ANALYSIS OF SRTM HEIGHT MODELS

Sefercik, U. *, Jacobsen, K.**
* Karaelmas University, Zonguldak, Turkey, ugsefercik@hotmail.com
**Institute of Photogrammetry and GeoInformation, University of Hannover, jacobsen@ipi.uni-hannover.de

KEY WORDS: SRTM, DEM, Analysis

ABSTRACT

By Interferometric Synthectic Aperture Radar (InSAR), during the Shuttle Radar Topography Mission (SRTM) height models have been generated, covering the earth surface from 56° south 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 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 and have been analysed in a cooperation between Zonguldak Karaelmas University (ZKU) and University of Hannover. As reference height model the digitized contour lines from the topographic map 1 : 25 000 and also a more precise height model directly from large scale photogrammetric mapping are given.

The terrain inclination has a strong influence to the accuracy, but also the direction of the inclination in relation to the radar view direction, the aspects, are important. Independent upon the aspects, the analysed results do have root mean square differences against the reference data fitting very well to the Koppe formula SZ=a+b*tan α. The analysis was made separately for open and for forest areas, with clear accuracy differences between both. The C-band data are only available with a spacing of 3 arcsec, corresponding to 92m x 70m, while the X-band data do have a spacing of 1 arcsec. This is important for the interpolation in the mountainous test area. The accuracy of the height points is approximately the same for the C- and the X-band data. But the three times larger spacing of the C-band data is not including the same morphologic information like the X-band data, resulting in very generalised contour lines for the C-band data and with quite more details in the X-band DSM.

1. INTRODUCTION

Digital elevation models (DEMs) are a basic component of any geo information system (GIS). The terrain cannot only be described by the horizontal components; the height belongs to a complete information. In addition height models are required for the generation of orthoimages – one of the most often used photogrammetric product. DEMs can be generated by laser scanning, photogrammetric methods or interferometric synthetic aperture radar (InSAR). In any case it is time consuming and expensive. The worldwide lack of qualified and accessible DEMs has been improved with the Shuttle Radar Topography Mission (SRTM) in February 2000. Based on InSAR height models have been generated covering the world from 56° southern up to 60.25° northern latitude. The DEMs based on the US C-band are available free of charge in the internet (http://edcsgs9.cr.usgs.gov/pub/data/srtm/) with a spacing of 3arcsec, corresponding to approximately 92m at the equator. Only for the USA the data with a spacing of 1" (~ 30m) are also in the WEB. The DEMs based on the German / Italian X-band can be ordered from the DLR, Germany with a spacing of 1 arcsec. In the area of Zonguldak, Turkey, C-band and also X-band height models have been investigated.

2. USED DATA SETS

The mountainous test area Zonguldak shown in figure 1 is ranging from the Black Sea up to an elevation of 1646m. The average terrain inclination is 23% (figure 5). In the reference DEM the inclination is changing from one spacing of 40m to the next by 32%. This rough terrain is causing quite more problems for DEMs like more smooth areas.

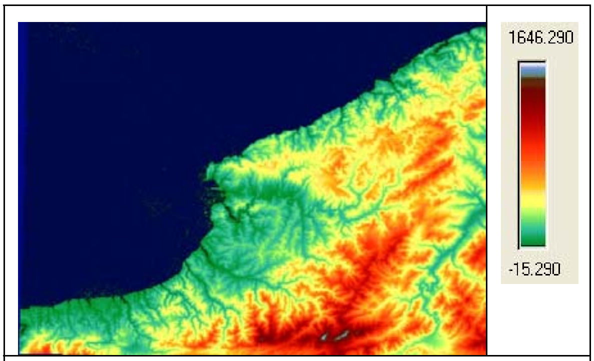

Fig. 1: SRTM C-band height model Zonguldak

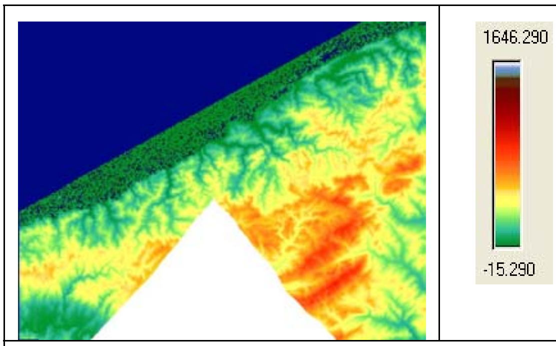

Fig. 2: SRTM X-band height model Zonguldak

The C-band height model has used the scanSAR-mode with a swath of 225 km while the X-band was limited to a swath of 45 km (figure 3).

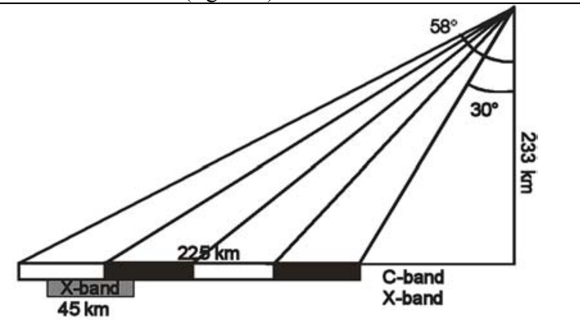

Fig. 3: swath width SRTM C-band and X-band

By this reason the X-band DSMs do not cover the area completely while the C-band DSMs in the average are covering 94.6% of the area twice and approximately 50% three times. This has compensated the by theory better accuracy of the X-band DSMs (3cm wavelength) in relation to the C-band DSMs (5.6cm wavelength).

Together with the X-band data a height error map is distributed including the estimated height accuracy (fig. 4). In the test area an ascending and a descending X-band strip are crossing. The city of Zonguldak is located in the crossing area (3 in figure 4) where the results of both orbits are averaged. Corresponding to this, in the crossing area 3 the estimated height accuracy is between 3 and 7m while in the areas 1 and 2 the accuracy is estimated with 7m up to 95m. The extreme values of 95 m can be seen as colour spots in figure 4. They are located in very steep areas and at the coast line. At the cost the terrain is partially vertical going up, causing radar overlays. On the other hand from the flat sea there is nearly no energy reflected back to the antenna, causing a poor accuracy.

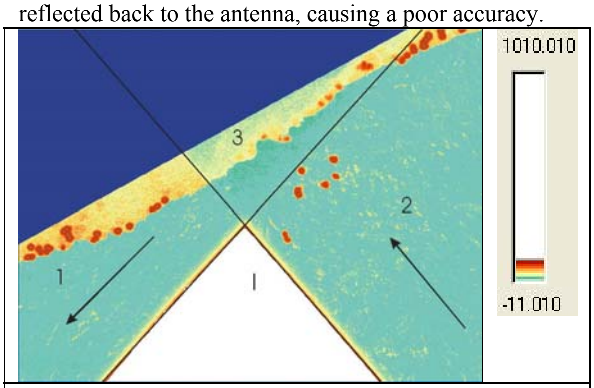

Fig. 4: colour coded height error map of X-band DEM, test area Zonguldak

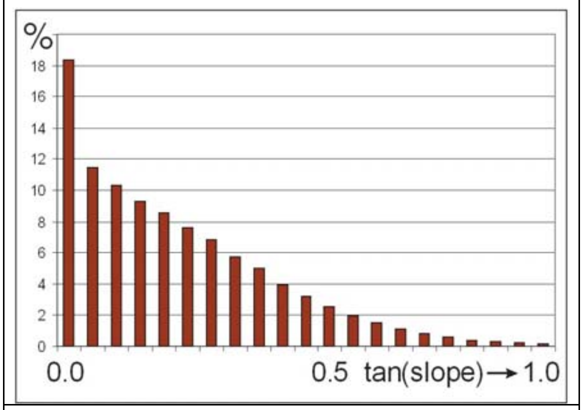

Fig. 5: distribution of terrain inclination

3. SRTM

The data acquisition by Synthetic Aperture Radar (SAR) is based on the direction perpendicular to the orbit and the distance. The determination of the location based on distances is causing some problems in steep terrain. If the terrain inclination is exceeding the incidence angle, the position of a higher elevated point is shown before the position of a lower point even if this is reverse in the object space (point 4 in figure 6 is located in the slant range image before point 3). This so called layover is mixing the radar signals and there is no possibility of a correct reconstruction in such steep parts. Caused by the higher incidence angle of SAR the shadows (areas with no information) are larger like usually in optical images. The compression of the information by the foreshortening is reducing the information in these parts.

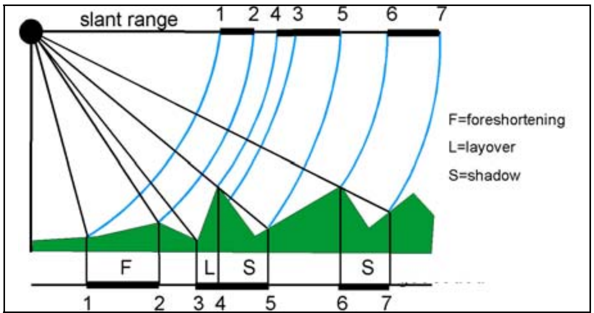

Fig. 6: location determination by SAR

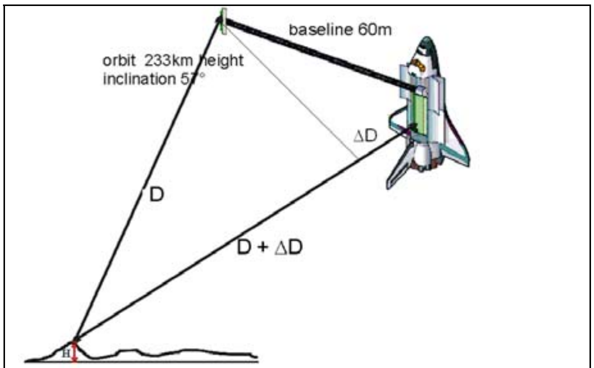

Fig. 7: principle of InSAR

InSAR is based on the difference of the distances of the energy reflected from the ground to two antennas (see figure 7). This cannot solve the problems described before, so in steep areas some data may be missing or just before reaching the layover it is becoming less accurate.

4. RESULTS ACHIEVED IN THE TEST AREA ZONGULDAK

Since 2005 in the central part of the Zonguldak test area a reference height model from a large scale photogrammetric survey is existing having a point spacing of 10m. Before only a reference height model based on the topographic map 1:25 000 was available. This was not so accurate like the SRTM height models, so no correct analysis was possible before.

A first comparison of the SRTM height information with the reference DEM showed root mean square errors (RMSE) in the range of 25m. A detailed view to the data indicated a horizontal shift caused by the national datum, but also a part may come from the absolute orientation of the SRTM height models. The shifts have been determined and respected with the Hannover program DEMSHIFT by least square adjustment. Only a shift in X and Y has been made as pre-correction because the national datum is only influencing the horizontal location. The height is related to the geoid or the ellipsoid in the case of the SRTM X-band data, so these data have been corrected by the geoid undulation.

The X-band and also the C-band are short radar waves, they cannot penetrate the vegetation. That means, the SRTM height models are digital surface models (DSM) and presenting the visible surface. In city areas the height is influenced by the buildings and in the forest it is influenced by the trees. The forest in the Zonguldak area is usually not so high and dense, so the average height shift in the forest of the SRTM DSMs against the reference DEM must not be so large.

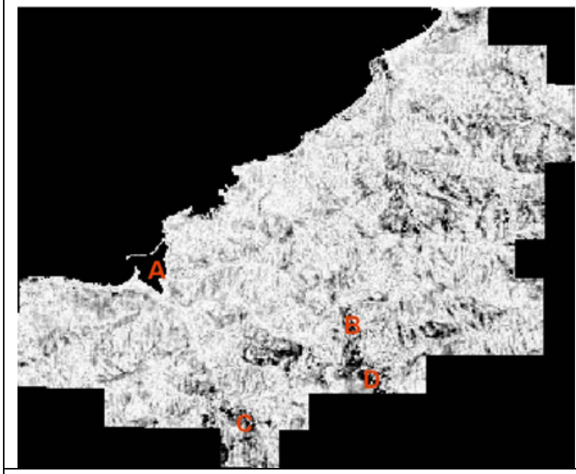

Fig. 8: grey value coded height differences X-band white = 0.0m, black = 30.0m or no data

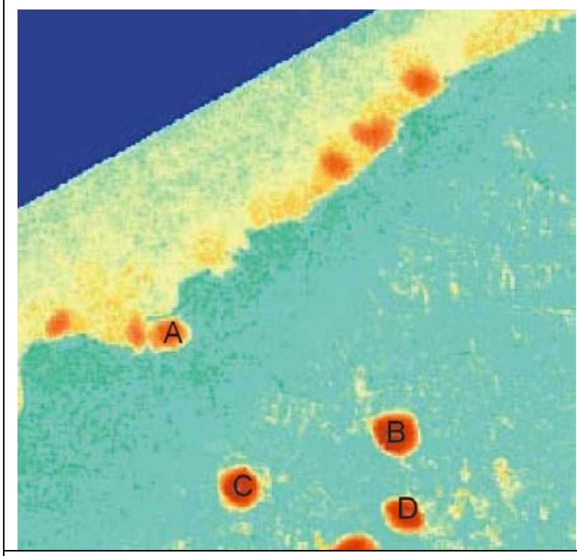

Fig. 9: colour coded height error map of SRTM X-band in the area of the reference DEM

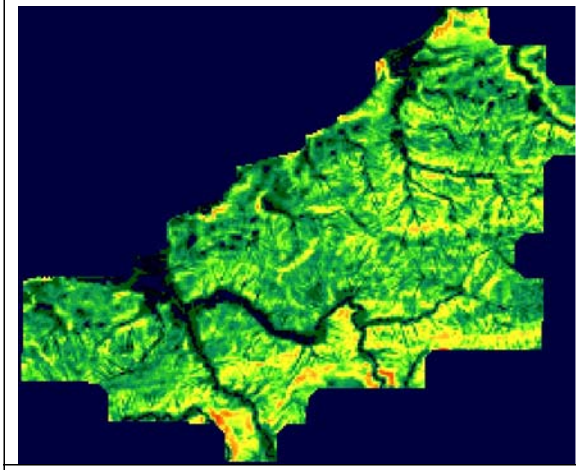

Fig. 10: colour coded slope map of reference DEM blue = flat, red = largest inclination

Figure 8 shows the height discrepancies of the C-band DSM against the reference height model. A not equal distribution of the discrepancy size is obvious. 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 (figure 9) is not so detailed. A comparison with the slope map (figure 10) 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 here we do have also the influence of the buildings in the city.

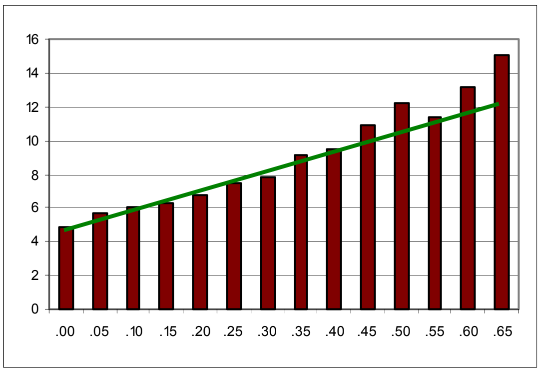

Fig. 11: root mean square height differences SRTM X-band DSM against reference DEM for open areas as function of terrain inclination

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

The RMSE of the height differences of the SRTM X-band DSM against the reference DEM for open areas are shown in figure 11 as a function of the terrain inclination. All other results show a similar linear dependency. So the accuracy of the SRTM DSM cannot be described just with one RMSE, a function depending upon the terrain inclination is required. In above example it can be expressed by SZ = 4.74m+ 11.32m ∗ tan (slope). Such a dependency can be explained by the basic geometry of SAR (figure 6) dependent upon the foreshortening and also the accuracy of the location in X and Y. Also for other data sources like photogrammetric point determination and laser scanning we do have a similar dependency.

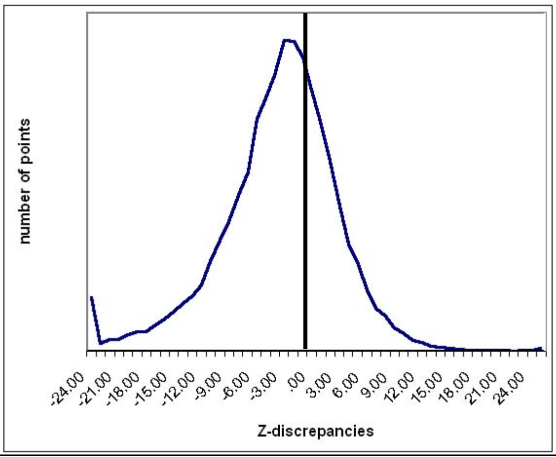

Fig. 12: frequency distribution of height differences SRTM X-band DSM against reference DEM for open areas

The frequency distribution of the height differences (figure 12) is slightly asymmetric. This is also shown by the bias of -3.67m. Negative values do mean the SRTM height data are above the reference DEM, so the higher number on the left hand side of the frequency distribution is caused by buildings and vegetation in the open area.

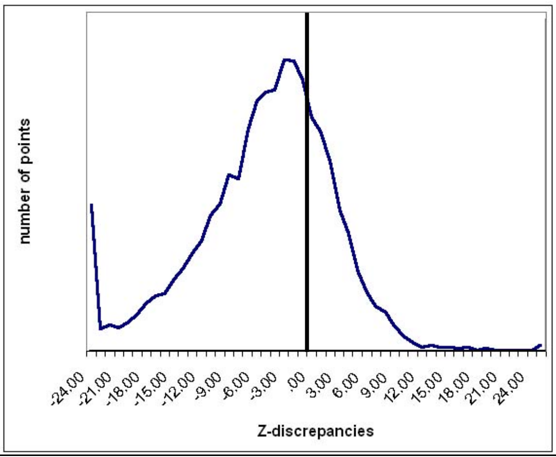

Fig. 13: frequency distribution of height differences SRTM X-band DSM against reference DEM for forest areas

The frequency distribution in the forest area is still more asymmetric caused by the vegetation. The corresponding bias with -5.30m is also larger like in the open areas.

A height data set from laser scanning or automatic matching of photogrammetric images has to be filtered for elements not belonging to the bare ground to get a DEM (Passini, Betzner, Jacobsen 2002). The same can be done with SRTM DSMs. The height values of the C-band data available with 3 arcsec spacing are the average of the 9 height values of the original data set having 1 arcsec spacing. This averaging is smoothing the DSM and together with the large spacing a filtering in mountainous areas like Zonguldak does not lead to an improvement. This is different for flat areas e.g. the city of Bangkok where the influence of the buildings could be removed by filtering with the Hannover program RASCOR. The situation for the SRTM X-band data with only 1 arcsec spacing is better. A filtering removed 26.2% of the points, a usual number for a filtering. The overall RMSE has been reduced from 8.02m to 6.54m but mainly influencing the error component depending upon the terrain inclination. The bias also has been reduced from -3.67m to -3.07m.

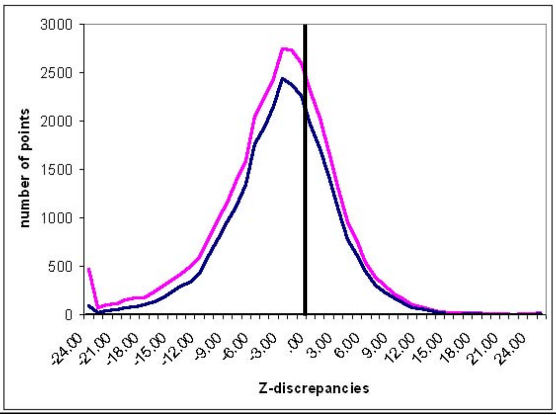

Fig. 14 frequency distribution of height differences SRTM X-band DSM against reference DEM for open areas red (upper line): before filtering, black (lower line): after filtering

The influence of the filtering can be seen at the frequency distribution (figure 14). More values on the left hand side representing points located above the reference DEM have been removed. But in general the terrain has been smoothened and that is not optimal in the mountainous area of Zonguldak. By this reason the original and not the filtered data have been used.

	RMSZ [m]	bias [m]	RMSZ without bias [m]
open areas	4.72+10.4*tan α	-3.67	4.05+9.6*tan α
forest	6.50+15.8*tan α	-5.30	5.56+12.2*tan α

table 1: SRTM X-band DSM against reference DEM

	RMSZ [m]	bias [m]	RMSZ without bias [m]
open areas	5.93+5.6*tan α	-4.40	4.51+5.8*tan α
forest	6.28+6.5*tan α	-4.85	5.92+1.9*tan α

table 2: SRTM C-band DSM against reference DEM

Not a major difference in accuracy between the X-band and the C-band data can be seen in table 1 and 2. The C-band data are less depending upon the terrain inclination but reverse the accuracy for the horizontal parts is more accurate for the X-band data. The results without influence of the terrain inclination can be seen in table 3.

	X-band			C-band		
	RMS	bias	RMS no bias	RMS	bias	RMS no bias
open	7.67	-3.67	6.66	7.41	-4.40	5.88
forest	9.87	-5.30	8.21	8.24	-4.85	6.66

table 3: SRTM DSMs against reference DEM without influence of terrain inclination

The terrain inclination is the same for both data sets, so they can be compared also with the RMSE not respecting the influence of the terrain inclination. The C-band data are a little better like the X-band data.

Both data sets do show a clear bias (systematic error) which partially may come from the influence of the buildings and vegetation, but also from the sensor orientation. A bias in this range has been seen also in other areas (Jacobsen 2005). The bias can be determined by means of control areas, so an improvement of the SRTM DSMs is possible to the results listed as without bias.

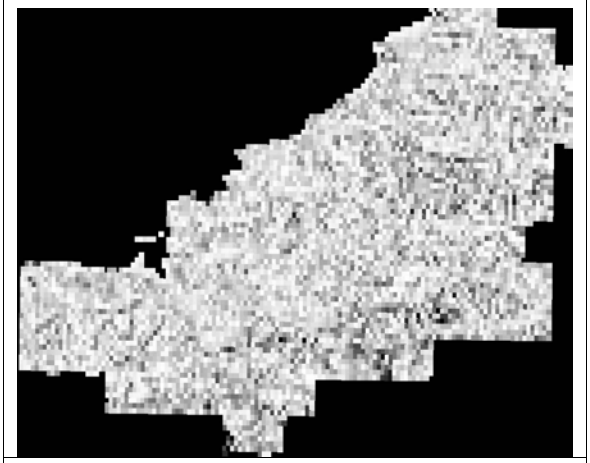

Fig. 15: grey value coded height differences C-band white = 0.0m, black = 30.0m or no data

The lower dependency of the C-band data from the terrain inclination can also be seen at the grey value coded height differences shown in figure 15. There are not so large values (dark parts) in the inclined areas. One of the reason can be seen in the averaging of the individual height values, but also the averaging of more than one coverage – as mentioned, the C-band data are representing in average a double coverage for 94.6% of the cases and approximately three times for 50%. This is reducing the accuracy effects of the terrain inclination in the direction perpendicular to the orbit. As visible in figure 4, the descending and the ascending orbit are close to perpendicular in the Zonguldak area. So an effect in the view direction cannot be seen for the average of the height values taken in the descending and the ascending orbit. For the X-band data this is different in the sub-area 2 shown in figure 4. By this reason a separate analysis has been made for the X-band data located in sub-areas 2 and 3. In sub-area 1 there are no accurate reference data available.

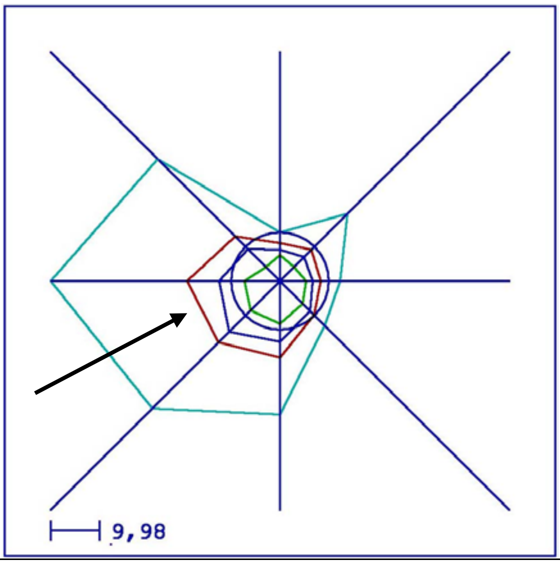

Fig. 16: accuracy of SRTM X-band data for open area in sub-area 2 depending upon the aspects (direction of terrain inclination)

centre: accuracy for horizontal parts
both following blue lines: mean value independent upon size of terrain inclination – circle = average
following red line: accuracy for average terrain inclination
outer line: factor for multiplying with tangent of slope

The X-band DSM shows a very clear dependency upon the aspects (figure 16). The maximal values correspond to the view direction (arrow in figure 16). 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. In the sub-area 3 (figure 4), where the height values from both orbits are averaged for the X-band data, the X-band DEM is approximately 15% more accurate like in the sub-area 3.

The results presented up to now do show the accuracy of the height points of the X-band and C-band data. The influence of the point spacing cannot be seen by this. The influence of the interpolation of course is larger for the 3 arcsec spacing of the C-band data like for the 1 arcsec spacing of the X-band data and the terrain itself. The area of Zonguldak is extremely mountainous with an average change of the terrain inclination from 40m to 40m of 32%.

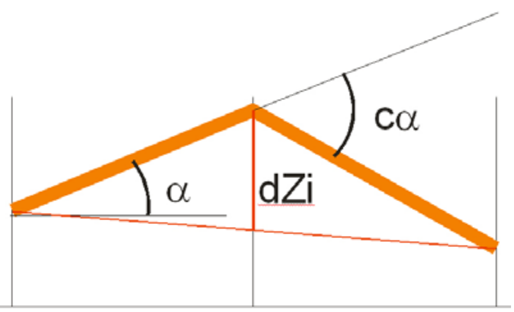

Fig. 17: influence of interpolation depending upon the change of the terrain inclination

$$dZi = d * \tan(c\alpha / 2)$$

dZi = height error of interpolation
d = half spacing distance
cα = change of inclination

formula 1: loss of accuracy by interpolation

For the Zonguldak area the loss of accuracy by interpolation over a distance of 80m is estimated with 12m. This has been verified by an interpolation of the C-band DSM to a spacing of 40m and the X-band data to a spacing of 15m and a comparison with the reference DEM having a spacing of 10m.

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

table 4: influence of DSM interpolation

As expected the loss of accuracy by interpolation is not so much for the X-band data having a spacing of 1 arcsec (30.8m / 23.3m) but quite higher for the C-band data with the spacing of 3 arcsec (92.5m / 69.8m). For the C-band data the interpolation is causing a loss of 79% in the open areas and 93% in the forest areas for the flat parts (relation of the first component in the formula describing the RMSE as function of the terrain inclination). For the X-band it is limited to 23% and 18%.

	RMSZ DSM points	RMSZ interpolated points	relation
X-band open	7.67	9.26	1.21
X-band forest	9.87	11.09	1.12
C-band open	7.41	14.67	1.98
C-band forest	8.24	16.32	1.98

table 5: influence of DSM interpolation independent upon terrain inclination

The loss of accuracy caused by the interpolation of the C-band DSM is higher for inclined areas; here we do have a loss of 98%. With usual error propagation it corresponds very well with the above estimated loss of accuracy of 12m. For the shorter spacing of the X-band data, the loss of accuracy by interpolation is limited to 21% and 12%.

6. CONCLUSION

The analysed SRTM X-band and C-band DSMs in the area of Zonguldak do have accuracy similar to other not so mountainous areas. In general the accuracy has to be expressed as a function of terrain inclination and it is not the same for forest and open areas. The height discrepancies against the reference height model are not exactly normal distributed; some remaining effects of buildings and vegetation can be seen at the frequency distribution of the differences. So for open areas without influence of vegetation and buildings the accuracy will be better. The X-band DSM shows accuracy depending upon the aspects, for the C-band data this cannot be seen because of the averaging of the height models based on different orbits.

The height points of the C-band and the X-band DSM are in the same accuracy range. An improvement of the quality is possible by means of control areas allowing the determination of the bias. The difference in spacing can be seen by the interpolation in the very mountainous area of Zonguldak. This is causing a loss of accuracy by the factor of 2.0 for the C-band data. The smaller spacing of the X-band data is only leading to a loss of accuracy by interpolation in the range of 20%. In not so mountainous areas the loss of accuracy by interpolation will be significantly smaller. In general both SRTM height models can be used for several applications. They do have the advantage of being homogenous in all covered areas.

ACKNOWLEGMENTS

Thanks are going to TUBITAK, Turkey and the Jülich Research Centre for the financial support of the investigation and to the DLR, Germany for making SRTM X-band data available.

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