ACCURACY ANALYSIS OF SRTM HEIGHT MODELS

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ABSTRACT

An accuracy analysis of the digital height models from SRTM C-band over large areas has been carried out. Statewide Digital Elevation Models (DEMs) acquired using digital photogrammetric techniques and LIDAR were used as base for the analysis. Classification of the terrain based on land use/land cover and topographic characteristics was previously carried out for a detailed analysis showing the dependency upon object characteristics. The horizontal relation between the reference DEM and the SRTM height data have been determined after datum transformation by an adjustment of shift parameters separately for sub-areas indicating also the horizontal accuracy of the SRTM data. The SRTM height models are showing the visible surface – a Digital Situation Model (DSM). The possibilities of a filtering from DSM to DEM are analyzed. Special care was taken for the filled voids of the SRTM data.

INTRODUCTION

Digital elevation models (DEMs) are a basic part of the information about an area. They are required for the generation of orthoimages and several planning purposes. The worldwide lack of qualified and accessible DEMs has been improved with the Shuttle Radar Topography Mission (SRTM) in February 2000. It was an international project leaded by the National Geospatial-Intelligence Agency (NGA) and NASA whose objective was to obtain the possible most complete high-resolution digital topographic database of the Earth.

SRTM used the technique of radar interferometry. In radar Interferometry - two synthetic aperture radar images are taken from slightly different locations. Differences between these images allow for the calculation of surface elevation. To get two radar images taken from different locations the SRTM hardware consisted of one transmitting and receiving radar antenna in the shuttle payload bay and a second only receiving antenna attached to the end of a 60m mast (figure 1).
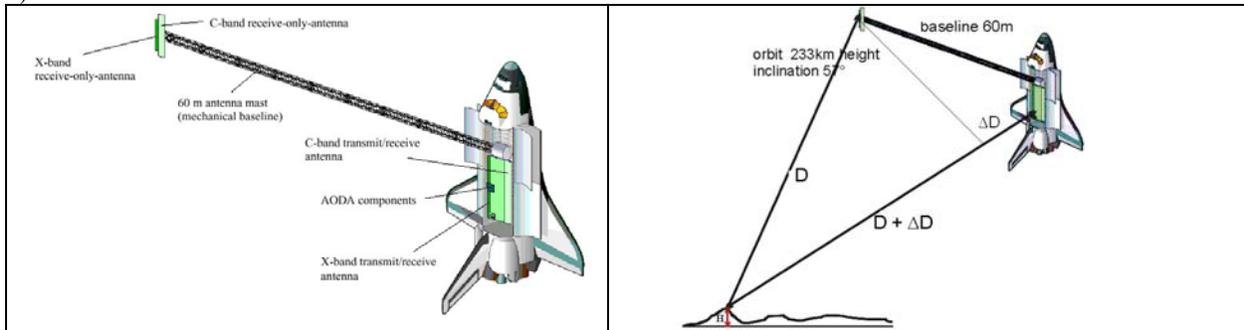

Figure 1. principle of SRTM synthetic aperture radar interferometry

The C-band and X-band radar equipment was supported for the orientation by star tracker, gyros and GPS. Because of some mast vibrations, the accuracy of the orientation based on GPS, gyros and star trackers was limited,

requiring a correction based on the sea level close to the coast. This caused some long wavelength height errors (table 1) having a period in the range of 3000km, so systematic height errors of the SRTM height models have to be expected. The X-band was operated by Germany and Italy but it did not include the scan SAR function, so not a complete coverage of the area was possible. In addition the height models based on X-band are not available free of charge like the C-band height models. The C-band height models are covering 80% of the Earth surface with 30 m resolution from 56° southern up to 60.25° northern latitude. The original resolution has been transformed into a 1arcsec grid, having a spacing of 31m at the equator, but with this resolution the data are only available for the area of the United States, outside it is reduced to 3arcsec spacing.

In relation with the achieved accuracy of the SRTM data several studies have been conducted by the scientific community. Several types of data have been used as a base of comparison, ranging from ground-truth to digital elevation models (DEMs) derived from Space-borne imagery. The most extensive ground-truth effort was made in collecting a globally distributed set of ground check points using kinematic GPS transects. A typical transect spanned a substantial part of a continent, thus allowing for the characterization of errors at all lengths scales. The number kinematic GPS check points ranged from 64,000 to 400,000 (table 1).

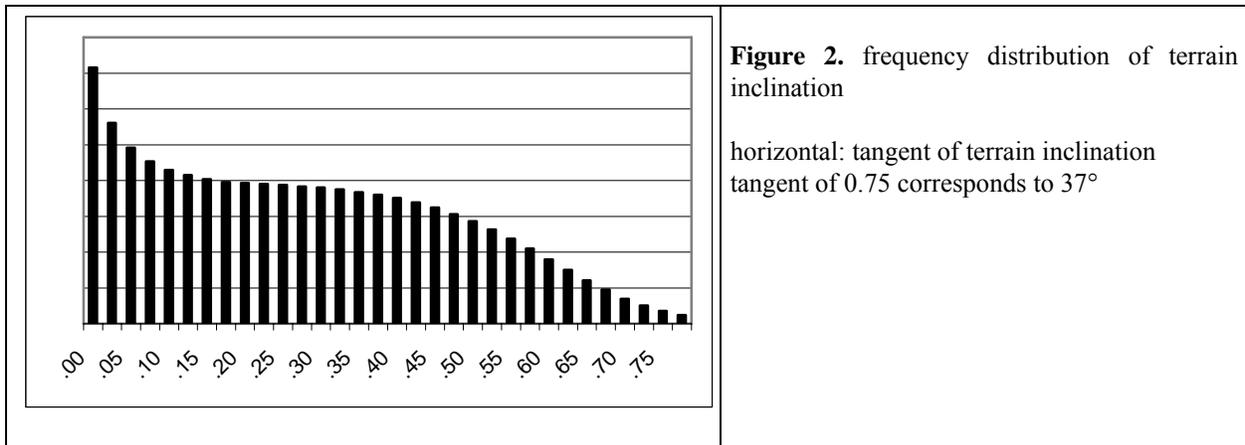|	Africa	Australia	Eurasia	Islands	North America	South America
Absolute geolocation RMS error	7.2	4.4	5.3	5.5	7.6	5.5
Absolute RMS height error	3.4	3.6	3.8	4.9	5.5	3.8
Relative RMS height error	5.9	2.8	5.3	3.8	4.2	3.3
Long wavelength height error	1.9	3.6	1.6	2.2	2.4	3.0
Table 1. accuracy investigation of SRTM height models (Rodriguez et al 2005) values converted to standard deviation (68% probability level) [m]						

In this presentation the accuracy is shown as root mean square error of the Z-values (RMSZ) corresponding to standard deviation. It has a probability level of 68%. This can be converted to LE90 with the multiplication factor 1.65. Although the results in table 1 achieved the expectations, they correspond to point wise error behaviour. If digital elevation models are compared, usually less accurate values are achieved because the DEM points may be located also in not optimal positions. In addition the values shown in table 1 are not detailed enough; they do not respect the land use / land coverage, the characteristics of the terrain and the possibility of improvement by filtering. In this sense 4 areas containing photogrammetric acquired DEMs were selected. They are located in the State of West-Virginia, Pennsylvania, New Jersey and the city of Philadelphia. Table 2 shows the main characteristics of the study area.

| Area	Terrain type	Land use land cover	Area (km^2)	Photo scale	RMSZ	spacing
West Virginia (Wyoming Co.)	mountainous and rough	high forest (conifers)	2090	1:24,000	0.8 m	15.24 m (50')
Pennsylvania (Lancaster Co.)	undulated and semi-rough	farm land	1325	1:19,200	0.6 m	15.24 m (50')
Atlantic County, NJ	flat and smooth	farm land, bushes	988	1:19,200	0.55 m	15.24 m (50')
City of Philadelphia	central city area	with large tall buildings	25	1:9,600	0.27 m	4.572 m (15')
Table 2. photogrammetric reference data for detailed analysis						

West-Virginia

The test area West-Virginia includes the Counties of Wyoming and McDowell (figure 3). The covered area of 2090 km^2 corresponds to 4 USGS DQ. It is a very mountainous and rough terrain covered with high forest (conifers). The study area was covered with colour aerial photography at scale 1:24,000 during spring 2004. Break lines and mass points were extracted manually. A Triangular Irregular Networks (TIN) was formed and its accuracy tested against field GPS measurement check points (Passini 2004). The same data were used to compute the reference grid with spacing of 50 * 50 feet. The SRTM height model ranges from 1251ft (381m) up to 2906ft (886m).

Figure 2. frequency distribution of terrain inclination

horizontal: tangent of terrain inclination
tangent of 0.75 corresponds to 37°

Very often a datum shift between different DEMs can be seen. This of course enlarges the root mean square height differences of the comparison. In the case of the reference DEM from photogrammetric survey in relation to the SRTM DEM, only a shift of 4.53m in X and -2,30m in Y has been adjusted with the Hannover program DEMSHIFT. This reduced the root mean square differences just by 2%. A scaling of the SRTM height model in X and Y has no effect.
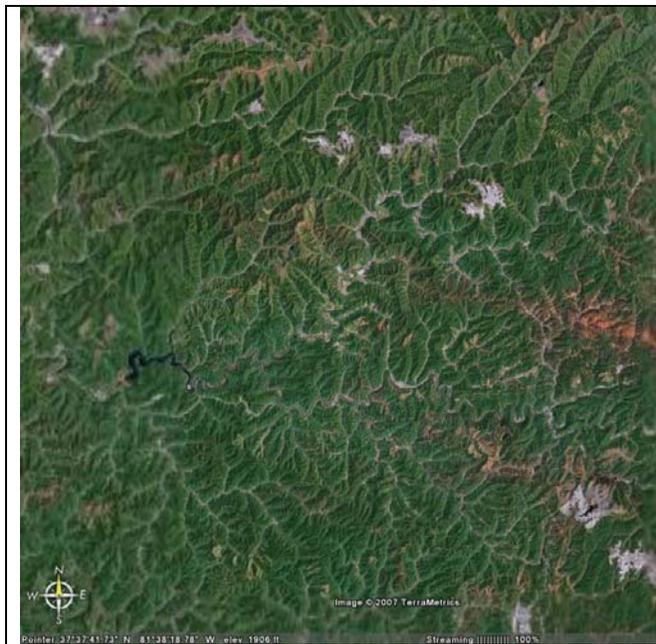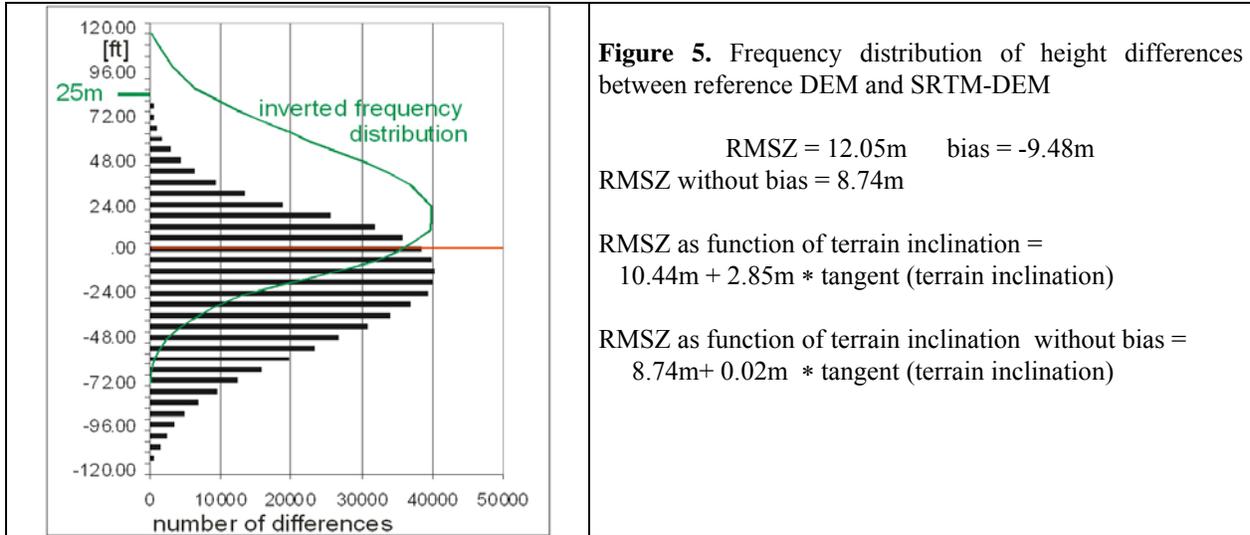

Figure 3. GOOGLE Earth image of test area West-Virginia
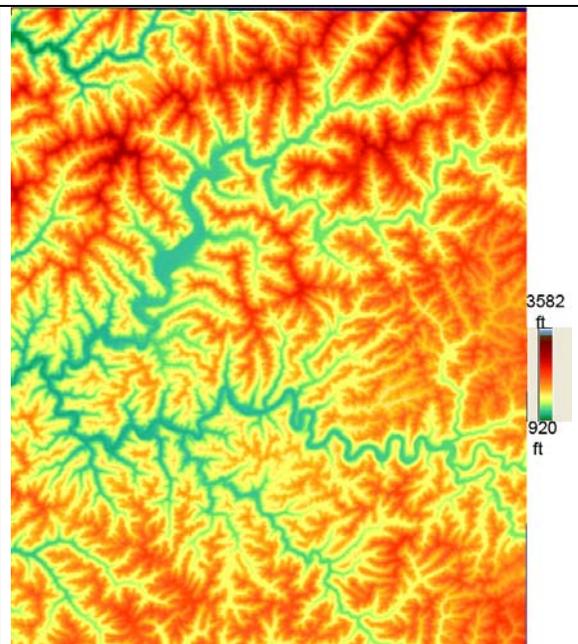
Figure 4. SRTM-DEM of test area West-Virginia

The SRTM-DEM shows large systematic differences (bias) against the reference DEM (figure 5). Discrepancies are shown with the sign of the correction - points located above the reference DEM have negative values. So the negative bias (systematic error) can be explained by the vegetation. The reference DEM includes the height of the bare ground, while the Radar C-band cannot penetrate the trees; that means the SRTM-height model is a digital surface model (DSM). If a height model includes a mixture of points on top of the vegetation or buildings and points on the ground, the points not located on the ground can be removed by filtering. But as obvious in figure 3, nearly the whole area is covered by forest. Only in the valleys the vegetation is not so dense. By this reason a valley layer has been generated and the points located in the valleys have been analyzed separately. In addition the

SRTM-DSM was filtered by the Hannover program RASCOR (Passini et al 2002), but this had only a very limited effect (table 3). Usually the root mean square height difference shows a clear dependency on the terrain inclination which can be formulated as: RMSZ = a + b* tangent (terrain inclination). In the West-Virginia test area this is only the case up to inclination of approximately 15°, for steeper parts there is no more change of the accuracy against the inclination of 15°. Such an effect has not been seen before.

Figure 5. Frequency distribution of height differences between reference DEM and SRTM-DEM

RMSZ = 12.05m   bias = -9.48m
RMSZ without bias = 8.74m

RMSZ as function of terrain inclination =
   10.44m + 2.85m * tangent (terrain inclination)

RMSZ as function of terrain inclination without bias =
   8.74m+ 0.02m * tangent (terrain inclination)

The 3arcsec SRTM data are calculated from the 1arcsec data by averaging it over a cell of 3 x 3 points. So in addition to the reduced morphologic details, also different height values are included in both SRTM DSMs. By this reason also both SRTM height models have been compared (table 3). The root mean square difference of 3.09m can be explained by the rough terrain, causing differences by linear averaging of the height values in a 3x3 point cell. Against the reference DEM the height values of both SRTM height models have approximately the same accuracy. This is also confirmed by other data sets. The less detailed information caused by the larger spacing of the SRTM 3"-data becomes obvious if points are interpolated based on the input height values. If a grid of points with 50ft (15.24m) spacing is interpolated and compared with the reference data, the SRTM 1"-data show only an enlargement of RMSZ from the original 12.05m to 12.11m, while the SRTM 3"-data are reducing the accuracy from RMSZ = 11.80m to 13.62m. There is still a dominating effect of the vegetation to these results; that means in a similar rough terrain without forest, the loss of accuracy by interpolation over spacing of 3arcsec will become more obvious.

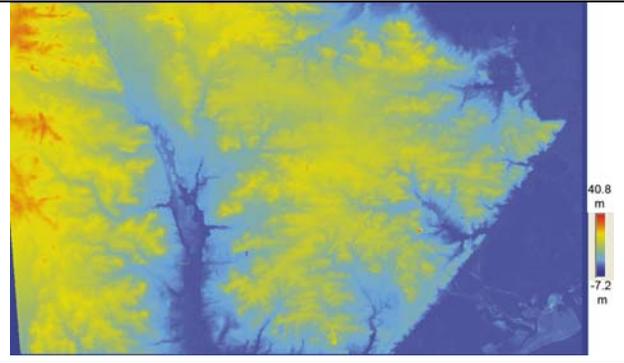|	RMSZ	bias	RMSZ without bias	RMSZ as F(terrain inclination)	RMSZ without bias as F(terrain inclination)
reference – SRTM 1"	12.05	-9.48	8.74	10.44 + 2.85*tan α	8.74 + 0.02*tan α
reference – SRTM 1" only in the valleys	11.56	-7.75	8.59	7.35 + 7.18*tan α	6.63 + 2.79*tan α
reference – SRTM 3"	11.80	-8.10	8.59	9.86 + 3.76*tan α	7.96 + 1.15*tan α
SRTM 1" – SRTM 3"	3.09	0.02	3.09	1.65 + 2.93*tan α	1.65 + 2.93*tan α
reference – SRTM 1" (filtered)	12.10	-7.32	9.64	9.95 + 3.96*tan α	8.37 + 1.94*tan α
reference – SRTM 1" – interpolated to raster 50 ft	12.11	-8.39	8.76	11.08+ 2.02*tan α	7.63+ 4.57*tan α
reference – SRTM 3" – interpolated to raster 50 ft	13.62	-7.90	11.08	13.61+ 0.15*tan α	10.44+ 8.55*tan α
Table 3. analysis of SRTM height models against reference DEM from photogrammetry, West-Virginia [m]					

ATLANTIC COUNTY, NJ

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The Atlantic County in New-Jersey was flown with color images in scale 1:19,200 during March 2003. The selected area corresponds to a farm land and forest with small bushes, crossed by canals, highways, with ponds and some small towns (figure 6). Break-lines were manually extracted and mass points by automatic image matching. Filtering techniques were used to remove non ground points. A TIN was formed and its accuracy tested against field GPS check points with 0.55m standard deviation. The same data were used to compute the reference grid with spacing of 50 ∗ 50 feet. No significant shift of the SRTM-height model against the reference DEM exists.
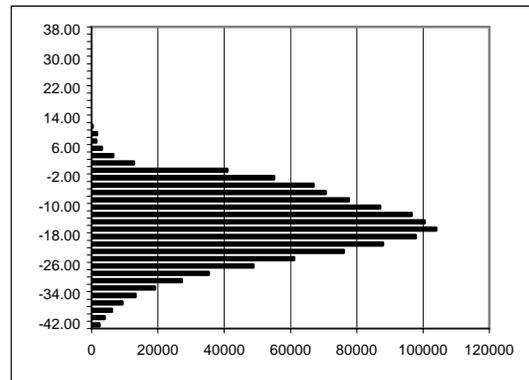

Figure 6. GOOGLE Earth image of test area Atlantic County, NJ

Figure 7. SRTM-DEM of test area Atlantic County, NJ
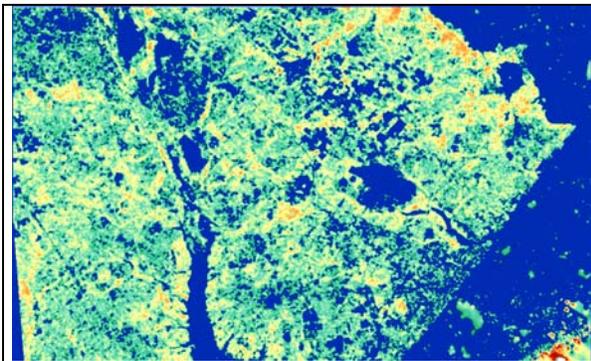
Figure 8. difference SRTM height model – reference DEM

Figure 9. Frequency distribution of height differences between reference DEM and SRTM-DEM

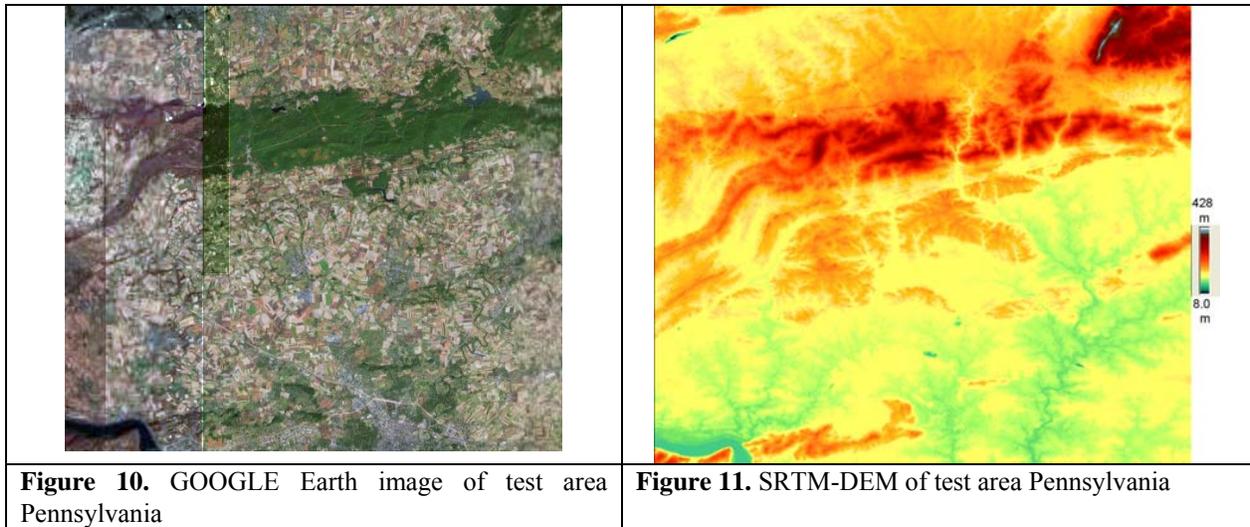|	RMSZ	bias	RMSZ without bias
reference – SRTM 1"	5.38m	-4.56m	2.84m
reference – SRTM 1" (filtered)	3.92m	-3.10m	2.40m
reference – SRTM 1" open area	4.37m	-3.38m	2.78m
reference – SRTM 1" forest	6.07m	-5.46m	2.65m
reference – SRTM 1" (filtered) open area	2.76m	-1.94m	1.96m
reference – SRTM 1" (filtered) forest	4,77m	-4.14m	2.36m
Table 4. analysis of SRTM height models against reference DEM from photogrammetry, Atlantic County			

As in West-Virginia, also in Atlantic County the influence of vegetation and buildings can be seen at the negative bias, but with a smaller amount caused by the partially open area and the not so high vegetation. The more open character of the area (figure 6) makes a filtering of objects not belonging to the bare ground more efficient, but nevertheless larger parts without points on the ground exist and limit the effect of the filtering. Even because of these problems, the filtering improves the result. Especially the bias is reduced showing the positive effect. The achieved

accuracy without bias is an excellent result for SRTM-height models. In the flat area no significant dependency upon the terrain inclination can be seen.

The frequency distribution of the differences between the SRTM height model and the reference DEM (figure 9) is not well normal distributed, showing that the data are not belonging to the same group of points. This is confirmed by the color coded differential DEM (figure 8) – the open areas are shown with clear blue color while the forest and mixed areas appears with different color. By this reason, the analysis has been made separately for the forest and the open areas. This was leading for both groups to nearly normal distributed frequency distributions. The results in table 4 (3rd up to last line) are underlining the situation. In the forest the bias is larger than in the open areas. The open areas are still influenced by buildings and single or groups of trees; this can be improved by filtering the points not belonging to the bare ground. After filtering the result is quite better, the bias is reduced to -1.94m in the open areas and -4.14m in the forest. After filtering and bias correction, excellent standard deviations of 1.96m for the open areas and 2.36m for the forest are reached.

PENNSYLVANIA

The study area includes parts of the Counties of Lancaster and Lebanon. It is a farm land area on undulated or rolling terrain. There are areas with moderate high trees. The area was flown in spring 2005 with color aerial photography at scale 1:19,200. As before, break lines and mass points were extracted manually. A TIN was formed and its accuracy tested against measurement GPS check points. The same data were used to compute the reference grid with size of 50∗50 feet. The also included foot hills of the Appalachian are totally covered by forest. The height level goes from sea level up to 423m. No significant shift of the SRTM-height model against the reference DEM exists.
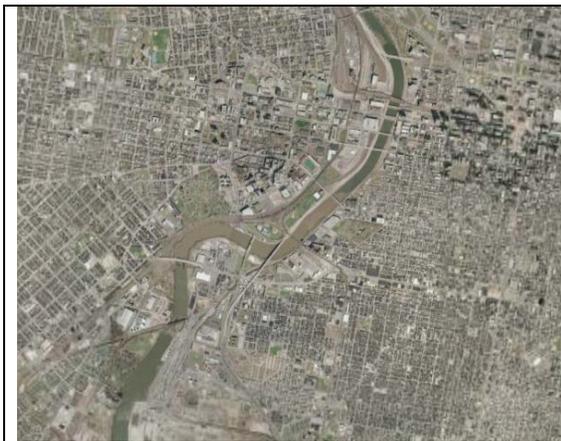
Figure 10. GOOGLE Earth image of test area Pennsylvania

Figure 11. SRTM-DEM of test area Pennsylvania

|	RMSZ	bias	RMSZ without bias	RMSZ as F(terrain inclination)	RMSZ without bias as F(terrain inclination)
reference – SRTM 1"	6.46	-1.75	6.21	5.90 + 22.4∗tan α	5.87 + 9.45∗tan α
reference – filtered SRTM 1"	5.99	-1.21	5.87	6.67 + 11.6∗tan α	5.65 + 10.1∗tan α
reference – SRTM 1" flat -rolling	5.40	-0.17	5.39	5.30 + 9.4∗tan α	5.30 + 9.1∗tan α
reference – filtered mountains	7.90	-4.34	6.60	6.98 + 6.4∗tan α	6.28 + 5.2∗tan α
reference – filtered SRTM 1" flat - rolling	5.20	0.06	5.20	5.06 + 9.4∗tan α	5.06 + 9.4∗tan α
reference – filtered SRTM 1" mountains	7.23	-3.54	6.30	6.57 + 9.7∗tan α	6.04 + 12.4∗tan α
Table 5. analysis of SRTM height models against reference DEM from photogrammetry, Pennsylvania [m]					

The test area Pennsylvania is a mixed area with flat parts and foot hills of the Appalachian (figures 10 and 11). So from the beginning a mixed result has been expected. This can be seen at the frequency distribution of the height discrepancies. By this reason a separate analysis has been made for the mountainous and the more flat parts. The separation corresponds approximately to the height level of 480ft (146m). The filtering of points not belonging to the bare ground is reducing the bias. In the flat up to rolling part there is nearly no more bias, but it is also reduced in the mountainous part. Here more dense forest exists, limiting the effect of filtering.
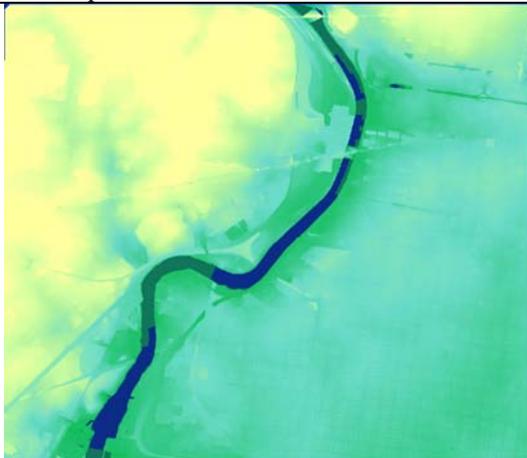
PHILADELPHIA

The Philadelphia test area covers the city area and the central business district, including large and tall buildings. The city was flown with color aerial photography during spring 2004. Photo scale was 1:9,600, break lines and mass points were extracted manually and through automatic image matching. A TIN was formed and its accuracy tested against field GPS measurement check points. The same data were used to compute the reference grid with spacing of 15*15 feet. The SRTM height model is in general influenced by the buildings, but also by some imaging problems of radar in build up areas. In city areas very often total reflection by corner reflectors appears besides problems of lay over.
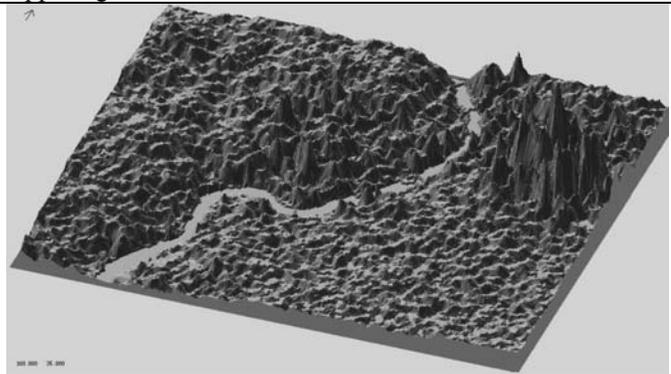

Figure 12. GOOGLE Earth image of test area Philadelphia
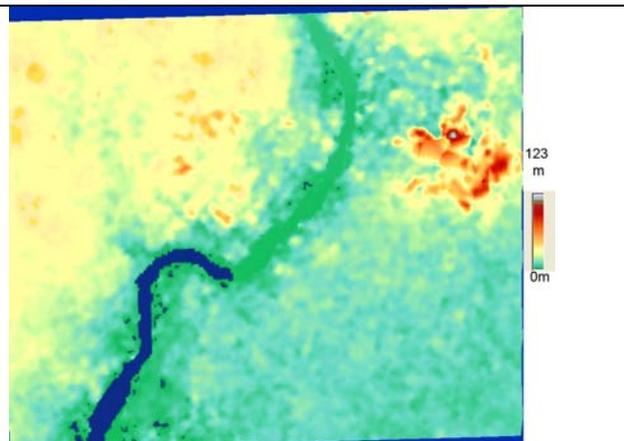
Figure 13. SRTM 1"-DEM of test area Philadelphia, upper right = central business district

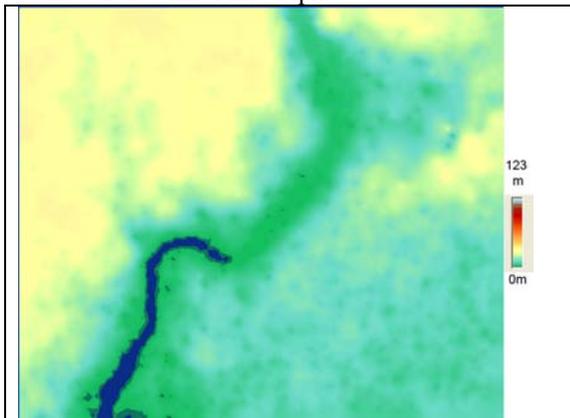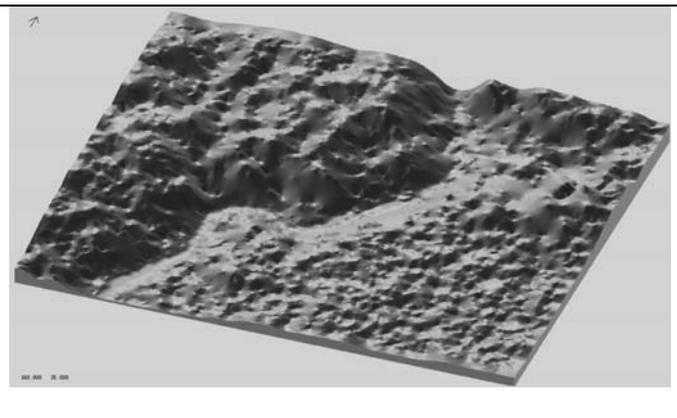**Figure 14.** reference DEM of test area Philadelphia – same colour coding like figure 12

Figure 15. 3D view to SRTM 1" height model, 10 times exaggeration, upper right = central business district

As obvious in comparing the SRTM height model with the reference DEM (figures 13 and 14) and also shown as 3D-view to the differential height model (figure 15), the SRTM height model is a DSM including an average of the

heights of the buildings and the surrounding area. Such information has to be removed by filtering like with the Hannover program RASCOR. RASCOR removed 54% of the original SRTM height values leading to a DEM shown in figures 16 and 17. Figures 16 and 17 are showing a loss of details of the filtered SRTM height model, nevertheless the main influence of the buildings has been removed. This can be seen also at the results listed in table 6. The bias is reduced by filtering from -3.42m to -1.32m. In addition the mean square differences have been reduced from 5.82m to 3.16m. In the dominating flat area no significant dependency of the height accuracy from the terrain inclination exists. Of course even after filtering there are some remaining effects of the buildings, but they can be accepted in relation to the general accuracy of the SRTM height model. Also the 3arcsec SRTM height model has been investigated (figures 18 – 21). The less detailed information against the 1arcsec SRTM height model is obvious – especially in the comparison of figures 15 with 19 and 17 with 21. The results of the original SRTM height models in relation to the reference DEM (table 6) is nearly the same for both SRTM height models. After filtering, the less detailed 3arcsec SRTM height model is a little better than the other. This of course cannot be said in general, it is only the case for such a smooth area like Philadelphia.
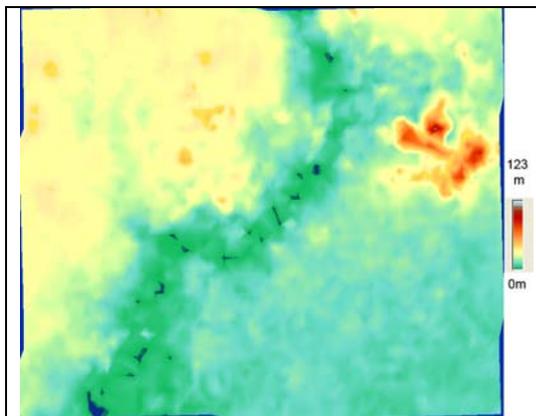

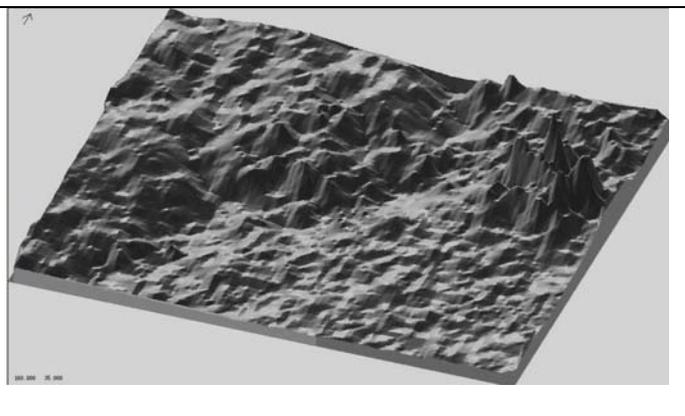| **Figure 16.** SRTM 1"-DEM of test area Philadelphia filtered for elements not belonging to bare ground | **Figure 17.** 3D view to SRTM 1"-DEM of test area Philadelphia filtered for elements not belonging to bare ground, exaggeration 10 times |

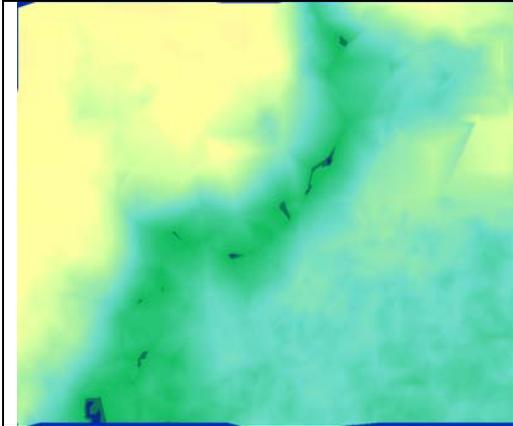|	RMSZ	bias	RMSZ without bias
reference – SRTM 1"	5.82 m	-3.42m	4.72m
reference – filtered SRTM 1"	3.16m	-1.32m	2.87m
reference – SRTM 3"	5.85m	-3.60m	4.61m
reference – filtered SRTM 3"	2.85m	-1.82m	2.19m

Table 6. analysis of SRTM height models against reference DEM from photogrammetry, Philadelphia   [m]
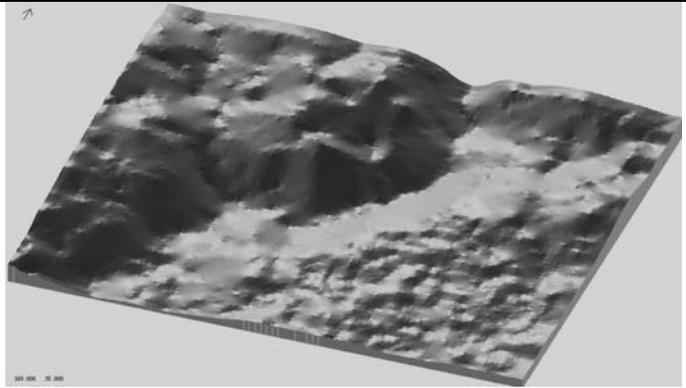

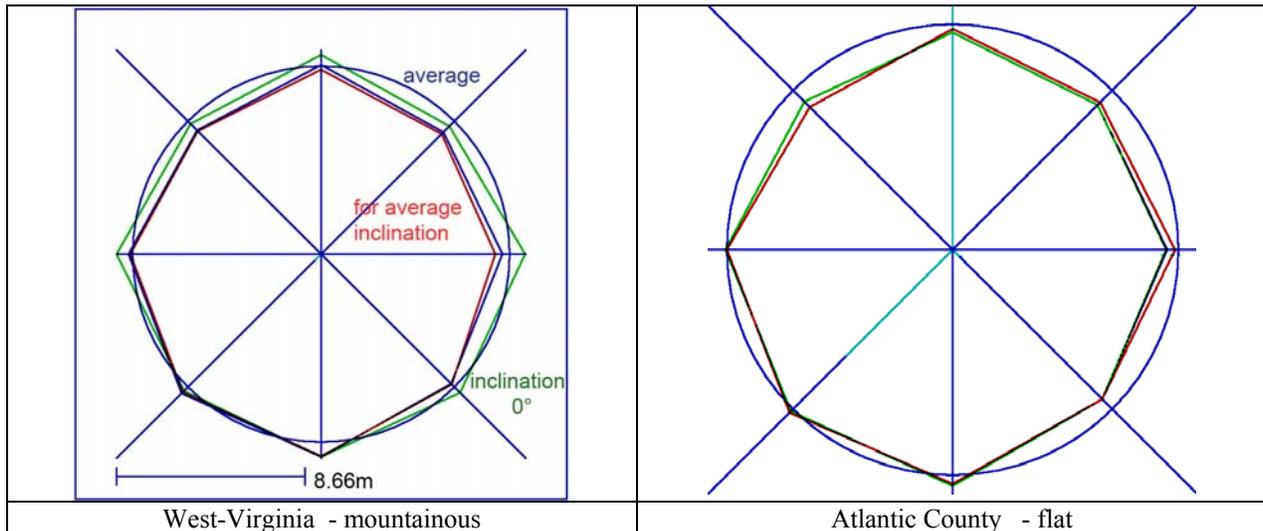| **Figure 18.** 3"-SRTM-DEM of test area Philadelphia, | **Figure 19.** 3D view to 3"-SRTM height model, exaggeration 10 times |

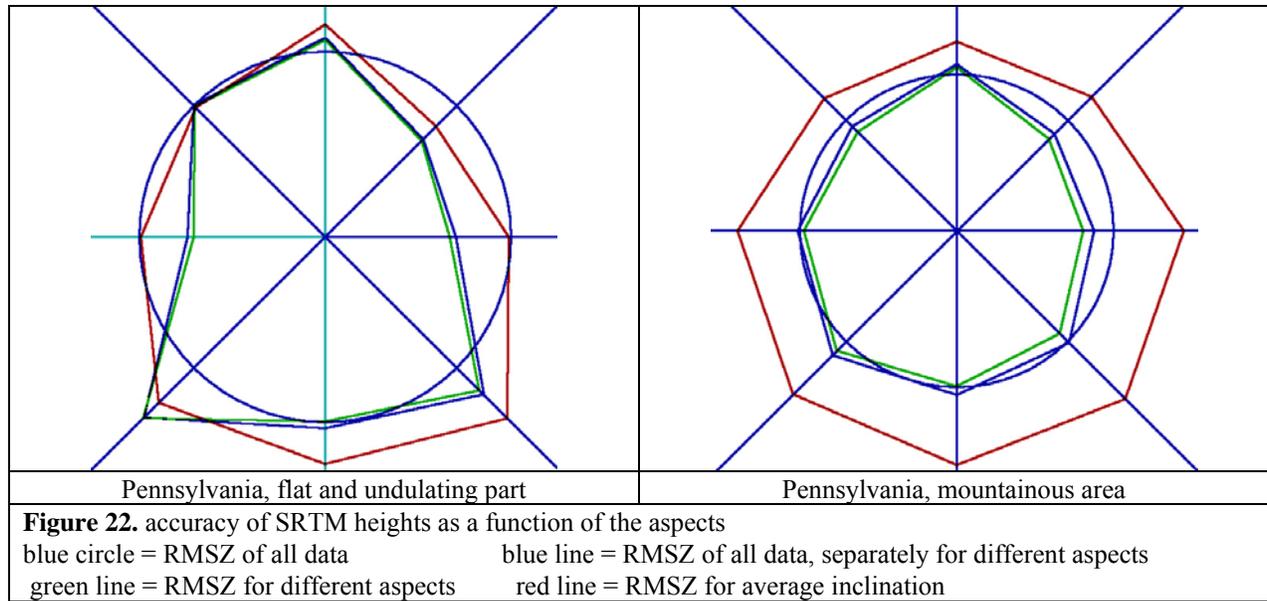| **Figure 20.** 3"-SRTM-DEM of test area Philadelphia, filtered for elements not belonging to bare ground	**Figure 21.** 3D view to 3"-SRTM-DEM of test area Philadelphia filtered for elements not belonging to bare ground, exaggeration 10 times

INFLUENCE OF ASPECT

The quality of synthetic aperture radar (SAR) images depends upon the view direction. In the view direction the terrain inclination is causing foreshortening or even lay over. The foreshortening influences the accuracy of the generated SRTM-height model. By this reason the accuracy may depend upon the aspect (north direction of terrain inclination). The Space Shuttle orbit had an inclination of 58°, with the location of the area at 39° northern latitude, the view direction of the imaging radar has a direction of +48° or -48° against the south direction depending upon the imaging from ascending or descending orbit. The SRTM C-band is covering 94.6% of the area twice and approximately 50% three times, that means the height information may be based on the ascending and also the descending orbit together. The dependency of the accuracy upon the aspects is shown in figure 22.

West-Virginia - mountainous	Atlantic County - flat

Pennsylvania, flat and undulating part	Pennsylvania, mountainous area

Figure 22. accuracy of SRTM heights as a function of the aspects
blue circle = RMSZ of all data   blue line = RMSZ of all data, separately for different aspects
 green line = RMSZ for different aspects   red line = RMSZ for average inclination

For West-Virginia there is only a small tendency of larger standard deviations for the south-west direction. In Atlantic County there is the same tendency. In all parts of the test area Pennsylvania, the south-west and the south-east slope direction show larger standard deviations, especially for larger terrain inclination.

SUMMARY AND RESULTS OF OTHER TEST AREAS

Investigations of SRTM height models have been made also in other areas (Jacobsen 2005, Passini et al 2002, Sefercik et al 2006). No general difference of the SRTM C-band height values for 1arcsec and 3arcsec data could be found. Of course this is different for randomly distributed, interpolated points. Especially in mountainous areas the denser point raster of the 1arcsec data reduces the loss of accuracy by interpolation and includes more morphologic details.

	RMSZ [m]	bias [m]	RMSZ F(terrain inclination) [m]
Arizona, open area (flat – smooth mountains)	3.9	1.3	$2.9 + 22.5 * \tan \alpha$
Williamsburg NJ, open area (flat)	4.7	-3.2	$4.7 + 2.4 * \tan \alpha$
Atlantic City NJ, open area (flat)	4.7	-3.6	$4.9 + 7.6 * \tan \alpha$
Bavaria, open area (rolling)	4.6	-1.1	$2.7 + 8.8 * \tan \alpha$
Bavaria, open area (steep mountain)	8.0	-2.4	$4.4 + 33.4 * \tan \alpha$
Zonguldak, open area (rough mountain)	7.0	-4.4	$5.9 + 5.6 * \tan \alpha$
West-Virginia, forest (mountainous)	11.6	-7.7	$7.3 + 7.2 * \tan \alpha$
Atlantic County, open area (flat)	4.4	-3.4	4.4
Pennsylvania, open area (flat – rolling)	5.4	-0.2	$5.3 + 9.4 * \tan \alpha$
Pennsylvania, forest (mountainous)	7.9	-4.3	$7.0 + 6.4 * \tan \alpha$
Philadelphia, city area, filtered (flat)	3.2	-1.3	3.2
Table 7. root mean square Z-discrepancies of SRTM C-band height models [m] α = terrain inclination			

CONCLUSION

The SRTM height models are influenced by systematic height errors (bias) depending upon the scene orientation and elements above the bare ground. Points not belonging to the bare ground can be filtered if other points located on the bare ground are located in the neighbourhood. A filtering of homogenous forest areas is not possible. In general the accuracy of the height values can be described by a constant value plus a value multiplied by the tangent of the terrain inclination. Only in flat areas a dependency upon the terrain inclination is not significant. In general a lower accuracy in mountainous areas can be expected, caused by the SAR-interferometric conditions, but the mayor limiting factor for mountainous areas is the coverage of the investigated areas by forest. The influence of buildings usually can be eliminated by filtering. Nevertheless the advantage of filtering in most cases is limited to flat up to undulated areas. In mountains the influence of vegetation may be less than the roughness of the terrain causing wrong eliminations by filtering.

The accuracy of the flat parts also in undulated or mountainous areas can be seen at the constant coefficient of the formula depending upon the terrain inclination. In the open or filtered build up areas, the standard deviation of the SRTM elevations is in the range of 3m up to 6m. In flat terrain usually the accuracy is better than 5m. If the influence of the bias is eliminated by means of control areas, usually the flat parts have standard deviation for Z not exceeding 4m. Only in the open areas of the flat up to rolling terrain in Pennsylvania, 5m have been exceeded. The lowest accuracy was found for the mountainous area of West-Virginia, covered by forest, but this mainly is caused by the forest like in the mountainous area of Pennsylvania.

The nearly worldwide and free of charge available SRTM C-band height models are an important component of the knowledge about our spatial environment. The accuracy is sufficient for several applications and for wide areas of the world it includes more detailed information about the surface than known before.

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