DEMS BASED ON SPACE IMAGES VERSUS SRTM HEIGHT MODELS

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ABSTRACT

Digital elevation models (DEMs) determined by interferometric synthetic aperture radar (InSAR) based on the SRTM mission are available free of charge. The spacing of 1 arc second corresponds to the pixel size of the used SAR images, so no better resolution is possible with the used technique. But the morphologic details are even a little below the possibility of such spacing, limiting the possibility to remove the height values not belonging to the bare ground. Approximately the same accuracy, but more morphologic details can be achieved with height models determined by automatic image matching of SPOT 5 stereo scenes. Outside the USA where the spacing of the SRTM DEMs is limited to 3 arc seconds, even with ASTER stereo models in mountainous areas more details can be reached.

The C-band SAR as well as optical images do lead to height models describing the top of the visible surface. Morphologic details enable a filtering of points located on buildings and on top of the forest surface, leading to a better DEM definition. Nevertheless in open areas a better accuracy is available like in forest areas. A clear dependency of the root mean square errors upon the tangent of the terrain inclination can be seen in all data sets. Available small horizontal shifts of the DEMs should be respected by a least squares fitting of the analysed DEMs.

1. INTRODUCTION

Digital elevation models (DEM's) are a basic component of Geo Information Systems (GIS). With the DEMs of the Shuttle Radar Topography Mission (SRTM) available free of charge for the area 56° latitude south up to 60.25° north (http://edcsgs9.cr.usgs.gov/pub/data/srtm/) a data set sufficient for several applications is existing. There must be a reason for the time consuming generation of DEMs based on other space data. The higher number of existing and proposed space systems enabling the generation of elevation information may be used separately or in combination with the SRTM DEMs to solve remaining problems.

By InSAR based on the C-band (λ= 5.6cm) or the X-band (λ= 3cm) and also with the optical data the height of the visible surface will be generated. The short Radar waves cannot penetrate the vegetation. The so achieved digital surface model (DSM) usually has to be reduced to a DEM describing the height of the bare ground. This can be made by special filtering (Jacobsen, 2001, Passini et al 2002) if at least some height information of the bare ground is available and the noise of the DEM is below the influence of the vegetation and the buildings.

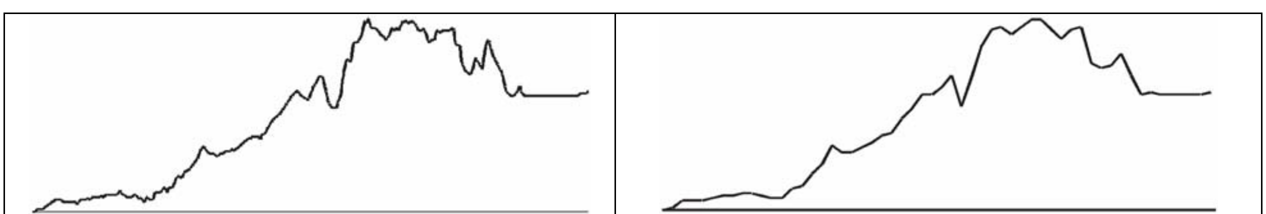


Fig. 1: height profile length = 5km, ΔZ=80m, left: 5m spacing, right: 90m spacing

Not only the accuracy of the height points of a DEM, also the spacing of the points is important (see figure 1). The DEM used for the profile shown in figure 1 has been generated by LIDAR and is available with 5m spacing. If only every 18th point will be used corresponding to a spacing of 90m and if these points are interpolated to a spacing of 5m and compared with the original information, a root mean square height difference of 2.4m has been shown. In some cases not only the accuracy itself, also the morphologic details are important.

A loss of accuracy may happen also by horizontal shifts of the DEMs (see figure 2). Such a shift may be caused by the location accuracy of DEMs resulting from the limited accuracy of the direct sensor orientation which is based on GPS positioning of the satellite and the influence of the attitudes based on gyroscopes and star sensors. Another problem may be the datum of the national coordinate system in relation to the international terrestrial reference frame (ITRF) which sometimes is not known exactly and which is often not respected for DEMs. By this reason a check of the horizontal position of the used DEMs is recommended. The results shown later on are improved by least squares horizontal shift corrections to avoid such an influence.

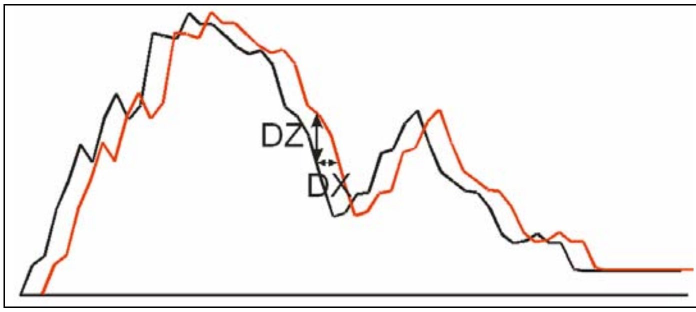


Fig. 2: differences in Z caused by horizontal shift of the DEM

$DZ = DX * \tan \alpha$

α = terrain inclination

2. SHUTTLE RADAR TOPOGRAPHY MISSION

The Shuttle Radar Topography Mission took just 11 days in February 2000. It included the US C-band as well as the German-Italian X-band. The computation of the DEMs based on InSAR was time consuming so it took up to July 2004 to make the data completely available in the WEB. From the area of the US the C-band DEMs are published with a spacing of 1 arc sec corresponding to approximately 30m at the equator; outside the US the data are reduced to 3 arc sec corresponding to approximately 90m at the equator. The X-band DEMs are available with a spacing of 1 arc sec from the German Aerospace Center DLR, but the X-band was not used in the scan SAR mode so the generated DEMs do have large gaps between the covered areas.

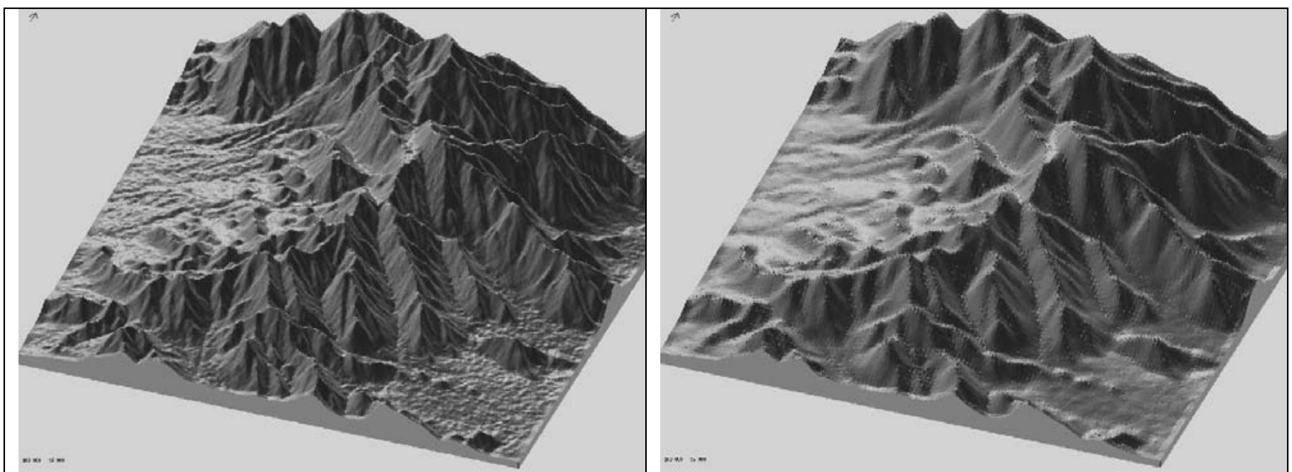


Fig. 3: SRTM C-Band DEM covering 10km x 10km
left hand: DEM with 1” arc sec spacing right hand: DEM with 3” arc sec spacing

SAR images are influenced by layover and shadows in steep areas, so gaps in the InSAR DEMs may occur. In the extreme case of the 1° x 1° area around Mount Everest, 9% of the C-band DEM-points are missing by this reason. Worldwide the gaps are limited to 0.15% including also lakes and large rivers where no energy was reflected back to the antenna. The loss of information caused by the spacing also can be seen in figure 2 showing a detail of a C-Band DEM in Arizona based on the 1 arc sec and the 3 arc sec data. The 3 arc sec C-band DEMs available in the WEB are showing the average height of the neighbored 9 height points of the 1 arc sec data. This is also causing a low pass filtering.

Table 1: loss of accuracy by interpolation				
	spacing	average terrain inclination	average change of terrain inclination	RMSZ
Zonguldak	80m	0.27	0.32	12.0 m
Arizona	90m	0.17	0.09	4.8 m
New Jersey	60m	0.024	0.015	0.45 m
New Jersey	120m	0.024	0.015	1.12 m

The loss of accuracy by interpolation in different terrain types is listed in table 1. In the extremely mountainous area of Zonguldak there is a large loss of accuracy by the larger DEM spacing while in the flat area of New Jersey the loss of accuracy is unimportant in relation to the accuracy of DEMs based on space information.

In the area of Zonguldak, Turkey, the SRTM C-band data as well as the X-band data have been analyzed. The area is very rough with height values from sea level up to 847m. The change of the terrain slope from one spacing to the next is with tangent = 0.32 (32%) larger as the slope itself (see table 1). As reference the height values from topographic maps 1 : 25 000 are given. A first check showed clear horizontal shifts of the SRTM DEMs against the reference DEM. By this reason the horizontal shifts have been determined and respected by least squares adjustment with the Hannover program DEMSHIFT, reducing the root mean square height differences by the factor 2. A corresponding preparation has been made with all analyzed data sets.

Table 2: root mean square height differences of SRTM-DEMs in the area of Zonguldak								
	DZ > 50m	RMSZ [m]	Bias [m]	RMSZ F(slope) [m]	DZ > 50m	RMSZ [m]	Bias [m]	RMSZ F(slope) [m]
	X-band DHM				C-band DHM			
open area	0.67%	10.7	-3.5	$7.6 + 9.5 * \tan\alpha$	2.11%	9.9	-2.9	$7.8 + 6.4 * \tan\alpha$
forest	0.39%	13.8	-8.1	$11.4 + 10.5 * \tan\alpha$	0.03%	13.6	-8.3	$11.6 + 10.5 * \tan\alpha$
check points	0	5.4	-2.0	$1.3 + 40.6 * \tan\alpha$	0	9.4	-2.0	$4.0 + 122 * \tan\alpha$

45% of the area is covered by forest. The C-band and the X-band RADAR cannot penetrate the visible forest surface. So digital surface models and not digital elevation models are available. This can be seen at the bias (systematic differences) in table 2. The bias is shown with the sign of the correction – the InSAR height values are above the reference DEM which is related to the bare ground. But even in the open areas there is a negative bias which may be caused by the high number of buildings and single trees.

The analysis with the Hannover program DEMANAL showed a clear dependency of the root mean square error from the terrain inclination in the form $RMSZ = a + b * \tan\alpha$, with α as terrain inclination. In the open areas the C-band DEM has mean square height differences of 7.8m for flat terrain and 14.2m for terrain with an inclination of 45°. The reference DEM is also not free of errors, it is estimated with +/- 6m - this would lead to an accuracy of the SRTM DEMs in the range of +/-5m for flat parts. At check points a quite better accuracy has been reached (see table 2). This is typical also for optical data. Check points are located in not disturbed areas having a flat ground. But this is not typical for a whole DEM, so the accuracies determined at check points are usually too optimistic for a DEM. A higher number of height discrepancies are exceeding the tolerance limit of 50m. This is the case for 2.11% of the C-band data and 0.67% of the X-band data. Most of these points are located at the shore line which partially has vertical cliffs. Because of the larger swath width by the scan SAR mode of the C-band, the layover starts at 30° terrain inclination while for the X-band it starts at 50° inclination, explaining the higher number of blunders in the C-band data.

Caused by the technique and the averaging of 9 neighbored height points, the SRTM DEMs are usually smoother like the real surface. This can be seen also at the profile shown in figure 4.

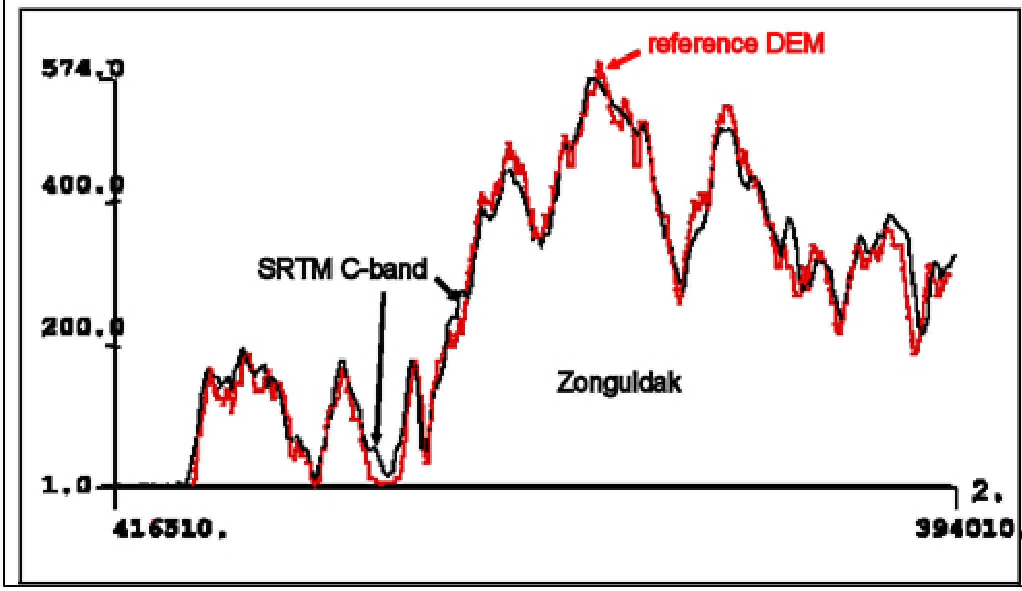


Fig. 4: height profile through SRTM C-band DEM in relation to the reference DEM

Points not located on the bare ground can be removed by a special filter technique if at least some points in the local area are located on the bare ground and if the height of the vegetation or the buildings is smaller than the roughness of the terrain. In the Zonguldak area the root mean square change of the slope is 32%. Together with an average spacing of 80m this corresponds to a height change of the bare ground of 25m. This does not allow a filtering from a DSM to a DEM. But for example in the flat area of the city of Bangkok the situation is quite different. Figure 5a shows a 3D-view to the SRTM C-band DSM of the city area of Bangkok viewed with a vertical angle of 1°. The elevation goes up to 44m. The ground of the Bangkok area is extremely flat with heights not exceeding 4m, so figure 5a shows more the skyline than the bare ground. After filtering with the Hannover program RASCOR the largest elevation is only 6m – this is a realistic value for some artificial raised ground levels. By the filtering in the city area 59% of the height points are eliminated, this is also realistic.

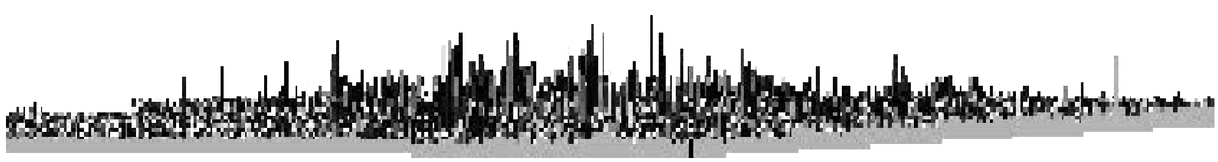


Fig. 5a: 3D-view with 1° elevation angle to SRTM C-band DSM of Bangkok

Fig. 5b: 3D-view with 1° elevation angle to SRTM C-band DEM of Bangkok after filtering

In the US and in Germany very accurate reference DEMs have been available, so the real height accuracy of the SRTM data could be analyzed. In general the same problems like in the Zonguldak area showed up. Some systematic height errors in the range up to 4m exist. This can be explained by the absolute orientation of the SRTM models. Such a bias can be removed by means of control points. Even after filtering the accuracy in the forest areas is not as good as in the open areas. The mean square height differences have to be expressed by a constant value plus a value linear depending upon the terrain inclination. The standard deviation of the SRTM height values for flat and open areas is in the range of 2.7m up to 4.9m and after removing the bias between 2.5m and 3.7m (see table 3). The same accuracy has been reached with C-band and X-band elevation models. It is typical for the mountainous area of Bavaria that 3% of the height values are not available; this always has to be expected in steep locations.

	RMSZ [m]	Bias [m]	RMSZ F(slope)
Arizona, flat up to mountainous	3.9	1.3	2.9 + 22.5 * tan α
Williamsburg NJ, flat	4.7	-3.2	4.7 + 2.4 * tan α
Atlantic City NJ, flat	4.7	-3.6	4.9 + 7.6 * tan α
Bavaria, rolling, open area	4.6	-1.1	2.7 + 8.8 * tan α
Bavaria, mountainous, open area	8.0	-2.4	4.4 + 33.4 * tan α

Table 3: accuracy of SRTM C-band DEMs in different test areas

3. SPACE IMAGES

The accuracy of the height determination based on optical space images is depending upon the height to base relation, the ground sampling distance (GSD = pixel size on ground) and the accuracy of the x-parallax in units of pixels (formula 1).

$$RMSZ = \frac{height}{base} \bullet GSD \bullet S(x - parallax)$$

formula 1: accuracy of object height determined by optical space images
Standard deviation of x-parallax in [pixels]

The standard deviation of the x-parallax is in the range of 0.2 up to 3 pixels depending upon the image contrast, the image quality and the differences in the details. Under differences in the detail we have to understand the differences in the sub-matrixes used for image matching. If a building is viewed in one image from the left hand side and in the other from the right, we can see in the left sub-matrix the left hand wall and the top of the building and in the right sub matrix the right hand wall and the top of the building. Such a difference in the detail is reducing the matching quality, so for a large height to base relation (small base) the standard deviation of the x-parallax is smaller like for a small height to base relation (large base). That means the optimal height to base relation is usually not in the range of 1.0 but more in the range of 1.6 as an average. The optimal configuration of images is depending upon the roughness of the area and the objects on top of the bare ground. For a smooth area without trees and buildings, the optimal height to base relation may be in the range of 1.0, but for an urban or mountainous area the optimal height to base relation may be above 2.0.

The nominal GSD is not in any case identical to the effective pixel size on the ground. For example IKONOS images taken under an incidence angle of 45° do have a physical pixel size of 1.15m ∗ 1.62m, but they are distributed with 1m pixel size. In addition also the image quality and the atmospheric condition has an influence. The effective GSD can be determined by an edge analysis.

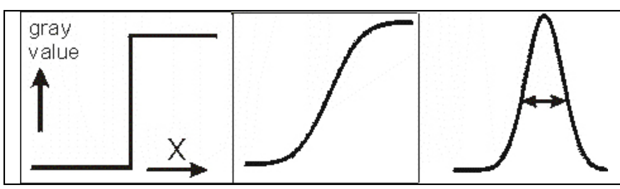


Fig. 6: edge analysis
left: grey value profile in object space
center: grey value profile in image
right: differentiation of gray value profile in image → point spread function with effective GSD

	nominal GSD	effective GSD
ASTER	15 m	16.5 m
TK 350	(10 m)	13 m
Kompsat-1	6.6 m	6.6 m
IRS-1C	5.8 m	6.9 m
SPOT 5	5 m	5 m
IKONOS pan	1 m	1.0 m
QuickBird	0.62 m	0.62 m

Table 5: effective ground sample distance determined by edge analysis

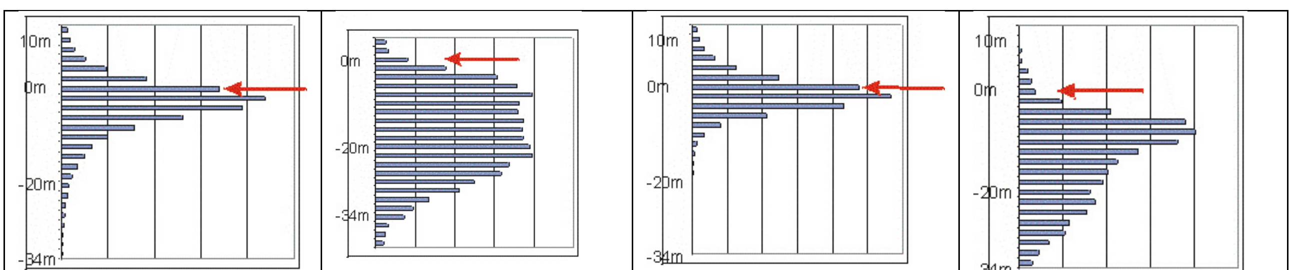
In the test area Zonguldak, Turkey different space images have been checked by edge analysis. For ASTER, TK350 and IRS-1C the effective GSD was exceeding the nominal values. TK350 is a scanned Russian space photo, so the pixel size used for scanning did not match the image resolution. The IRS-1C has the disadvantage of just 6 bit gray values influencing also the image contrast. For ASTER it may also depend upon the actual atmospheric conditions. The effective GSD should be used for the estimation of the height accuracy determined by automatic image matching.

These images also have been used for the DEM generation by automatic image matching with the Hannover program DPCOR. DPCOR is based on least squares matching – the most accurate method for the automatic generation of height information.

Sensor	GSD [m]	height / base	area	RMSZ [m]	RMSZ F(slope) [m]	RMSpx [pixels] flat area
TK 350	(10 /13)	2.0	open	23.3	20.0+23.9*tanα	0.8
			forest	51.3	49.0+11.4*tanα	1.9
			check points	6.6	4.7 + 2.2*tan α	0.2
ASTER	15	1.7	open	25.0	21.7+14.5*tanα	0.8
			forest	31.2	27.9+18.5*tanα	1.1
			check points	12.7		0.5
KOMPSAT-1	6.6	2.0	open	13.6	11.3+11.5*tanα	0.9
			forest	14.7	14.1+12.1*tanα	1.1
SPOT 5	5	1.85	open	11.9	8.4 + 6.3*tan α	0.8
			forest	15.0	9.8 + 5.3*tan α	1.1
			check points	3.8	3.5 + 0.9*tan α	0.4
SPOT 5 HRS	5 * 10	1.2	Bavaria open	6.7	6.4 + 4.9*tan α	1.1
			Bavaria forest	17.0	16.4+ 2.2*tan α	2.7
SPOT 5 HRS filtered	5 * 10	1.2	Bavaria open	4.4	4.2 + 1.6*tan α	0.7
			Bavaria forest	12.3	10.0 + 6.9*tanα	1.7
IKONOS	1	7.5	Maras open	1.7	same orbit	0.2
IKONOS	1	3.8	Zonguldak open	5.8	Δt = 3 month	1.5
QuickBird	0.62	9.1	Arizona open	4.8	Δt = 10 days	0.8

Table 6: accuracy of DEMs based on space images

The clear difference in accuracy between forest and open area has been expected. The DSM achieved with SPOT HRS has been filtered by RASCOR leading to a clear improvement. Of course even after filtering the results in the forest areas are not the same like in the open areas. At first gray value variation in the panchromatic spectral range is very limited for the forest area and if there are no matched points on the ground, the improvement by filtering is limited. This can be seen also with the histogram of discrepancies against the reference DEM – this histogram after filtering is symmetric for the open areas and close to a normal distribution, but for the forest it indicates very well the remaining influence of the trees (figure 7).



open area, no filtering	forest, no filtering	open areas filtered	forest filtered

Fig. 7: histogram of discrepancies SPOT HRS height model against reference LIDAR DEM

The absolute accuracies are quite different depending upon the GSD and the image configuration. If the standard deviation of the x-parallax is computed with formula 1, for the open and flat areas and filtered where it was possible, the results are becoming very similar. With the exception of IKONOS the standard deviation of the x-parallax (Spx) is only in the range of 0.7 up to 0.9 pixels, allowing a good estimation of the DEM accuracy for any type of optical space sensors. The results at check points is with Spx = 0.2 up to 0.5 GSD pixels better. This is always the case because check points are located in areas with good contrast and they are not disturbed by vegetation or buildings. With check points the sensor quality can be checked but not the accuracy of a DEM which includes also parts with poor contrast and is disturbed by elements on top of the bare ground.

The Russian space photos do have a poor contrast in the forest areas causing large gaps in the matched areas. In general the results in the forest could not be accepted.

Based on the 2 optics, ASTER always has a stereoscopic coverage within the same orbit. The inclined stereo channel is only available with the near infrared band, this has the advantage of a good contrast also in the forest areas where the range of gray values is very narrow in the panchromatic spectral range. Automatic image matching allows a DEM spacing of approximately 3 GSD, corresponding to 45m for ASTER. A smaller spacing leads to high correlation of the neighbored height values because the result is based nearly on the same pixels in the image. With a spacing of 45m ASTER has an advantage against the SRTM C-band with 3 arc sec spacing.

The not well known South Korean Kompsat 1 offers with 6.6m GSD possibilities not far away from SPOT 5. The images could be handled without any problem. The only disadvantage is the limited swath width of 17km.

The same SPOT 5 images have been available as level 1A (close to original images) and level 1B (projected to a plane with constant height). The geometry of both products is quite different requiring different programs for the solution, but the final results have been nearly identical. If the images are handled in the correct manner, the product level is unimportant.

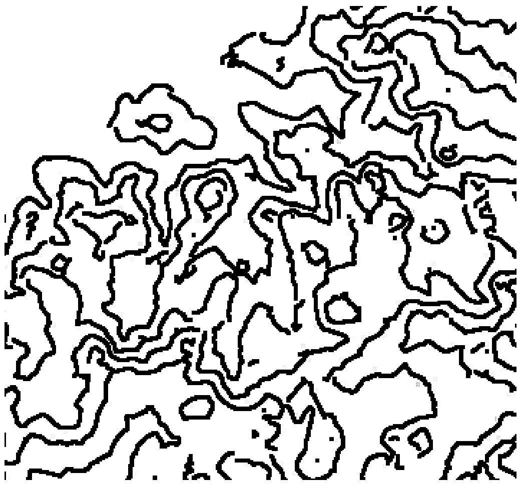
SPOT 5 has as an independent sensor the High Resolution Stereo (HRS), viewing in the orbit direction forward and with a second optic backward. So a stereo coverage can be generated having just 90 seconds difference in time, avoiding the problems of large time differences of images taken from different orbits. With larger time differences the radiometric condition may change as well as the shadows. So in some cases severe problems exists in matching such images. The accuracy achieved with SPOT HRS is in the same range like for SRTM. The GSD of 5m x 10m allows a spacing of 15m x 30m, so more morphologic details can be expected with this sensor like with SRTM. With the exception of a test organized by the ISPRS, SPOT Image is not distributing the HRS-images, only the generated DEMs can be ordered. But in near future with the IRS Cartosat I and ALOS similar stereo systems having even a smaller GSD of 2.5m will be available.

A stereo combination of IKONOS taken from the same orbit with a height to base relation of 7.5 has been analyzed. The images of such a view combination are very similar, so also in the city area no problems with automatic image matching appeared. The building heights have been generated with an accuracy of 1.7m corresponding to Spx=0.22 GSD. Of course this is not the quality of a DEM, but it shows the sensor capacity. In the area of Zonguldak an IKONOS scene combination having 3 month difference in time have been used for a DEM generation. The sun elevation was with 67° and 41° too different causing large radiometric differences in the very rough area. So the matching failed in the forest, but also in the build up areas it was difficult. The large gaps in the resulting DEM could not be accepted.

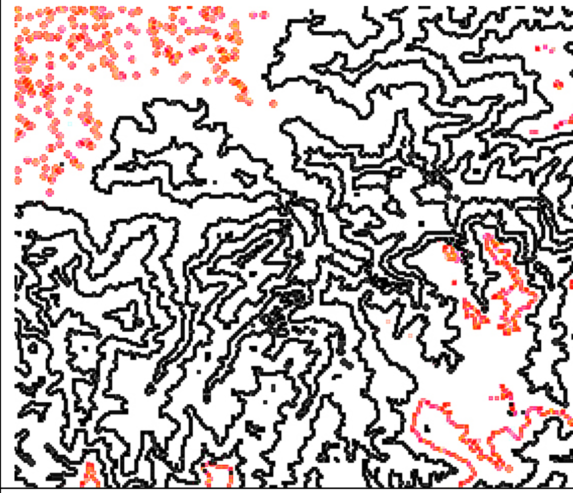
With a combination of QuickBird scenes having just 10 days difference in time no problems of the matching appeared. The DEM-accuracy is with Spx=0.8 pixels in the same range like for the other optical space sensors. In general the dominating effect is the specification of the surface and areas with limited image contrast.

The accuracy of the points of a DEM is one topic; important is also the relative accuracy – the accuracy of a point in relation to the neighborhood - and the spacing of the DEM points. The relative accuracy and the spacing are important for the morphologic details; that means also the fine structure of the generated contour lines.

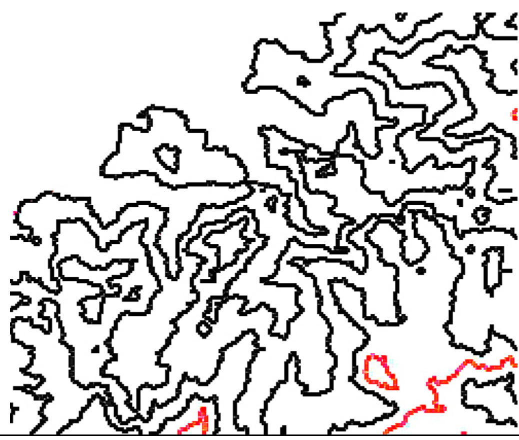
4. MORPHOLOGIC QUALITY



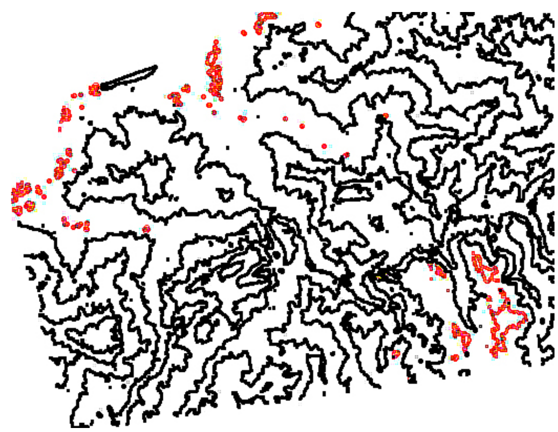
contour lines by SRTM C-band



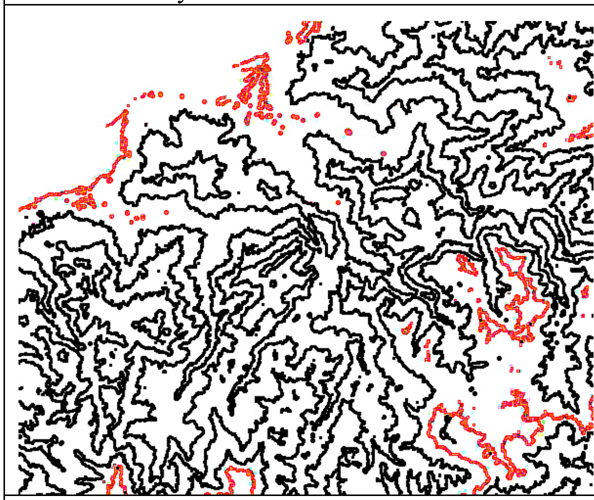
contour lines by SRTM X-band



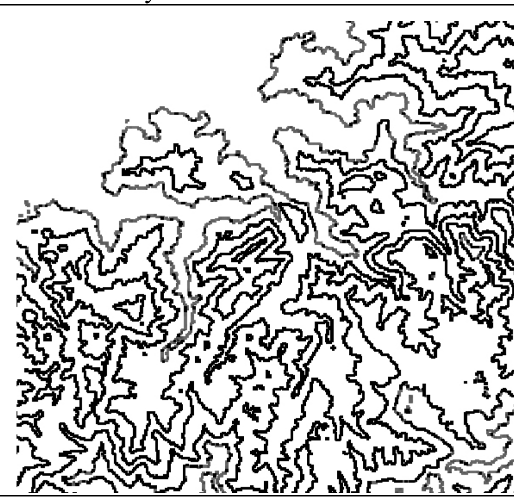
contour lines by ASTER



contour lines by KOMPSAT 1



contour lines by SPOT 5



reference map 1 : 25 000

Fig. 8: contour lines based on space information, Zonguldak area, contour interval 100m

The comparison of contour lines in the mountainous area of Zonguldak shows very well the morphologic quality. The SRTM C-band DEM with 3 arc sec spacing (approximately 80m in this latitude) only leads to rough details of the contour lines. With the 1 arc sec spacing of the SRTM X-band quite more details can be seen (see figure 8). Even with ASTER images a DEM can be generated with more morphologic details like with the 80m spacing of the SRTM C-band and this in spite of the limited accuracy of 21.7m for open and flat areas. The morphologic details of the DEMs based on SRTM X-band, Kompsat 1 and SPOT 5 are in the same level. The results based on the IKONOS combination having 3 month difference in time are more detailed in the areas where the matching was without problems, but too large gaps are caused by the large radiometric differences.

Of course the results are different in rolling and flat areas. Here the point accuracy is more important, so there is no advantage of ASTER images, but the possible small spacing of DEMs based on optical space images is leading to more details like the SRTM DEMs. This may be unimportant for the generation of ortho images but it should be respected if contour lines are required.

5. CONCLUSION

It is economic to generate digital elevation models by means of space information. For the mayor part of the land surface DEMs based on the SRTM mission are existing. The US C-band data are available free of charge in the Internet but only for the US with a spacing of 1 arc sec, outside the US only with 3 arc sec spacing. The high geometric quality of the SRTM data of +/-2.7m up to +/-4.9m for open and flat areas are justifying only the generation of DEMs based on optical space images if some advantages are existing and this is the case for the morphologic details.

The quality of a DEM cannot be described just by one figure, it has to be made as a function of the terrain inclination in the form $SZ = a + b * \tan(\text{slope})$. In addition the open and the forest areas have to be analyzed separately. If the roughness of the terrain is below the relative height accuracy, the DSMs should be filtered to DEMs. The exact analysis should be made not just with height differences but with the Euklidic distances – the shortest distance of the DEMs to be analyzed. This is not influencing the constant component of the standard deviation of the heights, but only the component depending upon the tangent of the terrain inclination. Intensive tests have shown just up to 5% smaller values for this component, so it is important only for theoretical investigations and not for real applications.

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