FIRST DATA ACQUISITION AND PROCESSING CONCEPTS FOR THE TANDEM-X MISSION

M. Eineder, G. Krieger, A. Roth

German Aerospace Center DLR
82234 Wessling, Oberpfaffenhofen, Germany

KEY WORDS: Earth Observation, Topography, DEM/DTM, Interferometer, Radar, SAR, Satellite, SAR & IFSAR

ABSTRACT:

TanDEM-X is a German Public Private Partnership project between DLR and EADS Astrium for a novel satellite constellation based on TerraSAR-X with the goal to generate a global digital elevation model (DEM) according to the HRTI-3 standard, i.e. 10 m horizontal spacing and 1-2 meter vertical accuracy. TerraSAR-X is a civil German X-Band Synthetic Aperture Radar (SAR) satellite to be launched in 2006 with the purpose to deliver X-Band images for scientific and commercial purposes. The key idea of the TanDEM-X proposal is to place a second TerraSAR-X satellite into the same orbit with a well controlled distance and to operate both satellites in a cooperative way. Our paper describes the TanDEM-X mission and the characteristics of the sensor system. Some special hardware modifications are foreseen on the satellites to enable proper synchronization of the flight paths, the timing of the microwave pulses and the carrier phase. The focus of the paper is on the structure of the SAR data processing chain to be developed at DLR. We describe the strategy of processing the raw data in different phases to a global mosaicked DEM. Intermediate data will be stored in an archive so that calibration or reprocessing with improved parameters or algorithms can be performed with minor impact. The processing will require some new algorithms, such as PRF synchronization, inter-satellite phase trend removal and multi-baseline phase unwrapping. Also the absolute vertical calibration of DEMs to the required 10 meter vertical accuracy will be a challenge.

1. INTRODUCTION

In the standard operational scenario, one satellite would transmit and both satellites would receive the echoes. From the parallax between both positions the three dimensional surface of the earth can be reconstructed. Compared to optical stereo matching methods, the SAR interferometry method requires no daylight and no scene contrast. It works in cloudy conditions and the relative vertical DEM error can be rather accurately predicted from the radar signal to noise ratio. This method to generate large scale DEMs from SAR interferometry has been successfully used by the Shuttle Radar Topography Mission (SRTM) in the year 2000 to produce a global DEM with 30 meter spacing and 6 meter vertical accuracy. TanDEM-X shall significantly improve this existing data set in many aspects:

First, the horizontal resolution shall be increased by a factor of three. This is accomplished by using at least 50 MHz of bandwidth. For special applications the bandwidth can be increased up to 300 MHz allowing sampling in the sub-meter range at the cost of decreased vertical accuracy. Second, the vertical accuracy shall be improved by a factor of three by using larger baselines in the range of 400 meters. For experimental purposes much larger baselines in the kilometre range can be flown which increases the vertical accuracy to the sub-meter range. Third, the SRTM orbit was limited to ±60 degrees latitude. TanDEM-X has a near polar orbit and can achieve a global coverage, apart from small areas at the poles. Fourth, during the 11 day mission SRTM could not achieve a full coverage even below 60 degrees of latitude. The reason is that the reconstruction of absolute heights from ambiguous relative phase measurements requires phase unwrapping, which is not always free of errors. This led to larger void areas in mountainous regions such as the Himalayas and other rugged land surfaces. TanDEM-X will operate for 3 years. This long time span allows to image complex surfaces from different aspect angles, different incidence angles and with different baselines. From these multiple observations reliable DEMs even in difficult areas can be constructed.

DLR will develop the complete mission operations and system calibration section as well as the payload ground data processing system (PGS). The PGS will inherit many concepts from SRTM processing performed at DLR. Known deficiencies – such as phase unwrapping – will be significantly modified to the capabilities and the needs of the TanDEM-X mission.

2. SYSTEM OVERVIEW

The interferometric SAR constellation is composed from the TerraSAR-X satellite to be launched in 2006 and the nearly identical TanDEM–X satellite to be launched in 2009. Both satellites follow elliptical orbits with slightly different parameters so that their relative position to each other follows a helix during one orbit (Moreira, 2004) as shown in Figure 2. This helix configuration allows maintaining a relatively small distance between both satellites while at the same time avoiding the collision risk at the poles.

In the nominal operation mode one satellite is transmitting SAR pulses and both satellites are receiving the echoes from the earth surface as shown in Figure 1. Using the Synthetic Aperture Radar (SAR) principle each satellite records a microwave radar image with a resolution of about 3 meters in the flight (azimuth) direction and about 5 meters in the cross flight track (range) direction. Due to the coherent SAR imaging principle each pixel contains an accurate carrier phase range measurement of the signal path between transmitter, surface and receiver. Thus, the transmitting satellite records the range $2 \cdot R_1$ while the second satellite records the range R_1+R_2. The differential range R_2-R_1 can be determined from the phase differences of the two SAR images with an accuracy of millimetres. Together with the interferometric baseline B which is in the order of some hundreds of meters the terrain height can be determined with an accuracy of one meter. Note that in contrast to optical stereo technique no scene contrast is required because the phase is available for each individual pixel.

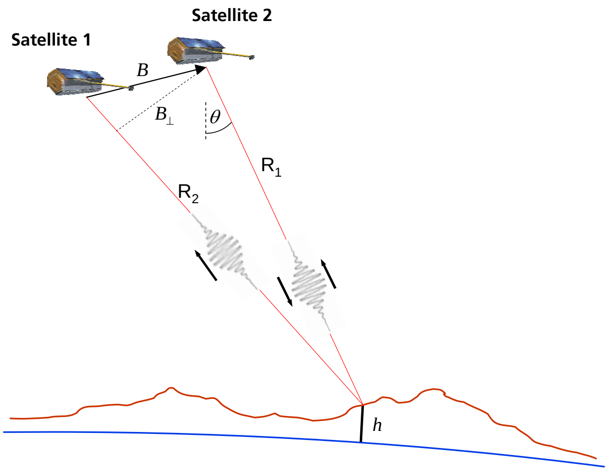

Figure 1. Imaging Geometry of TanDEM-X

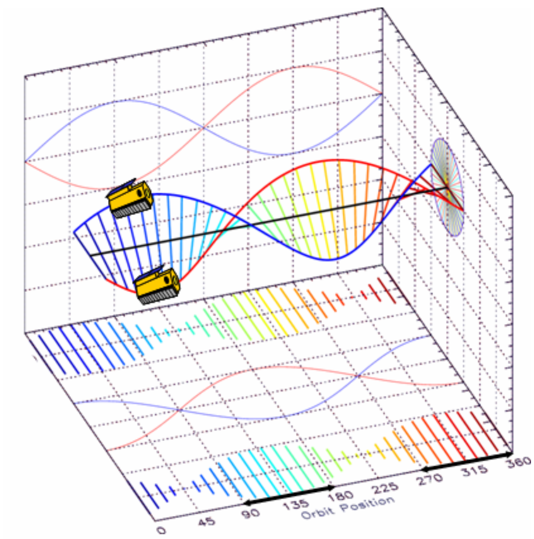

Figure 2: Helical shape of interferometric baseline during one orbit

Orbit height	514 km
Wavelength	3.1 cm
Pulse Repetion Frequency	3-6 kHz
Bandwidth	50-150 MHz
Swath width	30 km
Incidence angle	20°-50°
Baseline	50 – 500 m
Baseline knowledge	1-2 mm

Table 1. TanDEM-X Mission and System Parameters

This measurement concept is called single pass interferometry because both observations from different perspectives are performed simultaneously. It resembles very much the concept of the Shuttle Radar Topography Mission (SRTM) (Werner, 2001) but has one fundamental difference. In the TanDEM-X mission two separate radar systems are used while SRTM used one radar system with two synchronized channels. In consequence a number of technical challenges are faced in order to form one virtual coherent microwave instrument from two spatially separated radar systems.

2.1 Sampling Window Synchronization

In order to ensure that both satellites receive the reflected radar pulse right in time the start of the echo window at the beginning of the data take must be synchronized to a small fraction of the pulse repetition frequency, i.e. on microsecond level. The echo windows must still be correctly synchronized at the end of a 200 seconds duration data take, i.e. the PRF must be accurate on the 0.001 Hz level. PRF switching during a data take may be used to adjust slight known differences between both oscillators.

2.2 Phase Synchronization

In a conventional SAR system the range derived from the phase contains only the oscillator phase errors during the short pulse travel time (some milliseconds). In the TanDEM configuration it contains all the accumulated phase errors between the two oscillators (Eineder, 2003) since the start of a data take. Even smallest differences in the carrier frequency make this error very large . It can only be isolated and removed by processing if the role of the transmitter and receiver is periodically exchanged during a data take (ping pong mode) or if oscillator synchronization signals are exchanged between the satellites. For that purpose each of the TanDEM-X satellites is equipped with 6 small horn antennas that are used to exchange X-band synchronization pulses with a frequency of about 10 Hz. This allows for a phase synchronisation with an accuracy in the order of 1°.

2.3 Baseline Control

There are a number of requirements on the ideal baseline for interferometric terrain mapping:

a) the baseline in flight direction must be so small, that the received Doppler spectra of both satellites overlap significantly, i.e. less than about 3 km
b) the effective baseline B⊥ must be large enough to provide sufficient accuracy for the height triangulation, i.e. in the order of 400 meters
c) the effective baseline B⊥ must be smaller than about 10 kilometers to avoid decorrelation of plain surfaces and less than 1 km to avoid decorrelation of surfaces with a roughness of more than 5 meters, e.g. forests
d) the baseline must be small enough to allow resolution of integer phase cycle ambiguities. This task becomes a problem in mountainous topography where baselines smaller than 100 meters are required.

From the above requirements the orbital configuration is defined depending on the expected topography, the geographic latitude and previous acquisitions of the area. In order to maintain this baseline, the TerraSAR-X satellite transmits its position to the TanDEM-X satellite which can perform small orbit control manoeuvres using a cold gas system.

2.4 Baseline Measurement

As depicted in Figure 1 the height accuracy depends on the accuracy of the range measurements and of the baseline vector B, i.e. its length and its orientation in space. An analysis showed that the baseline vector can be determined with an accuracy of 1-2 millimetres by the use of differential GPS measurements.

2.5 Mission and Data Acquisition Concept

An analysis of the global slope distribution led to a strategy to map the earth topography efficiently using SAR interferometry. From the analysis it is predicted that 50% of the earth are of moderate topography and can be mapped with a single observation and a rather large baseline. Another 30 % will require two passes with different baselines and 20 % will need different baselines and viewing geometries to recover SAR layover and shadow effects (Eineder, 2005b). More details on the expected performance can be found in (Krieger, 2006) and on the data acquisition scenario in (Fiedler, 2006).

2.6 Data Downlink

About 400 Gigabytes of data are recorded by both satellites each day. DLR's primary receiving station at Neustrelitz / Germany is capable of receiving 90 Gigabytes per day. The rest is downlinked via additional stations preferably located close to the poles.

3. DATA PROCESSING

The data processing chain is developed completely at the Remote Sensing Technology Institute IMF and the German Remote Sensing Data Center DFD at DLR. It is based on the existing SAR processor developed for TerraSAR-X (Schättler, 2004) and on the interferometric DEM processing system that has been used for SRTM. Those systems contain many functionalities and modules that may be reused for TanDEM-X. However the different nature of this much more complex mission has of course impact on the structure of the processing system. In the following the processing chain from SAR raw data to the global DEMs is briefly described.

3.1 Multi-instrument processing

All interferometric products have to be generated from the data of two instruments. The data of the two instruments may be downlinked at different receiving stations and may be available at different times. Therefore instances must be foreseen to track the status of data acquisition status for the two channels and to collect and assemble the data for the SAR processing.

3.2 Gobal and Content Driven Processing

The sequence of data processing is not based primarily on single scenes but managed on a global scale. The task of global DEM generation will be finished after several years when the whole earth has been mapped successfully. Furthermore, the success criterium is not only that an area has been covered by an acquisition. For global DEM generation the success criteria are a) gapless coverage of the Earth with DEM products and b) gapless coverage within each single DEM products (avoiding shadow and layover) and c) successful DEM reconstruction, i.e. correct resolution of the integer phase ambiguities.

To achieve gapless coverage in mountainous areas involves combination of several scenes with different observation geometries as shown in (Eineder, 2005b). For successful digital elevation mapping it is required to image some areas several times. The required number of observations may not be known before processing has finished. The DEM processing chain will therefore consist of several stages that may have to be repeated in difficult locations. Therefore instances are foreseen to plan the required acquisitions based on previous experience, to track the successful creation of the final product, e.g. the DEM, to request additional acquisitions with optimized imaging parameters (baseline, incidence angle, ascending or descending) and to control a multi-image and multi-pass DEM processing system.

3.3 Reception and Archiving

The data streams of the two satellites are downlinked to different receiving stations where they are deformatted and recorded. A first quality analysis is performed immediately and a report sent to the Payload Ground Segment (PGS) at DLR in order to ensure that the data are complete and both receive channels are available. The SAR raw data, also called Level 0 data, are then mailed or transmitted via network to the PGS archive for further processing which starts with a detailed screening process.

3.4 SAR Data Screening

Once the Level 0 data are in the archive, the Level 0 SAR screening is performed with detailed echo and instrument calibration data analysis. Since the satellites work in bistatic mode, they must be considered as one instrument by the Level 0 SAR screening. For example, the signal power received by the passive satellite depends on the signal power of the transmitting satellite and on its own receiver gain. Therefore new bistatic analysis and data correction algorithms must be applied. After Level 0 SAR screening the data are catalogued and archived as a two-channel SAR raw data product together with quality information about bistatic usability. It could, e.g. happen that due to instrument instabilities only a part of the data take can be processed to DEMs.

3.5 SAR and InSAR Processing

At this point the two channels of the two satellites have been screened and logically compiled to one interferometric data take. Interferometric processing will be performed in portions of scenes of approximately 30 by 30 kilometres. The processing strategy is based on proven concepts from SRTM and several improvements. At first all processing steps are performed that can be done automatically without iteration and with predictable processing time. This part of processing is shown in Figure 3.

Bistatic Timing and Calibration Data Analysis

Due to different oscillator frequencies the sampling grids and the phase of the two sensors are expected to diverge. For example, assuming a relative frequency offset $(f_1-f_2)/f_1$of only 10^{-5}, the divergence between start and end of a 5 second duration scene would be
- a misregistration of 0.2 samples in azimuth (@PRF=4 kHz)
- a misregistration of 8000 samples (@RSF=165 MHz) in range which is approximately 20 % of the swath

- a phase error of 170 million degrees

Therefore the timing between both satellites is synchronized stepwise in increasing accuracy levels. Starting with GPS time tags, the time correlation is increasingly refined down to phase level by evaluation of the GPS time annotation tags, the peak position of intersatellite cal-puses, the cross correlation of adjacent rangelines and finally the phase of the intersatellite cal-pulses.

Bistatic Corrections

This step involves several corrections to be made on the SAR data before SAR focussing, e.g. the filtering of range and azimuth spectra to the common range, oscillator phase compensation, timing correction and swath truncation to the common range.

Bistatic Focussing Geometry

Since in bistatic mode the range history of a point on ground for the synthetic aperture parameters is not necessarily hyperbolic as it is the case for monostatic mode, a special bistatic SAR parameter calculation is required. It was shown (Bamler, 2005) that the almost parallel orbits of TanDEM-X mission cause only moderate deviations from hyperbolic trajectories and can be processed with standard correlation algorithms if the velocity parameter is adapted adequately.

Level 1 SAR processor

The chirp scaling correlator developed for TerraSAR-X is designed to be phase preserving in all imaging modes stripmap, spotlight and ScanSAR and can be reused with minor modifications. The special bistatic geometry has been analysed in a module before and transformed into a pseudo-monostatic geometry.

Common Band Filtering

This step filters the azimuth spectra of both channels to a common Doppler bandwidth and the range spectra to a common ground wavenumber.

Bistatic Coregistration

In this step the passive channel is registered to the active channel with high accuracy (goal 1/100 of a pixel).

Detection

In this step a high quality intensity image with the exact sampling of the interferogram is formed.

Interferogram Formation

The phase difference between the two SAR channels is calculated and the spatial resolution is adopted to the required product spacing by averaging adjacent samples while at the same time reducing the phase noise.

Coherence Estimation

A coherence map between both channels is estimated which serves as a local quality indicator for the DEMs.

IFDS Archive

This archive holds the intermediate interferometric data sets (IFDS), composed from intensity, phase and coherence maps that can be later processed to DEMs.

I-SSC Archive

This archive is intended for interferometric single look complex images (SSCs), a multi-purpose product that can be used for scientific purposes other than operational DEM production, e.g. for along track interferometry, oceanography, glaciology, multistatic SAR, Pol-InSAR, digital beamforming, processing with different resolution etc. (Hajnsek, 2006).

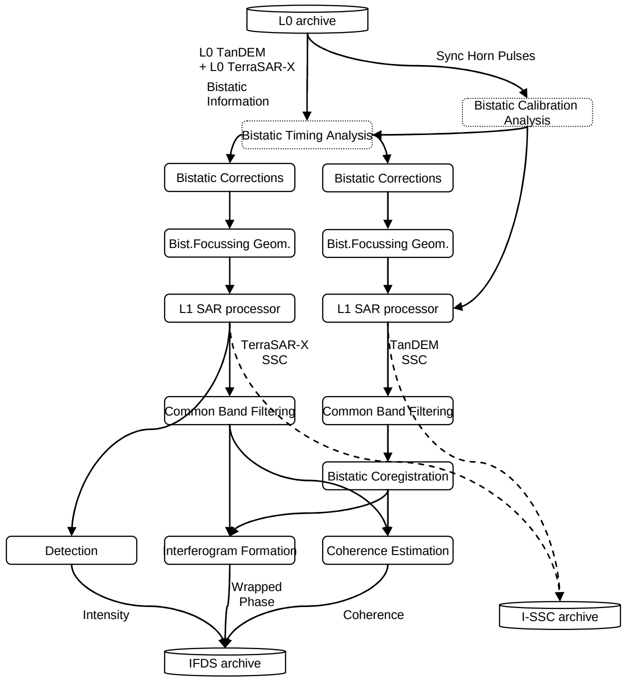

Figure 3: Interferometric Processing for TanDEM-X

3.6 Raw DEM reconstruction

The DEM reconstruction step is decoupled from the previous InSAR processing step because it needs careful inspection of results and because it has a varying processing duration, depending on the complexity of the terrain and the quality of the SAR and geometry data. The following steps are performed in sequence as shown in Figure 5.

Multi Baseline Phase Unwrapping

Phase unwrapping is the most critical step in DEM reconstruction. From SRTM a good implementation based on the minimum cost flow method (MCF) is available that processes single interferograms. This method is welll suited for an estimated 50 % of all TanDEM-X scenes. But it is expected from SRTM experience and from simulation experiments that for large baselines and for difficult terrain this algorithm is not sufficient and new methods based on multi baseline or even multi incidence angle techniques must be applied. Figure 4 shows how the low frequency interferometric fringe patterns of smaller baselines may help to recover the absolute cycle number of the larger baselines which provide the finest fringe pattern with the better height accuracy. A more general technique capable to fuse even different observation geometries is described in (Eineder, 2005a).

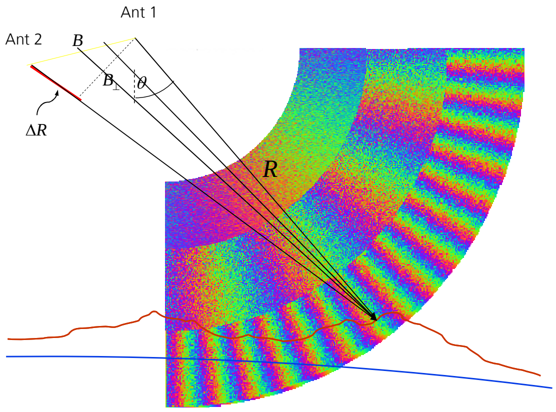

Figure 4: Visualization of multi baseline phase unwrapping concept

Coarse Calibration

Before geocoding the unwrapped interferometric phase from the radar geometry to a geographical grid, the absolute phase constants or known geometric distortions must be compensated. This is done using low resolution reference DEMs that are transformed to radar geometry in order to estimate and compensate differences which are modelled by low order polynomials.

Water Body Detection

Potential water bodies are identified using the SAR and coherence images. The generated maps are later used to support DEM editing.

Geocoding

The geocoding step transforms data from the azimuth-range-phase coordinates to a regular grid in north-east-height coordinates on ground. The results are Raw-DEMs which are calibrated on a scene by scene basis to a vertical accuracy of approximately 10-100 meters depending on the quality of the pre-existing DEMs. Local distortions due to decorrelation of water surfaces or due to extremely bright targets are still present in these DEMs. The Raw-DEMs are archived for later mosaicking or other usage.

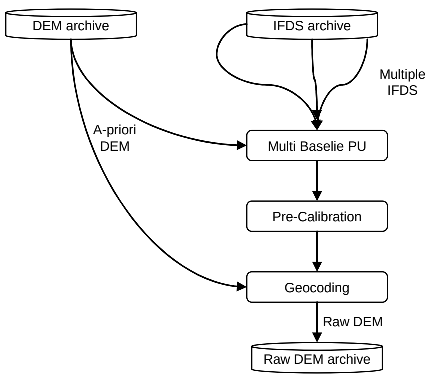

Figure 5: Raw DEM Generation for TanDEM-X

3.7 Calibration and Mosaicking

In this processing step the final global DEM is mosaicked from several available Raw DEMs as shown in Figure 7 and described in the following.

Bundle Adjustment

This processing step analyzes the relative deviations between pre-calibrated Raw-DEMs and the absolute calibration references over larger areas, up to continental size. Relative references can be derived from the overlap area of adjacent data takes and from overlap areas from crossing tracks. Crossing data takes are especially required to detect range tilts of approximately 0.3 meters over 30 km originating from orbital errors of 1 mm at 100 meter baseline. Like the crossing tracks, the small overlap area between adjacent tracks can be used for detection of abnormal errors (consistency checks) and to some degree for along track error reduction. Absolute references are required additionally to the relative references. Such absolute references may origin from many different sources like SRTM DEMs where available, low resolution DEMs (in flat areas only), GPS tracks, Space based laser altimeter tracks, radar altimeter measurements in flat areas and ocean surfaces.

Based on the relative and absolute differences, adjustment parameters are calculated in order to minimize the bundle error.

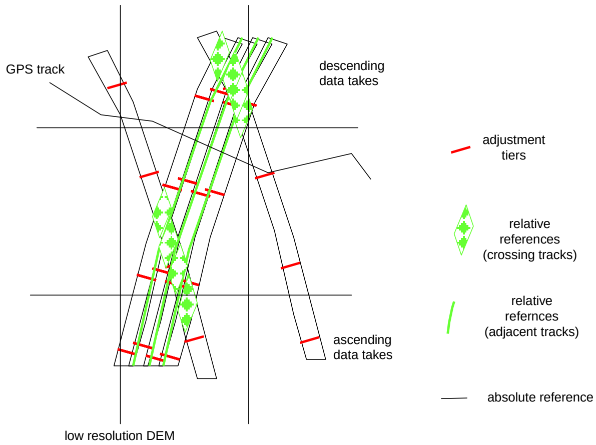

Figure 6: Residual estimation and bundle adjustment. Relative errors are estimated between adjacent and crossing tracks. Absolute errors are estimated from low resolution reference DEMs, GPS tracks, etc. Corrections are applied via adjustment tiers.

The representation of the adjustment parameters depends on the nature of the errors. From the current system knowledge it is expected that linear (constant and slope) corrections over range are required. Since the range and azimuth geometry of the SAR is well known down to millimetre level, the adjustments refer to the precise off-nadir angle, i.e. the interferometric phase. These corrections must be updated in azimuth depending on the stability of orbits and SAR instrument. For every update a crossing orbit is required. It is expected that adjustments are updated only every 500-1000 kilometers, i.e. every 70 – 140 seconds. Experience with bundle adjustment exists at DLR from ERS and from SRTM. The derived adjustment parameters are passed on to the mosaicking step.

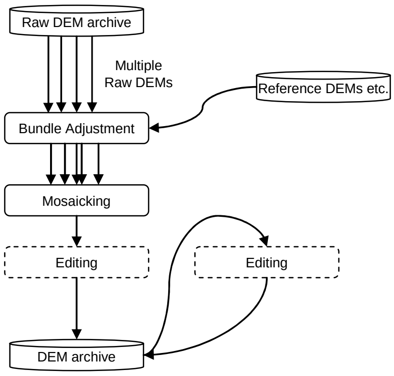

Figure 7: Calibration, bundle adjustment and mosaicking

Mosaicking

Mosaicking applies the vertical and horizontal shift as well as tilt adjustments derived at the bundle adjustment to the Raw DEMs. It performs a weighted averaging of several Raw DEMs to produce a higher quality DEM for the global mosaik. Averaging also removes boundary effects between adjacent DEMs.

DEM Editing

After mosaicking local distortions due to decorrelation of water surfaces or ambiguities of bright targets may still be present. In the editing step DEM artefacts are removed using the potential water body mask provided by the RAW-DEM generation, but also external information (e.g. water masks from optical data) and intensive operator interaction. Editing can also be postponed, i.e. performed offline on the archived final DEMs in order not to slow down the process of mosaicking of an area or if external information becomes available at a later time.

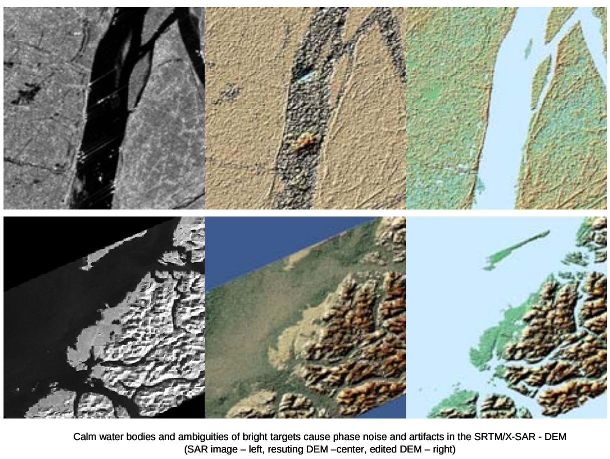

Figure 8: Demonstration of DEM editing as performed by DLR for the SRTM-X band data for a river (upper) and a coastal area (lower).From left to right: intensity, raw DEM, edited DEM.

4. SUMMARY

TanDEM-X is a highly innovative radar mission based on proven technology with a number of significant improvements. Together with optimized data acquisition concepts a global DEM with a quality known so far only from local DEMs will be generated.

5. REFERENCES

Bamler, R., Boerner, E., 2005, On the Use of Numerically Computed Transfer Functions for Processing of Data from Bistatic SARs and High Squint Orbital SARs, IGARSS 2005, Seoul.

Eineder, M., 2003, Ocillator Clock Drift Compensation in Bistatic Interferometric SAR. IGARSS 2003, Toulouse, IEEE, Proceedings of IGARSS'03.

Eineder, M., Adam, N., 2005a, A maximum likelihood estimator to simultaneously unwrap, geocode and fuse SAR interferograms from different viewing geometries into one digital elevation model, IEEE Transactions on Geoscience and Remote Sensing, Vol. 43, Iss. 1, pp. 24-36.

Eineder, M., 2005b, Interferometric DEM Reconstruction of Alpine Areas – Experiences With SRTM Data and Improved Strategies for Future Missions, Proceedings of EARSEL 3D workhop, Porto, 2005.

Fiedler, H., Krieger, G., Werner, M., Reiniger, K., Eineder, M., D’Amico, S., Dietrich, E., Wickler, M., 2006, The TanDEM-X Mission Design and Data Acquisition Plan, Proceedings of EUSAR, Dresden.

Hajnsek, I., Moreira, A., 2006, TanDEM-X: Mission and Science Exploitation during the Phase A Study, Proceedings of EUSAR 2006, Dresden.

Krieger, G., Moreira, A., Fiedler, H., Hajnsek, I., Zink, M., Werner, M., Einder, M., 2006, TanDEM-X: Mission Concept, Product Definition and Performance Prediction, Proceedings of EUSAR 2006, Dresden.

Werner, M., 2001, Shuttle Radar Topography Mission (SRTM) Mission Overview, Frequenz – Journal of Telecommunications, vol. 55, 2001.

Moreira, A., Krieger, G., Werner, M., Hounam, D., Riegger, S., Settelmeyer, E., 2004, TanDEM-X: A TerraSAR-X Add-On Satellite for Single Pass SAR Interferometry, Proceedings of IGARSS 2004, Anchorage.

Schättler, B., Wolfmüller, M., Reissig R., Damerow, H., Breit, H., et al., 2004, A Description of the Data-Driven SAR Data Workflow in the TerraSAR-X Payload Ground Segment. IGARSS, Anchorage, Alaska, USA, 20 - 24 September 2004, IEEE, Proceedings of IGARSS'04.