CHARACTERISTICS OF NEARLY WORLD WIDE AVAILABE DIGITAL HEIGHT MODELS

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ABSTRACT

Height models are a basic component for any GIS and are required for the generation of several remote sensing products. Today height models can be based on satellite information as optical stereo models or interferometric synthetic aperture radar (InSAR). The generation is time consuming and requires the image products, which are usually not free of charge. With the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) from USGS, the height models from Shuttle Radar Topography Mission (SRTM) and also the ASTER Global Digital Elevation Model Version 2 (GDEM2) height models with 7.5, 3 respectively 1 arc-second ground spacing are available free of charge. Against the predecessor versions GTOPO30, SRTM and GDEM versions 1, they have been improved in resolution, accuracy and voids. In addition also SPOT 5 reference 3D and SRTM X-band height models with not so complete coverage can be used, but the reference 3D is not free of charge. An overview about the characteristics of these height models is given including detailed accuracy specification and analysis and limitations of the individual height models.

Keywords: digital height models, GMTED2010, SRTM, GDEM2, Reference 3D, accuracy, resolution, limitations

INTRODUCTION

Digital height models (DHM) are required for several remote sensing and GIS application. The generation of DHM is time consuming and expensive, so available nearly worldwide covering height models should be taken into account if they are able to solve the requirements of handled projects. For most of the height models information about accuracy is available in the internet, but it is necessary to take a view to the accuracy specification and in some cases limitations. The published accuracy information cannot directly be compared and the accuracy cannot be expressed just with one figure.

The world-wide old GTOPO30 of the USGS and US NGA has been replaced by the GMTED2010 (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/GMTED2010), which is available also with 7.5 arc-seconds (arcsec) point spacing, corresponding to 231m at the equator (Danielson & Gesch 2011). The former GTOPO30 with just 30 arcsec point spacing was very inhomogeneous, this has been improved for large areas by the use of SRTM-height models.

By interferometric synthetic aperture radar (InSAR) based on the Shuttle Radar Topography Mission (SRTM) in 2000 a height model has been generated for the area from 56° Southern up to 60.25° Northern latitude (http://www.cgiar-csi.org/data/elevation/item/45-srtm-90m-digital-elevation-database-v41) – NASA/USGS. The SRTM height model is available with 3 arc-seconds spacing, corresponding to 93m at the equator. The full information corresponds to 1 arc-seconds spacing, but this is available only for the USA and special national agreements. The first version available since 2003 included some gaps in mountainous and dessert regions which now are improved by gap-filling (Reuter et al 2007).

Based on the Japanese optical stereo sensor ASTER on the US platform Terra with 15m ground sampling distance (GSD) and a base to height relation of 1:2.1, several stereo models have been generated since 2000. All stereo models have been used for the generation of height models by automatic image matching (Tetsushi 2011). The ASTER GDEM is covering the range of the latitude from +83° up to -83° with a point spacing of 1 arc-second, corresponding to 31m at the equator. In the first version the three-dimensional shifts of the individual height models have not been respected correctly, leading to a loss of resolution of the height models (not so detailed contour lines as corresponding to the spacing). By this reason an improved version, the ASTER GDEM2 has been generated and is available free of charge since 2011. ASTER GDEM(2) is a product of the Japanese METI and the US NASA (http://www.gdem.aster.ersdac.or.jp/login.jsp).

In addition to the above mentioned free of charge available data also other height models are available. In parallel to the US C-band on the SRTM there was also the German/Italian X-band. Also based on this height models are available, but they are not covering the range from 56° Sothern up to 60.25° Northern latitude without gaps. On the other hand the data are available with 1 arc-second spacing (http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10212/332_read-817/).

SPOT 5 carries in addition to the large point able HRG instruments the HRS (High Resolution Stereo) a stereo sensor with 5m x 10m GSD and a base to height relation of 1:1.2, used as SPOT DEM for the generation of height models for large parts of the world with 30m spacing (http://www.astrium-geo.com/en/198-elevation30) (Jacobsen 2004).

Just now the radar satellites TerraSAR-X and TanDEM-X of the German Space Flight Center (DLR) are flying close together to generate worldwide height models by InSAR which shall be available mid 2013 as TanDEM-X Global Elevation Model with 12m spacing, 2m relative and 10m absolute accuracy.

SPECIFICATION OF ACCURACY

The expression “accuracy of a DHM” has to be specified in detail. At first as vertical accuracy we can use the standard deviation of the Z-component (SZ) which corresponds to the root mean square error of the height (RMSZ) if the bias is respected, but we also can use LE90, the linear error with 90% probability level. The standard deviation has 68% probability level, so we have the relation: LE90 = SZ∗1.65 or with 95% probability level LE95 = SZ∗1.96. This is based on normal distribution of height differences against an error free reference model. The next problem is that we may have a systematic shift in Z, but also in X and Y.

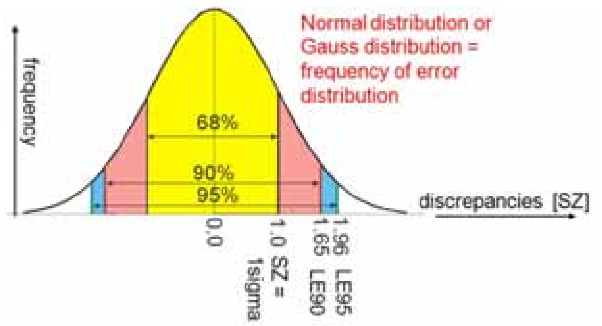

Figure 1. Relation SZ to LE90 / LE95

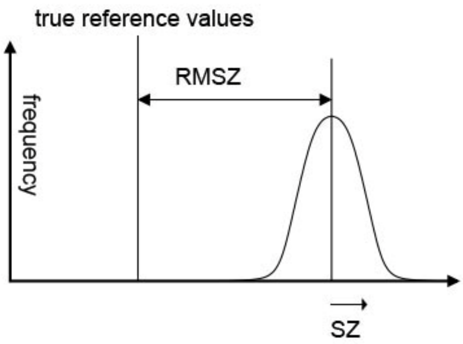

Figure 2. Relation SZ to RMSZ

The root mean square error is related to the height differences of the height model to be analyzed against the reference, while the standard deviation respects the systematic height errors (bias).

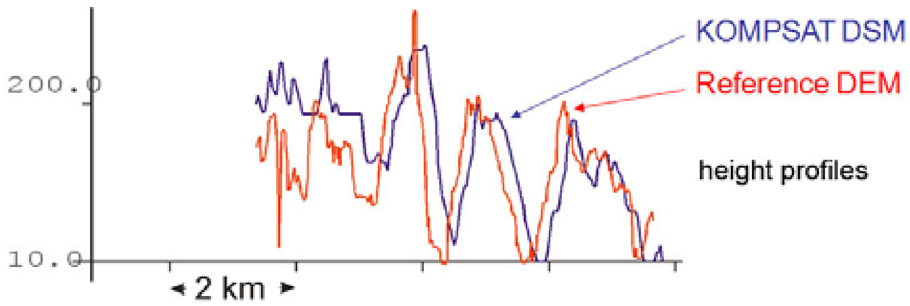

Figure 3. Shift of height models caused by datum problems in a mountainous area – shift in X=80m, in Y=187m, leading to RMSZ reduction from originally 50m to 15.8m

Shifts of height models in X, Y and Z are common and should be detected and respected by adjustment. Beside datum problems also orientation problems are appearing because the above mentioned height models are not oriented by means of ground control points. In general the InSAR-height models are not so much influenced by shifts in X and Y because radar is not influenced by the critical satellite attitude errors.

Even if the shifts are respected correctly, also blunders have to be handled. It is a question of the blunder specification. In the extreme case blunders are specified if they are exceeding 95% probability level or approximately 2∗SZ. Of course the standard deviation looks better in this case as with a higher threshold. Such low limits are partially used in publications, but it is not serious to use such a low threshold by eliminating at least 5% of the observations. In reality not a strict normal distribution is available, larger discrepancies are more often available as corresponding to the normal distribution.

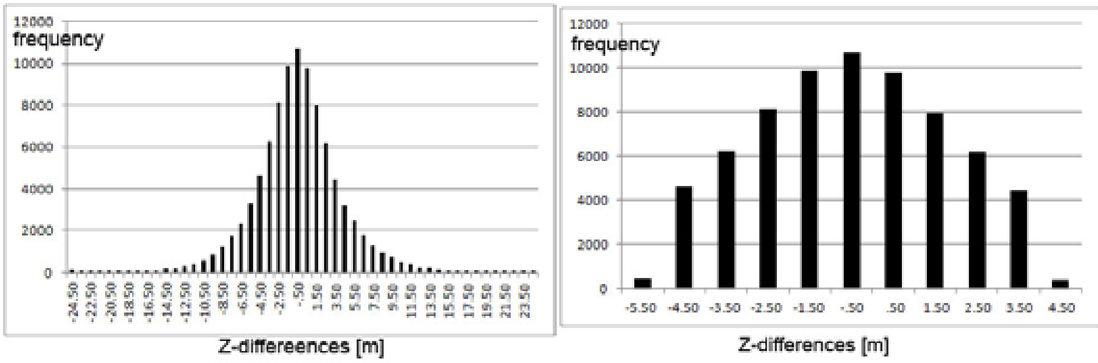

Figure 4. Frequency distribution of height differences – left: threshold 50m, right: threshold 4.6m

In figure 4, left hand side, the frequency distribution of the SRTM-height model for the area Jordan, based on a threshold of 50m is shown; while the frequency distribution on right hand side is based on a threshold of 2∗SZ. Based on a threshold of 50m, the SZ is 4.83m while it is 2.28m for the threshold of 4.6m. For the larger threshold 0.17% of the height differences exceeding 50m are handled as blunders, while it is 25.3% for the lower threshold – far away from the 5% in case of a real normal distribution. With such manipulations of not justified low blunder limits the results are looking better more as factor 2. If results from different sources are compared, such basic conditions have to be checked.

One of the reasons for a not optimal normal distribution of the height differences are dependencies upon terrain inclination and the number of used information for the determination of a single height point. The vertical accuracy by theory and in reality shows a function of SZ = A + B∗tan(slope).

The next question of definition for the accuracy of a DHM – shall it describe the accuracy of individual height points of the DHM or shall it describe the accuracy of the whole terrain surface. The difference between both is the influence of the interpolation between neighbored points which is strongly depending upon the terrain roughness. This can be roughly estimated via double differences: Δhm = height difference between neighbored points P1 and P2, Δhn = height difference between the directly neighbored points P2 and P3: $Zdiff = \sqrt{\frac{\Sigma(\Delta hm - \Delta hn)^2}{n}}$; RMSZdiff/4 is approximately the accuracy loss by interpolation in the center of neighbored points.

Finally we have the definition of the height model – do we like to have a digital surface model (DSM), describing the visual surface, or do we like to have a digital terrain model (DTM), describing the bare ground. DHM from optical images are DSM, while for InSAR it is depending upon the used wavelength. The commonly used C- or X-band are close to DSM, but in forest areas the height may be up to a third of the tree height lower as in case of optical images. With the long L-band the trees can be penetrated.

ANALYSIS OF HEIGHT MODELS

GMTED2010

The global GMTED2010 is available with 30, 15 and 7.5 arc-seconds point spacing. The version with the highest resolution has been analyzed in the mountainous test areas Jordan and Zonguldak. In these areas this version dominantly is based on the SRTM C-band height model. The downloading of GMTED2010 includes several files – DCS, MAX, MIN, MED, MEA and STD. STD shall be the standard deviation file, while all other are height models. A comparison of height profiles is shown in figure 5. It is obvious, that the DSC-file fits very well with the SRTM C-band, the profiles are so close together, that the second line cannot be seen clearly. MAX is clearly above and MIN clearly below the SRTM C-band data. On right hand side of figure 5 DSC, MEA and MED are plotted – also they are close together, but MEA and MED are smoothened. So for the best description of the terrain, the DSC-file has to be used, the justification of the other files is hardly to understand. The following accuracy information is only based on the DSC-file.

In the Jordan test area GMTED2010 shows against the reference height model a RMSZ of 4.86m with a bias of -1.18m and corresponding SZ of 4.71m. The bias is shown as correction – that means the GMTED2010 height model is above the reference DTM. As function of the terrain inclination we have: SZ=3.85m+1.53m*tan(slope). For the SRTM height model we have similar values with SZ=3.74m+2.21m*tan(slope). This is not a surprise because both are based on the same data set. But it should not be forgotten, that SRTM has 3 arcsec and the other 7.5 arcsec point spacing. So it will be different if also the interpolation effect is respected. This is the case if we check the reference DTM with 20m point spacing against the GMTED2010, all points of the reference DTM are interpolated in GMTED2010 and compared with the original values. This leads for GMTED2010 to SZ=14.27m or SZ=6.96m+53.0m*tan(slope), while for SRTM it is SZ=11.28m or SZ=5.67m+29.6m*tan(slope). The Jordan test area has no forest and it is not very rough, so the height values are more accurate as in other areas.

In the mountainous and very rough Zonguldak test area with an average slope of 0.3 and an average change of the slope from one grid to the next of 0.15 the conditions are not as optimal. GMTED2010 has an RMSE of 8.75m, a bias of -5.11m and SZ=7.10m or SZ=7.71m+2.89m*tan(slope), again this is very close to SZ=7.08m for SRTM C-band. A reverse investigation including the influence of DTM interpolation leads to SZ=15.34m for GMTED2010 or SZ=14.2m+10.0m*tan(slope), while it is for SRTM C-band: SZ=10.39m or SZ=7.80m+18.56m*tan(slope), showing the advantage of smaller DHM-spacing for a precise description of the surface.

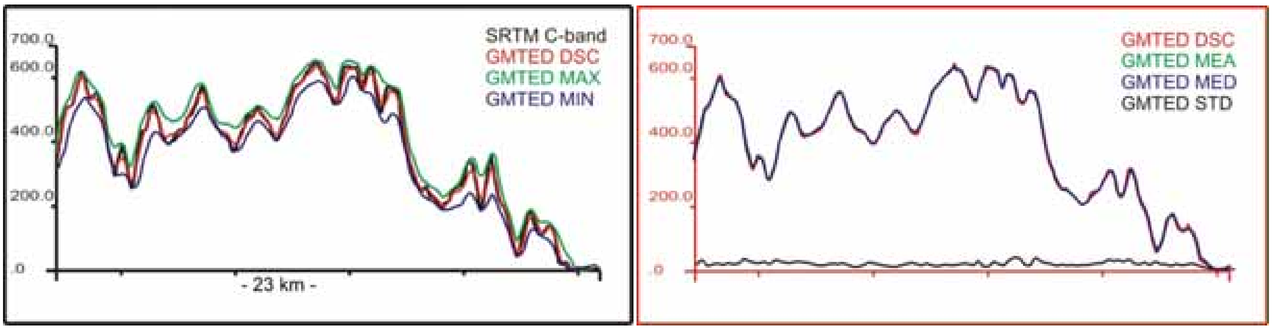

Figure 5. Comparison of profiles through different GMTED2010 height models – left together with SRTM C-band height model, right only GMTED2010 height models together with STD-data, test area Zonguldak

ASTER GDEM, GDEM2 and SRTM

ASTER GDEM is based on automatic matching of the ASTER stereo models while SRTM is based on InSAR, so some differences in the characteristics have to be expected. In nine test areas with different character the geometric quality of the height models have been analyzed. The test area Zonguldak is a rough mountainous area, partially covered by forest, while Jordan has nearly no vegetation and is smoothly mountainous. Mausanne includes forest areas and some rolling up to mountainous parts. Inzell is dominated by steep mountainous area, partially covered by forest, while Gars includes smooth mountainous parts. Pennsylvania has rolling parts and large forest areas, while Philadelphia includes downtown areas of the city. Arizona has nearly no vegetation and includes some mountainous parts. Warsaw is covered by forest areas and is dominantly flat, it has the disadvantage of a limited number of stacks used for the matching (number of stacks = number of images). The Warsaw test area of GDEM1 in the average has only 9.84 and GDEM2 14.5 stacks/object points. This is quite less as in the other test areas, explaining why in the flat area the standard deviation of the GDEM1 and GDEM2-data are higher as in other test areas. Here for GDEM1 the standard deviation of the height can be expressed as SZ = 17.00m – 0.85∗ number of stacks or 15.1m for 2 stacks up to 3.4m for 16 stacks and for GDEM2: SZ=19.05m – 0.72∗number of stacks or 17.61m for 2 stacks up to 3.21m for 22 stacks. In other test areas the dependency of the accuracy upon the number of stacks is not so clear.

It is the question, what is the height model accuracy. Figures 6 up to 9 present different results of the grid points, in addition we have the influence of the DHM interpolation being quite different depending upon the point spacing and the terrain roughness. Finally it depends upon the use of the height models and the individual frame conditions. The root mean square differences of the original data against reference data (fig. 6) are influenced by shifts in all 3 coordinate components. The standard deviations in fig. 7 do not differentiate between open areas and forest as well as the dependency upon the terrain inclination. In figure 8 the standard deviations for the open areas and flat parts are shown. Figure 9 compares the root mean square values of all test areas and shows the strong dependency upon the frame conditions. Depending upon the use of the height models, information about different geometric quality figures have to be used.

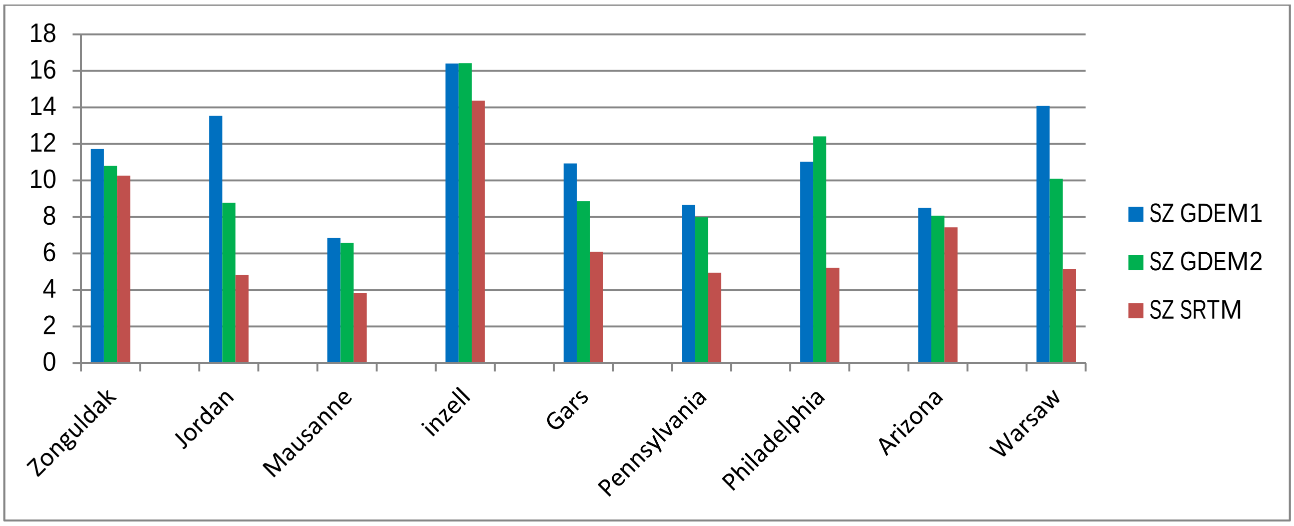

Figure 6. Root mean square differences of original data against reference data,
RMSZ over all test areas: GDEM1: 11.66m, GDEM2: 10.38m, SRTM: 7.60m

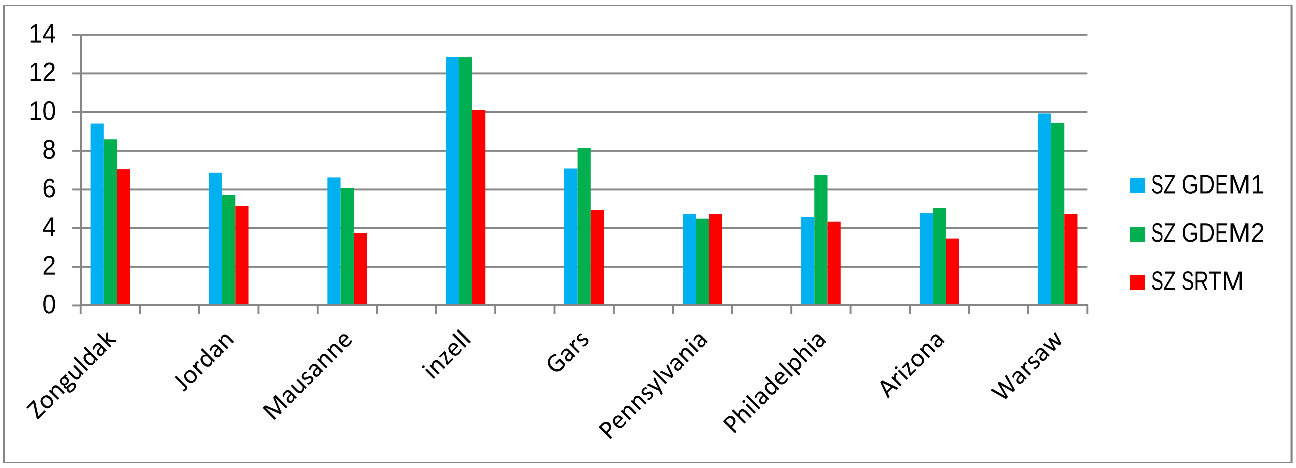

Figure 7. Standard deviation of height after shift correction,
SZ over all test areas: GDEM1: 7.88m, GDEM2: 7.85m, SRTM: 5.69m

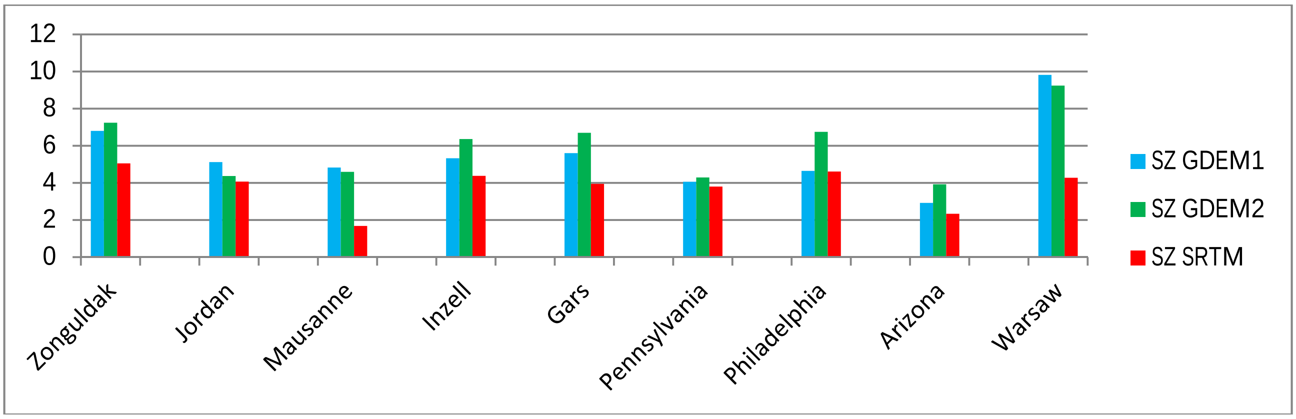

Figure 8. Standard deviation of height after shift correction for flat and open areas,
SZ over all test areas: GDEM1: 5.76m, GDEM2: 6.17m, SRTM: 3.93m

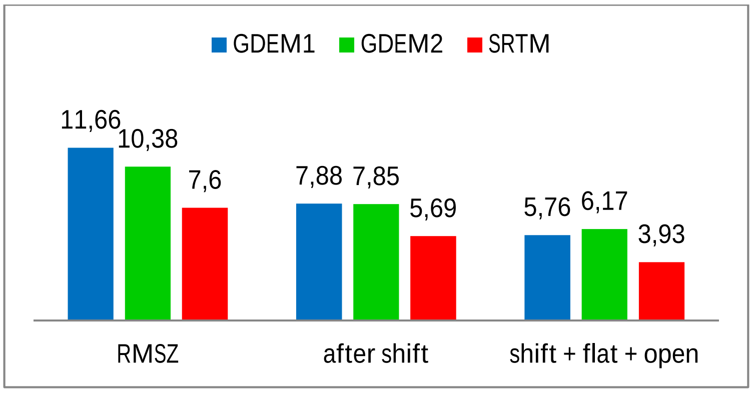

Figure 9. RMSZ / SZ average of all test areas

REFERENCE 3D

Large parts of the world are covered by Reference 3D, based on SPOT 5 HRS stereo models. They are not free of charge, but have the advantage of a point spacing of 20m. Within the ISPRS a scientific assessment of height models based on SPOT 5 HRS has been made (Baudoin et al. 2004), some details are presented in Jacobsen 2004. The orientation accuracy of the SPOT 5 HRS stereo models not supported by GCP is in the range of 5m to 9m. The root mean square height differences after bias correction for open areas is in the range of 5m to 6m; that means it is close to the results of the SRTM DSM. But the better point spacing has some advantages for the resolution. On the other hand SPOT 5 as well as the HRS sensor have a spectral range from 0.48 up to 0.70µm wavelength that means only the very first part of infrared is included, causing problems for image matching in forest areas. A HRS DSM in a forest area in Turkey demonstrated, that in such areas a gap filling by SRTM 1 arcsec data is made (Buyuksalih, Jacobsen 2008).

SRTM X-band

As mentioned, in addition to the height model based on the SRTM C-band, which is available free of charge in the internet, based on the German/Italian SRTM X-band also height models have been generated and are available via the WEB (http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10080/150_read-817/) now also free of charge. The SRTM X-band DHM by theory should be more precise as the SRTM C-band DHM, but the C-band DHM in most cases is not only based on one height model, it uses the average height based on all available models. By this reason the investigated X-band height models have nearly the same accuracy as the C-band height models (Jacobsen 2005). Nevertheless the SRTM X-band height model is available with 1 arcsec point spacing which is a big advantage against the 3 arcsec of the SRTM C-band.

RESOLUTION OF HEIGHT MODELS

The accuracy of a height model is the dominating criteria, but it is not the only one. For several applications the resolution of the DHM is important. Resolution is close to the relative accuracy – the accuracy of one point in relation to the neighbored. The relative accuracy in most cases is better as the absolute accuracy because it is not dependent upon a bias. The term relative accuracy has to be specified in detail – is it relative within one scene or is it relative just in relation to neighbored points (fig. 10). Figure 10 shows, that directly neighbored points have a standard deviation in height of 2.85m, while with 10 points spacing (approximately 290m) the relative standard deviation with 5.04m is not so far away from SZ=5.49m for the whole scene.

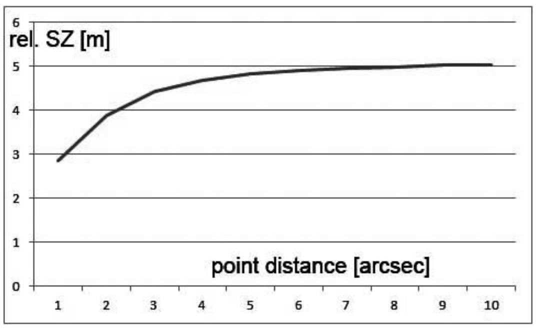

Figure 10. relative standard deviation of Aster GDEM2 in test area Jordan
Horizontal: point distance
Vertical: relative standard deviation

Visually the relative accuracy can be seen with the details of the contour lines. Figure 11 demonstrates the resolution of the different height models with a part of the area Zonguldak. The reference model has 10m point spacing, showing any details; the resolution of the SRTM X-band data with 27m spacing is not far away from this. The ASTER GDEM2 corresponds to this, while the first version of ASTER GDEM does not show the details, it corresponds with the resolution of SRTM C-band with approximately 80m point spacing. Of course with the GMTED2010, having 201m point spacing, the contour lines are quite more generalized, but it cannot be compared with the old GTOPO30 having 800m spacing and a lower accuracy. The improvement of the ASTER GDEM-resolution is also stated in Tetsushi et al. 2011.

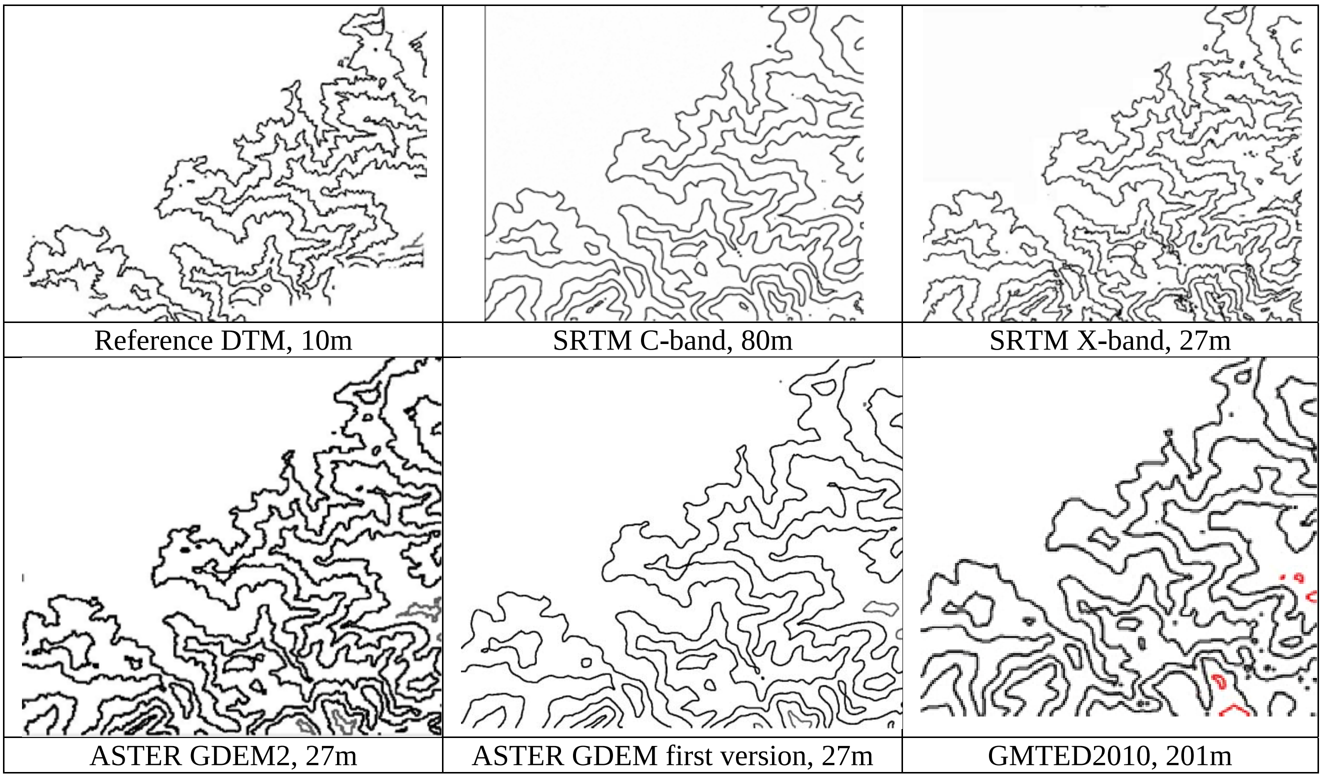

Figure 11. Contour lines based on different height models, below average point spacing

CONCLUSION

The shown investigation demonstrates that it is not possible to explain the accuracy of the nearly worldwide covering height models just with one figure. The accuracy depends beside the specification of the accuracy upon the characteristics of the test areas, especially the terrain inclination and roughness as well as the coverage by forest, because most of the height models are digital surface models with the height of the visible surface and not the bare ground. In the used test areas the worldwide GMTED2010 is dominated by SRTM heights, leading to similar accuracy of the included height points. ASTER GDEM2 has been improved against the first version of ASTER GDEM especially with the relative accuracy, clearly improving the resolution. Also the absolute location in all three coordinate components is better, but the standard deviation of height within the scenes is on the same level. The gap filling of the SRTM height models did not play an important role for all used test areas, so no clear difference between the first SRTM-version and the actual one has been identified. In general the SRTM height models are more accurate as the height models based on ASTER, but the GDEM2 now has a clearly better resolution, fitting to the spacing of 1 arcsec as SRTM C-band DHM available only with 3 arcsec point spacing. The SRTM X-band DHM, available only partially, has advantages against GDEM2 – it has the same resolution but a higher accuracy. SPOT reference 3D is on a similar accuracy level as SRTM but with 20m spacing it has a better resolution. In dense forest areas for reference 3D no money should be spend for SPOT reference 3D because there it is dominated by SRTM heights used for gap filling.

The planned use of the height models is important for the selection of the accuracy figures shown above – it is possible to respect / determine the shifts in X, Y and Z and shall a DSM be used or are only the open areas important. In addition the terrain inclination plays an important role. In addition for the description of the terrain itself the accuracy loss by interpolation, dominated by the point spacing and the terrain roughness, has to be respected.

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