QUALITY ASSESSMENT AND VALIDATION OF DIGITAL SURFACE MODELS DERIVED FROM THE SHUTTLE RADAR TOPOGRAPHY MISSION (SRTM)

Andreas KOCH, Peter LOHMANN
University of Hanover, Germany
Institute for Photogrammetry and Engineering Surveys
koch@ipi.uni-hannover.de
lohmann@ipi.uni-hannover.de

KEY WORDS: Accuracy, Land use, Land cover, Validation, Digital Terrain Model, Digital Surface Model.

ABSTRACT

The first mission using space-borne single-pass-interferometry was launched in February this year – the Shuttle Radar Topography Mission (SRTM). The goal of this mission has been to survey the Earth's surface and generating a homogeneous and dense elevation data set of the entire world. Antennas with two different wavelength were used. One of the hardware components was the German / Italian Synthetic Aperture Radar X-band antenna (X-SAR).
In this paper we report on an attempt to check the quality and accuracy of the elevation data derived from the X-band instrument of SRTM. First of all possible error sources influencing the data quality and accuracy will be described and the effects of these errors will be demonstrated.
Reference data of a well known test site will be used to assess the data and to derive quality measures. The area with a size of 50x50 km² is situated in Germany a few kilometers south of Hanover. Reference data are being made available by the Surveying Authority of Lower Saxony, Germany (Landesvermessung und Geobasisinformation Niedersachsen, LGN Hannover). The Digital Terrain Model of LGN (ATKIS DGM5) is said to have an accuracy of about ±0,5 meters. Also Trigonometric Points, which are the base of the fundamental geodetic network of Germany, are being used as reference data.
The tool used for assessing the data is a spatial transformation. As a result 7 parameters are being obtained, which describe the position, orientation and a scale of the SRTM elevation data with respect to the reference data. To obtain influences of terrain slope, the orientation of the terrain with respect to the sensor position, vegetation, land use and land cover the test side is divided into several subareas. The accuracy and quality of the data as a function of these parameters will be calculated.

1 INTRODUCTION

Six years after the successfull Shuttle Radar Lab (SRL) mission, the SRTM mission was flown in February this year using the SIR-C / X-SAR hardware again. For the first time the components comprised a space-borne single-pass-interferometric Synthetic Aperture Radar (InSAR). InSAR allows to obtain information about the third dimension of the Earth. Therefore, the standard product of InSAR is a Digital Elevation Model (DEM). The advantage of using radar is the independence of weather conditions and daylight. In this way it is possible to produce a homogeneous and high resolution DEM. The advantage of using single-pass-interferometry is the good correlation between the two radar images received from the antennas because there is no time difference between image aquisition.
To assess the quality and accuracy of the elevation data it is necessary to understand the principle of SRTM technique and the possible error sources of this method (Chapter 2 and 3). To derive accuracy values and quality measures a spatial transformation will be used. The implementation of this method is described in Chapter 4. Also the influence of different parameters and the derivation of quality measures as a function of these parameters will be illustrated.

2   THE SHUTTLE RADAR TOPOGRAPHY MISSION (SRTM)

2.1   Principle of SRTM

Many publications deal with the technique and the applications of SAR (Leberl, 1990) and InSAR (Hartl, 1994; Schwäbisch, 1995). The InSAR system of SRTM used two different wavelengths. The American C-band system operates with a wavelength of $\lambda = 5,6$ cm, the wavelength of the German / Ital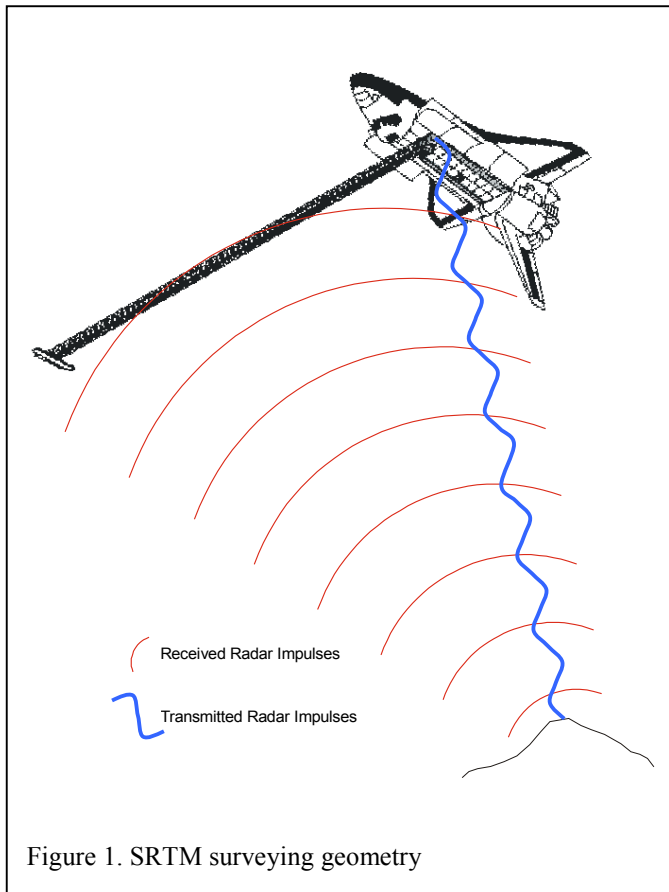ian X-band is $\lambda = 3$ cm. Two antennas establish the single-pass-interferometer of SRTM. The main antenna with a length of 12 meters is located inside the cargo bay of the Space Shuttle Endeavour. It transmits and receives microwave impulses (Figure 1). The second one, the outboard or slave antenna, is fixed at the end of the 60 meter long mast and only receives data. The mast realizes the interferometric baseline. Since knowledge of the precise length, location and attitude of the baseline is critical for InSAR a large variety of sensors is used to monitor any baseline changes. Light Emitting Diode (LED) targets are 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 are used by the Electronic Distance Measurement Unit on the AODA. Global Positioning System (GPS) antennas are 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 Earth's rotation the Shuttle has surveyed the ground strip after strip. With C-band it was possible to cover the Earth's surface without any holes between the strips. The C-band interferometer was operated in the so-called ScanSAR mode. In this mode the antenna beam is electronically steered towards different elevation angles in a repeated stepwise fashion. Thus, four narrow but overlapping subswaths were imaged

Figure 1. SRTM surveying geometry

quasi simultaneously to form the 225 km wide swath (Bamler, 1999). The expected relative vertical accuracy of C-band data is about 10 meters.

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 45 kilometers. The advantage of X-band is the expected higher relative vertical accuracy of about 6 meters resulting from the shorter wavelength. The disadvantage of X-band is the incomplete coverage. There are gaps between the swaths which become smaller with growing latitude.

2.2   SRTM standard data products

As mentioned before, the Synthetic Aperture Radar X-band hardware is a development of Germany and Italy. This paper deals with the assessment and validation of the data generated with X-SAR. The standard data sets will be available as Digital Elevation Models:

X-band **ITED-2** DEM: 1 arcsec **I**nterferometric **T**errain **E**levation **D**ata, Level **2**

The raw data will be processed and distributed by DLR (German Aerospace Center), except for data over Italian territory, which will be provided by Italian Space Agency ASI.

The DEM will be distributed in regular form. This means the height values will have a regular spacing in latitude and longitude of one arcsec. This value corresponds to approximately 30 meters at mid latitude. The coordinates relate to the geocentric World Geodetic System 1984 (WGS84), all values are ellipsoidal. In this paper the SRTM elevation product is called Digital Surface Model, because the transmitted impulse reflects at the upper vegetation, buildings also are integrated into the data set. In contrast, the reference Digital Terrain Model describes the terrain without points on vegetation or buildings.

Additionally, radar images are available in a slant range, ground range or geocoded representation. The geocoded radar images are in Universal Transverse Mercator (UTM) map projection, the ellipsoid is WGS84, too.

3   ERROR SOURCES OF INSAR

Data sets like Digital Elevation Models, contain three different types of errors. *Blunders* are large vertical errors usually exceeding the maximum standard deviation (3 σ). This error type is caused by careless observations, misreading contours or erroneous correlations. *Systematic errors* are induced by procedures or systems and follow some fixed rule or pattern. They appear as scale, offset or tilt in the final DEM. After removal of blunders and systematic errors the remaining error distribution is caused by random errors (Gens, 1998).

To understand accuracy and quality of Digital Elevation Models derived by SRTM it is necessary to illustrate possible error sources. The uncertainties influencing the data can be divided into three groups. The first one characterizes the InSAR parameters during data acquisition. Here only those parameters are described which have a significant influence in generating the elevation: baseline length and orientation, phase, slant range and position of the antenna (Zink, 1999). The second group deals with the processing steps after acquiring the raw data and the last group contains the influences of vegetation, land cover etc. The influences of the parameters of the last group will be investigated in Chapter 4.
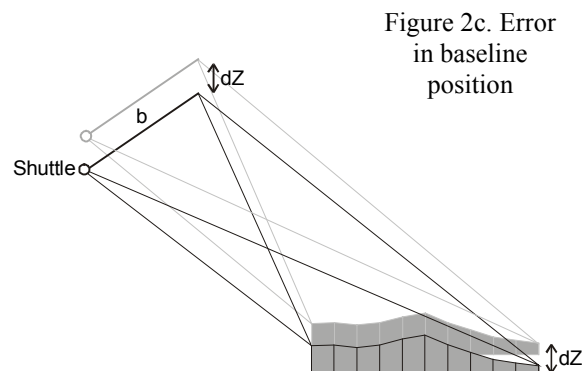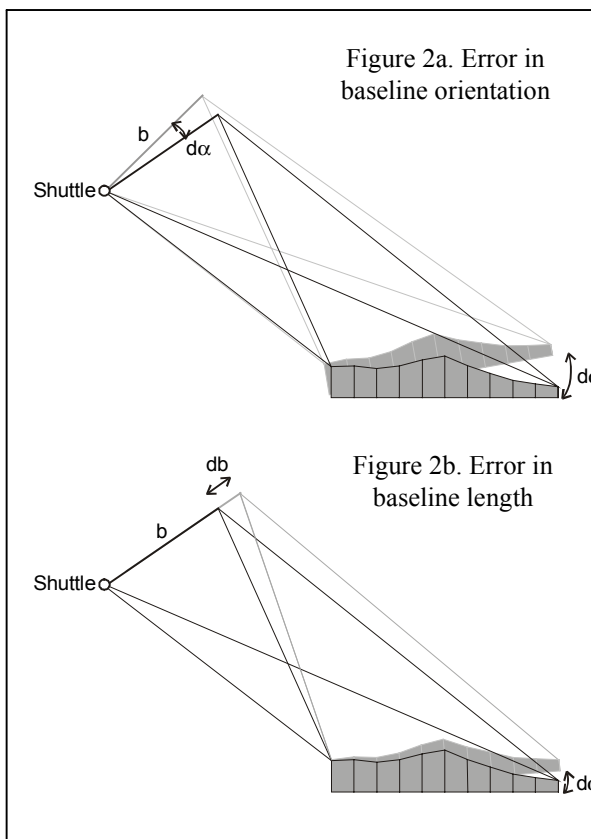
3.1   Data acquisition

As mentioned in Chapter 2, many sensors are used to obtain any changes in baseline length, orientation and position. Additionally the data will be calibrated to reduce systematic errors in the measurement unit. Nevertheless, remaining errors have to be determined.

Table 1 represents the error in elevation Δh caused by errors of the InSAR parameters. Any errors in the determination of the baseline orientation will cause a tilt of the DSM by the same angle (Figure 2a). An error of 1 arcsec causes an elevation error of 1,5 meters at a ground range of 300 kilometers. The accuracy expected for the distance

Error source	Δh [m]
baseline tilt angle [arcsec^{-1}]	1,5
baseline length [mm^{-1}]	-0,5
platform position [m^{-1}]	1,0
phase [deg^{-1}]	0,5
slant range [m^{-1}]	-0,5

Table 1. Changes in elevation as a function of system parameters, ground range: 300 km (Zink, 1999)

Figure 2a. Error in baseline orientation

Figure 2b. Error in baseline length

Figure 2c. Error in baseline position

measurement of the interferometric baseline is approximately 3 millimeters. This value causes a height error of 1,5 meters (Figure 2b).

Uncertainties in the determination of position will also have negative effects in the DSM. The errors occur in the final DSM as shifts in the same order of magnitude (Figure 2c).

The most critical part of the X-SAR electronics is the boom cable where very high temperature variations exist. This effect leads to phase variations in the order of several degrees. In addition possible range delay and time tag errors cause image shifts in slant range and azimuth direction.

Atmospheric inhomogenities will influence the phase measurement and consequently the range between the antenna and the target. In case of repeat-pass-interferometry different atmospheric conditions may lead to decorrelations between the received signals at the end of the interferometric baseline. In case of SRTM (single-pass-interferometry) and its small baseline both antennas "look" through the same atmosphere. The resulting errors will only be in the order of a fraction of a phase cycle.

3.2 Processing of acquired data

The processing of the acquired data is another important factor influencing the quality of the final DEM. Several complex processing steps are needed to obtain the elevation. First of all the co-registration estimates the optimal shift of one image called slave image with respect to the master image for a maximum coherence between slave and master image. No reliable results can be achieved if the co-registration is not sufficient. The interferogram is the product of the complex SAR values of the slave image and the complex conjugate of the master image, i.e. the amplitudes of the corresponding pixels are multiplied and the differences of the phase values for each point in the image is calculated. The information is given modulo 2π, the ambiguity solution is solved by phase unwrapping. Finally, the phase has to be converted into height. Here, the knowledge of precise orbit parameters and reference points, respectively, is needed. Any error in one of the processing steps will cause an error in the interferometric phase.

An additional a transformation is necessary because of the different coordinate systems of the reference data and the data to be assessed. The geoid undulation has to be considered as well, since our reference data are not ellipsoidal heights but refer to the geoid.

4   QUALITY ASSESSMENT OF DIGITAL ELEVATION MODELS

4.1 Requirements to the reference data

The use of different types of reference data is possible. The accuracy and quality should be at least one order better than the data to be evaluated. In case of SRTM the expected vertical accuracy for the X-SAR data is about 15 meters absolute and 6 meters relative. That means reference data with a precision of a few decimeters up to one meter is needed.

Such data is made available by the Surveying Authority LGN. The LGN distributes the ATKIS DGM5, a Digital Terrain Model with an accuracy of about ± 0,5 meters. The data set is in regular form, the grid width is 12,5 m. Also breaklines and morphological structures are present. Trigonometric Points (TP's), which are the fundamental points of the Surveying Authorities of Germany, are also available. The accuracy of these points is $\sigma_{X,Y}$ = 1-2 cm and σ_Z = 3 cm. The density is about 1 TP per 2 km².

As mentioned before, the SRTM elevation data represent a DSM, whereas the reference data describe the terrain. These considerations lead to the problem of comparing two data sets with different elevation definitions. To solve this problem information about the actual land cover and height of 3D objects such as buildings and vegetation is neccessary. A Digital Landscape Model (ATKIS-Basis DLM) of LGN and satellite images can provide the land cover and land use. The height of the 3D objects will be measured by photogrammetry. Additionally terrestrial measurements of the actual vegetation and settlement status have been carried out parallel to the SRTM mission. In the following the strategy of using the reference data and the assessment method of the ITED-2 data is described.

4.2 The test site

The chosen test site is located in the south of Hanover, Germany, and has a size of 50x50 km². Figure 3 represents the Digital Terrain Model DGM50 of the Surveying Authority LGN of the area of investigation. The data is in regular form, the grid width is 50 meters. There are approximately 1500 TP's in our test site.

The north-east region covers the area of the Hanover EXPO 2000. Different other types and structures of human settlements are distributed over the area. The South-West is characterized by hilly terrain with different expositions to the sensor. The maximum height difference is about several hundred meters. A large part of the region is covered with foliage and coniferous forest. Some of the agriculture fields are without vegetation, elsewhere corn and grass specify a

Figure 3: Color coded image of the Digital Terrain Model DGM50 of the test site
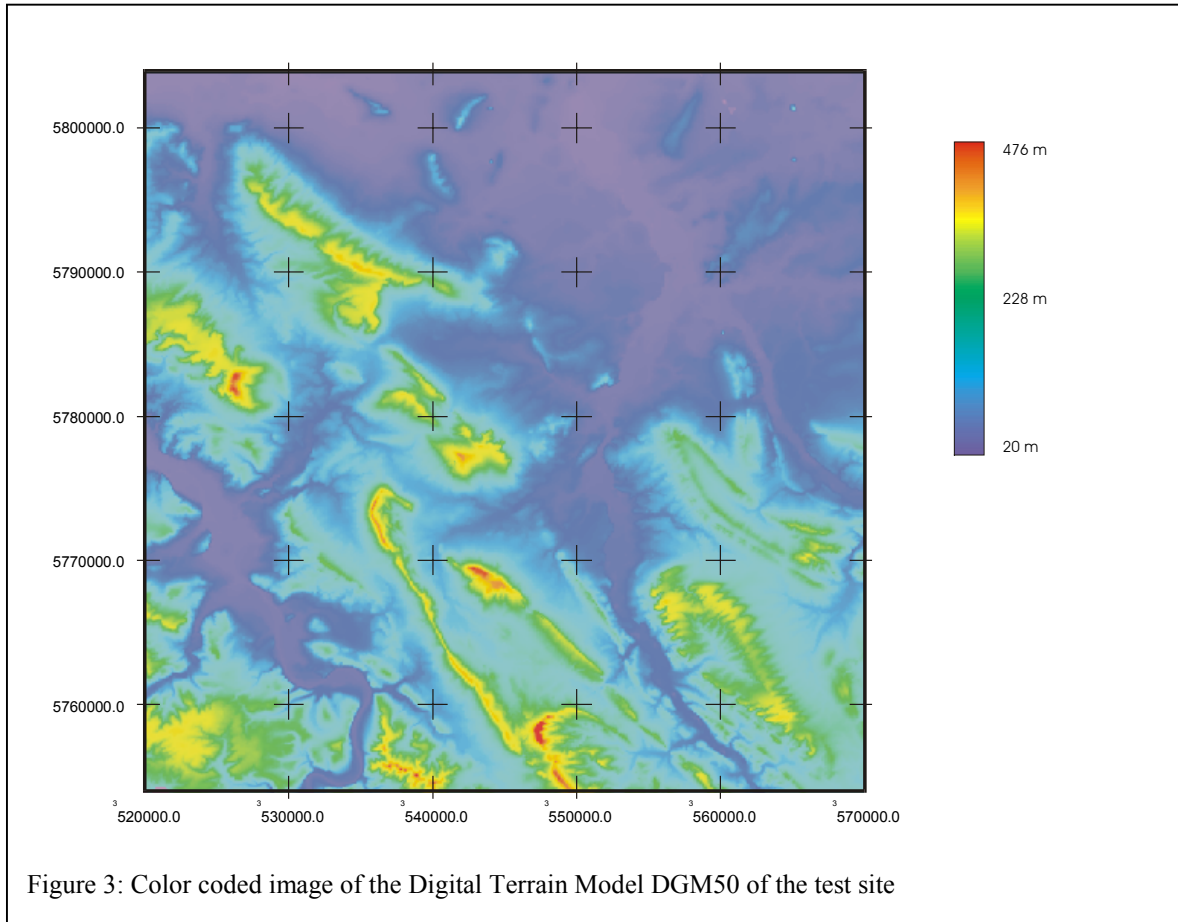
low vegetation canopy.

4.3 Accuracy investigation method

4.3.1. Spatial transformation. A spatial transformation allows the comparison of two three-dimensional data sets, e.g. Digital Terrain Models. Because the Trigonometric Points are regularly distributed within our test site, these reference data can be used to analyze the position, orientation and scale of the SRTM Digital Surface Model with respect to these higher level reference data. In order to obtain, these TP's have to be identified in the SRTM radar imagery and / or the DSM, which will only be possible with a limited accuracy in planimetry. Additional planimetric control points taken from ATKIS or topographic maps and representing objects which can be well identified in the SRTM imagery can alliviate this problem to some extent. The mathematical equation describing the context reads as follows:

$$X_{SRTM} = X_0 + m \cdot R(\omega, \varphi, \kappa) \cdot X_{TP}$$

(1)

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{SRTM} = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} + m \cdot R(\omega, \varphi, \kappa) \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{TP}$$

X_{TP} contains the coordinates of the TP. X_{SRTM} represents coordinates of the SRTM data set which are considered as observations. The vector X_0 contains shifts in X, Y and Z. m is a scale factor, the matrix $R(\omega, \varphi, \kappa)$ is the rotation matrix of the coordinate axes (see also Figure 4). X_0, m and $R(\omega, \varphi, \kappa)$ are unknowns.

Using the identical points, equation 1 represents the observation equation of a least squares adjustment.

The residuals being considered, are ($\hat{X}_{SRTM}$ are the adjusted observations, X_{SRTM} are the given values)

$$v_{SRTM} = \hat{X}_{SRTM} - X_{SRTM} \tag{2}$$

and the problem becomes to find a solution such that

$$v^T v \Rightarrow minimum \tag{3}$$

The observation equations express the dependency of the measured coordinates as a function of the seven unknown.

$$\hat{X}_{SRTM} = X_{SRTM} + v_{SRTM} = \varphi(\hat{Y}) \tag{4}$$

$$\hat{Y}^T = \begin{pmatrix} \hat{X}_0 & \hat{Y}_0 & \hat{Z}_0 & \hat{m} & \hat{\varphi} & \hat{\omega} & \hat{\kappa} \end{pmatrix}$$

As a result the seven unknown parameters (3 shifts, 3 rotations, 1 scale factor) caused by errors of the SRTM data, the processing and exterior influences will be obtained. Additionally the residuals of the observations, i.e. of the SRTM DEM, will be computed.

If a local coordinate system is introduced with its origin within the Shuttle, the differentiation between rotation and shift is impossible due to the high correlations between the respective unknowns. For this reason a local coordinate system with its origin in the test area is used.
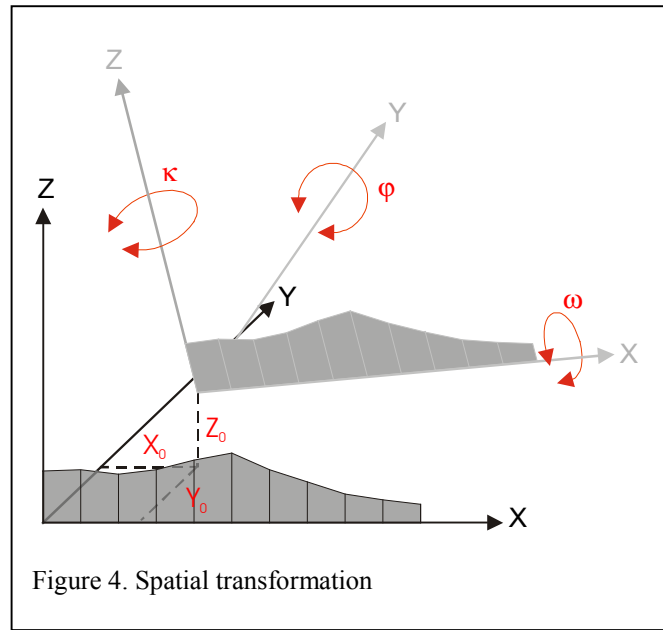

Figure 4. Spatial transformation

Assuming that only a shift in Z or a vertical shift and rotations ω and φ are to be determined, equation 1 can be simplified accordingly. In this case the TP's and additional control points do not have to be identified in the radar imagery, and the problem becomes similar to the one of using a DTM for exterior orientation of a photogrammetric block (Ebner et al, 1988).

The distribution of the points to be compared is of course of high importance. The TP's have to be well distributed all over the whole area. Besides they should be representative for the terrain, i.e. it has to be checked if the points are covered by vegetation or buildings. In this case the results are influenced by these local offsets. Consequently it is necessary to eliminate these points.

4.3.2   Local systematics. Local systematic errors can be caused by buildings, vegetation canopy, land use or land cover. A possibility to recognize such errors is the covariance analysis or the calculation of relative standard deviations. The normed covariance is a value for the description of the dependency of one difference from another as a function of the point distance. The expectation value for the covariance is identical to the correlation coefficient. If neighbored points have nearly the same differences, they are usually correlated stronger. The difference vectors have the same tendency. If the differences are normal distributed without any systematic error, the signs of the differences alternate. As a result, the covariance value tends towards zero.

Similar to the covariance, the relative standard deviation will be computed by the combination of two differences. Caused by positive correlation the relative standard deviation for neighbored points is usually smaller for points close to each other than for points having larger distances. For larger distances the expectation value of the relative standard deviation is identical to the absolute standard deviation. If any local systematic error occurs, the covariance is high and the relative standard deviation is low.

In order to determine the influences which local systematic errors cause, it is necessary to divide the test site into several subareas which characterize and represent the mentioned parameters. In case of our investigations twenty subareas with a size of 2x2 km² were selected. The information describing the terrain is available with the help of a Digital Landscape Model of the LGN (ATKIS Basis DLM). A DLM divides the topography into several object classes like settlement, vegetation, and public transport. These classes are also divided into object groups, e.g. vegetation area. The next level describes the group more precise, forest in our example. Attibutes further describe the individual objects, they divide the forest into deciduous, coniferous or mixed forest.

The contents of the DLM will be suplemented by satellite imagery. It is possible to perform a multispectral classification to obtain the actual vegetation or land use. But the most important method to revise the DLM is the terrestrial data acquisition in the terrain, carried out simultaneously with the SRTM mission.

The DLM and the acquired data will be integrated into a GIS (Geographic Information System). Different layers will be generated, so that it becomes possible to obtain information about the influences of the mentioned parameters. The statistical analysis like covariances and relative standard deviations and the selected vegetation or land cover will be merged. As a result the accuracy and quality measures will be obtained as a function of these parameters.

The calculation of a value which describes the quality of a DEM can also be done by including factors like terrain slope and breakline effects, i.e. factors which characterize the morphological structure of the terrain. The direction of the inclination and the orientation of the terrain in relation to the look direction of the sensor is very important, since the local incidence angle can be a factor influencing the data quality and accuracy.

5   FINAL REMARKS

Up to this moment (March 2000) the SRTM ITED-2 elevation data are not yet available. Because of the repeated postponements of the mission the space shuttle Endeavour launched late in February this year. The data has been recorded and after the landing the calibration phase started. When this part is finished the assessment and validation of the data will begin.

For this reason no actual results can be presented in this paper. Only the processing steps to assess the data were explained. Possible error sources and their effects on the data quality and accuracy were described.

6   ACKNOWLEDGEMENT

REFERENCES

AEC-Able Engineering Company, Inc. of Goleta, California, 2000. Description of mast hardware of Shuttle Radar Topography Mission (SRTM),
http://www.aec-able.com/corporate/srtm.htm (13.3.2000)

Bamler, R., 1999. The SRTM Mission: A World-Wide 30 m Resolution DEM from SAR Interferometry in 11 Days, in: D. Fritsch / R. Spiller (Eds.), Photogrammetric Week 1999, Wichmann Verlag, Heidelberg, pp. 145-154.

Ebner, H., Strunz, G., 1988: Combined point determination using digital terrain models as control information, IntArchPhRS, Kongreß Kyoto, Kommission III, Vol. 27, Part B11, pp. III-578-587.

Gens, R., 1999. SAR-Interferometry: Software, Data Format and Data Quality, Photogrammetric Engineering & Remote Sensing, Dec 1999, pp. 1375-1378.

Gens, R., 1998. Quality Assessment of SAR interferometric data, Doctoral thesis, University of Hanover, Germany, Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover, Nr. 226.

Hartl, P., Thiel, K. H., Wu, X., Xia, Y., 1993. Practical Application of SAR-Interferometry, Experiences made by the Institute of Navigation, in: Proceedings Second ERS-1 Symposium, Hamburg, pp. 717-722.

Hounam, D., Werner, M., 1999. The Shuttle Radar Topography Mission (SRTM), ISPRS Joint workshop "Sensors and Mapping from Space 1999", Institute for Photogrammetry and Engineering Surveys (IPI), University of Hanover, Germany, CD.

Leberl, F. W., 1990. Radargrammetric Image Processing, Artech House, Morwood, MA.

Santitamnont, P., 1998. Interferometric SAR Processing for Topographic Mapping, Doctoral thesis, University of Hanover, Germany, Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover, Nr. 230.

Schwäbisch, M., 1995. Die SAR-Interferometrie zur Erzeugung digitaler Geländemodelle, Doctoral thesis, University of Stuttgart, Germany, DLR-Forschungsbericht 95-25, 125 p.

Zink, M., Geudtner, D., 1999. Calibration of the Interferometric X-SAR System on SRTM, Proceedings of the CEOS SAR Workshop '99, Toulouse, France, ESA.