in time and in amount of data that can be acquired [R5, R9]. In figure 4.3 application examples for across and along-track SAR interferometry and new SAR techniques are listed.

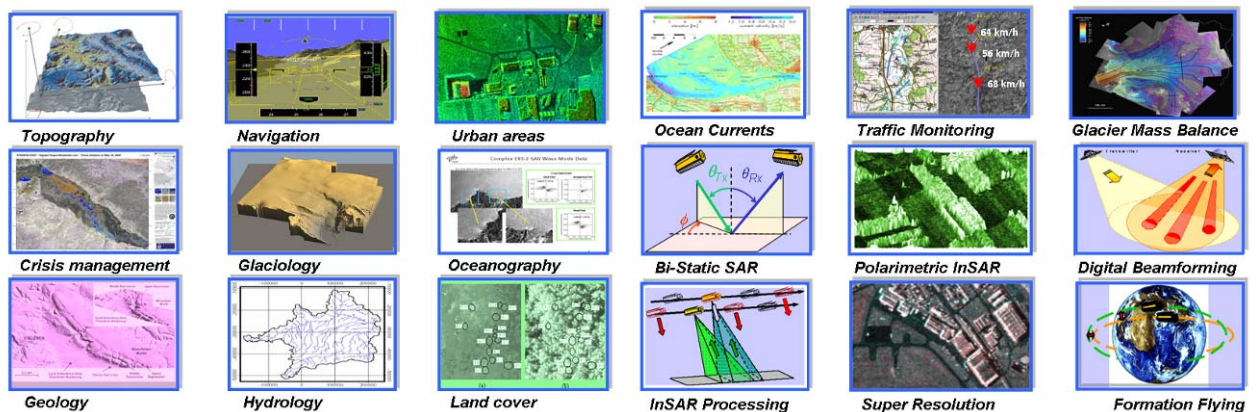


Figure 4.3: Application examples for the across-track, along-track SAR interferometric and new SAR techniques

4.3 Orbital Configuration

The TanDEM-X operational scenario requires a coordinated operation of two satellites flying in close formation. The adjustment parameters for the formation are the node line angle, the angle between the perigees, the orbit eccentricities and the phasing between the satellites. With these parameters, several options have been investigated during the phase A study, and the Helix satellite formation illustrated in figure 4.4 has finally been selected for operational DEM generation [R1]. This formation combines an out-of-plane (horizontal) orbital displacement by different ascending nodes with a radial (vertical) separation by different eccentricity vectors resulting in a helix like relative movement of the satellites along the orbit. Since there exists no crossing of the satellite orbits, one may now allow for

arbitrary shifts of the satellites along their orbits. This enables a safe spacecraft operation without the necessity for autonomous control. It is furthermore possible to optimize the along-track displacement at predefined latitudes for different applications: cross-track interferometry will aim at along-track baselines which are as short as possible to ensure an optimum overlap of the Doppler spectra and to avoid temporal decorrelation in vegetated areas, while other applications like along-track interferometry or super resolution require selectable along-track baselines in the range from hundred meters up to several kilometers.

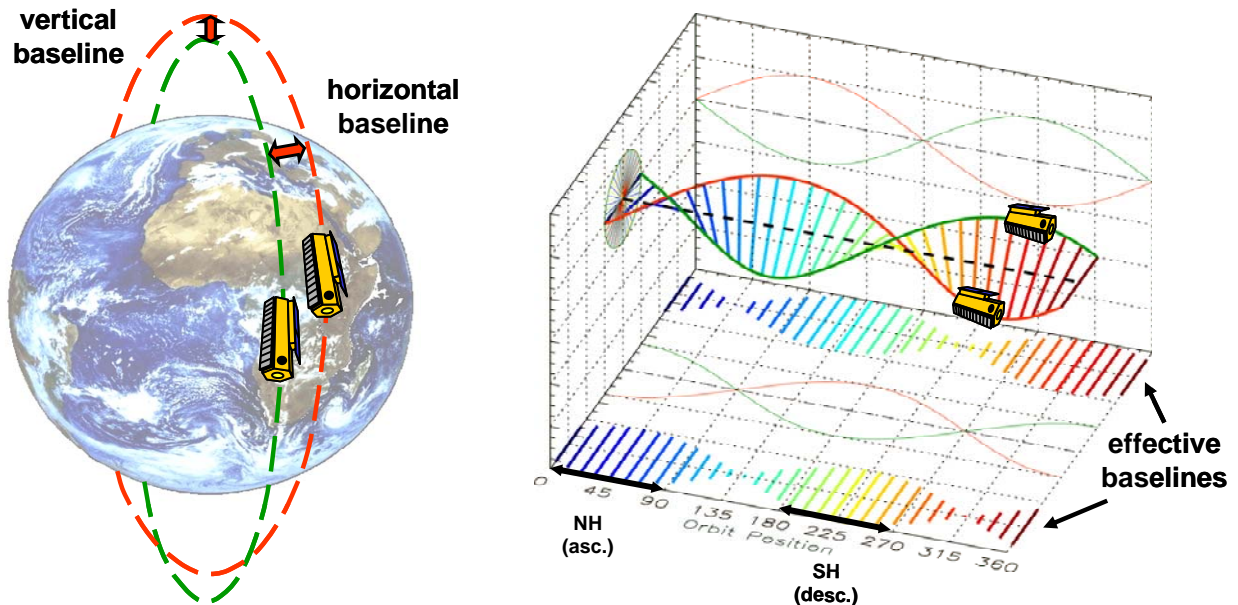


Figure 4.4: Helix satellite formation for TanDEM-X. Left: orbital arrangement. Right: cross-track baselines as function of the orbit position. The positions correspond to one complete orbit cycle where NH and SH mean northern and southern hemisphere, respectively. The Helix formation enables an interferometric mapping of the complete Earth surface with a stable height of ambiguity using a small number of formation settings. Southern and northern latitudes can be mapped with the same formation by using ascending orbits for one and descending orbits for the other hemisphere, as illustrated in figure 4.4 on the right.

4.4 Data Acquisition Modes

Interferometric data acquisitions with the TanDEM-X satellite formation can be achieved in three cooperative modes: Bistatic, Pursuit Monostatic, and Alternating Bistatic. The three cooperative modes may further be combined with different TSX and TDX SAR imaging modes like Stripmap, ScanSAR, and Spotlight, the last mode being in sliding spotlight acquisition geometry [R4]. Note that only the bistatic stripmap mode will be used for the acquisition of standard TanDEM-X DEM products, while others may be used for system calibration, validation and verification as well as for the acquisition of non-operational experimental data.

4.4.1 Bistatic Mode

This mode uses either TSX or TDX as a transmitter to illuminate a common radar footprint on the Earth's surface. The scattered signal is then recorded by both satellites simultaneously (figure 4.5). This simultaneous data acquisition makes dual use of the available transmit power and is mandatory to minimize possible errors from temporal decorrelation and atmospheric disturbances. A prerequisite for

bistatic InSAR operation is PRF synchronization between the two satellites. Accurate interferometric measurements require moreover relative phase referencing to compensate the mutually uncorrelated phase noise from the two local oscillators. The bistatic mode will be the standard mode during the data acquisition for the TanDEM-X digital elevation model.

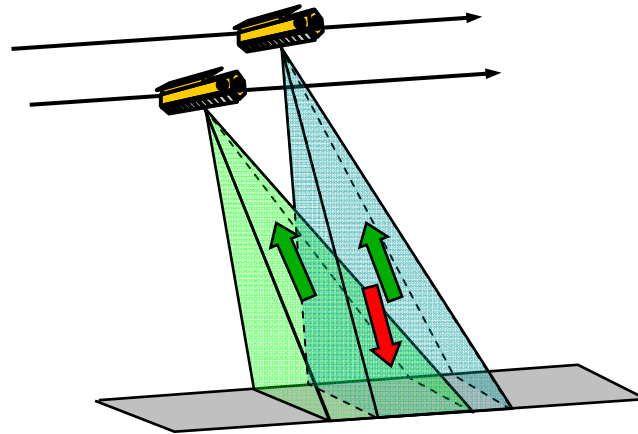


Figure 4.5: Bistatic mode for TanDEM-X data acquisition.

4.4.2 Pursuit Monostatic Mode

In the pursuit monostatic InSAR mode, the two satellites are operated independently from each other, thereby avoiding the need for synchronization (figure 4.6). The along-track distance should be larger than 10 km to avoid RF interference between the radar signals. Temporal decorrelation is still small for most terrain types except vegetation at moderate to high wind speeds as well as for water. The interferometric height sensitivity is doubled with respect to the bistatic operation and this requires higher baseline determination accuracy. Neither pulse nor phase synchronization is required in the pursuit monostatic mode. This mode could hence be used as a backup solution in the case of synchronization problems and/or problems with close formation keeping. Monostatic data takes are planned during the commissioning phase, in an intermediate phase when the satellites are separated from each other for a formation swap, and at the end of the mission when the satellite formation is flown with an increasing along-track separation.

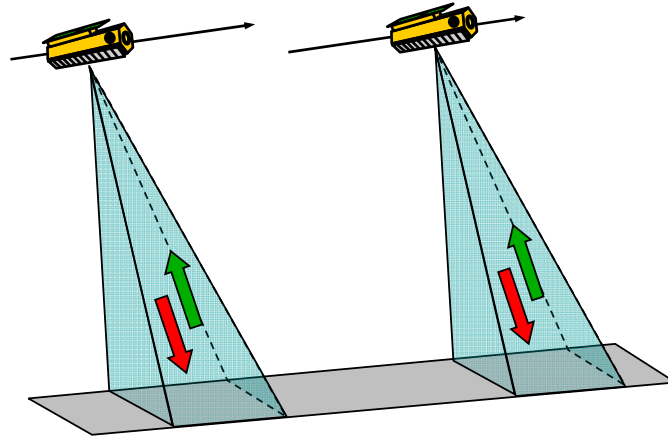


Figure 4.6: Pursuit monostatic mode for TanDEM-X data acquisition.

4.4.3 Alternating Bistatic Mode

A third operational mode is the alternating bistatic mode, where the transmitter is switched on a pulse-to-pulse basis. The scattered signal from the ground is then recorded by both receivers simultaneously as shown in figure 4.7.

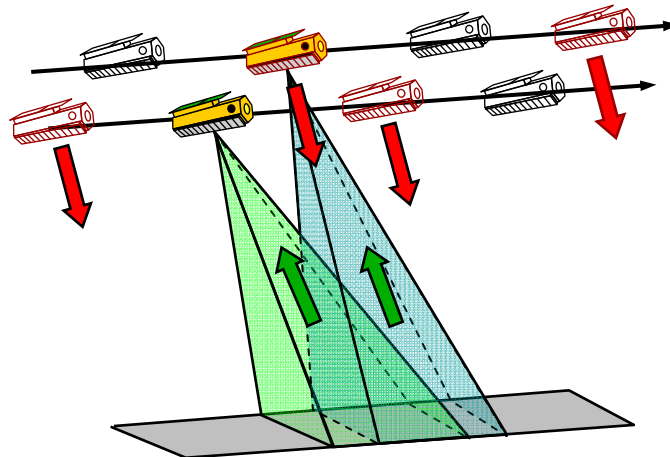


Figure 4.7: Alternating bistatic mode for TanDEM-X data acquisition.

The alternating bistatic mode acquires two monostatic and two bistatic SAR images during a single pass of the satellite formation. A comparison of the bistatic and monostatic images is hence well suited for the measurement of oscillator induced phase errors, thereby enabling an accurate phase calibration of the bistatic SAR interferometer. After phase calibration, the two bistatic images can be combined into a single bistatic SAR image with double PRF. For cross-track interferometry, two interferograms with different phase-to-height sensitivities can be derived:

- The combination of one monostatic and the bistatic image yields a cross-track interferogram with a height of ambiguity of $h_{amb} = (\lambda r \sin(\theta)) / B_{\perp}$, where λ is the wavelength, r the slant range, θ the incident angle, and B_{\perp} the baseline perpendicular to the line of sight. Either the

first or the second monostatic image can be selected, and a combination of both interferograms can be used to improve both the phase calibration and the phase stability.

- The combination of the two monostatic SAR images yields a second interferogram with double phase-to-height sensitivity resulting in a height of ambiguity of $h_{amb} = (\lambda r \sin(\theta)) / (2 B_{\perp})$.

The use of alternating transmitters in the bistatic mode allows hence for the simultaneous acquisition of two cross-track interferograms with phase-to-height sensitivities differing by a factor of two which will facilitate the process of interferometric phase unwrapping if the monostatic baseline is adjusted to fulfill the height determination accuracy requirements, i.e. half of the bistatic baseline is selected. The simultaneous availability of mono- and bistatic SAR interferograms will furthermore provide additional information in case of volume scattering and it may be of help to distinguish between direct and double bounce scattering from the ground. Data takes in the alternating bistatic mode will be used for system verification and calibration purposes.

4.5 TanDEM-X Mission Timeline

The TanDEM-X mission life time is 5 years with an overlap with the TerraSAR-X satellite of at least 3 years. Within the three years there will be 6 month of commissioning phase, conducting system calibration and product evaluation, followed by two years of dedicated data acquisition for the global digital elevation model with different baseline configurations, continued by a 6-month transition phase where for difficult terrain digital elevation model data acquisitions are still acquired and at the same time dedicated experiments are conducted. Any remaining time is specifically dedicated to the data acquisition for experimental products in large baseline configurations. During the first two years a limited number of science data takes other than the regular DEM acquisitions can be ordered with the restriction that they fit within the predefined system configuration (small baselines in the first year and larger baselines for the second year). In table 4.2 the different mission phases are displayed.

Table 4.2 TanDEM-X mission phases within the 3 years lifetime.

3 years mission & data acquisition time				
6 months	1 year	1 year	6 months	Additional mission lifetime
Commissioning Phase	1 global DEM acquisition with small baselines	1 global DEM acquisition with scaled (larger) baselines	DEM data takes for difficult terrain with different viewing geometry	acquisition of scientific radar data products
	+ acquisition of scientific radar data products	+ acquisition of scientific radar data products	+ acquisition of scientific radar data products	+ customized DEMs with large interferometric baselines

The science proposals requesting data during the first two years need to fit to the predefined baseline configurations. An overview of the baseline configurations for the first three years is summarised in table 4.3 and can be selected during proposal submission at the Science Service System.

Table 4.3 Baseline configurations for the different TanDEM-X mission phases

Baseline formation	Across-track	Along-track	Comments
1st & 2nd year	200-600 m (1 st year: 200-450 m 2 nd year: 250-600 m)	0-1000 m standard and < 250 m on best effort for predefined latitudes	1 st small across-track baseline preferred & 2 nd larger across-track baseline
3rd year	500-3000 m		Large to huge across-track baseline preferred. Exact settings will be defined after the response of the PI's

The effective baselines for the first DEM acquisition year range between 200 m and 450 m, depending on latitude and incident angle. In the second year, it is planned to scale the baselines by a factor of approx. 1.3, resulting in somewhat larger across-track baselines. After the second complete DEM acquisition, a formation switch will be conducted, and the baselines will be adjusted to acquire additional interferometric data to fill in any gaps from the previous acquisitions and to minimize errors from shadows, layover and phase wrapping in difficult terrain. It is planned that this phase lasts half a year. Any remaining overlap of TDX with TSX is then available for experimental products in variable baseline configurations. The specific baseline values will be selected based on the feedback from the scientific users. For the DEM acquisition phases, the along-track baselines are defined to range between 0 m and 1000 m. With the availability of the TanDEM-X autonomous formation flying (TAFF) at later mission phases, it is planned to perform dedicated campaigns which provide short along-track baselines at predefined latitudes, as required for many applications that employ the technique of along-track interferometry (e.g. oceanography).

5 The TanDEM-X Science Application Examples

5.1 Introduction to the Application Techniques

The demand for accurate topographic information and the demonstration of new techniques have been derived from numerous application areas. The TanDEM-X science applications are based on three operation techniques, across-track SAR interferometry, along-track SAR interferometry and new SAR techniques. The three radar techniques evolve from the system specification defined by the TerraSAR-X satellite and the interferometric configuration itself. Due to its manifold system configurations, TanDEM-X is a flexible and multimode mission, which delivers a wide variety of application possibilities.

- **Across-track SAR interferometry** is an established technique to measure the terrain topography. The application of this technique is based on the evaluation of phase differences measured with two SAR antennas separated by an appropriate baseline. This allows estimating the radar elevation angle to the phase center of each image resolution cell, where the height information is derived from the interferometric phase difference.
- **Along-track SAR interferometry** is an established technique to measure velocities of moving objects. The application of this technique is based on a phase difference measurement as for the across-track SAR interferometry whereby the two SAR antennas acquire complex SAR images of the same area with a short time lag. Hence, the two interferometric SAR antennas image the same area with the same geometry but with a well defined time shift. This makes it possible to detect moving objects on the ground.
- **New SAR techniques** will demonstrate the feasibility of innovative SAR techniques that have yet not or only partially been demonstrated on ground or with airplanes. Major goal is the implementation, test, and verification of innovative techniques and algorithms for the development of new scientific application products and/or new technologies.

TanDEM-X Science Applications		
<i>Across-track</i>	<i>Along-track</i>	<i>New SAR Techniques</i>
<ul style="list-style-type: none"> • Oceanography • Land Cover and Vegetation • Geology • Glaciology/Hydrology • Land Environment 	<ul style="list-style-type: none"> • Hydrology/Glaciology • Oceanography • Traffic 	<ul style="list-style-type: none"> • Interferometric Processing • Formation Flying • Superresolution • Digital Beamforming • Polarimetric SAR Interferometry • Bistatic Processing

Figure 5.1. TanDEM-X science applications based on the three radar techniques (across-track InSAR, along-track InSAR and new SAR techniques) and the corresponding application areas.

Within each of the three radar operation techniques, selected scientific application areas are sorted according to the application requirements.

5.1.1 Across-Track SAR Interferometry Technique

Five application areas have been defined under the *across-track SAR interferometry technique*, which require directly the digital elevation model or derived products from the digital elevation model (see table 5.1). The application topics related to land environment use primarily the DEM information derived from across-track SAR interferometry techniques in order to develop topographic maps. The scientific interests focus on the development of new algorithms for the validation of measured heights and the development of tools for the 3D visualization of terrain maps as well as for safety critical aviation

applications. The scientific objective is the understanding of SAR interferometry derived heights and the development of mathematical formulations for their interpretation and utilization. Additionally, DEMs are of high importance for the application areas glaciology/hydrology, geology and land cover and vegetation also in combination with other remote sensing data. Scientists are also using the DEM information in order to retrieve relevant environmental parameters as an input for global or local models. Their scientific interest lies in the identification and the understanding of complex natural system interaction as well as in the development of tools for the changes, causes and possible predictions of environmental system functions.

Across-track SAR Interferometry	
Application Area	Application Topic
Land Environment	<i>Topographic Mapping, Navigation, Crisis management</i>
Glaciology/Hydrology	<i>Ice and Snow, Sea Ice, Morphodynamic and Hydrology</i>
Geology	<i>Geological Mapping and Morphology, Earthquake & Volcanoes, Landslides, Subsidence</i>
Land Cover and Vegetation	<i>Land Cover and Surface Parameter, Forest</i>
Oceanography	<i>Wind and Waves/Ocean Dynamics, Coastal Zone</i>

Table 5.1: Application areas and application topics under across-track SAR interferometry

5.1.2 Along-Track SAR Interferometry Technique

The TanDEM-X satellite formation will allow exploring innovative applications as the detection of moving objects on the ground and the estimation of their velocity. *Along-track SAR interferometry* can either be performed by the so-called dual receive antenna mode from each of the satellites or by adjusting the along-track distance of the two satellites to the desired size. The present orbit concept allows distances (called along-track baseline) to be adjusted from zero to one kilometer. This feature is essential as this application requires the measurements of a wide range of different velocities. Mainly four scientific application areas are identified to explore the innovative along-track mode: oceanography, traffic monitoring, glaciology and hydrology. Of scientific interest is the detection of moving objects as well as the validation of different velocity estimates. For the application areas listed in table 5.2 the knowledge of the velocity will improve model predictions for environmental, economical as well as social aspects.

Along-track SAR interferometry	
Application Area	Application Topic
Oceanography	<i>Ocean Currents</i>
Traffic	<i>Traffic Flow Monitoring</i>
Hydrology / Glaciology	<i>Ice Flow Monitoring, River Flow Monitoring</i>

Table 5.2: Application areas and application topics using along-track SAR interferometry

5.1.3 New SAR Technique

TanDEM-X will allow the demonstration and exploitation of *new SAR techniques*, which opens up new perspectives for future SAR systems. The focus will be on the research areas multistatic SAR, polarimetric SAR interferometry, digital beamforming and super resolution. The main interest for these research areas lies in the understanding and the development of new algorithms. In principle, the application areas InSAR processing and formation flying will be operationally used during the mission, but there exist still some challenging scientific tasks, which need to be investigated. Six scientific

application areas under the heading new SAR techniques are listed and can be extended by new proposals arriving through the Science Service System. They are listed in table 5.3.

New SAR Techniques	
Techniques	Topic
Bistatic Processing	<i>Investigation of bistatic scattering behaviour for improved classification</i>
Pol-InSAR	<i>Pol-InSAR for different application areas & development of new techniques and algorithms</i>
Digital Beamforming	<i>Wide swath imaging and ambiguity suppression</i>
Super Resolution	<i>Spatial resolution enhancement</i>
InSAR Processing	<i>Ultra high resolution DEM with multiple baselines</i>
Formation Flying	<i>Precise baseline determination and orbit control</i>

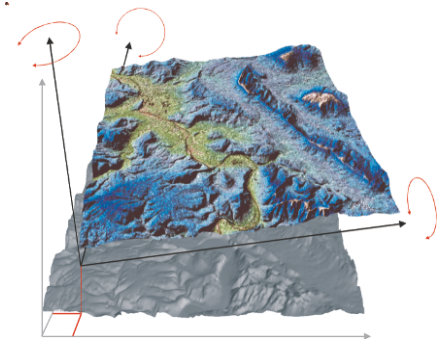
Table 5.3: Application areas and application topics under the heading new SAR techniques

5.2 Science Needs

The scientific needs were collected within several submitted and evaluated queries and are summarised for the three techniques below [R5].

5.2.1 Across-Track SAR Interferometry (Digital Elevation Model)

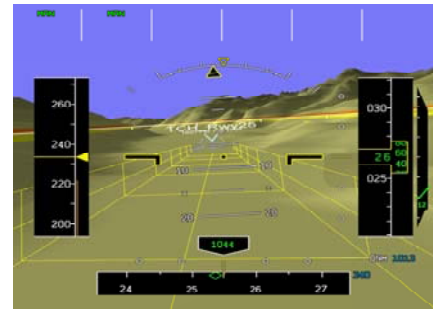
Topography: Today on a local scale in industrialised regions, topographic maps are available but on a global scale the topographic information is inadequate, lacking in accuracy, resolution, having different formats and map projections and is acquired at different times. The main research in this domain is directed towards the derivation of a DEM from SAR interferometry, whereas the main activities are concentrated on the development of algorithms for the validation and calibration of heights and tools for their 3D visualisation. In addition, a high resolution DEM is required for all data which need to be orthorectified. This means a high resolution DEM is a prerequisite for all image data products, as for example optical data. The best application of a pure DEM is its integration into a GIS, where different information spaces are combined in order to obtain a reliable and integrated information system. Nevertheless, the scientific objective is the understanding of radar remote sensing derived heights and the development of mathematical formulations for their interpretation and utilization. TanDEM-X will provide what is missing at a global scale and with a reliable data set. **Requirement: High resolution DEMs for topographic mapping with global access.**



Topographic map derived from DEM

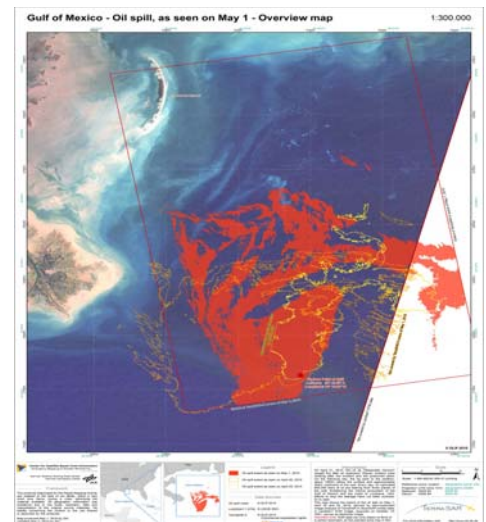
Navigation: There is a need for the development of world wide terrain databases and related system processes for use in safety critical aviation applications like Enhanced Ground Proximity Warning Systems or Synthetic Vision Systems. Such data bases use today contributions from multiple sources with different specifications and standards, and will benefit by a consistent data source. The processing supported by the system will also include reliable, verified, and standardized quality parameters supporting accuracy and statistical needs for a consistent safety critical terrain database. The TanDEM-X data set will be a highly desirable contribution to improve the overall system performance and the quality of future products in an ongoing development effort for the improvement of safety critical aviation terrain databases.

Requirement: Strong need of a world wide precise and reliable terrain data base, where a DEM represents one of the essential input parameters.



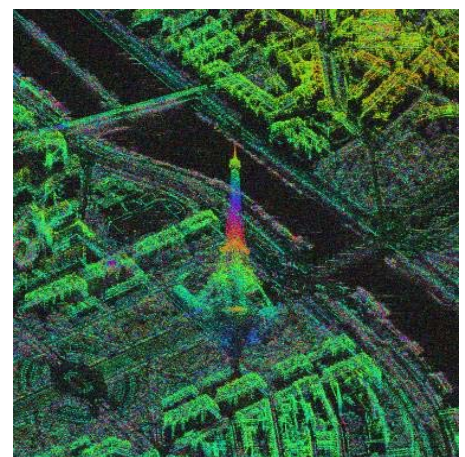
Procedure Display with Tunnel in the Sky

Crisis Management: The awareness of the civil crisis information, disaster management and international humanitarian relief support is increasing with the changing political situation. Typical areas of operation in this domain are the generation of rapid mapping products and situation assessments at different spatial scales and for different thematic areas. TerraSAR-X is already supporting, complementing and improving the existing optical observing capacities in the 1 m class by SAR derived information. Extending the TerraSAR-X mission by a TanDEM-X satellite, operated in a single pass interferometry constellation, would even allow enlarging the observing capacities in different ways. Topographic height information with a global accessibility is one of the main input parameters for the determination of infrastructures and thus enhances the potential and effectiveness of crisis management and humanitarian aid. It is also a valuable source of thematic information for all types of disaster assessment tasks. Not only for earthquake damage assessment, but also for rapid mapping or flood analysis operations. **Requirement: High resolution DEM for crisis management**



Oil Spill Disaster May 2010

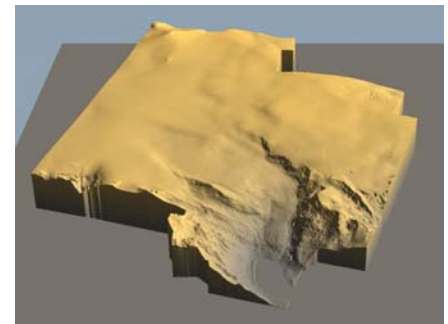
Urban Area: There is a great interest in the estimation of Digital Surface Models (DSM) from urban areas for infrastructure planning, environmental issues and security related applications. In urban areas, it is however very difficult to interpret the SAR image and interferometric phase due to layover and shadow effects, discontinuities, strong isolated backscatterers and multiple reflection effects. Several scene understanding and height extraction algorithms are being developed using high resolution interferograms which are based on the modeling of the different scattering mechanisms and scene phenomenology. The goal is to estimate on a reliable way the Digital Surface Model using information from the amplitude radar data, coherence, interferometric phase, scene statistics and stochastic geometry as well as using a supervised procedure. In some cases, information from different interferometric passes (multi-track approach) are



Interferogram of the Eiffel Tower (Paris)

combined to improve scene understanding and to decrease the shadow areas. TanDEM-X will provide single-pass high resolution interferometric data that are well suited for DSM extraction from urban areas. In addition, the full polarimetric capability of TerraSAR-X can be explored to improve the modelling in the case that several scattering mechanisms are present in the same resolution cell.
Requirement: High resolution interferometric data for the Digital Surface Model generation in urban areas.

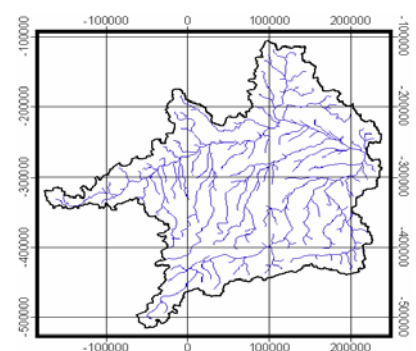
Glaciology: Accurate maps of surface topography are a pre-condition for monitoring and modelling glacier mass balance, glacier climate interactions and run-off from glacier basins. In addition, temporal changes of glacier topography over several years would provide detailed and unique information of multi-year glacier mass balance with near global coverage, which are up to now unknown quantities. Surface lowering of retreating glaciers may amount to meters per year, thus being well detectable by time series of surface topography. Not only glacier but also Polar Regions are of high importance for the calculation and prediction of climate changes. Due to the low X-band penetration, TanDEM-X will provide a unique data set on changes of glacier/ice mass and on the sea level contribution due to glacier retreat. ERS-1/2 InSAR applications over glaciers have become an important input for glaciological modelling, in particular in Polar Regions. Also CryoSAT-2 data will have an impact on the understanding of the current ice topography status, but will not provide the necessary information in mountainous terrain with its rather large footprint. Further, the detection of the grounding line position is an important parameter in glaciology. With TanDEM-X it would be potentially possible to measure these important environmental parameters.



DEM over a Glacier derived from X-band

Requirement: Accurate maps of surface topography are a pre-condition for monitoring & modelling glacier mass balance, glacier climate interactions, run-off from glacier basins & detection of the grounding line.

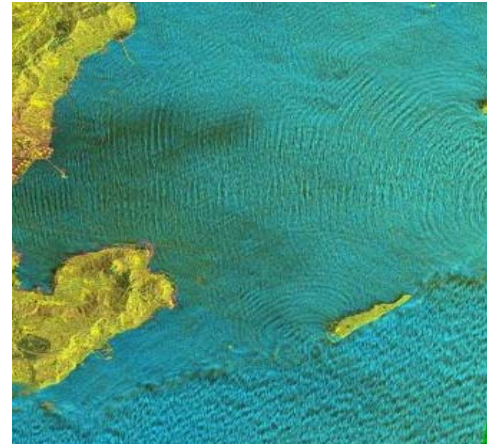
Hydrology: Highly resolved DEMs are used to produce regional flood plain maps (e.g. for risk assessment) and to derive hydrological relevant topographic features, such as drainage networks or wetness index, which serve as input data and parameters for multi-scale model applications. The evaluation of TanDEM-X data will close existing model parameterisation gaps. Transboundary watershed simulations depend on reliable and consistent topographic and plant-specific data, which can be provided at a continuous high level of accuracy even for remote locations. The possibility to spatially and temporally monitor small-scale changes of topography and plant development is breaking new ground for remote sensing applications in hydrology.



Watershed map derived from DEM

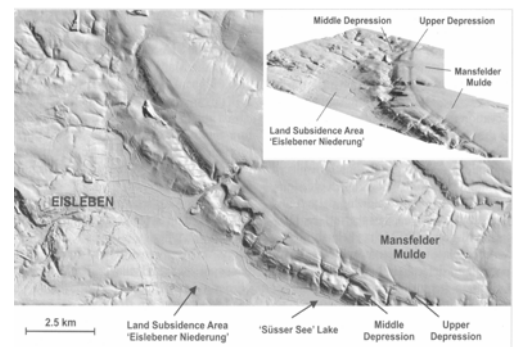
Requirement: High spatial resolution DEMs for regional flood plain maps.

Oceanography: Up to now spaceborne SAR wave measurements are mainly based on single antenna systems like ERS SAR and ENVISAT ASAR. It is expected that some of the limitations of these conventional measurements (e.g. uncertainties of SAR transfer function) can be overcome using interferometric data leading to improved estimates of wave spectra. The additional current information will open up a wide range of new applications, like e.g. the investigation of current wave interaction, which plays a key role in the prediction of sea states. In particular two ocean parameters are of importance, the estimation of the two-dimensional ocean wave spectra and the estimation of wind fields. Measurement of two-dimensional ocean wave spectra: Wave spectra provide information on wave height, wave propagation direction and wavelength. Up to now spaceborne SAR is the only instrument which is able to provide this kind of information on a global and continuous basis and TanDEM-X will provide new findings. Estimation of high resolution wind fields: SAR is able to provide information on high resolution wind fields, which are of particular value for coastal applications like offshore wind farming. **Requirement: Estimation of the two-dimensional ocean wave spectra and the estimation of wind fields.**

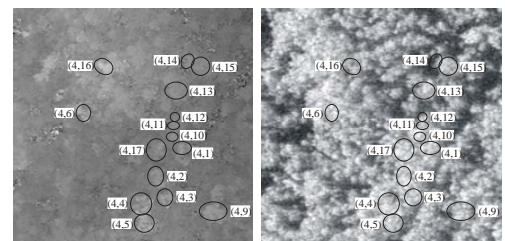


Different ocean current types

Geology: DEMs provide an essential basis for all areas in geological science, thus the request for accurate and reliable height information is of indisputable importance. For example DEMs are a prerequisite for the development of geological maps. Further, regions with volcanoes and expected earthquakes events need an up to date high resolution DEM to account for changes after events. In addition, reliable and precise DEMs are needed for the identification of critical urbanised regions being affected by tsunamis. The global coverage of topographic data at sufficient high spatial resolution is currently not available and would be provided by the TanDEM-X mission. **Requirement: High spatial resolution DEMs for all areas of geological science mapping.**

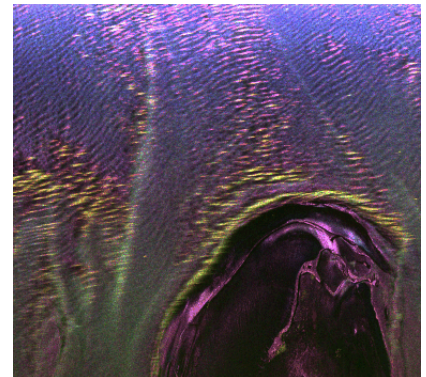


Land Cover and Vegetation: High resolution radar interferometry allows the assessment of three dimensional canopy architectural descriptors. These descriptors, such as crown size statistics, vertical distribution of the crown layer, gap occurrence intensity, etc., allow forest degradation, regeneration stage mapping or natural regeneration mosaic mapping. Information on the forest state is needed for land use planning, forest rehabilitation planning, forest protection, fire prevention and nature conservation. Better knowledge of the forest state is of importance for forest management and forest ecology (biodiversity). The TanDEM-X mission will provide a unique data set in terms of resolution and temporal consistency to satisfy these requirements. **Requirement: High spatial resolution DEMs for forest state assessment (upper layer).**



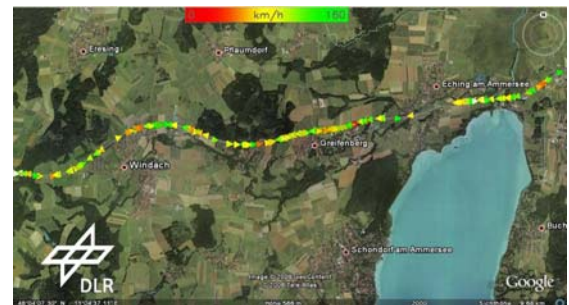
5.2.2 Along-Track SAR Interferometry

Oceanography: A strong demand for high-resolution current measurements in coastal regions has been identified in several research projects. Typical applications comprise high-resolution current fields in coastal areas for the generation of current atlases, the monitoring of bathymetric changes, determining locations for tidally-driven electric power generators. Furthermore there is a demand for current measurements in rivers which are not accessible with in-situ measurements. The water levels in such rivers can already be measured by radar altimeters, but current measurements are required to compute the actual volume transport. Only along-track InSAR can provide such measurements. The technique of current measurements by along-track InSAR is well understood and has been demonstrated with data from a number of airborne InSAR experiments as well as with spaceborne InSAR data acquired by opportunity from the SRTM. The main new aspects of the proposed measurements with TanDEM-X lie in a better data quality and in the possibility to define test areas and data acquisition strategies for a period of at least some months according to the requirements of potential users. **Requirement: High spatial resolution ocean current fields and river current estimation.**



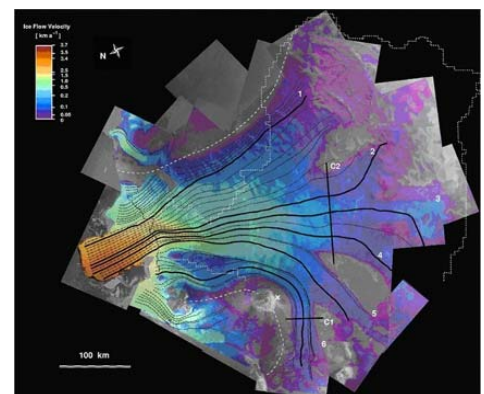
Bathymetry at the Waddensee

Traffic: There is a need in several applications for the detection of ground moving objects and the estimation of their velocity. Along-track SAR interferometry is capable for wide area traffic monitoring. Signal processing for ground moving target indication using a tandem configuration shows great potential for more accurate estimation of the moving object velocity, especially due to the combination with the dual-receiving antenna mode of both TerraSAR-X and TanDEM-X satellites. With such a configuration, new algorithms can be developed for the estimation of the true broadside position, the heading, the velocity and the acceleration of a moving object without additional inclusion of information. **Requirement: High spatial resolution traffic flow estimation.**



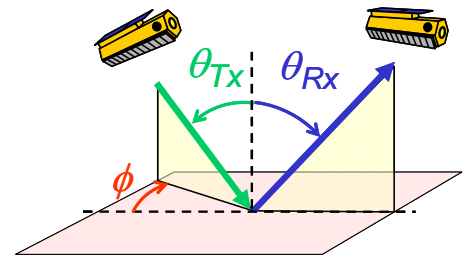
Velocity of moving cars on a motorway (TerraSAR-X)

Glaciology: Apart from the topography and the grounding line position, the flow velocity of glaciers or ice is a demanded parameter and of high importance for the interpretation of the mass balance of ice caps and glaciers. Monitoring, flow velocity of fast glaciers requires 1 day or shorter temporal baseline for SAR interferometry, or the use of image correlation/speckle tracking techniques. Depending on the mission concept, the use of super resolution might additionally help to improve the SNR and/or resolution of these not always precise techniques. The possibilities to obtain very large baselines make TanDEM-X an ideal sensor for improved glacier velocities measurement. **Requirement: Large baseline configuration for glacier velocity estimation.**



5.2.3 New SAR Techniques

Bistatic SAR: Bistatic SAR imaging provides additional observables for the extraction of important scene and target parameters. Bistatic data can also be combined with monostatic data to obtain a highly informative set of multi-angle observations. For example, a quantitative evaluation of the bistatic radar cross-section (RCS) facilitates the detection and recognition of targets based on their characteristic bistatic radar signatures. The segmentation and classification in radar images is expected to be substantially improved by comparing the spatial statistics of mono- and bistatic scattering coefficients. Bistatic SAR imaging has great potential for the retrieval of sea state parameters, the estimation of surface roughness and terrain slope, as well as in forestry, stereogrammetric, meteorological and atmospheric applications. Innovative processing algorithms will be required to exploit all these potentials. The bistatic data acquired with TanDEM-X will hence provide a unique data source to improve our understanding of bistatic imaging and its exploitation for future remote sensing applications. **Requirement: Demonstration of bistatic SAR imaging in various configurations.**

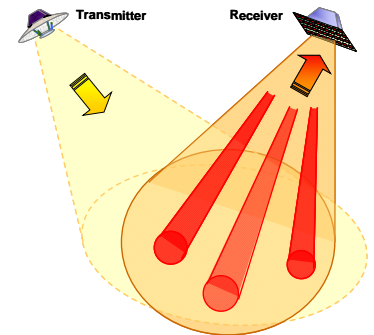


Pol-InSAR: DEM optimisation using polarisation diversity helps to minimise interferometric phase variance and hence to achieve high quality interferograms as well as high resolution DEMs over land surfaces. Estimating the vegetation bias in X-band SAR interferometry and combining it with data from other sensors (L-band air and space borne SAR) is essential to extract maps of forest and agriculture vegetation structure parameters such as height, canopy layering etc. These application products require a sensor capable of quasi single pass polarimetric SAR interferometry. The TanDEM-X mission provides such a novel sensor configuration and will deliver exemplarily first DEMs without a reduced vegetation height offset in forest areas and important crop parameters needed for an efficient agricultural management. **Requirement: Demonstration of the estimation of volumetric biases and short vegetation parameters.**

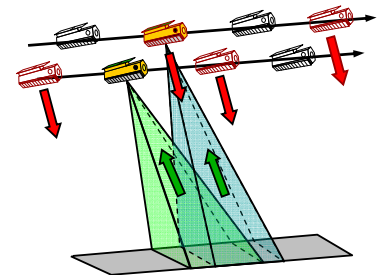


Super Resolution: The signals received by two satellites have different aspect angles for each scattering point on ground. This property can be used to achieve a finer resolution by combining the received signals coherently. The product of such a mode is a SAR image with increased resolution – super resolution. There is a need on developing adapted signal processing tools to separate or extract individual reflectors or clusters that are close to each other (compared to the image resolution cell), while preserving their phase as much as possible. These algorithms could then be applied on structures such as buildings, electric poles, bridges etc. (also called “micro-reliefs”) to get a better understanding of their contribution (especially 3D and multi-path) and of their interaction with the background (for clutter height measurement for instance). **Requirement: Demonstration of the super resolution technique.**

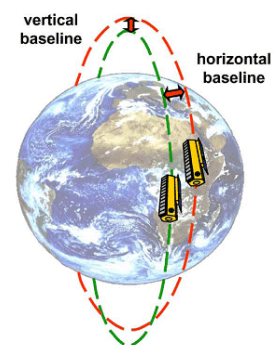
Digital Beamforming: Smart antennas are becoming one of the promising technologies to meet the rapidly increasing demands for more capacity of satellite systems. Digital Beamforming is the combination of radio signals from a set of small non-directional antennas to simulate a large directional antenna. Due to the split antennas and dual receiver channels of TSX and TDX, four phase centers can be obtained in a tandem mode. This combination enables not only a wide image swath with high spatial resolution, but it is also of great advantage for advanced interferometric SAR modes like the alternating bistatic mode where it allows for a reduction of the PRF, thereby resolving potential timing conflicts. TanDEM-X will be the first configuration which demonstrates this highly innovative technique from space. **Requirement: Demonstration of the digital beamforming technique.**



InSAR Processing: TanDEM-X is a highly flexible interferometric SAR sensor which offers a wealth of powerful imaging modes. To reduce both mission and processing complexity, operational DEM generation is only based on a small subset of these combinations using standard instrument settings as far as possible. The potentials of more sophisticated InSAR modes will then be demonstrated for selected areas during dedicated mission phases. Examples are improvements in performance, resolution and coverage achieved by ScanSAR and Spotlight interferometry, double baseline alternating bistatic SAR, or split bandwidth InSAR. Further potentials arise from a combination of the interferometric data from multiple TanDEM-X passes. This allows not only for a calibration and improvement of the DEM accuracy by applying innovative multi-baseline InSAR processing techniques, but it enables also a wealth of highly innovative data products by evaluating the higher-order differential phases and coherences of double difference InSAR measurements. Examples are the detection of the grounding line, monitoring of vegetation growth, mapping of atmospheric water vapour, measurement of snow accumulation, or detection of anthropogenic changes of the environment. Note that most of these combinations rely on a comparison of two or more single-pass cross-track interferograms and do hence not necessarily require coherence between the different passes. TanDEM-X enables hence the entry into a new age of interferometric (and tomographic) processing techniques as it was ERS for the development of classical repeat pass SAR interferometry. **Requirement: Demonstration of multibaseline InSAR processing.**



Formation Flying: The great variety of TanDEM-X applications will require adaptive baselines. This demand can be satisfied by a set of two satellites orbiting in close formation. For a close formation of the satellites, collision avoidance becomes a major issue. Safe operation for DEM generation can be achieved by choosing the Helix formation, in which the two orbits are completely separated in space. The demonstration of some innovative SAR techniques may require modified and, in specific cases, also closer formations. An example is short baseline along-track interferometry in combination with vanishing cross-track baselines. Such formations can be achieved by exploiting either natural formation drifts or appropriate orbit manoeuvres. TanDEM-X will be the first system which demonstrates these highly innovative formation flying techniques in space. **Requirement: Demonstration of operational formation flying satellites.**



6 Science Data Products

6.1 Science Data Policy

For the TanDEM-X mission the following science data policy has been defined:

- DLR as German Space Agency is the owner of the TerraSAR-X and TanDEM-X satellites. It administers this ownership as trustee for the Federal Republic of Germany. All data provided by these two satellites are therefore attributed to DLR.
- DLR will provide satellite operations and payload operations scheduling, generation and dissemination of standard products, quality control and archiving of these data. DLR will facilitate access to the data by producing and maintaining a unified global catalogue of all TanDEM-X data.
- The operation of the TerraSAR-X mission with the delivery of its basic products will continue in parallel to the TanDEM-X mission.
- The research results will be the property of the investigators. The processed TanDEM-X data may only be used for scientific, non-commercial purposes.
- Data requests for science purposes should not interfere with commercial interests.
- The commanding/acquisition and data provision are governed by national security regulations. This includes the supervision of data requests from crisis areas.
- The status “Scientific Use” needs to be gained via a selection process (e.g. an Announcement of Opportunity (AO)).
- The usage of TanDEM-X data is regulated via a license agreement.
- The TanDEM-X mission has specific scientific objectives (see chapter 4). TanDEM-X data will be provided to satisfy these objectives.

6.2 Science Data Products

The science data products of the TanDEM-X mission are divided into Digital Elevation Models, operational mode and experimental mode products.

6.2.1 Digital Elevation Model Products

Three different DEM product classes will be available for the TanDEM-X Science Team [R7]:

- **TanDEM-X DEM:** The standard TanDEM-X DEM is a product derived from multiple TanDEM-X acquisitions and will be available 4 years after the satellite launch with global access. The specification of the DEM is given in table 6.1. Additionally, standard TanDEM-X DEMs will be available with pixel spacings increased by a factor of 2 and 4 and with improved relative vertical height accuracy.
- **TanDEM-X intermediate DEM:** The intermediate DEM is a product derived from the first global coverage only and therefore it has reduced performance compared to the standard TanDEM-X DEM (described above). The processing of one baseline could cause some phase unwrapping artefacts especially in mountainous regions. In addition it could happen that data gaps exist due to acquisition failures and over shadow/layover regions. It is planned to make the intermediate DEM available 2.5 years after satellite launch. As for the standard TanDEM-X DEM

an intermediate DEM with increased pixel spacing by a factor of 2 and 4 and improved relative vertical height accuracy will be available.

- **DEMs on special user-request:** These DEMs are generated on special user-request for a limited number and size of areas of interests. Two types of user-requested DEMs are available, DEMs based on TanDEM-X DEM acquisitions processed to a finer pixel spacing and lower height accuracy (FDEM) and higher resolution DEMs (HDEM) with higher relative height accuracy based on additional DEM acquisitions to improve the relative height error. Additional DEM data will be acquired after completion of the acquisitions for the standard TanDEM-X DEM and will be processed after the delivery of the standard TanDEM-X DEMs.

Table 6.1 DEM product list of the TanDEM-X mission

DEM Product	Spatial Resolution	Absolute Vertical Accuracy (90% linear error)	Relative Vertical Accuracy (90% linear error)	Availability
TanDEM-X DEM				
TanDEM-X DEM (standard)	12 m (0.4 arc sec @ equator)	<10 m	2m (slope < 20%) 4m (slope > 20%)	4 years after launch.
TanDEM-X DEM (reduced by factor 2)	24 m (0.8 arc sec @ equator)	<10 m	1m (slope < 20%) 2m (slope > 20%)	4 years after launch.
TanDEM-X DEM (reduced by factor 4)	48 m (1.6 arc sec @ equator)	<10 m	0.5m (slope < 20%) 1m (slope > 20%)	4 years after launch.
TanDEM-X Intermediate DEM				
IDEM (standard)	12 m (0.4 arc sec @ equator)	~10 m	> 2 m (slope < 20%) > 4 m (slope > 20%)	2.5 years after launch.
IDEM (reduced by factor 2)	24 m (0.8 arc sec @ equator)	<10 m	> 1 m (slope < 20%) > 2 m (slope > 20%)	2.5 years after launch.
IDEM (reduced by factor 4)	48 m (1.6 arc sec @ equator)	<10 m	> 0.5 m (slope < 20%) > 1 m (slope > 20%)	2.5 years after launch.
TanDEM-X DEM on Special User Request				
FDEM (Finer pixel spacing resulting in a higher random height error)	6 m (6 arc sec @ equator)	<10 m	4 m (slope < 20%) 8 m (slope > 20%)	Requests will be processed after the delivery of the standard TanDEM-X DEMs.
HDEM (High resolution DEM with additional DEM acquisitions)	6 m (6 arc sec @ equator)	<10 m	Up to 0.8 m (90% random error)	These DEMs require additional large baselines data acquisitions in the third mission year. Demands have to be specified in time and HDEMs will be processed after the delivery of the standard TanDEM-X DEMs.

6.2.2 Operational Mode Products

A TanDEM-X acquisition is a coordinated SAR instrument data take by both satellites of the TanDEM-X mission. During such an acquisition, each satellite is operated in instrument modes similar to those for the TerraSAR-X mission. A further dimension is defined by the degree of cooperation of both SAR instruments – acting as one coordinated and synchronised SAR instrument or just two separate ones. TanDEM-X product characteristics like focusing quality and radiometry are thus ruled by the effectiveness of this cooperation. The highly variable system allows manifold combinations of the following modes [R8]:

- **Imaging mode** of each instrument (stripmap, spotlight, scanSAR, high-resolution spotlight, experimental dual receive antenna along-track interferometry, aperture switching, etc.)
- **Polarisation mode** (single, dual and experimental quad and twin)
- **Cooperative mode** (bistatic, alternating bistatic, pursuit monostatic, none (TS-X mission) & other experimental commandings)
- **Formation geometry** (small or large along & across-track separation/effective baselines)

Classified as operational are acquisitions in which both satellites acquire in the same imaging and polarisation mode. The operational modes and products are summarised in table 6.2 and are available to the science user after proposal acceptance.

Table 6.2 TanDEM-X acquisition modes and products (all basic imaging modes includes Stripmap:SM, Spot-light:SL, High-resolution Spotlight:HS, ScanSAR:SC)

<i>Operational Mode</i>			
<i>Commanding</i>			
<i>TanDEM-X cooperative mode</i>	<i>Bistatic</i>	<i>Alternating Bistatic</i>	<i>Pursuit Monostatic</i>
<i>Imaging mode</i>	Stripmap	Stripmap	all basic modes
<i>Polarisation mode</i>	all basic polarisation modes (incl. DRA mode for quad polarimetry)	Single	all basic polarisation modes (incl. DRA mode for quad polarimetry)
<i>Formation Geometry</i>			
<i>Across-track baseline</i>	< 4 km	< 4 km	< 4 km
<i>Along-track baseline</i>	< 1 km	< 1 km	any
<i>Processing and Products</i>			
<i>Experimental products generated from the TanDEM-X processor</i>	CoSSC (coregistered slant range single look complex) and interferograms for all acquisitions	Two CoSSC (coregistered slant range single look complex) for all acquisitions	CoSSC (coregistered slant range single look complex) for Stripmap and single polarisation
<i>Experimental products generated by the TerraSAR-X processor</i>	Standard TerraSAR-X level 1b products*(including geocoding) of the monostatic channel for all acquisitions	Non	Two standard TerraSAR-X level 1b products*(including geocoding) for all acquisitions

* The TerraSAR-X basic product specification may not apply in terms of performance

Please note, that the pursuit monostatic mode and the polarisation DRA mode will be only available for dedicated mission phases.

6.2.3 Experimental Mode Products

Data from acquisition modes beyond the variety of operational modes are not routinely processed to higher level products by the TanDEM-X ground segment. The respective modes are called experimental modes.

Experimental products are the result of special scientific SAR experiments based on new techniques which are possible due to the innovative configuration given by the TanDEM-X mission. It is foreseen that the ordering of such kind of products is coordinated by a SAR expert team and is currently not available. The experimental mode products will be only available during the last mission phase for a limited number of dedicated experiments.

6.3 Priority Concept

TanDEM-X DEM and scientific acquisitions are planned in advance with high priority according to the TerraSAR-X Priority Concept. The majority of TerraSAR-X data takes are placed and planned around the already defined TanDEM-X time line. A limited number of high priority TerraSAR-X data takes may overwrite already planned TanDEM-X data takes that are re-ordered according to pre-defined ground segment rules.

6.4 Science Product Pricing

The TanDEM-X science product price has been evaluated according to the cost of fulfilling user requests (COFUR) and is provided on the TanDEM-X home page. All scientific proposal submitted during the commissioning phase will be free of charge.

The connection of the science user to the TanDEM-X ground segment is given by the TanDEM-X Science Service Segment and its infrastructure provides a communication platform between the scientists, the science coordinator, and the evaluators. The TanDEM-X Science Service Segment is built up by three main components (figure 7.1):

1. The Science Service System and its core, the Science Service System homepage as a web interface. The Science Service System is a web content management system for the TanDEM-X science coordinator to administrate the science coordination work and to organize the science user community. Herein the Science Service System homepage as the central part is the most important tool providing the necessary communication infrastructure. The Principal Investigator may use the web interface to submit and track his scientific proposal, and request for scientific data acquisitions. The PI has to submit progress and final reports of his research work using this web interface as well.
2. The EOWEB as a web interface. Here the science user may browse and order data from the catalogue, or track the acquisition of his data acquisition requests. The data delivery is also organized here.
3. The Protagonists: The Science Coordinator, External and Internal Evaluators, and the Science Users

The procedure for TanDEM-X data provision is following three main steps.

- First the PI needs to submit a science proposal for evaluation using the web interface to the Science Service System homepage (<https://tandemx-science.dlr.de>) with a detailed description of the test site and the requested data.
- Second the science coordinator, after proposal acceptance (operational and experimental products), is translating the requests and transmitting the translation to the IOCS for acquisition planning and execution.
- Third the PI can then track the acquisition status and, after data acquisition, order the data product at the EOWEB. The DEM products can be directly ordered from the archive in the EOWEB (web site: <https://www.eoweb.de>).

As mentioned above, the operational scenarios for the TanDEM-X mission differ from those of the TerraSAR-X mission in a variety of aspects. While future data acquisitions of the TerraSAR-X mission are ordered by the PI using the EOWEB human machine interface (HMI), this will not be accomplished for the TanDEM-X mission. Due to the complexity of the mission, its constraints on imaging geometry and instrument options, and its limited time frame during the global DEM phase balanced by a well weighted priority mechanism in relation to the TerraSAR-X mission, requests of the science users must be carefully moderated by the science coordinator and finally integrated into the acquisition plan by the ground segment systems.

In general, scientific use is a special use case for TanDEM-X, which is strictly assigned to non-commercial objectives and is limited to registered and approved science users only. Within the TanDEM-X mission, these approved science users may have a restricted and quoted access to the TanDEM-X data products. The status “scientific use” for TanDEM-X is gained via a proposal submission by the science user and an iterative acceptance procedure within the science service segment. For the TanDEM-X science coordinator the Science Service System is an important tool to administrate the scientific requests. The submitted proposals are crucial for the extraction of parameters of concrete TanDEM-X science data acquisitions that are not part of the systematic DEM data acquisition.

7.2.2 Proposal Submission

The proposal submission and the concrete proposal procedure steps the science user has to undertake is briefly described in the following. More detailed instructions are available online from the homepage of the TanDEM-X Science Service System Web Interface that is also the starting point for registration and proposal submission. Its web address is <http://tandemx-science.dlr.de> or alternatively, if a protected (https) access is preferred <https://tandemx-science.dlr.de>.

Investigator's basic registration

If the PI is not an already registered user a basic registration to the science service system is needed first. A special link is provided for that purpose on the start page that guides to a web form, where the science user has to fill in a user name, a valid email address, and an initial password. By pressing a submit button the registration request process is initialised. The science user will receive a confirmation email, if the rules for the user name and password are not violated, and the email address is valid. The confirmation email provides a link that directs to a special verification page. Here the user should login with the user name and the initial password used for the initial registration. If the verification succeeds, a success message is displayed, and the basic registration step is completed, and the verification page may be closed. The user should from now on login using the login form fields provided on the left side menu of the start page, whose web address is given above. After login, the user is redirected to an individual user page. If the redirection fails, the link 'Registered User Access/Investigator' provided on the left side menu of the start page may be used for that purpose. In case of a failure (e.g. network interruption), the user may restart this basic registration to the science service system at any time simply by following the link provided in the first verification email. A similar registration procedure on a separate web page exists for the evaluators; the evaluators are invited by the science coordinator.

Proposal entering

With the first login a web form is asking for the PI's full contact details. By submitting this contact details, the registration process will be finalised, and an individual proposal page for the PI is created, where he may enter the proposal, maintain the contact details, or change the login password using the left side menu.

The science user may immediately create a new proposal accessing the link 'Create New Proposal. If the user follows this option, a unique proposal ID is created. Within the proposal entering area the PI is asked to fill out a web form with respect to the different aspects of the planned research work. The topics are:

- Title of the proposal
- Application domain
- Team composition and expertise of the team
- Region(s) of interest
- Main scientific objectives
- Schedule
- Confidentiality
- Special requirements
- Data requirements
- Executive summary of the proposal

The science user may edit the proposal in successive sessions. The procedure for requesting TanDEM-X data acquisitions within the proposal procedure is one of the most important tasks. In case of requesting experimental radar data products the PI is asked to specify interactively on a special web page the data needs. The page can be reached following a link from the data requirement section. The proposed acquisition requests are evaluated for feasibility in the ground segment. A similar procedure will be implemented to specify the location and amount of DEM products by the science user.

Proposal submission and tracking

After the proposal has been finally submitted to the system, the editing option is disabled. The PI may re-visit his personal proposal page at any time after login from the entry page, all proposals related to his login credentials are further listed in a table. A read access to the submitted proposal is given by a table field holding the unique proposal ID, which provides a link to the full version of the proposal. In a separate table field the status of the proposal may also be tracked. The following flags for the proposal are foreseen:

- **Entered:** The proposal has been initiated by the PI and may be edited
- **Submitted:** The proposal has been submitted to the system for the approval procedure. The proposal can be accessed in a read-only mode
- **Handed-Over:** The proposal has been handed-over by the science coordinator to the evaluators
- **Evaluated:** The proposal has been evaluated and commented by the evaluator
- **Approved:** The proposal has been evaluated and has been finally approved by the Science Coordinator. The PI is asked via email or fax to provide a signed license agreement and a declaration of funding. The license agreement may be downloaded from the start page.
- **Licensed:** A valid license agreement and a declaration of funding provided by the PI have been accepted by the Science Coordinator, but the final release of an EOWEB account is still pending.
- **Released (EOWEB):** This is the final status of the proposal approval. An EOWEB account has been initiated by the Science Coordinator.
- **Finished:** The research work is finished and the final report is approved by the science coordinator.
- **Rejected:** The proposal is rejected by the science coordinator

A full list of approved proposals can be accessed from the left side menu of the start page. Clicking the proposal ID field in the table the proposal team composition and a short summary of the planned research work of the selected proposal is reported. Setting the confidentiality flag to 'yes' during the proposal entering procedure the PI can suppress the publication on the web page entirely. The confidentiality of the proposal needs to be explained in the proposal text.

With the final proposal status 'released' the approval procedure is finalised. The PI receives an email from the science coordinator with the final judgement, the allocated quota, and the initial EOWEB account. Having this user credentials in hand the PI may login at the EOWEB interface to order data from the catalogue, or to track the status of data acquisition requests. At the first session in the EOWEB the PI is advised to change the initial login password. Within EOWEB the PI should also maintain the contact details, the delivery and billing address.

Proposal evaluation and approval

With the final submission the evaluation process is initialised. The science coordinator delegates the proposal to the evaluators, the status of the proposal is set to 'handed-over'. The evaluator may reach the proposals he is delegated to by login on the science service system homepage. He may find the proposals on an individual web page, where the proposal he is asked for to comment is listed in a table. The proposal can be accessed by clicking the link placed on top of the proposal ID. The evaluator is asked to fill out the comment text fields corresponding to the different aspects of the proposal. To finalise the evaluation process the evaluator has to submit the comments and the final judgement to the science coordinator. If the proposal needs minor or major improvements after the first review, the

science coordinator may reject the proposal or return the comments to the PI; in the latter case the status will be set again to 'entered' and the PI may incorporate the proposed improvements. If no further improvement is needed the status of the proposal is set to 'approved'. The PI will receive an email notice about this status update. In order to get an EOWEB account, the PI is obliged to send back two important documents, and in addition an identity confirmation (e.g. copy of passport, identity card) to the science coordinator. The two forms are:

- A signed TanDEM-X license agreement
- A signed funding allocation

A list of authorized users that will have access to the data in addition to the PI and the Co-PIs needs to be maintained by the PI, too. The list can be accessed online by a link provided in the table listing the proposal on the PIs' individual page. The list of authorized users is accessible and editable throughout the lifetime of the proposal.

Other responsibilities of the PI

The PI is advised to:

- Maintain the contact and address details and announce changes to the DLR
- Document and archive the order history
- Inform the DLR, in case the status 'scientific use' is changed
- Inform the DLR about changes of the composition of the PIs team
- Maintain online a list of authorized users the PI or the Co-PIs want to give in addition access to the data covered by the proposal.

7.2.3 Science Data Ordering

With the EOWEB account in hand the status of the acquisition request for the TanDEM-X data takes specified in the proposal can be tracked within the EOWEB web interface. Finally acquired data takes are listed in the EOWEB catalogue and need to be ordered by the PI in the EOWEB. The EOWEB provides also the ordering interfaces for all other products for scientific use of the TanDEM-X mission. The data delivery is organized by a secure FTP procedure.

7.3 Science User Communication and Reporting

The PI is obliged to submit a short progress report every half a year to the DLR and the TanDEM-X science coordinator in order to document the scientific use. A detailed final report has to be prepared after the end of the project as well. The interface for this action will be given by the science system home page. A web form will be provided for this task including the option for document uploads. In addition a presentation of proposal status and results is required at the science workshops organised by the science coordinator. The science workshop will take place once a year. The PI is also asked to update the reference list of publications made with the provided TanDEM-X data on the science system homepage.