ACCURACY ANALYSIS FOR DEM AND ORTHOIMAGES DERIVED FROM SPOT HRS STEREO DATA WITHOUT USING GCP

Peter Reinartz, Manfred Lehner, Rupert Müller, Manfred Schroeder
German Aerospace Center (DLR), Remote Sensing Technology Institute
PO Box 1116, D-82230 Wessling, Germany
peter.reinartz@dlr.de

Commission I/2

KEY WORDS: Stereoscopic data, image matching, orthoimages, DEM generation, DEM fusion, accuracy analysis

ABSTRACT:

ISPRS and CNES announced the HRS (High Resolution Stereo) Scientific Assessment Program during the ISPRS Commission I Symposium in Denver in November 2002. 9 test areas throughout the world have been selected for this program. One of the test sites is located in Bavaria, Germany, for which the PI comes from DLR. For a second region, which is situated in Catalonia – Barcelona and surroundings – DLR has the role of a Co-Investigator. The goal is to derive a DEM from the along-track stereo data of the SPOT HRS sensor and to assess the accuracy by comparison with ground control points and DEM data of superior quality. For the derivation of the DEM, the stereo processing software, developed at DLR for the MOMS-2P three line stereo camera is used. As a first step, the interior and exterior orientation of the camera, delivered as ancillary data (DORIS and ULS) are extracted. According to CNES these data should lead to an absolute orientation accuracy of about 30 m. No bundle block adjustment with ground control is used in the first step of the photogrammetric evaluation. A dense image matching, using very dense positions as kernel centers provides the parallaxes. The quality of the matching is controlled by forward and backward matching of the two stereo partners using the local least squares matching method. Forward intersection leads to points in object space which are then interpolated to a DEM of the region in a regular grid. Additionally, orthoimages are generated from the images of the two looking directions. The orthoimage and DEM accuracy is determined by using the ground control points and the available DEM data of superior accuracy (DEM derived from laser data and/or classical airborne photogrammetry). DEM filtering methods are applied and a comparison to SRTM-DEMs is performed. It is shown that a fusion of the DEMs derived from optical and radar data leads to higher accuracies. In the second step ground control points are used for bundle adjustment to improve the exterior orientation and the absolute accuracy of the SPOT-DEM.

1. INTRODUCTION

The derivation of digital elevation models (DEM) from along track stereo data from space has up to now only been possible with the German MOMS-2P (Müller et al. 2001) and the Japanese/American ASTER sensor on TERRA (Toutin et al. 2001). Both of them have lower resolution (15-18 meter pixel size) than the new HRS sensor on SPOT 5. HRS produces image stereo pairs with two optics looking forward and backward (±20 degrees) with respect to the nadir direction. The camera has a spatial resolution of 10 meter across track and along track, but a ground sampling distance of about 5 m along track for obtaining higher resolution of the parallaxes for the DEM generation. The swath of the HRS is 120 km (12000 CCD elements) and one acquisition sequence extends 600 km along track.

After the ISPRS Commission I Symposium in Denver in November 2002, the HRS Scientific Assessment Program has been established. This program gives the user community the opportunity to test HRS data, which are usually not available, for generating DEM and for comparison with other DEM generation methods. Further it should provide CNES an international scientific performance assessment of the HRS which will be taken into account for future programs. For the investigations 9 test areas around the world with corresponding PIs and co-investigators have been selected. Only those areas have been selected, where the PIs could provide a sufficient data set of ground control points and a high precision DEM for comparison and accuracy checking of the derived HRS-DEM.

The data which have been provided by SPOT IMAGE contain the following parts:

- 2 sets of 8 bit panchromatic image data (size 12000 x 12000 pixel = 120 km across x 60 km along track) of the Bavarian and Catalonian test area from two viewing directions in TIF format
- in the Catalonia area as well HMA and HMB data: 5 m x 5 m resolution panchromatic nadir looking channels of part of the test site (size 12000 x 12000 pixel = 60 km across x 60 km along track)
- XML-files containing all additional information regarding time synchronization, position (DORIS), attitude (star sensors and gyros), interior orientation
- text files containing information on the delivered data.

The data of Bavaria have been acquired on October 1st 2002 with a sun elevation of 38º and nearly no clouds. The data of Catalonia have been acquired on October 15th 2002 with a sun elevation of 39º and no clouds. The radiometric quality of the Catalonia images is superior to the Bavarian imagery.

The HRS-data have been received in July 2003. First results have been presented at the ISPRS Workshop High Resolution Mapping from Space, Hannover ’03 (Reinartz et al. 2003).

2. TEST AREAS AND GROUND REFERENCE DATA

The test area chosen by DLR is a region of about 40 x 50 km² in the southeastern part of Bavaria. The elevations range from 400 to 2000 meters in a mostly hilly, post-glacial landscape including some lakes and also mountains of the German Alps. This selection allows the comparison of DEM for different land surface shapes, including forest and steep terrain.

The ground reference data selected for this test area are the following (see also fig.1):

- Four regions have a grid spacing of 5 meters and an overall size of about 5 km x 5 km, derived from airborne laser scanning. The height accuracy is better than 0.5 meter.
- One region (area of Inzell, total: 10 km x 10 km, 25 meter spacing) consists partly of laser scanner data (northern part). The height accuracy is better than 0.5 meter.
  The southern part of the DEM is derived from contour-lines 1:10 000. The height accuracy is about 5 meter due to the mountainous area.
- A large region (50 km x 30 km) is covered by a coarser DEM with 50 meter grid spacing and height accuracy of about 2 meters, derived from aerial photogrammetry
- The exact locations of 81 GCP (fix points) are listed in a pdf document.

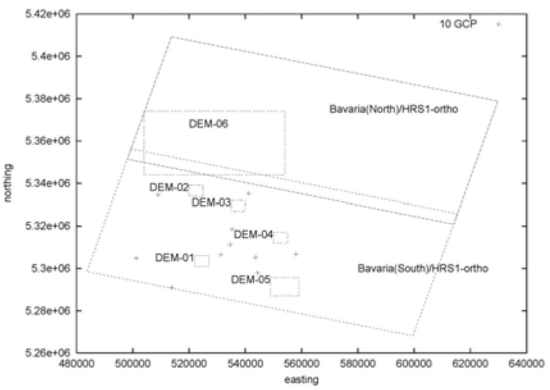

Figure 1. Location of the test area at the most southeastern part of Germany, location of the SPOT-HRS scenes with DEM reference sites and ground control points.

3. PREPROCESSING OF THE ANCILLARY DATA

The delivered SPOT 5 HRS Level 1A product consists of the image data in standard TIF format and the meta data in DIMAP format. The following information is extracted for each CCD array from the XML ancillary file for further processing:

- satellite ephemeris data containing position and velocity measured by the DORIS system every 30 seconds with respect to the ITRF90 (International Terrestrial Reference Frame 1990) system during the data take and at least four times before and after image data acquisition,
- corrected attitude data with respect to the local orbital coordinate frame measured by gyros and the star tracker unit ULS with 8Hz, the data are already corrected for different effects (Bouillon et al. 2003)
- look direction table for the 12000 CCD elements expressed within the sensor coordinate frame
- data used for time synchronization like line sampling period and scene center time.

According to the „SPOT Satellite Geometry Handbook“ (SPOT IMAGE 2002) Lagrange interpolation of the ephemeris data and linear interpolation of the attitude data are recommended to calculate the exterior orientation for each scan line. After transformation to a local topocentric system (LTS) with a fundamental point located at the center of the image scene, this serves as input for DLR’s processing software. For orthoimage production the exterior orientation is expressed in the Earth Centered Earth Fixed (ECEF) WGS84 Cartesian frame.

4. IMAGE MATCHING

Matching of the two images is performed purely in image space with DLR software. Details on this software are described in Lehner et al. 1992. It relies on a 7-step image resolution pyramid and applies intensity matching in two forms: normalized correlation coefficient for pixel accuracy and subsequent local least squares matching (LLSQM) for refinement to sub-pixel accuracy (for mass points 0.1 to 0.3 pixel standard deviation). Interest points are generated with the Förstner operator and the homologous points are searched for in the other image. Only points with high correlation and quality figure are selected as tie points for bundle adjustment (see chapter 7) and a less stringent criterion is valid for the usage as seed points for the subsequent Otto-Chau region growing procedure for dense matching (Heipke et al 1996). This local least squares matching starts with template matrixes of 13 x 13 pixels around the seed points with a step of 1 to 3 pixel in each direction. For cross checking a backward match is performed for all points found. Some details are described in Müller et al. 2004.

5. ORTHOIMAGE GENERATION AND ACCURACY ANALYSIS

To get an impression of the absolute and relative accuracy of the position and attitude data, and to get an estimation of the necessity to improve the ancillary data by bundle adjustment or other methods, orthoimages are derived using an already available DEM.

The inputs for the orthoimage production are the interior orientation (CCD look angles), the six parameters of the exterior orientation for each image line (interpolated from the measured sampling points) and the DEM. In the case of Bavaria the DEM has been derived by DLR from several ERS 1/2 Tandem pairs, the accuracy is in the order of 5 to 10 meter in flat and hilly terrain and 10 to 50 meter in mountainous terrain (Roth et al. 1998). Therefore the more reliable part of the orthoimages is found north of the foot of the Alps.

The principle of the orthoimage production is based on the intersection of the actual sensor viewing direction (pointing vector) with the DEM applying the rigorous collinearity equation. The orthoimage processor calculates the object space coordinates of the points within the local topocentric system and then transforms them to the desired map projection of the output image using geodetic datum transformation parameters (Müller et al. 2003). Bilinear resampling to a 10 x 10 m grid has been performed.

After generation of the two orthoimages without any ground control information, a check of the accuracy using 20 of the ground control points has been performed. For the quality assessment the measurements have been carried out in bilinearly enlarged orthoimages to achieve sub-pixel accuracy. Table 1 shows the deviation in x and y direction for the orthoimages in comparison to the control points.

Table 1: Mean values and standard deviations for the difference to the orthoimages of 20 ground control points in meter in Gauss-Krüger coordinate system (Bavaria)

x1, y1 – Coordinates of ground control points
x2. y2 – Coordinates in orthoimage from forward looking
x3. y3 – Coordinates in orthoimage from backward looking

	x2 – x1	y2 – y1	x3 – x1	y3 – y1
MEAN	-4,3	5.0	-14.3	11.5
Std. dev	5.89	7.35	6.23	8.64

The result shows that even without any ground control, the absolute georeferencing accuracy of the HRS sensor is better than 20 meter and standard deviation less than one pixel. This is expected, since the values for the absolute pointing accuracy is given by (Bouillon et al. 2003) to about 33 meters with 90% accuracy. More detailed analysis can be found in the conference paper by Müller et al 2004.

6. DEM PRODUCTION FROM TWO RAY STEREO DATA

Having the mass points from the matching process as well as the exterior and interior orientation of the camera system, the object space coordinates can be calculated using forward intersection. This is done by least squares adjustment for the intersection of the image rays. The irregular distribution of points in object space after the forward intersection is regularized into a equidistant grid of 15 to 50 meter spacing. The interpolation process is performed by a moving plane algorithm (Linder 1999). The resulting DEMs, which are surface models, are compared to the reference DEMs, which are terrain models. Therefore a distinct difference is expected e.g. in forest areas.

In the test area of Bavaria six reference DEMs are available for testing the accuracy (see Fig. 1). Fig. 2 shows area #6 (size: 50 km x 30 km) east of Munich with moderate terrain, which is the largest of the six test regions. The DEM calculated from HRS data for this area is shown in Fig. 3.

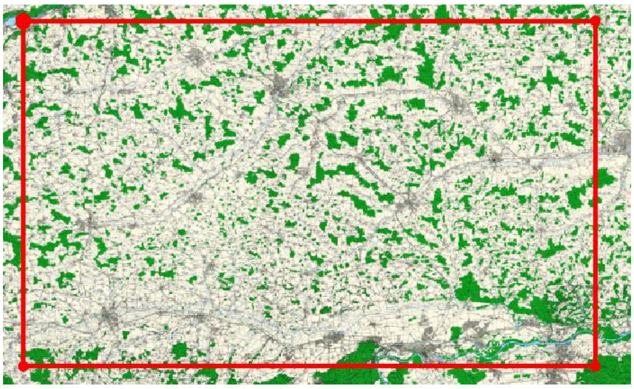

Figure 2. Part of the test area showing the region of reference DEM #6 (50 x 30 km)

The comparison of the derived DEMs to the reference DEMs is performed in several ways. At first only those points, which are found during the first matching process (Lehner 1992), and therefore are highly accurate homologous points, are investigated. They are compared for all the areas where a reference DEM is present (see fig. 1).

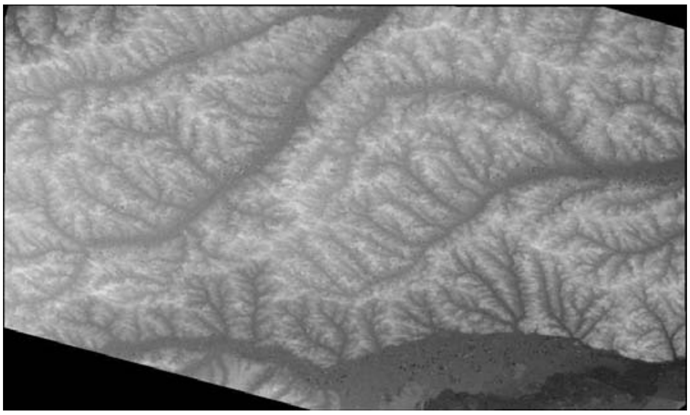

Figure 3. DEM from SPOT-HRS stereo data (region in fig 2).

The result is shown in table 2. The mean height differences are due to absolute orientation errors, they seem to be very similar for all reference areas, and can be eliminated using bundle adjustment methods (see chapter 9). The low standard deviation shows a very good agreement with the reference DEM. A second comparison is performed in using the regularized SPOT-DEM to perform an area oriented analysis.

Table 2: Comparison of height for high quality homologous points in SPOT-DEM and reference DEM

Reference area	Size and Accuracy of Ref-DEM	Mean Height Difference [m]	Std. Dev. [m]	Points [#]
DEM-01, Prien	5 x 5 km, 0.5 m	6.8	2.0	240
DEM-02, Gars	5 x 5 km, 0.5 m	6.2	2.2	184
DEM-03, Peterskirchen	5 x 5 km, 0.5 m	5.6	1.8	261
DEM-04, Taching	5 x 5 km, 0.5 m	4.9	2.0	254
DEM-05, Inzell	10 x 10 km, 5 m	5.7	3.5	458
DEM-06, Vilsbiburg	50 x 30 km, 2-3 m	6.1	3.6	15177

The area oriented approach should distinguish between at least two types of classes (forest and non-forest areas) because of the anticipated discrepancy between terrain models and surface models. The matched objects inside a forest area are distributed among different height levels and therefore the standard deviation for their heights should be higher. Table 3 shows the result for two of the reference areas in Bavaria.

The mean height differences are of the same order (around 6 meter) as for the single points in table 2. The standard deviations are much higher in this area due to lower matching accuracy of the densely matched points and due to interpolation errors in areas where the region-growing matching algorithm could not find enough well correlated points (e.g. low contrast). In the forest areas the differences are about 12 meter higher, what is due to the surface/terrain model discrepancy. Also the standard deviation is much higher in forest areas as was expected.

There are many filtering techniques which can be applied to the DEM data. For this paper two techniques have been applied: an analysis of the statistics of correlating points (kernels) such as variance and roundness (Förstner operator), and a median filter with a window size of 3 x 3 pixel. Table 3 shows that in all cases the filtering leads to significantly lower standard deviations and only little change in absolute differences. The higher change in forest areas is due to mismatching in these areas. Many falsely matched points are eliminated in the case of the first filter and blunders are eliminated by the median filtering.

Table 3: Comparison of the regularized SPOT-DEM and the reference DEM for selected areas and two surface types (SPOT DEM – Reference DEM)

Reference area	Mean Height Difference [m] non-forest / STDV	Mean Height Difference [m] forest / STDV	Height-difference forest/non-forest
DEM-02	7.8 / 5.6	17.8 / 9.7	11.9
DEM-02 statist. filter	8.5 / 4.8	15.0 / 8.0	7.5
DEM-02 median filter	8.0 / 3.9	17.2 / 8.2	9.2
DEM-06	6.5 / 6.5	19.0 / 9.0	12.5
DEM-06 median filtering	6.2 / 4.2	16.9 / 6.8	10.7

Fig. 4 shows the difference image of the Laser reference DEM to the SPOT DEM, forest areas can be seen clearly (brighter grey values) because of the higher mean difference. Also some blunders can be seen in the lower right part of the DEM, which has not been filtered in this case.

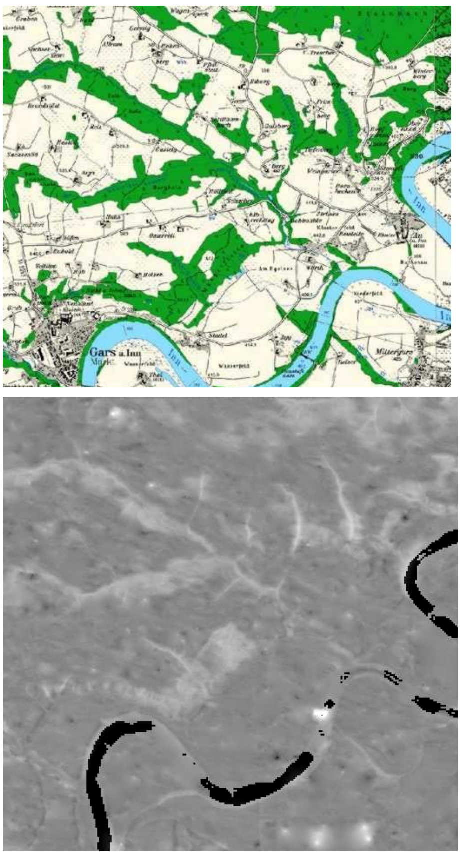

Figure 4. Lower part: Difference DEM (SPOT DEM – Reference DEM): Bright: forest areas and some blunders, the black parts have no value in the reference DEM. Upper part: Map of the same

Another possibility of comparison is to look at profiles of the DEMs along a given line. In the profiles, the structure of the DEM and its variability can be seen easily. Fig 5 shows the profiles along the same line for the SPOT DEM and the reference DEM. The rough structure of the profile is very similar, but there is more variability in the SPOT DEM (Fig. 5 without filtering!).

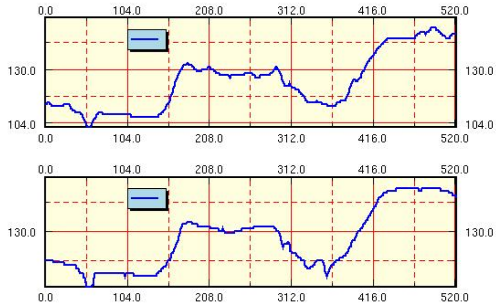

Figure 5. Profiles of SPOT-DEM (upper) and reference DEM (lower)

7. COMPARISON AND FUSION OF SPOT-DEM WITH SRTM-DEM FOR BARCELONA AREA

Additional to an area based comparison with the reference DEM, a SRTM-DEM (derived from data of the Shuttle Radar Topography Mission, Bamler et al. 2003) which is available for most of the area has been investigated. Table 4 shows the mean differences as well as standard deviation and min/max values of the differences for four different areas in and around Barcelona.

Table 4: Area-wise comparison of height of SPOT-/SRTM-DEM and reference DEM

Reference area	Size of Area	Mean Height Difference [m]	STDV [m]	Min / Max
SPOT-HRS-DEM				
Barcelona City	71 km²	11.2	4.4	-47 / +37
Rural Area	161 km²	10.4	5.3	-59 / +53
Moderate Mountain	105 km²	11.1	6.5	-62 / +63
Montserrat	84 km²	9.8	13.5	-158 / +191
Whole area	1882 km²	10.0	6.3	-158 / +191
SRTM-DEM				
Barcelona City	71 km²	1.0	4.7	-22 / +25
Rural Area	161 km²	-1.5	7.2	-98 / +62
Moderate Mountain	105 km²	-1.4	8.7	-218 / +135
Montserrat	84 km²	-1.8	25.2	-484 / +394
Whole area	623 km²	-1.2	8.5	-484 / +394

Mean height differences are very similar in all four cases, while the standard deviation for HRS-DEM gets higher with more slopes and forest areas. In the case of Montserrat, with very steep slopes (many above 45°) the standard deviation and the min/max values become very high. Applying a coarse classification of forest areas, the mean height difference in those areas is only 2-3 meters higher. This can be due to less dense forest cover than in the Bavarian case. The SRTM-DEM shows a very high accuracy in absolute height values due to the sea level calibration. But it can be seen clearly that the standard deviations and min/max values become significantly higher in mountainous regions, which could be expected due to various effects (shadowing, foreshortening, layover etc.) and more difficult matching situation. In flat or moderate terrain both models are of similar quality and can easily be used for DEM-fusion.

A DEM fusion has been performed with the support of accuracy layers from both DEM data sets. In the SRTM case this layer is produced on a routine base by using features of coherence and density of residuals in the DEM generation process. For the optical data, an accuracy layer was generated by using the mean standard deviation as a lower limit and the density of the matched points after the region growing process. The fused DEM shows lower standard deviations especially in moderate and mountainous terrain. Table 5 shows the results of the comparison of the reference DEM to the fused DEM. The absolute height was taken from the SRTM-DEM, therefore the mean height difference is as low. The standard deviation is improved in all cases compared to the DEM produced only by one method. This result shows that the usage of several DEM from different sources of similar quality can improve the overall quality.

Table 5: Area-wise comparison of height of FUSED-DEM and reference DEM

Reference area	Size of Area	Mean Height Difference [m]	STDV [m]	Min / Max
Barcelona City	71 km²	0.9	3.7	-23 / +28
Rural Area	161 km²	-1.3	4.9	-62 / +48
Moderate Mountain	105 km²	-1.0	5.6	-70 / +78
Montserrat	84 km²	-1.5	11.1	-183 / +201
Whole area	623 km²	-1.0	5.7	-183 / +201

8. BUNDLE BLOCK ADJUSTMENT

From the results of the analysis based on the orientation data provided in ancillary data files it can be seen that small biases in all three coordinates, in the order of an HRS pixel size, still remain. These can be removed with the help of a few ground control points using bundle block adjustment. For the bundle block adjustment the software CLIC, developed by TU Munich is used (Kornus 1997). To apply the CLIC interior orientation model the values of the model parameters have to be derived from the given look angles of CCD elements. The type and values for the CLIC interior orientation parameters are given in table 9. Focal length and pixel size are taken from Gleyzes et al. 2003). Standard deviations are estimated. In the MOMS case a CCD curvature parameter was additionally used, which was not introduced for SPOT because an equal distribution of GCP over the whole image swath is necessary for its determination which was neither available for the Bavarian nor for the Catalonian test site.

Table 6: Interior orientation of HRS1/2 as input to bundle adjustment

		HRS1	σ	HRS2	σ
f	focal length [mm]	580.5	0.01	580.3	0.01
x_0	principal point offset[pixel]	0	0.5	0	0.5
y_0		6 (39 µm)	0.5	16 (104 µm)	0.5
δ	rotation of CCD [°]	-0.05649	0.001	0.00735	0.001
γ	stereo angle [°]	20.0378	0.001	-19.95754	0.001

Because of the special optics employed for HRS the parameters of table 6 cannot fully describe the interior orientation. The remaining deviations are shown for HRS1 in figure 6. These values are introduced into CLIC as 'synthetic' calibration tables.

All calculations are done in the LTS. Exterior orientation for HRS1 and HRS2 is directly used as specified by the image providers with the following standard deviations:

$\sigma_x = \sigma_y = \sigma_z = 0.5$ m and $\sigma_\varphi = \sigma_\omega = \sigma_\kappa = 0.000005°$

The relative accuracy of all exterior orientation values is therefore taken to be very high. More variation is allowed for some bias parameters of the exterior orientation which can be modelled separately in CLIC. Because of the nearly constant offset seen in the shifts between the orthoimages only the bias of the pitch angle φ for sensor HRS2 is specified with a higher standard deviation of 0.002° (input value for the bias itself: 0º). This value has been estimated from the shifts of the orthoimages. The bias values for x, y, and z have been set to 0 m with a standard deviation of 1 m. For each camera 15 orientation images (857 image lines for one orientation interval) have been used for modelling the exterior orientation.

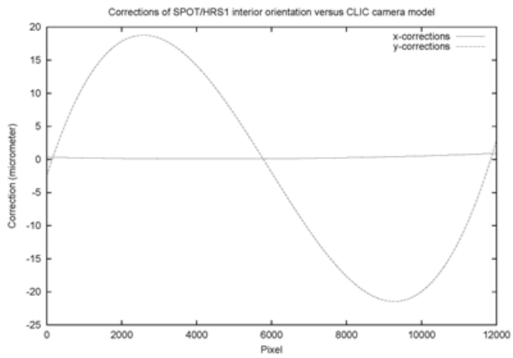

Figure 6. Residuals of the HRS1 camera model fed into CLIC as "calibration file"

From mass tie points generated by DLR matching software a well distributed subset of about 15000 points is introduced into CLIC. In the Catalonian case 28 ground control points are measured in six of the orthoimages provided by ICC. First, the GCP image coordinates are measured manually in the HRS1/2 images, and then the HRS2 coordinate is refined by local least squares matching to subpixel accuracy. For the Bavarian case 10 GCP are used. All GCP map coordinates are introduced into CLIC with standard deviations

$\sigma_x = \sigma_y = 10$ m and $\sigma_z = 5$ m

Standard deviation of image coordinates (tie points and GCP):

$\sigma_x = \sigma_y = 0.2$ pixel for tie points and

$\sigma_x = \sigma_y = 0.3$ pixel for GCP

Table 7 gives the values of the interior orientation parameters after bundle adjustment. No substantial changes can be detected.

Table 7: Interior orientation after adjustment

	Bavaria		Catalonia	
	HRS1	HRS2	HRS1	HRS2
f (mm)	580.50407	580.29826	580.49962	580.29999
x_0 (µm)	-0.465	-0.528	0.642	0.250
y_0 (µm)	40.760	89.790	37.426	103.473
δ (deg)	-0.05130°	0.01196°	-0.05606°	0.00734°
γ (deg)	20.03824°	-19.9570°	20.03718°	-19.9577°

The output values for the bias parameters for exterior orientation can be seen in table 8.

Table 8: Adjusted bias values of exterior orientation

Test site	x bias (m)	y bias (m)	z bias (m)	φ bias (°)
Catalonia	0.09	0.02	-0.01	0.0007
South Bavaria	-0.16	0.01	-0.01	0.0012

Only negligibly small bias values have been found for x, y, and z. The bias of the pitch angle φ corresponds to a shift on the ground in the order of one pixel which is in good agreement with the nearly constant shifts between the orthoimages.
Another main result of the bundle block adjustment with CLIC is the object space coordinates of all tie points. These can be checked against the available DEM. Table 9 summarizes the results of these comparisons. In the Catalonian case the standard deviation of the height differences is the same as before whereas the mean difference is much reduced. For the Bavarian test site the standard deviation of the height differences of the CLIC points to the high quality reference DEM is quite small and comparable to the Catalonian case. A small tilt of the DEM plane from Northwest to Southeast is found in the CLIC point heights: high quality GCP in Austria were not available, unfortunately. The comparison with the ERS-DEM which covers the full area gives a nice mean difference of 0 m but a high standard deviation because of the partly low accuracy of the ERS-DEM, in connection with the tilt mentioned above.

Table 9: Object space heights of tie points after bundle adjustment with CLIC compared to reference DEM

Test site	reference DEM	Analysis of terrain height differences		
		Nr. of points	mean diff. (m)	stand. dev. (m)
Catalonia	ICC-DEM	15029	-1.2	3.5
Bavaria (south)	DEM-01	75	3.6	2.4
	DEM-02	59	6.0	2.0
	DEM-03	75	1.2	2.2
	DEM-04	71	-3.9	2.0
	DEM-05	198	-3.7	3.9
	DEM-06	635	8.4	4.8
	ERS-DEM	15912	0.0	10.6

9. CONCLUSION

It could be shown that a stereoscopic evaluation of SPOT-HRS data, only using ancillary data delivered by the image provider, leads to an absolute accuracy of terrain heights in the order of 5 to 9 meter (mean height error), with standard deviations of about 2 to 4 meter for single points and 4 to 7 meter for the interpolated DEM in comparison to the reference DEM. A fusion with a DEM from the SRTM mission shows the potential of merging DEM from optical and radar data. The absolute accuracy can be improved by this merging or using ground control to reach a mean height difference in the order of 1 meter if sufficiently accurate ground control points are available. The standard deviations are reduced by DEM filtering, which also leads to a smoother DEM. The relative accuracy of course depends on terrain steepness and land use classes, since image matching algorithms depend on these image features. Orthoimages can be derived to an absolute location accuracy of 1 to 2 pixels (10 to 20 meter) without ground control.

The difficulty in getting sufficiently accurate and well distributed GCP stresses once more the benefits of highly accurate exterior orientation measurements.

10. REFERENCES

R. Bamler, M. Eineder, B. Kampes, H. Runge, H., N. Adam.: "SRTM and beyond: Current situation and new developments in spaceborne SAR and InSAR", Proceedings of the ISPRS Workshop High Resolution Mapping from Space, Hanover, Oct. 6.-8. 2003, IPI, Universität Hannover, on CD-ROM

A. Bouillon, E. Breton, F. De Lussy, R, Gachet, "SPOT5 Geometric Image Quality", IGARSS 2003, Toulouse, 21.-25. July 2003, IEEE International Geoscience and Remote Sensing Symposium

J.P. Gleyzes, A. Meygret, C. Fratter, C. Panem, S. Baillarin, C. Valorge : "SPOT5 : System overview and image ground segment", IGARSS 2003, Toulouse, 21.-25. July 2003, IEEE International Geoscience and Remote Sensing Symposium

C. Heipke, W. Kornus, A. Pfannenstein, "The evaluation of MEOSS airborne 3-line scanner imagery – processing chain and results", Photogrammetric Engineering and Remote Sensing, Vol. 62, No. 3, pp. 293-299, 1996

M. Lehner, R.S. Gill, "Semi-automatic derivation of digital elevation models from stereoscopic 3-line scanner data", IAPRS, Vol. 29, Part B4 Washington, USA pp. 68-75, 1992

W. Linder, "Geo-Informationssyteme", Springer-Verlag Berlin, Heidelberg, Germany, ISBN 3-540-65276-0, 1999

Ra. Müller, M. Lehner, Ru. Müller, "Verification of Digital Elevation Models from MOMS-2P data" Proceedings of the ISPRS Workshop "High Resolution Mapping from Space 2001", Hannover, Germany, on CD-ROM, September 2001

Ru. Müller, G. Palubinskas, P. Reinartz, M. Schroeder, V. Amann, R. Stätter, "From Airborne Digital Raw Data to Image Maps" PFG Photogrammetrie, Fernerkundung, Geoinformation, Germany, 4, 4, (2003), S. 317-326

Ru. Müller, P. Reinartz, M. Lehner, M. Schroeder, "Comparison of the Accuracy of DEM from SPOT HRS two-fold Stereo Data and HRS/HRG three-fold Stereo Data in Barcelona Test Site", Proceedings of the ISPRS XXth Congress, Istanbul 12-23 July 2004

P. Reinartz, M. Lehner, Ru. Müller,M. Schroeder, "First Results on Accuracy Analysis for DEM and Orthoimages Derived from SPOT HRS Stereo Data over Bavaria", Proceedings of the ISPRS Workshop High Resolution Mapping from Space, Hannover, Oct. 6.-8. 2003, IPI, Uni Hannov., on CD

A. Roth, W. Knoepfle, S. Gebhardt, B. Rabus, D. Scales, "Evaluation of Interferometric Digital Elevation Models Derived from ERS Tandem Data" ISPRS Commission II Symposium, Cambridge, UK, 13.-17.7.1998, ISPRS, International Archives of Photogrammetry and Remote Sensing, S. 242-247, (1998)

SPOT IMAGE, "SPOT Satellite Geometry Handbook", S-NT-73-12-SI, Edition 1, Rev. 0, Toulouse, France 2002

T. Toutin, P. Cheng, "DEM Generation with ASTER Stereo Data", Earth Observation Magazine, Vol. 10, No. 6, pp. 10-13, June 2001