Generation and Analysis of Height Models based on Satellite Information

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ABSTRACT:

With the availability of digital elevation models (DEMs) generated by the Shuttle Radar Topography Mission (SRTM) a homogenous height model is given for most parts of the world. The spacing of 3 arc sec for the published SRTM C-band DEM is reducing the morphologic information especially in mountainous regions. With a spacing of 1 arc sec the SRTM X-band DEMs do include quite more details about the terrain surface, but large gaps between the X-band flight paths do exist. Even with the 15m ground sampling distance of ASTER images, based on automatic image matching in mountainous areas more morphologic details can be achieved like with the SRTM C-band DEM. The higher resolution of SPOT 5, KOMPSAT-1, IKONOS or others will lead to more morphologic details.

As well the X- as the C-band RADAR cannot penetrate the vegetation, so not only the optical images, also SRTM will lead to digital surface models showing the visible surface and not the bare ground. If the noise of the DEMs is below the influence of the buildings and the vegetation, by filtering large parts of the influence of the vegetation and the buildings to the height model can be removed.

The analysis of different height models has shown in nearly every case a clear dependency of the vertical accuracy upon the terrain inclination. Often systematic errors not only in Z, also in the horizontal location can be seen. This requires a horizontal shift determination and correction by least squares adjustment.

Especially the results of intensive tests with different products in the Zonguldak test area will be shown, supplemented by results achieved in other areas.

1. INTRODUCTION

Digital elevation models are a basic part of a GIS. They are not only required for the description of the three-dimensional surface, they are also required for the generation of ortho-images, the today most often used photogrammetric product. If no DEM is available, it can be digitized from existing topographic maps, but not in any country they are reliable with a homogenous and satisfying accuracy or in some countries they are still classified. Most height models are based on aerial photographs but with the improved resolution of space images new possibilities exist. An alternative solution is the interferometric synthetic aperture radar (InSAR) enabling a very fast and nearly automatic generation of digital surface models (DSM). A DSM is describing the height of the visible surface – the top of the vegetation and the buildings. The usually used short wavelength radar of the X- and the C-band is not able to penetrate the vegetation, so the height models based on InSAR do correspond to the results from automatic image matching. Usually not a DSM but a DEM showing the height of the bare ground is required, so the points not belonging to the bare ground have to be removed from the DSM. This can be made in a time consuming process manually or fast by program based filtering.

2. SHUTTLE RADAR TOPOGRAPHY MISSION

During the 11 days of the Shuttle Radar Topography Mission (SRTM) in February 2000 the mayor part of the world has been mapped by InSAR with the US C-band and the German-Italian X-band. The US-C-band has had the advantage of Scan-SAR with a swath width of 225km, so the area from 58° southern up to 60.25° northern latitude is covered nearly without gaps, while the X-band with just a swath width of 45km has large gaps between the strips. Outside the USA for a handling fee the C-band height model is available only with a spacing of 3 arc seconds corresponding to 92m at the equator while the X-band data can be bought with a spacing of 1”.

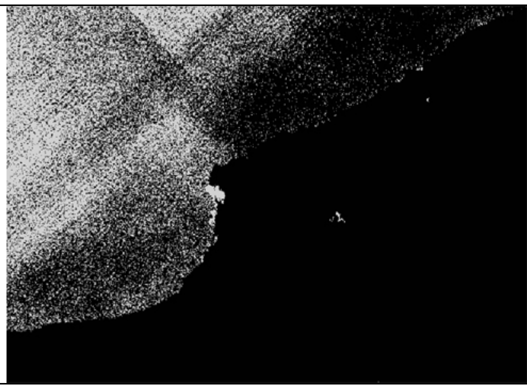


Fig. 1: distribution of available points in C-band data set upper left part = Black Sea

On a sea surface without waves the radar signal is reflected, so no energy will be received by the sensor causing gaps in the covered area. This can be seen in figure 1 showing the area around Zonguldak with the Black Sea in upper left. In addition there is a small lake without height information. No gaps are caused by radar layover like it happens in extreme mountain areas, so for example in the 1° x 1° area including Mount Everest 9% of the height values are missing.

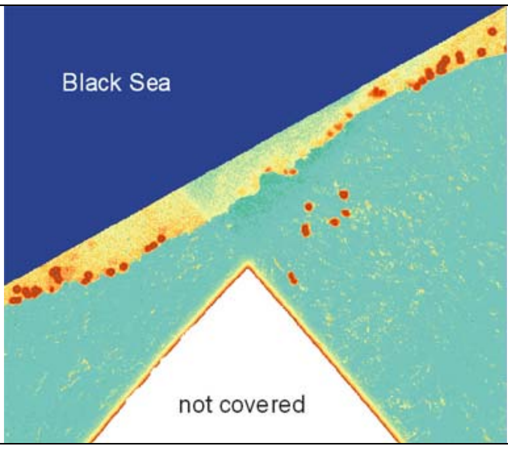


Fig. 2: colour coded height error map of SRTM X-band

Together with the height information of the X-band data a height error map (HEM) is distributed. It includes the estimated standard deviation for Z. In the area of Zonguldak (fig. 2) the values are reaching from 2.5m in the flat area and especially the area covered by two SAR strips up to 95m in some spots in the centre in locations with very steep terrain. In addition some parts of the sea surface (upper part in figure 2) and the shore line do have similar values. The shore partially is very steep including also vertical rocks, causing problems of radar overlay.

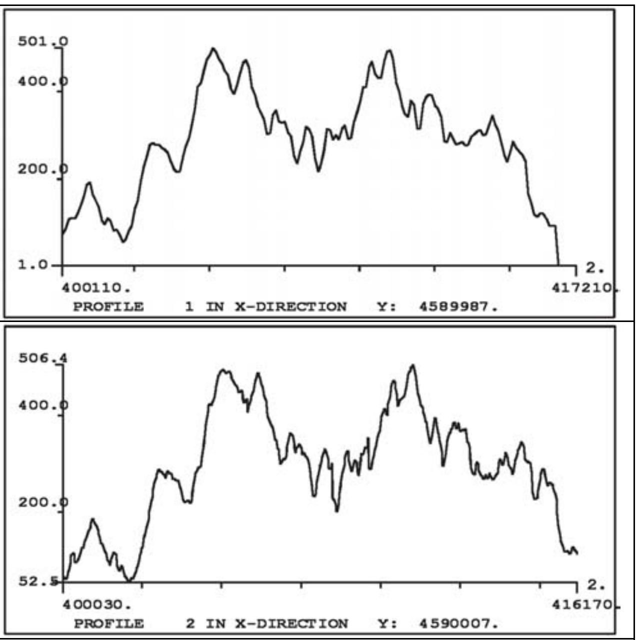


Fig. 3: above height profile through SRTM C-band DEM, below through X-band DEM, Zonguldak test area

The loss of details because of larger spacing in the C-band DEM against the X-band DEM shown in figure 3 is obvious. An analysis of the loss of accuracy by bridging the average spacing of 80m of the C-band DEM in the Zonguldak test area has been made with the reference DEM having a raster width of 40m, generated from topographic maps 1 : 25 000. The mean square difference of the elevations interpolated over a distance of 80m and compared with the original heights reached a mean square value of 12.0m. The best results came from a bilinear interpolation while a polynomial interpolation in the very rough and mountainous area did not reach the same quality. Of course such an extreme influence of an interpolation over 80m will not be reached in a flat, rolling or smoother area. In a rolling area of Bavaria root mean square discrepancies of +/-2.4m of an interpolation over 80m and in a more flat area in New Jersey +/-1m has been seen. So the loss of accuracy is quite depending upon the area, but it is not negligible.

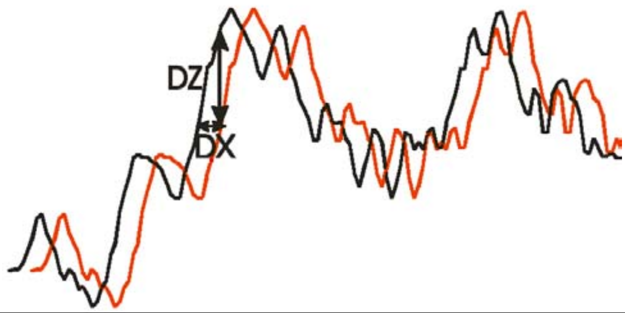


Fig. 4: difference in Z caused by horizontal mismatch of the DEMs

A comparison of the horizontal location of the SRTM C-band data against the reference DEM in the Zonguldak area by adjustment was leading to a shift in X of 15m and in Y of 137m. This reduced the root mean square difference between the reference DEM and the C-band heights from 26.4m to 13.1m; for the X-band data the shift of 50m in X and 197m in Y improved the root mean square height differences from 27.3m to 10.7m. In both cases outliers exceeding 50m differences in Z have not been respected. A horizontal shift of DEMs has been seen very often, by this reason an improvement or check of horizontal shift has be made in any case.

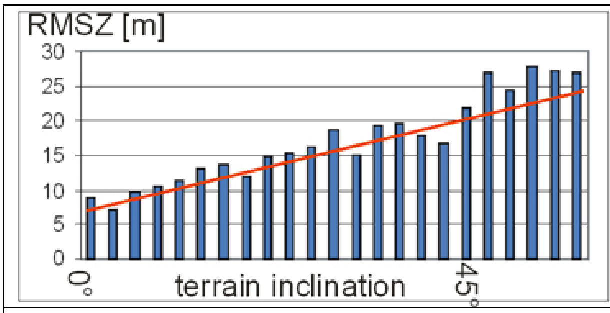


Fig. 5: root mean square height differences C-band DEM against reference DEM as function of the terrain inclination

Any comparison of DEMs against reference height values even after optimal horizontal fit by adjustment showed a clear dependency upon the terrain inclination like visible in figure 5. There is also a clear difference of the results achieved in open areas against forest. The X-band and also the C-band radar are not penetrating the forest which is covering 45% of the test area Zonguldak, they are showing the height of the visible surface – a digital surface model (DSM). If enough points on the bare surface are still available in the DSM, by filtering the points not belonging to the bare ground can be removed (Passini et al 2002). In addition the accuracy of the determined points must be below the noise of the terrain.

Zonguldak, Turkey is located in a rough mountainous area with an average terrain inclination of 27% and more important, an average change of the terrain inclination from one mesh to the next by 32%. The change of the terrain inclination is determining the interpolation accuracy as mentioned above. The inclination is influencing the radar foreshortening and layover. This is more important for the X-band DSM like for the C-band DSM because 95% of the C-band data are the average of two determinations taken from different directions and in 50% of the cases a triple coverage is given. So the effect of the layover and foreshortening has been reduced.

	DZ > 50m	RMSZ [m]	Bias [m]	RMSZ F(slope) [m]
	X-band DHM			
open area	0.67%	10.7	-3.5	7.6 + 9.5 * tan α
forest	0.39%	13.8	-8.1	11.4 +10.5 * tan α
check points	0	5.4	-2.0	1.3 + 40.6 * tan α
	C-band DHM			
open area	2.11%	9.9	-2.9	7.8 + 6.4 * tan α
forest	0.03%	13.6	-8.3	11.6 +10.5* tan α
check points	0	9.4	-2.0	4.0 + 122 * tan α

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

The determined discrepancies at check points are quite better like against the reference DEM, this is typical also for DEMs determined by automatic image matching of optical data. Check points are optimal located without influence of disturbing elements and they are usually in flat areas. The check point accuracy is explaining the system accuracy, but it is too optimistic for a whole DEM including parts having not optimal conditions.

A filtering of the InSAR-DSMs with the Hannover program RASCOR removed between 20% and 26% of the points – a usual percentage. The root mean square differences have been reduced by 10% up to 20%, but the filtering was leading to a not realistic smooth surface. By this reason it cannot be recommended for the InSAR DSMs in the mountainous area of Zonguldak. This is quite different in other not so rough areas.

	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	4.6	-1.1	2.7 + 8.8 * tan α
Bavaria, mountainous	8.0	-2.4	4.4 + 33.4 * tan α

Table 2: accuracy of SRTM C-band DEMs in different test areas (only open areas)

In other not so rough and mountainous test areas having accurate reference data quite better results have been achieved with the SRTM C-band DEMs (table 2). The root mean square differences not taking care about the terrain inclination do show a variation from 3.9m up to 8.0m, but after respecting the terrain inclination, for flat areas there is only a variation from 2.7m up to 4.9m. If the systematic height errors (bias) are removed, the variation is reduced to 2.5m up to 3.7m, showing the very good accuracy of the SRTM height models.

3. OPTICAL SPACE IMAGES

In the Zonguldak test area height models have been generated based on the following optical space images: TK350, ASTER, KOMPSAT-1, SPOT 5 and IKONOS. The automatic DEM / DSM generation was done with the Hannover program DPCOR using a least squares matching.

	GSD	h/b	Δt
TK350 (photo)	13m	3.1	9 sec
ASTER	15m	2.1	50 sec
KOMPSAT-1	6.6m	2.1	11 days
SPOT 5	5m	1.9	5 days
IKONOS	1m	3.8	99 days

Table 3: space images and image combinations used for DEM generation in Zonguldak test area

The used TK350 photos do have an effective ground sampling distance (GSD) of 13m, determined by edge analysis. The photos have had a high number of scratches and the film grain was disturbing. Without scratch removal and low pass filter the automatic image matching was not successful. The contrast in forest areas was very poor, leading to gaps in the generated DEM.

With ASTER the DEM generation was without any problems. No gaps in the land area occurred. The near infrared band available in the nadir and backward view has the advantage of good contrast also in the forest area. Caused by the stereoscopic coverage from the same orbit there is no negative influence of changing shadows. Also with the stereo model from KOMPSAT-1 having just 11 days between take of both images, the automatic image matching was simple. Only in the forest areas the panchromatic images have had few problems with missing contrast in mountain shadow regions. The GSD of 6.6m allowed a DEM grid spacing of 20m.

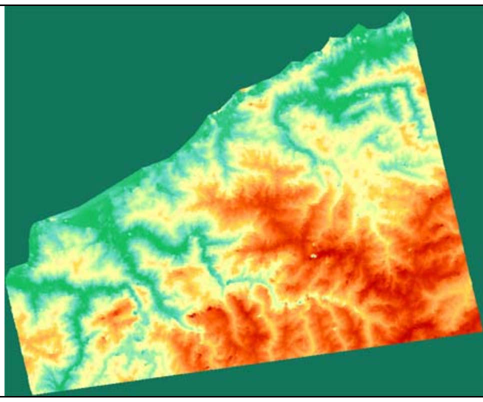


Fig. 6: colour coded KOMPSAT-1 DEM, Zonguldak

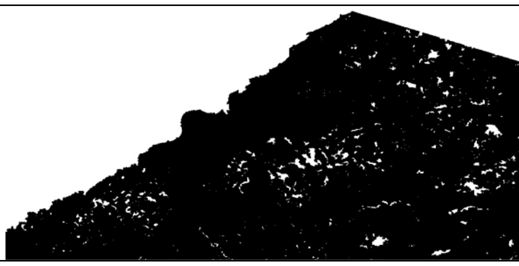


Fig. 7: SPOT 5 Zonguldak: white = not matched areas

The used SPOT image combination has only a time interval of 5 days, so only negligible radiometric differences have been caused by this. Like with the panchromatic KOMPSAT-1, SPOT 5-images have had some problems in mountain shadow regions because of very limited contrast (see figure 7 and 8).

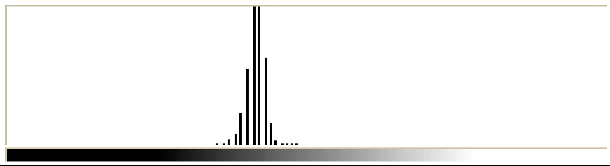


Fig. 8: Spot 5 Zonguldak: histogram in forest area

The IKONOS images used for matching are taken at 2nd of July with a sun elevation of 67.2° and at 9th of October with a sun elevation of 41.5°. The sun azimuth is differing 28°. This has caused quite different radiometric conditions and shadows (see figure 9) which could not be removed by high pass filtering, visible in lower part of figure 9.

Fig. 9: IKONOS Zonguldak, upper image taken at July 2nd, lower image taken October 9th

Especially in forest areas where in panchromatic images shadow causes the major part of the contrast, the automatic image matching failed, but also in the build up areas only a small part could be matched; such different images should not be used for automatic image matching. On the other hand an IKONOS model taken in another area from the same orbit was leading to excellent matching results. Because of the very high resolution in build up areas a too small height to base relation should be avoided. By simple theory a small height to base relation (e.g. h/b=1.0) could improve the accuracy of the object height, but with h/b=1.0 the buildings are shown from different directions – not the same wall can be seen together with the roof (see figure 10). This is enlarging the standard deviation of the x-parallax, shown in formula 1 as "GSD∗factor".

$$SZ = \frac{h}{b} \bullet GSD \bullet factor$$

formula 1: standard deviation of Z-coordinate (SZ)
h=flying height b=base GSD=pixel on ground

As a compromise for different terrain types, a height to base relation of 1.6 (see figure 10) can be used, but in cities a value of 3 and higher may be better. This is more important for very high resolution like for lower resolution not showing the details.

Fig. 10: buildings seen from different direction
height / base relation =1.6

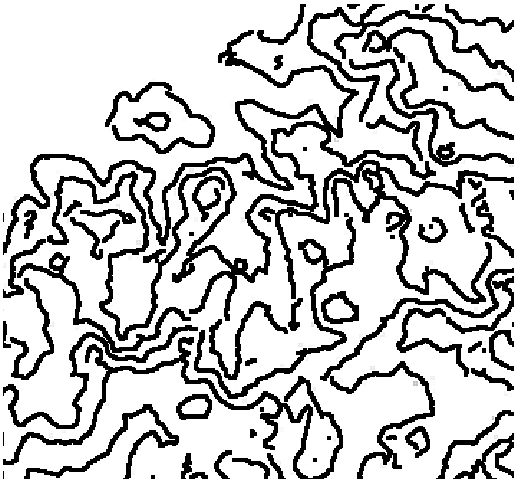
Sensor	area	RMSZ [m]	RMSZ F(slope) [m]	RMSpx [GSD] flat area
TK 350	o	23.3	20.0+23.9*tanα	0.5
	f	51.3	49.0+11.4*tanα	1.2
	c	6.6	4.7 + 2.2*tan α	0.12
ASTER	o	25.0	21.7+14.5*tanα	0.7
	f	31.2	27.9+18.5*tanα	0.9
	c	12.7		0.4
KOMPSAT-1	o	13.6	11.3+11.5∗tanα	0.8
	f	14.7	14.1+12.1∗tanα	1.0
SPOT 5	o	11.9	8.4 + 6.3*tan α	0.8
	f	15.0	9.8 + 5.3*tan α	1.1
	c	3.8	3.5 + 0.9*tan α	0.4
IKONOS	o	5.8		1.5

Table 4: accuracy of DEMs generated by automatic image matching in Zonguldak test area – see also table 3
o=open area f=forest c=check points

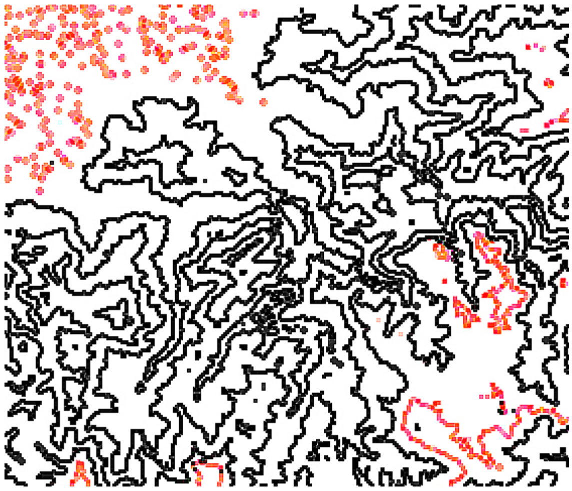
With the exception of the IKONOS model having different imaging conditions, the standard deviation of the x-parallax (≡factor in formula 1) is in the sub-pixel range for open and flat areas. In any case there is a clear dependency upon the terrain inclination. The quite better results achieved with check points are a too optimistic result for the accuracy of a DEM.

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 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 quite more actual coverage by ASTER which can be ordered just for a handling fee.

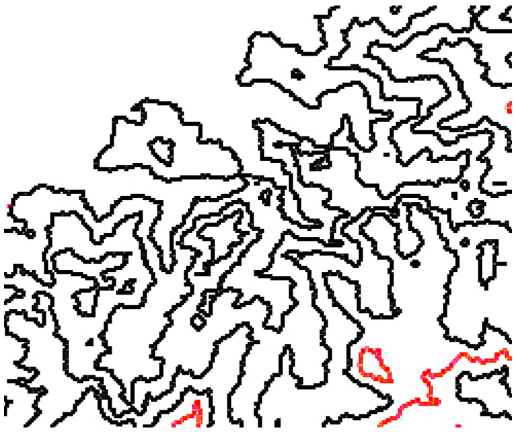
Like with SPOT, a stereo model is generated by KOMPSAT with a view across the orbit. This does not allow the generation



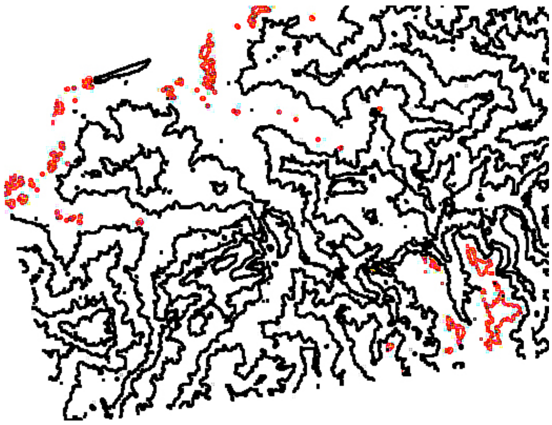
contour lines by SRTM C-band



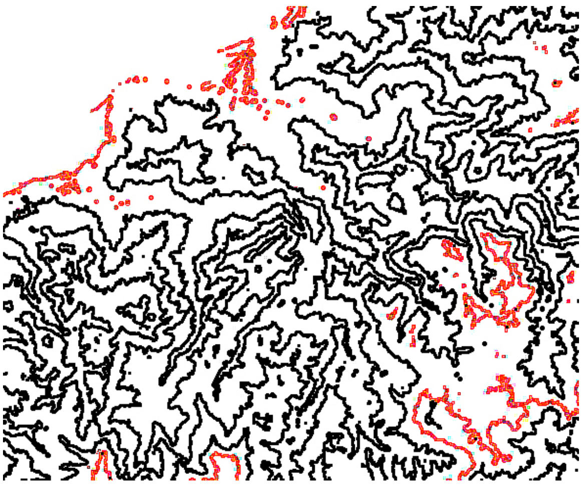
contour lines by SRTM X-band



contour lines by ASTER



contour lines by KOMPSAT 1



contour lines by SPOT 5

reference map 1 : 25 000

Fig. 11: contour lines based on space information, Zonguldak area, contour interval 100m

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. 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 7 are from the matched images improved by filtering for points not belonging to the bare ground (Passini et al 2002, Jacobsen 2004). This filter process is more successful with better accuracy of the object points. It works very well in the open areas, but it has some limitations in the forest areas having no matched point on the bare ground. In the forest area the borders can be improved and it keeps the points on the level of lower vegetation.

4. MORPHOLOGIC QUALITY

The comparison of contour lines in the mountainous area of Zonguldak shows very well the morphologic quality (see figure 11). 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. Even with ASTER images a DEM having a raster width of 45m 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 of ASTER

. The morphologic details of the DEMs based on SRTM X-band (raster width 27m), KOMPSAT-1 (raster width 20m) and SPOT 5 (raster width 15m) are on the same level. The results based on the IKONOS combination having 3 month difference in time (raster width 3m) are more detailed in the areas where the matching was without problems, but too large gaps are caused by the severe radiometric differences.

Of course the relations 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 smaller spacing of DEMs based on optical space images leads to more details like the SRTM C-band-DEMs. This may be unimportant for the generation of ortho images but it should be respected if contour lines are required.

CONCLUSION

With the better coverage of the earth by high and very high resolution space images also a better stereoscopic coverage is available. The generation of DEMs by space images is in competition with available data and aerial images. Aerial images do have a better resolution, but they are covering only small areas and have to be supported by a higher number of control points. In addition aerial images in several countries are classified, making the use difficult. For not too high accuracy requirements the use of space images for DEM generation is an economic solution. But this must have an advantage against the height model generated by the Space Shuttle Topography Mission. The DEMs based on the C-band have been free available in the Internet up to few month ago, now they can be ordered for a handling fee. The major disadvantage of the SRTM DEMs is the 3 arc sec raster width of the height values for the areas outside the USA, leading to reduced information especially in mountainous areas. Even with the not so accurate ASTER height models more morphologic details can be obtained. That means there is a justification of the generation of DEMs with space images.

The accuracy range of up to +/-4m in open and flat areas for the SRTM DEMs only can be reached or exceeded with very high resolution space images coming from the same orbit or having only few days difference in imaging. In general the C-band height model as well as the result from automatic image matching is a digital situation model related to the height of the visible surface. With the exception of closed forest areas the points not belonging to the bare ground can be excluded by filtering if the roughness of the terrain is smaller like the influence of the vegetation and the buildings.

The accuracy of the DEMs cannot be expressed just by one standard deviation, it is different for open and forest areas and it is depending upon the terrain inclination.

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