DEM GENERATION BY SPOT HRS

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TS HRS DEM Generation from SPOT-5 HRS Data

KEY WORDS: satellite, orientation, matching, DEM/DTM, analysis

ABSTRACT:

The HRS (high resolution stereo) is an autonomous imaging system on SPOT 5. It has been designed especially for the generation of digital elevation models (DEMs). The combination of a forward and a backward view do allow a stereoscopic imaging with a height to base relation of 1.2 and just 90 seconds time interval. Some images, which are usually not accessible and used only by SPOT Image for the generation of DEMs, have been made available for the SPOT HRS study team. The test area Bavaria has been analysed.

Just based on the known view direction, the orientation of a HRS stereo pair has been adjusted with the Hannover program BLASPO. The mean square Z-discrepancies at the control points of 3.9m corresponds to an x-parallax of 0.6 pixels, a realistic value for points located in areas with sufficient contrast. Depending upon the area, between 80% and 90% of the points could be matched successful by a least squares method. The determined ground points do describe a digital surface model (DSM) and not the requested DEM. Points located not on the solid ground have to be removed. For the 17 million points of one HRS stereo pair this can be made only by an automatic process. The Hannover program RASCOR removed approximately 35% of the DSM points. Nevertheless in dense forest areas several points still may be located not on the ground. Corresponding to this, in the forest areas a height shift against the reference data could be seen. But also the relative accuracy in the forest is not so good like in the open areas caused by limited contrast and the not visible ground. In the open areas a vertical accuracy in the range of 5m and a little better has been reached with a slight dependence upon the tangent of the slope.

1. INTRODUCTION

The high resolution stereo sensors (HRS) of SPOT 5 includes two optics viewing forward and after in the orbit direction with incidence angles of 23°, generating a stereo model with a height to base relation of 1.2. With 12 000 pixels a swath width of 120km is available. In the orbit direction, the pixel size on the ground is just 5m, so a standard scene with 12 000 x 12 000 pixels is covering an area of 120km x 60km. The smaller pixel size in orbit direction has advantaged for the vertical accuracy.

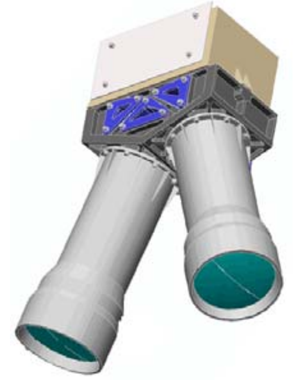

Figure 1.
SPOT HRS camera system

Two slightly overlapping HRS-models, located in the south-east of Germany, in the federal state of Bavaria, covering also parts of Austria, have been evaluated. As control and check points for the scene orientation trigonometric points have been used. These points cannot be identified directly in the scenes, only based on sketches the location usually close to road crossings can be estimated; so not the optimal accuracy of positioning can be reached.

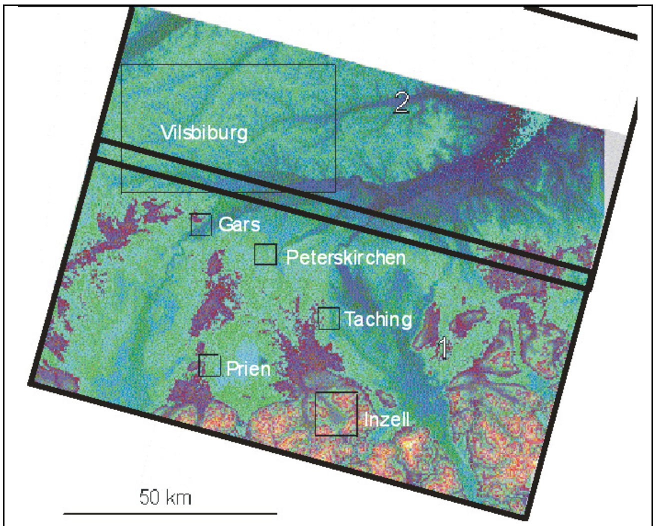

Figure 2: colour coded DEM generated with the HSR data and location of the evaluation areas

The investigated area has a height ranging from 270m up to 1850m above sea level. Approximately 20% is covered by a mixture of smaller and larger forests. Also some lakes are included. The main part is flat up to rolling, only small parts of the Alps are included (see figure 2).For the analysis of the determined DSM / DEM, reference data from the Bavarian Survey Administration have been made available by the DLR Oberpfaffenhofen. The location of the reference areas is shown in figure 2. For the areas Prien, Peterskirchen, Gars and Taching laser scanner data with a spacing of 5m and a vertical accuracy better than 0.5m are available. Each of these areas does have a size of 5km x 5km. For the 10km x 10km area of Inzell in the moderate northern part laser scanner data with SZ < 0.5m and in the mountainous southern part a DEM based on digitised contour lines from maps 1 : 10 000 with an accuracy of only SZ=5m and a spacing of 25m has been distributed. The reference DEM of the 30km x 50km area Vilsbiburg has a spacing of 50m and a vertical accuracy of 2m.

2. DEM DETERMINATION

The image orientation has been determined with the Hannover program BLASPO using just the information of the view direction together with the general orbit information and control points. The image positions of the control points and some seed points for the image matching have been measured manually using the Hannover program DPLX. From the shell of DPLX, the matching program DPCOR can be started. DPCOR is using the least squares matching in the image space. The core of this program was developed by C. Heipke. The matching in the image space is independent from any orientation information. Only some seed points (corresponding points in the both images) are required for the matching based on the region growing. Also control points can be used as seed points. The automatic matching has been done for every third pixel with a window size of 10 pixels x 10 pixels leading to sufficient independent ground points in a raster of approximately 15m x 30m.

Based on the orientation determined by BLASPO, the ground points of the DEM points are computed by an intersection. The orientation by BLASPO will be adjusted in a tangential coordinate system to avoid the negative influence of the map projection. In the program COMSPO, the intersection is followed by a transformation to the map projection, so finally the height information is available in a chosen national coordinate system. For a more fast data handling the not totally regular distributed ground points are interpolated into a raster arrangement by program LISA.

The so derived height model includes the visible surface of the objects, that means it is a digital surface model (DSM) and not a digital elevation model (DEM) of the solid ground. The points not belonging to the bare ground have to be removed before a comparison with the reference DEMs. This has been done with the Hannover program RASCOR (Jacobsen 2001, Passini et al 2002). RASCOR is using a sequence of different methods for the filtering of a DSM in raster form. The operational use showed, from a random arrangement a raster arrangement can be interpolated and this can be analysed by RASCOR with sufficient results even under the condition of not using the original data.

RASCOR is analysing the DSM and based on this it is determining the procedure and tolerance limits automatically without user interaction. RASCOR starts with an analysis of the height distribution itself. Based on the structure of the achieved histogram of height distribution an upper and lower limit of the accepted height can be identified automatically. This methods requires flat areas, it does not work in rolling and mountainous terrain. It is followed by an analysis of the height differences of neighboured points. The accepted height limit of neighboured points is depending upon the slope and the random errors. With this method only small objects and the boundary of larger elements can be eliminated, but it is still very efficient.

Even large buildings can be found by a sudden change of the elevation in a profile to a higher level and a later corresponding change down, if no vegetation is located directly beside the buildings. This method can be used for laser scanning, but it is not optimal for DEMs determined by automatic image matching where the buildings are looking more like hills.

Other larger objects not belonging to the bare ground are identified by a moving local profile analysis; at first shorter and after this longer profiles are used. The required length of the moving local profile is identified by an analysis of a sequence of shorter up to longer profiles. In flat areas the individual height values are checked against the mean value of the local moving profile, in rolling areas a linear regression is used, in mountainous areas polynomials have to be used. It will be combined with data snooping taken care about a not even point distribution caused by previously eliminated points. All these methods are applied in X- and Y-direction. Elements which have not been removed by this sequence of tests are analysed by a moving surface which may be plane, inclined or polynomial. The size of the moving surface is identified by the program itself by checking the data set with a sequence of cells with different size. As final test a local prediction can be used, but it is usually only identifying few points not belonging to the ground after the described sequence of tests.

In the case of the check for height differences of directly neighboured points, the upper point will be eliminated if the tolerance limit will be exceeded. The other methods are using a weight factor for points located below the reference defined by the neighboured points. This will keep points located in a ditch or cutting in the data set. Usually points determined by laser scanning do not have blunders causing a location below the true position, but this may happen in the case of a DSM determined by automatic image matching, justifying a weight factor.

In forest areas at first only the trees are removed by the program, smaller vegetation is remaining, so a second iteration is necessary. A second iteration in other cases may remove also terrain points leading to a more generalised DEM. This may be useful for the generation of contour lines, but it is not optimal for the correct description of the terrain.

The derived DEMs have been investigated by a comparison with the reference DEM. Because of the general different situation of points located in forest or open areas, a separation of both terrain types has been made in the used Hannover program for the DEM analysis DEMANAL. DEMANAL can use a geo-referenced layer for different terrain types. It also determines the dependency of the vertical accuracy as a function of the terrain inclination. It is possible to define tolerance limits for the terrain inclination and the discrepancies of the DEM-points. The forest layers have been extracted from the topographic maps 1: 50 000.

3. IMAGE ORIENTATION

The identification of the trigonometric points in the HRS-images was not so simple. Not in any case the correct location based on the trigonometric point description could be found.

The points are usually located closely to road junctions, so the distance to the exact image position had to be estimated (see figure 3).

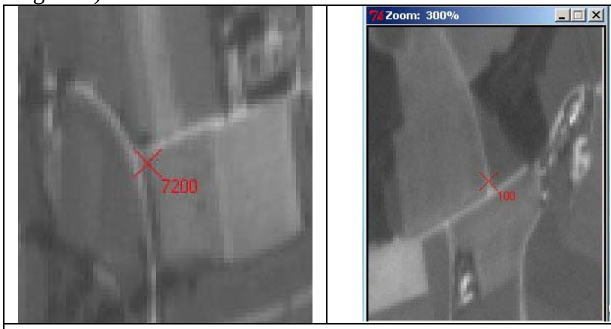

Figure 3. typical location of control points with estimated position close to street junction

The image orientation has been determined with the Hannover program BLASPO for the bundle orientation of satellite line scanner images. It is using just the given view direction and the general orbit information (inclination and ellipse specification) in addition to control points. 4 unknowns have to be determined together with some additional parameters. At least one additional parameter has to be used for respecting the satellite speed. So by theory, the orientation could be determined just with 3 control points, but finally 46 have been used for the southern and 14 for the northern model. No control points are available in the Austrian part, so on the right hand side (figure 4) no points are located. For the northern model control points have been distributed only for the south-west part (figure 4, right hand side). This is not an optimal distribution, but the test area Vilsbiburg is well surrounded by control points, so no problems have to be expected.

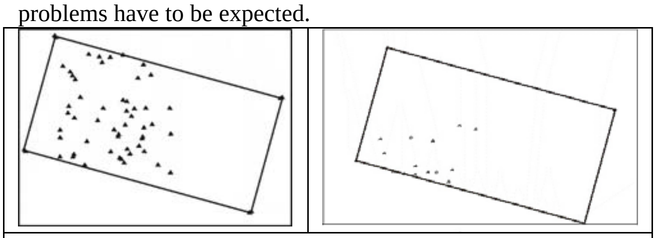

Figure 4. distribution of control points:
left: southern scene right: northern scene

The bundle orientation was leading for the southern model to following root mean square discrepancies at the control points: SX=6.0m, SY=5.8m, SZ=3.9m and in the northern model to: SX=7.7m, SY=5.0m, SZ=3.5m. So the results for both models are similar. Respecting the problems of the point identification this is a sufficient result in relation to the pixel size of 5m x 10m. The better results for the height are demonstrating the higher accuracy potential of the SPOT HRS system. The vertical accuracy corresponds to a standard deviation of the x-parallax of 0.6 pixels (in relation to the 5m pixel size in orbit direction).

The orientation accuracy has been confirmed by the image matching. The rmse between vertical differences of the control points and the matched DEM is just 3.06m; that means it is better than the Z-discrepancies of the orientation. This can be explained by problems of the manual pointing of the control points which is not so accurate like automatic matching.

4. IMAGE MATCHING

The image matching for the generation of the DEM has been made with program DPCOR. It is using a least squares matching in the image space with region growing. The least squares method is the most accurate possibility of image matching with advantages especially in inclined areas. A matching in the image space allows a use for any image geometry; no special mathematical model is required. At least one start point with the corresponding positions in both images must be given. From this seed point neighboured points in any direction are determined by matching and these are again seed points for the next.

An image matching is only possible with some image contrast, so a matching on a water surface is not possible, but also in the forest some problems may occur because of limited grey value variations.

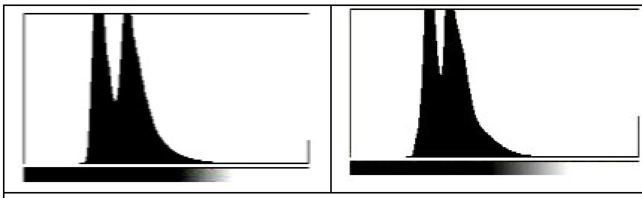

Figure 5: grey value histogram of both HRS-scenes
for both: standard deviation = 24 grey values

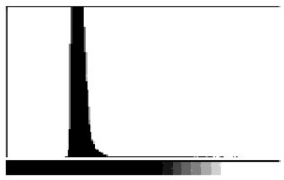

Figure 6: typical grey value histogram of an open forest, standard deviation = 6.1 grey values

The grey value variation for both scenes (figure 5) is not optimal, but sufficient with the exception of some parts in the forest (figure 6). Depending upon the area, 85% to 90% of the possible points in the southern model have been matched with a sufficient correlation coefficient exceeding the used limit of 0.6. As it can be seen in figure 7, the success of matching is not equal distributed. A matching is very difficult if it is too steep. In addition a matching is also not possible in the snow covered parts – only the border of the snow can be used. But in general the coverage is satisfying and sufficient for a DEM generation.

The quality map of the image matching (figure 7) shows very well the areas where the matching is more difficult. Especially in the forest areas (dark parts) the contrast is limited causing also a low correlation coefficient which sometimes is also below the used tolerance limit of 0.6. The frequency distribution of the correlation coefficient is varying dependent upon the landscape. On the left hand side of figure 9, the frequency distribution of the typical sub-area shown in figure 8 is shown, where 92% of the possible points have exceeded the acceptance limit of r=0.6, while on the right hand side the extreme situation of the steep mountains, partially with forest and also several small lakes is shown, where only 85% of the points have been above the limit.

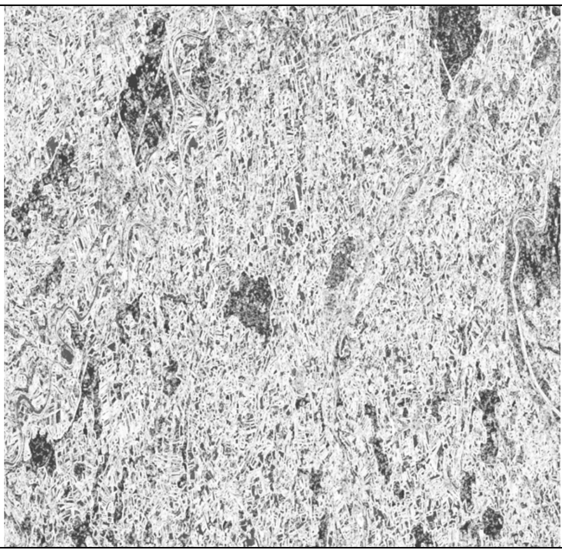

Figure 7: quality map of matching a sub-scene – size of correlation coefficient displayed as grey value
grey value 255 (white) = correlation coefficient 1.0
grey value 51 (dark grey) = correlation coefficient 0.6

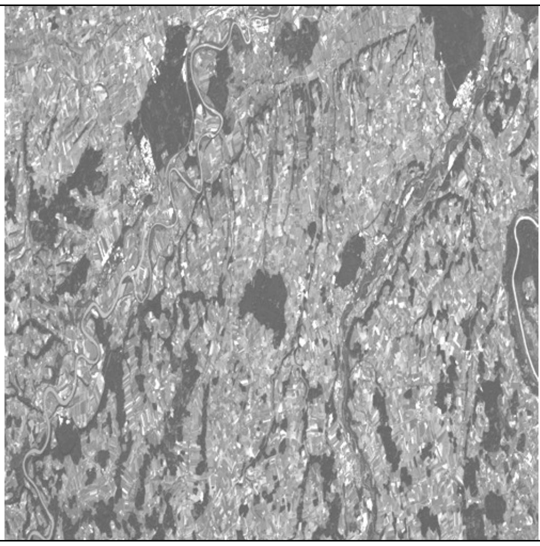

Figure 8: HRS sub-scene corresponding to figure 7

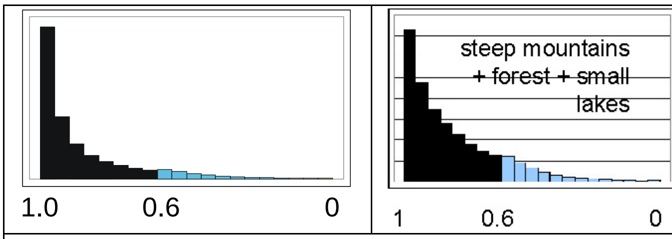

Figure 9: frequency distribution of correlation coefficient,
left: area shown in figure 8 right: difficult sub-area
horizontal scale = correlation coefficient vertical = frequency

5. ANALYSIS OF THE ACHIEVED DSM / DEM

Based on the orientation determined with program BLASPO, ground coordinates of the matched points have been computed by intersection. The matching in the image space has the freedom in all directions, so the y-parallax of the intersection can also be used as quality indicator. The matching has been done in 15 main sub-areas separately. The root mean square y-parallax error is ranging from Spy=4.67m up to 7.11m with a mean value of Spy=6.0m corresponding to 0.6 pixel (pixel size in y-direction = 10m). 0.9% of the intersected points have not been accepted; they exceeded the tolerance limit for the y-parallax of 30m. In total, approximately 27 million points have been determined in the southern model where the whole area of 12000 x 12000 pixels has been used and the northern model where only 12 000 x 8000 pixels where included. The spacing of 3 pixels in both directions corresponds to 15m in the orbit and 30m across the orbit direction.

The matching has been done independently for both models. A comparison of the overlapping part is showing approximately the same results for the different terrain classes and also only a very small dependency upon the terrain inclination. The root mean square difference of 4.1m corresponds to 2.9m for the individual model and this to a standard deviation of the x-parallax of 0.5 pixels – similar to the discrepancies at the control points.

	RMS [m]	bias [m]	RMS - bias	RMS F(slope)
all points	4.1	0.7	4.0	3.3 + 0.85 x tan α
open area	4.0	0.8	4.0	3.2 + 1.27 x tan α
forest	4.5	1.6	4.2	3.9 + 0.22 x tan α

Table 1. root mean square discrepancies northern against the independent southern model

5.1 Test areas with laser scanner data as reference

As mentioned in the introduction and shown in figure 2, only for some sub-areas reference data are available. The test areas with laser scanner DEMs do have a size of each 5km x 5km. The reference DEMs with a spacing of 5m do have an accuracy better than 0.5m, but available only in a resolution of full meters. These test areas do have a similar topography which is between flat up to rolling with height variations in the range of 200m. In the average 20% is covered by forest, which is located primarily in steep parts.

	RMSE [m]	bias [m]	RMSE - bias	RMSE F(slope)
DSM: all points	10.2	-5.5	8.5	8.7 + 10.6 x tan α
DSM: open areas	6.7	-3.0	5.9	6.4 + 4.9 x tan α
DSM: forest	17.0	-14.3	9.2	16.4 + 3.4 x tan α
DEM: all points	5.7	-2.0	5.1	5.0 + 5.4 x tan α
DEM: open areas	**4.4**	-1.3	4.1	**4.2 + 1.6 x tan α**
DEM: forest	12.3	-8.5	8.6	10.0 + 6.9 x tan α

Table 2: root mean square difference DEM / DSM of test areas against reference DEM determined by laser scanner

The automatic matching of all optical images leads to a DSM with the points on top of the visible objects like trees and buildings. Also Interferometric Synthetic Aperture Radar (InSAR) using a shorter wavelength like the X-band, but also the C-band corresponds to this. Only long wavelength InSAR is partially penetrating the vegetation. Caused by this, the large RMSE-values of the first three lines in table 2 can be explained. The DSM includes several points not located on the bare ground like the reference DEM. This is indicated also by the negative bias, which has the sign of the correction (reference height – matched height), so a negative sign is indicating a location of the matched points on top of the vegetation and buildings. A filtering of the DSM to a DEM by RASCOR removes between 35% and 55% of the points depending upon the type of filtering. The DEM-results in table 2 are based on 45% removed points. Also the frequency distribution of the discrepancies demonstrates the reason of the chosen data handling (figures 11 and 12).

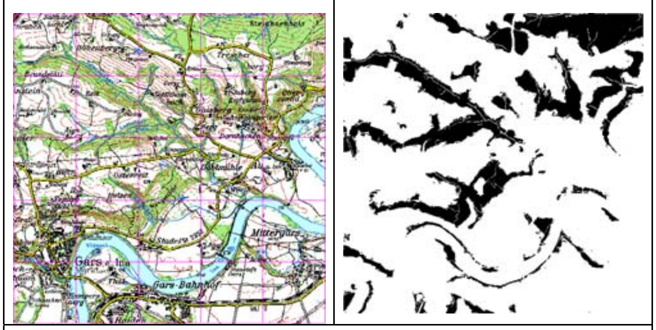

Figure 10: test area Gars,
left topographic map right: forest layer

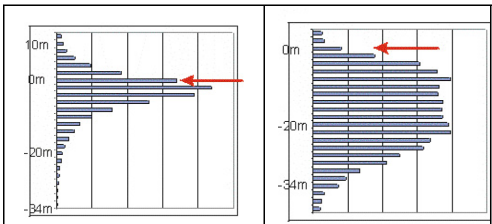

figure 11: frequency distribution of ΔZ before filtering: left open areas, right forest

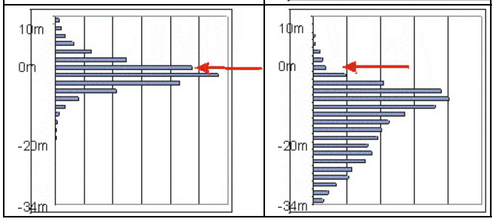

figure 12: frequency distribution of ΔZ after filtering: left open areas, right forest

The frequency distribution of the discrepancies (figures 11 and 12) also do show the influence of remaining points on top of the vegetation in the forest area. Also RASCOR is not able to identify points on top of the forest if all neighboured points are elevated. Only if at least some points are located on the bare ground, the points not belonging to the bare ground can be identified and removed. Nevertheless, also for the forest there is a clear advantage of the filtering.

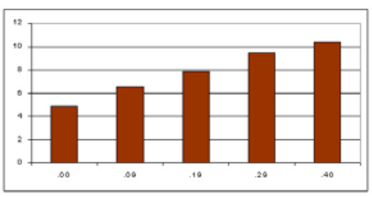

Figure 13: accuracy depending upon tangent of slope

test area Gars

slope →

vertical: rmse ΔZ

There is a clear dependency of the accuracy from the terrain inclination as visible in figure 13. It shows the situation of all points after filtering by RASCOR. The dependency upon the terrain inclination can be caused by errors in the horizontal location between the reference and the HRS-data. This reason is not very probable - the orientation of the HRS-scene has been based on trigonometric points from the survey administration, which are also base for the topographic maps. Another reason is the reduced accuracy of matching inclined objects, which are more often covered by vegetation.

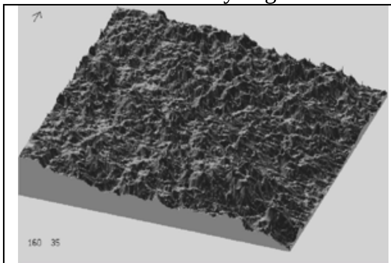

figure 14.1

matched DSM

test area Taching

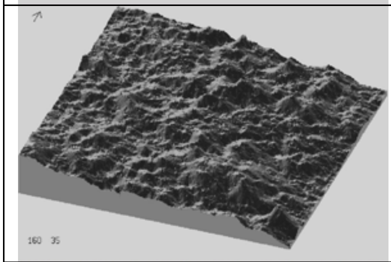

figure 14.2

DSM after filtering with RASCOR to a DEM

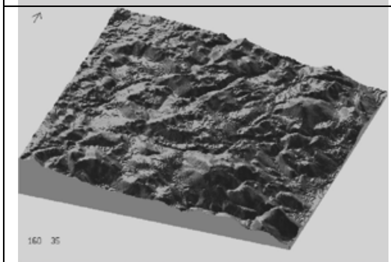

figure 14.3

reference DEM

The filtering of the DSM to a DEM is very important – not only in the forest, but also in the open areas. The open areas do include settlements and several single trees and bushes, so also here a higher percentage of matched points are not located on the ground. This cannot be seen only with the standard deviation, but also at the bias. The remaining systematic height difference of -1.3m for the open areas after filtering with program RASCOR, is small but realistic. The filtering of the DSM to a DEM requires height differences larger than the noise. Small objects like bushes cannot be identified as not belonging to the bare ground if they are below the root mean discrepancies. On the other hand there are several points located in the forest which are on top of closed areas where the ground cannot be seen.

Also a visual comparison of the original DSM with the filtered DEM and the reference DEM shows the justification of the filtering. The morphologic structure of the filtered DEM is quite more similar to the reference DEM like the matched DSM (see figure 14).

5.2 Test area Vilsbiburg

In the larger test area Vilsbiburg the reference DEM has a spacing of 50m and only a limited accuracy of 2m, but this should be sufficient. Only 13.7% is covered by forest and the forest areas are small.

The a little larger rmse for the test area Vilsbiburg can be explained by the lower accuracy of the reference together with the interpolation over 50m. The smaller bias of the forest areas after filtering has been caused by the smaller size of the individual forest areas.

	RMSE [m]	bias [m]	RMSE without bias	RMSE F(slope)
DSM: all points	10.4	-4.1	9.5	9.2 + 7.0 * tan α
DSM: open areas	9.0	-2.8	8.6	7.9 + 5.0 * tan α
DSM: forest	16.5	-11.8	11.5	17.7
DEM: all points	6.5	-0.3	6.5	6.0 + 4.4 * tan α
DEM: open areas	**5.9**	0.2	5.9	**5.3 + 2.4 * tan α**
DEM: forest	10.9	-5.1	9.7	9.4 + 3.3 * tan α

Table 4: analysis of test area Vilsbiburg located in the northern model

5.3 Test area Inzell

The test area Inzell is quite different from the other parts. With heights ranging from 610m up to 1681m it includes parts of the Alps which are covered by forest. Only 32% is belonging to the open areas. For this steep terrain the reference DEM is mainly based on the topographic map 1:10 000 with a vertical accuracy in the range of 5m. A small steep isolated mountain has not been matched, so it is automatically not in the analysis because of the gap in the achieved DEM.

	RMS [m]	bias [m]	RMS -bias	RMS F(slope)
DSM: all points	17.2	-10.3	13.8	10.7 +36.1 x tan α
DSM: open area	9.8	-4.7	8.7	6.1 + 39.6 x tan α
DSM: forest	19.9	-13.0	15.0	17.9 + 8.5 x tan α
DEM: all points	13.7	-7.1	11.7	7.9 + 45.7 x tan α
DEM: open area	**6.7**	-2.5	6.2	**4.8 + 26.1 x tan α**
DEM: forest	17.4	-10.8	13.7	16.2 + 7.4 x tan α

Table 5: analysis of test area Inzell

The larger root mean square values of this area can be explained by the landscape, but also by the reference DEM. If the influence of the reference DEM with SZ = 5m is respected, for the open area after filtering the accuracy value would be reduced from 6.7m to 4.5m, that means to the same range like before. This is realistic because the open areas are mainly not so steep. The limited accuracy of the reference DEM can also be seen at the morphologic character, the reference DEM is too smooth for this type of terrain. The matched DEM shows more realistic structures of the mountains. A stronger dependency upon the terrain inclination also may be caused by this and a limited horizontal accuracy of the reference data.

6. CONCLUSION

The orientation of the SPOT HRS stereo models has not caused problems. The orientation accuracy is sufficient, shown at the RMSE of 3.5m and 3.9m for the Z-control point coordinates. Because of the high number of control points, the influence of the orientation accuracy to the finally generated DEM is limited.

The advantage of imaging corresponding scenes from the same orbit can be seen at the high quality of the automatic image matching. Only in dense forest areas where the grey value distribution is limited, the matching had difficulties. A problem exists in the very steep parts of the Alps, but this is a general case for matching with all optical images. Also InSAR is not better in such areas.

By automatic image matching the height of the visible surface and not the bare ground will be determined. This is again a problem for all optical images, but also for short wave InSAR. The points not located on the ground have to be removed by a special filter method like used in program RASCOR. This is eliminating approximately 45% of the points with a clear improvement of the final results visible at the statistics, the distribution of the discrepancies but also the 3D-views of the DEMs.

For flat terrain in open areas after filtering a standard deviation for the height between 3.8m and 5.3m has been reached with the mean value of 4.5m. If the bias is respected, the mean value is reduced to 4.2m. In inclined parts, a factor up to 26.1m multiplied with the tangent of the terrain inclination has to be added, but with the exception of the very steep area, the dependency upon the slope is only in the range of up to 3.8m multiplied with the tangent of terrain inclination. In the forest areas after filtering several points are still located on top of the trees.

The standard deviation of 4.2m up to 4.5m for the height corresponds to a standard deviation for the x-parallax of 0.7 pixels. This final result is confirming the high accuracy level which can be reached with SPOT HRS-stereo models. Under operational conditions better results cannot be expected from optical sensors. The main limitation is vegetation covering the bare ground. Its influence can only be respected and removed if at least few ground points with a sufficient small distance are available. So the height information in dense forest can never reach the quality like in open areas.

As advantage of the DEMs generated by automatic image matching against DEMs based on Interferometric Synthetic Aperture Radar (InSAR) we do have the quite higher details and also a smaller spacing.

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