Analysis of SRTM DTM - Methodology and practical results*

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dedicated to Prof. Dr. Kennert Torlegard at the occasion of his retirement from the Royal Institute of Technology, Stockholm

Abstract

In February 2000 the first mission using space-borne single-pass-interferometry was launched – the Shuttle Radar Topography Mission (SRTM). The goal of the mission was to survey the Earth surface and to generate a homogeneous elevation data set of the world with a grid spacing of 1 arcsec. Antennas with two different wavelengths were used: Beside the American SIR-C the German / Italian X-SAR system was on board.
This paper deals with the assessment of the Interferometric Terrain Elevation Data derived from the X-SAR system. These so called ITED-2 data were compared to reference data of higher quality of a well known test site in the south of Hannover (Trigonometric Points and Digital Terrain Model). The approach used is based on a spatial similarity transformation without using any kind of control point information. The algorithm matches the SRTM data onto the reference data in order to derive seven unknown parameters which describe horizontal and vertical shifts, rotations and a scale difference with respect to the reference data. These values describe potentially existing systematic errors.
The standard deviation of the SRTM ITED-2 was found to be ±3,3 m in open landscape, after applying the spatial similarity transformation. Maximum systematic shifts of 4-6 m were detected, representing only 20-25 % of the ITED-2 grid size. In summary, it can be stated that the results are much better than predicted before the start of the mission. Thus, the quality of the SRTM ITED-2 is indeed remarkable.

1. Introduction

Interferometric SAR (IfSAR) allows to obtain information about the third dimension of the Earth surface. Thus, the main product of this method is a Digital Terrain Model (DTM) or Digital Surface Model (DSM) in case of using a short wave system. The SRTM mission (Werner, 2001, Rosen et al., 2001a) has been the first mission using space-borne interferometric SAR. The advantage of using radar is the independence of cloud cover and daylight. Therefore within the mission is was possible to produce a homogeneous and dense DTM of the Earth.
The goal of the project at the Institute for Photogrammetry and GeoInformation (IPI) of the University of Hannover was the assessment of the SRTM X-SAR data. The quality

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of the data has been obtained by comparison to reference data of higher quality in a well known test site.
To assess the quality of IfSAR DTMs it is necessary to understand the principles of SRTM technique (see chapter 2). The following chapter 3 describes the algorithm used for the assessment of the SRTM data. The method is based on a spatial similarity transformation without using any kind of control point information. An overview about the used reference and SRTM data sets is given next (chapter 4) and the results of the validation process are presented in chapter 5 and 6. The paper concludes with a short summary. A similar investigation was e.g. carried out by Kleusberg & Klaedtke (1999) for airborne IfSAR data and by Rosen et al. (2001b) for SRTM.

2. Principle of SRTM

The IfSAR system of SRTM used two different wavelengths. The American C-band system SIR-C operated with a wavelength of λ=6,0 cm, the wavelength of the German / Italian X-band system was λ=3,1 cm. Two antennas constituted the single-pass-interferometer of SRTM. The main antenna with a length of 12 meters was located inside the cargo bay of the Space Shuttle Endeavour. It transmited and received microwave pulses (see figure 1). The second one, the outboard or slave antenna, was fixed at the tip of a 60 meter long mast and acted as a receiver only. The mast realised the interferometric baseline. Since knowledge of the precise length, location and attitude of the baseline is critical for IfSAR a large variety of sensors was used to monitor possible baseline changes. Light Emitting Diode (LED) targets were used by the Target Tracker on the Attitude and Orbit Determination Avionics (AODA) to measure the alignment of the outboard antenna with respect to the main antenna. To determine the length of the mast corner-cube reflectors were used by the Electronic Distance Measurement Unit on AODA. Global Positioning System (GPS) antennas were used to gather accurate position information of the Shuttle. In order to obtain a global coverage between 60 degrees north and 58 degrees south the Shuttle was flown at an altitude of 233 km and an inclination of 57 degrees. Because of the Earth rotation the Shuttle surveyed the ground strip after strip. With C-band it was possible to cover the Earth surface completely. The C-band interferometer operated in the so-called ScanSAR mode (Bamler, 1999). In this mode the antenna beam is electronically steered towards different elevation angles in a repeated stepwise fashion. Thus, four narrow but overlapping sub-swaths were imaged quasi simultaneously to form the 225 km wide swath.

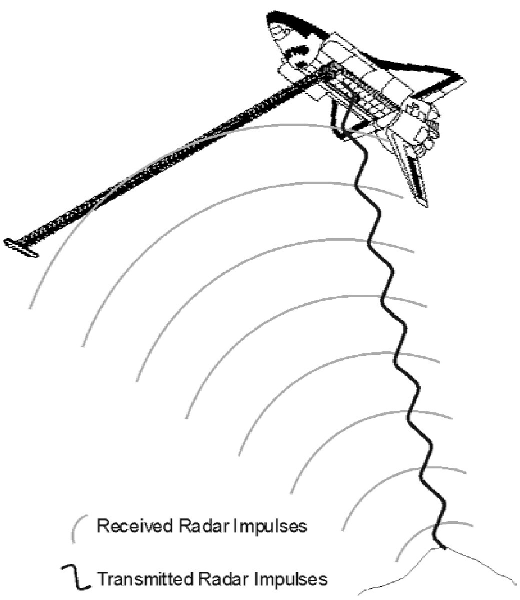

Figure 1. SRTM surveying geometry

The X-band antenna could not be steered electronically. It operated at a fixed depression angle of 38 degrees and a swath width of about 50 kilometres. The advantage of X-band is the higher relative vertical accuracy resulting from the shorter wavelength. The disadvantage of the X-band system used on board SRTM was the incomplete coverage of the Earth. There are gaps between the swaths which became smaller with growing latitude.

3. Algorithm for matching Digital Surface Models

The developed algorithm (see also Koch & Heipke, 2001) is based on a spatial similarity transformation. The seven parameters of this transformation describe systematic errors of the SRTM data set detected within the test area. Remaining errors after having applied the similarity transformation can be considered as either local systematic errors or random errors.

3.1. Mathematical Model

Single points P (X,Y,Z) contain height information about a given area.
The points are combined to vectors:

$$\begin{aligned} G_1 &= \{P_{11} \quad P_{12} \quad \cdots \quad P_{1i} \quad \cdots \quad P_{1n}\} \\ G_2 &= \{P_{21} \quad P_{22} \quad \cdots \quad P_{2j} \quad \cdots \quad P_{2m}\} \end{aligned} \tag{1}$$

The reference data set G_1 contains n regularly or irregularly distributed points. G_2 consists of m points, which describe the same physical surface as G_1. G_2 is the data set to be investigated. For the remainder of this paper we consider points P_{1i} and P_{2i} to have the same planimetric coordinates. If for a point P_{1i} no such corresponding point P_{2i} exists a priori (or vice versa) a height Z_{2i} must be interpolated from the other data set at the position X_{2i},Y_{2i} using e.g. a bilinear interpolation.

In the ideal case the following equation is fulfilled under the above mentioned assumptions:

$$Z_{1i}\left(X_{1i}, Y_{1i}\right) = Z_{2i}\left(X_{2i}, Y_{2i}\right) \tag{2}$$

Because of possible global systematic errors the two elevation data sets can be shifted and rotated against each other and can have different scale factors. Consequently a spatial similarity transformation is introduced:

$$Z_{1i}\left(X_{1i}, Y_{1i}\right) = Z0 + \left(1+m\right) \cdot \underline{r}_3 \cdot \underline{X}_{2i} \tag{3}$$

where

$$\begin{pmatrix} X_{1i} \\ Y_{1i} \end{pmatrix} = \begin{pmatrix} X0 \\ Y0 \end{pmatrix} + \left(1+m\right) \cdot \begin{pmatrix} \underline{r}_1 \\ \underline{r}_2 \end{pmatrix} \cdot \underline{X}_{2i} \tag{4}$$

$$\underline{X}_{2i}^T = \left(X_{2i} \quad Y_{2i} \quad Z_{2i}\right); \quad \underline{R}^T = \left(\underline{r}_1 \quad \underline{r}_2 \quad \underline{r}_3\right)$$

In this way the points P_{2i} are transformed into the coordinate system of the reference data set by means of the seven parameters of the spatial similarity transformation. Z0 is the height translation, (1+m) is the scale. The vector $\underline{r}_3$ contains the rotations ω, φ and κ, it is the third row of the rotation matrix $\underline{R}$ of the spatial similarity transformation. Note that we use the rotation sequence ω, φ and κ. The centre point of rotation is the centre of the test site.

Z_{1i} on the left side of equation (3) is the corresponding height value of the reference data set with the planimetric coordinates X_{1i}, Y_{1i}. X_{1i} and Y_{1i} are computed according to equation (4) by transforming the coordinates X_{2i}, Y_{2i}, Z_{2i} of the investigated data set by means of the seven parameters. The vectors $\underline{r}_1$ and $\underline{r}_2$ are the first two rows of the rotation matrix $\underline{R}$. X0 and Y0 are the planimetric translations of the similarity transformation. In order to determine Z_{1i} in general the mentioned interpolation must be carried out, since we cannot assume that for the computed planimetric position (X_{1i},Y_{1i}) a value Z_{1i} exists in the reference data set.

3.2. Least squares adjustment

Equations (3) and (4) form the base of a least squares adjustment. We introduce the heights Z_{2i} (X_{2i}, Y_{2i}) as observations and consider the parameters of the similarity transformation as unknowns. The observations are assumed to be independent of each other and of equal accuracy resulting in an identity matrix for the covariance matrix of the observations. Equations (3) and (4) can then be formulated as observation equations, one for each height value Z_{2i}:

$$v_i\left(Z_{2i}\right) = Z_{1i}\left(X0 + \left(1+m\right)\underline{r}_1\underline{X}_{2i}, Y0 + \left(1+m\right)\underline{r}_2\underline{X}_{2i}\right) - \left(Z0 + \left(1+m\right)\underline{r}_3\underline{X}_{2i}\right) \quad (5)$$

This equation is the fundamental equation for calculating the unknown parameters of the spatial similarity transformation. Because of the non-linearity of equation (5) it has to be expanded into a Taylor series, and the unknowns are computed iteratively starting from approximate values. The design matrix of the least squares adjustment contains the partial derivatives of the observation equations with respect to the unknown transformation parameters. It should be noted that the explained method relies on height variations within the area under consideration, because – with the exception of $\partial v_i / \partial Z0$ - the partial derivatives all depend on $\partial Z/\partial X$ or $\partial Z/\partial Y$ (see equation 6).

$$\begin{aligned}
\frac{\partial v_i}{\partial X0} &= \frac{\partial Z_{1i}}{\partial X_{1i}} \\
\frac{\partial v_i}{\partial Y0} &= \frac{\partial Z_{1i}}{\partial Y_{1i}} \\
\frac{\partial v_i}{\partial Z0} &= -1 \\
\frac{\partial v_i}{\partial \omega} &= \frac{\partial Z_{1i}}{\partial Y_{1i}} \cdot \frac{\partial Y_{1i}}{\partial \omega} - \frac{\partial Z'_{2i}}{\partial \omega} \\
\frac{\partial v_i}{\partial \varphi} &= \left(\frac{\partial Z_{1i}}{\partial X_{1i}} \cdot \frac{\partial X_{1i}}{\partial \varphi} + \frac{\partial Z_{1i}}{\partial Y_{1i}} \cdot \frac{\partial Y_{1i}}{\partial \varphi}\right) - \frac{\partial Z'_{2i}}{\partial \varphi} \\
\frac{\partial v_i}{\partial \kappa} &= \left(\frac{\partial Z_{1i}}{\partial X_{1i}} \cdot \frac{\partial X_{1i}}{\partial \kappa} + \frac{\partial Z_{1i}}{\partial Y_{1i}} \cdot \frac{\partial Y_{1i}}{\partial \kappa}\right) - \frac{\partial Z'_{2i}}{\partial \kappa}
\end{aligned} \quad (6)$$

$$\frac{\partial v_i}{\partial m} = \left(\frac{\partial Z_{1i}}{\partial X_{1i}} \cdot \frac{\partial X_{1i}}{\partial m} + \frac{\partial Z_{1i}}{\partial Y_{1i}} \cdot \frac{\partial Y_{1i}}{\partial m} \right) - \frac{\partial Z_{2i}^{'}}{\partial m}$$

$Z_{2i}^{'} = Z0 + (1+m)\underline{r}_3 \underline{X}_{2i}$ is the transformed height value.

The unknown parameters are then computed according to the well-known equations of the least squares adjustment. The standard deviation of unit weight is identical to the standard deviation of the height differences after applying the transformation.

3.3. Special case of unknown shift Z0

The algorithm was implemented such that different unknown parameters can be introduced. If only a vertical shift Z0 is to be obtained the algorithm can be simplified. The obtained transformation parameter Z0 is identical to the mean value of the height differences between the two data sets. The observation equations have the following form:

$$v_i(Z_{2i}) = Z_{1i}(X_{2i}, Y_{2i}) - \left(Z0 + Z_{2i}(X_{2i}, Y_{2i})\right) \quad (7)$$

The result of the algorithm introducing only a vertical shift Z0 corresponds with calculating a difference DTM.

4. The test site and used data sets

As mentioned before the aim of the project was the assessment of the SRTM X-SAR elevation data set. This task can be accomplished by comparing the data with reference data of a well known test site.

The test site of IPI is situated in the south of Hannover. The north-eastern part of the area is characterized by urban regions and flat terrain. The south-western part is more undulated, forest and agrigultural regions cover the area. The size of the test site is 50x50 km². The maximum height difference is about 450 m.

The accuracy of the reference data - provided by the surveying authority of Lower Saxony "Landesvermessung und Geobasisinformation Niedersachsen LGN" in our case - has to be at least one order of magnitude better than the SRTM data. The expected vertical accuracy of the SRTM data is several meters. Thus, highly accurate coordinates of Trigonometric Points (TP) and the Digital Terrain Model of LGN, the ATKIS DGM5, had to be used as reference data sets.

Trigonometric Points are part of the fundamental network of the surveying authorities of Germany. The planimetric coordinates are Gauß-Krüger coordinates, the heights are normal heights. The planimetric and vertical accuracy is 1-3 cm.

The DGM5 is a data set representing the terrain surface. The data consist of regularly distributed points with a grid spacing of 12,5 m. Together with morphological information the data represent a hybrid DTM. The vertical accuracy is about 0,5 m and depends on the terrain undulation. The DGM5 covered parts of the test site, altogether 4,7 million DGM5 points were available.

The SRTM ITED-2 data (Figure 2) represent the surface including vegetation and buildings because of using a short-wave X-band system. Thus, the data set is a Digital Surface Model in contrast to the reference Digital Terrain Model. The data are given in ellipsoidal coordinates referring to the geocentric ellipsoid WGS84. The grid spacing is 1 arcsec in both directions. For comparing the data sets the ITED-2 data were transformed into the coordinate system of the reference data set. A datum transformation between the two ellipsoids WGS84 and Bessel was carried out, additionally the ellipsoidal heights were corrected using geoid undulations. The geoid has an extent of 43-45 m in the test site. After these transformation steps the ITED-2 data are approximately distributed in a rectangular grid. The grid spacing in north-south direction is about 30 m, the grid spacing in east-west direction depends on the ellipsoidal latitude. The test area is situated at a latitude of about 52°. Therefore the grid spacing in east-west direction is about 20 m. The available data set consists of 5,5 million points.

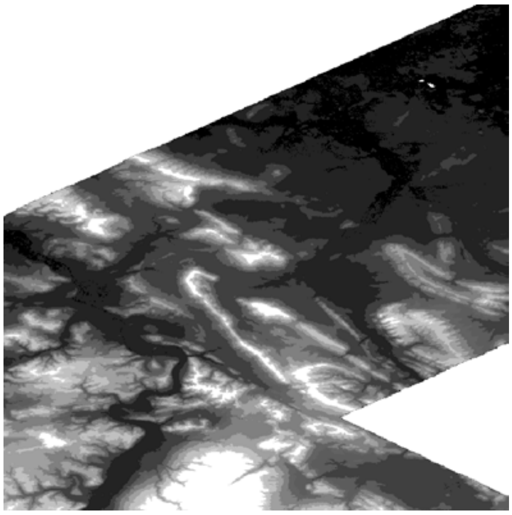

Figure 2. The test site, SRTM ITED-2

5. Quality assessment by using coordinates of Trigonometric Points

The first experiments were performed by using the coordinates of Trigonometric Points (TPs). 1.068 TPs were available in our test site which are covered by the SRTM ITED-2 data. To obtain the vertical accuracy only those TPs were considered which lie clear of vegetation and buildings. To classify the TPs a Digital Landscape Model (DLM) of the surveying authority LGN (ATKIS Basis DLM) was used. The DLM is a two-dimensional representation of the topography. 368 points in urban regions, inside or near forests were excluded.

By means of the planimetric positions of the TPs the corresponding height values of the ITED-2 data set were obtained. The height differences were calculated and the quality measures were obtained (see equation 7). Any kind of planimetric systematic error or errors in rotation or scale were neglected. Table 1 shows the results:

	Values
Z0 [m]	+3,18
s [m]	±4,27
s_{Z0} [m]	±2,86
n	700

Table 1. Quality measures using TPs

The positive value Z0 means that the height level of the SRTM ITED-2 data is lower than the height level of the TPs. The data set contains a systematic vertical shift of +3,2 m. The standard deviation of the height differences s is ±4,3 m. After considering the mean value, the standard deviation s_{Z0} is ±2,9 m. These values confirm the high vertical accuracy of the SRTM ITED-2 data. Unfortunately, a conclusive reason for the shift cannot be given. A possible explanation can be derived from the calibration of the ITED-2 data used for the investigation. An error in the heights selected for the calibration directly influences the results of our study. While in many cases IfSAR orbits are processed and calibrated from coast to coast and thus the ocean serves as absolute reference, the orbit containing the data of the test site was shorter and had to be handled in a different way. If any buildings and vegetation existed in the areas selected for calibration and were not properly accounted for, the absolute ITED-2 heights would indeed come out too low, explaining the obtained results. It should be pointed out, however, that this hypothesis could not be further tested, because no additional information about the calibration sites and procedure was available.

6. Quality assessment by using the Digital Terrain Model ATKIS DGM5

In a first step the height differences between corresponding values were calculated neglecting the influence of any kind of "terrain noise" (buildings, trees). In a second step only the height differences outside urban and forest regions were used. The algorithm described in chapter 3 was utilised introducing one and seven unknown transformation parameters.

6.1. Investigations with all DGM5 height values

About 1,2 million reference DTM points were available inside the test site. In contrast to the investigations before, the planimetric positions of the ITED-2 data were used to obtain the corresponding height values of the DGM5 using a bilinear interpolation. Then the height differences were calculated and the quality measures were derived (see equation 7). The following table 3 shows the results:

	Values
Z0 [m]	-2,63
s [m]	±9,08
s_{Z0} [m]	±8,68
n	1.234.815

Table 2. Quality measures using all DGM5 points

The sign of the mean value of the height differences Z0 is negative. It means that the height level of the ITED-2 data is higher than the level of the DGM5. This result is in contradiction to the obtained value of the investigations using the Trigonometric Points (see table 1). A possible reason is the influence of vegetation and buildings. Whereas in chapter 5 only points which are not influenced by terrain noise were used, here the height values are distributed over the complete test area, also across forests and urban regions.

Figure 3 shows the influence of terrain noise on the sign of local vertical systematic errors. The figure represents a positive vertical systematic error in open terrain. The height level of ITED-2 is lower than the height level of the reference data. Additionally, it can be seen that terrain noise (vegetation and buildings) increases the height level of the SRTM ITED-2 data and thus decreases the systematic vertical shift. The value Z0 can thus become negative.

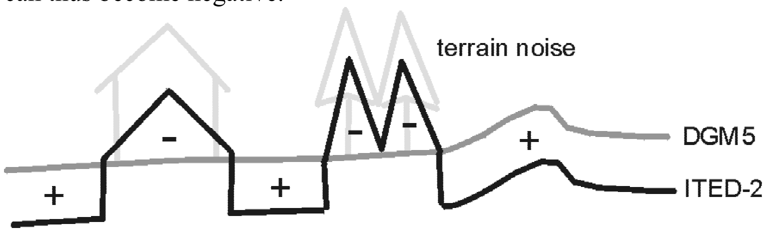

Figure 3. Height differences between DGM5 and ITED-2

The relative frequency distribution in figure 4 confirms the obtained results. The non-symmetric distribution is caused by objects lying above the terrain. Obviously the left negative part of the histogram represents these objects. Additionally in contrast to the calculated mean value Z0 (see table 2) the maximum of the histogram is in the positive part. This means that the vertical systematic error seems to be again positive. This result confirms those of chapter 5.

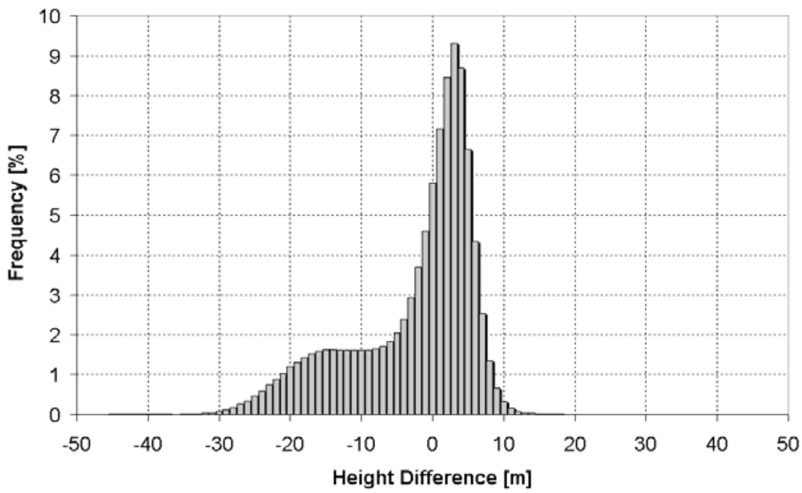

Figure 4. Relative frequency distribution of the height differences between DGM5 and ITED-2

6.2. Investigations with DGM5 height values in "open landscape"

Again the ATKIS-Basis DLM of LGN was used for the classification of the DGM5 height values. Because the mission was flown in February, the SRTM data also represent the terrain in agricultural fields. The vegetation heights are completely negligible. Values in forest and urban regions were excluded amounting to approximately 500.000 points or 40 % of the available DGM5 height values.
The results (see table 3) confirm the investigations before. The sign of the mean value Z0 is positive. The influence of large negative differences caused by terrain noise thus is significant.

As was to be expected the value Z0 does not correspond exactly to the value using the TPs (see chapter 5). There remains a difference caused by borders of forest and urban regions and other secondary effects. The standard deviations are nearly the same. The results show high quality of the SRTM data set.

	Values
Z0 [m]	+ 2,62
s [m]	± 4,32
s_{Z0} [m]	±3,44
n	669.685

Table 3. Quality measures using DGM5 points in "open landscape"

6.3. Investigations using seven unknown transformation parameters

In this paragraph the results obtained with the algorithm based on a spatial similarity transformation are presented (see chapter 3). As in section 6.2. only height values in open terrain were used. The results are shown in table 4.

		Value
X0	[m]	+0,60
Y0	[m]	-2,32
Z0	[m]	+2,28
ω	[grad]	-0,003
φ	[grad]	+0,002
κ	[grad]	-0,007
m	[ ]	+0,0000306

Table 4. Transformation parameters

The value Z0 is comparable to the mean value in table 3. The horizontal shifts X0 and Y0 describe systematic differences between the data sets. The values amount to only a fraction of the spacing between neighbouring height values. Accordingly the horizontal accuracy of the SRTM data seems to be quite good.
The rotation angles ω and φ cause maximum vertical shifts of ±1,22 m and ±0,98 m at the border of the test site. The scale factor causes maximum horizontal shifts of ±0,76 m in both directions. Altogether the seven parameters lead to maximum planimetric shifts of 4 m in north-south and 6 m in east-west direction. The maximum vertical shift is 4,5 m at the borders of the test site.

669.466 observations were used in the investigation. The standard deviation of the SRTM heights, comparable to s_{Z0} above, amounts to ±3,3 m, the vertical shift and the standard deviation of the heights reported in this section are rather close to those presented in section 6.2. (see table 3). Thus, the SRTM ITED-2 is free of systematic errors which can be modelled by the spatial similarity transformation.

7. Further investigations

As mentioned before the quality of the SRTM ITED-2 data, i.e. the order of magnitude of random and systematic errors, is influenced by terrain noise: The larger the percentage of regions containing vegetation and buildings the larger is the systematic vertical shift and the larger is the standard deviation of the remaining residuals.
In order to properly assess the SRTM data not only in open landscape but also in urban and forest areas, two sample sites with a size of 2x2 km² were analysed by obtaining a Digital Surface Model by using analytical photogrammetry. The photogrammetric measurements have a height accuracy of about 0,4 m.
The first sample site is situated in Hildesheim. The area is characterised by single and complex houses with gardens. The second test area is mainly characterised by deciduous forest. Additionally, agricultural fields and a freeway are in the centre of the area. It is a region in the south of Hannover.

		urban region	forest region
DGM5	Z0 [m]	-5,13	-13,19
-	s [m]	±8,46	±15,18
ITED-2	n	6.794	6.814
DSM	Z0 [m]	+1,05	+1,84
-	s [m]	±5,09	±4,57
ITED-2	n	6.612	6.675

Table 5. Quality measures in urban and forest regions, upper part: comparison between DGM5 and ITED-2, lower part: comparison between measured DSM and ITED-2

Table 5 shows the results of comparing the ITED-2 data with the reference DGM5 and the photogrammetrically obtained DSM. The spatial similarity transformation using the seven parameters of table 4 was applied before calculating the height differences. Thus, the expected value for Z0 under ideal conditions (DSM from SRTM and photogrammetry represent the same surface) is zero, and the standard deviation s should be close to the results obtained in chapter 5 and 6. The three upper rows represent the results from the comparison of DGM5 and ITED-2, the lower part shows the results of comparing the DSM of SRTM with the photogrammetrically measured DSM.

Considering the DGM5 both regions are characterised by a negative vertical shift Z0, i.e. the values are influenced by terrain noise. Additionally the standard deviations are very large.
Using the measured DSM the shift becomes positive. That means, that the ITED-2 lies significantly below the DSM (the values of table 4 and 5 must be added to obtain the complete shift). For the urban area this result can be explained with interpolation effects: there are probably some points on the ground influencing the result. In the forest area, an additional explanation may be the fact that the X-band signals somewhat penetrate into the canopy (remember that the mission was flown in February, thus the trees did not cover leaves). Also the standard deviations are larger than in the open landscape. As an overall result, it can be stated that in urban and forested areas, the quality of the ITED-2, while still meeting the predicted values, is somewhat poorer than in open landscape.

8. Conclusions

This paper contains the results of assessing the quality of the SRTM ITED-2 data. The algorithm used is based on a spatial similarity transformation without using any kind of control point information. The SRTM data was matched to a reference data set of better accuracy, the obtained seven transformation parameters describe potentially existing systematic errors of ITED-2.
First investigations were carried out by introducing just a vertical systematic shift. This procedure corresponds to the calculation of a difference DTM and yields the mean value and standard deviation of the height differences. Investigations using only regions without vegetation and buildings lead to a positive vertical shift of about 2,6 metres. Thus, the height level of the SRTM data seems to be too low. A possible explanation for this result is the fact that the ITED-2 DSM was calibrated over land rather than coastal waters.
The standard deviation of the SRTM ITED-2 was found to be ±3,3 m in open landscape, after applying the spatial similarity transformation. Maximum systematic shifts of 4-6 m were detected, representing only 20-25 % of the ITED-2 grid size. In summary, it can be stated that the results are much better than predicted before the start of the mission. Thus, the quality of the SRTM ITED-2 is indeed remarkable.

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