Quality Assessment of Digital Surface Models derived from the Shuttle Radar Topography Mission (SRTM)

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Abstract – **In February 2000 the Shuttle Radar Topography Mission (SRTM) was flown on board the space shuttle Endeavour. The aim of the mission was to survey about sixty percent of the complete landmasses of the Earth's surface [2]. During the mission US C-band antenna and a German/Italian X-band antenna were installed on board the shuttle. The main result of the mission will be a three-dimensional digital surface model (DSM) obtained from single-pass interferometry.**

During the validation process the SRTM elevation data will be analysed by comparing them to reference data of a well-known test site. This paper describes and investigates an algorithm for this task which was developed at the Institute for Photogrammetry and Engineering Surveys (IPI) of the University of Hannover. It is based on a spatial similarity transformation which matches the SRTM data onto reference data of higher accuracy. The algorithm is comparable to the absolute orientation of a photogrammetric block by means of a DTM [1]. Any detected transformation parameters which differ from the identity transformation point to potentially existing systematic errors of the SRTM data, the standard deviation of the remaining height differences represents the accuracy of the SRTM data.

The algorithms was successfully tested using simulated and real data, the obtained results are reported in this paper.

I. INTRODUCTION

Three-dimensional data like digital surface or terrain models (DSM or DTM) are very important for many applications. They are being used for geology, hydrology, mapping, telecommunication, planning and navigation to name only a few areas of application. According to the use of the DTM or DSM a different accuracy is required.

Accuracy measures for a DTM or DSM can be recognized by comparing it to reference elevation data (DTM or irregularly distributed 3D point cloud) with an accuracy of at least one order of magnitude better than the data set to be assessed (see [3] for a study using airborne InSAR data). For the SRTM mission the reference data can be a DTM of higher accuracy, at least in Germany available from the surveying authorities, or the coordinates of a basic surveying network like Trigonometric Points.

An algorithm which was developed at the Institute for Photogrammetry and Engineering Surveys (IPI) of the University of Hannover is described in this paper (Section II). Because the calibration processes of the SRTM data is not finished at the time of writing (April 2001) no real SRTM data could be analysed for this paper. Thus, section III shows simulations based on a DTM of the State Surveying Authority of Lower Saxony (Landesvermessung und Geobasisinformation Niedersachsen, LGN Hannover). The paper concludes with some remarks on DTM verification, see section IV.

II. ALGORITHM FOR MATCHING DIGITAL SURFACE MODELS

The developed algorithm is based on a spatial similarity transformation. The seven parameters of this transformation describe global systematic errors. Remaining errors after having applied the similarity transformation can be considered as either local systematic errors or random errors.

A. Mathematical Model

Single points P (X,Y,Z) contain height information about a given area. Often the planimetric coordinates X and Y are Gauß-Krüger or Universal Transverse Mercator coordinates. The heights Z are often ellipsoidal, orthometric or normal heights. In locally restricted areas these coordinates can be understood as values of a Cartesian coordinate system. The points are combined to vectors:

$$G_1 = \{P_{11} \quad P_{12} \quad \cdots \quad P_{1i} \quad \cdots \quad P_{1n}\}; G_2 = \{P_{21} \quad P_{22} \quad \cdots \quad P_{2j} \quad \cdots \quad P_{2m}\} \quad (1)$$

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 in the absence of errors. If for a point P_{1i} no such corresponding point P_{2i} exists (or vice versa) it must be interpolated from the other data set using e.g. a bilinear interpolation.

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

$$Z_{1i}(X_{1i}, Y_{1i}) = Z_{2i}(X_{2i}, Y_{2i}) \quad (2)$$

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:

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

with

$$\begin{pmatrix} X_{1i} \\ Y_{1i} \end{pmatrix} = \begin{pmatrix} X0 \\ Y0 \end{pmatrix} + (1+m) \cdot \begin{pmatrix} \underline{r}_1 \\ \underline{r}_2 \end{pmatrix} \cdot \underline{X}_{2i}; \textit{ where } \underline{X}_{2i}^T = (X_{2i} \quad Y_{2i} \quad Z_{2i}) \quad (4)$$

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.

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.

B. 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}:

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

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:

$$\frac{\partial v_i}{\partial X0} = \frac{\partial Z_{1i}}{\partial X_{1i}}\,;\; \frac{\partial v_i}{\partial Y0} = \frac{\partial Z_{1i}}{\partial Y_{1i}}\,;\; \frac{\partial v_i}{\partial Z0} = -1$$

$$\frac{\partial v_i}{\partial \omega} = \frac{\partial Z_{1i}}{\partial Y_{1i}}\cdot\frac{\partial Y_{1i}}{\partial \omega} - \frac{\partial Z'_{2i}}{\partial \omega}$$

$$\frac{\partial v_i}{\partial \varphi} = \left(\frac{\partial Z_{1i}}{\partial X_{1i}}\cdot\frac{\partial X_{1i}}{\partial \varphi} + \frac{\partial Z_{1i}}{\partial Y_{1i}}\cdot\frac{\partial Y_{1i}}{\partial \varphi}\right) - \frac{\partial Z'_{2i}}{\partial \varphi} \qquad (6)$$

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

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

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

The unknown parameters are then computed according to the well-known equations of the least squares adjustment.

III. Experiments and Results

The calibration of the SRTM digital surface models is still going on. Therefore, no data sets were available for validation of the suggested algorithm, and the investigations reported in this paper are based on simulated data sets and also on real data sets comparable to the SRTM X-band standard elevation products. The SRTM data will be available with a planimetric resolution of 30 meters, the expected vertical accuracy is about six to eight meters. The following two sections show the results of our investigations.

A. Simulated Data Sets

The data set used for simulations is a part of the so called DGM50 of the State Surveying Authority of Lower Saxony. The area is situated in the South of Hannover and has a size of 10x10 km². The data are in regular form with a point spacing of 50 meters, 40401 points belong to the data set. The maximum height difference in the area is 341 meters; the mean terrain slope is 4.7 grad.

Table (1) shows some results of the simulation studies. The first investigation was carried out by creating a second DTM using the inverted spatial similarity transformation with 100 meters translation for all three coordinates, 0.5 grad rotation for all three angles and a scale of 1.01. The choice of these values is motivated by the fact that the systematic errors of the SRTM elevation data are assumed to be much smaller, and thus these values constitute an upper bound for the applicability of the suggested algorithm for assessing SRTM data.

In the first experiment the sensitivity of the algorithm with respect to noise is investigated by adding white noise of different standard deviation to the data set G_2 and then computing the parameters of the similarity transformation.

The results are shown in table (1). The first row in the table shows the results without adding any kind of noise; the standard deviation of the noise is zero. Four iterations have to be computed until the break off condition is fulfilled. The variations in translation, rotation and in scale have to be smaller than one centimetre, one milligrad and 0.0001, respectively. The differences between the calculated and the true transformation parameters are all zero, see last three columns in table (1). This is no surprise because the data sets are identical.

TABLE 1
CONVERGENCE OF DIFFERENT NOISY DATA SETS
(X0,Y0,Z0=100m, ω,φ,κ=0.5grad, (1+m)=1.01)

Noise standard deviation [m]	Number of iterations	Differences						
		X0	Y0	Z0	ω	φ	κ	m
		[m]			[mgrad]			[--]
0.0	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0000
5.0	5	0.6	0.0	0.1	0.7	0.8	0.2	0.0004
8.0	5	1.3	0.0	0.1	1.0	1.8	0.6	0.0009
10.0	6	2.0	0.1	0.2	1.1	2.6	0.8	0.0013

The second, third and fourth row show the results of experiments with white noise of different standard deviation. The first column shows the standard deviation of the added noise, the second column presents the number of iterations needed for reaching convergence, the last three columns show the differences to the true transformation parameters. It can be seen that for increasingly noisier data sets the differences between the computed and the true transformation parameters become increasingly larger. With a noise standard deviation of ten meters the differences in translation reach a maximum of two meters, the effect of the rotations is still negligible, the difference in scale, however, causes an error of six meters.

These results are based on somewhat hilly terrain. It is clear intuitively and also follows from an analysis of the elements of the design matrix (see equations 7) that the hillier the terrain the better will be the possibility to accurately determine the transformation parameters. Therefore, a second experiment was carried out, in which all the elevations were scaled down to produce flat terrain, however without adding noise. The size of the test site, the number of points and their spacing were taken identical to the data set used before. Two simulations were realized. The first simulated terrain has a maximum height difference of 3.41 meters; the mean slope is 0.047 grad, thus the heights of the original data set was multiplied by 0.01. For simulating the second data set the factor 0.001 was used. Thus, only a height difference of 0.34 meters and a mean slope of 0.0047 grad was present. The results are identical to the results presented in the first row of table (1). In a next step we will also add noise to these data sets to investigate the limits of the algorithm with respect to flat terrain. It is clear already now, that if the random noise values become larger than the height differences in the area it will be impossible to obtain a correct result, because the derivatives will not be consistent with the actual terrain anymore.

Depending upon the radar wavelength InSAR height data may contain not only information about the terrain surface, but also include 3D objects such as buildings and trees or forests, thus representing a DSM and not a DTM. This is the case for the SRTM X-band height data. The 3D objects constitute local systematic errors when comparing the DSM to a reference DTM. In order to study these effects the described DTM was altered by using the forest layer of an available GIS data set of the region (ATKIS BasisDLM in our case). About 33 % of the investigated area is forest. An offset of 15 meters in the forest regions representing trees and white noise with a standard deviation of 6 meters for the whole area were used.

The results show that the calculated height offset Z0 is identical to the percentage of the tree height. 33 percent of 15 meters lead to a height translation of approximately 5m. Also the translations X0 and Y0 are influenced also by the local systematic errors. These values are 11.39 m and 8.92 m or about 0.2 pixels, respectively, and are thus not of major importance. The magnitude of the rotations depends on the distribution of the forest regions. If these local errors are evenly distributed over the whole area, the rotation errors will be very small. On the other hand, an accumulation of the forest in one part of the area will increase the rotation errors. Thus, the difference between the DSM and the DTM has significant effects on the assessment of the SRTM data. It must be ensured that 3D objects are either removed before a comparison is carried out, or that the areas containing the 3D objects are excluded from the comparison.

B. Real Data Sets

The DTM that will be used for the evaluation of the SRTM data in our work is the DGM5 of the State Survey Authorities LGN. It has a point spacing of 12.5m and – according to LGN (http://www.lgn.de) - a standard deviation of 0.5m in easy and 1.5m in more difficult terrain.. Since the SRTM data are not yet available, a comparison was carried out between the DGM5 representing the reference data set and the DGM50 (point spacing 50 m), also from LGN, representing the SRTM data in order to test the developed algorithm. According to LGN the accuracy of the DGM50 is a few meters and can reach ± 10m in mountainous terrain. The results of this test have of course no direct connection to the SRTM mission. Nevertheless, they are interesting and are reported here.

The comparison between the two data sets yielded the following results: Convergence was reached after eight iterations. The translations amount to -24.83m for X0, 2.01m for Y0, and -1.36m for Z0, the rotation angles were determined at 0.01grad in ω, 0.03grad in φ, 0.16grad in κ and the scale factor was to -2.05ppm. The detected systematic error in X-direction amounts to approximately 0.5 pixels of the DGM50, the systematic error in κ leads to about 0.2pixels at the border of the area, the errors in ω and φ result in an height error of one to two meters. The systematic scale error also causes a height difference of 0.2pixels in position at the border of the area and a few decimetres in elevation. Given the accuracy of the DGM50 and of the reference data all these results are well within the range of the expected values. The same is true for the standard deviation of the remaining height differences which was determined at 5.1m. Similar results were obtained when in addition, the same systematic errors as in the simulation study were introduced.

IV. Conclusions

This paper shows first simulations on assessing the SRTM elevation data accuracy using an algorithm which compares two DTM based on a spatial similarity transformation. The simulation results show that the algorithm can be used to validate the SRTM standard elevation product. The algorithm was also used to successfully compare DTM data of different accuracy and point spacing. Problems can occur in areas with high local systematic errors caused by vegetation or urban regions. These areas have to excluded from the comparison, or the 3D objects have to be removed prior to the assessment. We now wait for the SRTM data to be delivered in order to assess their accuracy.

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