Performance of Large Area Covering Height Models

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Abstract. Digital height models (DHM) are a basic requirement for several applications. The generation of DHM is time consuming and expensive, but several large area covering height models are available free of charge or commercially. For practical use it is important to have some information about the quality, as accuracy, accuracy characteristics, areas with problems, height definition as digital surface model (DSM) or digital terrain model (DTM) with heights of the bare ground, resolution (point spacing), homogeneity and availability.

The free of charge available height model from the SRTM mission is well known and dominating up to now. It has been improved to different versions as by gap filling and spike removal and different products by merging with other data as in case of the ACE2 corrected by radar altimeter data. The point spacing of 3 arcsec has been improved by merging with the also free available ASTER GDEM2 to the commercial NEXTMap World 30 with 1 arcsec point spacing. ASTER GDEM2 has some problems with homogeneity caused by varying number of images used for the individual heights; nevertheless it is better as the GMTED2010 with 7.5 arcsec spacing, which replaced the GTOPO30. ETOPO1 is just limited to 1 arcmin point spacing. For 2016 ALOSworld DEM, using all usable ALOS/PRISM images, is announced with 5m spacing, which may change the situation.

Commercial height models as Elevation 30 based on SPOT 5-HRS, NEXTMap determined by airborne InSAR, Euro-MAPS 3D, based on Cartosat-1 and WorldDEM based on TanDEM-X have advantages in point spacing and accuracy. WorldDEM seems to dominate the commercial versions in future.

The characteristics and accuracy of the different height models are described to allow a selection corresponding to the individual requirements.

Keywords. DHM, optical satellites, InSAR, accuracy, characteristics

1. Introduction

Height models can be generated with aerial and space optical stereo pairs, based on synthetic aperture radar (SAR) and by LiDAR. Terrestrial survey and UAVs are in use only for small size projects. Independent upon the source, the generation of height models is time consuming and expensive. The use of existing free of charge or commercial height models may be an alternative. It has to be checked if the quality, determined by geometric relative and absolute accuracy, the accuracy dependency upon terrain slope and aspects of such height models fulfill the project requirements. In addition the information contents or morphologic accuracy, dominantly specified by the point spacing, is important as well as the definition as DTM or as DSM. Also the homogeneity, support by error map, actuality, percentage of blunders, special advantages and disadvantages, limitations in special areas as cities, steep mountains or deserts as well as required post-processing have to be taken into account.

In general the coverage of large areas by optical stereo pairs takes more time as by SAR, penetrating clouds. For very large areas stereo satellites are required or interferometric SAR (InSAR) constellations. Optical images have the advantage of better details, but they require satisfying light conditions as well as object contrast, while SAR or InSAR is influenced by foreshortening and more by viewing shadows as optical images. Finally each method has it advantage and disadvantage.

Height models from survey administrations are usually DTM, not often updated, nevertheless the request for DSM is growing. The reference of the DHM as ellipsoidal or geoid height has to be respected, but a transformation based on geoid is simple, for this EGM1996 or the actual version EGM2008 can be used.

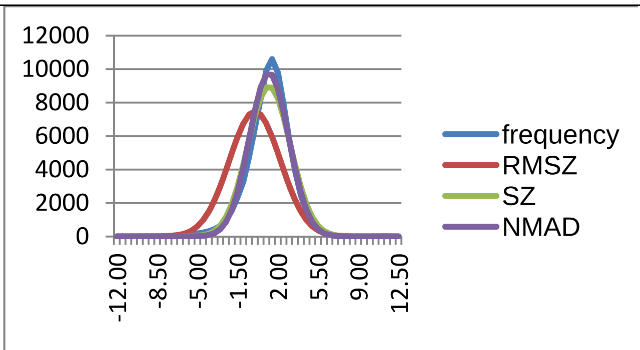
2. Accuracy figures

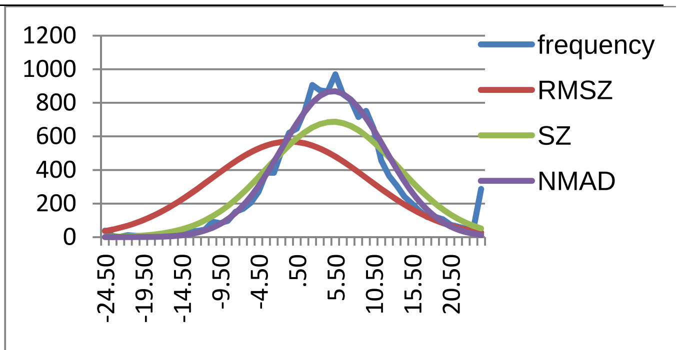
The expression "accuracy" for DHM is not unambiguously, different accuracy figures are used, so in any case the used accuracy figure has to be specified.

abbreviations	definition
RMSZ	Square mean of discrepancies
SZ	Square mean of (discrepancies – bias)
MAD	Median absolute deviation (linear) - 50% median value
NMAD	Normalized median absolute deviation - 68% median value
LE90	Threshold including 90% of absolute values of discrepancies
LE95	Threshold including 95% of absolute values of discrepancies

Table 1: accuracy figures

The threshold values LE90 and LE95 are used often for height models, but they are just depending upon the largest 10%, respectively 5%, of discrepancies and have no statistical justification. These threshold values should be avoided. RMSZ does not respect the bias as the standard deviation SZ. Both values are based on the square sum, so large discrepancies are dominating the values. In the case of normal distributed discrepancies NMAD and SZ are identical. In reality NMAD usually is smaller as SZ because in most cases more large discrepancies are available as corresponding to normal distribution caused by not respected dependency upon the terrain slope and not clear separation of blunders. Usually the normal distribution based on NMAD describes the frequency distribution of the height discrepancies quite better as the normal distribution based on SZ (see figure 1), by this reason NMAD should be preferred against SZ. The shown TanDEM-X frequency distribution (figure 1) are based on filtered height points causing a better fit of SZ in relation to NMAD while the ACE-data are not filtered and a higher percentage of larger discrepancies is included, enlarging the square sum values while the linear NMAD is not influenced as much. If the accuracy for a project has to be guaranteed, instead of LE90 also NMAD∗1.65 could be used as corresponding to the normal distribution.





TanDEM-X DHM against reference, Hannover	ACE2 DSM against reference, Pennsylvania

Figure 1: frequency distribution of height discrepancies together with normal distribution based on RMSZ, SZ and NMAD

3. Available height models

The first worldwide, free available height model was GTOPO30 based on data from different sources. The point spacing of 30 arcsec, corresponding to 926m at the equator, limited the information to just an overview and the accuracy was varying. This height model has been replaced by GMTED2010 with up to 7.5arcsec point spacing, corresponding to 231m. GMTED 2010 now mainly is based on SRTM-data. It is available in following versions: „minimum elevation“ (MIN), „maximum elevation“ (MAX), mean elevation (MEA), „median elevation“ (MED), “standard deviation of elevation” (STD), “systematic subsample” (DSC) and „breakline emphasis“. The reason for the different versions is not easy to understand – the version DCS fits better to reference data as the other. In the area covered by SRTM the vertical accuracy corresponds to SRTM, averaged for the sub-area, plus the influence of interpolation over 7.5 arcsec. Following standard deviations of the heights have been reached: test area Jordan SZ = 4.7m or as function of the terrain inclination: SZ = 3.7m + 5.0m ∗ tan(slope) or NMAD = 4.0m or NMAD=3.5m + 3.5m∗tan(slope) and in the mountainous Zonguldak: SZ = 8.7m or: SZ = 7.7m + 2.9m ∗ tan(slope) respectively NMAD = 5.9m or NMAD = 4.2m + 3.8∗tan(slope). The main difference against the SRTM height model is caused by the interpolation in the partially rough area, especially in Zonguldak.

Height model	*organization*	*source*	*range*	*spacing*
GMTED2010	USGS + NGA	mixed	global	7.5 arcsec
SRTM (C-band)	NGA+NASA	Shuttle InSAR	Latitude -56°to 60°	3 (1) arcsec
SRTM X-band	DLR	Shuttle InSAR (X-band)	Latitude -56°to 60° partially	1 arcsec
ACE2	ESA ESRIN Montfort University	SRTM+altimeter + other data	Latitude -56°to 60° remaining area other data sets	3 arcsec
ASTER GDEM-2	METI (Japan) + NASA	Optical ASTER stereo satellite	Latitude +/-83°	1 arcsec
NextMap World 30	Intermap	SRTM + ASTER	Latitude -56°to 60°	1 arcsec
Reference 3D	Airbus Defense and Space	Optical SPOT5 HRS	~ 40% of Earth land mass	30m
EuroMaps 3D	GAF + DLR	Optical Cartosat-1 stereo satellite	Some European and Near East countries + on request	5m
NextMap	Intermap	Airborne InSAR	USA, European countries	5m
WorldDEM	Airbus Defense and Space + DLR	TanDEM-X InSAR	global	12m

Table 2: investigated large area covering height models

The most often used, free of charge available DHM is from the Shuttle Radar Topography Mission (SRTM) C-band with data acquisition over 11 days in February 2000 for the whole area from 56° southern up to 60° northern latitude. The USGS made the DHM with 3 arcsec point spacing available in 2003. Only for the United States the original point spacing of 1 arcsec, corresponding to 31m at the equator, can be used without special arrangement. The original voids in mountainous areas, on water bodies and dry sand deserts of approximately 0.15% later have been filled with other data. The version 2 with void filling is available since 2005 and the version 2.1 since 2009. SRTM is a

DSM because the C-band radar cannot penetrate the vegetation. In not too dense forest areas the height level is approximately 1/3 of the vegetation height below the canopy.
Parallel to the SRTM C-band also X-band InSAR was operated by Germany and Italy. The X-band did not use the scan-SAR mode, so it does not cover the whole area (figure 2). The DSM based on SRTM X-band is available free of charge from the DLR with a point spacing of 1 arcsec. A serious of tests showed that the accuracy of the C-band DSM and the X-band DSM are approximately the same. The X-band has more morphologic details as the C-band, but the X-band DSM is only available partially (figure 2).

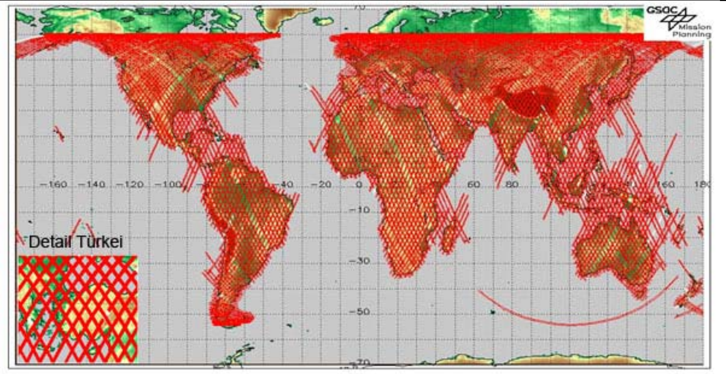


Figure 2: coverage by SRTM X-band DSM shown in red

Supported by the European Space Agency (ESA), ESRIN the SRTM height model has been corrected by satellite radar altimeter data from ERS-1, ERS-2, EnviSat and TOPEX (Smith and Berry 2011). The altimeter data reached the bare ground, enabling the change of the SRTM-data from a DSM to a DTM as Altimeter Corrected Elevation 2 (ACE2) Global Digital Elevation Model (GDEM). The ACE2 GDEM with a spacing of 3 arcsec is available free of charge in the WEB (http://tethys.eaprs.cse.dmu.ac.uk/ACE2/login).

The ASTER GDEM DSM is based on all usable images taken by the Japanese optical stereo sensor ASTER (Tetsushi 2011). It is covering the latitude range from -83° up to +83°. In the first version the three-dimensional shifts of the individual height models have not been respected, causing a loss of morphologic quality. By this reason an improved version, the ASTER GDEM2 has been generated and is available free of charge since 2011. ASTER GDEM2 is a product of the Japanese METI and the US NASA (http://www.gdem.aster.ersdac.or.jp/login.jsp).

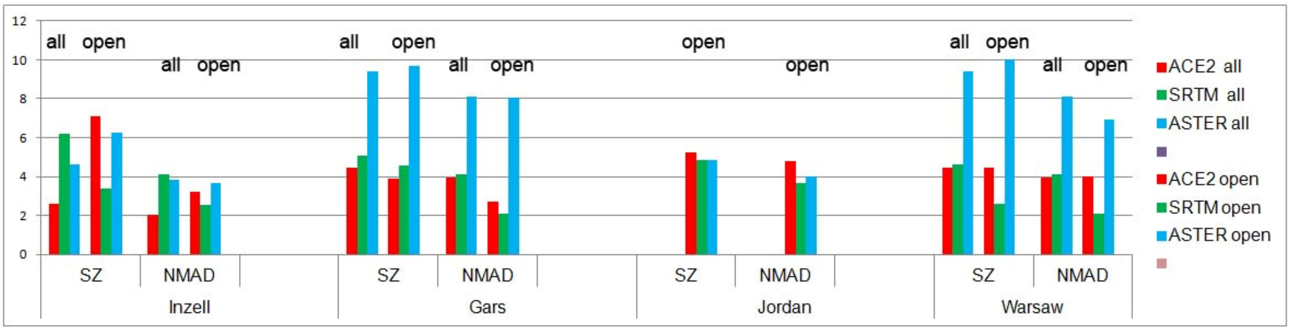


Figure 3: comparison of ACE2, SRTM and ASTER in 4 test areas

Figure 3 shows some typical results of the ACE2, SRTM and ASTER GDEM2 height models in relation to reference DTM. ACE2 shall be a DTM based on the corrections by satellite radar altimeter data. Figure 4 demonstrates that in the altimeter profiles this is the case, but between the profiles ACE2 remains to be a DSM. In addition in the open areas (no forest, no built up areas), as obvious in figure 3 and table 3, some not correct changes occurred, raising the discrepancies against the

original values. This was confirmed by other test areas. In the forest areas ACE2 has been improved against SRTM, but not in the other parts.
In the test area Warsaw between 2 and 16 stacks (number of images used for the height determination of the individual height values) with larger areas just covered by 2 or 4 stacks (figure 5). This results in a dependency of the standard deviation from the stacks with: SZ = 17.16m -.856 ∗ stacks, explaining the poor results of ASTER GDEM2 in the Warsaw test area. As average of 12 test areas a dependency of SZ = 8.8m – 0.06 ∗ stacks has been found.

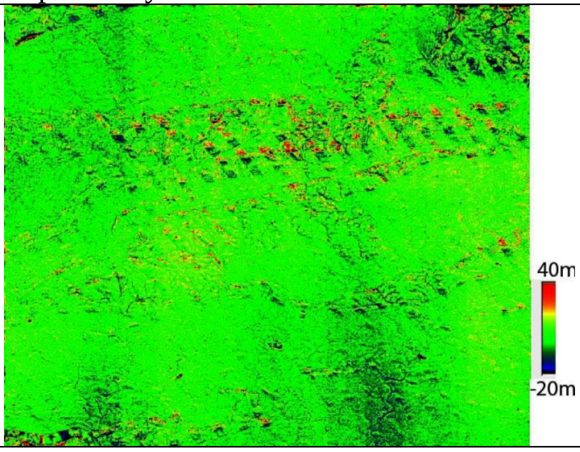


Figure 4: height difference ACE2 GDEM against reference DTM, Pennsylvania

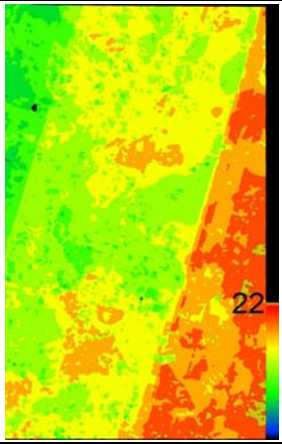


Figure 5: number of stacks used for ASTER GDEM2 in Warsaw test area

Height model	SZ all	SZ flat area	SZ open area
SRTM X-band	5.6m	5.1m	3.6m
ASTER GDEM2	8.2m	6.7m	5.8m
ACE2	4.2m	4.0m	5.2m

Table 3: average of standard deviations from 12 test areas

In general the accuracy of the SRTM DSM is better as for ASTER GDEM2, strongly dependent upon the number of used stacks, but with better resolution of 1 arcsec, while ACE2 leads to an improvement in forest areas, but the corrections are not optimal – this version needs an improvement.

NextMap World 30 is a commercial version fusing SRTM 3arcsec data with ASTER GDEM 1arcsec data, keeping the accuracy of SRTM and improving it with the better morphologic details of ASTER GDEM2. The NASA is just working at a similar height model under the name NASADEM or SRTM v4.1 (Buckley 2014), but up to now it is not decided if this height model will be available with point spacing of 1 arcsec.

Reference 3D, based on the stereo combination HRS on SPOT 5, can be bought with 1 arcsec point spacing from Airbus Defense and Space (Airbus DS) (former ASTRIUM). It is available for approximately 40% of the world land mass, but on request it can be generated also for the remaining area. This height model has no problems with lay over as InSAR height models, but it requires object contrast which is difficult in forest areas because the spectral range of HRS does not include near infrared in a satisfying extend. The advantage in mountainous areas against SRTM is the reason for use of it for SRTM gap filling, reverse SRTM is also in use for gap filling in Reference 3D. In general Reference 3D is slightly better as the SRTM height model (Jacobsen 2004) in addition to higher point spacing of 1 arcsec.

The company GAF in Munich in cooperation with the German Aerospace Center (DLR) created the EuroMap 3D with images of the optical stereo system Cartosat 1, having 2.5m GSD. The system accuracy officially is announced with SZ<<5m, SX=SY=5m, but the relative accuracy is in the range of SZ=2.5m and NMAD=2.2m for the DSM with 5m point spacing. This very accurate and detailed height model is available especially for most Western European countries, but it can be generated on request also for others with worldwide available Cartosat 1 images. For example it was generated within 3 month for whole Saudi Arabia. Of course the price corresponds to the quality.

The company InterMap determined height models by aerial InSAR covering Western Europe, USA, Malaysia and parts of Indonesia and Australia. For these areas DSM and DTM are available with 5m spacing. Caused by foreshortening and viewing shadows the quality in built up areas, mountains and forest are not as good as for the other parts. For this reason the height accuracy is specified as following: for 40% of the area SZ <0.6m, also for 40% SZ=0.6m up to 1.8m and for 20% SZ > 1.8m. The uneven accuracy is a disadvantage. In addition in Western Europe and the USA qualified height models of the survey administrations are available, limiting the importance of this height model.

A worldwide covering DSM by InSAR currently is generated based on the German TanDEM-configuration using the radar satellite TerraSAR-X, launched 2007, and the identical TanDEM-X launched in 2010. 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 required for high resolution (figure 6). The whole world has been covered twice from different directions and the difficult areas (red in figure 7) will be covered 4 times up to mid of 2014 with different base and view directions to reduce the effect of layover and viewing shadows. The yellow areas in figure 7 are dry sand deserts where the backscatter is poor.

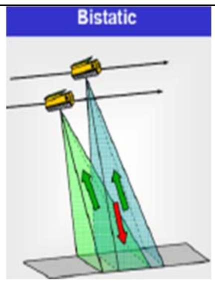
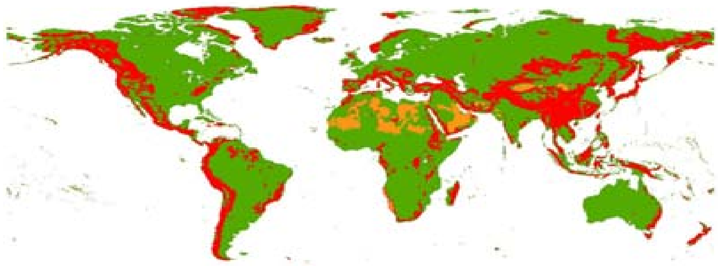
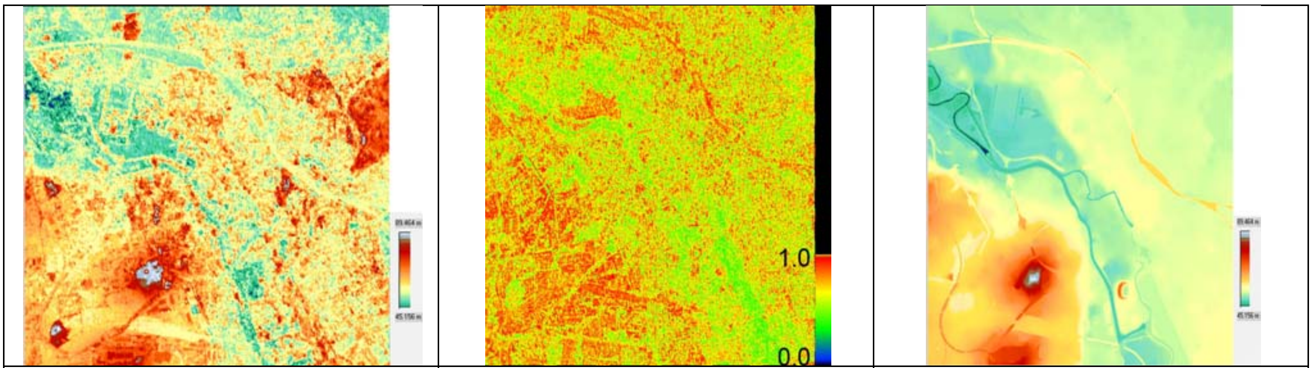
	

Figure 6: bistatic mode of TanDEM-C configuration	Figure 7: difficult areas of TanDEM-X InSAR red =mountainous, yellow= dry sand deserts source: Airbus DS

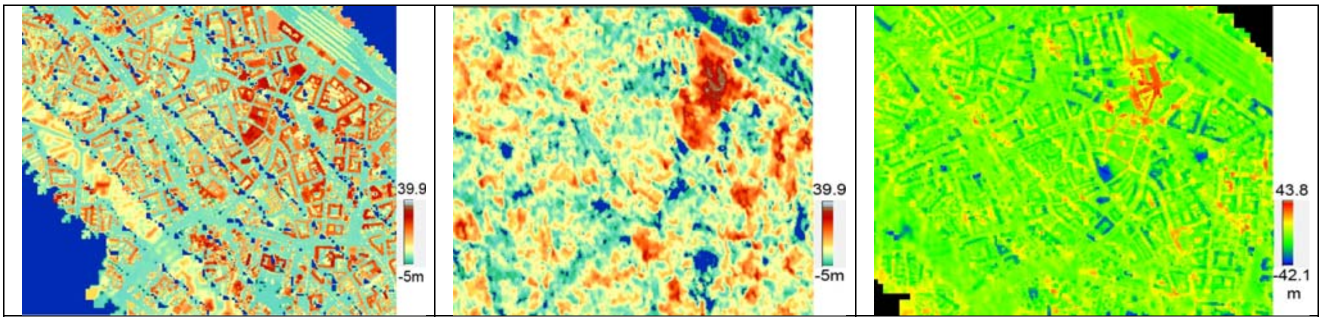
The first parts of the green areas in figure 7 are available via the distributor Airbus DS (former Astrium) at first as WorldDEM core – without editing and post-processing, later as WorldDEM^{TM}, edited for flattening of water bodies, improved shorelines and consistency flow of rivers. Later WorldDEM DTM will follow, including the height of the bare ground. WorldDEM is specified with relative CE90=2m (SZ=1.2m) within the handling unit of 1°∗1° (111^2km^2 at the equator) and the absolute CE90=4m (SZ=2.4m) for terrain inclination below 20%. Above 20% slope it is specified with twice the standard deviation. The absolute accuracy is better as originally announced. Together with the 0.4° point spacing, corresponding to 12m at the equator, this height model has a quality quite better as the other worldwide or nearly worldwide height models. The quality is related to the accuracy, morphologic details and homogeneity. On request later also height models with approximately 6m point spacing can be ordered.

A single TanDEM-X image combination was investigated in the city area of Hannover by generating the DSM with the commercial software ENVI SARscape (Sörgel et al. 2013) (figure 8). Of course here only one view direction has been used, enlarging the problems of layover and viewing shadows. In addition to the reference DTM from the survey administration also a LiDAR DSM is available for the difficult city area (figure 9 left).



DSM based on TanDEM-X | Quality image (covariance) | Reference DTM

Figure 8: DSM generation of a single TanDEM-X image combination



LiDAR-DSM | TanDEM-X DSM | Difference of both

Figure 9: analysis of DSM detail based on single TanDEM-X image pair

	RMSZ	bias	SZ	NMAD	LE90	LE95
TDX – reference DTM in open area	2.22	1.16	1.89	1.74	3.57	4.32
TDX – LiDAR DSM	4.26	3.01	3.02	2.28	6.48	8.44

Table 4: analysis of DSM based on single TanDEM-X image pair

The generated DSM (figure 8, left) shows the top of vegetation and buildings as obvious in comparison to the reference DTM from the survey administration (figure 8, right). With the used single image combination the street level could not be reached in Hannover city center with high buildings and partially narrow streets (figure 9). For this reason the accuracy level of WorldDEM could not be reached with the single TanDEM-X image combination (table 4). Nevertheless the DSM details are quite better as with the SRTM DSM with 3 arcsec point spacing and ASTER GDEM2 with 1 arcsec point spacing.

4. Future Developments

The NASA is working at a merged height model of SRTM and ASTER GDEM2 under the name of NASADEM or SRTM v4.1 (Buckley 2014). Up to now it is not decided if this height model will be available with 1 arcsec point spacing.

JAXA generates a worldwide DSM based on all usable ALOS/PRISM tri-stereo image combinations, supported by ICESat profile points. This DSM shall be available in March 2016 under the name ALOSworld DEM (Tadono et al. 2014, Takaku et al. 2014); it shall have 5m point spacing. First tests have root mean square height differences against a LiDAR reference DSM of approximately SZ = 1.6m + 5.0m∗tan(slope). This height model has the potential to replace the SRTM DSM because of better accuracy and morphologic details.

5. Conclusions

Some large area covering height models are available free of charge or in case of more details and higher accuracy commercially. From the free of charge available height models SRTM is dominating up to now. ASTER GDEM2 has more morphologic details, but the accuracy is lower as for SRTM and it is strongly depending upon the number of stacks used for the individual height values. This may change with ALOSworld DEM announced for 2016 having 5m point spacing and higher accuracy as SRTM.

The commercial height models will be dominated by the new WorldDEM based on TanDEM-X. The accuracy even is better as for most height models from the survey administrations. Of course at first only DSM can be ordered, but DTM is announced – here the accuracy has to be checked if it can be on the same level as for the DSM. Of course height models from high resolution optical stereo pairs taken from space have higher quality, but the higher quality has to be paid. Next Map, Next Map World 30 and Reference 3D will have problems to play a role beside this. Next Map World30 corresponds to the announced NASADEM, so it will not have a change beside this free of charge height model.

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