

GENERATION AND VALIDATION OF DIGITAL ELEVATION MODELS BASED ON SATELLITE IMAGES

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ABSTRACT:

Digital elevation models (DEMs) are available free of charge for most areas of the world. For example the C-band height model of the Shuttle Radar Topography Mission (SRTM) has with a standard deviation of 3m to 5m for flat and open areas accuracy sufficient for several cases, but the spacing of 3 arcsec is causing a loss of morphologic information in mountains. Even with quite less accurate DEMs based on ASTER, more morphologic details can be achieved. With the very high resolution satellite images a higher accuracy and quite more details than with the SRTM DEM can be reached. In open areas the vertical accuracy is linear depending upon the height-to-base-ratio, but in the city this is quite more difficult. With a height-to-base-ratio of 1.0 in the city the corresponding image details of the high resolution scenes are too different, so that only a limited percentage of the model points can be matched automatically. The optimal convergence angle is quite smaller. In addition with a height-to-base-ratio close to 1.0 only few points on the street level can be achieved in densely build up areas.

Different types of satellite image models have been analysed for completeness, accuracy and morphologic details in relation to a reference DEM based on large scale photogrammetry.

1. INTRODUCTION

Digital Elevation Models are a basic requirement for several purposes. They can be generated with Interferometric Synthetic Aperture Radar (InSAR), photogrammetric methods with space and aerial images, laser scanning and classical ground survey. The classical ground survey is economic only for small areas. Aerial laser scanning is detailed and accurate, but expensive and laser scanners are mainly only available in Europe and North America. Aerial photogrammetry is still the major source for DEMs, the classical method is based on manual survey of point clouds or directly contour drawing. The manual measurement today is widely replaced by automatic image matching. For medium up to lower accuracy and large areas space images can be used. The use of space images has to be justified in relation to the free available DEMs from the Shuttle Radar Topography Mission. In the Zonguldak test area SRTM C-band and X-band height models have been investigated like DEMs based on different space images.

2. SRTM HEIGHT MODELS

By Interferometric Synthetic Aperture Radar (InSAR), during the Shuttle Radar Topography Mission (SRTM) height models have been generated, covering the earth surface from 56° south up to 60° north. With the exception of small gaps in steep parts, dry sand deserts and water surfaces the free available US C-band data are covering the area completely while the X-band data, distributed by the German DLR, are covering it only partially. The short wavelength C-band and X-band radar cannot penetrate the vegetation so the height models are Digital Surface Models (DSMs) representing the visible surface including vegetation and buildings. In the area of Zonguldak,

Turkey, C-band and X-band DSMs are available and have been analysed. As reference a height model with a spacing of 10m based on large scale aerial photogrammetry is available.

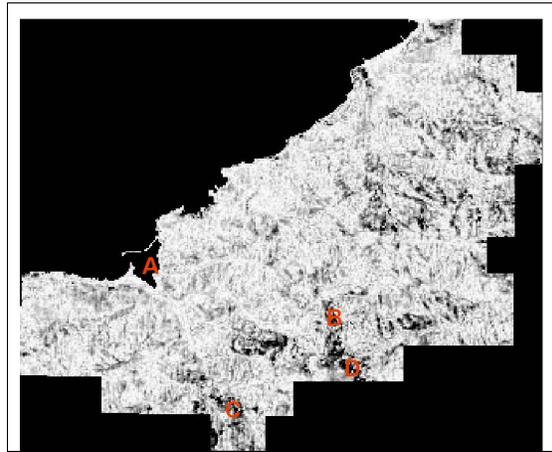


Fig. 1: grey value coded height differences SRTM X-band height model against reference DEM
white = 0.0m, black \geq 30.0m or no data

Figure 1 shows the height discrepancies of the X-band DSM against the reference height model. A not equal distribution of the discrepancies is obvious. The DLR is distributing together with the X-band height model a height error map with estimated accuracy. A comparison with the SRTM X-band height error map in this sub-area leads to a good correlation between both. The location A is different – in the harbour of Zonguldak the

water surface is flat causing a mirror effect, so no energy is going back to the antenna. The areas B, C and D are corresponding, but demonstrating that the height error map is not so detailed. A comparison with the slope shows a more detailed correlation and also the reason for larger height differences – it is mainly depending upon the inclination.

For a more precise analysis the used Hannover program DEMANAL for the height analysis can use a classification layer for the analysis separately for different classes. In this case only the forest and not forest area have been separated, the latter is named as open area, but it is also influenced by buildings in the city.

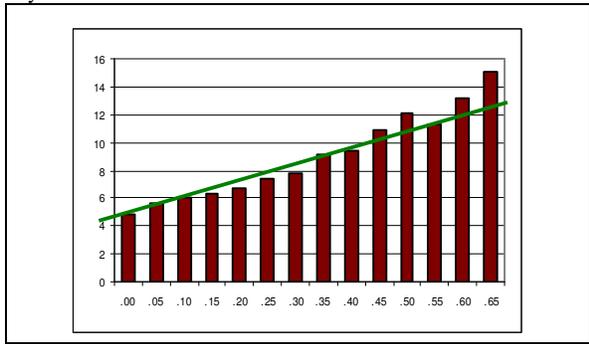


Fig. 2: root mean square height differences SRTM X-band DSM against reference DEM for open areas as function of terrain inclination

horizontal axis: tan (terrain inclination)
vertical axis : RMSE [m]

The clear dependency of the accuracy from the terrain inclination has been seen also at all other height models. This requires an expression of the vertical accuracy as function $A+B \cdot \tan(\text{terrain inclination})$. Before height models can be compared, it has to be checked if the horizontal location corresponds. Very often there are horizontal shifts caused by limited orientation accuracy or by datum problems of the national net.

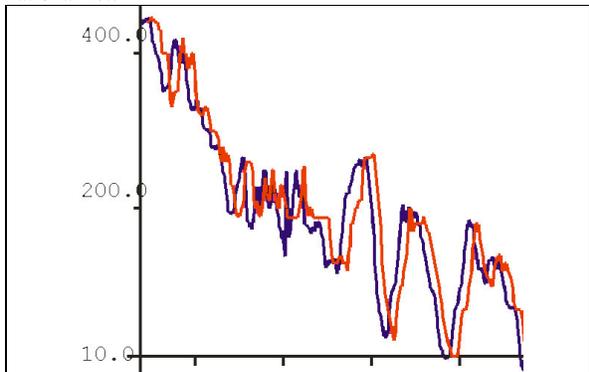


Fig. 3: Z-profile reference DEM (left), original SRTM X-band DEM (right)
 $DX = DZ / \tan(\text{terrain inclination})$ formula 1

For all analysed height models the horizontal shifts have been determined and respected by adjustment with the Hannover program DEMSHIFT. Horizontal shifts up to 200m, mainly caused by datum problems, were existing, causing root mean square height discrepancies up to 40m in the very mountainous area of Zonguldak.

By InSAR with C-band and X-band as well as with automatic image matching DSMs are generated. If the influence of the vegetation and the buildings is exceeding the terrain roughness in relation to the point spacing together with the accuracy of the height determination, a DSM can be filtered to a DEM (Passini et al 2002). Some limitations exist in forest areas if no point is located on the ground. The Zonguldak area for most data sets is too rough for a successful filtering, so the influence of the vegetation and the buildings could not be separated.

	RMSZ [m]	bias [m]	RMSZ without bias [m]
open areas	$4.72+10.4 \cdot \tan \alpha$	-3.67	$4.05+9.6 \cdot \tan \alpha$
forest	$6.50+15.8 \cdot \tan \alpha$	-5.30	$5.56+12.2 \cdot \tan \alpha$

table 1: SRTM X-band DSM against reference DEM

	RMSZ [m]	bias [m]	RMSZ without bias [m]
open areas	$5.93+5.6 \cdot \tan \alpha$	-4.40	$4.51+5.8 \cdot \tan \alpha$
forest	$6.28+6.5 \cdot \tan \alpha$	-4.85	$5.92+1.9 \cdot \tan \alpha$

table 2: SRTM C-band DSM against reference DEM

No major difference in the vertical accuracy of the height points from the SRTM X-band and C-band can be seen (tables 1 and 2). The X-band is more accurate in the flat parts, but has a stronger dependency upon terrain inclination.

The accuracy of the height points is only one type of information about the DEM quality, the point spacing is also important. The free available SRTM C-band DSM has a point spacing of 3 arcsec corresponding to 92m x 69m while the SRTM X-band DSM is distributed with 1 arcsec spacing corresponding to 31m x 23m in the Zonguldak area. The Zonguldak test area is very rough with an average change of the terrain inclination by 32% related to a grid with 40m spacing. The SRTM height models have been interpolated to a 10m grid like the reference height model.

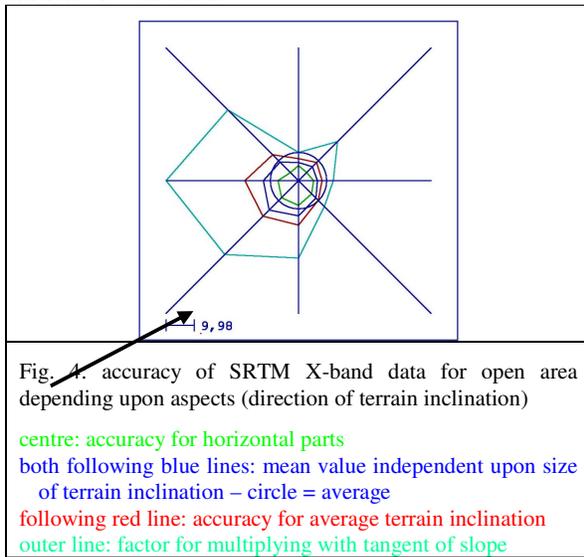
	RMSE interpolated DSM	RMSE – relation interpolated / original heights for flat parts
X-band open	$5.59+14.1 \cdot \tan \alpha$	(5.59/4.55) 1.23
X-band forest	$6.78+15.5 \cdot \tan \alpha$	(6.78/5.73) 1.18
C-band open	$10.58+16.9 \cdot \tan \alpha$	(10.58/5.92) 1.79
C-band forest	$12.20+16.0 \cdot \tan \alpha$	(12.20/6.32) 1.93

table 3: influence of DSM interpolation

There is a strong loss of accuracy for the interpolated C-band DSM in relation to the original height points by the factor of 1.79 and 1.93 while the more dense spacing of the X-band DSM is causing only a loss by the factor 1.2.

The X-band DSM shows a very clear dependency upon the aspects (figure 4). The maximal values correspond to the radar view direction (arrow in figure 4). For the average terrain inclination the largest RMSE is in the terrain inclination ascending to the view direction and the smallest values are in the descending direction. For the C-band data in the Zonguldak area the accuracy is not depending upon the aspects because

they are representing the average of the heights based on different view directions.



3. HEIGHT MODELS GENERATED WITH OPTICAL SPACE IMAGES

For the Zonguldak test area stereo image combinations taken by TK350, ASTER, KOMPSAT-1, SPOT 5, IKONOS and OrbView-3 are available. The images do have ground sampling distances (GSD = distance of the neighboured pixel centres projected to the ground) between 15m and 1m. The Russian TK350 is an analogue camera; its effective GSD has been determined by edge analysis. Also for the digital cameras the effective GSD has been checked - it was for all listed sensors identical to the nominal values. The vertical accuracy can be estimated by formula 2.

$$SZ = \frac{h}{b} \cdot S_{px} \quad \text{formula 2: standard deviation of height}$$

h/b=height to base relation
 S_{px} = standard deviation of x-parallax [GSD]

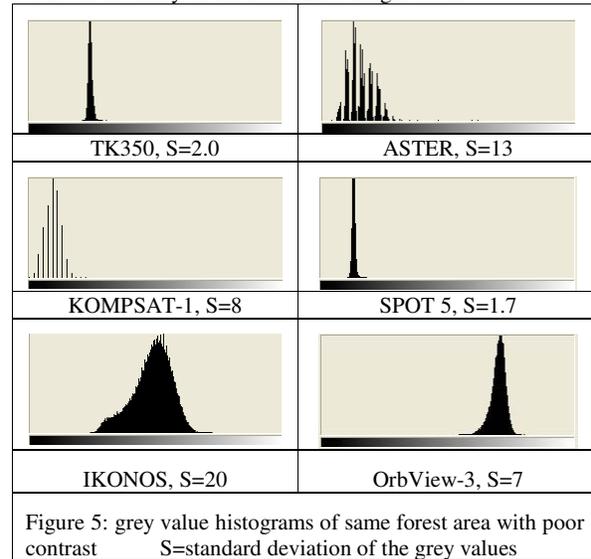
	GSD	h/b	Δt	estimated SZ for S _{px} = 1.0*GSD
TK350 (photo)	13m	3.1	9 sec	40 m
ASTER	15m	2.1	50 sec	31 m
KOMPSAT-1	6.6m	2.1	11 days	14 m
SPOT 5	5m	1.9	5 days	10 m
IKONOS	1m	3.8	99 days	3.8 m
OrbView-2	1m	1.4	40 sec	1.4m

Table 4: in Zonguldak test area available stereo models

The TK350, the ASTER and the OrbView-3 models have been taken from the same orbit. For the other sensors there was a longer time interval between the images of a model. Especially two IKONOS scenes have been taken under quite different conditions with sun elevations of 67° and 41° causing quite different shadows.

The image matching has been made with the Hannover program DPCOR by least squares matching. It was tried to match every third pixel with sub-matrices of 10 * 10 pixels. The matching of

directly neighboured pixels is leading to highly correlated results because it is based on 90% of the same pixels and it has been shown that with every third pixel nearly the same description of the terrain will be reached but in a quite shorter computation time. As lower tolerance limit a correlation coefficient of 0.6 was used. In some detailed tests with precise reference data in the Hannover area no significant dependency of the height accuracy from the correlation coefficient above the value of 0.6 could be seen. Below a correlation coefficient of 0.6 lower accuracy of the determined height occur.



The matching in the forest area is depending upon the contrast and the shadows depending upon the sun elevation. The contrast is dominated by the spectral range of the image. In the real panchromatic range, visible also by human eyes, the contrast in the forest is poor and only based on shadow effects. This can be seen at the histogram of the TK350 and SPOT 5. ASTER is using the near infrared for the stereo combination. In near infrared the vegetation shows a strong variation of reflectance like visible at the standard deviation of the grey values in figure 5. KOMPSAT-1 and SPOT 5 do have a similar spectral range with a small part of the near infrared (0.7μm wavelength). The very narrow histogram of SPOT is also caused by the time of the year. IKONOS and OrbView-3 do have an extended spectral range including also near infrared, leading also to a good variation of the grey values in the forest.

Beside the disturbing change of the shadows caused by larger time intervals of imaging the both scenes of a stereo model in the build up area, the automatic image matching is influenced by the convergence of the view directions. A large angle of convergence is imaging buildings quite different – on both scenes the roof top is visible, but different vertical parts (figure 6). This is not a problem for human operators, they do have a nice stereo view, but it is very difficult for automatic matching. There are gaps in matching and problems with the approximate location of conjugate points. With larger GSD this is not a problem because the size of the vertical walls is only few pixels, but it is a problem for very high resolution images. In the example in figure 6 the vertical wall has a size of 15 pixels.

As obvious in figure 6, the GSD of 1m together with the height to base relation of 1.4 is causing problems in the build up areas, so remarkable matching gaps in the city area could not be avoided.

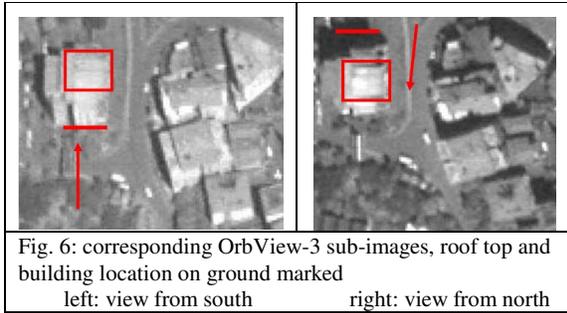


Fig. 6: corresponding OrbView-3 sub-images, roof top and building location on ground marked
left: view from south right: view from north

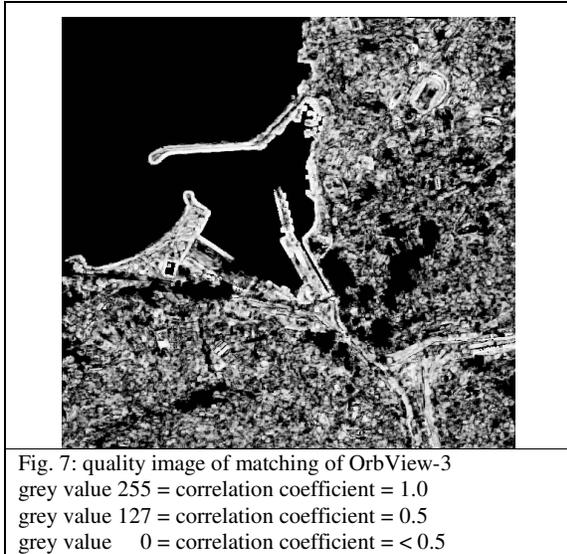


Fig. 7: quality image of matching of OrbView-3
grey value 255 = correlation coefficient = 1.0
grey value 127 = correlation coefficient = 0.5
grey value 0 = correlation coefficient = < 0.5

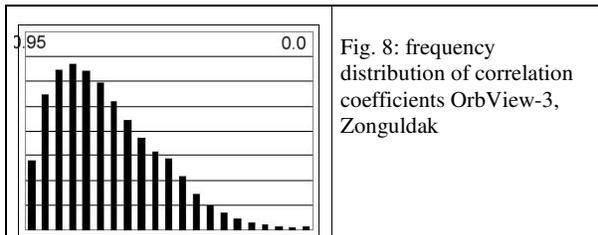


Fig. 8: frequency distribution of correlation coefficients OrbView-3, Zonguldak

The matching quality image (figure 7) as well as the frequency distribution of the correlation coefficients (figure 8) of OrbView-3 in the city area of Zonguldak demonstrate the problem of matching very high resolution images with larger convergence angles. The correlation coefficients are limited and in not negligible parts the matching could not be accepted. Reverse very good results have been reached in matching IKONOS-images having just a height to base relation of 7.1 (Jacobsen 2006).

The photo quality of the TK350-images is limited. As visible in Fig. 9, many scratches are available in the images. In addition, the film grain is not negligible. Automatic image matching without scratch and low pass filter failed. In the forest area the poor contrast (see also histogram in figure 5) caused problems. With the height to base relation of 3.1 and the effective GSD of 13m a standard deviation of the height of 40m would be caused if the standard deviation of the x-parallax (Spx) is in the range of 1 pixel. For good contrast Spx should be in the range of 0.3 up to 0.5 pixels. In relation to the reference height model in

open areas a vertical accuracy of $SZ = 21.1m + 18.8 * \tan \alpha$ has been reached, in forest areas $SZ = 53.9m + 11.4 * \tan \alpha$. For the open areas this is within the expectation even if this is quite above the value of 7m published by Chekaline and Fomtchenko, 2000, but with this low photo quality an accuracy of 7m cannot be reached. The results in the forest areas cannot be accepted. In general there is no justification to use TK350 photos for the DEM generation if the SRTM C-band data are available.

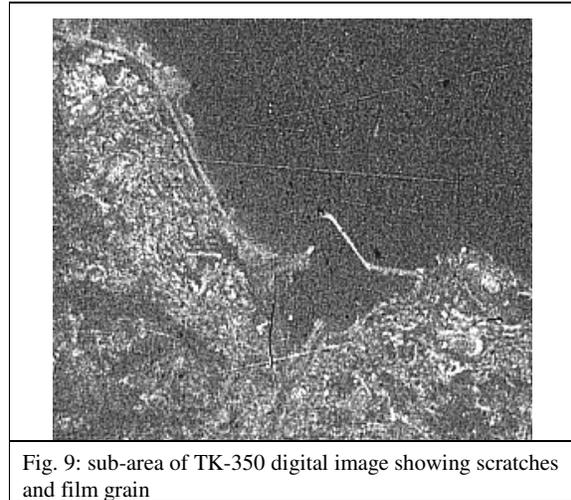


Fig. 9: sub-area of TK-350 digital image showing scratches and film grain

The completeness of matching with ASTER, KOMPSAT-1, SPOT 5 and IKONOS can be seen in figure 10. The generated ASTER DEM has more or less no gaps. Also the results achieved with KOMPSAT-1 is satisfying, gaps are limited to water bodies and very dark forest located in shadow. Even if it looks different for SPOT 5, it is similar to KOMPSAT-1. The larger percentage of matching gaps is caused by larger shadow parts depending upon lower sun elevation.

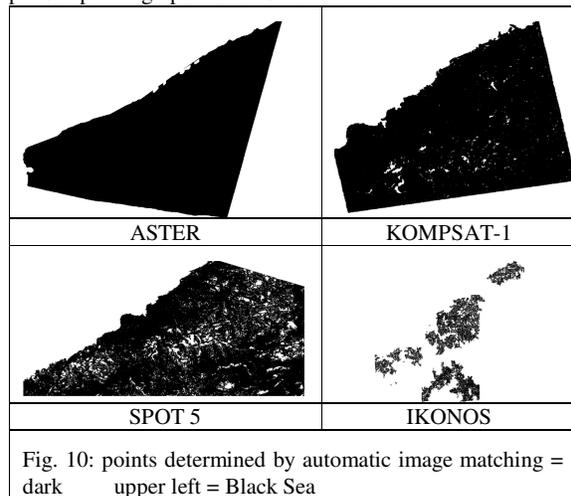


Fig. 10: points determined by automatic image matching = dark upper left = Black Sea

The matching with IKONOS images having 99 days difference in time was not successful. Both IKONOS scenes have been taken not under same conditions with sun elevations of 67° and 41° causing quite different shadows (see also figure 11). In the forest area the contrast is dominated by shadows and in the build up areas it is not possible to match objects with different shadow limits.

Corresponding to the matching problems the frequency distribution of the correlation coefficients varies and the percentage below the acceptance limit is not the same (fig. 12).



Fig.11: same buildings imaged by IKONOS with 67° sun elevation (left) and 41° (right)

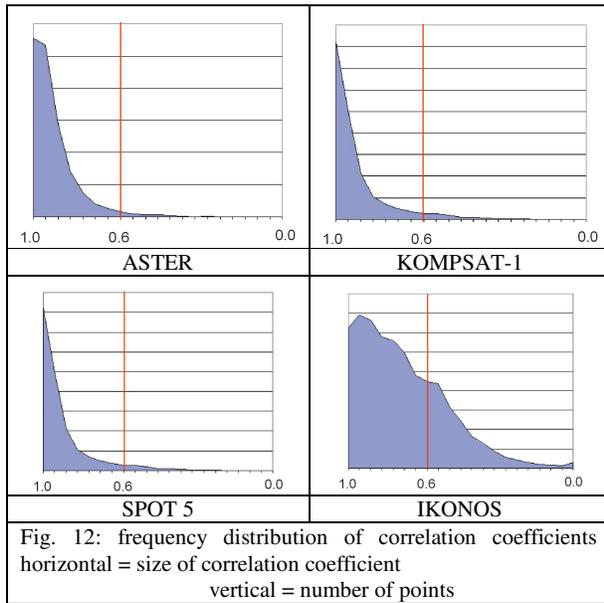


Fig. 12: frequency distribution of correlation coefficients
horizontal = size of correlation coefficient
vertical = number of points

Sensor	area	RMSZ [m]	RMSZ F(slope) [m]	RMSpx flat areas [GSD]
TK 350	open	23.3	$20.0+23.9*\tan\alpha$	0.5
	forest	51.3	$49.0+11.4*\tan\alpha$	1.2
	check points	6.6	$4.7 + 2.2*\tan \alpha$	0.12
ASTER	open	25.0	$21.7+14.5*\tan\alpha$	0.7
	forest	31.2	$27.9+18.5*\tan\alpha$	0.9
	check points	12.7		0.4
KOMPSAT-1	open	13.6	$11.3+11.5*\tan\alpha$	0.8
	forest	14.7	$14.1+12.1*\tan\alpha$	1.0
SPOT 5	open	11.9	$5.3 + 5.9*\tan \alpha$	0.6
	forest	15.0	$6.6 + 6.3*\tan \alpha$	0.7
	check points	3.8	$3.5 + 0.9*\tan \alpha$	0.4
IKONOS	open	5.8		1.5

Table 5: accuracy of height models generated by automatic image matching in Zonguldak test area

The scene geometry can be seen at the accuracy achieved at check points (table 5). It is 0.4 pixels and smaller. Check points are well defined with good contrast, not influenced by neighbored elements, located in approximately horizontal areas and known precisely. The quite larger values for the DEM accuracy are caused by vegetation, buildings and not optimal contrast. The influence of the vegetation can be seen by the difference between open areas and forest where the open areas are still influenced by buildings. With exception of ASTER, in the forest the contrast is not so good like in the open areas. In addition of course the reference is also not free of error. First tests have been made with a DEM based on a map 1 : 25 000 having an accuracy in the range of 6m to 8m. This was limiting the results, so now with the quite better reference height model from large scale mapping the results are still better.

In the open areas for flat parts the vertical accuracy corresponds to a standard deviation of the x-parallax of 0.5 up to 0.8 pixels. This is a satisfying result for the very rough area of Zonguldak including a remaining influence of buildings and partially also vegetation.

Like with SPOT, a stereo model is generated by KOMPSAT with a view across the orbit. This does not allow the generation of a stereo model within the same day. With 6.6m GSD the resolution of KOMPSAT-1 is not far away from SPOT 5. This can be seen also at the achieved accuracies which are not too different. The disadvantage of KOMPSAT-1 is the limited swath width of 17km and the not optimal image distribution network. With SPOT 5 excellent results have been reached at check points, showing the potential of the system geometry. Of course the height model cannot reach the same accuracy.

The results listed in table 4 are from the matched images not improved by filtering for points not belonging to the bare ground (Passini et al 2002). This filter process is more successful with better accuracy of the object points. It works very well in open areas, but it has some limitations in the forest areas having no matched point on the bare ground. In the forest area the forest borders can be improved and it keeps the points on the level of lower vegetation. A filtering with the Hannover program RASCOR improves the SPOT 5 data in the open areas to $SZ = 4.49m + 3.08m * \tan \alpha$ and in the forest areas to $SZ=5.24m + 9.36m * \tan \alpha$. For flat and open areas this corresponds to $Spx = 0.47$ pixels.

4. MORPHOLOGIC QUALITY

The morphologic details in the mountainous area of Zonguldak are mainly depending upon the DEM spacing; the accuracy has a limited influence. The point spacing leads to a generalization of the mapped area. The contour lines based on the SRTM C-band show the strongest generalization effects. Even in the quite less accurate ASTER height model more morphologic details can be seen. KOMPSAT-1 and SPOT 5 do agree very well and even may show more details like the topographic map 1:25000. In general the morphologic details of KOMPSAT-1, SPOT 5 and also SRTM X-band are very similar to the topographic map. The SRTM X-band shows some noise in the sea. The investigated DEM points of the SRTM C-band are more accurate like of ASTER, KOMPSAT-1 and SPOT 5. Of course for flat areas the results will be different; here the accuracy is more important like the DEM point spacing.

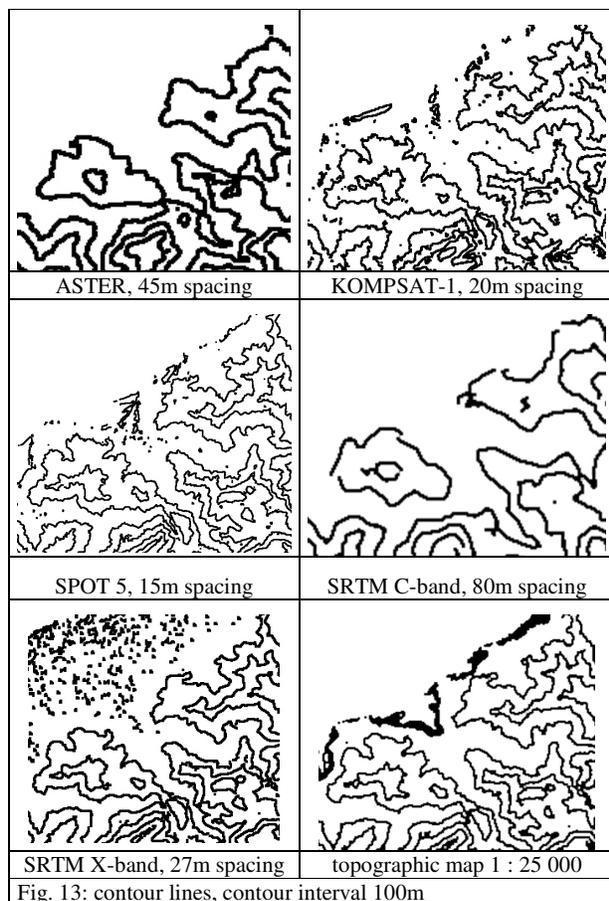


Fig. 13: contour lines, contour interval 100m

5. CONCLUSION

The height models generated and analysed in the area of Zonguldak are dominated by the very rough terrain. The change of the inclination over 40m spacing is even exceeding the inclination itself. By this reason not the best results could be achieved and some of the conclusions are valid only for such a mountainous terrain.

The generated as well as the SRTM height models are digital surface models presenting the height of the visible surface, influenced by the vegetation and the buildings. Usually DEMs representing the solid ground are requested. A filtering from a DSM to a DEM is possible if the point accuracy together with terrain roughness is below the influence of the vegetation and the buildings. By this reason the SPOT 5 height model having a spacing of 15m and accuracy in the range of 5m could be improved. For the other models the filtering did not lead to better results. The accuracy of the height points from SRTM C-band and X-band was on a similar level, but the spacing of the C-band was too large for a filtering in the very rough area of Zonguldak. In addition the SRTM height models are smoothing the surface, limiting the possibility of a filtering. In the area of Zonguldak there is a remarkable difference between the point accuracy from SRTM and the accuracy of interpolated points – the C-band height model shows for interpolated points approximately the double root mean square difference like for the original points, while for the X-band height values there is only a loss of 20% by interpolation over a spacing of 1 arcsec.

The DEM based on the TK350 was disappointing, the photo quality is poor and there is more or less no contrast in the forest area, so there is no advantage against the free of charge available SRTM C-band height model.

Even if the height accuracy of the DSMs / DEMs based on KOMPSAT-1 and ASTER are not so good like for the SRTM C-band height model, their morphologic quality is better in the mountainous area of Zonguldak caused by the point spacing of 3 arcsec for the available C-band DSM.

The used IKONOS image combination having 99 days time difference of imaging did not lead to successful results, the sun elevation is too different for automatic matching. If the images have been taken with limited difference in time, quite more details can be seen in the generated DEM.

The height to base relation of 1.4 for the OrbView-3 model caused problems in the densely build up area of Zonguldak city. The buildings viewed from quite different direction are looking quite different in the images, causing problems for the automatic image matching. For city areas the convergence angle of both view directions should be smaller.

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