LEAST SQUARES MATCHING FOR COMPARISON OF DIGITAL TERRAIN MODELS AND ITS APPLICATION POTENTIAL FOR THE BRAZILIAN MODELS AND THE SRTM MODEL

Combinação de mínimos quadrados na comparação de modelos digitais de terreno e seu potencial de aplicação para o modelo brasileiro e o modelo SRTM

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ABSTRACT

Digital Terrain Models are being used for planning and hydrological applications, but also for visualization and many other tasks. For all applications, it is necessary to know the model quality, because it has an impact on the quality of the decisions that are drawn from the terrain model applications. In this paper we present a method that is suitable for comparing two terrain models to each other. Vertical, but also horizontal displacement of terrain features can be found automatically, which are systematic errors and are in the main focus of this paper. However, random errors can be quantified, too. This method allows establishing a vector field of differences between two models, measuring the deviation from one to the other. These deviations are a measure of quality of one model against the other. Emphasis will be put on comparing terrain model from NASA's Shuttle Radar Topographic Mission to terrain models of known quality in Brazil.

1 INTRODUCTION

A Digital Terrain Model (DTM) is a surface that is derived from a cloud of points on the visible earth surface and is a topic of growing interest due to its potential applications in mapping and monitoring of the earth's surface in three dimensions. DTMs are used in many applications in the context of earth sciences. The required accuracy and reliability of them is dependent on the application. The production costs of a DTM are strongly correlated with its quality. Ground-based methods can result in DTMs of very high quality, but they are also very expensive.

A DTM that is created using data from space is at a relative low range in price because large areas can be covered, but also in quality is poorer. At this moment, many researchers are looking for the quality improvement of the DTM produced by methods that are based on the different datasets (Ouarzeddine, 2002). In between these extremes of terrestrial and space methods, the DTM creation by airborne sensors like aerial cameras and multi-spectral sensors can be found, by measurements of the topography. With active remote sensing technologies, including airborne laser scanning (LiDAR, Light Detection and Ranging) and Interferometric Synthetic Aperture Radar (InSAR) it is possible to provide directly, and therefore automatic, three-dimensional measurements of the topography over extensive areas of the landscape.

InSAR is a technique that makes a significant contribution to the topography mapping. The DTM generation from InSAR as a technique is not a new one and it was used in the SRTM (Satellite Radar Topographic Mission) of NASA to recover topography globally, i.e. for the entire earth. Measurements were performed in the C-band and in the X-band. Each data take includes an orthorectified SAR image and the corresponding DTM. For low resolution SRTM data is available for free.

In the literature a diversity of approaches on SRTM data is found. Gamba et al (2002) detected buildings in urban areas using SRTM digital elevation models (DEMs). The results showed that is possible to detect tall structures and identify the major buildings in the area. But, classical algorithms for building detection and recognition are not immediately useful. Ouarzeddine (2002) generated DTMs using InSAR polarimetric data and compared the singular interferometric coherence obtained from conventional interferometry with the optimized coherence obtained from fully polarimetric data, using histograms. The results revealed that the optimization applied in this study brought significant improvement to the quality of the coherence. Andersen et al (2003) compared forest canopy models derived from LIDAR and SRTM data in a pacific Northwest conifer Forest and showed that both of these active remote sensing technologies have the potential to provide critical, spatially-explicit information relating to forest canopy structure, biomass, and volume. According to Lemos et al (2004), the evaluation process between a topographic map and SRTM data demonstrated that for many applications, the SRTM can substitute digital topographical models that were obtained form 1:250.000 scale topographical map. In order to do the comparison the topographic map was digitalized manually. Barros et al (2004) demonstrated that orthorectification of images (panchromatic band of the SPOT 4) may be realized by using DEMs generated through SRTM data, without loosing geometric quality, if compared with the use of the DEM generated through contour lines of the official maps at 1:50.000 scale.

The above approaches can be seen as tests, whether the quality of a certain DTM (here the SRTM model) is suitable for a specific application. These investigations are limited to their specific application, and it is of interest to have a more general quality description of a DTM. Quality measures that are derived from the measurement system specifications cannot provide this, because they give accuracy values for optimal situations and systematic errors are usually not specified. Manually measured checkpoints give some insight, but their number is usually small and their selection, i.e. the location in the terrain, has a large impact on the result. Consider, e.g. check points only in flat areas, which cannot give any information on the DTM accuracy for inclined areas, whereas it is know that e.g. photogrammetrically derived DTMs have a vertical accuracy depending on the image scale *and* the terrain slope (Kraus, 2000).

The approach taken here is different: we want to compare two DTMs. If for the first DTM, the "better" one, the quality is known, the quality difference allows to determine the quality of the second model. The contribution of this paper is to present a methodology that is suitable for the comparison of one DTM to another. We are especially interested in comparison to the situation in Brazil and comparison of the SRTM to other data sources. It was realized using synthetic experiments and the results presented showed that it was possible to recover systematic errors in *height and planimetry*. This is an important contribution as comparison between terrain models is usually only performed in height. With this new method it is possible to distinguish between errors, systematic or random, in height (e.g. the wrong height of a mountain peak), from errors in planimetry (e.g. the wrong location of a mountain peak). Image matching algorithms were used to determine the similarity between two digital terrain models. The method of least squares matching was applied to compare two grid- or raster- digital terrain models and derive horizontal and lateral offsets between those two.

The paper is organized as follows. In Section 2 the least square matching in digital images will be recapitulated which is the basis for the new method, and in section 3 least square matching will be extended to digital terrain models. Section 4 elaborates on the Brazilian elevation model and SRTM data and our plans for comparison. Section 5 contains discussion and conclusions.

2 LEAST SQUARE MATCHING IN DIGITAL IMAGES

Least squares matching is generally used for measuring homologous points in stereo image pairs. In one digital image, gray values $G(i,j)$, the location of a point $\boldsymbol{p}=(p_x,p_y)$ is given by its row and column coordinate. In the second image $H(i,j)$ only an approximate position q_0 of the corresponding, homologous point is required. Least squares matching is a so-called area based matching method and does not work on a point (or a feature), but for an image patch, i.e. a window of w by w pixels, that is centered on $\boldsymbol{p}$ and q_0, respectively.

An image patch of G around $\boldsymbol{p}$ is similar to an image patch of H around q_0, but due to perspective distortion and different illumination, both caused by different viewing angles and viewing positions, and because q_0 is only an approximate position for $\boldsymbol{p}$, the two image patches are not exactly equal.

A transformation T_P in the image plane has to be used to account for the different geometry of the patches, and a radiometric transformation T_G has to be used to account for the different illumination. If q_0 is the exact position of $\boldsymbol{p}$ in the second image, then $T_P(\boldsymbol{p})=q_0$, and if the gray values are the same in both image patches, the radiometric transformation T_G is the identity. Applying the transformations to the second patch yields the transformed patch $T_G(H(T_P(\boldsymbol{p})))$.

Image matching makes the two patches, i.e. the patch in G around $\boldsymbol{p}$, and the transformed patch at the corresponding location in H, in the least squares sense as similar as possible, determining in an iterative way the parameters of the transformations T_P and T_G. The location q_i is part of the geometric transformation and updated in each iteration. Mathematically, it is formulated as:

$$\sum_{i=-w/2}^{i=w/2} \sum_{j=-w/2}^{j=w/2} T_G(H(T_P(p_x+i, p_y+j))) - G(p_x+i, p_y+j) \rightarrow \text{Minimum} \tag{1}$$

For finding the minimum the derivatives after the transformation parameters have to be calculated and set to zero. For one patch w^2 equations are obtained. A criterion for the difference between q_{i-1} and q_i is used to determine, if the adjustment is end-iterated. In image matching T_P is usually an affine transformation (Schenk, 1999), and T_G a linear transformation (affine in one variable).

Equation (1) leads to an adjustment problem, and therefore the statistical quantities (standard deviation, accuracy of unknowns, etc.) can be computed. However, the estimation of $\sigma_{0 \text{ a posteriori}}$ is known to be too optimistic because of the correlation introduced in the resampling necessary for computing $H(T_P(\boldsymbol{p}))$. Also the correlation coefficient between the two image patches $G(\boldsymbol{p})$ and $H(T_P(\boldsymbol{p}))$ is a measure of similarity.

3 LEAST SQUARE MATCHING FOR DIGITAL TERRAIN MODELS

Digital terrain models (DTM) describe the relief of the earth and can be given in different data structures, amongst those are the triangulation, so-called hybrid grid models, i.e. a grid including break lines (Kraus, 2000), and raster models. In a raster model heights are sampled in a regular raster, which can also be viewed as a matrix or a digital image with – possibly – real valued gray values.

A difference to digital images is that all 3 dimensions, i.e. the first 2 dimensions in the image plane, and the 3rd dimension of the "gray values", are in meter, whereas in digital images the image plane dimension is typically millimeter or pixel and the 3rd dimension is intensity.

Image matching algorithms can therefore be used to determine the similarity between two digital terrain models, not only in the z-direction, but also in the lateral position. If both terrain models are given in the same coordinate system with the same raster cell size horizontal and vertical displacements of one DTM against the other can be detected.

Assuming that there are only shifts between the two terrain models, i.e. rotation and scale differences between the two terrain patches are negligible, the transformations of Eq. (1) become $T_P(\boldsymbol{p}) = \boldsymbol{q} = \boldsymbol{p}+\Delta\boldsymbol{q}$, $T_G(H(q)) = H(\boldsymbol{q})+\Delta h$, with 3 parameters: $\Delta\boldsymbol{q}$ the shift in planimetry, and Δh the shift in height. One linearized observation equation is then:

$$\frac{\partial H}{dx}(p_x+i+\Delta x, p_y+j+\Delta y)\Delta x+\frac{\partial H}{dy}(p_x+i+\Delta x, p_y+j+\Delta y)\Delta y$$
$$+1\cdot\Delta h+H^{\mathrm{res}}(p_x+i+\Delta x, p_y+j+\Delta y)-G(p_x+i, p_y+j)=0 \qquad (2)$$

Here H^{res} indicates that the height values of H have to be resampled, using e.g. bilinear interpolation, and the first derivatives of H are the slopes of the terrain. The Δx, Δy, Δh are the unknowns, the first three terms – without the unknowns: $\partial H/dx$, $\partial H/dy$, 1 – build the design matrix, and the last 2 terms form the reduced observation.

From image matching it is known that the approximate position of $\boldsymbol{p}$ in the second image, $\boldsymbol{q_0}$ has to be accurate to a few pixels, otherwise the adjustment system does not converge during the iterations or may converge to a wrong solution. Assuming that the errors in planimetry are not too large, $\boldsymbol{q_0}$ can be set equal to $\boldsymbol{p}$.

There are different possibilities for the overdetermined system of equations of (2) to become singular:

1. The slope in x-direction is constant everywhere, because then the first and the third column of the design matrix are linearly dependent. This means that the terrain surface in the patch can be described as a family of parallel lines which are additionally parallel to the xz-plane.
2. The slope in y-direction is constant everywhere, because then the second and the third column of the design matrix are linearly dependent.

3. The slope in x-direction is a multiple of the slope in y-direction everywhere, because then the first and the second column of the design matrix are linearly dependent. This is the case if the height function in the patch has the form *f(ax+by)*, for any function *f* and real numbers *a* and *b*. The surface consists then of a family of horizontal parallel lines.
4. The sum of the slope in x-direction and the slope in y-direction is constant everywhere. Then there is a linear dependency between all three columns of the design matrix. The patch can then be described with a family of parallel lines in general direction.

With the exception of these four cases, the transformation of a patch from the second terrain model to the first terrain model can be computed. It is obviously not possible to perform the matching, if the patch surface is translation invariant in a horizontal direction (3rd case), or if the terrain in the patch does not show any curvature in the x- or the y-direction (1st and 2nd case). The 4th case is the most general one, including all the other cases. In all these exceptional the surface can be shifted in one or more directions without changing it. It can be shown[1] that only general cylindrical surfaces, i.e. surfaces with Gaussian curvature zero, lead to singular design matrices.

To compare two terrain models in one point, matching of one patch pair, each patch centered on the point in either model, is performed. To compare two models in a region or entirely, a regular grid of points is compared. In each point the parameters of the transformation are computed.

3.1 Example with synthetic data

In order to demonstrate the comparison of two digital terrain models a height function is used and terrain elevations are sampled in a regular pattern. The function used is:

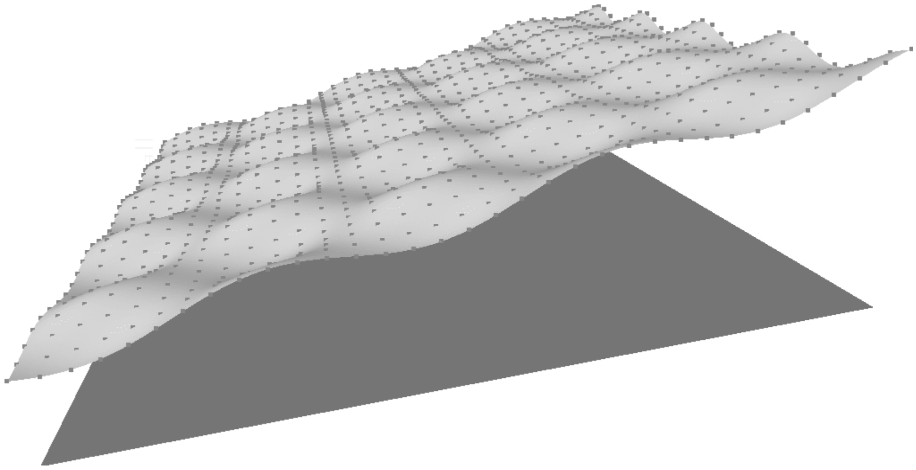
$$G(x, y) = 30*\sin(x/60)*\cos(y/100)+y*20/100 \qquad (3)$$

This corresponds to a landscape with hills, a maximum slope of 50% in x- and in y-direction. Heights are sampled every 5 meter, simulating a dense digital terrain model. The heights were stored as floating point values, but rounded to the centimeter. The second terrain model is a shifted version of the first one with the shift values in x, y, z-direction 7.5, 2.5, and 6.0 meter respectively. Additionally a normally distributed random height shift *r* with expectancy zero and a standard deviation of 30cm was added to the shift in z:

[1] Writing f_x in place of df/dx, and f_y for derivative after y, the surface normal vector of a surface (x,y,f(x,y)) is (f_x, f_y, -1). In case 3 the surface normal is f_x, C*f_x, -1), for a constant c, and in case 4 (f_x, C-f_x, -1). In the third case all normals are orthogonal to (C,-1,0), in the forth case, they are all orthogonal to (1,1,C). In both cases, the Gaussian image of the surface (i.e. its normal vectors plotted on the unit sphere) are a great circle, and therefore the surface is a general cylinder.

$$H(x, y) = G(x+7.5, y+2.5) + 6.0 + r \tag{4}$$

Figure 1: The surface used for testing the terrain matching. The red points are the locations of the test points. The y-axis points to the right in this view.



The matching between the two height models was performed with a patch size of w=10 by 10 pixel, corresponding to an edge length of 50m. Test points were laid out in a regular grid of 10 pixels, i.e. every 50m, and terrain patches centered on those points were matched onto each other. The terrain model and the location of the test points can be seen in Figure 1.

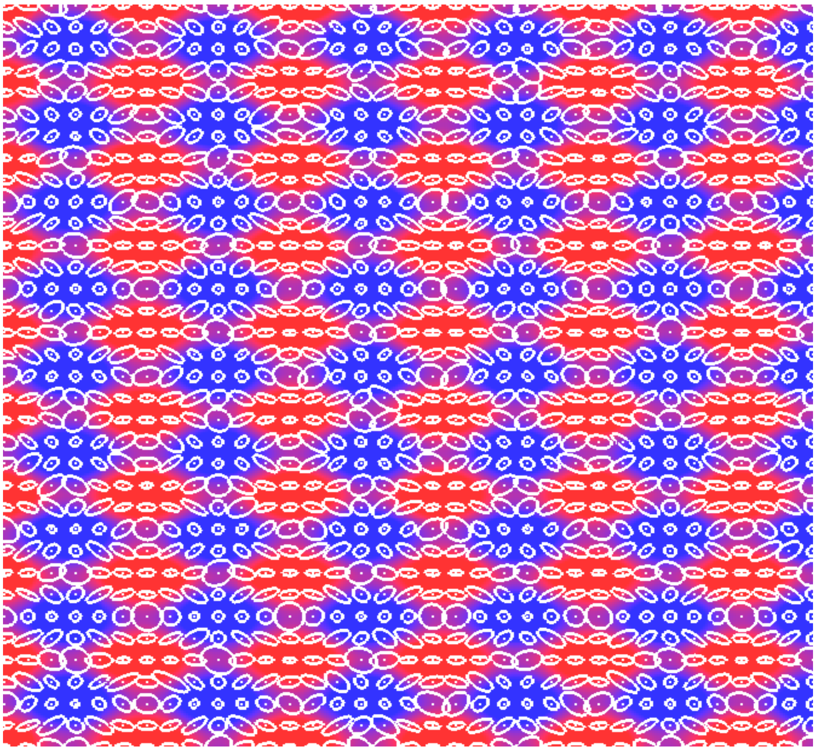
Before adjustment, the average height difference at the test points was -6.5m, reaching from –10.8m to –2.4m. Matching was performed independently for each of the 1225 test points. The unknowns Δx, Δy, Δh show the following distribution:

Table 1: Statistics from experiment 01.

	average	Std.dev.	minimum	maximum
Δx [pixel]	1.51	0.17	0.75	2.38
Δx [m]	7.53	0.86	3.74	11.89
Δy [pixel]	0.48	0.28	-1.09	2.34
Δy [m]	2.41	1.48	-5.45	11.18
Δh [m]	6.02	0.47	2.70	8.83

As it can be seen, the displacement in the x-direction was – on average – estimated correctly. In this direction the surface has stronger curvature. The displacement in y-direction was underestimated a little bit more by 0.02 pixel or 9cm. This is an effect of the noise introduced when generating the second terrain model. The height offset of 6m is estimated, on average correctly, and the standard deviation of this estimate is 47cm, but it has to be considered, that 30cm noise were added when generating the second terrain model.

Figure 2: Gaussian curvature of the test surface and error ellipses of the horizontal shifts for the test points, shown with an enlargement factor 50. As with the previous image, the y-axis points to the right.



Error ellipses of the horizontal offset parameters with a magnification factor of 50 can be seen in Figure 2. The background in this figure shows the gaussian curvature of the surface. Red areas correspond to elliptic surface regions and blue areas to hyperbolic regions. In the parabolic regions, the error ellipses are elongated and the major axis points in the direction of the smaller principle curvature. In the hyperbolic regions the error ellipses are more isotropic. Near to the regions, where one of the principal curvatures and therefore also gaussian curvaure is zero, the error ellipses are larger. The reason is that the condition of the adjustment system is worse, because the columns of the design matrix are approaching the case of linear dependency. The 2 points for which no solution was found are also situated in these regions of low curvature.

To demonstrate the effect of different terrain and data characteristics, different versions of the above test will be presented now. Increasing the wavelength of the "hills" by a factor two changes the terrain elevation function to $G(x,y)=30*\sin(x/120)*\cos(y/200)+y*20/100$. This decreases the slopes, from 50% to 25% in x- and 35%- in y-direction. Maintaining the window size of 10x10 pixels, this leads to less variation in height in the patch. The matching results become worse, and for 13 points the system does not converge within 200 iterations and the convergence criterion of a maximum shift of 0.001 pixel in Δx and Δy.

Table 2: Statistics from experiment 02.

	Average	Std.dev.	minimum	maximum
Δx [m]	6.73	3.40	-11.77	22.50
Δy [m]	1.73	4.54	-14.64	21.11
Δh [m]	6.13	1.18	-0.95	11.69

Increasing the patch size to 20x20 pixels compensates for the effect of reduced terrain variation. With this patch size and the terrain function with the increased wavelength, the number of not successful matches reduces to two. The average values are as good as the ones from the original example, but the show a slightly stronger variation.

Table 3: Statistics from experiment 03.

	average	Std.dev.	minimum	maximum
Δx [m]	7.46	0.93	1.75	11.39
Δy [m]	2.45	1.54	-5.86	11.09
Δh [m]	6.00	0.37	3.10	8.78

Increasing the slopes again by changing the overall height extent but maintaining the longer wavelength leads to G(x,y)=60*sin(x/120)*cos(y/200)+y*20/100 as the elevation function. With the patch size of 10x10 pixels this leads again to flatter patches. Geometrically this can also be described as maintaining the original terrain, but decreasing the patch size by a factor two.

For this example the least squares adjustment did not converge in three cases. The results are worse than for the original case, but better then the first variation with increased wavelength.

Table 4: Statistics to experiment 04.

	Average	Std.dev.	minimum	maximum
Δx [m]	7.20	2.16	-6.35	16.49
Δy [m]	2.07	3.23	-21.68	15.18
Δh [m]	6.05	1.15	0.55	12.96

In this case the patch size has to be increased to 15x15 pixels to compensate for the effect of less variation. Again, no solution was found for three patches.

Table 5: Statistics to experiment 05.

	Average	Std.dev.	Minimum	maximum
Δx [m]	7.49	0.94	2.75	12.49
Δy [m]	2.34	1.58	-6.23	8.90
Δh [m]	6.02	0.55	2.89	9.91

Taking the original example and increasing the random noise from 30cm to 60cm the results become, naturally, worse. The increase in noise has no influence on the number of successfully matched points, a solution is found for each point. The average values for the shifts are within 2cm, 7cm, and 9cm for the position and the height, respectively, but their standard deviations become much higher, by a factor 2 two.

Table 6: Statistics to experiment 06.

	average	Std.dev.	minimum	maximum
Δx [m]	7.42	1.77	-0.60	15.81
Δy [m]	2.17	2.87	-16.46	16.90
Δh [m]	6.09	0.99	1.28	15.14

To compensate for the effect of increased noise, the window size has to be enlarged to 13x13 pixels to compensate for the influence of the noise. On average the values are estimated better, but the standard deviation is slightly larger.

Table 7: Statistics to experiment 07.

	average	Std.dev.	minimum	maximum
Δx [m]	7.51	0.92	3.31	11.17
Δy [m]	2.44	1.62	-6.87	9.30
Δh [m]	6.01	0.53	2.86	10.46

Summarizing it can be said, that the effects of increase in noise or decrease in terrain variation can be compensated with increased window size. Of course, this result is in accordance with expectation and experience from image matching.

4 COMPARISON OF BRAZILIAN MODEL AND SRTM DATA

4.1 Brazilian Model

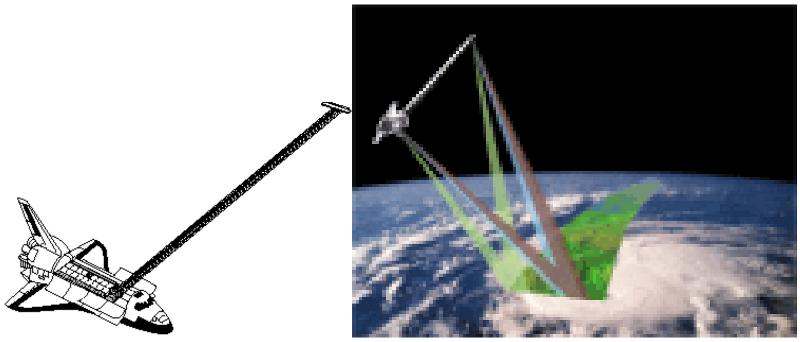
In Brazil, the surface behaviors are planes and mountain areas showing a mix of landforms, including some broad areas of consistent topographic patterns. The complete mapping and updating of landscape is a difficult task due its extensive extension. The IBGE (*Instituto Brasileiro de Geografia e Estatística*), DSG (*Diretoria de Serviços Geográficos*) are responsible official institute to provide DTMs. Usually, the DTMs data are captures by tachymetric, GPS measurements, and photogrammetry process, but nowadays, also in Brazil, LIDAR techniques are being used. Actually, other institutes of research are generation DTMs data.

4.2 Shuttle Radar Topography Mission (SRTM)

The Shuttle Radar Topography Mission provides a new class of digital terrain models acquired by spaceborne radar. Its data were acquired within 11 days because the radar system used was actively scanning the earth's surface independent of darkness or cloud cover. Between 2000 February 11 and 22, two antenna pairs operating in the microwave C- and X-bands (X-band use a shorter wavelength (3.1 centimeter) and high energy, and C-band a longer wavelength (5.6 centimeter) with medium energy) were simultaneously recording data of the entire more than 80% land mass of the earth between 60^0 N and 57^0 S (Gamba et al, 2002).

To acquire topographic data with single pass across track interferometry, the SRTM payload was outfitted with two radar antennas. One antenna was located in the shuttle's payload bay, the other on the end of 60 meters mast that extended from the payload pay once the Shuttle was in space. The figure 3 presents the localization of two antennas.

Figure 3: Localization of two antennas in the mission (http://www2.jpl.nasa.gov/srtm/mission.htm).



The SRTM use means of InSAR providing two sets of measurements, one in C-band and another one in X-band. Each data take includes an orthorectified SAR image and the corresponding DTM. The inboard SAR system had been in space twice already in 1994, during the Shuttle Radar Laboratory Mission SRL-1 and SRL-2, so that the newly acquired data can be used for change detection purposes (Rabus et al, 2003). The C-band data covering an area of 119 million km^2 are being processed by NASA (Pessagno, 2000) and the X-band data that cover approximately 58 million km^2 are processed by DLR (Rabus et al, 2003).

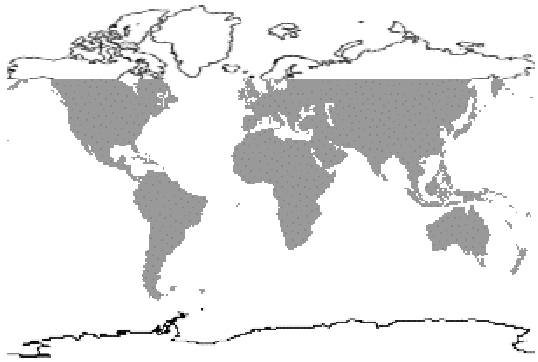
The DTM is provided in geographic coordinates, the elevation value is given in meters, WGS84 (World Geodetic System-84) is used as horizontal and vertical datum. Due to some drawbacks of radar imaging, the system does not allow a satisfactory accuracy of all objects. The results acquired by SRTM are degraded due to effects of perspective, shadows and occlusions.

The DTMs accuracy requirements are ± 30 m absolute and ± 15 m relative vertical accuracy. The relative accuracy describes the error in a local scale while the absolute value stands for the error budget throughout the entire mission (Gamba et al, 2002).

4.3 Project for Comparison

The use of SRTM data motived the development of the applications for compare his with DTMs in Brazil obtained by different techniques or sensors, such as, Photogrammetry and LIDAR. For South America the SRTM data was resampled with 90 meters of resolution approximately, to be more precise, the data is available in a 3 arc seconds grid. The process runs automatically anyway, so we could be to use a grid of 2km by 2km the displacement vector to comparison. Figure 4 presents the earth's surface mapped by SRTM including the Brazilian region.

Figure 4: Earth's surface mapped by SRTM (http://www2.jpl.nasa.gov/srtm/coverage.html).



The radar data products currently being released are generated from preliminary DTMs. Products made from the preliminary DTMs are uncalibrated and are released with the understanding that they are merely "showpiece" products. It is expected to take two years to generate the final precision DTM (http://www2.jpl.nasa.gov/srtm/nasa_release_july.html).

From perspective of the data simulated we intend to present an overview of the mission and in future to compare DTMs data acquired by LIDAR (or Photogrammetry) and SRTM to validate the motion compensation between them. This will provide the evaluation of the DTM product quality from SRTM for the Brazilian models.

For the possibilities to compare the current Brazilian elevation model with the SRTM model DTMs derived by LIDAR or by the photogrammetric process will be used. The study area for investigation will be the entire country, but the extension of study area will be estimate further. In case the photogrammetric process is used, the DTMs will be acquired by image matching techniques with a specific resolution, according to the resolution of the SRTM data.

The aim of the project for comparison is mainly presents an evaluation of altimetry data quality DTM using matching techniques and the problems with motion compensation of InSAR related, geocoding procedure, incompatible of resolutions, problems within orbit determination of SRTM and discusses the parameters in relationship to the Brazilian model.

The methodology that will be employed use the techniques of least squares area based matching of surfaces as described in this paper. The window size has to be chosen depending on the quality of the reference data. In Section 3.1 the effect of varying the window size has been shown. For each point in a regular grid the displacement vectors and the statistical quantities (correlation coefficient) will be derived.

Analysis of this vector field gives insight into the absolute vertical and horizontal displacement, i.e. the average offset, and relative vertical and horizontal accuracy form the SRTM to the Brazilian models. The applications to this methodology could be evaluation of DTMs generated by SRTM to Brazil, complex morphology of the canopy surface, analyze the characterization of SRTM in urban areas etc.

5 DISCUSSION AND CONCLUSIONS

In this paper the method of least squares matching, known from digital image processing, was applied to digital terrain models. It is possible to compare two grid- or raster-models and derive horizontal and lateral offsets between those two. If one of the models is of superior quality, this allows detecting errors in the second one. Going beyond the z-offsets determined in difference models, also horizontal errors, i.e. dislocation of terrain features, can be determined.

Matching has been applied to synthetic data with a transformation model that included shifts only. More elaborate models can account for rotations and scales differences additionally. However, as it has been shown for the transformation including only shifts, the terrain must not have the shape of a generalized cylinder, or equivalently have zero Gaussian curvature. With more unknowns, i.e. with more elaborate transformation models, the terrain has to show more variation, too. Using an affine transformation model for planimetry and a linear model for height transformation, mountain ridges with parabolic cross sections introduce a linear dependency between the scale in cross sections direction and the height scale. Singularities in matching, however, do not have to be considered as a problem. They rather give an indication, that not all parameters of the transformation can be estimated. If the terrain has the form of an inclined plane, it is not possible to say if there is a height or a planimetric error.

Detecting the singularites and the parameters causing them gives therefore more information on the comparison process. The accuracy of the estimated transformation parameters serves this purpose, too. In the synthetic example it was shown that error ellipses are larger in areas of less curvature.

Matching terrain patches has been shown for terrain models of equal resolution. Also different resolutions can be taken into account, matching a finer model to a coarser model. Observations should in this case be made for every height (every pixel) of the finer model, but the question arises if the gradients should be computed from the finer or the coarser model. As it is known from image matching, the (variation of the) gradients determines the accuracy of matching. Gradients should therefore be taken from the less noisy source.

An alternative approach for matching two models of different resolution is to resample one model in order to bring both models to the same resolution. If the coarser model is sampled denser, with bilinear or cubic convolution resampling, correlations in the heights are introduced. This has the consequence, that the sigma a posteriori of the least squares adjustment is too optimistic. This is already the case when matching between patches of the same resolution, because of the resampling necessary for the transformation, but aggravated in the described case.

The synthetic example presented showed that it was possible to recover systematic errors in height and planimetry. The systematic errors introduced were constant for the whole area, in order to allow computing mean and standard deviation of the estimated errors. On average they were estimated correctly, but less height variation or an increase in noise makes the results worse. This can be compensated by an increase in patch window size.

The C-band processed by NASA-JPL from SRTM provided a global DTM data recovering almost every earth's surface including Brazil. Its data has been used for researches and presents peculiarities important. The approaches showed the efficient cover of the earth's surface but with limitations of resolution.

The growing interest in SRTM data motives a project for comparison of topography between SRTM and Brazilian model data to obtain an evaluation of SRTM data acquired over the Brazilian region. The project future will characterize a collaboration between UFPR (Federal University of Parana) and TU Delft (Delft University of Technology).

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