DEM Generation and Validation based on Optical Satellite Systems

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ABSTRACT: Digital elevation models (DEMs) are important for several applications. The height model generated by interferometric synthetic aperture radar (InSAR) of the C-band during the Shuttle Radar Topography Mission (SRTM) is available for a handling fee or even free of charge, having a spacing of 3 arcsec (~92m at the equator). A spacing of 92m is not sufficient for the generation of detailed morphologic information especially in mountainous areas. By this reason in the test area Zonguldak, Turkey, different types of space images like ASTER, KOMPSAT-1, SPOT V and IKONOS have been used for DEM generation by automatic image matching. All these stereo combinations do lead to more morphologic details in mountainous areas like the SRTM C-band.

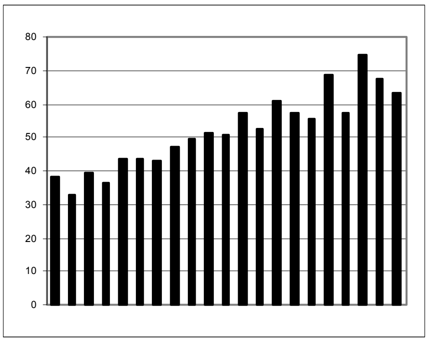
By automatic image matching the visible surface and not the bare ground will be determined. If the terrain roughness is below the influence of the vegetation and the buildings, a filtering to a DEM is possible including only points located on the bare ground. The vertical and the horizontal location of a DEM are important. Horizontal shifts may be caused by datum problems of the used national coordinate systems or simple orientation problems. By this reason a check of one DEM against another must include also the check for horizontal shifts.

1 INTRODUCTION

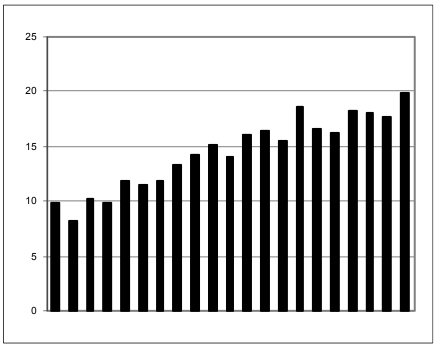
DEMs are a basic requirement for the geo-reference of single images. In addition it is a fundamental component of a GIS. DEMs based on aerial images are not available in all parts of the world and sometimes they are classified. For several applications SRTM height models do lead to satisfying results, but in very mountainous areas the point spacing may lead to a loss of important morphologic details justifying the generation of DEMs based on space images.

2 PREPARATION OF HEIGHT MODELS

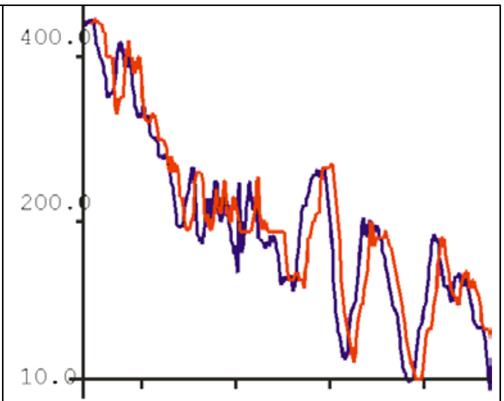
In the Zonguldak test area a reference DEM from the topographic map 1 : 25 000 is available with an estimated height accuracy of 6m. The main area is covered by the German/Italian SRTM X-band height model having a spacing of 1 arcsec corresponding to 31m at the equator and in Zonguldak to 23m x 31m; also the SRTM C-band DEM has been analysed. A direct comparison of the X-band height model with the reference height model was leading to root mean square differences of 43.5m or as function of the terrain inclination to $SZ = 36.3m + 30.0m * \tan \alpha$. This result cannot be accepted, it is far away from the expectation. Even an influence of 43% forest area cannot explain the problems. The analysis restricted to the open areas (not forest) shows $SZ = 35.4m + 29.9m * \tan \alpha$, that means there must be another reason for discrepancies. A direct comparison of height profiles through SRTM X-band data and the reference DEM (figure 1 right hand side) explains it – there is a horizontal shift of approximately 200m between both height profiles.



RMSZ as F(α) – original data
left: α = 0°, right α = 45°
SZ = 36.3m + 30.0m ∗ tan α



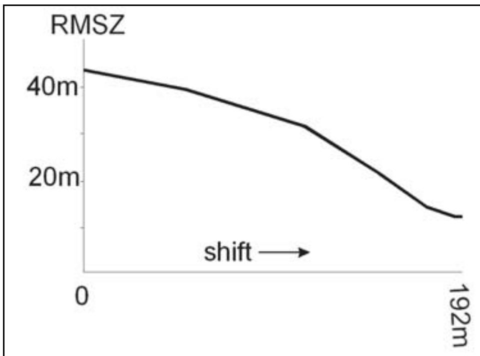
RMSZ as F(α) – shifted data
left: α = 0°, right α = 45°
SZ=9.1m + 11.2m∗tan α



Z-profile reference DEM, original SRTM X-band DEM

Figure 1: comparison SRTM X-band height model against reference DEM

The root mean square discrepancies between the original height models for the different inclination classes always starts for horizontal parts at 36m and reaches for 45° inclination 66m (figure 1 left hand side). The shift of the SRTM height model against the reference height model has been adjusted with the Hannover program DEMSHIFT; it resulted in a horizontal shift of 45.3m in X and 192.2m in Y. This can be explained by the datum shift of the Turkish national coordinate system used for the reference DEM against the ITRF / WGS84 system used for the SRTM data, which was not known in advance. But nevertheless in nearly all cases horizontal shifts have been identified between the different height models. The size of the shift values was different and in most cases quite smaller, but usually not negligible. So the shift of height models against each other at least has to be checked.



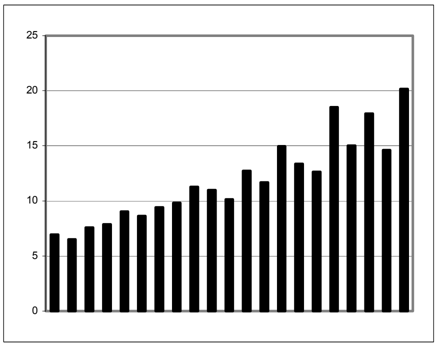


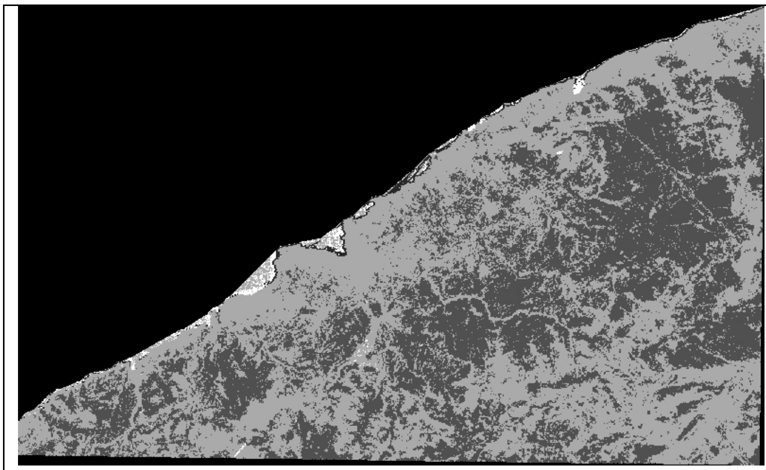
Figure 2: result of shifted and filtered DEM

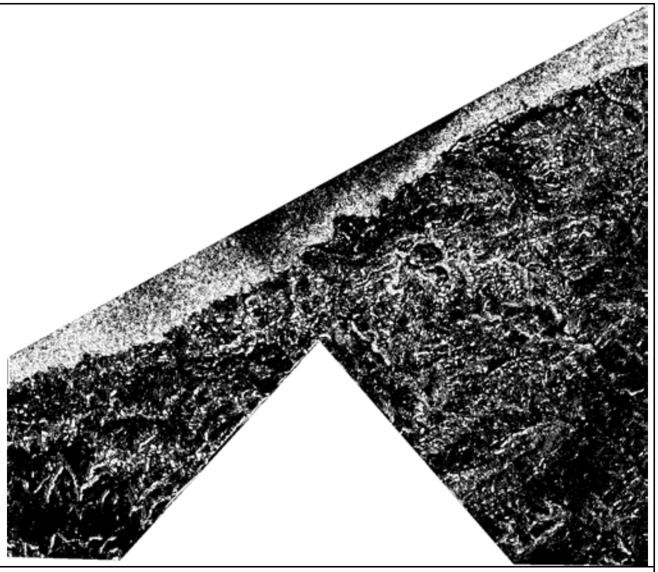
left: change of the RMSZ as function of horizontal shift

centre: RMSZ as F(α) – shifted and filtered data for open areas
left: α = 0°, right α = 45°
SZ=6.8m + 8.2m∗tan α

The shift by 45.3m in X and 192.2m in Y reduced the root mean square differences in Z to the acceptable function of SZ=9.1m + 11.2m∗tan α (figure 1, centre). The SRTM height model shows the height of the visible surface – the top of the trees and the top of the buildings. This is also the case for height models determined by automatic matching of optical images. If the noise of the DEM is exceeding the roughness of the terrain, the points not belonging to the bare ground can be filtered. A filtering by the Hannover program RASCOR reduced the discrepancies in the open areas to SZ=6.8m + 8.2m∗tan α (figure 2, centre). The automatic elimination of points not belonging to the bare ground requires a sufficient number of points located on the ground. This is the case in the open areas - outside the forest. In the forest the results can be improved by filtering but not on the same level like in the open areas. By this reason the analysis of the height models has to be done separately for the open and the forest areas. The Hannover program for DEM analysis DEMANAL can use a forest layer (figure 3 left hand side) for the separation of the areas. In the forest area after shifting and filtering the SRTM X-band height model the root mean square difference against the reference model was SZ=10.7m + 7.2m∗tan α with a bias (systematic error) of 6.5m. The bias gives some information about the average height of the not removed points located on top of the trees. In the mountainous Zonguldak test area the average tree height is not far away from this value. If the bias will be removed, the discrepancies are SZ=7.3m + 8.8m∗tan α what is close to the result in the open areas.

In any case the linear dependency of the vertical standard deviation from the tangent of the terrain inclination is obvious, by this reason the accuracy of the height model has to be expressed by a constant value plus a value multiplied with the tangent of the terrain inclination. In addition the analysis has to be made separately for the open and the forest areas. Just one value for the description of DEM accuracy is not enough.





black = no data (Black Sea), dark grey = forest, light grey = open areas, white = points with ΔZ > 50m in SRTM X-band height model	available points after filtering = black, upper part = Black Sea, lower triangle = no X-band data available

Figure 3: test area Zonguldak, Turkey

A similar refinement by filtering has been made also with the SRTM C-band height model having an average spacing in the Zonguldak area of 80m. The DEM points achieved by filtering were leading to better results like the original points, but after interpolation for filling the gaps caused by the filtering, the result has not been better like with the original height model. In the Zonguldak test area the terrain is extremely rough, so with the large spacing of the C-band data the terrain roughness exceeds the height of the trees and buildings.

3 DEM OF SHUTTLE RADAR TOPOGRAPHY MISSION

The height values based of the US SRTM C-band are available free of charge in the internet or they can be ordered on CD for a handling fee. The more dense results of the German / Italian X-band can be ordered from the German Aerospace Centre DLR for Euro 300.- / (¼° * ¼°). Because of the limited swath width of 45km large gaps are between the individual X-band strips. The US C-band was operated with scan-SAR mode having a swath width of 225km and covering the whole area from 56° southern up to 60.25° northern latitude.

	DZ > 50m	RMSZ [m]	bias [m]	RMSZ F(slope) [m]
X-band DEM				
open area	0.67%	10.7	-3.5	$7.6 + 9.5 * \tan\alpha$
forest	0.39%	13.8	-8.1	$11.4 + 10.5 * \tan\alpha$
C-band DEM				
open area	2.11%	9.9	-2.9	$7.8 + 6.4 * \tan\alpha$
forest	0.03%	13.6	-8.3	$11.6 + 10.5 * \tan\alpha$

Table 1: root mean square height differences of SRTM-DEMs against reference DEM in Zonguldak test area

In the Zonguldak test area the results shown in table 1 have been achieved with not filtered data (details see Jacobsen 2005). In other areas better results of 3m – 5m for open and flat areas in relation to more accurate reference DEMs have been seen. There must be an advantage in the generation of DEMs based on optical space images if the expenditure for the generation of DEMs is justified against the use of the free available C-band data or if available, the not too expensive X-band data.

4 HEIGHT MODELS GENERATED WITH OPTICAL SPACE IMAGES

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

$$SZ = \frac{h}{b} \bullet \mathrm{Spx}$$

formula 1: standard deviation of height   h/b=height to base relation

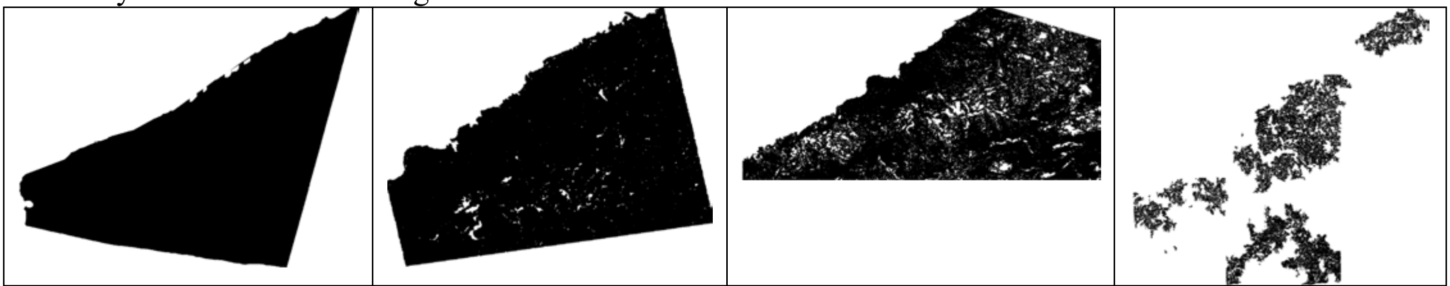
Spx = standard deviation of x-parallax [GSD]

	GSD	h/b	Δt	estimated SZ for Spx = 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

Table 2: in Zonguldak test area available stereo models

Only with TK350 and ASTER the two images of a stereo model are taken within few seconds. For the other sensors there was a longer time interval between the images of a model. Especially the both IKONOS scenes have been taken under quite different conditions with sun elevations of 67° and 41° causing quite different shadows.

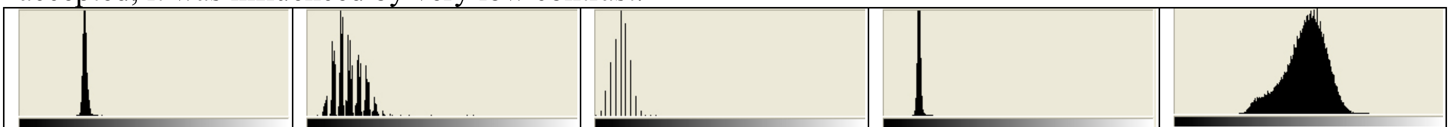
The image matching has been made with the Hannover program DPCOR by least squares matching. It was tried to match every third pixel with sub-matrixes of 10 ∗ 10 pixels. The matching of directly neighbored pixels is leading to highly correlated results because it is based on 90% of the same pixels and it has been shown that with every third pixel 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 occured.



ASTER	KOMPSAT-1	SPOT 5	IKONOS

Figure 4: points determined by automatic image matching = dark   upper left = Black Sea

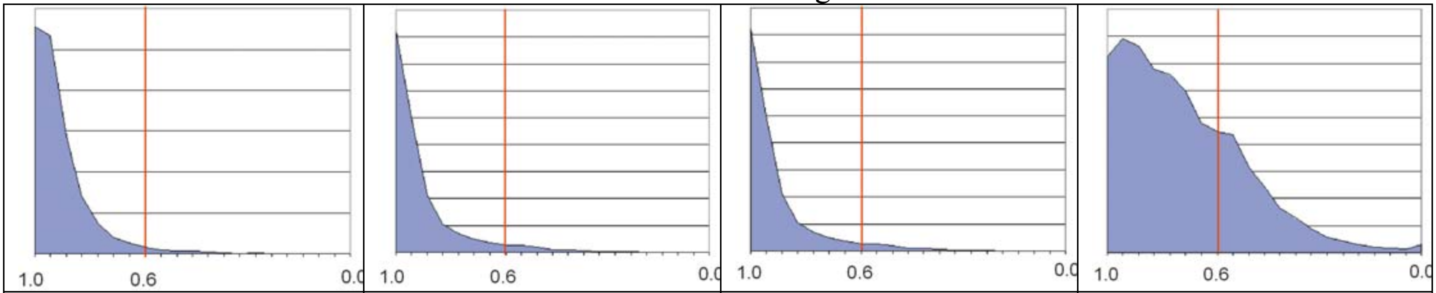
With the exception of ASTER all height models do have some gaps. Of course no points are available from the sea - a matching of the sea surface with moving waves and different sun reflection is not possible. The matching of TK350 photos was influenced by the film grain and several scratches on the film requiring a scratch removal filtering. But also after filtering the results especially in the forest areas could not be accepted, it was influenced by very low contrast.



TK350, S=2.0	ASTER, S=13	KOMPSAT-1, S=8	SPOT 5, S=1.7	IKONOS, S=20

Figure 5: grey value histograms of same forest area   S=standard deviation of the grey values

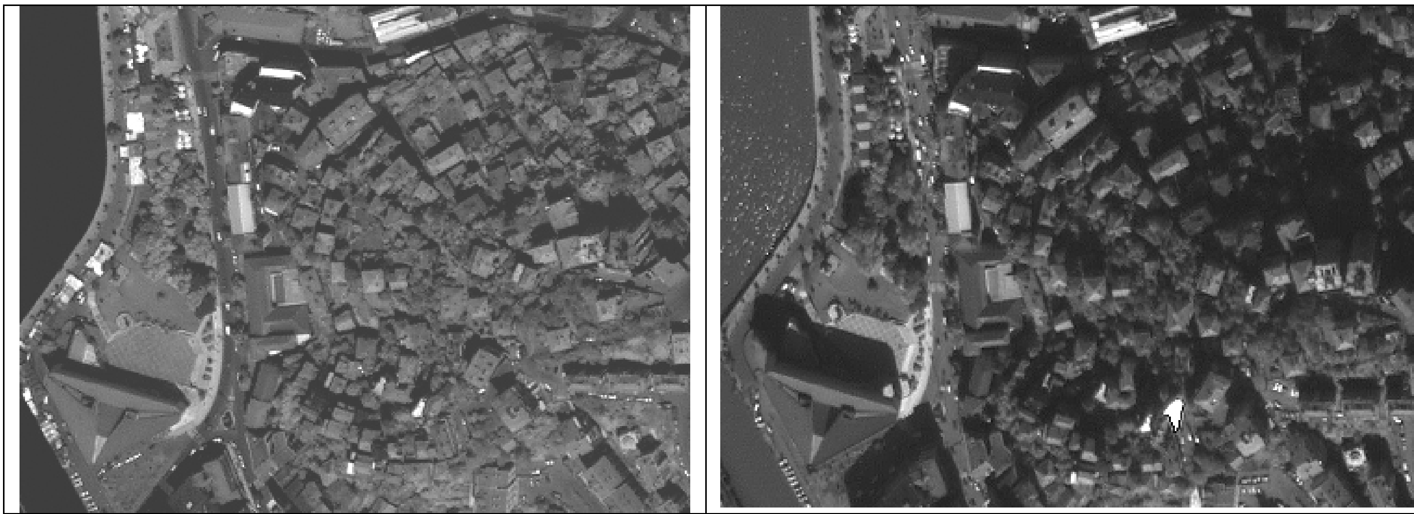
The problems of the grey value distribution in the forest areas can be seen in figure 5. The grey value histogram of a forest area close to the city of Zonguldak for TK350 has only a standard deviation of 2.0; for ASTER it is quite better with 12.9, for KOMPSAT-1 it is 7.9, for SPOT 1.7 and for IKONOS 19.8. Corresponding to this the matched DEMs show gaps for TK350, KOMPSAT-1 and SPOT 5. The ASTER DEM has no gaps caused by the good grey value distribution in the near infrared band which has to be used for matching. The gaps in the KOMPSAT-1 DEM are limited to forest in mountain shadow areas. With SPOT 5 more gaps can be seen corresponding to the very narrow grey value histogram. The gaps in the IKONOS DEM has other reasons, the grey value distribution in the forest is still good caused by the panchromatic band extended to the near infrared and tree shadows visible in this high resolution.



ASTER	KOMPSAT-1	SPOT 5	IKONOS

Figure 6: histogram of correlation coefficients from matching   horizontal = size of correlation coefficient
vertical = number of points

The problems of matching can be seen also in the histograms of the correlation coefficients from matching (figure 6). ASTER has the highest correlation values and only few points do have correlation coefficients below the limit of acceptance of 0.6. For KOMPSAT-1 the distribution of the correlation coefficients is not bad, but still not so good like for ASTER. For SPOT the distribution of the correlation coefficients is also not bad, but the number of points below the limit of acceptance is still a little larger. IKONOS shows very clear the problems of matching caused by the quite different imaging conditions.



IKONOS, July 2nd, sun elevation 67°	IKONOS, October 9th, sun elevation 41°

Figure 7: differences of IKONOS images caused by quite different sun elevation

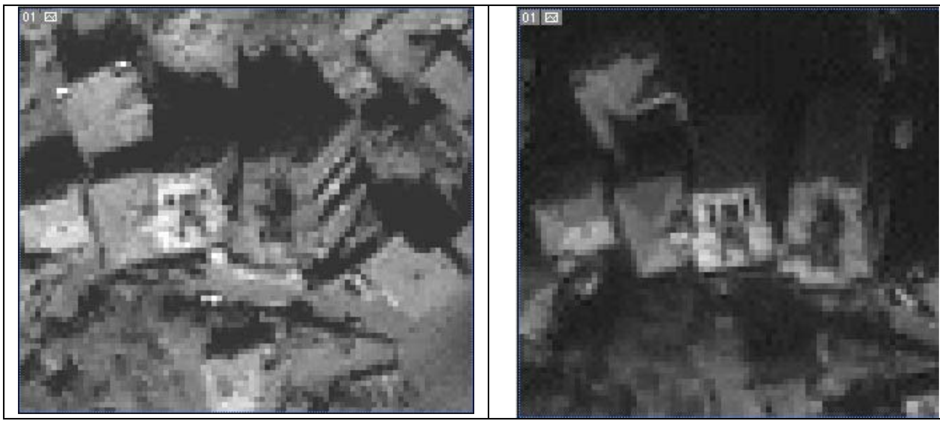


Figure 8: same buildings seen from different directions

In figure 7 the influence of the quite different sun elevation to the images in the city area can be seen. In the forest areas the contrast is mainly caused by the shadows and so in the forest areas a matching with such an image configuration was nearly impossible. In another area the matching of IKONOS images taken from the same orbit was excellent, reaching a standard deviation of the x-parallax of 0.22m for a height to base relation of 7. By simple theory (formula 1) the vertical accuracy should be linear depending upon the height to base relation, but the standard deviation of the x-parallax will be larger for a smaller height to base relation. A small height to base relation means also a quite different view direction, so in build up areas the houses do look quite different (figure 8). This is not a problem for models with large GSD, but for the high resolution of IKONOS it has a strong influence to the matching result. By this reason with a height to base relation of 1.6 better results can be reached like with the relation 1.0.

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

Table 3: accuracy of height models generated by automatic image matching in Zonguldak test area

With the exception of the IKONOS model having different imaging conditions, the standard deviation of the x-parallax is in the sub-pixel range for open and flat areas. In any case there is a clear dependency upon the terrain inclination. With check points always better results have been achieved like by the comparison of DEMs. Check points are located at optimal positions – flat terrain without influence of disturbing objects just beside and with optimal image contrast. This only shows the accuracy potential of the sensors but it is not realistic for a whole DEM including also image parts with low contrast. So in the average the root mean square x-parallax for check points is just 0.3 GSD while it is 0.7 GSD in open and flat areas based on the comparison of DEMs without the special results from IKONOS. Similar results have been reached also in other test areas.

The results achieved with the TK350 photos in the forest areas cannot be accepted. In addition the TK350 photos are still expensive and compared with the cheep ASTER scenes not a good solution. With the combination of the nadir and the backward view ASTER is generating in any case a stereo model from the same orbit. There is a better and more actual coverage by ASTER.

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 like shown at check points located in optimal areas with good contrast and not influenced by the vegetation.

The results listed in table 3 are from the matched images 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.

The results based on the IKONOS images are not useful; such a difference in the imaging conditions cannot be tolerated for image matching. There was no problem with the KOMPSAT-1 and the SPOT 5 models having 11 and 5 days difference in taking the images of the stereo model. All used digital images are based on sun-synchronous orbits taking the images always at the same time of the day and during 11 days the sun elevation is not changing so much.

5 MORPHOLOGIC QUALITY

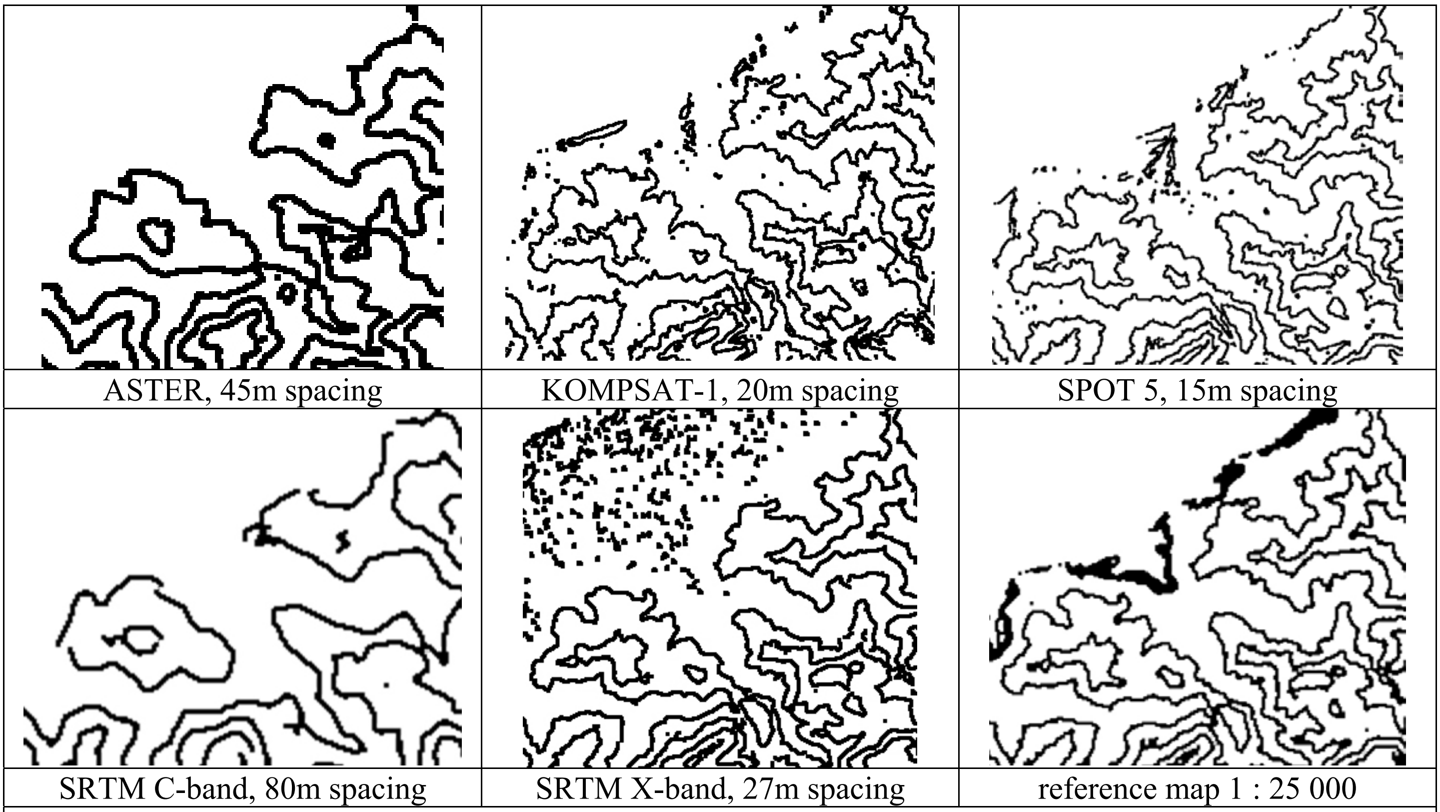


Figure 9: contour lines of generated DEMs, contour interval 100m

The morphologic details in the mountainous area of Zonguldak are mainly depending upon the DEM spacing; the accuracy has only a small influence. The general rule of an accuracy of at least 1/3 of the equidistance is reached for all DEMs. 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 may show also more details like the reference map. In general the morphologic details of KOMPSAT-1, SPOT 5 and also SRTM X-band are very similar to the reference 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.

CONCLUSION

The accuracy of the DEM points from the SRTM C-band and X-band are approximately on the same level like based on SPOT 5. The KOMPSAT-1 DEM accuracy is also not far away from this. But even in the quite less accurate ASTER DEM in mountainous areas like Zonguldak more morphologic details can be seen like in the C-band DEM having an average spacing of approximately 80m. If SRTM X-band data are available, it is not justified to generate DEMs based on SPOT 5-images or other images with larger GSD. For IKONOS the situation is different, if the images have been taken with limited difference in time, quite more details can be seen in the generated DEM. For the very high resolution space images the height to base relation should not be below 1.6 to avoid problems in build up areas.

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