# Analyses of SRTM Elevation Models

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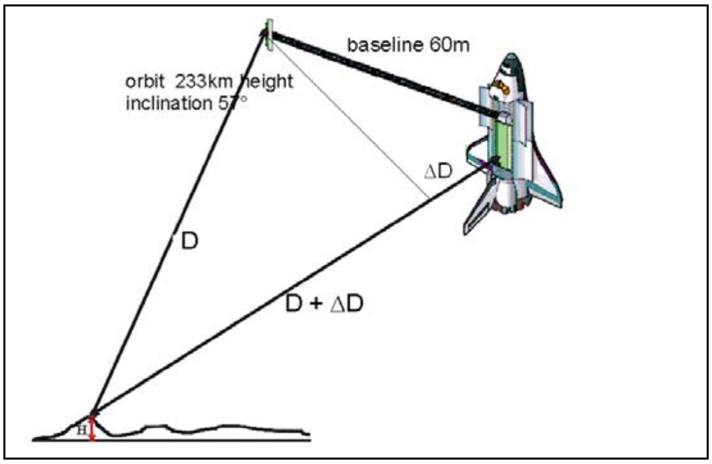
ABSTRACT: Based on the Shuttle Radar Topography Mission (SRTM), by Interferometric Synthetic Aperture Radar (InSAR) digital elevation models (DEMs) have been generated covering the earth from 56° south to 60.25° north. The SRTM included the American C-band working in a scan-SAR-mode with a swath width of 225km and the German-Italian X-band having only a swath width of 45km. By this reason the X-band DEM has large gaps between the strips while the C-band DEM is covering the area nearly without gaps. The X-band DEMs can be ordered for Euro 300 / (0.25° x 0.25°) with a grid width of 1 arcsec, corresponding to approximately 30m at the equator, while the C-band DEM is available for a handling fee with a spacing of 3 arcsec.
In mountainous areas the grid width of 3 arcsec is leading to a loss of morphologic details against the 1 arcsec data. The point height has approximately the same accuracy for both systems. The C-band as well as the X-band radar cannot penetrate the vegetation, so the SRTM height models are digital surface models (DSMs) representing the visible surface of vegetation and buildings. Only in areas with a terrain having a roughness below the noise of the data, a filtering for elements not belonging to the bare ground is successful. So the analyses has to be made separately for forest and open areas. The height accuracy is clearly dependent upon the terrain inclination. Respecting the terrain inclination and the vegetation, for flat and open areas a standard deviation of 3m to 4.5m has been achieved, sufficient for several applications.

## 1 INTRODUCTION

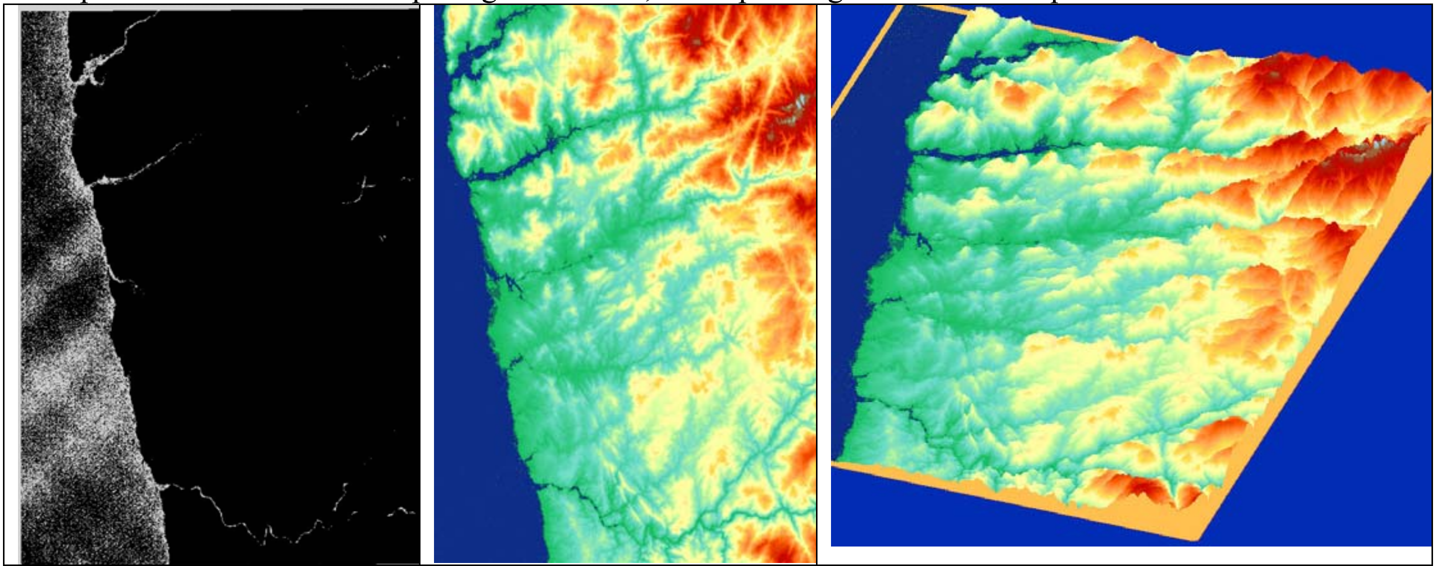



Based on the Shuttle Radar Topography Mission (SRTM) digital elevation models of the area from 56° southern up to 60.25° northern latitude have been generated. During the 11 day mission in February 2000 two different radar systems have been in the Space Shuttle – the US C-band with 5.6cm wavelength and the German-Italian X-band with 3cm wavelength. In addition to the active antenna systems in the Shuttle, passive systems have been available at a 60m long arm outside the Shuttle (figure 1).

figure 1: InSAR configuration of SRTM

With the combination of the active and the passive antenna by interferometric synthetic aperture radar (InSAR) the visible surface on the ground could be determined three-dimensional leading to digital surface models (DSM) showing the height of the upper part of the vegetation and the buildings. The C-band as well as the X-band radar cannot penetrate the vegetation, so a DEM with the height of the bare ground only can be achieved by filtering the SRTM height model.

The US C-band was operated with a scan-SAR mode having a swath width of 225km while the X-band was limited to a swath width of 45km. By this reason, the X-band data do have large gaps between the strips while the C-band has nearly a complete coverage and 94.6% of the mapped area is covered at least twice and approximately 50% at least three times. Only in very steep areas gaps of in total 0.15% are caused by radar layover. In the 1° x 1° area around Mount Everest 9% of the possible points are missing..
Outside the USA the C-band height model is limited to a point spacing of 3 arcsec, corresponding to 92m at the equator or 92m x 70m at the latitude of Porto. The X-band data can be bought from the German Aerospace Centre DLR with a spacing of 1 arcsec, corresponding to 31m at the equator.

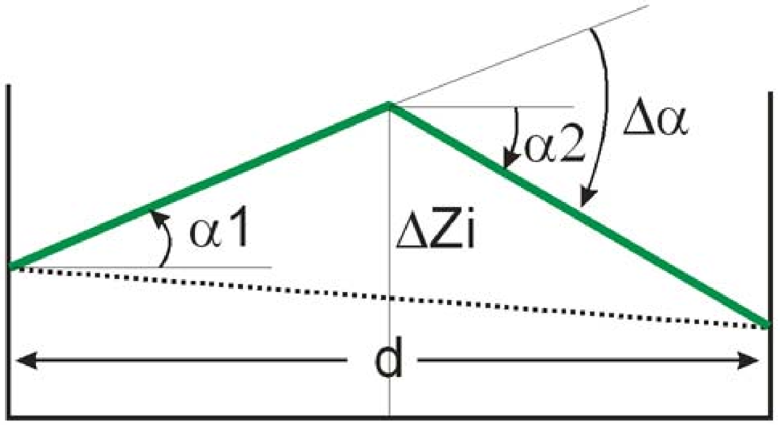


| dark = available height values | colour coded height model | 3D-view to colour coded height model |
|---|---|---|

Figure 1: SRTM C-band height model 1° x 1° area around Porto

As it can be seen in figure 1 on the left hand side, gaps in the height model are caused by water bodies. Without waves the water surface acts like a mirror and no signal is reflected to the antenna.

## 2 INFLUENCE OF DEM SPACING




$$\Delta Zi = \frac{d}{2} \bullet \tan \frac{\Delta\alpha}{2}$$

Formula 1: error caused by interpolation

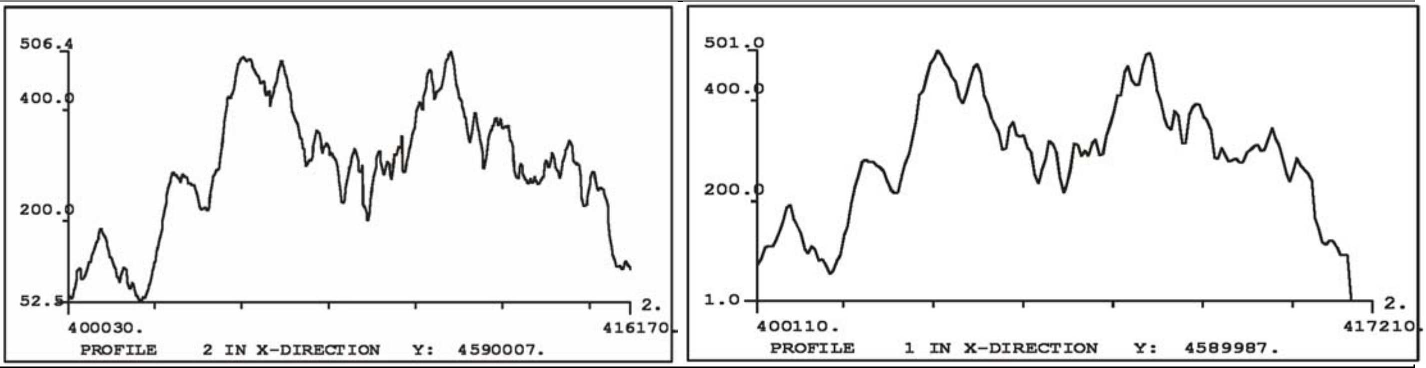
Figure 2: height error caused by interpolation depending upon point spacing d and change of inclination Δα

The accuracy loss caused by the point spacing of a height model depends upon the roughness of the terrain – especially the change of the terrain inclination and the point spacing (figure 2 and formula 1). It can be investigated based on reference DEMs having half the spacing like the DEM which shall be analysed. Table 1 shows the results of the interpolation analyses of 4 different areas. The Zonguldak test area in Turkey is very rough and has a stronger change of the terrain inclination from a spacing to the neighboured spacing like the terrain inclination itself. Corresponding to this, the root mean square height difference of points interpolated for the centre of a distance of 80m and compared with reference values reaches 12.0m. Based on this the average loss of accuracy caused by the spacing is estimated to 8.5m. For the also mountainous, but not so rough test area in Arizona, the loss of accuracy caused by the interpolation over 90m is 3.4m while flat and smooth area of New Jersey it is just approximately 0.4m over a distance of 80m. This loss of accuracy by the interpolation is independent upon the accuracy of the investigated data sets.

Table 1: loss of accuracy by DEM interpolation

| | spacing | average inclination | average change of terrain inclination | RMSZ | SZ for whole DEM |
|---|---|---|---|---|---|
| Zonguldak – mountainous, very rough | 80m | 0.27 | 0.32 | 12.0m | 8.5m |
| Arizona – mountainous | 90m | 0.17 | 0.09 | 4.8m | 3.4m |
| Bavaria - rolling | 80m | 0.084 | 0.12 | 2.9m | 2.1m |
| New Jersey – flat up to rolling | 60m | 0.024 | 0.015 | 0.45m | 0.32m |
| New Jersey – flat up to rolling | 120m | 0.024 | 0.015 | 1.12m | 0.80m |

The generalisation effect of the point spacing can be seen also at the height profiles shown in figure 3 and also in relation to the reference DEM based on the topographic map 1 : 25 000 (figure 4).




SRTM X-band DEM, 30m spacing | SRTM C-band DEM, 90m spacing

Figure 3: height profiles test area Zonguldak

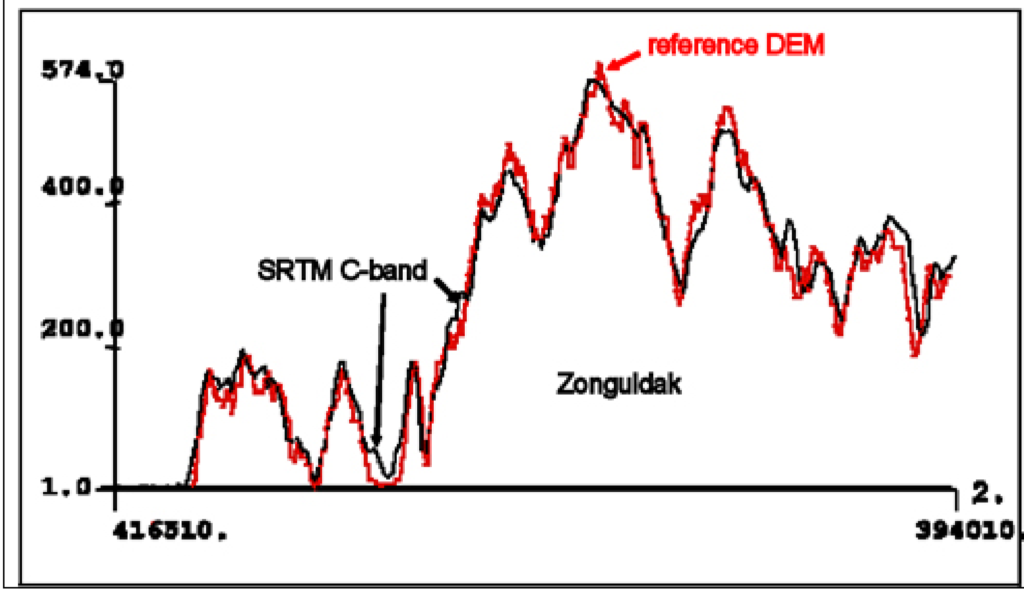



Figure 4: height profile through SRTM C-band DEM in relation to the reference DEM, test area Zonguldak

## 3 FILTERING A DSM TO A DEM

Like a height model generated by automatic image matching, the height model based on C-band and X-band InSAR corresponds to the visible surface. Such a DSM can be reduced by automatic filtering to a DEM if enough height points are available for the bare ground and if the accuracy of the height values is below the terrain roughness; this usually is not a problem in open and build up areas, but it is difficult in closed forest areas where no point is located on the bare ground (Passini et al, 2002). In forest areas the DSM still can be improved by filtering, especially at the border, but not in the center. Only with long wave length radar like the P-band or with the expensive laser scanning (LIDAR), the bare ground can be estimated.

The characteristics of the SRTM C-band DSM can be seen very well in the flat area of the city of Bangkok. Figure 5a shows a 3D-view to the SRTM C-band DSM of the city area viewed with a vertical angle of 1°. The elevation goes up to 44m. The ground of the Bangkok area is extremely flat with heights not exceeding 4m, so figure 5a shows more the skyline than the bare ground. After filtering with the Hannover program RASCOR the largest elevation is only 6m – this is a realistic value for some artificial raised ground levels. By the filtering in the city area 59% of the height points are eliminated - this is realistic.

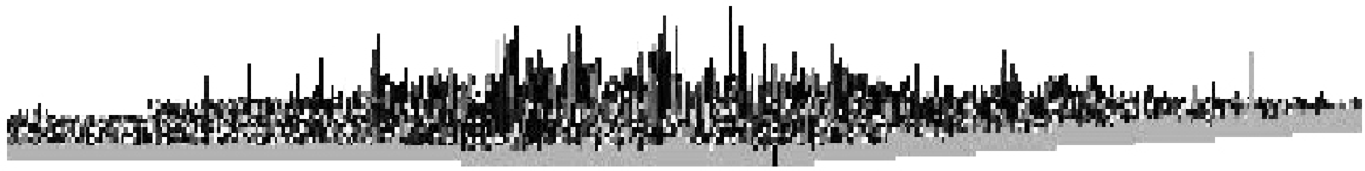
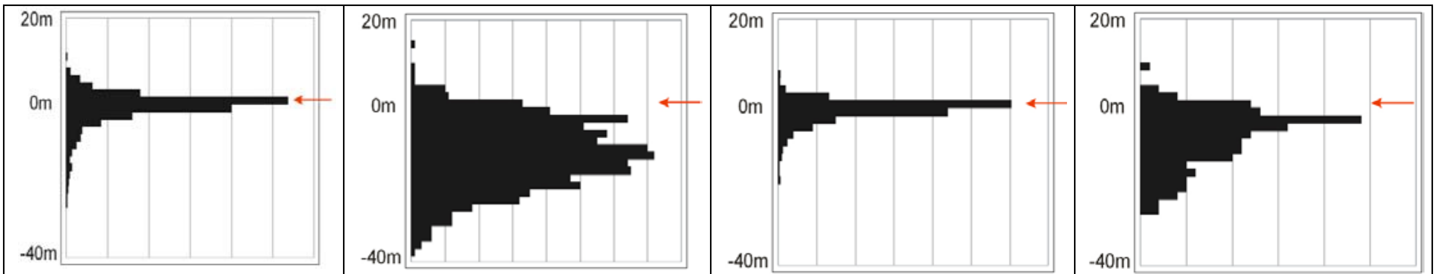


Fig. 5a: 3D-view with 1° elevation angle to SRTM C-band DSM of Bangkok

Fig. 5b: 3D-view with 1° elevation angle to SRTM C-band DEM of Bangkok after filtering

The possibility of an automatic filtering of a DSM to a DEM is shown in detail for a rolling area in Bavaria, Germany where a laser scanner reference DEM with accuracy better than 0.5m is available (figure 6 and table 2). The analyses has been made separately for the forest and for the open areas. Before comparison of the height models, the horizontal shift between both has been checked and adjusted with the Hannover program DEMSHIFT. In most cases horizontal shifts between DEMs has been seen – caused for example by datum problems or limited horizontal location accuracy. The determined shift of 212m in X and 11m in Y corresponds to the influence of the datum shift of the old German national coordinate in relation to ITRF / WGS84 which was not respected in advance and it covers also the horizontal orientation accuracy of the SRTM height model. The frequency distribution of the height differences can be seen in figure 6. The height differences are shown with the sign of the correction; that means in the case of negative differences, the SRTM C-band heights are above the reference heights. The height differences in the forest area (second frequency distribution) are large and negative – the height values are on top of the trees and the frequency distribution shows more the height variation of the trees in the forest area. Also in the open area there is not a normal distribution of the height differences. This may be caused by buildings in villages and individual trees.




open area, no filtering | forest, no filtering | open areas filtered | forest filtered

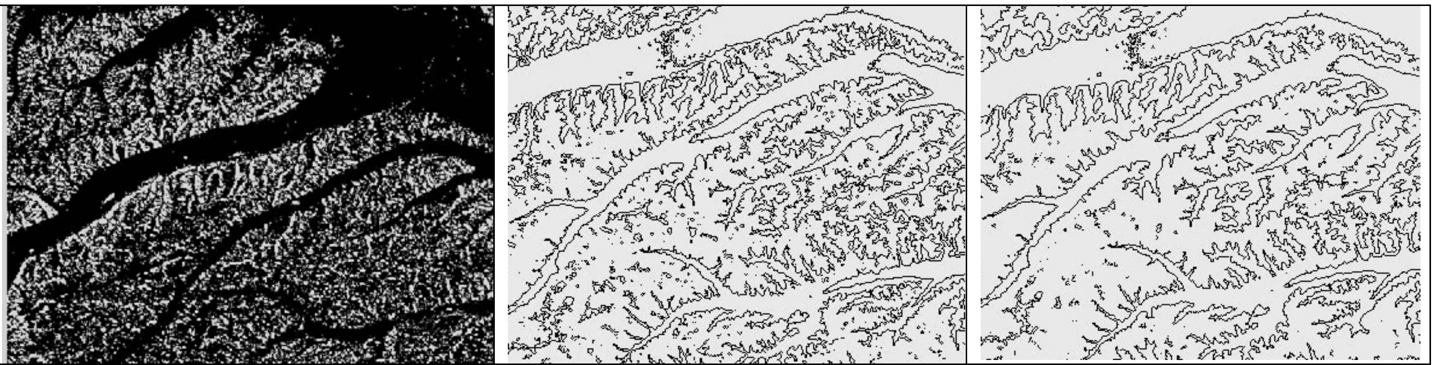
Figure 6: frequency histogram of discrepancies between SRTM C-band height model and reference LIDAR DEM – test area Gars, Bavaria

| | RMSZ [m] | bias [m] | RMSZ F(inclination) [m] |
|---|---|---|---|
| open areas, no filtering | 5.44 | -2.33 | 4.37 + 2.5 ∗ tan α |
| forest, no filtering | 16.46 | -13.84 | 14.98 + 3.8 ∗ tan α |
| open areas filtered | 4.03 | -2.15 | 3.45 + 1.9 ∗ tan α |
| forest filtered | 11.77 | -9.07 | 10.76 + 3.5 ∗ tan α |

Table 2: analyses of SRTM C-band height model against laser scanner reference – test area Gars, Bavaria

Also the numerical results of the analyses are typical for the SRTM C-band DEM / DSM. The structure is the same also for height models generated by automatic image matching of optical space images (Jacobsen 2005).

Table 2 shows a clear bias (systematic error = mean value of the height differences) which is smaller for open areas like for the forest areas because of the location of the height values on top of the visible surface. The automatic filtering of the SRTM C-band DSM by the Hannover program RASCOR removed 33.8% of the points – a usual percentage. By filtering the bias has been reduced for the forest area from -13.84m to -9.07m and corresponding to this, the root mean square of the height differences has been reduced from 16.46m to 11.77m. This result is not satisfying, but if no points are located on the bare ground, in the forest area the automatic improvement is limited. Also a manual editing will not lead to better results.
The accuracy is depending upon the terrain inclination. At first a horizontal displacement is causing an error as a linear function of the tangent of the terrain inclination, but the horizontal shift has been determined in advance. In addition caused by radar foreshortening also a reduced accuracy for inclined parts can be expected – this is again similar to height models determined by automatic matching of optical images. All empirical tests do show a very clear function of the vertical standard deviation as a constant value plus a linear term as function of the tangent of the terrain inclination, so the used Hannover analyses program DEMANAL is calculating this function by adjustment. Table 2 shows an improvement of the vertical accuracy for the flat parts (without part as function of tan $\alpha$) by the filtering from 4.37m to 3.45m and for the forest from 14.98m to 10.76m; that means, the filtering was justified.



| white = eliminated points | contour lines without filtering | contour lines after filtering |
|---|---|---|

Figure 7: SRTM C-band height model, test area Bavaria

The eliminated points of the filtering (figure 7 left) are concentrated mainly to the forest areas. A comparison of the contour lines without and with filtering shows more clear lines after filtering (figure 7 right hand side); not so many isolated contour lines (closed circles) are left after filtering.
In the rolling test area of Bavaria the filtering of the SRTM C-band height models was successful. This was not the case for the very rough area in Zonguldak (see also table 1). After filtering the remaining points are still better like the whole original SRTM C-band DSM; but for the practical use of a DEM the gaps have to be closed by interpolation and the filtered and interpolated SRTM C-band DEM was in relation to the reference DEM not better like the original DSM. The Zonguldak area is too rough for a filtering of a DSM with an average point spacing of 80m shown also by the loss of accuracy of an interpolation over 80m of 12m (table 1). In this case a reference DEM was available, but for most operational projects this is not given. It is possible to analyze a height model without reference. In the Hannover program ZANAL the DEM heights are analyzed based on the neighboured values. A bilinear interpolation over the double grid spacing leads in the area of Zonguldak to root mean square discrepancies between the interpolated and the original values of 18.4m while for the rolling Bavaria test area it is limited to 6.4m. This can be used for the decision of a DSM filtering. In any case a visual inspection of the DEM in form of a grey value or colour coded height model, a 3D-view or the check of contour lines should be made for getting the correct impression and also for checking gaps in the original data. Of course the filtering depends also upon the planned use of the final DEM. In any case a filtering has advantages for the creation of contour lines – it has a similar effect like a soft generalization, leading to more smooth contour lines and removing isolated circles which can be interpreted simpler (see also figure 7 centre in relation to right hand side).

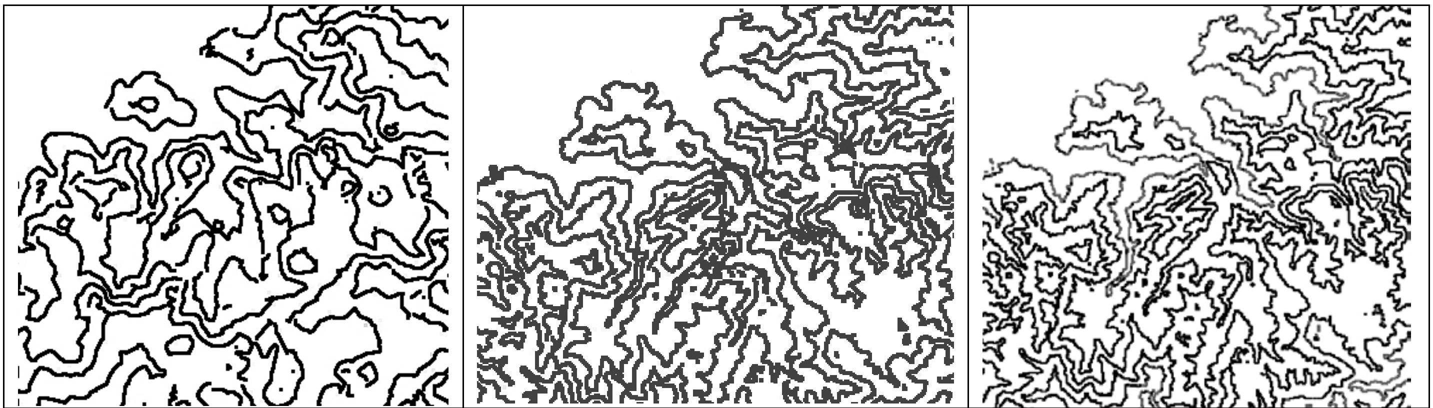
## 4 ACCURACY ANALYSES

In the Zonguldak test area beside the SRTM C-band height information also X-band data are available. The X-band height model has the advantage of a spacing of just 1 arcsec – in Zonguldak this corresponds to a spacing of 23m in east and 31m in north direction. In addition the X-band height model comes together with a "height error map" – an estimated accuracy of the individual points based on the radar covariance. Especially for the coast line and some very steep parts larger standard deviations are estimated. The coast line is very steep, partially vertical, causing problems with radar layover. The indicated areas of lower height accuracy do correspond very well with the discrepancies against the reference height model, but also the near neighboured areas are still influenced by InSAR-problems.

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

Table 3: root mean square height differences of SRTM-DEMs against reference DEM in test area Zonguldak

The comparison of the C-band and the X-band data with the reference DEM leads to very similar results for both. Only the number of large discrepancies is larger for the C-band height model, but this is partially caused by the situation that the X-band height model is not covering some more critical areas. The reference DEM is also not free of error, it is estimated with SZ=+/-6m. The results achieved at check points determined by GPS survey are quite better in relation to the reference DEM. This is typical because check points are located in optimal positions without influence of neighboured buildings and trees. In general the results based on check points are too optimistic. Table 3 only shows results at the given height points, it does not say something about the influence of the DEM interpolation, so the different spacing of C-band and X-band data has no influence to it.



SRTM C-band DEM | SRTM X-band DEM | reference DEM

Figure 8: contour line of a sub-area in Zonguldak, Turkey

The contour lines based on the SRTM DEMs in relation to the reference DEM from the topographic map 1:25000 shows the strong influence of the point spacing to the morphologic details of the DEMs. The contour lines based on the X-band DEM are very close to the reference data while the linear three times larger spacing of the SRTM C-band DEM (only 11% of the X-band data volume) is causing a loss of details and a strong generalisation. By this reason, X-band data should be preferred if they are available. X-band data can be bought from the German DLR for 300 € / (¼° x ¼°) while the C-band data are available for a handling fee.
SRTM C-band height models have been analyzed also in other areas where accurate reference DEMs have been available. The results from the rolling area in Bavaria listed in table 4 are not the same like in table 2 because in table 4 also additional test areas in Bavaria have been used. The accuracy is on the same level, but not identical. The root mean square differences of the SRTM C-band DEMs not respecting the terrain inclination do show a variation from 3.9m up to 8.0m, but after taking care of 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 in open and flat areas. The bias can be determined if a sufficient number of reference points (control or check points) are available and can be used for a vertical shift. The bias is caused by the limited accuracy of the model orientation influenced by instability of the 60m arm for the second antenna at the Space Shuttle, so the height orientation was improved by the height of the sea surfaces leading to long period orientation errors in the range of 3 to 4m.

| | RMSZ [m] | bias [m] | RMSZ F(slope) |
|---|---|---|---|
| Arizona, flat up to mountainous | 3.9 | 1.3 | $2.9 + 22.5 * \tan \alpha$ |
| Williamsburg NJ, flat | 4.7 | -3.2 | $4.7 + 2.4 * \tan \alpha$ |
| Atlantic City NJ, flat | 4.7 | -3.6 | $4.9 + 7.6 * \tan \alpha$ |
| Bavaria, rolling | 4.6 | -1.1 | $2.7 + 8.8 * \tan \alpha$ |
| Bavaria, mountainous | 8.0 | -2.4 | $4.4 + 33.4 * \tan \alpha$ |

Table 4: accuracy of SRTM C-band DEMs in different test areas (only open areas)

## 5 CONCLUSION

For the area from 56° southern up to 60.25° northern latitude DEMs based on the SRTM mission are existing. The US C-band data are available for a handling fee, but only for the USA with a spacing of 1 arcsec, outside the USA just with 3 arcsec spacing. The high geometric quality of the SRTM data of +/-2.7m up to +/-4.9m for open and flat areas is sufficient for several applications like the generation of ortho images from very high resolution space images if the incidence angle is not too large. The SRTM C-band spacing of 3 arcsec is leading to a loss of morphologic details in mountainous areas, here the German-Italian SRTM X-band DEMs do have advantages with their spacing of just 1 arcsec, but the X-band DEMs do have large gaps between the neighboured strips.

The quality of a DEM cannot be described just by one figure, it is a function of the terrain inclination in the form SZ = a + b ∗ tan (terrain inclination). In addition the height models do show the height of the visible surface and not the height of the bare ground. If the roughness of the terrain is below the relative height accuracy, the DSMs should be filtered to DEMs. This is not a problem for open areas, but if no ground points are available in the forest, the filtering in the forest areas still improves the accuracy but it never can be on the same level like for the open areas.

## ACKNOWLEGMENTS

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