TanDEM-X DEM Calibration Concept and Height References

Jaime Hueso González, Markus Bachmann, Hauke Fiedler, Gerhard Krieger, Manfred Zink
German Aerospace Center (DLR), Germany

Abstract

TanDEM-X is the first bistatic space borne SAR mission [1]. It is formed by adding a second, almost identical spacecraft to TerraSAR-X and flying them in a closely controlled formation with typical distances between 250 m and 500 m. The primary goal of the mission is the derivation of a high-precision global Digital Elevation Model (DEM) according to HRTI level 3 quality [2]. To achieve this accuracy, height references have to be applied in the calibration of the DEM, together with a least squares adjustment of adjacent interferograms. Content of this paper is the description of the general DEM calibration concept, which has a key incidence on mission aspects like the data acquisition plan, and the summary of the different analysis and research activities to validate it, with special stress on the height references selection.

1 Introduction and objectives

The challenge of calibrating the TanDEM-X DEM lies on the complexity of the system and the strong height accuracy requirements. The interferometric height, from which the DEM is derived, depends on the phase difference between the two images and on the spatial geometry. The phase stability of the system is disturbed by instrument drifts and phase noises. The concept assumes that the satellites have already been calibrated for their standalone operation. However, residual height errors still remain. Additionally, baseline errors intrinsic of the bi-static SAR configuration introduce errors in the interferometric height. Thus, the DEM has to be corrected to achieve the accuracies defined (**Table 1**).

Requirement	Specification	HRTI-3
Absolute vertical accuracy (global)	90% linear error	10 m
Relative vertical accuracy (100 km × 100 km)	90% linear point-to-point error	2 m (slope<20%) 4 m (slope>20%)

Table 1 TanDEM-X DEM Specifications

By means of calibration height references and block adjustment methods of the datatakes, the residual absolute and relative height errors, more precisely their systematic component, ought to be minimised.

The final potential of the DEM calibration concept, currently in its Critical Design Review status, is to refine the strategy for the data acquisition plan [3] in order to assure global coverage within the mission time and to set a robust basis for the “Mosaicking and Calibration Processor” (MCP), which will adjust the raw DEM by means of the most suitable least-squares block corrections [4].

2 Error Sources

The first step fro the derivation of the calibration concept is the analysis of the potential errors of the interferometric system. Here, it is expected that the positioning of the DEM is correct due to precise geocoding and that the interferometric processing minimizes other error sources like phase unwrapping errors, aided by dual-baseline techniques [3]. Thus, the main sources of the arising residual phase errors can be classified into three groups: inaccuracies in the baseline determination, phase errors in the radar instruments and interferometric phase errors modelled as uncorrelated, additive random process. Contrarily to the random errors, the baseline inaccuracies and the systematic instrument drifts can be mainly classified as *low frequency* in terms of their variation with respect to the datatake length.

Simulations of the noise-like contributions of these errors [5] show that they already exhaust most of the 2 m relative error margin allowed for an area of 100 km × 100 km. In order to keep the total error under this requirement, a relative error of 0.5 m has been defined as the threshold for the “low frequency” height errors.

Inaccuracies in the precise determination of the relative orbit are the main sources errors in the baseline knowledge, which is the vector that links the two SAR antenna phase centers of the TanDEM-X formation. They cause slow changing errors with amplitudes of around 1 mm and result in offsets and slopes in azimuth and range [3] in the height error realisation.

On instrument side, slow errors occur due to remaining interpolation errors after internal calibration. The internal calibration is used to correct systematic drifts within the instruments, exemplarily caused by temperature drifts of the amplifiers in the transmit/receive modules. Also in the synchronisation path, residual drift errors occur. The synchronisation loop is used to measure relative drifts in the satellites oscillators. As the loop is not covered by the internal calibration correction, temperature drifts in the amplifiers have to be corrected using house keeping data of temperature sensors on these amplifiers, which only have a finite accuracy. When a datatake is acquired, these phase errors lead to a height error in the resulting raw DEM.

3 DEM Calibration

3.1 Mission scenario

The mission scenario for TanDEM-X is designed to obtain a global coverage of the earth within mission time (3 years), and to guarantee a DEM with the specified accuracies. Hence, the mission plan foresees that all land surfaces will be covered at least twice with different heights of ambiguity to support multi-baseline phase unwrapping [3]. The northern hemisphere will be mapped in ascending orbits, whereas the southern hemisphere in descending orbits. The length of the datatakes will be maximized within the resource limits in order to simplify the adjustment.

3.2 Height error modelling and adjustment

In order to reduce the phase errors introduced in section 2 several datatake adjustments and calibration strategies had to be considered. Relative corrections can be derived from concurring swath overlaps and crossing orbits in the datatake scenario, by means of a block adjustment. Absolute height calibration requires accurate height references. The references have to be adequately distributed depending on the datatake adjustment scenario.

Concerning the relative corrections, it is important to know how the remaining errors described in section 2 develop within the raw DEMs. Knowing the impact of these errors on the shape, a suitable adjustment can be performed to further minimise the errors, and to establish the required height calibration targets.

According to this, several software modules were developed in order to simulate the height errors and the possible methods to solve them in realistic mission configurations (see **Figure 1**).

A statistical study of the systematic height error behaviour has been performed, confirming some assumptions about the height error evolution:

- The height errors can be mainly described by a function depending on the time (evolution in azimuth) and an almost constant slope in range.
- The azimuth evolution of the height error depends mainly on the phase error behaviour of the different contributions, plus the baseline changes.
- The slope in range (tilt) can be described as a linear function that depends on the parallel baseline error. A small (and linear) change in tilt slope can be identified (torsion of the DEM in azimuth).

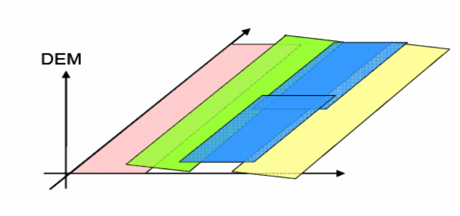

Figure 1 Exemplary error realisations (systematic components of the residual errors).

This will help to establish a functional description of the error behaviour and to quantify the error magnitude. The functional model will be directly used for the correction of the DEM scenes by the least-squares adjustment.

4 Height references

4.1 Selected Sources

The absolute height calibration references, also called Ground Control Points (GCP), have to fulfil certain conditions in order to ensure a successful calibration:

- Reference data coverage must be global (maximum separation of 200 km between each GCP and accuracies in the order of dm are desired).
- They should be available on all significant isolated land masses.
- Information in open terrain is preferable, because uncertainties between terrain and surface models do not need to be considered then.

One of the most promising global height sources are the *ICESat* Space-borne Laser Altimeter data [6]. They provide good absolute accuracy and a good global coverage for hooking in the DEM, as well as evaluation and classification information for each measurement point. This will be the main height reference source for TanDEM-X. Even in certain regions, where an improved DEM accuracy is desired to fulfil a HRTI-4 DEM (secondary mission goal), the ICESat database will be applied.

Above this, locally high resolution DEMs, ground calibration targets like corner reflectors or GPS measurements can be introduced into the adjustment as a fall-back solution.

Cinematic Global Positioning System (KGPS) transects (*GPS tracks*) were already used by the SRTM mission [7]. Height accuracies of the GCPs of around 50 cm could be achieved. Globally distributed GPS tracks (partially re-used from SRTM mission) with an accuracy of several decimetres are foreseen for validation of the global DEM.

Airborne SAR Interferometry or *Lidar DEMs* are commercially available and offer accuracies in the order of 10 cm. However, these reference DEMs is very high and will only be applied exceptionally.

The last of the considered sources are interferograms over *ocean-land transitions*. The ocean surface topography, the tidal changes and the ocean circulations are well known (with precisions at cm levels), thus these DEMs are useful for DEM calibration, as proved by the SRTM experience [8]. For acquiring coherent DEMs over ocean surfaces with TanDEM-X (proved in [9]; better accuracy than SRTM expected), short along-track baselines in the order of 35 m to 150 m are needed. Otherwise, de-correlation occurs [3]. In addition, ocean currents should be minimal in the ocean interferogram, which would otherwise contain phase shifts (height offsets). Very short along-track baselines below 100 m can be adjusted without any collision risk, owing to the helix formation [1], therefore enabling the use of this method. However, due to the changing helix formation, the optimal baseline configuration for this kind of acquisitions will not always be available.

Another aspect to consider is the stability of the GCPs correction values. In the TanDEM-X DEM adjustment, a set of GCPs will be ideally available per data-take. Under certain conditions (limits of the antenna beam, regions with low RCS…) the random phase noise of the DEM might reach the 2 m amplitude [5]. In these cases, a direct comparison of the GCP height value with the DEM height can originate big height errors in the correction functions of the DEM (**Figure 2**).

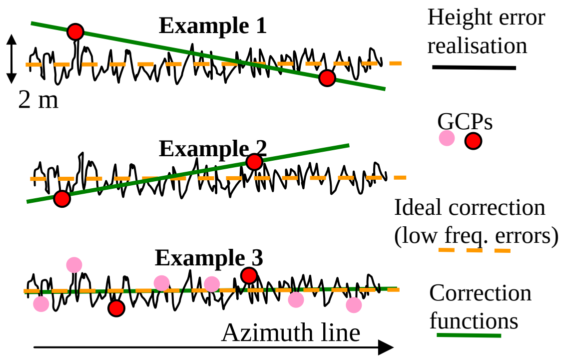

Figure 2 Correction examples with high random error. Ex. 1 and 2, with single point correction and Ex. 3 with GCP averaging.

The curves in the plot show a height error realisation (random error with 2 m amplitude) corrected with GCPs in different ways. If few (1 or 2) GCPs are used to generate the correction function, errors like the ones of Ex. 1 and 2 of **Figure 2** may appear.

In order to avoid this, and if several GCPs available (as expected), the suggested solution is to use several GCPs to statistically eliminate the random height error (Ex. 3 of **Figure 2**). Thus, better correction functions can be derived. Moreover in flat areas, DEM height points can be averaged with their neighbours to reduce this noise.

Table 2 summarizes the topics of this section:

GCP source	Coverage	Accuracy
ICESat	Global	0.1 m - 1 m (weather/terrain)
GPS tracks	SRTM campaigns; selected regions	0.5 m
Ocean-land	Global (theory); restricted to optimal along-track distance and no ocean currents	0.5 m
Lidar/Airborne DEM	Local	0.1 m – 0.5 m

Table 2 TanDEM-X height reference sources

4.2 ICESat quality assessment

In order to validate the TanDEM-X DEM calibration approach, a flight campaign of the E-SAR (experimental airborne radar [10]) has been carried out in the southeast of Munich, close to Miesbach (**Figure 3**).

Figure 3 Miesbach region for E-SAR acquisition.

The acquisition region combines flat land, forests and mountainous areas. Three parallel overlapping stripes of 3 km width and 30 km length were acquired. The main goal of this campaign is to assess the accuracy of the available height references, primarily ICESat data, for different terrain types. The three stripes were acquired two times, each one for different flight heights, in order to be able to test the dual baseline phase unwrapping algorithms which will be applied in the generation of the TanDEM-X DEM [3]. The ICESat height references available over this area will be compared with the E-SAR DEMs and with other available DEMs like GPS samples and SRTM data (after appropriate averaging with the ICESat laser footprint [6]). Nevertheless, it will provide information about the averaging of E-SAR/TDX DEMs around GCPs in order to reduce the random noise. As an extra information source, MODIS vegetation coverage data [11] will be used to identify highly forested regions.

ICESat data contain information parameters of every height sample concerning their individual accuracy. According to this, it is possible to define a basic strategy for the selection of "high quality" ICESat data. Only laser echoes with a simple pulse shape (1 peak) and with a reduced width (6 ns) will be considered reliable. These points are supposed to come from flat areas with little vegetation, and are therefore being more accurate. Vegetated or mountainous areas have more dispersive echo shapes. The plot of **Figure 4** shows the height values of the E-SAR DEM in the position of one of the ICESat tracks over the test area with their corresponding height differences (orange crosses correspond to “selected” ICESat points and the blue the rest).

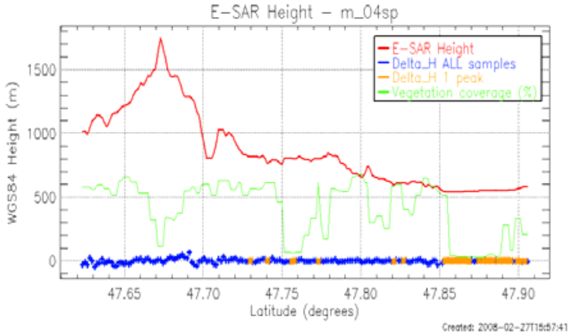

Figure 4 Height values of the E-SAR DEM and difference with ICESat samples.

The plot indicates very clearly that flat zones contain most of the “high quality” ICESat points. In the southern part of the ICESat track, where the Alps start, the mountainous terrain and the increase in vegetation coverage (see green MODIS curve) motivate more unreliable ICESat echoes.

After a preliminary analysis of the data (current status), it could be observed that the mean height difference is close to 0 m for blue and orange points, which proves that the ICESat data do not have significant trends or systematic errors. The scattering of the blue points seems to be higher than the one of the orange points, which validates the previously described selection criteria. Although, a more detailed analysis is necessary for establishing more precise accuracy values and to assess if and which of the “rejected” points could be used for DEM Calibration purposes in case of necessity and accepting a relative accuracy drop.

As a last result, in the height comparison of some of the other ICESat tracks, some strange phenomena were detected. Individual or groups of ICESat points, mainly “blue” points, but also some “orange” ones, showed huge height differences (300 m-2000 m) with respect to the E-SAR measurements (as in **Figure 5**). This was not consistent with the rest of difference samples and could not be motivated by phase unwrapping errors or slopes in the DEM. Therefore an independent height reference source, the SRTM C-Band DEM (90 m resolution and ±8.5 m vertical accuracy at 90% confidence [7]) was also compared with the ICESat data, finding the same inconsistencies. Establishing a threshold of 200 m in the difference with SRTM heights, unreliable samples were successfully withdrawn.

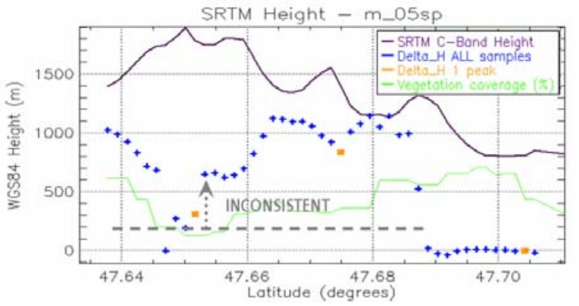

Figure 5 Example of inconsistent ICESat samples compared with SRTM C-Band Data. Threshold ICESat-SRTM height = 200 m.

However, certain ICESat height samples are still affected by other parameters that may decrease their accuracy (cloud coverage, surface properties and pulse saturation).Therefore the comparison studies are still ongoing and the solutions for the identified problems are being investigated.

Acknowledgement

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