TANDEM-X DEM CALIBRATION: CORRECTION OF SYSTEMATIC DEM ERRORS BY BLOCK ADJUSTMENT

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ABSTRACT

This paper gives an overview of the DEM adjustment within the TanDEM-X mission. The DEM adjustment estimates residual, systematic height offsets and deformations of each single interferometric DEM acquisition. The challenge of calibrating the TanDEM-X DEMs lies in the magnitude of the systematic errors: these errors are in the same order like the random error of about 2 m. For the estimation of the corrections a least-squares adjustment of adjacent, overlapping interferometric DEMs over a certain earth region is described in this paper. Adjustment results on simulated DEM data are shown to validate the approach. The tests are carried out for different dense ground control point configurations. Further the improvements by a combined adjustment of the two coverages are demonstrated.

***Index Terms*—**TanDEM-X, InSAR, block adjustment, DEM/DTM, calibration

1. INTRODUCTION

The goal of the German spaceborne SAR interferometry mission TanDEM-X (TerraSAR add-on for Digital Elevation Measurements) is the generation of a global DEM. It shall be available four years after the start of the TanDEM-X satellite [2]. The height accuracy requirements of 10 m absolute vertical error and 2 m relative vertical error are very ambitious.

The designed mission plan foresees that all land surfaces will be covered at least twice with different heights of ambiguity to minimize the height error by averaging DEM acquisitions and to facilitate the phase unwrapping by multi-baseline methods. Each interferometeric DEM acquisition still consists remaining systematic height errors like offset and tilts. In order to correct these systematic errors a least-squares adjustment of adjacent, overlapping DEM acquisitions is set up.

The DEM adjustment is part of the operational "DEM Mosaicking and Calibration Processor" [3], which will adjust the interferometric DEMs globally to produce the TanDEM-X DEM product.

In order to estimate and correct the remaining systematic errors, a functional model has been set up. This allows the design of a subsequent DEM block adjustment (Ch. 2). In Ch. 3 the block adjustment will be evaluated by a simulated test site.

2. DEM BLOCK ADJUSTMENT

The goal of the DEM adjustment is to estimate systematic height errors to fulfil the required height accuracies. In this chapter the design of the DEM block adjustment is described.

The main sources of residual systematic height errors in bi-static interferometric DEMs are inaccuracies in the baseline determination. Baseline inaccuracies and other systematic instrument errors introduce mainly low frequency errors in terms of the data take length. Baseline errors parallel to the line of sight cause a vertical displacement and a tilt of the DEM.

The systematic errors can be approximately expressed by a third order polynomial for one TanDEM-X DEM acquisition:

$$g_I(rg, az) = a_I + b_I rg + c_I az + d_I rg\ az + e_I az^2 + f_I az^3, \qquad (1)$$

where a, b, c, d, e, f = unknown error parameters
I = index of the DEM acquisition
rg, az = image coordinates (range, azimuth)

This error description was found through a statistical study. Main influences are the height offset *a* and slopes in range *b* and azimuth *c* that cause errors above 0.5m. The influence of the torsion *d* between range and azimuth and second *e* and third order *f* errors in azimuth are expected to be much smaller. Above this, a random phase that can be regarded as noise is present. A noise level slightly above 2m is expected for one interferometric TanDEM-X DEM acquisition.

For the block adjustment it is assumed that each DEM acquisition is solely distorted by the errors expressed in Eq. 1. The positioning of the DEM acquisitions is assumed to be correct within the limit of 10 m absolute horizontal accuracy. The challenge of calibrating the TanDEM-X DEM lies in the magnitude of the systematic errors: these errors are in the same order like the random error of about 2m.

2.1. Adjustment set-up

Prerequisite for the adjustment is the availability of suitable ground control points to assess the absolute height error offset with respect to WGS84. Also reliable tie-points, i.e. identical points in overlapping DEM areas, are needed to fulfil the strong relative vertical requirement of 2m.

2.1.1. Ground control and tie-points

As absolute height reference ICESat (Ice, Cloud, and land Elevation Satellite) data will be the main height reference source for TanDEM-X. The ICESat space-borne laser altimeter data provide globally distributed, accurate height information as well as evaluation and classification information for each measurement point [4]. Therefore, ICESat provides a good global coverage for hooking in the DEM with a point distance of 270 m in along-track and a point distance of 30 km in across track. The accuracy could be proven to be less than 2m for selected measurements [1].

Tie-points are identical points in at least two overlapping DEMs. A good distribution and a high reliability regarding the height error should be given. The DEM acquisition length is about 500 to 1000km in azimuth and about 30km in range. The overlap area to adjacent across-track DEMs is at least 3km. To derive a good tie-point distribution the tie-points are evenly distributed in each overlap. An image chip is extracted. At the moment inside this chip the most appropriate location for the tie-point is chosen, in the way, that the DEM is analyzed for the most flattest region inside the chip as well as for the minimal noise (height error). The final tie-point height will be averaged over e.g. 3 x 3 pixel to reduce the noise, although, the noise is partly coloured noise and wont be reducible completely by such a small image size. Therefore, in future studies a tie-point concept will be developed that takes into account larger regions for averaging.

2.1.2. Functional model

The constraint of the adjustment is that the heights in overlapping areas should be identical. A function has to be found that expresses this relationship, contains the unknown coefficients X (a - f) and is additionally independent from the absolute terrain height. Against this background height differences are introduced. The observation equation follows the functional description for adjustment with constraints:

$$[\hat{H}_{i,J} + \hat{g}_J(rg,az)] - [\hat{H}_{i,K} + \hat{g}_K(rg,az)] = 0\,, \qquad (2)$$

where $\hat{g}(rg,az)$ is the height error function with the adjusted parameters and $\hat{H}$ is the adjusted elevation value at the tie-points.

Eq. 2 will be set up for each tie-point. Height offsets to WGS84 are estimated by introducing GCPs into the functional model in the same way as observables.

2.1.3. Stochastical model

All observables have accuracies that are used as weights for the stochastic model. The cofactor matrix is

$$Q_{bb} = \begin{pmatrix} Q_{bb,GCP} & & \\ & Q_{bb,DCP} & \\ & & Q_{bb,TIE} \end{pmatrix}. \qquad (4)$$

The cofactor matrix includes the standard deviations for the ground control points (GCP), the corresponding DEM height error of the GCP point (DCP) and the tie-points (TIE).

According to tests the best standard deviation for the GCPs (ICESat points on flat bareland) can not be assumed better than 1.6 m and usually 2m. With this accuracy the GCPs fulfil the condition that GCPs should be one order better to influence the adjustment. The standard deviations of the heights are taken from the interferometric height error. A noise level of 2 m for one single pixel is expected.

In the tests we assume a standard deviation of the absolute ground control points of 2 m. For tie-points we assume not filtered heights with a standard deviation of 2 m, and filtered, i.e. averaged heights with a standard deviation of 0.7 m and 0.4 m.

2.2. Iterative adjustment

The parameters are estimated iteratively. In the first iteration, all 6 parameters are estimated. If the significances

$$t = \frac{\hat{x}_{est}}{\sigma_{\hat{x}_{est}}}\,, \qquad (5)$$

where $\hat{x}_{est}$ is the estimated parameter and $\sigma_{\hat{x}_{est}}$ its standard deviation, of all parameters for one data take are not smaller than a given value (t>=1 in the tests), the parameters are accepted. If not, the adjustment is computed again, no longer estimating the parameters with the smallest significance.

3. ADJUSTMENT RESULTS ON SIMULATED DATA

The proposed block adjustment is evaluated on simulated distorted DEM data. For this task, heights of a test area of 3x4 data takes (each 30x500km wide) were simulated with noise and errors as described in Eq. 1. Also, the coverage in the second year was simulated (see Figure 1).

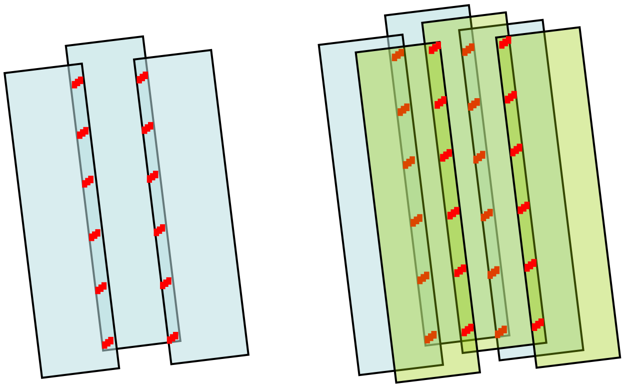


Figure 1: *In blue the first coverage, in blue and green the first and second coverage. The second coverage is shifted by the half of the data takes width. In red: tie-points.*

In our simulations the following parameters were varied:

- the noise of the tie-points (0.4m, 2m),
- the distance between two adjacent ICESat ground tracks in across track (at the equator 80km, in temperate zones 55km, and at the pole 15km),
- the distance between ICESat points in flight direction (1000km, 100km, 10km),
- the number of simulated parameters (1, 3, 6),
- and the distance between the tie-points.

	EQUA	**TMPZ**	**POLE**
1000 km	0.8	1.6	8
100 km	8	11	46
10 km	77	108	440

Table 1: *Number of ICESat points per data take. The columns stand for the different regions (equator, temperate zone and pole) respectively to the different GCP distances in across-track (80km, 55km and 15km), the rows for the distance between ICESat points in flight direction (1000km, 100km and 10km).*

The distance between a tie-point triple in range is 5 km in azimuth. The noise of the ground control points is set to 2 m. The first and second year coverage is adjusted first separately and then also together.

For each of the configurations listed above the least-squares adjustment described in Ch. 2 is carried out. In order to check, if the parameter model is estimated correctly, the differences between the initially simulated and the resultant estimated height error function are calculated:

$$\Delta H_{\max} = \max(g_{sim}(rg, az) - \hat{g}_{est}(rg, az)) \qquad (6)$$

where g_{sim} = simulated height error function
$\hat{g}_{est}$ = estimated height error function.

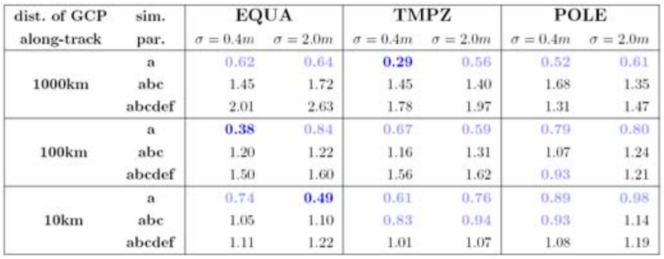
In order to ensure to fulfil the relative accuracy of 2m, the maximum height difference $\Delta H_{\max}$ should not be higher than 1m. The maximum of g_{sim} is 2m compared to the undistorted DEM.

The Tables below show the results of different test configurations. The columns show the three different regions (equator, temperate zone and pole) and are subdivided into another two columns describing the different noise levels of the tie-points (0.4 m and 2.0 m). The rows show the distance between the ICESat points in flight direction (1000 km, 100 km and 10 km). They are also subdivided into another three rows, describing the number of simulated parameters (a, abc and abcdef). The first row and the first column of the second row include the results of the worst configurations, including less than 10 ground control points per data take (see Table 1). These configurations will only appear in very difficult areas, e.g. in rain forests and high mountains. Most of the areas will contain at least 400 ICESat points or even more.

3.1 Results for varying noise, simulated parameters, number of GCPs and tie-points

Table 2 shows the maximum height differences averaged over all data takes. The estimated parameter set (whose significances lie under 1) is approved, if the maximum height difference (described in Eq. 6) is smaller or equal 1m. Is the absolute mean smaller or equal 0.5m and 1m respectively, the value is indicated with dark and light blue respectively. Especially for the best configurations (POLE/10km, POLE/100km, TMPZ/10km, EQUA/10km), it shows that the results are near to 1 m difference. Note, that in these tests, first and second year were adjusted together, i.e. the number of tie-points was higher.

Note, that the criterion for the acceptance of the parameter set is 1m, whereas the simulated height error is 2m. That means, that the height model is often improved, even though the parameter set is not approved. Otherwise in regions with less than one ground control point per data



dist. of GCP along-track	sim. par.	EQUA $\sigma = 0.4m$	EQUA $\sigma = 2.0m$	TMPZ $\sigma = 0.4m$	TMPZ $\sigma = 2.0m$	POLE $\sigma = 0.4m$	POLE $\sigma = 2.0m$
1000km	a	0.62	0.64	**0.29**	0.56	0.52	0.61
	abc	1.45	1.72	1.45	1.40	1.68	1.35
	abcdef	2.01	2.63	1.78	1.97	1.31	1.47
100km	a	**0.38**	0.84	0.67	0.59	0.79	0.80
	abc	1.20	1.22	1.16	1.31	1.07	1.24
	abcdef	1.50	1.60	1.56	1.62	0.93	1.21
10km	a	0.74	**0.49**	0.61	0.76	0.89	0.98
	abc	1.05	1.10	0.83	0.94	0.93	1.14
	abcdef	1.11	1.22	1.01	1.07	1.08	1.19

Table 2: *Absolute mean of maximum height differences of all data takes.*

dist. of GCP along-track	sim. par.	EQUA		TMPZ		POLE	
		$\sigma = 0.4m$	$\sigma = 2.0m$	$\sigma = 0.4m$	$\sigma = 2.0m$	$\sigma = 0.4m$	$\sigma = 2.0m$
1000km	a	-0.91	-0.11	0.13	-0.07	-0.57	0.13
	abc	**-1.31**	-0.24	-0.22	-0.41	0.48	0.21
	abcdef	-0.60	0.70	-0.22	-0.28	-0.79	-0.22
100km	a	**-2.04**	-0.05	-0.01	0.08	0.14	0.04
	abc	-0.68	-0.47	-0.00	0.01	-0.08	0.17
	abcdef	-0.21	-0.02	0.26	0.03	-0.20	-0.04
10km	a	-0.53	-0.33	-0.28	0.03	-0.07	-0.04
	abc	-0.18	-0.12	-0.11	-0.13	-0.09	-0.01
	abcdef	-0.03	-0.13	-0.13	-0.09	-0.09	-0.01

Table 3: *Difference of absolute mean between adjustment with and without tie-point triple*

take, the heights can be worsen as the maximum height difference is sometimes greater than 2m.

To estimate a higher number of parameters, at least 40 ground control points per data take should be available. In this case the absolute mean is about 1m or less. Note, if only two ground control points per data take or less are available, only one parameter can be estimated. Therefore, if only the offset is simulated, the results are better in areas with few ground control points. Using a greater number of ground control points, often more than one parameter is estimated significantly, even though only the offset is simulated. This shows a limitation of the adjustment approach, if the height errors are in the same order like the noise, the results are randomly too.

In order to evaluate, if one tie-point instead of a tie-point triple (see Figure 1) is enough, Table 3 was created. It shows the difference of the absolute mean between the adjustment with and without tie-point triples. In areas with few ground control points, it is better to use the tie-point triple, in areas with many ground control points, the adjustment with the tie-point triple improves the results less.

3.2 Results for combined adjustment of 1st and 2nd coverage

Table 4 shows the difference between combined (first and second year adjusted together) and separate solution (first and second year adjusted separately). Adjusting first and second year together improves the results considerably, mainly in areas with few ICESat points. This is up to the higher number of tie-points and the higher constraints between the data takes. However, in most areas (containing at least 400 ground control points) the results cannot be improved by a combined adjustment.

dist. of GCP along-track	sim. par.	EQUA		TMPZ		POLE	
		$\sigma = 0.4m$	$\sigma = 2.0m$	$\sigma = 0.4m$	$\sigma = 2.0m$	$\sigma = 0.4m$	$\sigma = 2.0m$
1000km	a	-0.74	**-1.32**	-0.41	-0.07	-0.50	0.02
	abc	-0.98	-0.14	-0.03	-0.26	0.05	-0.09
	abcdef	**-1.34**	**-1.80**	0.01	-0.04	-0.05	-0.24
100km	a	-0.47	-0.19	-0.29	0.13	0.12	0.06
	abc	-0.21	-0.08	0.05	-0.25	0.07	0.06
	abcdef	-0.11	-0.43	0.03	-0.17	-0.30	-0.01
10km	a	-0.20	-0.03	-0.07	-0.03	0.09	0.14
	abc	0.19	-0.02	-0.17	-0.04	0.12	0.14
	abcdef	-0.14	-0.08	-0.15	-0.18	-0.07	0.04

Table 4: ***Difference of absolute mean between combined and separated adjustment.***

4. CONCLUSIONS

In this paper an approach for height adjustment of interferometric DEMs for the TanDEM-X mission is proposed. For each DEM several error parameters are estimated within a block adjustment. The difficulty is that the magnitude of the errors is in the same order like the noise of the tie-points and the accuracy of the ground control points (2m). Therefore, tests with different configurations have been carried out to evaluate the reliability of the adjustment. It can be stated that the offset could be estimated in all scenarios with an accuracy of 1m and better. For higher order parameters like the tilts, the results improve with increasing number of GCPs. Luckily, the necessary amount of GCPs will be present for most regions of the world. A combined adjustment of the first and the second coverage improves especially the results with less GCPs and has less influence of the good conditioned cases as expected. Further studies will be made regarding a new tie-point averaging concept that will probably achieve better standard deviations.

5. ACKNOWLEDGMENTS

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