Design of the DEM Mosaicking and Calibration Processor for TanDEM-X

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Abstract

The primary goal of the TanDEM-X mission is the derivation of a high-precision global Digital Elevation Model (DEM) according to HRTI level 3 accuracy. This paper focuses on the generation of the global DEM from previously processed interferometric "Raw DEMs". The system involved, the DEM Mosaicking and Calibration Processor (MCP), estimates remaining offsets and tilts by a new region-wide block adjustment for thousands of Raw DEMs. Furthermore, it enables the fusion of the Raw DEMs into a quality-controlled global DEM product that is presented at the end of this paper.

1 Introduction

The TanDEM-X mission (TerraSAR add-on for Digital Elevation Measurements) is a spaceborne SAR interferometry mission that is based on two TerraSAR-X satellites. The main goal of the TanDEM-X mission is the generation of a global DEM. It shall be available four years after the start of the TanDEM-X satellite for 90% of the earth surface [1]. In order to obtain a global coverage that meets the height accuracy requirement derived from HRTI-3 standard (Table I and [2]) of 10m absolute and 2m relative vertical error, the mission scenario sets up two coverages of the earth with two different baselines. These two coverages will be acquired subsequently in the first and in the second DEM acquisition year.

TABLE I
TANDEM-X DEM SPECIFICATIONS

Requirement	TanDEM-X	SRTM
Absolute vertical accuracy (global)	**10 m** 90% linear error	**16 m** 90% linear error
Relative vertical accuracy (100 km × 100 km)	**2 m** (slope<20%) **4 m** (slope>20%) 90% linear point-to-point error	**6 m** vertical error
Raster size (Lat x Lon)	0.4’’ x 0.4’’(- 4.0’’) (~12 x 12m)	1’’ x 1’’ (~25 x 25m)

The interferometric processing chain for TanDEM-X will be a highly automated and data-driven process. This paper focuses on the generation of a global TanDEM-X DEM from individual interferometric DEM acquisitions. One DEM acquisition is splitted for processing reasons into several "Raw DEM" tiles. The main processing steps are the calibration of individual DEM acquisitions and the mosaicking of the Raw DEMs. This is done within the TanDEM-X DEM Mosaicking and Calibration Processor (MCP).

The MCP utilizes techniques available from the TerraSAR-X and SRTM projects. One new challenge lies in the calibration of thousands of TanDEM-X DEM acquisitions (see **Figure 1**). Each interferometeric DEM acquisitions still consist remaining systematic height errors like offset and tilts. In order to correct these systematic errors a functional model has been set up. This allows the estimation of the errors by a least-squares adjustment of adjacent DEM acquisitions (Section 2.2).

The estimated calibration corrections for offset and tilts will be applied and a mosaicking of the two coverages will be performed (Section 2.3). Other processing steps like detection of water bodies, tie-points or editing tasks require still more operator interactions. These interactions were optimally planned and separated in automatic and interactive quality control steps (Section 2.1).

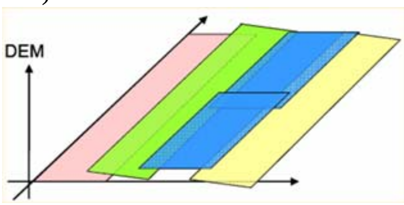

Figure 1 Adjacent DEMs with vertical offsets and tilts in range and azimuth due to base line errors

2 The MCP Processor

The DEM Mosaicking and Calibration Processor consist of three components (see **Figure 2**) which are working independently from each other and are triggered by the Processing system.

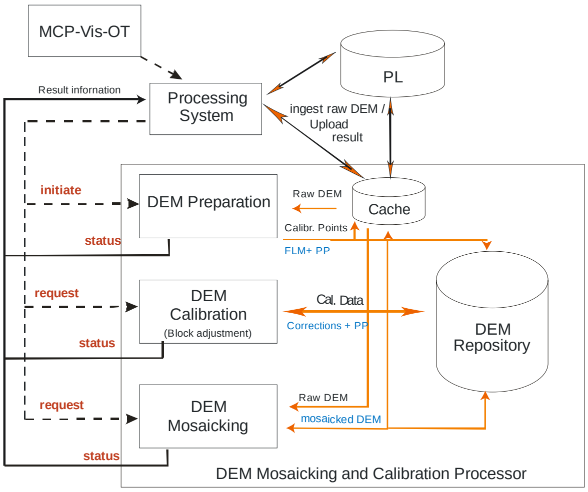

Figure 2 Overview of the MCP components

The first MCP component "DEM Preparation" is a data-driven process. Every new Raw DEM is automatically passed to MCP DEM Preparation Processor. There a first analysis of the Raw DEM is performed which comprises a height discrepancy detection, a water body detection and the extraction of calibration points as input for the DEM calibration processor. After interactive quality control the results of the DEM preparation processor are copied to a robot archive system (PL).

The second component, the DEM Calibration Processor, is initiated by an operator. Using a Visualization & Operating Tool (MCP-Vis-OT) a processing request for a dedicated region is generated and sent to MCP. During the DEM Calibration a block adjustment procedure calculates correction parameters for each DEM acquisition. After quality control the correction parameters are stored with the annotation information for each Raw DEM.

The third processor, the DEM Mosaicking Processor, is also initiated by an operator. A request for a defined region is generated and sent to MCP. Then, all Raw DEMs within the defined area are mosaicked with their four layers height values (DEM), height error map (HEM), amplitude (AMP) and flag mask (FLM). After the final quality control the mosaicked DEM is splitted into DEM product tiles, which are archived to the PL.

The following paragraphs will sequentially go through the system and highlight essential algorithms.

2.1 DEM Preparation Processor

The preparation processor contains the data-driven modules of the MCP. Each Raw DEM will be analysed and inspected for height discrepancies, water bodies, and suitable calibration points. The results for each Raw DEM are calibration points, interpolation mask that indicates height discrepancy areas and potential water bodies, and flags for re-processing. In the last step, a quality control of the extracted information is carried out.

2.1.1 Height Discrepancy Detection

The height discrepancy detection allows the detection of phase unwrapping errors and suspicious areas of height discrepancies. It flags Raw DEMs for interferometric multi-baseline re-processing, if Raw DEM errors are present, and it assists in the extraction of calibration points to exclude potential height discrepancy areas. In general, the detection of height discrepancies like phase unwrapping errors, i.e. larger DEM differences is important, because those differences can't be averaged reliable within the mosaicking processor. In the first acquisition year the Raw DEMs are compared to other reference data (e.g. SRTM-C Band), in the following acquisition years previously acquired TanDEM Raw DEMs are pulled out of the archive for differences.

2.1.2 Water body Detection

The task of this module is to detect water bodies reliably from TanDEM-X data. Amplitude and coherence values are used in this process but also additional external water masks. In a first step a potential water body check will be performed to test, if the image area does contain potential water bodies.

The aim of this check is to exclude desert regions from the water mask generation which leads to the benefit of saving processor time and capacity. External water masks are used for this task, e.g. the SRTM water mask and the GSHHS (Global, Self-consistent, Hierarchical, High-resolution Shoreline) Database [3]. For the potential water body check the water areas will be expanded in order not to omit potential water bodies. If a TanDEM-X Raw DEM contains only tiles with a dry area flag no water detection has to be done. Otherwise, the water body detection will be applied with a set of different analysis methods. This will be a threshold analysis to the amplitude and coherence dataset. Further methods planned are the application of a dedicated texture filter and speckle analysis. These tools will be applied optionally if the threshold analysis would not be sufficient to detect the water bodies reliably.

The water body detection generates a flag mask (FLM) where water areas are flagged with different probability classes. This mask may be used for flattening of water areas later on.

2.1.3 Extraction of Calibration Points

The purpose of this module is to provide Calibration Points (CP) serving as input for the DEM Calibration Processor. There are three sorts of CPs: first tie-points (TP), i.e. identical points present in different Raw DEMs, second Ground Control Points (GCPs), which provide information from external sources (e.g. ICESat), and third verification points (VP), which consist of GCPs that are not used for calibration.

Extraction of tie-points

A Raw DEM covers approximately a 30 x 50 km area resulting in 6000 x 10000 pixels at a 5 m pixel-spacing in ground range. The overlap area to the adjacent across-track Raw DEMs is 3km (600 pixels). Three by ten tie-points are evenly distributed in each overlap area in across and along-track. This results in an approximate distance of about 750 m (150 pixels) in range direction and about 5000 m (1000 pixels) in azimuth direction. In order to derive a tie-point an image chip in the dimension of about 100 by 100 pixels is extracted at the corresponding location from the Raw DEM, the Amplitude and the Height Error Mask (HEM). Inside the chip the most appropriate location for the tie-point is evaluated (see **Figure** 3). In the way, that the Raw DEM is statistically analysed (e.g. noise) and the HEM is taken into account. Additional information is gained from the previously generated Height Discrepancy Mask, Water Mask, and the shadow/layover flags in the Flag Mask (FLM).

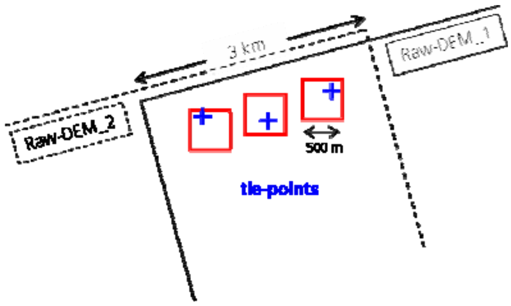

Figure 3 Distribution of tie-points inside image chips

Provision of ground control points

Absolute height calibration requires accurate height references. This can be achieved by using global data sets. The ICESat Space-borne Laser Altimeter data [3] provide accurate, globally distributed height information as well as evaluation and classification information for each measurement point. This will be the main height reference source for TanDEM-X. IceSAT will already provide a good absolute accuracy of up to 14cm (theoretically) and a good global coverage for hooking in the DEM. For ICESat points all underlying Raw-DEM pixels are averaged in order to achieve a comparable height value. This averaging is done according to a Laser specific weighting function (energy characteristic), which has also the advantage to reduce the noise significantly. Additional information about the standard deviation is gained from the Height Error Mask. Above this, locally high resolution DEMs, Ground Calibration Targets like corner reflectors, or GPS measurements can be introduced into the adjustment.

Verification points

GPS tracks with an accuracy of several decimetres are foreseen for the verification of the DEM calibration and the accuracy of the final DEM product. The measurement of world-wide GPS tracks is foreseen. As a rule of thumb the accuracy of the reference data shall be one magnitude better than the aimed HRTI-3 accuracy. That leads to required accuracies for verification data of 1m for absolute and 0.3m for relative vertical error.

2.1.4 DEM Preparation Quality Control

After the previous three steps within the DEM Preparation Processor a quality control is performed. At the end of each previous processing step a quality flag is determined automatically by statistical evaluation. In suspicious cases an interactive inspection is foreseen. For the detection of height discrepancies differences to reference DEMs (e.g. SRTM) and differences between overlapping Raw DEMs will be inspected. The water body mask will be checked for completeness and plausibility. The quality control of the extraction of calibration points checks the amount and distribution of extracted tie-points, GCPs, and verification points. The results will be visualized on an interactive webpage, where the operator has the possibility for detailed examination of the DEM preparation results of each Raw DEM. A re-run of the water body detection and the extraction of tie-points can be initiated and the quality flags may be edited.

2.2 DEM Calibration

The purpose of this processor is to estimate remaining systematic height errors in the TanDEM-X DEM acquisitions. The satellites have already been calibrated for their standalone monostatic operation. Only some systematic errors remain. These effects are due to baseline errors intrinsic of bi-static SAR acquisitions and errors and drifts of the radar instrument. They can be modelled by a polynomial function (Eq. 1) of 1. order in range (x) and a third order function in azimuth (y)

$$g_I(x,y) = a_I + b_I x + c_I y + d_I xy + e_I y^2 + f_I y^3 \; . \quad (1)$$

The coefficients will be estimated by means of a least-square adjustment within the DEM Calibration Processor. It is expected that the positioning of the DEM is correct due to precise geocoding.

2.2.1 Least-squares Adjustment of TanDEM-X DEM acquisitions

Eq. 1 will directly be used as functional model for least-squares adjustment with constraints [5]. The polynomial correction parameters (a_I – f_I) will be estimated within the adjustment as unkowns. The idea is that the heights in overlapping areas should be identical, apart from the random noise, after the error function is applied. The advantage of this method is that the correction parameters can be found independent from terrain types.

As all DEM acquisitions overlap, we use tie-points (TP), i.e. identical points placed in different DEMs. The observables $\underline{l}$ are averaged heights at each tie-point. The constraint equation (Eq. 2) follows the functional description for adjustments with constraints $\varphi(\tilde{L}, \tilde{X}) = 0$:

$$[H_{TP,I} - \hat{g}_I(x,y)] - [H_{TP,J} - \hat{g}_J(x,y)] = 0 \qquad (2)$$

To fix the datum, we introduce ground control points in the same way as observables, but with better accuracy in the stochastic model (Eq. 3). The weights for the tie-point heights are taken from the height error.

$$\Xi_{ll} = \begin{bmatrix} \sigma_{GCP} & 0 \\ 0 & \sigma_{TIE} \end{bmatrix} \qquad (3)$$

As result we also get information about the quality of the adjustment. The calibrated height values for each DEM acquisition I (H_I) are finally calculated by

$$H_I(x,y) = h_I(x,y) + g_I(x,y) \qquad (4)$$

2.3 DEM Mosaicking Processor

Purpose of the DEM Mosaicking Processor is the fusion of information contained in different Raw DEMs. This includes fusion of all layers of Raw DEM: DEMs, height error maps, amplitude data and the generation of a fused water body mask from the flag mask.
An outlier test is performed. Single peaks and dwells are detected and interpolated. This leads to an update of the height errors.
The calibrated corrections are applied to each Raw DEM. The amplitudes are adjusted radiometrically by a histogram optimization.
Then, an auxiliary height error map for borders is generated to prevent rough edges at data borders.
In the last step, the information contained in the different layers is combined in the Mosaicking Data Fusion step. DEM heights are weighted according to the error numbers. Amplitude and HEM values are fused with the help of the auxillary height error map. Water body values of different acquisition times are extracted from the flag masks and fused.

3 TanDEM-X DEM Products

The TanDEM-X DEM is formatted in tiles of 1° x1°, 1° x 2°, or 1° x 4° tiles with all auxiliary information. The DEM values are in ellipsoidal heights referring to WGS84. The height error map (HEM) values quantify the expected random (pixel-to-pixel) error of the corresponding elevation value by the standard deviation of elevation values. In the Flag Mask (FLM) mainly water bodies and shadow areas are flagged. Also, interpolated areas are indicated. The amplitude (AMP) is a by-product generated for the DEM production and consists of a mosaic of the amplitude images used in creating the FLM (see Table II). Two years after TanDEM-X launch an intermediate version with lower accuracy will be available.

TABLE II
TANDEM-X DEM PRODUCTS

Component name	Description	standard	Optional
DEM	elevation data	X	
HEM	height error map data	X	
FLM	flag mask		X
AMP	amplitude data		X

4 Conclusions

The DEM Mosaicking and Calibration processor is designed to enable the generation of the global DEM for the TanDEM-X mission within four years of processing. The DEM Mosaicking and Calibration Processor design is currently in its Critical Design Review status. Current work includes the implementation and further design of the processor modules.

References

[1] Krieger, G.,et al.: *TanDEM-X: A Satellite Formation for High Resolution SAR Interferometry*. IEEE Trans. on Geoscience and Remote Sensing, Vol. 45, No. 11, Nov. 2007, pp. 3317 - 3341

[2] *HRTI-3-DEM draft document.* NGA, MIL-PRF-89048.

[3] Wessel, P., Smith, W.: *A global, self-consistent, hierarchical, high-resolution shoreline database.* Journal of Geophys. Research, Vol. 101, No. B4, 1996, pp. 8741 - 8743

[4] Abshire, J. et al.: *Geoscience Laser Altimeter System (GLAS) on the ICESat Mission: On-orbit measurement performance.* Geophysical Research Letters, Vol. 32, 2005.

[5] Mikhail, E.M.: *Observations and Least Squares*. IEP, New York, 1976.