Analysis of Digital Elevation Models Based on Space Information

K. Jacobsen
University of Hannover, Germany

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ABSTRACT: Digital Elevation Models (DEMs) are a standard requirement for several applications. They are important as one source for the description of the terrain, but they are also required for the correct georeferencing of single images. Existing DEMs are often not accurate, not detailed enough or too expensive. By economic reasons there is a requirement to generate or to use DEMs based on space information. They may come from stereo models of optical images or from Interferometric Synthetic Aperture Radar (InSAR). In both cases the achieved results do not describe the usually required height of the bare ground, but the height of the visible surface – the Digital Surface Model (DSM). Only InSAR using long wavelength can at least partially penetrate the vegetation covering the surface, but in any case in build up areas the height of the building tops are described. This may be useful for the generation of orthoimages but not for an analysis of the water flow.

The accuracy of DEMs based on space information has reached a high level so the influence of the objects on top of the surface cannot be neglected. Another problem is the real information about the accuracy. Published investigations very often do show nice results, valid only for open areas with nearly horizontal surface and good contrast. This may be quite different for other terrain types. With different optical space images DSMs have been computed by automatic image matching using lower resolution like presented by ASTER up to the highest resolution currently available by QuickBird. The influence of the elements on top of the surface, but also matching errors has been reduced by a special filtering analyzing the DSMs and reducing it to DEMs including only points of the bare ground. This is effective if the terrain noise is below the noise of the matching and if at least some points are available on the bare ground. In a dense forest area the achieved height will be near to the top of the trees. The accuracy is strongly depending upon the location in open areas or in forest, depending upon the image contrast and depending upon the terrain inclination. Details are shown. Also the InSAR-DEMs like generated by the Shuttle Radar Topography Mission (SRTM) do include similar problems. The C-band does not penetrate the forest and the accuracy is strongly depending upon the terrain inclination.

1 INTRODUCTION

Not only for mapping purposes, also as a general component of a GIS the height of the terrain is required. Independent upon this, complete and accurate height information must be available for flood simulation or water run computation or for the determination of aspects for agricultural reasons and check for erosion and engineering purposes. With the free availability of the C-band Interferometric Synthetic Aperture Radar (InSAR) height information from the Shuttle Radar Topography Mission (SRTM) (http://edcsgs9.cr.usgs.gov/pub/data/srtm/) the situation has been improved, but it is necessary to have knowledge about the accuracy characteristics of these data in relation to other height information which may be achieved with different space data. The C-band Radar as well as optical data leads to height information on top of the visible surface – the DSM. Usually the points not belonging to the bare ground have to be eliminated from the achieved data set.

A digital elevation model usually will be categorised by the accuracy, but the accuracy is quite more complicate than it can be described just by a simple figure. We do have a geometric accuracy and a morphologic accuracy. The morphologic accuracy of course is depending upon the geometric quality but it is also depending upon the spacing of the DEM, the accuracy of one point in relation to the neighboured and details which do not so much influence the geometric accuracy.

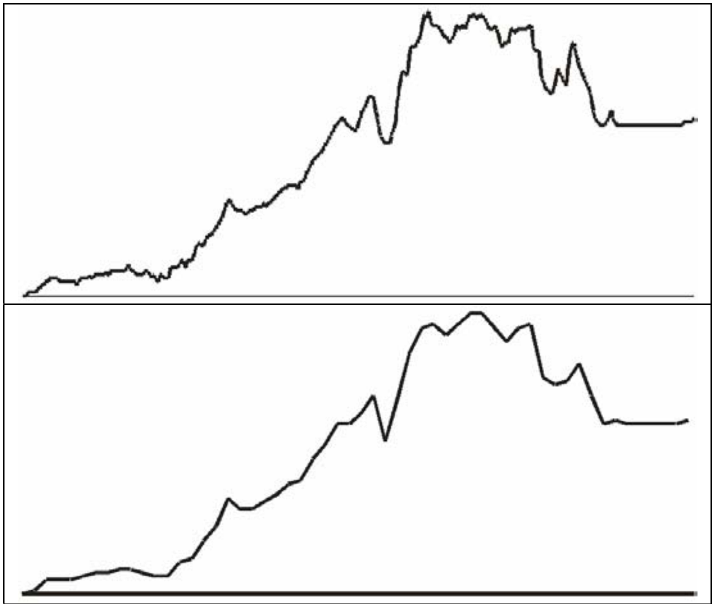


Fig. 1: profile through a DEM, 5km length, ΔZ=80m
above: spacing 5m below: spacing 90m

The geometric accuracy is also a little more complicate – we may have an absolute and a relative accuracy. The geometric problems may not only be based on the vertical position, also the horizontal position has an influence. The relative accuracy is independent upon shifts in X, Y and Z.

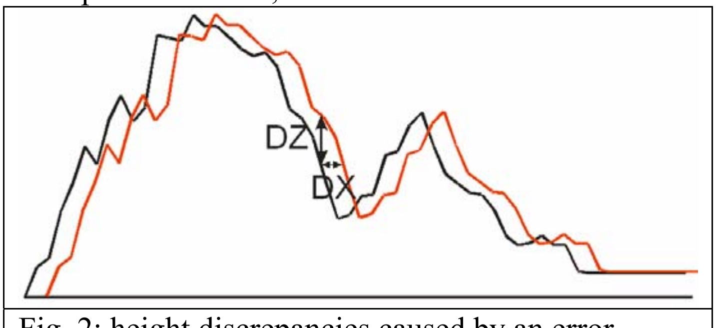


Fig. 2: height discrepancies caused by an error in horizontal position DZ = DX * tan α
α = terrain inclination

In addition the accuracy is usually not the same in the whole model, it is a function of the terrain inclination, criteria important for the point determination - like contrast for optical images or the inclination of the surface in the view direction for InSAR and the elements located on top of the bare ground like vegetation and buildings. Most methods for the generation of DEMs do show the top of the visible surface. The points not belonging to the bare ground have to be removed from the data set. This can be made by some qualified programs, but if the spacing of the DEM is too large or no point in the neighbourhood is located on the ground, like it may happen in forest areas, even by manual interaction we cannot reduce the digital surface model to a DEM.

2 SHUTTLE RADAR TOPOGRAPHY MISSION

With InSAR used by the SRTM in February 2000 the main part of the earth land area between the latitude of 56° south and 60.25° north has been covered by DSMs. The Space Shuttle carried the US C-band and the German/Italian X-band system. By the scanSAR mode the C-band has had a swath width of 225km while the X-band was limited to a swath width of only 45km. So the X-band system has not covered the whole area while the C-band has covered 94.6% of the land mass within the named limits twice and approximate 50% three times. This multiple coverage improved the accuracy of the C-band DSMs which are by theory not so accurate like the X-band-DSMs because of the longer wavelength. The used X-band with the wavelength of 3cm cannot penetrate the vegetation, but also the C-band with a wavelength of 5.6cm shows nearly the top of the vegetation. The C-band elevation models available in the Internet are unedited and do include artefacts and gaps in steep areas. The C-band SAR has an incidence angle (nadir angle at the ground) between 31° and 61° while the X-band is limited to 50° up to 54°. Corresponding to this the radar layover where the returned signal cannot be separated depending upon the location, is in the range of a terrain slope across the orbit direction of the same value. In such areas no height information is available from InSAR.

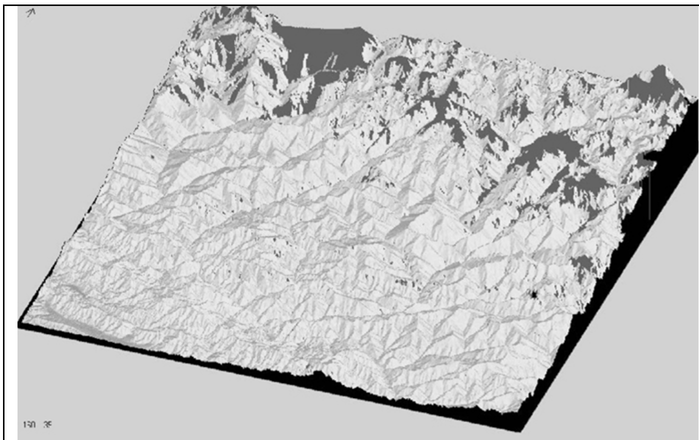


Fig. 3: Coverage by SRTM C-band
height information available = white,
area around Mt. Everest, Himalayan

Of course the extreme case of the area around Mt Everest in the Himalayan with 9% voids is not representative. World wide just 0.15% of the data are missing because of imaging problems in steep parts.
With the exception of the area of the USA, the C-band height information is only available with a spacing of 3 arc seconds corresponding to 90m at the equator while the X-band data can be ordered from the German DLR with a spacing of 1 arc second (~30m). Of course the loss of information by the larger spacing is depending upon the roughness of the area. Figure 4 shows the loss of details in a mountainous landscape in Arizona. The upper 3D-view is based on 1”-C-band-data while the lower represents the 3”-C-band-data.

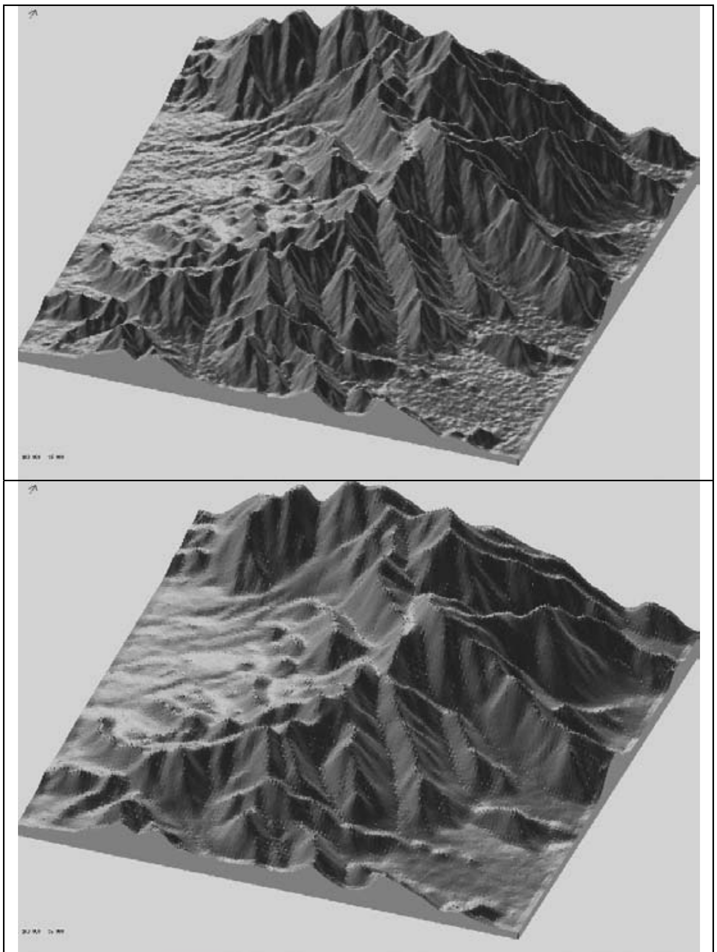


Fig. 4: SRTM C-band DEM 10km x 10km
Above DEM spacing 1 arc second
Below DEM spacing 3 arc seconds

Table 1: influence of DEM interpolation				
	spacing	average tilt	average change of tilt	RMSZ
Zonguldak	80m	0.27	0.32	12.0m
Arizona	90m	0.17	0.09	4.8m
New Jersey	60m	0.024	0.015	0.45m
New Jersey	120m	0.024	0.015	1.12m

The root mean square Z-differences of an interpolation of a DEM over the spacing listed in table 1 and compared with the available height values of the interpolated points is quite depending upon the roughness of the terrain. The terrain roughness can be expressed by the change of the tilt from one spacing to the next. In the very rough terrain of Zonguldak, Turkey an interpolation of a 40m grid over a spacing of just 80m leads to root mean square height differences of 12m, while in the smooth terrain of New Jersey even over 120m only a loss of accuracy by 1.12m is caused.
In the area of Zonguldak SRTM C-band and also X-band height information are available together with a reference DEM from a map 1 : 25 000.

X-band DEM	DZ > 50m	RMSZ [m]	Bias [m]	RMSZ F(slope)
Open areas	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

Table 2: RMS discrepancy of the SRTM X-band DEM against the reference DEM from the map 1:25000 and check points, area Zonguldak

C-band DEM	DZ > 50m	RMSZ [m]	Bias [m]	RMSZ F(slope)
Open areas	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 3: RMS discrepancy of the SRTM C-band DEM against the reference DEM from the map 1:25000 and check points, area Zonguldak

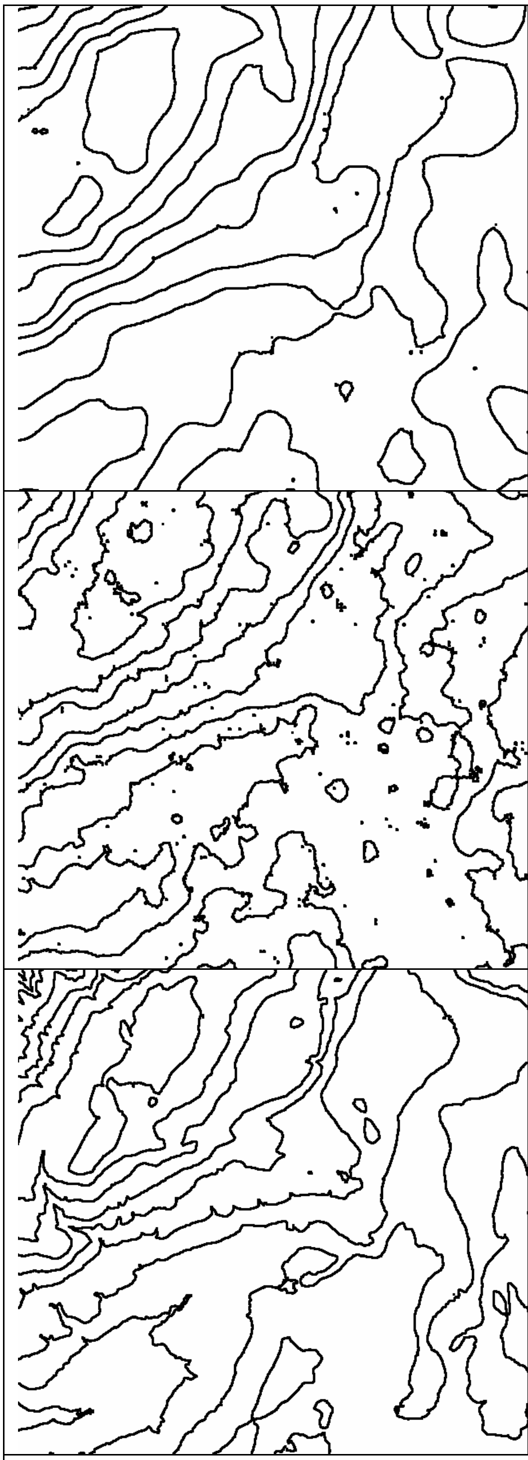
45% of the Zonguldak test area is covered by forest. Of course in the forest areas not the same height accuracy can be expected from the SRTM data, by this reason the analysis was made separately for the forest and for the open areas. The analysis showed a very clear linear dependency of the DEM accuracy upon the tangent of the terrain inclination.
The analysis of the SRTM C-band and X-band DEMs shows a very similar accuracy for both in relation to the reference DEM which is also not free of error. The reference DEM is estimated with an RMSZ of approximately 6m. It is based on the Turkish national coordinates and had to be transformed to UTM with the WGS84 ellipsoid. The datum of the Turkish coordinate system in relation to the ITRF reference frame was not known by the author. This is a typical problem for several countries. By this reason at first the reference DEM has been shifted by an adjustment with the Hannover program DEMSHIFT to the SRTM DEMs in X and Y. The shift of

the DEM in the range of 150m has improved the accuracy by the factor 2. In addition the X-band DEM had to be improved by the Geoid undulation.
The lower accuracy of the forest area is mainly caused by the vertical shift to the top of the vegetation. For both SRTM DEMs the systematic shift in the forest is in the range of 8m - not too far away from the average tree height of approximately 10m. The clear dependency of the vertical accuracy depending upon the terrain inclination can be explained by an error in the position having a linear dependency upon the tangent of the terrain inclination but also the lower accuracy of the InSAR for inclined parts.
The SRTM DEMs have also been checked against some precise control points. Control points are located in open areas not influenced by vegetation, explaining the better accuracy especially for the X-band data. Especially for flat areas the accuracy is with 1.3m and 4.0m quite better like in the case of a comparison with the reference DEM.

	RMSZ [m]	Bias [m]	RMSZ F(slope)
Arizona	3.9	1.3	2.9 + 22.5 * tan α
Williamsburg NJ	4.7	-3.2	4.7 + 2.4 * tan α
Atlantic City	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 4: accuracy of C-band DEM in different test areas

In the USA and in Germany accurate reference DEMs have been available. In all cases the SRTM DEMs have been shifted to the reference DEMs by adjustment with program DEMSHIFT. The influence of the horizontal location discrepancies of the SRTM DEMs is linear depending upon the tangent of the terrain inclination, so the influence is limited in the flat area of Williamsburg, NJ and Atlantic City, but it is quite high in mountainous regions. In the mountainous test area in Bavaria (linear mean of slope = 0.27) RMSZ-discrepancies of 23.0m have been available before the shift in X and Y to the reference DEM. Like Zonguldak, both Bavarian test areas do include a higher percentage of forest. In the forest areas a Z-shift of the SRTM-DEM against the reference DEM of 8.4m and 11.6m showed up, enlarging the RMS discrepancies. The test area Arizona does not include remarkable vegetation and it showed the highest accuracy. In Williamsburg and Atlantic City a smaller percentage of forest is included, enlarging the discrepancies in Z. For example in the forest areas of the mountainous Bavarian test area the root mean square height discrepancies is reaching 15.2m or as a function of the slope: 14.3m + 2.2 * tan α. As typical for very steep areas, in this case 3% of the height values are missing in the SRTM-DEM.



contour lines based on SRTM C-band DEM spacing 92m * 63m

contour lines based on SPOT HRS images, spacing 15m * 30m

contour lines based on airborne laser scanning with 5m spacing

Fig. 5: comparison of contour lines, contour interval 20m, test area Bavaria, rolling

In all cases a clear dependency of the vertical accuracy upon the terrain inclination is available. In the mountainous part of Bavaria this is influencing the RMS value, so it is with 8m quite higher like in the other areas. But a separation of the influence of the inclination shows for flat parts in open areas a similar accuracy. It is between 2.7m and 4.9m. In the case of the larger values an influence of the forest is still included.

The spacing of 3” for the C-band DEMs does not enable a filtering of the elements not belonging to the surface. The identification of the elements not belonging to the surface requires a smaller spacing and also better relative height accuracy. The loss of details caused by the spacing of 3” can be seen in figure 5 in relation to DEMs based on SPOT HRS-images and an airborne laser scanning with a spacing of 5m.

3 OPTICAL IMAGES

3.1 GENERAL

The accuracy of a DEM based on optical images is depending upon the height-to-base-relation multiplied with the pixel size on the ground and a multiplication factor.

$$SZ = \frac{height}{base} \bullet pixel\_size\_ground \bullet factor$$

Formula 1: height accuracy by optical images

By theory the best accuracy will be reached with a small height/base ratio. This is really the case for flat areas with good contrast and no elements like trees or buildings on top of the surface. For an automatic image matching the correspondence between the sub-windows of both used images is better for a large height to base ratio. So the optimal height to base relation for the best vertical accuracy is depending upon the roughness of the surface and will be more in the range of the relation 1.5 (see also Börner et al 1997).

The multiplication factor usually is between 0.3 and 3.0 depending upon the contrast in the image and the geometric and radiometric image quality. Not in any case the nominal pixel size is identical to the pixel size corresponding to the information contents. For example IKONOS images are always distributed as Geo-product with 1m pixel size even if the incidence angle is 45°. The physical pixel size of such an image with inclined view is 1.15m * 1.62m, so with 1m it is oversampled.

The effective pixel size can be determined by an edge analysis. At a location in the image with a sudden change of the grey value in the object space, grey value profiles over the edge should be measured in the image (figure 6). The response to the edge in the image will not be so sharp like on the ground. The inclination of the grey value profile in this location includes the information about the effective pixel size. The same edge available in different space images (in figure 6 marked by red line) has been investigated for the edge response.

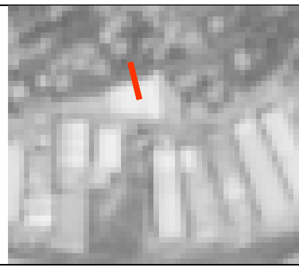
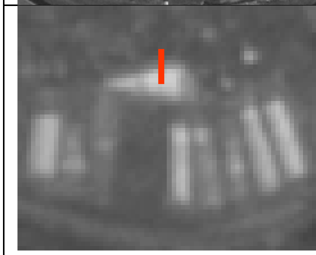




Fig. 6: edge analysis:
upper left: IKONOS pan 1m ground pixel size
upper right: SPOT 5 5m ground pixel size
lower left: IRS-1C 5.8m ground pixel size

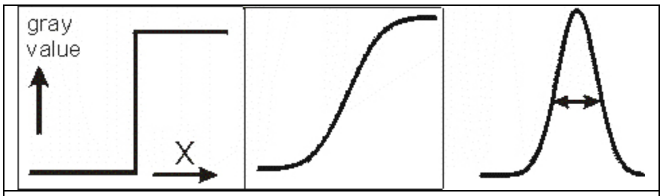


Figure 7: edge analysis
left: grey value profile in object space
centre: grey value profile in image space
right: differentiation of grey value profile in image
→ point spread function

The differentiation of the grey value profile in the image leads to the point spread function. The width of the point spread function at 50% height can be used as effective pixel size. In the area of Zonguldak, Turkey, different space images have been analysed at the same location. Of course not only a single profile has been used for the analysis but all possible profiles at the edge.

	nominal pixel size	effective pixel size
ASTER	15 m	16.5 m
TK 350	(10 m)	13 m
IRS-1C	5.8 m	6.9 m
SPOT 5	5 m	5 m
IKONOS pan	1 m	1.0 m

Table 5: effective pixel size determined by edge analysis

Only the digital images ASTER and IRS-1C do show an effective pixel size larger than the nominal pixel size. The TK350 is originally an analogue space photo. It has been scanned with a pixel size of approximately 10m. For analogue images of course it is the question if the pixel size used for scanning corresponds to the image resolution and so it is not astonishing if we do have here a larger difference between the nominal and the effective pixel size. Sojuzkarta talks about a smaller pixel size for the Russian space photos, but they are always a little optimistic.
Different optical space images, partially in different areas, have been used for the generation of DEMs. The automatic image matching has been done with the Hannover program DPCOR based on a least squares matching.

sensor	ground pixel size	height / base
TK 350	(10m / 13m)	2.0
ASTER	15m	1.7
SPOT 5	5m	(1.85)
SPOT 5 HRS	5m x 10m	1.2
IKONOS	1m	(3.8 / 7.5)
QuickBird	0.62m	(9.1)

Table 6: used space images for DEM generation

sensor	area	RMSZ [m]	RMSZ F(slope) [m]
TK 350	open	23.3	20.0+23.9*tanα
	forest	51.3	49.0+11.4*tanα
	check p.	6.6	4.7 + 2.2*tan α
ASTER	open	25.0	21.7+14.5*tanα
	forest	31.2	27.9+18.5*tanα
	check p.	12.7	
SPOT 5	open	11.9	8.4 + 6.3*tan α
	forest	15.0	9.8 + 5.3*tan α
	check p.	3.8	3.5 + 0.9*tan α
SPOT 5 HRS	open	6.7	6.4 + 4.9*tan α
	forest	17.0	16.4+ 2.2*tan α
SPOT 5 HRS filtered	open	4,4	4,2 + 1.6*tan α
	forest	12.3	10.0 + 6.9*tanα
IKONOS	Maras	1.7	same orbit
IKONOS	Zonguldak	5.8	Δt = 3 month
QuickBird	Arizona	4.8	Δt = 10 days

Table 7: accuracies of DEMs based on space images

3.2 TK 350

The used Russian space photo TK 350 has not had a good quality; it was disturbed by a high number of scratches and film grain. The contrast in the forest was poor, so finally the results achieved in the forest areas could not be accepted. The root mean square discrepancies of the generated DEM against the reference DEM (RMSZ) of 20.0m for flat areas correspond to a standard deviation of the x-parallax (Spx) of 0.8 pixels in relation to the effective pixel size of 13m. Against check points the DEM has only a RMSZ-value of 6.6m or for flat areas 4.7m corresponding to Spx= 0.25 / 0.2 pixels showing the possible quality in areas with good contrast. But this is not a realistic accuracy for a DEM which includes also areas with low contrast.

3.3 ASTER

The near infrared spectral band used by ASTER for the stereoscopic coverage causes quite better contrast also in the forest area, so the loss of accuracy in the forest against the open area is limited. The accuracy of 21.7m in the open and flat areas corresponds to Spx=0.85 pixels. Also here the discrepancies of the generated DEM against check points is with 12.7m (Spx=0.5 pixels) quite smaller, but again this is not the accuracy information for a DEM including also areas with low contrast.

3.4 SPOT 5

SPOT 5 images with just one day of difference in imaging have been analysed as level 1A and level 1B products. Of course the different geometry requires different mathematical models for the handling - Hannover program BLASPO for the handling of the satellite line scanner images presented as level 1A and Hannover program CORIKON for the handling of the projection of the images to a plane with constant height presented as level 1B. The achieved results are nearly identical, so in table 7 there is no separation between both products. The panchromatic spectral range is not optimal for forest areas leading to a very narrow range of the grey values (figure 8)

Figure 8: histogram of panchromatic SPOT 5 image area Zonguldak (over 256 grey values)
left: whole image right: forest

Of course with the 5m pixel size better results can be achieved like with the 15m of ASTER. In the open and flat area the RMSZ of 8.4m (Spx=0.9 pixels) is still influenced by the quality of the reference DEM which is in the area of Zonguldak just in the range of

6m. If the quality of the reference DEM is respected, the RMSZ of the SPOT 5 DEM in open and flat areas would be in the range of 5.9m (0.6 pixels). Again at locations of check points determined by GPS survey, with 3.5m for flat areas (Spx=0.4 pixels) better results have been achieved. The limited accuracy in the forest areas of 16.4m for flat parts can be explained by the height of the vegetation, but also the limited range of the grey values.

3.5 SPOT 5 HRS

SPOT 5 includes as additional sensor the High Resolution Stereo (HRS) which is looking forward and backward in the orbit direction and so generating a stereo model with just 90 seconds difference of time between both images. The HRS-images are usually not distributed, SPOT Image likes to generate the DEMs themselves, but for investigation by the SPOT HRS study team, images have been available. The HRS images do have a pixel size of 5m in the orbit direction and 10m across. The pixel size in the orbit direction is important for the vertical accuracy. In the test area Bavaria, Germany, against laser scanner data having an accuracy better than 0.5m, an accuracy of 6.4m in open and flat areas (Spx=1.1 pixels) has been reached. As also visible at the quite lower quality in the forest areas, the height models generated by optical images do represent the visible surface that means a DSM. The filtering of the DSM to a DEM by the Hannover program CORIKON (Jacobsen 2001), that means removing of all points not belonging to the bare ground, is possible with the quality of the SPOT HRS having noise below the height of trees and buildings. The filtering has improved SPOT HRS DEM in open and flat parts to 4.2m (Spx= 0.7 pixels). This is approximately the same accuracy like available by the C-band SRTM data, but HRS allows a spacing of the DEM-points of 15m x 30m and so quite more details are available in the HRS DEM (see figure 5). A spacing of the DEM below 3 pixels does not improve the information about the visible surface. Based on sub-matrixes for image matching by least squares of 10 pixels times 10 pixels, a sufficient independent information requires at least a different position by 3 pixels to the neighboured ones.
In the forest area even after filtering the accuracy of the DEM is limited to 10m for the flat parts. The bias in the forest areas has been reduced by the filtering from 14.3m to 8.5m. If all neighboured points are located on top of the vegetation, a filtering has only a very limited effect. If the systematic shift is respected, also in the forest the accuracy is quite better, but the correlation coefficients are still smaller in the forest areas like in the open areas because of the same reason like for SPOT 5. The quality map (figure 9) shows very well the location of forest parts. All dark areas having smaller correlation coefficients are forest areas. On the right hand side a road is crossing the forest. The road can be identified very well by the higher correlation coefficients (nearly white).

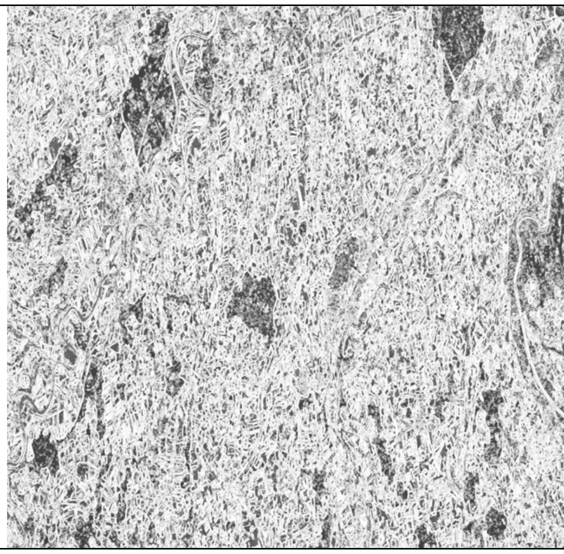


Figure 9: quality map of matching a SPOT HRS sub-scene – size of correlation coefficient displayed as grey value
grey value 255 (white) = correlation coefficient 1.0
grey value 51 (dark grey) = correlation coefficient 0.6

3.6 IKONOS

The quite better resolution of IKONOS and QuickBird by theory allows better height accuracy. This was the case in the area of Maras, where a stereo model taken from the same taken from the same orbit is available. Even with the poor height to base relation of just 7.5, a height accuracy of 1.7m has been reached in urban areas. This corresponds to a standard deviation of the x-parallax of just 0.22 pixels. The details of the generated DEM do allow the creation of a 3D-city model.
In the area of Zonguldak two IKONOS images taken in July and October with a height to base relation of 3.8 could be used for image matching. The change of the sun elevation from 67° to 41° caused large differences of the shadow leading to problems of the image matching. In the forest areas the matching failed nearly completely, but also in the build up areas the changes of the shadow length made the matching difficult. Only in limited areas an automatic image matching was possible. The final accuracy of 5.8m corresponds to a standard deviation of the x-parallax of 1.5 pixels – a quite higher value like in the area of Maras. But in general it can be

said, such a combination of quite different very high resolution images is not useful for the generation of a digital elevation model.

3.7 QuickBird

From QuickBird, two partially overlapping images taken with 10 days difference in time over the suburbs of Phoenix-Arizona, having a limited height to the base ratio of 9.1, have been used for generation of a DEM. Between imaging both scenes, the change in the vegetation and the sun elevation were negligible, so good conditions for image matching exists. The automatic image matching gave excellent results with a vertical accuracy of ±4.8m in relation to a 7.5' USGS DEM that is also not free of errors. This corresponds to a standard deviation of the x-parallax of 0.8 pixels. The average correlation coefficient was in the range of 0.95. The matching failed only in few limited areas with very low contrast like roads, sandy areas and a few roofs.

4 CONCLUSIONS

Digital elevation models can be generated in an economic manner by space information. For the largest parts of the world today height information taken by InSAR during the Shuttle Radar Topography Mission are available free of charge in the internet. If instead of this, DEMs shall be generated based on optical images, there must be a special reason. This may be: better accuracy, more details, different characteristics of the determined surface or no gaps in steep parts.
It is not possible to describe the geometric quality of a DEM with just one figure – this is the case for the InSAR DEMs like also the DEMs based on space images. At first there is a clear difference in the characteristics for open areas and forest and we do have a clear dependency upon the terrain inclination. If the DEMs are not based on control points, also the horizontal location is important. The good standard deviation of the SRTM DEMs for open and flat areas of 2.7m up to 4.9m could be reached only after shifting it to the reference DEMs.
The clear lower accuracy reached with TK350 and ASTER models in comparison to the SRTM data does not justify the expenses for their use. With SPOT 5 in the area of Zonguldak approximately the same accuracy has been reached like with the C-band and the X-band SRTM data. SPOT 5 includes the advantage of generating a DEM with a spacing of 15m, including more details and having a better morphologic accuracy. Similar it is with the SPOT HRS images having also the advantage of being taken from the same orbit.
With IKONOS and QuickBird even a DEM with a better resolution and also accuracy can be generated if the images are taken from the same orbit or if the radiometric changes are limited. With the height to base relation the accuracy can be influenced directly.

For several cases the SRTM DEMs are sufficient, but the horizontal location should be checked and in forest areas they do present the top of the trees. More details can be reached with SPOT 5 and SPOT HRS models. A filtering of the generated DSMs to DEMs is required. The very high resolution images like IKONOS and QuickBird can lead to better accuracy and details, but for quite higher expenses.

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