

ANALYSIS OF ASTER GDEM ELEVATION MODELS

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ABSTRACT:

Digital elevation models (DEM) are of fundamental importance for remote sensing. With a DEM the three-dimensional positioning, requiring a stereo model can be reduced to a two-dimensional solution just based on a single image. With the free of charge availability of the SRTM-height models, covering the land area from 56° southern up to 60.25° northern latitude a nearly world wide coverage is given. But especially in mountainous regions and dry sand deserts the original SRTM DEMs have gaps in the original SRTM data. Now with the also free of charge available ASTER GDEM the area from 83° southern up to 83° northern latitude is covered. For areas where both height models exist, it is the question which height model should be preferred. Outside the USA the SRTM height data have a spacing of 3 arcsec (nearly 90m), while the ASTER GDEM has a spacing of just 1 arcsec (nearly 30m). The decision for the selection of the DEM is based on accuracy, homogeneity, reliability, completeness and morphologic details.

In test areas with precise reference height models, located in the USA, Germany, France, Poland, Turkey and Jordan and with different morphology as mountainous, rolling, flat and urban and also with different land classes, the ASTER GDEM has been analyzed and compared with SRTM DEM as well as with SPOT 5 HRS and Cartosat 1 height models. ASTER GDEM in most cases shows improved accuracy with a higher number of number of stacks (number of images used for overlapping height models). But the accuracy improvement with more stacks is smaller as it should be for random data. The number of used stacks per DEM-point varies strongly depending upon the area. Especially in areas with low cloud coverage and higher imaging priority a high number of stacks have been used opposite to areas often covered by clouds and having lower imaging priority, where the dominating number of DEM-points may be located only in 2 stacks. Based on own matching results with ASTER images quite more morphologic details have been expected in ASTER GDEM having 1 arcsec point spacing as in SRTM height models with 3 arcsec spacing, but the analyzed data show only slightly more morphologic details as the SRTM 3" height model. SRTM as well as ASTER height models are strongly depending upon the morphology and the land coverage, so not a homogenous accuracy can be expected. In addition, as all height models, the accuracy depends usually linear upon the tangent of terrain slope, so the standard deviation of height (SZ) should be given in the form $SZ = a + b \cdot \tan(\text{terrain slope})$. Not only the standard deviation is important, the height models have different systematic errors (bias). The bias in X, Y and Z is larger for ASTER GDEM as for SRTM DEMs. Horizontal shifts have been determined by adjustment of the ASTER GDEMs against the reference height model. In general the SRTM height models are slightly more accurate as the ASTER GDEM.

1. INTRODUCTION

The nearly worldwide coverage by the free of charge available ASTER GDEM height model, covering the world from -83° up to 83° latitude extends the possibilities of the also free of charge available SRTM height model, limited to -56° up to 62.5° latitude. In addition the original SRTM height model includes gaps in steep mountainous areas, dry sand deserts and water surfaces. The water surfaces do not cause problems because the height can be interpolated from the surrounding area. Of course today also SRTM height models with gap-filling is available, but the gap filling has a very varying quality. So the ASTER GDEM with a spacing of 1 arcsec (~31m at the equator) instead of 3 arcsec for SRTM outside of the USA is promising some improvements. There are always some investigations of the ASTER GDEM (ASTER Global DEM Validation, Summary Report – see references), but some important topics are missing – in general the accuracy of a height model cannot be expressed just by a standard deviation, the dependency of the standard deviation from terrain inclination should be respected in the given accuracy numbers, information about morphologic details

are only rough and the dependency of the individual height from the number of stacks (the number of ASTER images used for image matching of the individual object point) has not been shown in a satisfying manner. Also the direct comparison between ASTER GDEM and SRTM height models for a sufficient number of test areas is missing.

2. TEST AREAS

ASTER GDEM-data and in parallel SRTM height models have been investigated in the test areas Jordan (smooth mountainous), West Virginia, USA (mountainous, nearly 100% covered by forest), Atlantic County, USA (flat), Pennsylvania, USA (partially mountainous and partially covered by forest), Philadelphia, USA (city area), Arizona, USA (smooth up to mountainous), Mousanne, France (flat and smooth mountains, partly covered by forest), Poland close to Warsaw (flat, few forest parts), Zonguldak, Turkey (steep mountains, partially city areas and forest), Istanbul, Turkey (suburb, rolling), Bavaria Gars, Germany (rolling and flat, partially forest) and Bavaria Inzell, Germany (mountainous, partly covered by forest).

ASTER GDEM and SRTM-data are corresponding to a digital surface model (DSM), describing the height of the visual surface, but the reference digital elevation models (DEM) are related to the bare earth. In dense forest areas filtering of DSMs for elements not belonging to the bare surface is very limited in its result, so forest areas have to be investigated separately from open areas to estimate the influence of the vegetation.

The ASTER GDEM may have horizontal shifts against the reference DEMs. By this reason the ASTER GDEMs and also the investigated SRTM DSMs have been shifted by an adjustment to the reference height models to avoid an influence of a horizontal misfit. Some shifts of test areas with precisely known national datum are listed in table 1.

| | Shift X | Shift Y |
|----------------------|---------------|---------------|
| USA, Atlantic County | -2.11 m | -8.71 m |
| USA, Pennsylvania | 7.82 m | 3.01 m |
| USA, West Virginia | 7.28 m | 11.60 m |
| France, Mausanne | 6.14 m | 5.41 m |
| Jordan | -2.98 m | 9.89 m |
| <i>RMS</i> | <i>5.75 m</i> | <i>8.33 m</i> |

Table 1. Shift of ASTER GDEM against reference DEM

3. DEPENDENCY OF ASTER GDEMS ON NUMBER OF STACKS / POINT

The ASTER Global DEM Validation, Summary Report 2009 (see references) gives a global overview about the number of used stacks (number of used ASTER images) (fig. 1), but this is just a rough overview. The number of stacks used for any object point is available in the "num"-file, distributed together with the GDEM height values. It is varying strongly within the individual GDEM-files, covering an area of 1° * 1° (fig. 2 and 3).

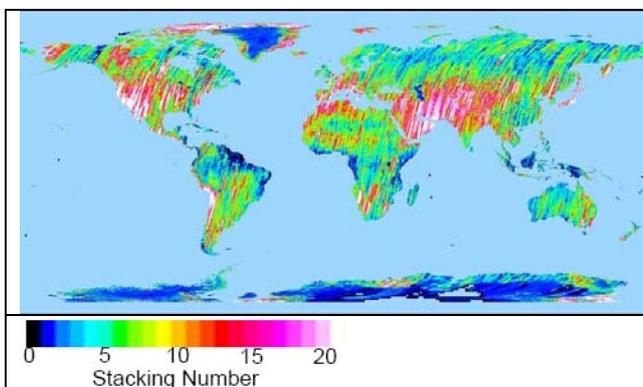


Figure 1. ASTER GDEM global stacking number map showing numbers of ASTER DEMs contributing to the GDEM by location (from ASTER Global DEM Validation, Summary Report 2009)

In the investigated test areas the number of stacks is reaching 60, that means up to 30 stereo models have been used for the determination of the object points. The distribution of the number of stacks shows a strong local variation (figure 1). Available small gaps have been filled mainly by SRTM-data, so usually no gaps exist, with the exception of water areas.

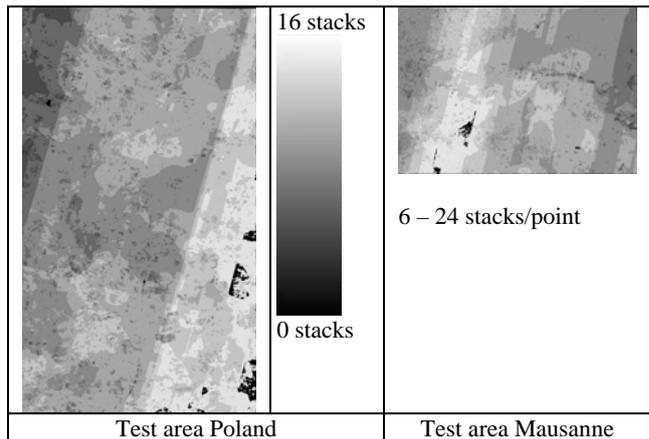


Figure 2. grey value coded spatial distribution of number of stacks

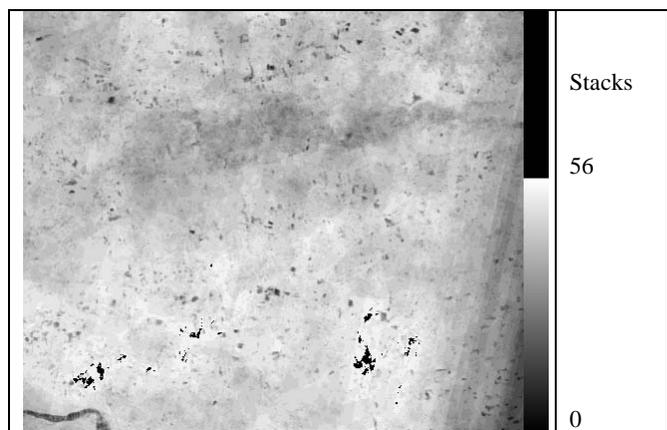


Figure 3. test area Pennsylvania - grey value coded spatial distribution of number of stacks

In the used Hannover analysis program DEMANAL the information about the number of stacks can be used for the investigation of the individual object points. The root mean square height discrepancies (RMSZ) are computed as a function of the number of stacks as shown in figures 4 up to 6.

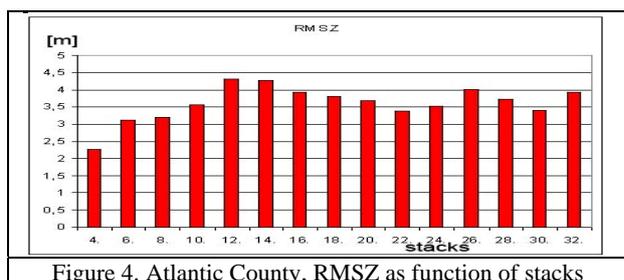


Figure 4. Atlantic County, RMSZ as function of stacks

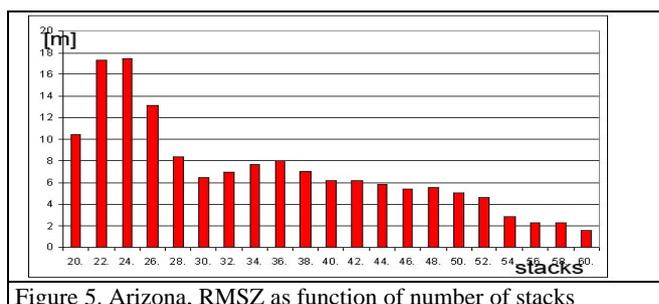


Figure 5. Arizona, RMSZ as function of number of stacks

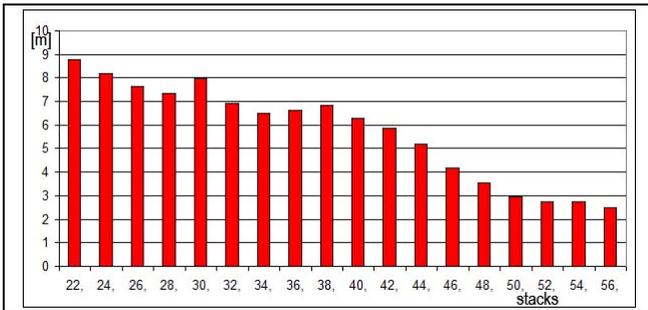


Figure 6. Pennsylvania, RMSZ as function of number of stacks

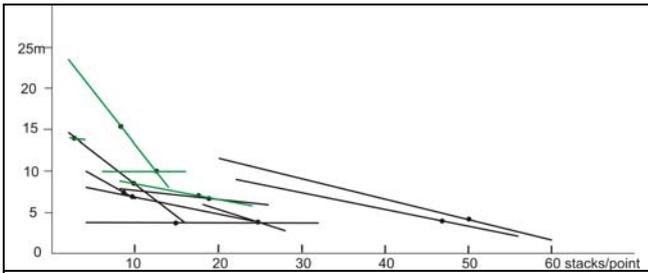
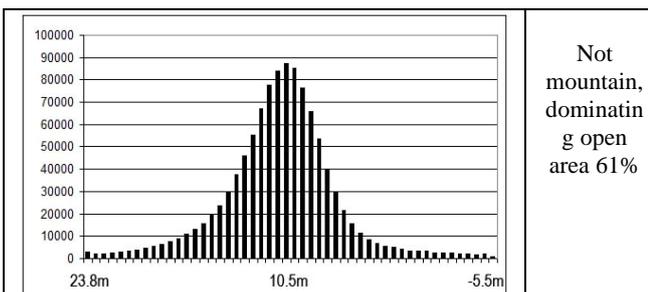


Figure 7. RMSZ as function of number of stacks/point green: influence of forest dot = average number of stacks/point

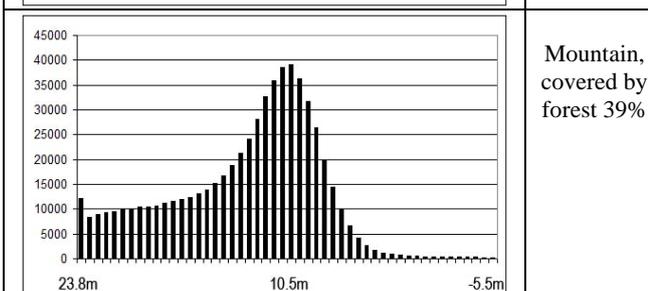
Figure 7 gives an overview of the root mean square Z-discrepancies as linear adjusted function of the number of stacks per point for all test areas. As obvious in figure 4, not in any case an improvement of the accuracy by a higher number of stacks/point can be seen, but there is a clear trend to an improvement, especially if the results are not so precise for a smaller number of stacks/point. Especially in the areas covered by forest the improvements by the number of stacks is not as clear as shown in figures 5 and 6.

As average over all test areas the relation $RMSZ = 12.43m - 0.35m \cdot \text{number of stacks/point}$ exist, which has to be seen together with an average of 18.7 stacks/point, leading to an average RMSZ of 5.88m.

4. ACCURACY ANALYSIS



Not mountain, dominant open area 61%



Mountain, covered by forest 39%

Figure 8. Frequency distribution of Z-discrepancies in test area Pennsylvania

As mentioned before, the influence of the vegetation to the height models cannot be neglected. The frequency distribution of the Z-discrepancies in the test area Pennsylvania, separated for not mountainous areas, not covered by forest and the mountainous area, covered by forest demonstrates the problem (figure 8). In the open area the Z-discrepancies are nearly normal distributed, while in the mountainous forest areas the influence of the forest is obvious with the domination of positive height discrepancies.

As obvious in figure 9, the root mean square (RMS) discrepancies between ASTER GDEM and the reference heights are approximately linear depending upon the tangent of the terrain slope, by this reason the accuracy has to be expressed with a function $SZ = A + B \cdot \tan(\text{slope})$ as used in following tables. The dependency upon the tangent of the terrain slope is computed by adjustment, respecting the number of discrepancies for the different slope groups as weight.

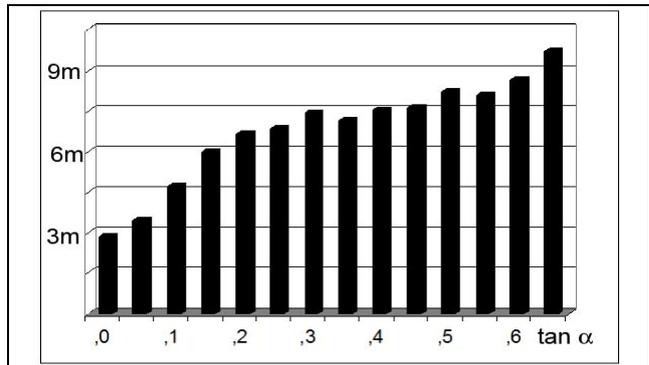


Figure 9. test area Pennsylvania – RMS Z-discrepancies as function of tangent of terrain slope

| | RMSZ | bias | SZ | SZ |
|--------------|------|------|------|---------------------------------|
| Whole area | 9.32 | 8.30 | 4.25 | $3.63 + 23.2 \cdot \tan \alpha$ |
| Not mountain | 9.71 | 9.17 | 3.19 | $2.86 + 12.8 \cdot \tan \alpha$ |
| mountainous | 8.69 | 6.94 | 5.23 | $4.71 + 12.2 \cdot \tan \alpha$ |

Table 2. analysis of test area Pennsylvania – mountainous corresponds to forest.

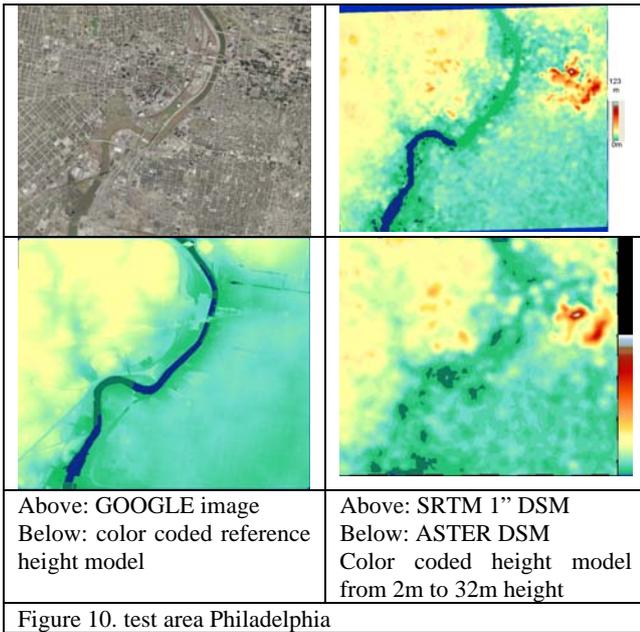
| | RMSZ | bias | SZ | SZ |
|------------|-------|------|------|---------------------------------|
| Whole area | 10.42 | 7.64 | 7.08 | $6.25 + 1.78 \cdot \tan \alpha$ |
| Open area | 10.90 | 9.12 | 5.98 | $5.60 + 0.05 \cdot \tan \alpha$ |
| forest | 8.18 | 1.53 | 8.03 | $7.32 + 0.2 \cdot \tan \alpha$ |

Table 3. analysis of test area Bavaria, Gars – separately for open area and forest

| | RMSZ | bias | SZ | SZ |
|------------|-------|-------|-------|---------------------------------|
| Whole area | 13.31 | -3.52 | 12.84 | $7.88 + 17.6 \cdot \tan \alpha$ |
| Open area | 8.70 | 3.37 | 8.02 | $5.33 + 22.2 \cdot \tan \alpha$ |
| forest | 14.98 | -6.76 | 13.36 | $7.98 + 16.7 \cdot \tan \alpha$ |

Table 4. analysis of test area Bavaria, Innzell – separately for open area and forest

As examples the separate analysis of the open and the forest area is shown for the test areas Pennsylvania, Bavaria, Gars and Bavaria Innzell (tables 2–4). The negative influence of the forest to the height accuracy is obvious; especially it can be seen at the standard deviation after respecting the bias and also the constant part of the standard deviation as function of the terrain inclination after respecting the bias. Similar results have been achieved for the other test areas.



In the test area Philadelphia (figure 10) the buildings of the downtown area are influencing the ASTER GDEM as well as the SRTM height model. The high buildings of the city (upper right hand side) have an influence up to 30m. Also the higher buildings in the upper center are causing large height discrepancies.

| | RMSZ | bias | SZ | SZ |
|----------------|-------|-------|-------|---------------------------------|
| Jordan | 13.62 | 11.92 | 6.59 | $5.03 + 2.4 \cdot \tan \alpha$ |
| W. Virginia | 14.04 | -2.66 | 13.78 | $12.79 + 1.6 \cdot \tan \alpha$ |
| Atlantic C. | 5.15 | -3.36 | 3.90 | $3.90 + 0.0 \cdot \tan \alpha$ |
| Pennsylvania | 9.32 | 8.30 | 4.25 | $3.63 + 23.2 \cdot \tan \alpha$ |
| Philadelphia | 7.07 | -5.33 | 4.65 | $4.65 + 0.0 \cdot \tan \alpha$ |
| Arizona | 5.82 | 3.32 | 4.78 | $2.92 + 17.4 \cdot \tan \alpha$ |
| Mausanne | 7.06 | 2.45 | 6.62 | $4.83 + 9.8 \cdot \tan \alpha$ |
| Poland | 14.08 | 9.99 | 9.93 | $9.61 + 1.7 \cdot \tan \alpha$ |
| Zonguldak | 9.26 | 1.79 | 9.08 | $6.63 + 11.7 \cdot \tan \alpha$ |
| Istanbul | 7.20 | 1.44 | 7.06 | $6.04 + 3.6 \cdot \tan \alpha$ |
| Bavaria Gars | 10.42 | 7.64 | 7.08 | $6.25 + 1.78 \cdot \tan \alpha$ |
| Bavaria Inzell | 13.31 | -3.52 | 12.84 | $7.88 + 17.6 \cdot \tan \alpha$ |
| RMS | 10.21 | 6.13 | 8.17 | 6.74 for $\alpha = 0.0$ |

Table 5. summary of the ASTER GDEM analysis for all test areas

| | RMSZ | bias | SZ | SZ |
|----------------|-------|-------|-------|---------------------------------|
| Jordan | 5.10 | 0.28 | 5.09 | $4.05 + 1.8 \cdot \tan \alpha$ |
| W. Virginia | 12.05 | -8.30 | 8.73 | $8.53 + 0.02 \cdot \tan \alpha$ |
| Atlantic C. | 2.85 | 0.08 | 2.85 | $2.85 + 0.0 \cdot \tan \alpha$ |
| Pennsylvania | 4.58 | -1.89 | 4.18 | $3.48 + 22.5 \cdot \tan \alpha$ |
| Philadelphia | 5.85 | -3.60 | 4.61 | $4.61 + 0.0 \cdot \tan \alpha$ |
| Arizona | 3.70 | 1.32 | 3.46 | $2.34 + 11.1 \cdot \tan \alpha$ |
| Mausanne | 3.86 | -0.86 | 3.76 | $1.68 + 12.4 \cdot \tan \alpha$ |
| Poland | 5.15 | 2.05 | 4.73 | $5.15 + 0.0 \cdot \tan \alpha$ |
| Zonguldak | 9.33 | -3.38 | 10.40 | $7.17 + 10.1 \cdot \tan \alpha$ |
| Istanbul | 4.95 | -1.30 | 4.77 | $3.37 + 6.2 \cdot \tan \alpha$ |
| Bavaria Gars | 5.44 | -2.33 | 4.92 | $3.95 + 2.29 \cdot \tan \alpha$ |
| Bavaria Inzell | 8.02 | -2.38 | 7.66 | $4.38 + 25.4 \cdot \tan \alpha$ |
| RMS | 6.62 | 3.12 | 5.85 | 5.08 for $\alpha = 0.0$ |

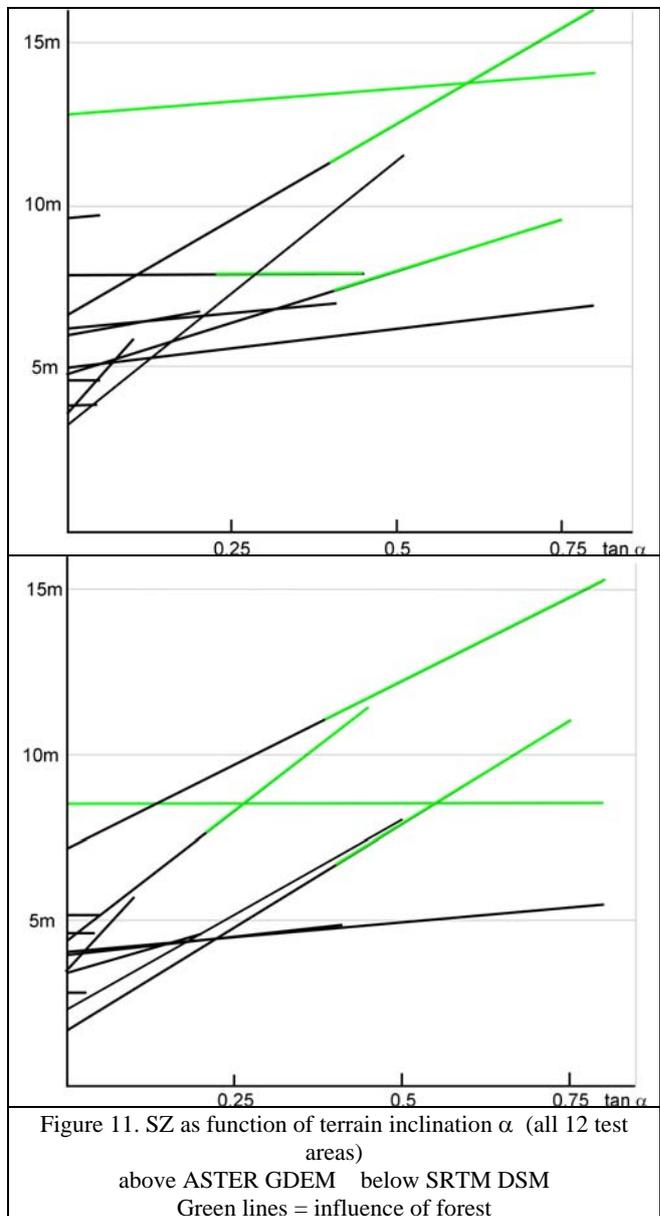
Table 6. summary of the SRTM DSM analysis for all test areas

Table 5 includes the accuracies achieved with ASTER GDEM against the reference height models and table 6 the corresponding results achieved with SRTM C-band height models. The results are partially influenced by vegetation and buildings, but this is similar for the height models based on the optical ASTER-images as well as for the InSAR-height models based on the C-band. By this reason the direct comparison of ASTER GDEM with the SRTM DSM, as shown for test area Istanbul in table 7, shows smaller root mean square height differences and a smaller standard deviation after respecting the bias (systematic error) between both as the comparison of ASTER GDEM with the reference height model. In any case the horizontal shifts between the height models have been respected in advance.

Istanbul ASTER GDEM - SRTM

| | RMSZ | bias | SZ | SZ |
|------------|------|------|------|---------------------------------|
| Whole area | 5.22 | 2.40 | 4.63 | $3.36 + 14.6 \cdot \tan \alpha$ |

Table 7. direct comparison of ASTER GDEM with the SRTM DSM



In general the accuracy analysis shows some variations, mainly caused by the test areas, especially the percentage of forest, but also the type of terrain. Large discrepancies appear for both types of height models for the test area Zonguldak, but this area has very rough mountainous parts, partly covered by forest. The rough terrain causes a loss of accuracy by interpolation over a distance of 80m – the average point spacing of the SRTM C-band DSM in this area – up to the same range as the results achieved by the SRTM DSM.

A faster overview as the tables 5 and 6 give the graphic representations of figure 11. The dependency upon the tangent of the terrain inclination (shown by inclination of the adjusted lines) is very similar for both types of height models, but the standard deviations are clearly smaller for the SRTM DSM as for the ASTER GDEM. This is also obvious at least for the root mean square discrepancies shown in the last lines of table 5 and 6. Not only is the standard deviation, also the bias is smaller for the SRTM-data as for the ASTER-data.

Of course not the same accuracy and details as with the high resolution stereo sensor Cartosat-1 (fig. 14) having 2.5m GSD (Jacobsen 2006) can be reached. With Cartosat-1 stereo pairs standard deviations of DEM-heights up to 2m can be reached, while with SPOT 5 High Resolution Stereo (HRS), having 5m GSD in orbit direction, up to 4m standard deviation for open and flat areas is possible (Baudoin et al 2004, Jacobsen 2004).

5. MORPHOLOGIC DETAILS

The accuracy of the height models is only one aspect, same importance have the morphologic details, describing the landscape characteristics. The description of morphologic details is more complex, the best overview is given by the details of the contour lines. Of course the contour lines are influenced by forest and buildings, so only in more steep areas it can be used for comparison of the morphologic details.

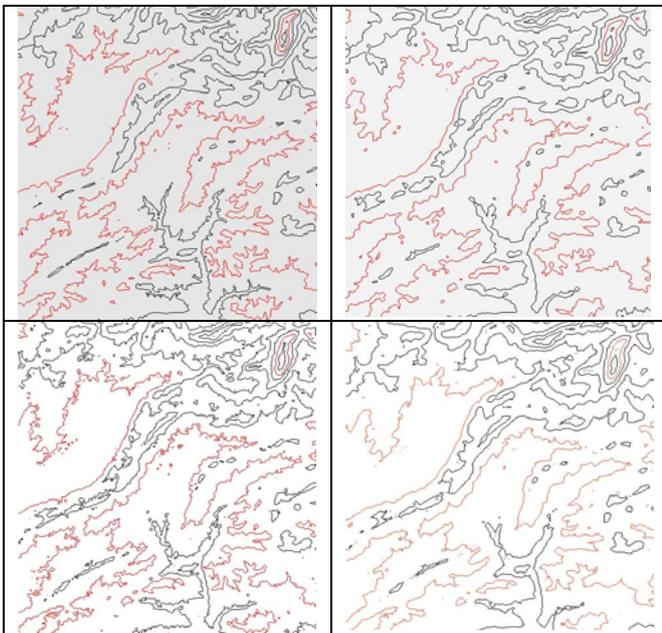


Figure 12. Test area Pennsylvania, contours with 1000 ft interval

Upper left: contours reference DEM
 Upper right: contours ASTER
 Lower left: contours SRTM 1''
 Lower right: contours SRTM 3''

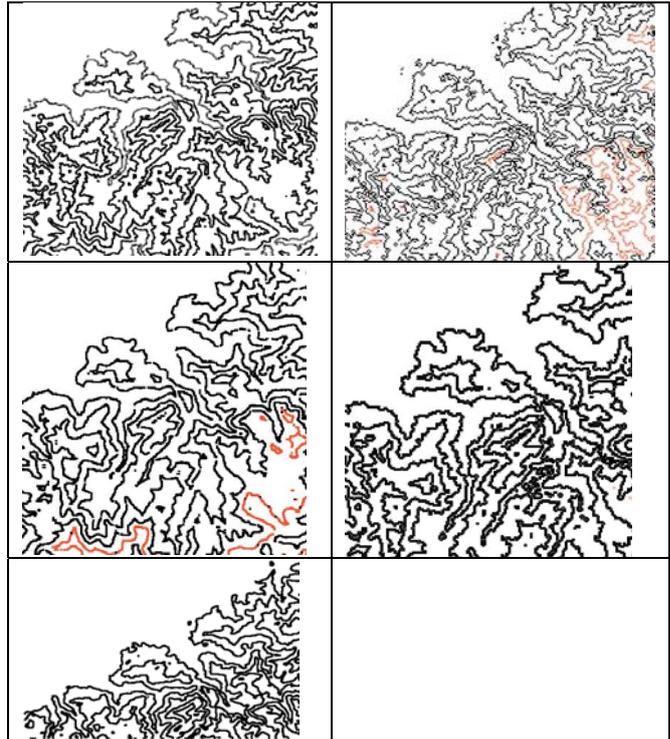


Figure 13. Test area Zonguldak, contours with 100m interval

Upper left: contours reference DEM
 Upper right: contours ASTER GDEM
 Centre left: contours SRTM 3''
 Centre right: contours SRTM X-band 1''
 Lower left: contours based on matched single ASTER scene (45m spacing)

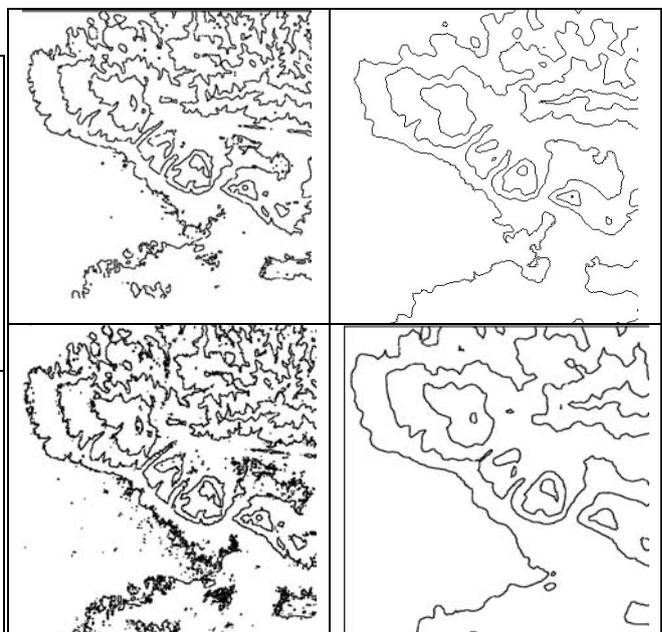


Figure 14. Test area Mausanne, contours with 50m interval

Upper left: contours reference DEM
 Upper right: contours ASTER GDEM
 Lower left: contours Cartosat (7.5m spacing)
 Lower right: contours SRTM 3''

The comparison of the contour lines shown in figures 12 up to 14 is not very simple. Of course the contour lines based on the

reference height models as well as the Cartosat-1-height model with a point spacing of 7.5m are more detailed as SRTM-DSM and ASTER GDEM. It is also obvious that the SRTM 1arcsec data with a point spacing of approximately 30m include more details as the ASTER GDEM with the same point spacing. But the ASTER GDEM includes slightly more morphologic details as the SRTM 3 arcsec data (SRTM C-band) having a point spacing of approximately 90m. This means, the morphologic details of ASTER GDEM do not correspond to the spacing of approximately 30m, it is more in the range corresponding to 60m GSD. It seems by the averaging of the partially high number of stereo models some details have been lost. In own matched single ASTER scenes having 45m spacing (Sefercik et al 2007) at least the same morphologic details can be seen (fig. 13).

In the ASTER Global DEM Validation, Summary Report 2009 (see references) the sharpness is mentioned as corresponding to 50m – this can be confirmed approximately by the own investigations.

6. CONCLUSION

ASTER GDEMs have to be shifted preferable by adjustment to the reference height models. The shifts in the range of 6m to 8m for X and Y cannot be neglected. Also vertical shifts, without influence of forest and buildings in the range of 6m exist. Such constant errors can be determined based on a limited number of height points and horizontal map information.

ASTER GDEMs as well as other height models based on matched optical images and also interferometric synthetic aperture radar using C- or X-band are defining the visible surface, influenced by vegetation and buildings. In open areas such DSMs can be filtered to the bare ground, but not in forest and densely build up areas.

Usually ASTER GDEMs are based on several images, named as stacks. In the used test areas up to 60 stacks per object points have been used. The height accuracy is influenced by this. As average over all test areas the relation $RMSZ = 12.43m - 0.35m \cdot (\text{number of stacks/point})$ exist, which has to be seen together with an average of 18.7 stacks/point, leading to an average RMSZ of 5.88m. As usual for all height models the vertical accuracy can be described by the formula $SZ = a + b \cdot \tan(\text{terrain slope})$. The dependency upon the terrain slope (factor b) is 7.5m in the average, but it cannot be determined in flat areas and it is depending upon elements on top of the ground – forests are located more in inclined as in flat areas. As root mean square height discrepancy in flat areas +/-6.7m have been achieved, but this is influenced by forest and buildings. In open and flat areas it is estimated with approximately 5m.

In comparison SRTM height models have smaller shifts in X, Y and Z – it is in the range of 3m. In addition in open and flat areas the SRTM height models have root mean square height discrepancies in the range of 3m to 4m against the same reference height models as the ASTER GDEMs.

With the higher resolution optical space stereo sensors Cartosat-1 (2.5m GSD) a vertical accuracy in open and flat areas of 2.5m can be reached (Jacobsen 2006) and with SPOT 5 HRS (5m GSD in orbit direction) 4m up to 5m (Baudoin et al 2004, Jacobsen 2004).

Morphologic details usually are dominated by the point spacing of the height models. With ASTER GDEMs the morphologic details are below the details which can be shown with 30m GSD, it corresponds more to the range of 60m GSD. The usual SRTM C-band scenes with approximately 90m spacing are including slightly less morphologic details. This is reverse with

the 1 arcsec spacing of the C-band data in the USA and also the SRTM X-band data (1 arcsec point spacing).

As concluding remark it can be stated that the availability of the nearly world wide covering ASTER GDEM is supporting several photogrammetric and remote sensing application. The homogeneity of this data set is very important. In steep mountainous areas it does not include gaps as the SRTM height model. Reverse the accuracy of the SRTM height model is slightly better for flat and rolling areas, but slightly more morphologic details are available in the ASTER GDEM as in the standard SRTM height models with 3 arcsec point spacing.

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