CHARACTERISTICS OF WORLDWIDE AND NEARLY WORLDWIDE HEIGHT MODELS

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ABSTRACT

Worldwide and nearly worldwide covering height models are partially available free of charge in the internet, partially the data are available without restrictions, but have to be purchased. These height models are based on optical or radar space imagery. Depending upon the type of input data and the used sensor orientation the spacing and accuracy, as well as the characteristics, of the height models are different. An overview about the absolute and relative accuracy, the consistency, error distribution and other characteristics as influence of terrain inclination and aspects is given. Not in any case the information content corresponds to the point spacing and partially the accuracy varies remarkably. Partially by post processing the height models can or have to be improved.

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 freely available height models some accuracy information is available, but the quality of a DEM cannot be described just with one figure for the accuracy. In addition different accuracy descriptions are in use and the accuracy may depend upon some parameters as terrain inclination, aspects and number of images used for the point determination. It is also necessary to separate between relative and absolute accuracy – the whole DEM may be shifted in X, Y and Z. In addition the definition of the height model as Digital Elevation Model (DEM) with the height of the bare ground or as Digital Surface Model (DSM) with the height of the visible objects as vegetation and buildings is important. Based on automatic matching of optical images DSMs are generated. Height models based on Synthetic Aperture Radar (SAR) covering large areas are usually determined by interferometry (InSAR) based on InSAR-configurations. By radargrammetry usually only smaller areas are handled. For height models based on SAR the height in the vegetation areas depends upon the wavelength – the long wavelength L- and P-band can penetrate the vegetation while with C- and X-band deliver heights close to the top of the vegetation.

SPECIFICATION OF ACCURACY

Traditionally the geometric quality of a DEM is determined with a more precise height model. For a correct definition of the accuracy it has to be checked if there are systematic differences between the

investigated DHM and the reference DHM (figure 1). The shifts and scale differences should be determined by adjustment to guarantee an optimal fit. Shifts are often based on datum problems, but it may be caused also by limitations of the orientation accuracy.
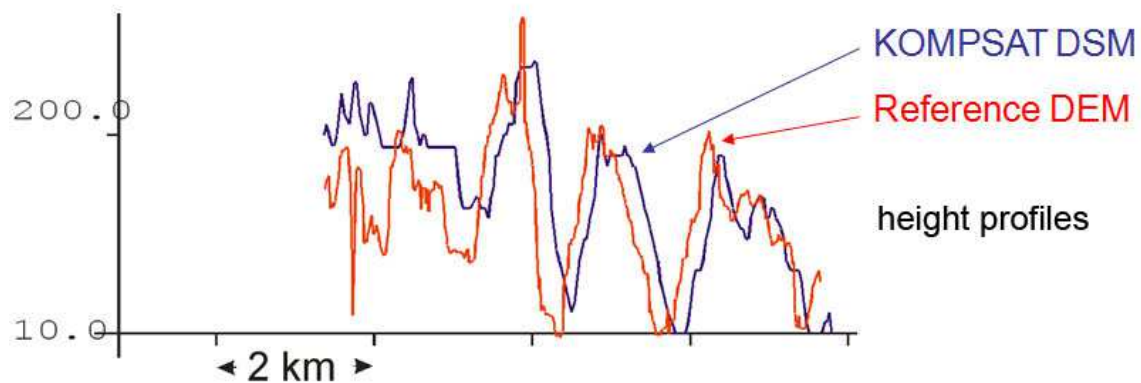

Figure 1: Shift of height models caused by datum problems in a mountainous area – shift in X=80m, in Y=187m, leading to RMSZ reduction from originally 50m to 15.8m

The accuracy figures or uncertainty parameters are "parameter, associated with the result of a measurement, that characterizes the dispersion of the value that could reasonably be attributed to the measurand" (JCGM 100:2008). JCGM 100:2008 (Evaluation of measurement data – Guide to the expression of uncertainty in measurement) of the Joint Committee for Guides in Meterology, where ISO is a member, is related to measurements. Of course computed object coordinates are no direct measurements, but the accuracy figures can be used for this if similar conditions for the determination exist. If this is not the case, we have to express the accuracy depending upon the different conditions e.g. terrain inclination or number of images per object point.
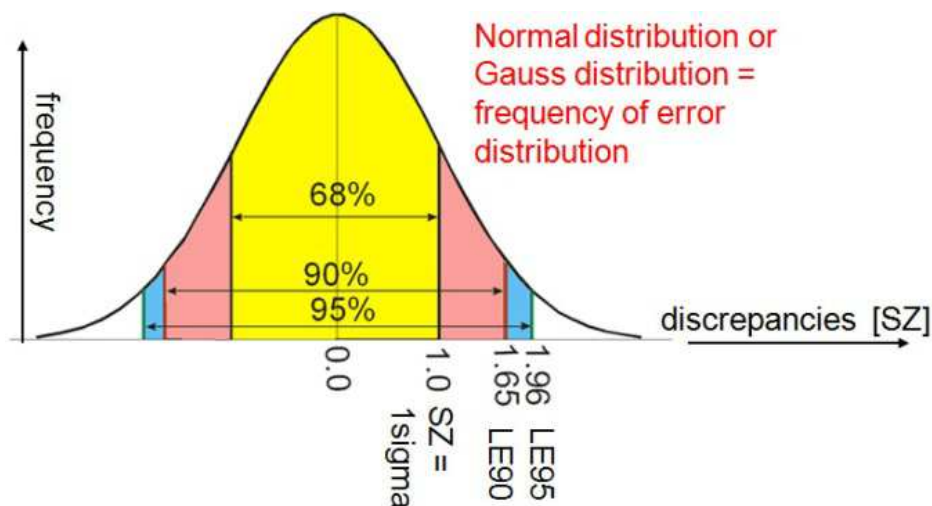

Figure 2: Relation SZ to LE90 / LE95

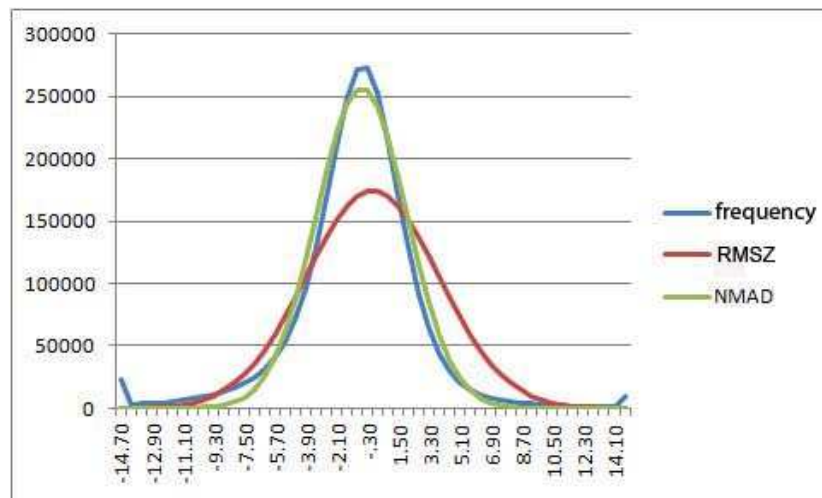| figures	Definition
RMSZ	Square mean of discrepancies
SZ	Square mean of (discrepancies – bias)
MAD	Linear mean of absolute values of discrepancies
NMAD	MAD related to 68% probability (MAD*1.48)
LE50	Median value of discrepancies
LE90	Threshold including 90% of discrepancies
LE95	Threshold including 95% of discrepancies

Table 1: accuracy figures

Figure 3: frequency distribution of discrepancies of Cartosat-1 DSM against reference DEM in open areas and normal distribution based on RMSZ and NMAD
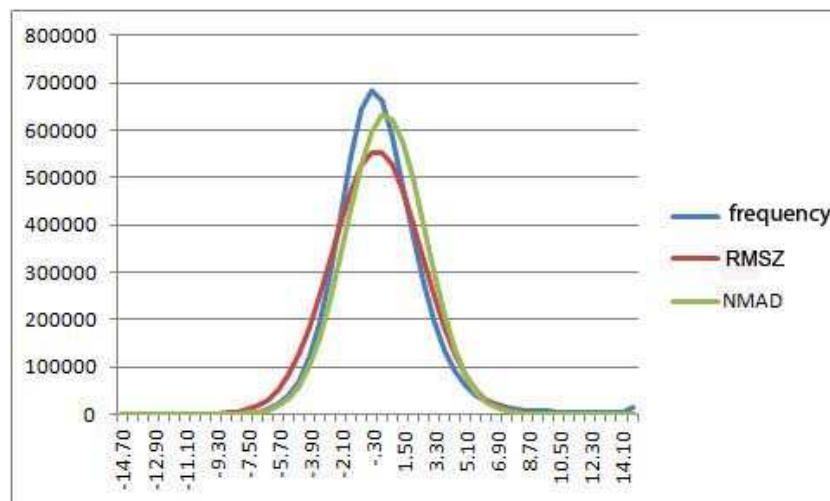

Figure 4: frequency distribution Cartosat-1 DSM against reference DEM in open areas after filtering points not belonging to bare earth and normal distribution based on RMSZ and NMAD

The justification and meaning of the accuracy figures has to be checked in relation to the frequency discrepancies of the height discrepancies of the evaluated DHM against the reference DHM. In figures 3 and 4 the frequency distributions (blue lines) are compared with the normal distributions for the same number of discrepancies and based on the root mean square discrepancies and the NMAD as standard deviations of the normal distribution. Under the condition of normal distributed discrepancies NMAD should be identical to SZ. If no bias is available RMSZ is identical to SZ. In figures 3 and 4 the function related to RMSZ is centered to the discrepancy 0.0, while the function related to NMAD is centered to the bias. In figure 3 the normal distribution related to NMAD is not far away from the frequency distribution, while the normal distribution related to RMSZ does not fit very well. This is caused by the higher number of larger discrepancies – the frequency distribution of the extreme positive and negative class contain all respected larger discrepancies, so it goes up significantly. The larger discrepancies influence the RMSZ via the square mean quite more as the normalized linear absolute mean. The "open areas" in the test field contain also elements not belonging to the bare earth, namely single trees and buildings. If such elements are filtered out, the normal distribution especially based on the RMSZ fits quite better (Passini et al. 2002). The shown relation is a typical result for all investigated height models.

Accuracy figures	Not filtered	filtered	Not filtered / filtered
RMSZ	3.77m	2.56m	1.47
SZ	3.72m	2.51m	1.48
MAD	1.75m	1.53m	1.14
NMAD	2.59m	2.27m	1.14
LE50	1.73m	1.51m	1.15
LE90	5.43m	4.09m	1.33
LE95	7.65m	5.21m	1.47
SZ (slope)	3.74m + 3.45m*tan(slope)	2.48m + 8.3*tan(slope)	
Not used (>40m)	0,02%	0%	

Table 2: accuracy figures of Cartosat-1 DSM/DEM against reference DEM – test area Warsaw

Table 2 shows the different accuracy figures. In the case of the not filtered DSM, which includes single trees and buildings, there is a relation of 1.46 between SZ and NMAD while this is reduced to the relation of 1.10 for the filtered data. For exactly normal distributed values SZ and NMAD should have the same value. Only for the filtered data we have a satisfying similarity between the Cartosat-1 DHM and the reference DEM. The dependency upon the terrain inclination can be neglected because of the dominating flat area. By filtering elements not belonging to the bare ground RMSZ, the standard deviation SZ and LE95 are strongly improved by factors 1.47 up to 1.48. Also LE90 is changed by the factor 1.33 while the change of MAD and NMAD is limited to 1.14. That means NMAD is not so sensitive for larger discrepancies.
The relation for this example is typical for all analyzed height models – it is not so simple to express the uncertainty of the determination just by one figure. NMAD expresses the uncertainty for the majority of the height discrepancies better as SZ, but a higher number of larger discrepancies have to be expected as expressed by the normal distribution. In addition for undulated terrain the

dependency upon the terrain inclination has to be respected. If elements not belonging to the bare ground are included in the data set, we have no homogenous relation for expressing the uncertainty. Under operational conditions usually the details of the accuracy are neglected and we are working with accuracy figures not describing the uncertainty precisely.

The often used linear errors LE90 and LE95 are thresholds in the frequency distribution. These thresholds are strongly depending upon the larger discrepancies which are usually caused by not homogenous data sets. By this reason LE90 and LE95 are not recommended.

ANALYZED DATA SETS

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.
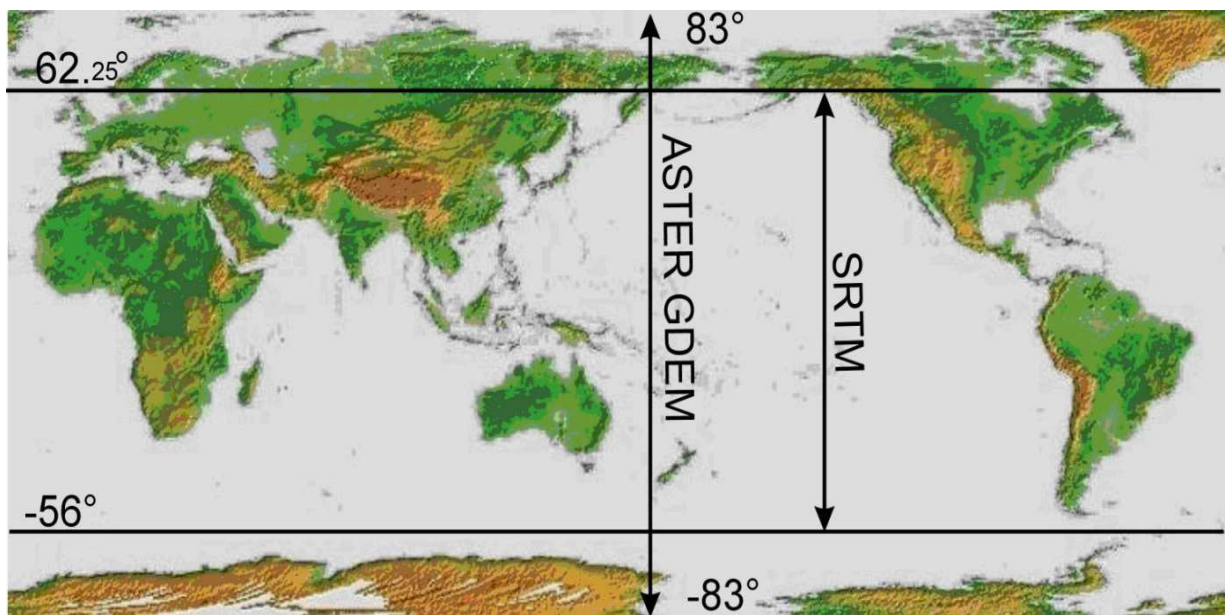

Figure 5: Worldwide coverage by SRTM DSM and ASTER GDEM

The SRTM height model is available with 3 arcsec point spacing, corresponding to 93m at the equator. The original information with 1 arcsec spacing up to now is available only for the USA and for other areas only under 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).

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 have larger gaps between the data stripes (figure 6). On the other hand the data are free available with 1 arcsec spacing (http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10212/332_read-817/).
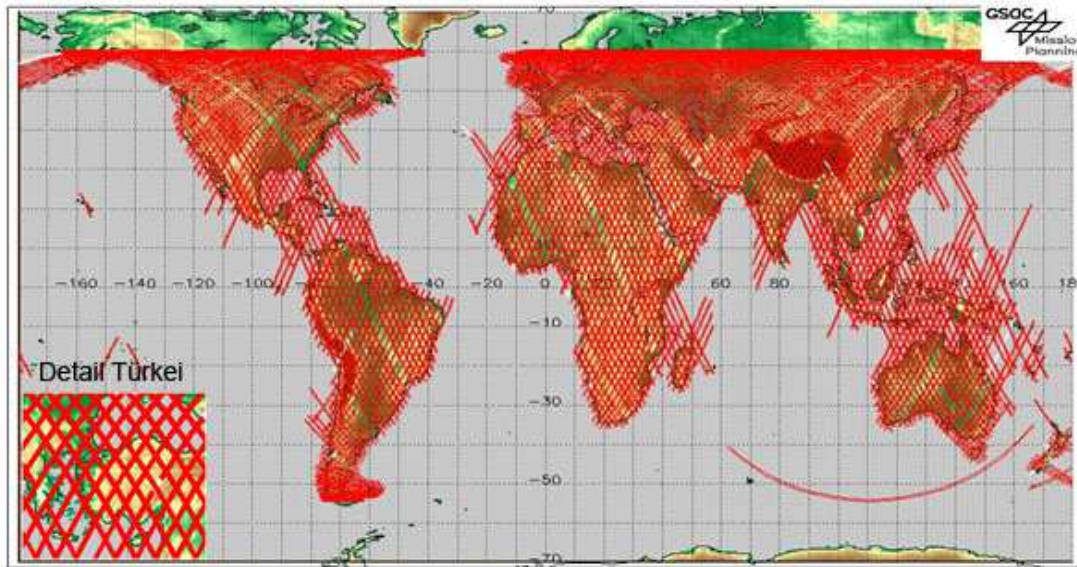
Figure 6: Gaps between the strips covered by STRM X-band

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 arcsec, 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 can be bought. SPOT 5 carries in addition to the large 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 for the generation of height models as SPOT DEM or Reference 3D for large parts of the world with 30m spacing (http://www.astrium-geo.com/en/198-elevation30) (Jacobsen 2004).

By the Indian optical stereo satellite Cartosat-1 (named also IRS P5) nearly the whole world has been covered. Cartosat-1 has 2.5m GSD, it has a view direction of 5° ahead and 26° behind, corresponding to a height to base relation of 1.6 if the curvature of the orbit is respected. So based on Cartosat-1 height models nearly at any location may be generated. For example the German company GAF in cooperation with the German Aerospace Center DLR offers the generation of Cartosat-1 height models.

The Chinese ZY-3 has two inclined views with 3.2m GSD and a nadir view with 2.1m GSD, so it can be used similar as Cartosat-1 for the DSM generation, but since the launch in 2012 not a corresponding coverage of the world has been reached.

Just now the radar satellites TerraSAR-X and TanDEM-X of the DLR are flying close together for the generation of worldwide height models by InSAR which shall be available 2014 as TanDEM-X Global Elevation Model with 12m spacing, 2m relative and 10m absolute LE90.

ANALYSIS OF HEIGHT MODELS

GMTED2010

GMTED2010, covering the whole world, is available with 30, 15 and 7.5 arc-seconds point spacing. It is available with different versions – DCS, MAX, MIN, MED, MEA and STD. STD is the quality layer including the estimated local standard deviation, while all other are height models. The DSC-file contains the best information about the DSM, 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 4.35m with a bias of -1.42m corresponding SZ of 4.11m and a NMAD of 3.43m. 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=3.36m+0.27m*tan(slope). For the SRTM height model similar values are computed but this is not a surprise because both are based on the same data set. It should not be forgotten, that SRTM has 3 arcsec and GMTED2010 only 7.5 arcsec point spacing, so the terrain can be described more precise by SRTM. The Jordan test area has no forest and it is not very rough, so the height values are more accurate as in other areas. The frequency distribution (figure 7) shows again a quite better fit to the normal distribution based on NMAD as on SZ.
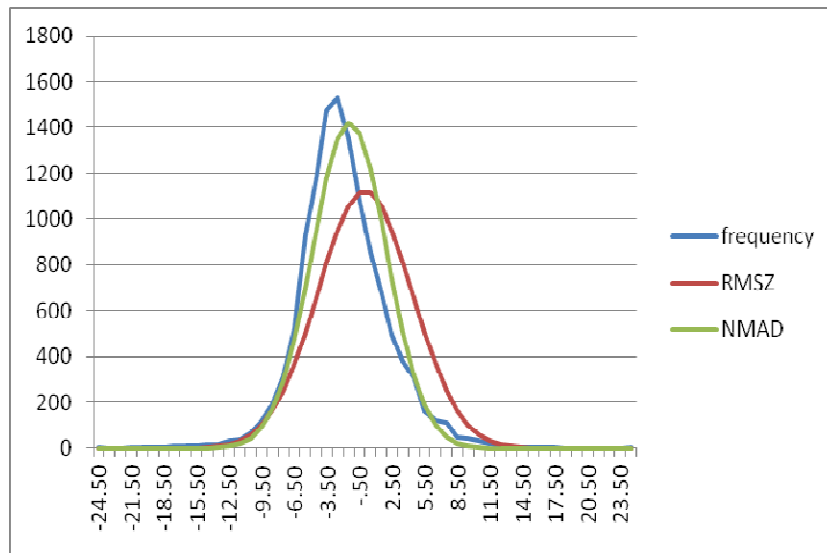

Figure 7: frequency distribution GMTED2000, test area Jordan

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 point 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 in mountainous area.

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. InSAR has some problems in mountainous areas with foreshortening (figure 8). In the foreshortening parts the

backscattered signal from different ground elements is overlaid and cannot be separated, so the height determination fails in such parts.

For ASTER GDEM all available stereo pairs have been used. This is varying strongly depending upon the location (figure 9), caused by cloud coverage and imaging priority. But also within one scene the number of images/object points is strongly varying as shown by the example in figure 10. Figure 12 gives an overview about the variation of the number of images/object point in 12 test areas. In one test area in the average just 2.5 images/point and in another 50.1 images/point have been used.

In nine test areas with different character the geometric quality of the height models from SRTM, ASTER GDEM and ASTER GDEM2 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 images/object point used for the matching. The Warsaw test area of GDEM1 in the average has only 9.84 and GDEM2 14.5 images/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 images or 15.1m for 2 images up to 3.4m for 16 images and for GDEM2: $SZ=19.05m – 0.72*$number of images or 17.61m for 2 images up to 3.21m for 22 images. In other test areas the dependency of the accuracy upon the number of images is not so clear.
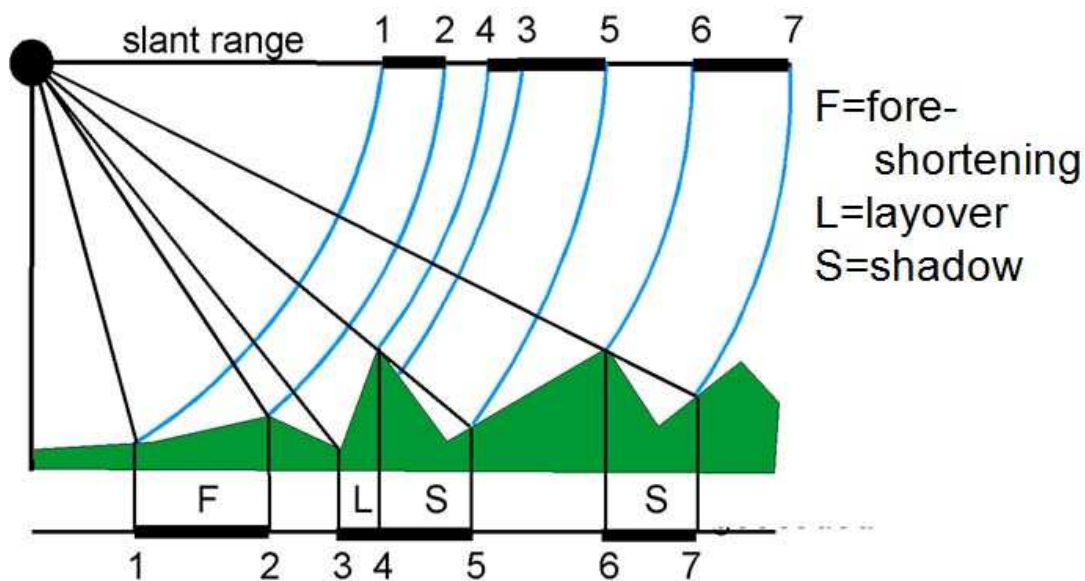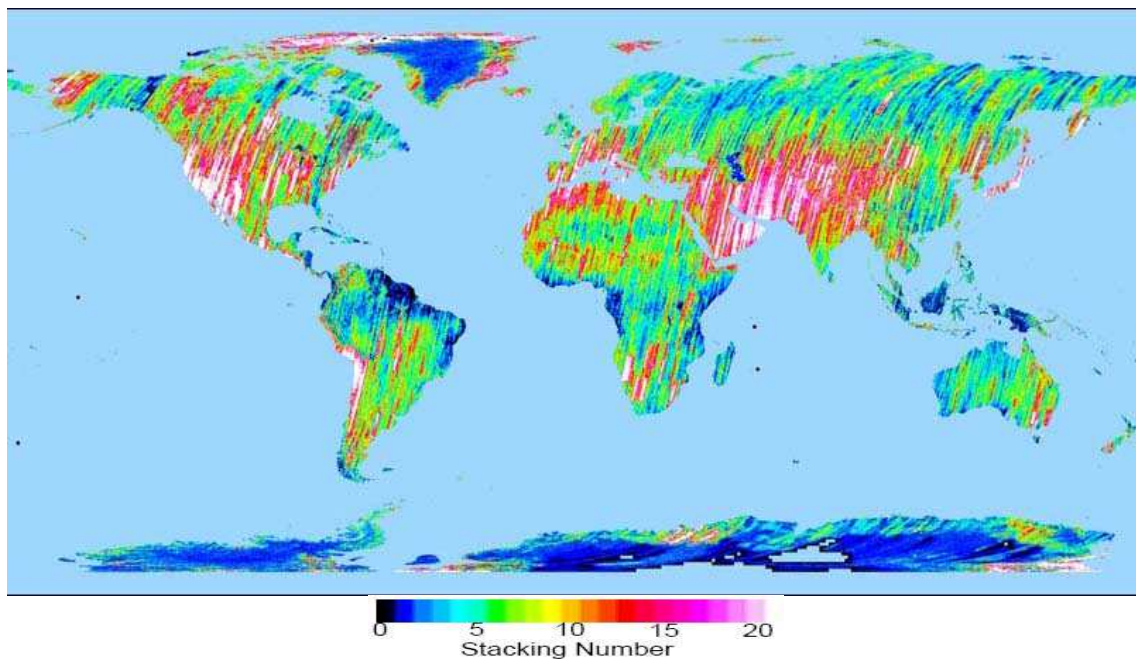

Figure 8: Slant range geometry of SAR

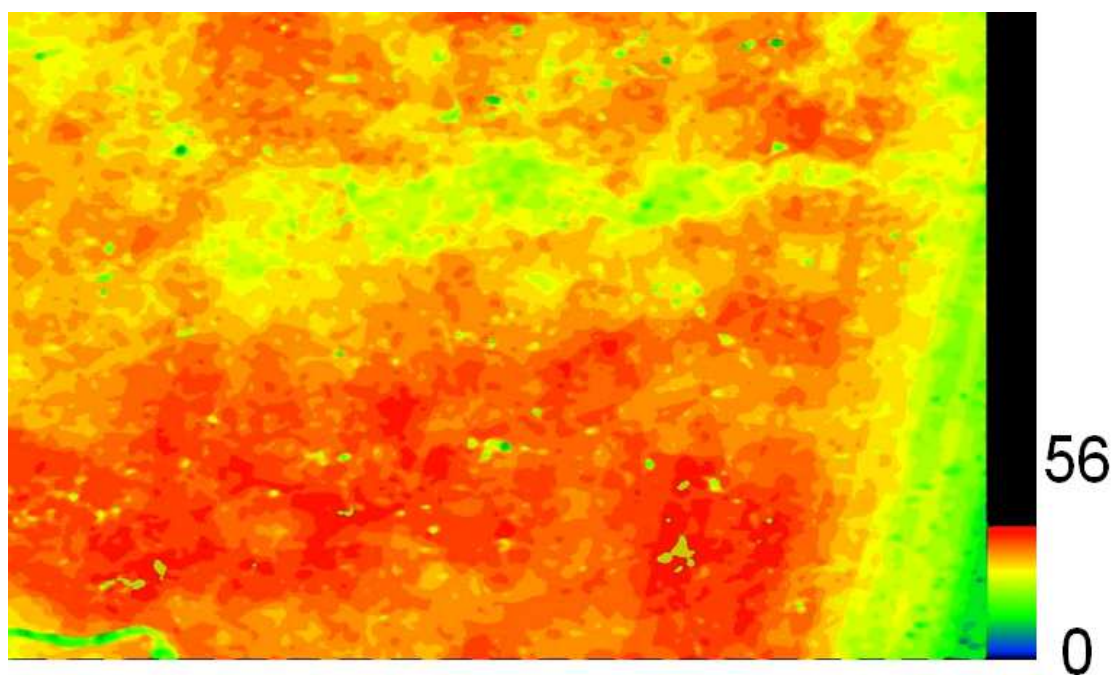Figure 9: Number of images/object point used for ASTER GDEM

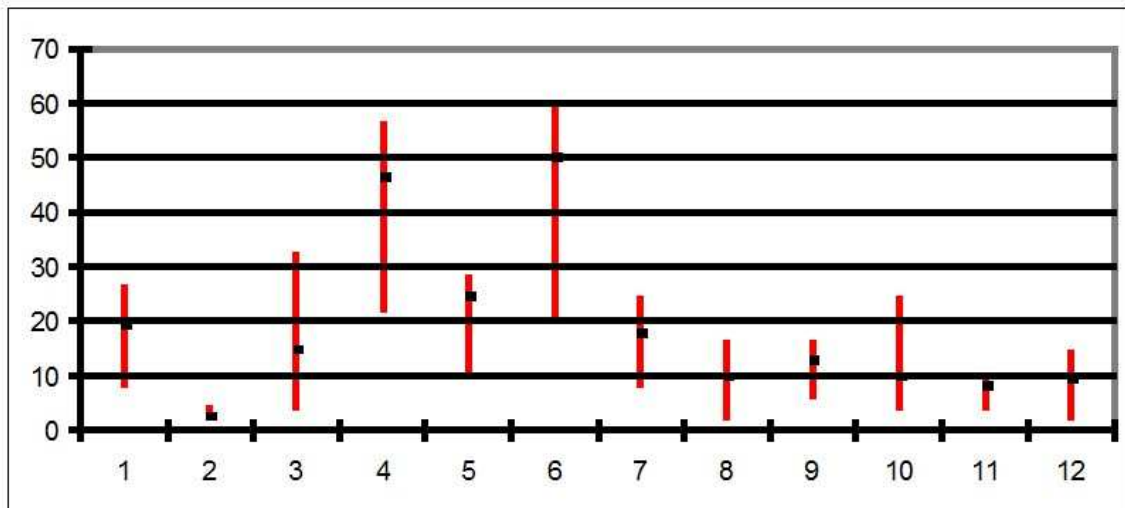Figure 10: Color coded number of images used for ASTER GDEM in test area Pennsylvania

Figure 11: Variation of number of images/object point in 12 ASTER GDEM test areas – in average 24.8 images/object point

It is the question, what is the height accuracy. Figures 12 up to 15 present different results of the point heights, 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. 12) are influenced by shifts in all 3 coordinate components. The standard deviations in fig. 13 do not differentiate between open areas and forest as well as the dependency upon the terrain inclination. In figure 14 the standard deviations for the open areas and flat parts are shown. Figure 15 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.
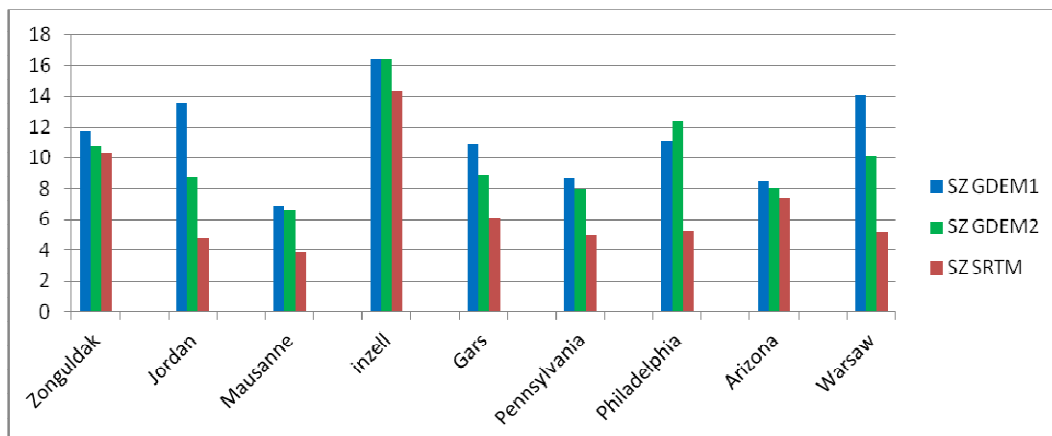

Figure 12: Root mean square differences of original data against reference data [m] (absolute standard deviation), RMSZ over all test areas: GDEM1: 11.66m, GDEM2: 10.38m, SRTM: 7.60m
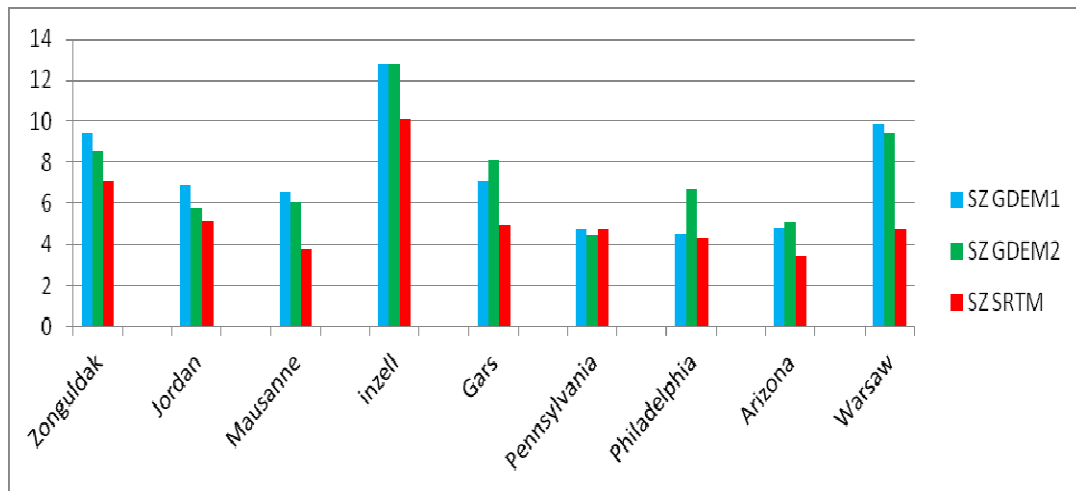
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Figure 13: Standard deviation of height after shift correction (relative standard deviation),
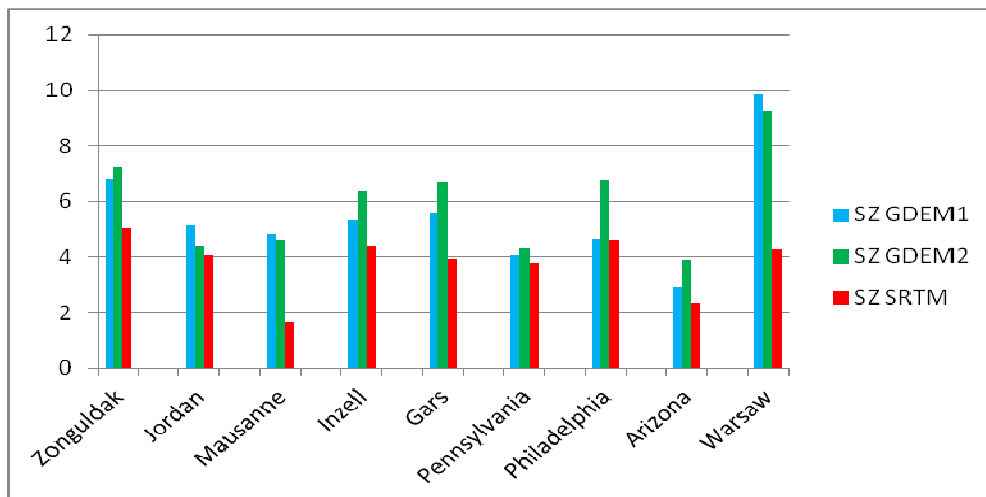SZ over all test areas: GDEM1: 7.88m, GDEM2: 7.85m, SRTM: 5.69m

Figure 14: Standard deviation of height after shift correction for flat and open areas,
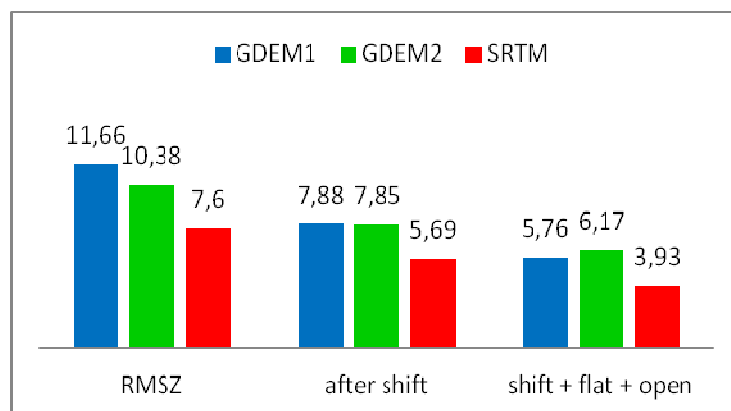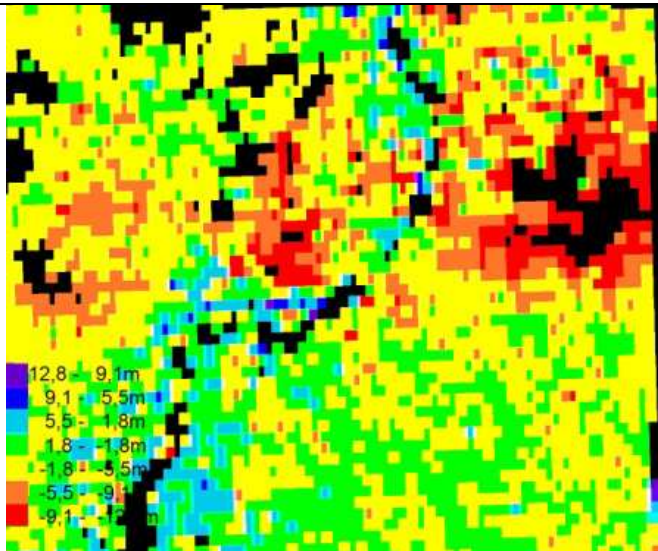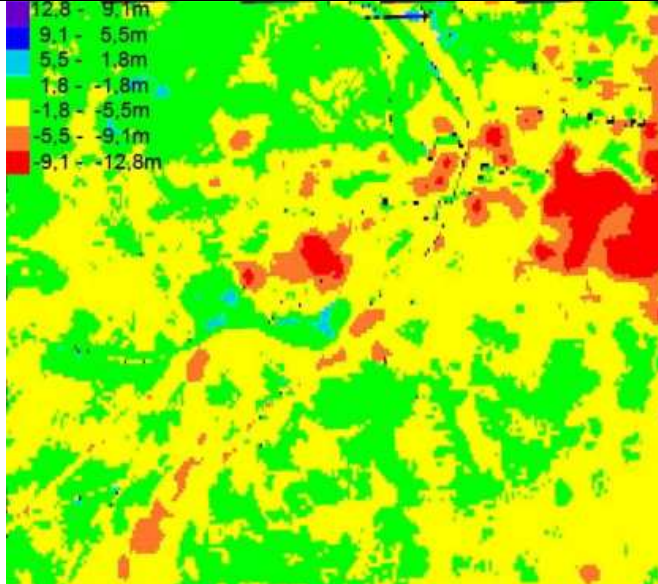SZ over all test areas: GDEM1: 5.76m, GDEM2: 6.17m, SRTM: 3.93m
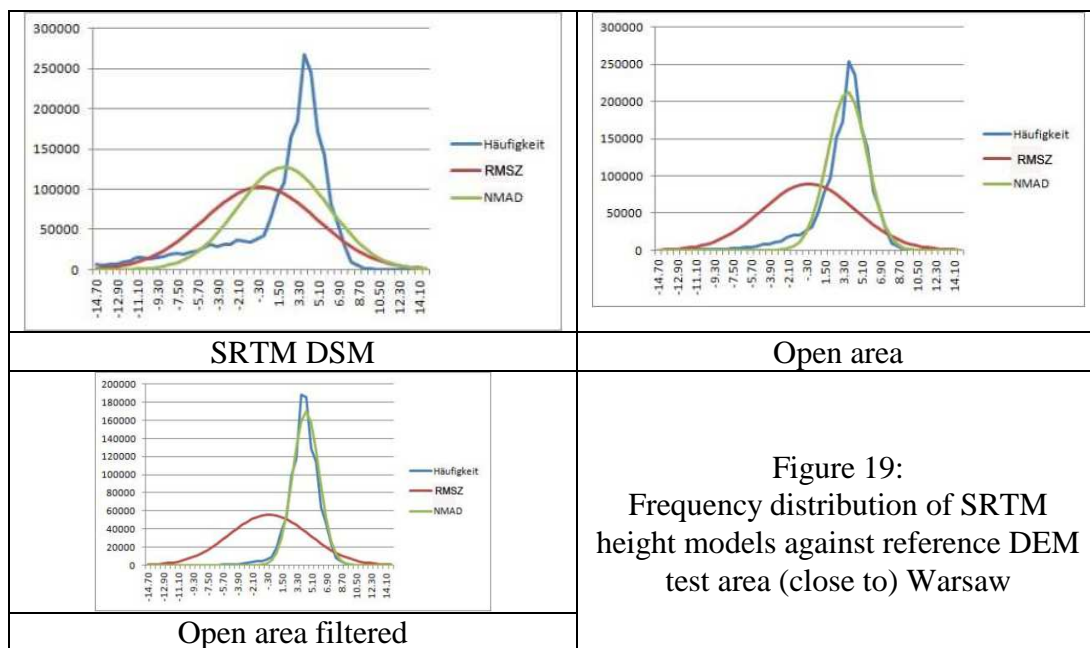

Figure 15: RMSZ / SZ average of all used test areas

Figure 16: Differences of original SRTM DSM without gap filling against reference DEM – Philadelphia city

Figure 17: Differences of ASTER GDEM2 against reference DEM – Philadelphia city

Figure 18: Google Earth of the same area – Philadelphia city

In general NMAD in flat and open areas is approximately 10% below SZ and in mountainous and forest areas up to 50% smaller.

The examples of the differences between SRTM DSM respectively ASTER GDEM2 and the reference DEM in figures 16 and 17 highlight some of the problems of these height models. Both are DSM with the height of the visible surface. The down town area on right hand side and in the center are shown in red color (above 9.1m height differences) caused by the buildings located above the bare ground. The original SRTM DSM has some gaps (shown in black) caused by radar layover and on the river. Such gaps are not present at ASTER GDEM2. The standard deviation of SRTM is 4.1m while it is 6.7m for ASTER GDEM2. This does not mean, that SRTM is better it only has gaps in the areas with larger discrepancies.

SRTM DSM	Open area
	Figure 19: Frequency distribution of SRTM height models against reference DEM test area (close to) Warsaw
Open area filtered	

The frequency distributions of the SRTM height models (figure 19) against a reference DEM show also some typical effects. In this case SRTM has a bias listed in table 3. In the SRTM DSM small forest areas included causing an asymmetric distribution (upper left). If the analysis is reduced to the open areas, there are still some single trees and buildings included, nevertheless the normal distribution based on the NMAD is not a bad description of the frequency distribution. This becomes better if the DSM is filtered to a DEM (lower left). In this case the normal distribution based on the NMAD and shifted by the bias fits satisfying to the frequency distribution of the discrepancies. The normal distribution based on SZ and not shifted by the bias does not describe the frequency in a satisfying manner.

	RMSZ	bias	SZ	NMAD
SRTM DSM	5.07	2.05	4.63	4.11
Open area	4.56	3.75	2.59	1.91
Open + filtered	4.83	4.47	1.84	1.59

Table 3: accuracy figures for SRTM DHM Warsaw [m]

The large values for the accuracy figures in table 3 are caused by small forest parts. For the open area there is still a larger discrepancy between SZ and NMAD, which becomes smaller in the case of filtered height data. In general the relative height accuracy of the SRTM-data in the Warsaw test area are very good.

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 DSM by theory should be more precise as the SRTM C-band DSM, but the C-band DSM 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 an important advantage against the 3 arcsec of the SRTM C-band DSM.

REFERENCE 3D

Large parts of the world are covered by Reference 3D, based on SPOT 5 HRS stereo models (figure 20). They are not free of charge, but have the advantage of a point spacing of 30m, partially distributed with 20m spacing. 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 RMSZ=5m to 9m. The root mean square height differences after bias correction for open areas is in the range of SZ=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 has a spectral range from 0.48µm up to 0.70µm wavelength that means only the very first part of infrared is included, causing problems for image matching in forest areas where the dominating reflection is in the infrared range. 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); reverse several SRTM gaps have been filled with HRS DSMs.
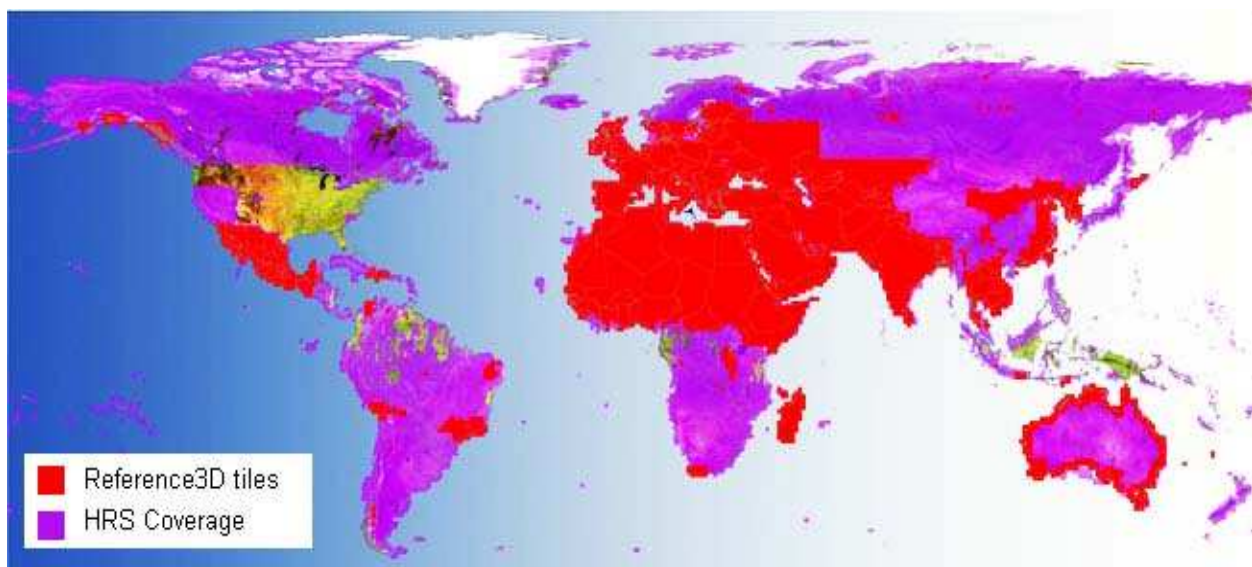

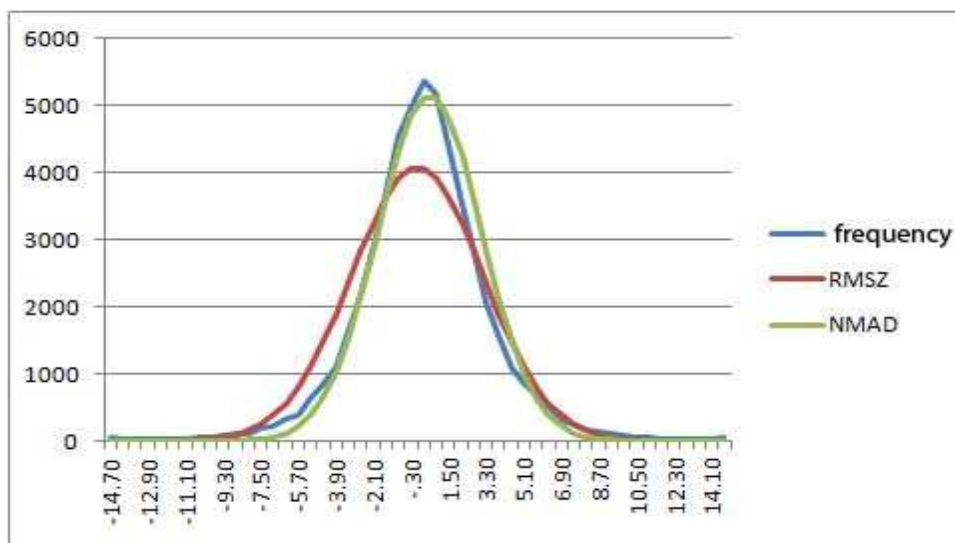Figure 20: Coverage by Reference 3D and SPOT-5 HRS images

Figure 21: Frequency distribution of Reference 3D in open areas, test field Black Sea

The frequency distribution of the height discrepancies in the test area Black Sea (figure 21) has the typical shape. In the open areas the distribution of the height discrepancies is expressed very well by the normal distribution based on NMAD. In this case Reference 3D has a very good accuracy in the open areas of SZ=3.1m and NMAD=2.5m, even LE90 reaches 4.5m. With 0.59m the bias of this height model is limited. As it is also shown in figure 21, Reference 3D is filtered for large discrepancies, so the normal distribution of Reference 3D data usually does not show a higher number of larger discrepancies as it is the case for other height models.

CARTOSAT-1

As shown by figure 22, nearly the whole world is covered by Cartosat-1 stereo pairs. In some areas (red in figure 22) several Cartosat-1 stereo pairs are available for the same area.
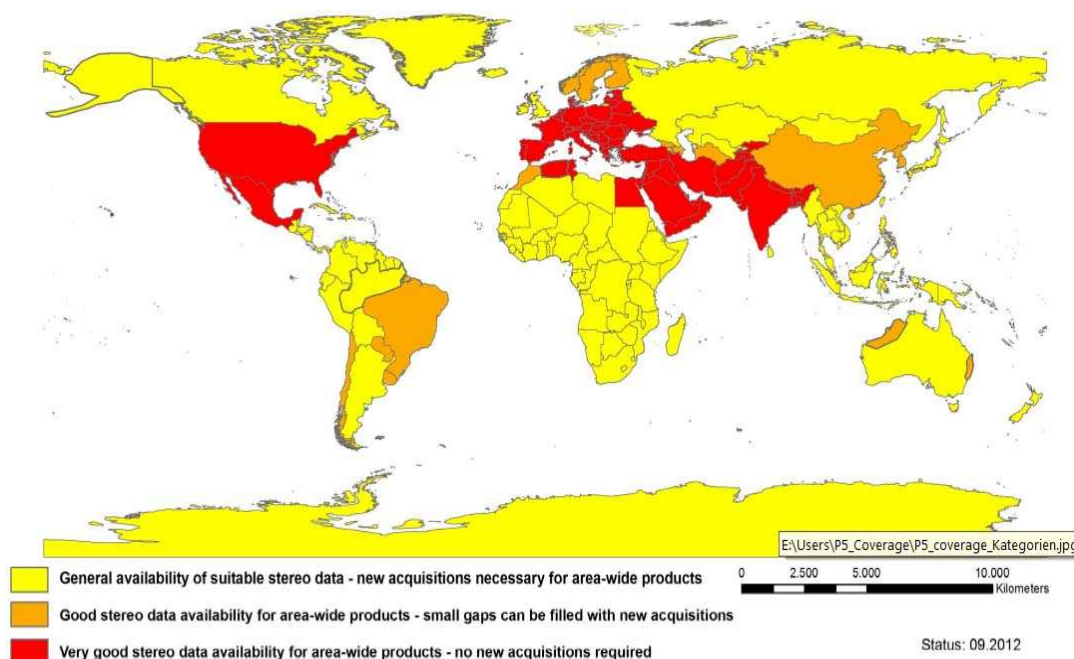

Figure 22: coverage by Cartosat-1 stereo scenes

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Cartosat-1 has 2.5m GSD, corresponding to this, the system accuracy as usual is one GSD in the height, corresponding to SZ=2.5m or NMAD 2.2m. The system accuracy is available for open and flat areas and a scene orientation based on ground control points. For usual terrain the standard deviation is in the range of 4m. The accuracy of the direct sensor orientation of Cartosat-1 even after calibration is not better as 100m. If no ground control points are available, Cartosat-1 height models can be geo-coded by means of the SRTM-height model. The absolute accuracy of the SRTM height model is in the range of 3m (figure 23), satisfying very often as reference for other height models.
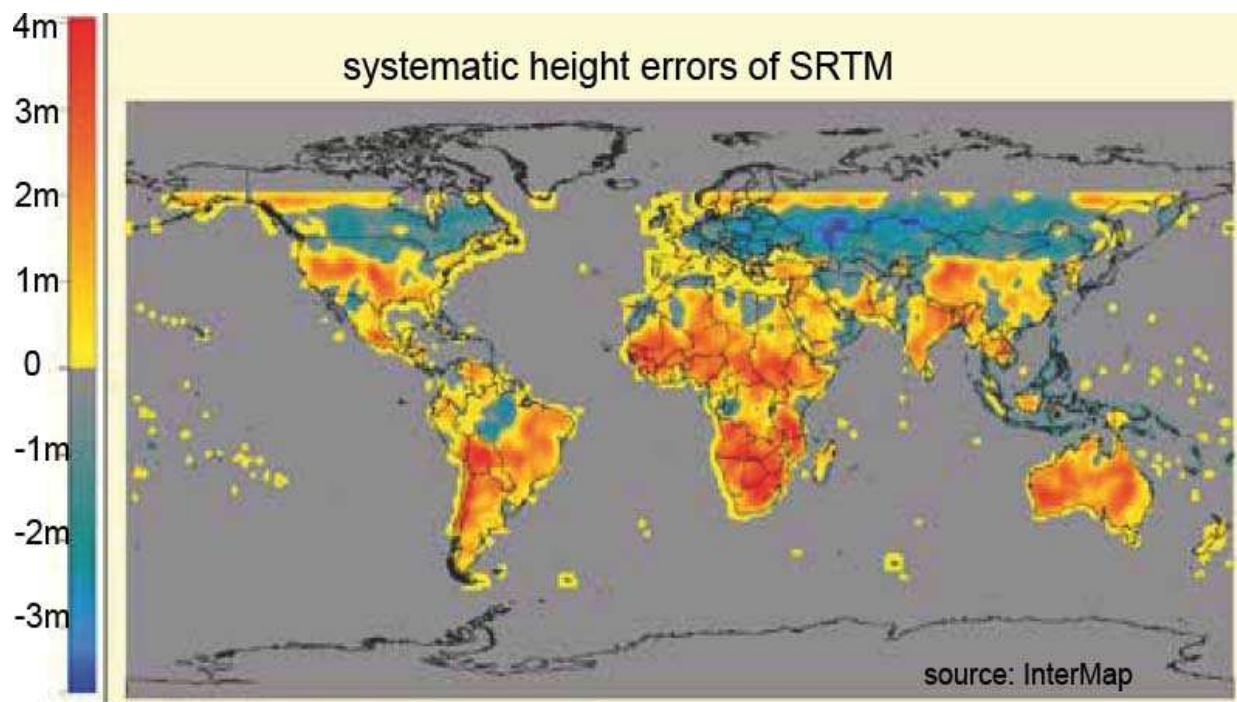

Figure 23: systematic height differences of SRTM DHM determined by height profile points of ICESat-data source: Intermap

NextMap World 30

The private company Intermap generated with a combination of the SRTM DSM with 3 arcsec spacing, ASTER GDEM-2 with 1 arcsec spacing and GTOPO30 for the polar regions with 30arcsec a worldwide height model with 1 arcsec spacing. The systematic positional errors have been improved by ICESat height profile points having accuracy in the range of 0.1m up to 0.2m. The morphologic details of ASTER GDEM2 have been combined with the accuracy of the SRTM DSM improved by ICESat data. The height models have been determined for blunders and gaps have been filled with other data. Meta data include information about the used input data. Intermap specifies the NextMap World 30 DSM in the average with 5m standard deviation. Water areas have been flattened and the height of the oceans is 0m.

TanDEM-X Global DEM

The German radar satellite TerraSAR-X has been launched 2007, since 2010 the identical TanDEM-X is available. Both satellites are flying since 2011 in a so called Helix configuration with a base component across the orbit of approximately 200m up to 400m (figure 24). This is an optimal configuration for height determination by Interferometric Synthetic Aperture Radar (InSAR).
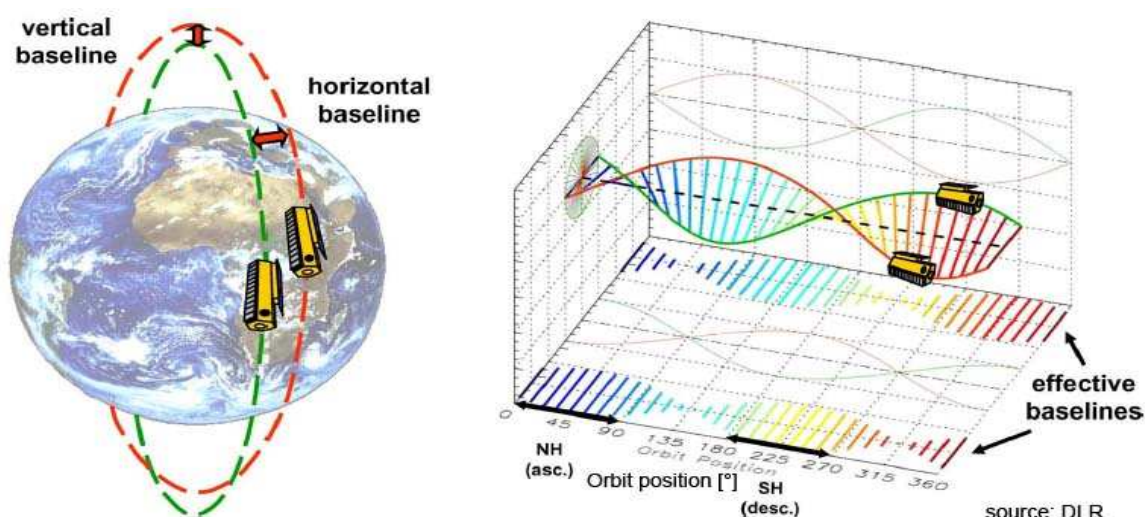
Figure 24: Helix orbit configuration of TanDEM-X

The first coverage of the whole world by TanDEM-X has been completed, now a second coverage is flown together with a repeated coverage in difficult areas as mountains and densely built up areas. With the repeated coverage the bottle neck of radar by layover shall be reduced.

The TanDEM-X Global DEM is specified with an absolute height accuracy LE90 < 10m and a relative accuracy within the tiles of 1° x 1° of LE90 < 2m, corresponding to RMSZ < 6m and SZ < 1.2m for terrain with inclination below 20%. For terrain with an inclination above 20% LE90 is specified with 2.4m. The grid spacing will be 0.4 arcsec, corresponding to 12m at the equator. On special request FDEM and HDEM are offered with 0.2 arcsec spacing (6m at the equator).

As usual with the X-band radar a DSM will be generated – the X-band radar only penetrates the vegetation slightly depending upon the incidence angle (figure 25).
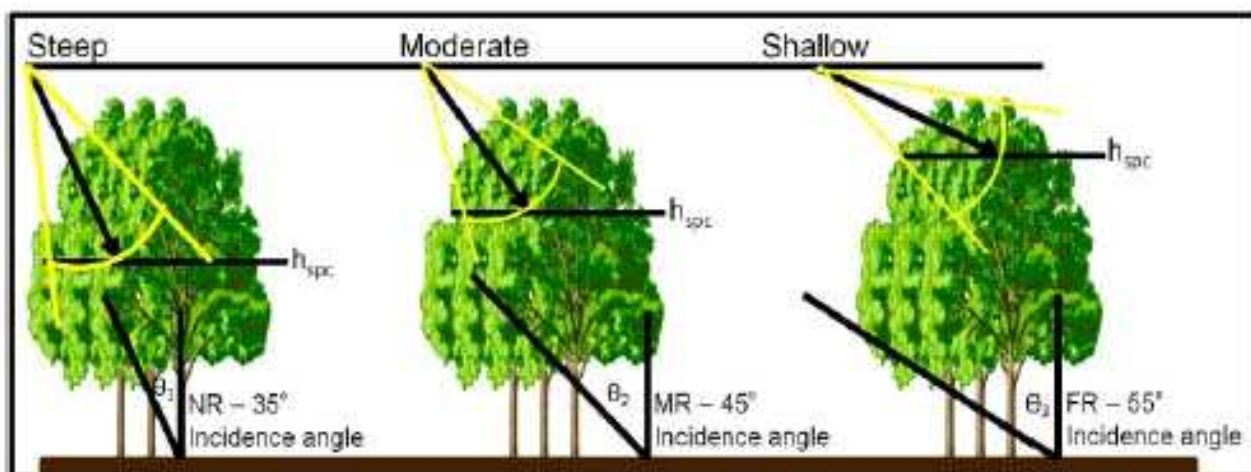

Figure 25: Penetration of X-band radar into canopy (Tighe et al. 2012)

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 caused by the orientation. 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 (figure 25). Figure 26 shows, that directly neighbored points of ASTER GDEM2 in the test area Jordan have a standard deviation in height of 2.87m, while with 10 points distance (approximately 290m) the relative standard deviation with 4.48m is not so far away from SZ=4.88m for the whole scene.
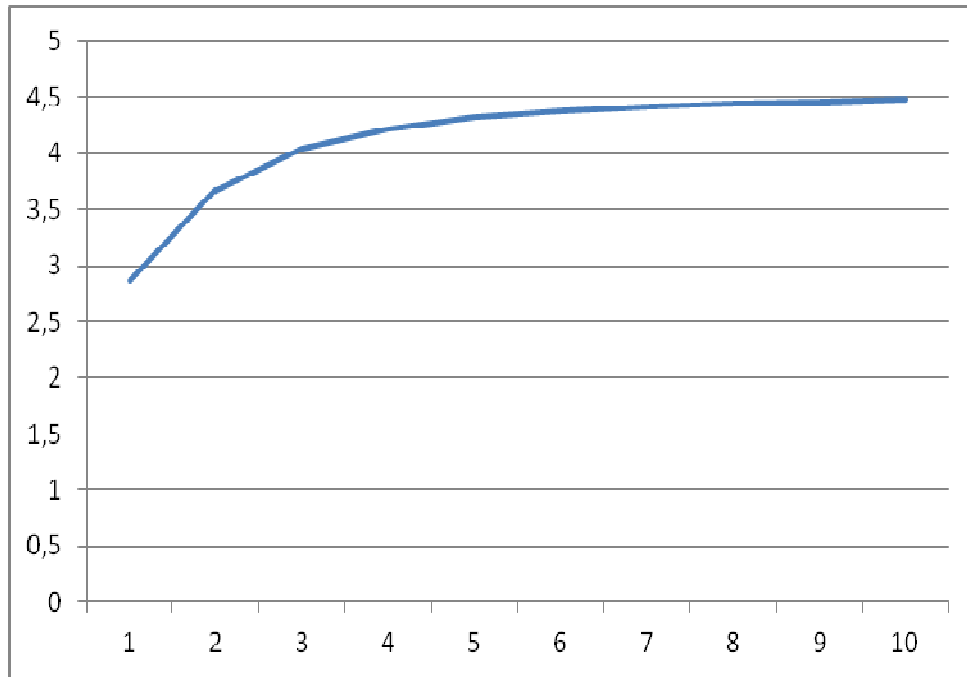

Figure 26: Relative standard deviation of Aster GDEM2 in test area Jordan   Horizontal: point distance [0.1 arcsec] Vertical: relative standard deviation [m]

Visually the relative accuracy can be seen with the details of contour lines. Figure 27 demonstrates the resolution of the different height models with a part of the test area Zonguldak. The reference model has 10m point spacing, showing any details; the contour lines of the SRTM X-band data with effective 27m spacing are 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 details of the contour lines to 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 obvious improvement of the ASTER GDEM-resolution is also stated in Tetsushi et al. 2011.
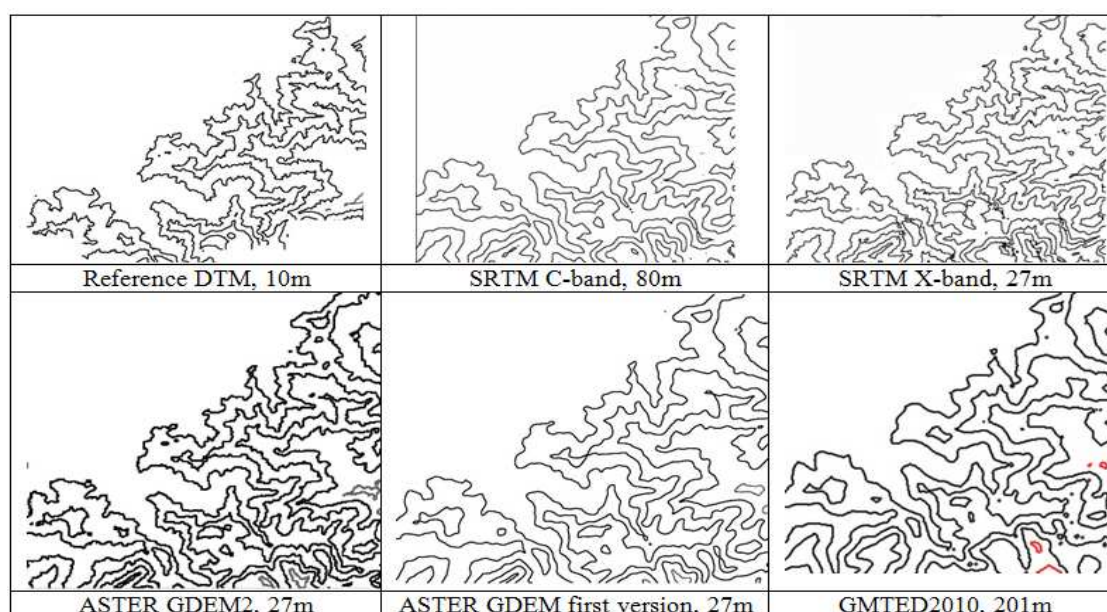
Figure 27: contour lines based on different height models

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 relative 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 for parts, 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 is not so much affected by large errors. 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. NextMap World 30 combines advantages of SRTM and ASTER GDEM2 together with an improved orientation, but it is not free of charge. In 2014 with the TanDEM-X Global DEM we will have a clear improvement against the existing large area covering DHM based on space information with the resolution and the accuracy. Nevertheless individual height models based on very high resolution space images with 0.5m GSD are with the system accuracy of 1.0 GSD for the height still better, but the generation is more expensive.

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. For the

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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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