

ANALYSIS OF DIGITAL ELEVATION MODELS DETERMINED BY HIGH RESOLUTION SPACE IMAGES

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ABSTRACT:

Digital Elevation Models (DEM) generated by automatic image matching of high resolution space images are used often for very high resolution orthoimage production. The published accuracies of such DEMs are not in any case realistic and do represent often only the quality which can be reached in flat areas with good contrast and without influence of buildings and vegetation. In the mountainous area of Zonguldak, Turkey, Digital Surface Models (DSM), representing the height of the visible surface have been generated by means of stereo models taken by TK350, ASTER, SPOT 5 and IKONOS. As reference, GPS control points and a DEM of the topographic maps 1:25 000 are available like also the DSM of the SRTM X-band and C-band.

The DSMs have been reduced by an automatic process to DEMs and are analysed separately for forest and open areas and as a function of the terrain inclination. The image matching of TK350 photos did require a scratch removal and a low pass filter because of several scratches and the film grain. Nevertheless, the results could be accepted only in the open areas. In the forest the image contrast was not sufficient and this was leading to large blunders and not accepted point matching. ASTER is using the near infrared band (NIR) for the stereo coverage and here we do have a good contrast also in the forest. Caused by this, the image matching was without any problems also in the forest. In the available SPOT 5 level 1A and level 1B images, the grey value variation in the forest is limited. With both products approximately the same accuracy has been achieved. Two IKONOS scenes taken with a time interval of 2 month have been used also for the DEM generation. The difference of 20° in the sun elevation caused quite different shadows, so a matching was not possible in the forest areas, but also in the build up parts it was difficult. Quite different results have been reached in another area where the IKONOS images have been taken from the same orbit; here the results have been excellent like also with QuickBird images taken with a time interval of just 10 days. The height models of the Shuttle Radar Topographic Mission (SRTM) are also referring to the visible surface, so in the forest areas a height shift can be seen. In addition there is a strong dependency upon the terrain inclination. The SRTM elevation models are better like the DEMs based on medium resolution space images.

1. INTRODUCTION

Digital elevation models are a basic requirement for any mapping and GIS. With the availability of SRTM C-band DSMs (<http://edcsgs9.cr.usgs.gov/pub/data/srtm/>) for large parts of the world, the situation has been improved, but up to now the data are not completely published. In addition the accessible SRTM DSM has only a spacing of 3", corresponding to approximately 90m and some gaps exist in very steep areas. Not for every purpose the accuracy and details are sufficient.

DSMs can be generated with different space images and accuracies corresponding to the ground pixel size, height to base relation and radiometric quality. Not in any case the claimed and published accuracy of the DEM generation is realistic. Sometimes the DEMs have been checked only at well defined points not taking care about areas with not optimal contrast, not taking care about the influence of the vegetation and also the terrain inclination. The detailed analysis of DEMs generated by different space images will be shown.

2. TEST AREA

Most of the following investigations have been made in the area of Zonguldak, Turkey located north of Ankara at the Black Sea. The area is mountainous with an average inclination of 23%. Approximately 45% of the land area is covered by forest with tree heights in the range of just 10m. In the north-west direction parts of the Black Sea are included. As reference a DEM from the topographic map 1 : 25 000 is available as well as some control and check points determined by GPS.

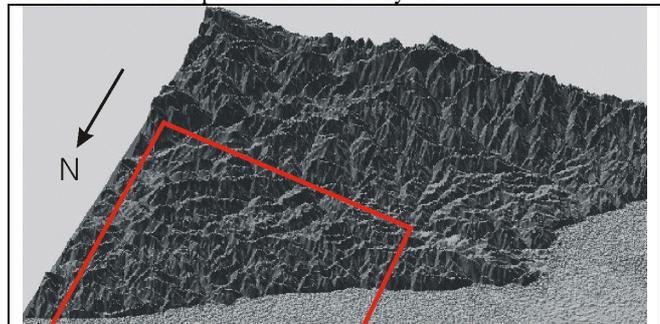


Figure 1: test area Zonguldak (SRTM C-band DEM) with the main investigation area

3. IMAGE MATCHING AND REFERENCE

The different digital elevation models based on space images have been matched with the Hannover program DPCOR using a least squares matching in the image space. This program is independent upon the image geometry – it is not using the epipolar information and requires some seed points in the matched area. As seed points the control points can be used, so it is not an additional effort. The ground points have to be calculated by programs using the correct geometry of the image orientation. The y-parallaxes of the intersection are indicating the quality of the matching in the level of the visible surface. Depending upon the image geometry, the image orientations have been made with the Hannover programs BLUH, CORIKON and BLASPO with standard deviations in X and Y between 0.8 and 0.9 pixels. The standard deviation for Z (SZ) is depending upon the height to base relation, but can be expressed also independent upon this with the root mean square accuracy of the x-parallax (Spx) respecting the relation: $SZ = h/b * Spx$ where Spx has the dimension of pixel size on the ground. The orientation accuracy in Z was in the range of 0.4 pixels $< Spx < 1.3$ pixels.

The achieved DSMs have been analysed with the Hannover program DEMANAL separating the area by a classification layer into forest and open areas. A more detailed separation was not necessary. The dependency of the accuracy upon the terrain inclination has been computed in DEMANAL beside a more detailed analysis.

The reference DEM is based on the topographic map 1 : 25 000 in the Gauss-Krueger coordinate system (transverse Mercator), using the Hayford ellipsoid, while the GPS-ground positions like also the SRTM-data are available in UTM with the WGS84 ellipsoid in the ITRF reference frame. The mathematical transformation is not a problem, but the datum of the Turkish national coordinate system in the area of Zonguldak was not known, leading to shifts in X and Y. By this reason the shifts of the height models have been determined by least squares adjustment with the Hannover program DEMSHIFT. This may also solve some orientation problems for example of the SRTM-data.

4. SRTM-DEMs

With Interferometric Synthetic Aperture Radar (InSAR) by the Shuttle Radar Topographic Mission (SRTM) in February 2000 the main part of the earth land area between the latitude of 56° south and 60.25° north has been covered by DSMs. The Space Shuttle carried the US C-band and the German/Italian X-band system. By the scan-SAR mode the C-band has had a swath width of 225km while the X-band was limited to a swath width of only 45km. Caused by this, the X-band system has not covered the whole area while the C-band has covered 94.6% of the land mass twice and approximate 50% three times. This multiple coverage has improved the accuracy of the C-band DSMs which are by theory not so accurate like the X-band-DSMs based on the shorter wavelength. The used X-band with the wavelength of 3cm cannot penetrate the vegetation, but also the used C-band with a wavelength of 5.6cm shows nearly the top of the vegetation. The published C-band elevation models are unedited and do include artefacts and gaps in steep areas. The C-band SAR has an incidence angle (nadir angle at the ground) between 31° and 61° while the X-band is limited to 50° to 54°. Corresponding to this the radar layover where the

returned signal cannot be separated depending upon the location is in the range of a terrain slope across the view direction of the same value.

In the area of Zonguldak, Turkey the X-band DSM and also the C-band DSM from the German aerospace organisation DLR have been analysed in relation to a DEM generated from the topographic map 1 : 25 000. The program DEMANAL is able to separate the analysis depending upon a classification layer. In this case only the forest and not forest areas (open areas) have been separated. The Zonguldak area is mountainous with an average slope of 23%. 6% of the slopes are exceeding 31° where the problem with the layover of the C-band SAR starts and 0.6% are exceeding 50°, where the problems with the X-band are starting. Together with the X-band data a so called height error map with estimated height accuracies is distributed showing very well the locations with problems. In the test area they are especially at the coast line where the terrain is partially extremely steep up to nearly vertical and in some steep valleys, visible in figure 2 as elevated parts. The DSM analysis confirmed the problems in these locations.

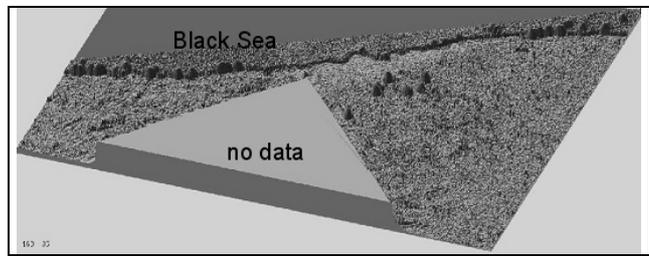


Figure 2. height error map of SRTM X-band in test area

X-band DSM	DZ > 50m	RMSZ [m]	Bias [m]	RMSZ – bias F(slope)
All points	0.55%	11.9	-5.7	$7.9 + 9.6 * \tan \alpha$
Open areas	0.67%	10.7	-3.5	$7.2 + 8.7 * \tan \alpha$
Forest	0.39%	13.8	-8.1	$7.8 + 9.6 * \tan \alpha$
check points	0	5.4	-2.0	$1.3 + 40.6 * \tan \alpha$

Table 1: RMS discrepancy of the SRTM X-band DEM against the reference DEM from the map 1 : 25 000 and check points

The analysis of the SRTM X-band DSM shows a clear dependency of the root mean square Z-differences upon the terrain inclination. In the flat areas the accuracy is in the range of 7m up to 8m. Quite better results can be seen at 43 check points which have been determined by GPS. The overall accuracy of 5.4m is still better with 2.9m for the 20 check points located in an area with an inclination below 7%. The larger discrepancies in the forest areas are shown in all data sets described in this presentation. In the case of Radar images the main influence is coming from the difference between the visible surface and the reference DEM, indicated by the clearly higher bias. A filtering of the DSM to a DEM has not improved this relation because no height values are available from the bare ground in the forest area (see Passini et al 2002). Nevertheless the influence of the forest is limited caused by the not very high trees.

The comparison of the C-band data with the reference DEM is leading to very similar results like the X-band data. Only the comparison with check points shows larger discrepancies. In the flat area with inclination below 7%, the root mean square discrepancies are 4.9m instead of 2.9m for the X-band data.

C-band DSM	DZ > 50m	RMSZ [m]	Bias [m]	RMSZ – bias F(slope)
All points	1.19%	11.7	-5.4	$8.3 + 7.8 * \tan \alpha$
Open areas	2.11%	9.9	-3.9	$7.5 + 6.6 * \tan \alpha$
Forest	0.03%	13.6	-8.3	$8.7 + 7.3 * \tan \alpha$
check points	0	9.4	-2.0	$4.0 + 122 * \tan \alpha$

Table 2: RMS discrepancy of the SRTM C-band DEM against the reference DEM from the map 1 : 25 000 and check points

A direct comparison of the X-band DSM with the C-band DSM shows root mean square Z-discrepancies of 8.4m or $RMSZ = 4.8m + 12.2 * \tan \alpha$ and only a negligible bias. For flat terrain the RMS discrepancy of 4.8m has to be divided by 1.4 under the condition of the same accuracy of both data sets leading to 3.4m accuracy for each data set. A similar accuracy has been reached in a smooth area in Arizona where the RMS discrepancies of the SRTM C-band DSM against the DEM of the USGS has been 3.7m or $2.7m + 22.7 * \tan \alpha$. Also the X-band DSM in a rolling area in Germany has been in the range of $RMSZ = 3m$ (Koch et al 2002).

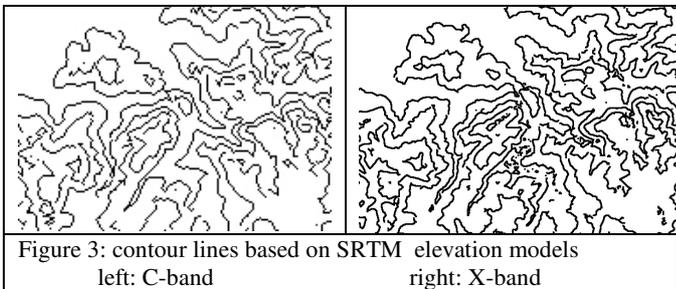


Figure 3: contour lines based on SRTM elevation models left: C-band right: X-band

5. TK 350

The TK350 are perspective Russian space photos flown with an endlap of 60%. Film copies of photos taken from a flying height of 220km have been available. The very large photo size of 460mm x 300mm leads with the focal length of 350mm to a covered area of 284km x 189km or a size of the stereo model of 179km x 189km with a height to base relation of 2.0. The ground resolution is announced corresponding to a pixel size of 5 to 10m, but an edge analysis of the used photos showed only an effective pixel size on the ground of 13m, nevertheless, the photos have been scanned with 16µm corresponding to 10m on the ground.

The image quality of the used TK350 photos was disappointing – an extreme high number of scratches could be seen like also a strong film grain requiring a scratch removal and low pass filter. The poor contrast in the forest area was leading to larger gaps and large errors. In the open areas the contrast was quite better, but nevertheless the results of the generated DSM at the location of the control points having optimal contrast was quite better like against the reference DEM. For the analysis Z-discrepancies exceeding 150m have not been respected.

TK350	RMSZ [m]	Bias [m]	RMSZ – bias F(slope)
Open areas	23.3	2.2	$20.0 + 23.9 * \tan \alpha$
Forest	51.3	7.3	$49.0 + 11.4 * \tan \alpha$
check points	6.6	0	$4.7 + 22 * \tan \alpha$

Table 3: RMS discrepancy of the TK350 DEM against the reference DEM from the map 1 : 25 000 and check points

The achieved results in the forest areas cannot be accepted, but also in the open areas the results are far away from the results published by Chekaline and Fomtchenko 2000 talking about a Z-accuracy of 5m to 7m. Only at the location of the well defined control points this has been reached in flat areas.

6. ASTER

The Japanese ASTER sensor on the US EOS AM-1 platform has in the near infrared band a vertical and by separate optics also an inclined view with 27.2° nadir angle enabling a stereoscopic coverage within the orbit with a height to base relation of 1.7. The short time interval of just 55 seconds between both images avoids problems of a change in the object space. The pixel size is 15m on the ground. The near infrared spectral range has the big advantage of good contrast also in the forest areas, so with the exception of the areas covered by water no larger gaps have been in the generated DSM and the correlation was very high. 72% of the points are correlated better than $r=0.95$ and 99% better than $r=0.6$.

ASTER	DZ > 100m	RMSZ [m]	Bias [m]	RMSZ – bias F(slope)
All points	0.15%	28.7	2.0	$25.3 + 13.2 * \tan \alpha$
Open areas	0.16%	25.0	0.7	$21.7 + 14.5 * \tan \alpha$
Forest	0.22%	31.2	-4.5	$27.9 + 18.5 * \tan \alpha$
check points	0	12.7-14	0	

Table 4: RMS discrepancy of the ASTER DEM against the reference DEM from the map 1 : 25 000 and check points

The RMSZ in the open areas and flat parts of 21.7m corresponds to a Sp_x of 0.85pixels. This is a satisfying operational accuracy for such a sensor. Of course in the inclined parts the quality is reduced like also in the forest parts. Like usual, in the forest parts there is a bias of -4.5m (matched points are located above the reference DEM). In addition the ASTER DSM has been tested against check points. The RMSZ at the check points, which have been used also as control points for the scene orientation, corresponds to Sp_x = 0.5 pixels. In a second test, GPS check points distributed over the city area of Zonguldak were used – this resulted in SZ=13.9m. As next, points were digitized from 1:2000 scale road maps produced by the Highway Department of Turkey. This resulted in root mean square differences for Z of 14.0m; however these values are influenced by steep slopes, just beside the roads in the mountainous region. All the check point results are quite better like the result in relation to the reference DEM. Even in flat areas there is a relation of 1 : 1.5 between the quality figures.

7. SPOT 5

SPOT 5 images do have a pixel size of 5m on the ground. The stereoscopic view is generated by viewing across the orbit, so there is always a remarkable time interval between imaging both

scenes of a stereo model. During this time interval the changes in the object space is often causing problems. The SPOT 5 satellite includes with the HRS-sensor (High Resolution Stereo) also a sensor which is generating a stereo model within the orbit with 5m pixel size in the orbit direction. These images are usually not available for standard applications – SPOT IMAGE like to use these images only for the generation of DEMs by themselves and like to sell only the generated DEMs (see also Jacobsen 2004b), so usually only the classical SPOT scene combination can be used for three dimensional mapping.

In the area of Zonguldak a SPOT stereo combination taken at August 13th and 14th of 2003 are available. Just one day of time interval is optimal. Only below 1% of the area is covered by clouds and cloud shadows and the atmospheric conditions are the same.



Figure 4: histogram of SPOT 5 image Zonguldak
left: whole image right: forest

The panchromatic SPOT images do have also some problems with the grey value variation in forest areas. Figure 4 shows on the left hand side the histogram of the SPOT scene from August 14th with a mean value of 119 and a standard deviation of +/-24.3 grey values. In a typical forest area the standard deviation of the grey values is just +/-6.3. The second scene is very similar.

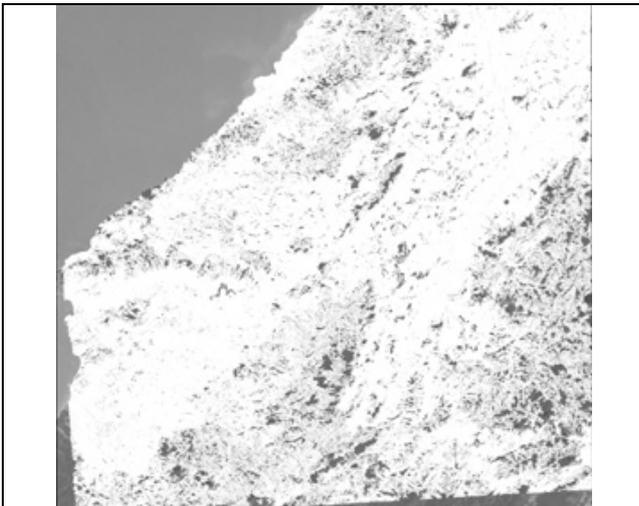


Figure 5: matched points of SPOT 5-model Zonguldak
Matched points = white Upper left: Black Sea

The scenes have been taken with incidence angles of 13.52° and -16.65° corresponding to a height to base relation of 1.85. By theory a height to base relation of 1.0 would be better, but such a relation has stronger differences between the matching windows of both scenes caused by objects above the terrain surface like trees, buildings and rocks, so with the exception of smooth areas, the generated DEM will have a similar accuracy like models with a height to base relation of 1.0.

In figure 5 the accepted matching results with correlation coefficients exceeding 0.6 are shown in white. The not accepted points are located on the water and in forest areas. Figure 6 shows the details of the distribution of the correlation

coefficients depending upon the areas. In the open areas the correlation coefficient is quite higher like in the forests. The darker areas – identical to a lower correlation coefficients – do fit very well with the forest areas. Corresponding to this also a lower accuracy of the generated DSM in the forest areas can be expected.

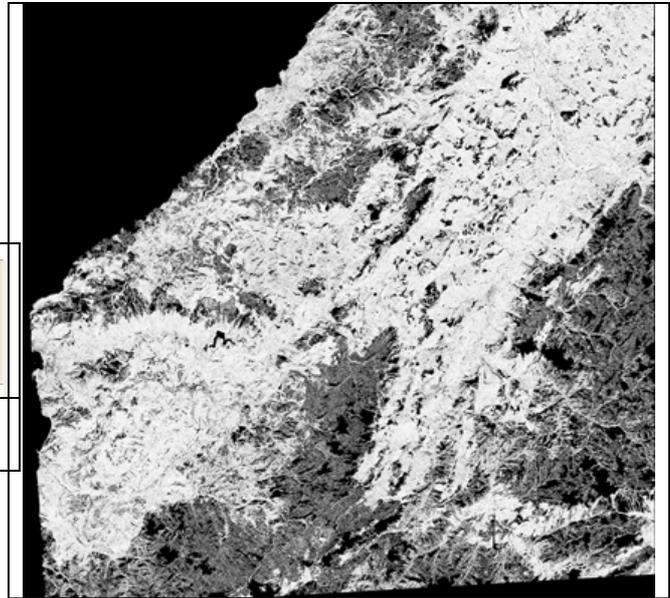


Figure 6: quality map of image matching - SPOT 5-model
grey value 51 = correlation coefficient 0.6
grey value 255 = correlation coefficient 1.0

Level 1A (original images) and Level 1B images (projection to a plane with constant height) of the same scene are available. The bundle orientation of the level 1A images has been with program BLASPO, while the different geometry of the level 1B images required program CORIKON. The orientation results are nearly identical, not indicating an advantage of one image product against the other.

SPOT 5 level 1A	DZ > 50m	RMSZ [m]	Bias [m]	RMSZ – bias F(slope)
All points	0.82%	13.5	7.1	$9.3 + 5.7 * \tan \alpha$
Open areas	0.87%	11.9	5.4	$8.4 + 6.3 * \tan \alpha$
Forest	0.76%	15.0	9.2	$9.8 + 5.3 * \tan \alpha$

Table 5: RMSZ of the SPOT 5 level 1A model against the reference DEM from the map 1 : 25 000

SPOT 5 level 1B	DZ > 50m	RMSZ [m]	Bias [m]	RMSZ – bias F(slope)
All points	0.84%	13.2	7.2	$9.5 + 3.9 * \tan \alpha$
Open areas	0.89%	11.6	5.4	$8.6 + 4.3 * \tan \alpha$
Forest	0.79%	14.9	9.4	$10.0 + 3.3 * \tan \alpha$

Table 6: RMSZ of the SPOT 5 level 1B model against the reference DEM from the map 1 : 25 000

The achieved root mean square differences of the DEMs based on the SPOT5 level 1A and level 1B models to the reference DEM from the topographic map 1 : 25 000 are nearly identical. No advantage of one image product against the other can be seen. For the flat parts of the open areas the root mean square Z-discrepancies corresponds to a x-parallax of 0.9 pixels.

The reference DEM is not free of errors, by this reason the SPOT5 DEMs have been compared also with the SRTM C-band and X-band DEM. Also here nearly the same results have been achieved with the level 1A and the level 1B product, justifying showing only the average of both.

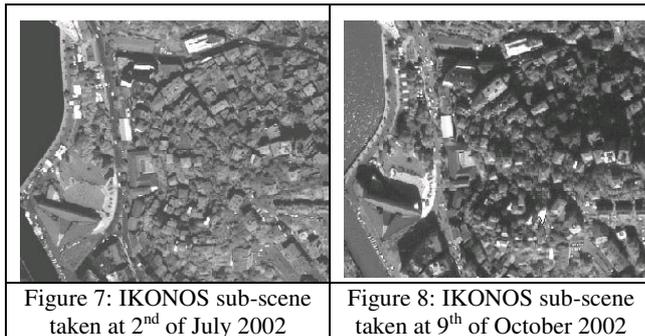
SPOT 5 Open areas	DZ > 50m	RMSZ [m]	Bias [m]	RMSZ – bias F(slope)
against C-band DEM	2.8 %	14.7	4.1	$10.6 + 10.4 * \tan \alpha$
against X-band DEM	0.6%	10.7	2.1	$7.9 + 7.7 * \tan \alpha$

Table 7: RMS discrepancy of the SPOT 5 models against the SRTM C-band and X-band DEM

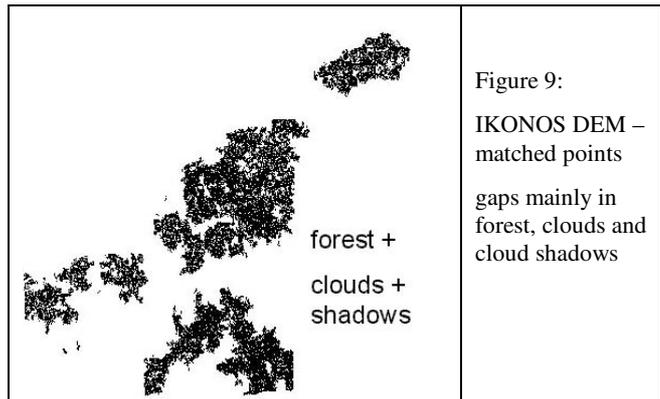
The discrepancies against the X-band DEM are remarkable smaller like against the C-band DEM. Also the number of discrepancies exceeding 50m is smaller in comparison to the C-band data. Such a different accuracy of the SRTM data is only indicated by a direct comparison against check points determined by GPS (tables 1 and 2). The spacing of the X-band DEM is just ~30m while the spacing of the C-band data is in the range of 90m. This may cause a reduction of the accuracy of interpolated values in the rough terrain of Zonguldak. The analysis of the SRTM-data (chapter 4) is independent upon this, because only the existing height values are compared with the reference DEM and the interpolation has been done in the reference DEM.

The root mean square Z-discrepancies of the SPOT5 elevation model against the X-band data are slightly smaller like against the reference DEM from the topographic map. This does not indicate a better accuracy of the X-band data in relation to the reference DEM because the matched points are influenced like the SRTM data also in the open areas by objects not belonging to the bare ground like buildings and single trees.

8. IKONOS



The both IKONOS images available in the Zonguldak test area have been taken in July and in October. The change of the radiometric situation, mainly caused by a quite different illumination, together with the very high image resolution resulted in large problems for the automatic image matching. Without low pass filter of the images by a Gauss-filter the matching did not work. After this it was possible to match partially the build up and open areas. In the forest areas the matching failed. The matched points do have an accuracy of just +/-5.8m, corresponding to a standard deviation of the x-parallax of $S_{px} = +/-1.5$ pixel. The y-parallax of the matching has reached $S_{py} = +/-2.2$ pixel and 25% of the matched points have not been accepted because of large Z-discrepancies.



In general, the generated DEM based on the two IKONOS images taken under quite different illumination conditions is not usable. This is quite opposite to excellent results achieved with an IKONOS stereo scene taken from the same orbit (Jacobsen 2004a).

9. CONCLUSION

Digital Elevation Models can be generated based on space information. With the availability of the SRTM C-band data, the absolute accuracy and the details of the DSMs / DEMs generated with different space images have to be compared with this. In general all data sets including the SRTM data will lead at first only to the height information of the visible surface. Because of missing ground information in forest areas it was not possible to reduce the DSMs to DEMs, leading to systematic shifts especially in the forest areas. The accuracy of all elevation models are depending upon the terrain inclination. In steep areas the quality is quite below like in flat areas. The InSAR DSMs from the SRTM mission do have small gaps and problems in the very steep parts caused by the Radar overlay and foreshortening. Nevertheless the accuracy of the SRTM DEMs is better like for all DEMs generated by the different space images with the exception of IKONOS in areas not so much influenced by radiometric differences. But IKONOS models which shall be used for DEM generation should be from the same orbit to avoid matching problems. Especially the very high resolution images are sensitive against a remarkable change of the sun elevation and change of the objects by the vegetation period.

In general for flat and open areas an accuracy of the x-parallax a little below 1 pixel has been reached if there is no change of the radiometric characteristics. But not only the accuracy of the individual DEM points is important, also the spacing should be respected. A spacing of 90m like for the SRTM C-band data is causing a not negligible loss of details in a mountainous area like Zonguldak justifying the generation of DEMs based on high resolution images starting with approximately 5m pixel size.

The DEMs based on image matching are quite depending upon the contrast. Optimal conditions we do have at check points, always selected in more flat parts with good contrast. But the results achieved with such points are not realistic for larger areas, where we may have some inclination and also areas with a small variation of the grey values. In the visible spectral range problems do exist with forest areas. Here the matching with near infrared images is quite better.

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