Evaluation of height models

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Abstract

Height models are a basic requirement for spatial data. For qualified use, it is necessary to have information about the geometric data quality. Several investigations of height models exist, but only very few are really qualified. It is not enough to determine just the accuracy for a terrain up to a threshold of 10% or 20% slope and above it, also shifts of the height model in X, Y and Z are required as well as more complex accuracy dependencies, higher degree systematic errors and the morphologic quality. Standard commercial programs usually do not allow a detailed analysis.
Several height models, based on LiDAR, aerial images, satellite images and satellite based Interferometric Synthetic Aperture Radar (InSAR) have been evaluated with specially developed programs. Reference height models with the same or a better accuracy have been used. The required detailed analysis and the achieved results for some typical height models are described.
Key words: evaluation, DSM, DTM, accuracy functions, systematic errors

1. Introduction

The quality of height models cannot be described just by one or two accuracy numbers. At first, different accuracy numbers are available, as Root Mean Square (RMS), standard deviation of the height (SZ), Median Absolute Deviation (MAD) and Normalized Medium Absolute Deviation (NMAD) and Linear Error with 90% (LE90) or 95% (LE95) probability; secondly, the accuracy depends on the terrain inclination and other parameters; at third, systematic errors exist, as constant height shifts and more complex systematic errors and at fourth, the relative accuracy – the accuracy of a height value in relation to the neighbored one – may not be the same as the absolute accuracy. In addition, also the horizontal accuracy of a height value has to be respected. In addition to the location accuracy, horizontal shifts of the height models are common. A height model may be a Digital Surface Model (DSM), describing the height of the visible surface or a Digital Terrain Model (DTM), describing the bare ground. A Digital Elevation Model (DEM), as general term for a height model, may be based on a raster of height data with optionally additional information as break lines or it may be based on randomly distributed height values, handled as Triangulated Irregular Network (TIN). The morphologic quality, describing the local variation of the terrain is important; it depends on the relative accuracy and the point spacing.
Nearly worldwide covering height models are available free of charge or commercially; their evaluations have been published. Especially the SRTM height model, based on InSAR, is used today as standard for several applications; it was investigated in detail, e.g. (Rodriguez et al. 2003, 143 pages). Also the improvement of SRTM to 1 arcsec point spacing (~30m) was

analyzed (Mukul et al. 2016). The ASTER GDEM2 DSM, based on all stereo combinations of the optical satellite ASTER, was investigated by (Tetsushi et al. 2011, Gesch et al. 2016). A strong improvement came with the ALOS World 3D (AW3D), based on all usable optical stereo combinations of ALOS PRISM having 2.5 m GSD (ALOS World DEM, http://alosworld3d.jp/en/). This was investigated by Tadono et al. (2014) and Takaku et al. (2014). From the commercial version AW3D with 5 m point spacing the free of charge version AW3D30 with 1 arcsec point spacing – approximately 30 m at the equator – is available and was analyzed by Tadono et al. (2014) and Takaku et al. (2014). As for the other height models a gap filling has been made with other height data. (Jacobsen 2016) gives an overview about the preceding listed height models and (Aldosari, Jacobsen 2019) are including also the following height models. The most homogenous and really worldwide height model is now available from the TanDEM-X InSAR which is commercially distributed as WorldDEM; it has been investigated in detail by the German Aerospace Center (DLR) (Rizolli et al. 2017, Wessel et al. 2018) and (Baade and Schmullius 2016). A reduced version of this is freely available as TDM90 with 3 arcsec point spacing (~ 90m).
DEM generation from aerial imagery is a standard process, described very often, so a naming of all references is not possible. As in all other areas of DEM generation the pixel wise Semi Global Matching (SGM) (Hirschmüller 2005 is used more often (Haala 2014)), especially in built up areas.
An overview about the ISPRS/EuroSDR benchmark test about the use of penta-cameras for 3D-evaluation is given in Gerke et al. 2016. The use of penta-cameras is growing. The complex matching of images with quite different view directions usually is based on Scale Invariant Feature Transform (SIFT) (Lowe, 2004). Penta-cameras often do not have very stable camera geometry, requiring an image orientation with self calibration for a satisfying ground coordinate determination (Jacobsen and Gerke 2016).
Similar it is with the Unmanned Aerial Vehicles (UAV), they also require a proper camera calibration and the matching usually is based on SIFT (Bakula et al. 2018). With UAV only small areas can be mapped opposite to the other methods. Commercial programs should be used for the orientation, allowing a block adjustment with self calibration and ground control points.
The height model determination by airborne LiDAR is a standard procedure based on calibrated systems with post-processing by commercial programs to compensate orientation uncertainties by overlapping flight lines and ground control points (Davidson et al. 2019).
InSAR from space allows the generation of height models for large area up to global coverage. The Shuttle Radar Topography Mission (SRTM) in 2000 was the first attempt to reach height accuracy, better as available for several national survey administrations by the classical methods. Now with the TanDEM-X Mission, available as commercial WorldDEM or with reduced spacing freely as TDM90, the accuracy and morphologic quality has been strongly improved (Rizolli et al. 2017, Wessel et al. 2018).
A number of benchmarks about DEM generation with the different methods exist (Bakula, Mills, Remondino, 2019).

2. Horizontal Accuracy and Improvement

Before the analysis of the vertical accuracy, the horizontal location of the height model has to be checked.

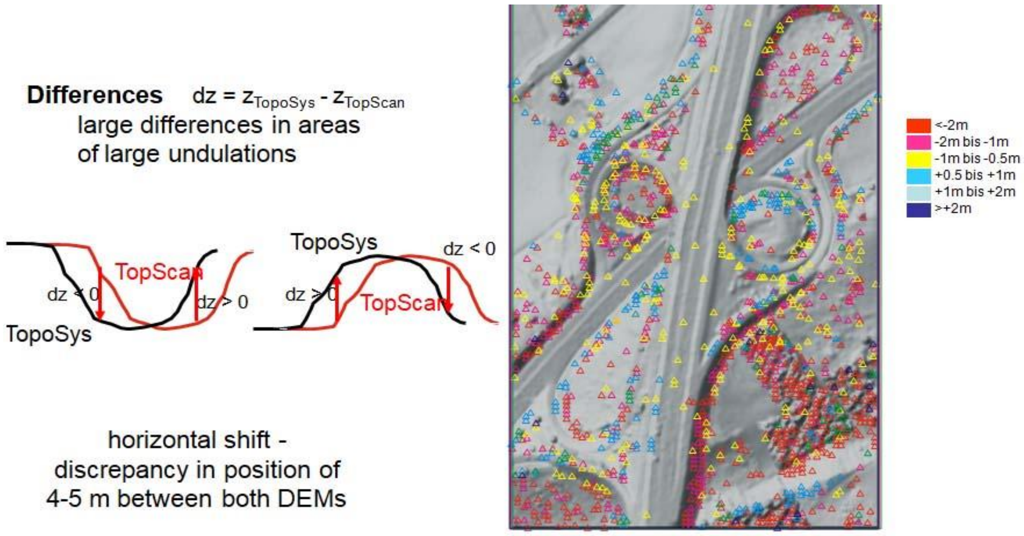

Figure 1. Horizontal shift between LiDAR height models

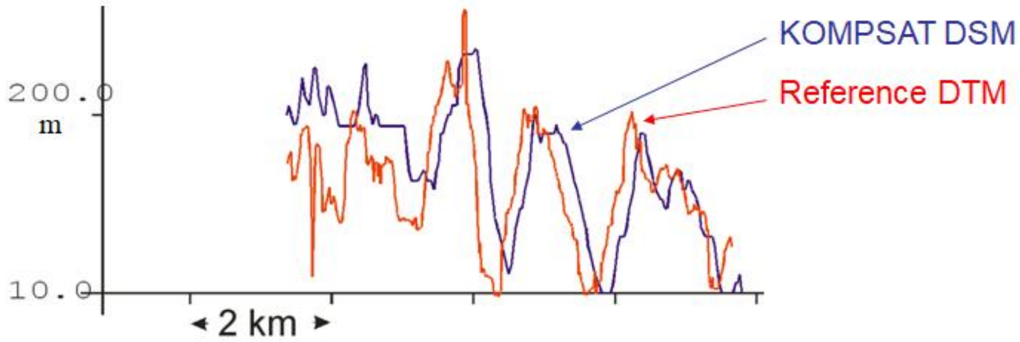

Figure 2. Horizontal shift between a DSM based on Kompsat-2 and the Turkish DTM

Horizontal shifts between height models are typical. In figure 1 a horizontal shift between two aerial LiDAR DTMs is shown. The horizontal shift of 4m up to 5m can be seen in inclined areas. The shift corresponds to DX=DZ / tan ax respectively DY=DZ / tan ay, with ax=slope in X-direction and ay=slope in Y-direction. Figure 2 shows a height profile of a DSM generated by images of the optical satellite Kompsat-2 (1m GSD) and the national Turkish DTM. On right hand side the height profile is not influenced by vegetation, while on left hand side the area is covered by forest. Nevertheless the Hannover program DEMSHIFT determined the horizontal shift correctly in X with 48m and in Y with 195m. Such large shifts are caused by datum problems of the Turkish reference. The DEM shift reduces the RMSZ from 27.09m to 10.35m. Also a tilt of the height models can be detected by this investigation.

3. Accuracy figures

Different accuracy figures are in use. The RMSZ is influenced by the bias (constant shift in Z), which is split of for the standard deviation. The Median Absolute Deviation (MAD) is the median of the height differences and corresponding to this it has 50% probability. For comparison with the standard deviation MAD is multiplied with the relation of the normal distribution for 68% to 50% probability the factor 1.4828, resulting to NMAD (Höhle and Höhle 2009). Under the condition of normal distributed height differences NMAD is identical to SZ. SZ is based on the square mean of the differences, while NMAD is a linear value. Very often the height discrepancies of a DEM against a reference DEM are not normal distributed and larger discrepancies are more frequent as corresponding to the normal distribution (figure 3, left, frequency distribution > |14m|). This is enlarging SZ more as NMAD.

Abbreviation	**Accuracy figures**
RMSZ	Root mean square height differences
SZ	Standard deviation of height differences (based on discrepancies minus bias), 68% probability
MAD	Median absolute deviation for height (median value of absolute differences), 50% probability
NMAD	Normalized median absolute deviation for height (MAD × 1.4826), 68% probability
LE90	Threshold including 90% of absolute values of discrepancies (90% median), 90% probability
LE95	Threshold including 95% of absolute values of discrepancies (95% median), 95% probability

Table 1: Accuracy figures

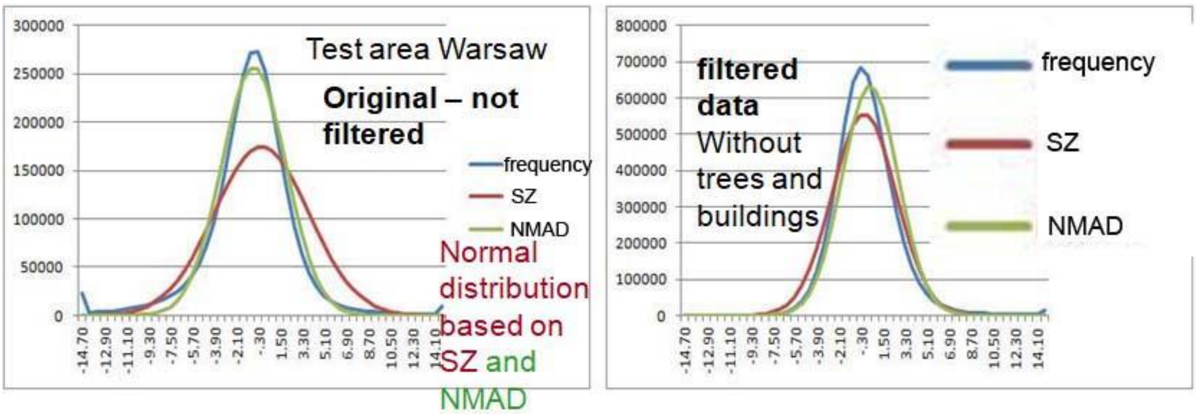

Figure 3. Overlay of frequency distribution and normal distribution based on SZ and NMAD Cartosat-1 DSM – national DTM, east of Warsaw

	Whole area **not filtered**	Open area **filtered**	Not filtered / filtered
RMSZ	3.77m	2.56m	1.47
bias	0.61m	0.50m	
SZ	**3.72m**	**2.51m**	1.48
MAD	1.75m	1.53m	1.14
NMAD	**2.59m**	**2.27m**	1.14
LE90	5.43m	4.09m	1.33
LE95	7.65m	5.21m	1.47

Table 2: Accuracy numbers corresponding to figure 3

In figure 3 and table 2 the analysis of a Cartosat-1 (2.5m GSD) DEM with a precise reference DTM based on the Hannover program DEMANAL is shown. On left hand side of figure 3 the not filtered DSM with influence of small forest parts and buildings can be seen, while on right hand side the Cartosat-1 DSM was filtered to a DTM. The influence of the small forest parts and buildings is obvious at the higher number of large discrepancies (left side of figure 3, blue line). Corresponding to this, NMAD with 2.59m is clearly below SZ with 3.72m. The filtered data (right hand side of figure 3) are closer to a normal distribution. Nevertheless also here NMAD with 2.27m is still smaller as SZ with 2.51m. In both cases the normal distribution based on NMAD (green line) is closer to the frequency distribution (blue line) as the normal distribution based on SZ. This is a typical result – in most cases the normal distribution based on NMAD is closer to the frequency distribution as the normal distribution based on SZ. This justifies the use of NMAD instead of SZ as accuracy criteria. Safe information of NMAD requires a satisfying high number of discrepancies, if only a limited number of discrepancies are available, SZ should be preferred.

Often also LE90 or even LE95 (90%, respectively 95% probability) are used. They are just based on the threshold of the largest 10%, respectively 5%, of the differences. Of course if a higher security for the height values is required, there is a reason for these threshold numbers, but they are presenting only 10%, respectively 5%, of the differences and not the large number of discrepancies, so LE90 or LE95 should not be used as the only accuracy criteria.

4. Filtering from DSM to DTM

By automatic image matching DSMs with the height of the visible surface are generated. Often a DTM with the height of the bare ground is required. In addition it is not correct to compare a DSM with a DTM, this would be dominated by the height of vegetation and buildings. Also the comparison of a DSM with a reference DSM is not as simple due to the fact that a DSM is changing faster as a DTM. In case of InSAR based on C- or X-band the canopy height is slightly below the height based on optical stereo pairs. Long wave length radar, as the L-band, is penetrating the vegetation, but there are only few L-band SAR-data available – it has also the disadvantage of a lower ground resolution.

Manual elimination of the height point groups not belonging to bare ground may be very time consuming, requiring programs for automatic filtering. Nevertheless by automatic filtering not all elements belonging to vegetation and manmade constructions can be removed. The elimination of buildings is not a problem if the GSD is not too small, but if in a forest no points are on the bare ground, the height of the bare ground cannot be estimated correctly. It has to be respected that the canopy height is equalizing the ground height and at the forest borders the trees are not as large as in the center, limiting the possibility to get the ground height just by subtracting an average tree height from the canopy height. Despite these limitations, in operational use by a large photogrammetric company the required time for the generation of a DTM based on a DSM could be reduced by 90% with the Hannover program RASCOR (Pasini, Betzner, Jacobsen 2002). This includes the manual measurements of break lines in few cases.

5. Analysis of height models

5.1 Dependency on terrain inclination

Under usual conditions the accuracy of the height models depends on the terrain inclination corresponding to formula (1).

$$SZ = A + B * \tan(slope) \qquad NMAD = A' + B' * \tan(slope) \qquad (1)$$

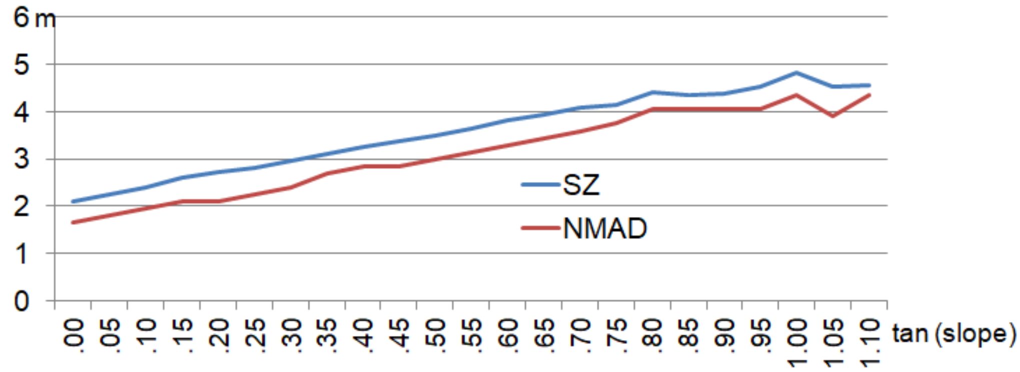

Figure 4. SZ and NMAD depending on slope groups Cartosat-1 DSM against AW3D30

Figure 4 shows the clear linear functions of SZ and NMAD on the tangent of the terrain slope for the comparison of a Cartosat-1 (2.5m GSD) DSM and AW3D30 in an area without forest and buildings (open area). The small uncertainties at higher slope are caused by the smaller number of compared points. In total 383 000 points have been compared. In the flat area approximately ~35000 points and in the steepest part ~ 700 points are in the slope groups. The adjusted function on the terrain slope is for SZ = 2.70m+1.48m∗tan(slope) and for NMAD = 2.25m + 1.49∗tan(slope). The linear dependency of the accuracy from the tangent of terrain slope is typical for all height models.

Due to this reason the accuracy of a height model should not be determined against ground control points (GCPs). Usually the terrain around GCPs is flat and open, leading to too optimistic results for steeper terrain.

```
DISTRIBUTION OF HEIGHT 16049232 POINTS
          <  1497.38     .41 %      .41 %
  1497.38 -  1518.37    3.88 %     4.29 %  *****
  1518.37 -  1539.36    5.30 %     9.59 %  *******
  1539.36 -  1560.35    5.53 %    15.12 %  ********
  1560.35 -  1581.34    7.41 %    22.53 %  ***********
  1581.34 -  1602.33   12.57 %    35.10 %  ******************
  1602.33 -  1623.32   16.67 %    51.78 %  **************************
  1623.32 -  1644.31   12.66 %    64.43 %  ******************
  1644.31 -  1665.30    6.97 %    71.40 %  **********
  1665.30 -  1686.29    6.28 %    77.68 %  *********
  1686.29 -  1707.28    5.61 %    83.29 %  ********
  1707.28 -  1728.27    6.58 %    89.87 %  *********
  1728.27 -  1749.26    5.28 %    95.15 %  *******
  1749.26 -  1770.25    3.09 %    98.24 %  ****
          >  1770.25    1.76 %             **
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SLOPE    %    FREQUENCY DISTRIBUTION OF SLOPE
  .00  19.876  *****************************************************
  .05  15.202  ****************************************
  .10  10.923  ****************************
  .15   8.208  *********************
  .20   6.450  *****************
  .25   5.256  **************
  .30   4.353  ***********
  .35   3.673  **********
  .40   3.142  *******
  .45   2.698  ******
  .50   2.282  *****
  .55   1.922  ****
  .60   1.623  ****
  .65   1.397  ***
  .70   1.211  ***
  .75   1.070  **
  .80    .958  **
  .85    .866  **
  .90    .790  *
  .95    .728  *
 1.00    .668  *
 1.05    .617  *
 1.10    .566  *
```
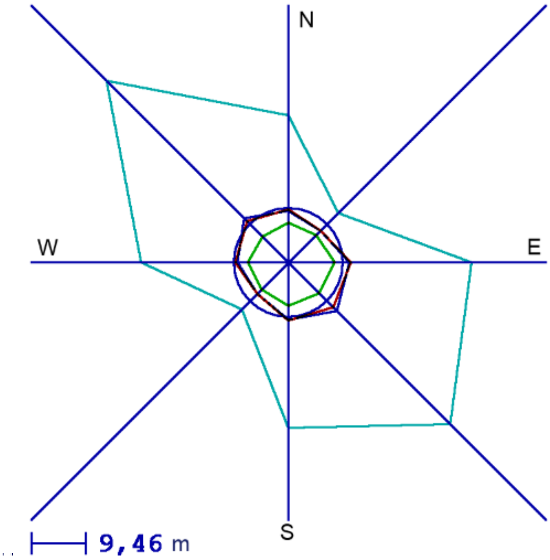

Figure 5. Frequency distribution of height values
Percentage for height group + accumulated

Figure 6: Frequency distribution of terrain slope

Cartosat-1 DSM against AW3D30 DSM, Nairobi

Aspects include the information about height accuracy as function of the slope direction (figure 7). Due to radar layover InSAR has a lower accuracy in inclined parts perpendicular to the satellite orbit. This causes larger standard deviations in the north-west and south-east direction. Especially the factor B in formula (1) – the accuracy dependency on the slope – is quite larger in this direction. For the average SZ the dependency on the slope direction is not as large, but it is still visible, it is ~ 10% larger as the overall accuracy, while it is in the north-east and south-west direction ~ 10% below the overall accuracy. In this case the data acquisition was made from descending satellite orbit (from north-north-east to south-south-west).



From center to outside
Standard deviation of height:

Green line: for slope = 0.0
Red line: for average inclination
Dark blue line: mean value
Dark blue circle: SZ
Light blue-green line: factor for multiplication with tangent (slope), B in formula (1)

above = north direction

Mountainous area at Black Sea coast north-west of Istanbul

Figure 7. Aspects – SRTM against LiDAR reference

Not in any case the dependency on the aspects is so clear, but especially InSAR shows this effect in mountainous areas, while a height model based on digital images does not show this.

5.2 Point spacing and terrain roughness

The statistic about the height values (figure 5) and the frequency distribution of the terrain slope (figure 6) are supporting the analysis.
The loss of accuracy by interpolation is shown for some examples, based on SRTM in table 3. Zonguldak is a rough mountainous area, partially covered by not dense forest, Arizona is smoothly mountainous, without vegetation, and New Jersey is flat, partly with buildings and few trees. The roughness of the areas can be identified at the average change of the terrain inclination from one point spacing to the next (cα) (table 3, figure 8). The influence of the interpolation was determined by interpolation between the left and the right neighbored points and compared with the height of the center points. As a rule of thumb, the loss of accuracy by interpolation usually is reduced by the factor 4 if the point spacing is reduced by factor 2; in other words, it depends usually approximately on the square of the point spacing.

	spacing	average terrain inclination	average change of terrain inclination	RMSZ
Zonguldak	80m	0.27	0.32	12.0 m
Arizona	90m	0.17	0.09	4.8 m
New Jersey	60m	0.024	0.015	0.45 m
New Jersey	120m	0.024	0.015	1.12 m

Table 3: Loss of accuracy by interpolation

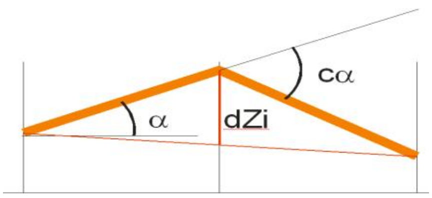


figure 8. Height value interpolation

With α = terrain inclination, cα = change of inclination, dZi = Z-discrepancy caused by interpolation

5.3 Frequency distribution

Figure 9 shows the frequency distribution for all height discrepancies (SZ=11.1m, NMAD=7.3m), while figure 10 shows the frequency distribution of the same data set, but only for the height points with slope < 10% (SZ=7.7m, NMAD=5.0m). The characteristics are not so different, with the exception that the overlaid normal distribution based on SZ and on NMAD are closer to the frequency distribution. In both cases NMAD is clearly smaller as SZ and the normal distribution based on NMAD is closer to the frequency distribution. In the partly rough area larger discrepancies may be caused by the interpolation of TDM90 (~90m point spacing), while the DSM based on SPOT-6 (1.5m GSD) has just 4.5m point spacing.

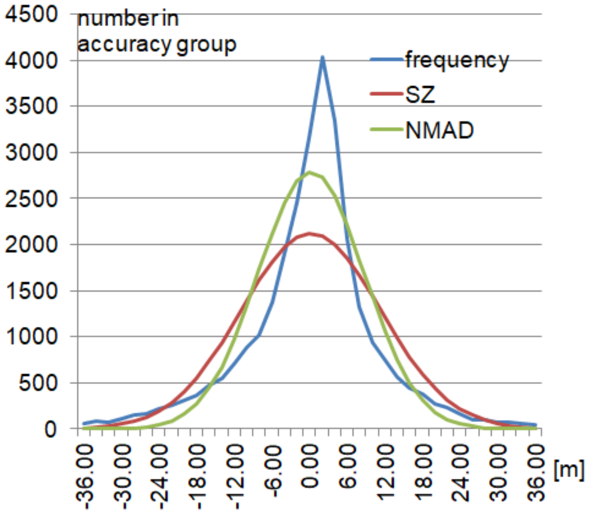


Figure 9. Frequency distribution all data

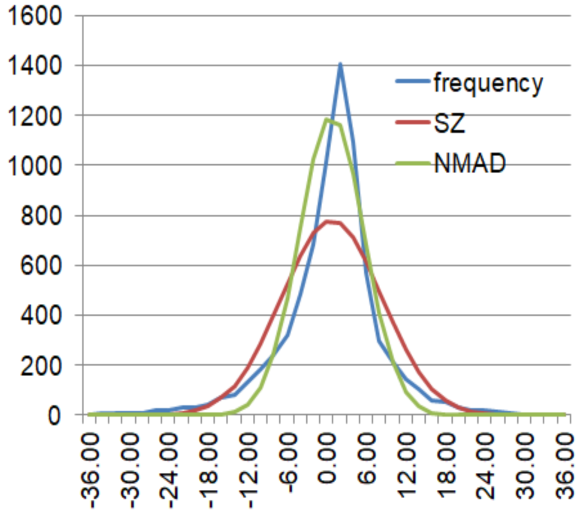


Figure 10. Frequency distribution for slope<0.1

SPOT-6 DSM against TDM90 – Bolivia, Sajama – mountainous, no vegetation

The frequency distribution and the overlaid normal distributions are indicating if a group of height differences are not belonging to the same population, as it is the case if a DSM with points on top of trees and buildings is compared with a DTM, including points only on bare ground. A tendency can be seen in figure 9 where the frequency distribution has more points on the left hand side as on the right hand side.

5.4 Color coded presentation and systematic errors

A visual interpretation of the height discrepancies is important. The comparison of a WorldDEM DSM (12m point spacing) with a LiDAR DSM (SZ=3.45m, NMAD=2.96m), shown by color coded height differences in figure 11, clearly indicates larger differences in the northern part. This is caused by forest, which has been eliminated by a forest layer (figure 11, right). The LiDAR DSM describes the canopy height different to InSAR based on X-band. In the open area without forest the differences are clearly smaller (SZ=2.50m NMAD=2.00m, NMAD= 1.55m + 5.76m ∗ tan(slope)). The strong dependency of the accuracy from the slope is typical for InSAR height models, for DEMs based on optical images it is smaller.
The color coded height differences may highlight also systematic DEM-errors as tilts or more complex deformations. As shown in figure 12, the height differences of LiDAR DSM against WorldDEM DSM have some systematic errors. In this case the influence is not too high, but also not negligible. Such systematic errors may be caused by image orientations or not optimal system calibrations. The determined systematic effects in relation to the reference DEM can be removed by adjusted linear functions (figure 12) of X, Y or Z, or even with the

smoothened functions as shown in figure 12. The degree of smoothening can be chosen. X and Y may be correlated with the corrections in Z, requiring an iterative improvement.

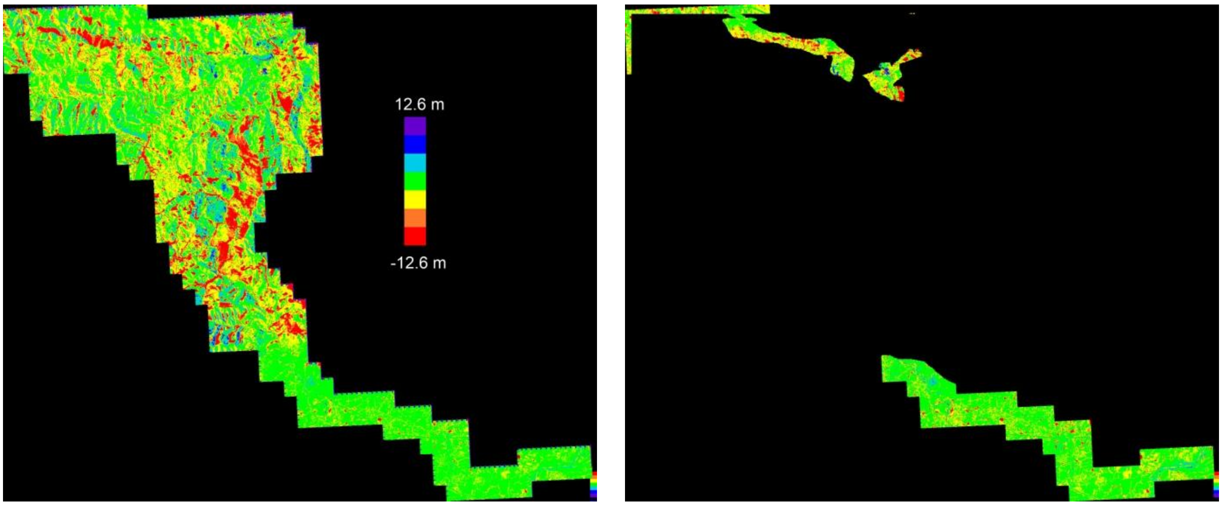
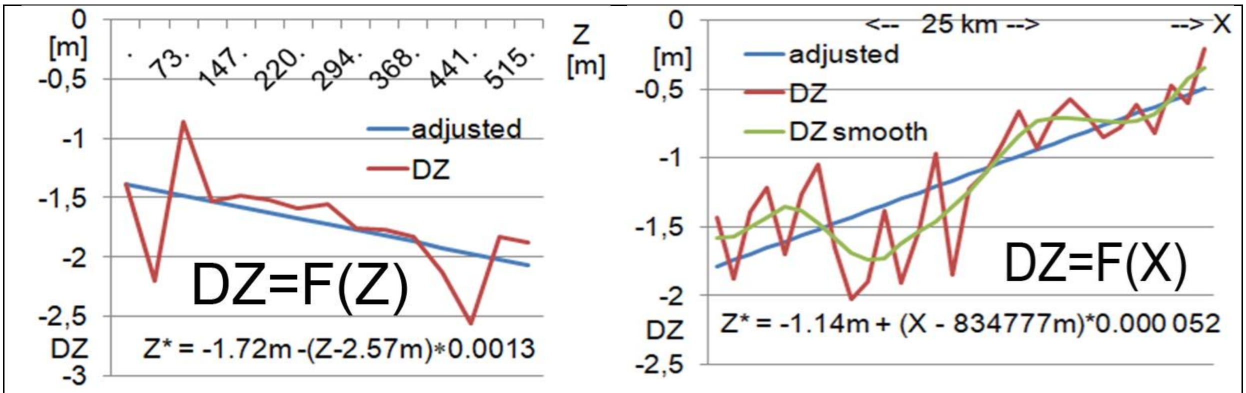


Figure 11. LiDAR DSM – WorldDEM, all points   LiDAR – WorldDEM without forest area
Dücze, Turkey, 25 km x 21 km



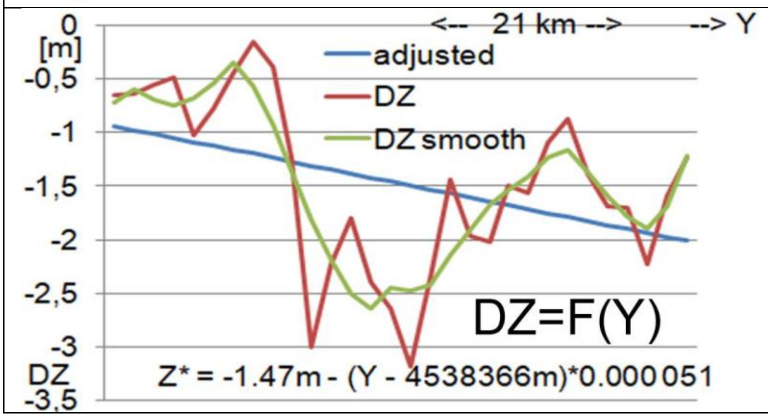


Figure 12. Systematic height errors as funktion of Z (upper left), X (upper right) and Y (lower left) together with linear functions of DZ depending on Z, X, respectively Y

LiDAR DSM – WorldDEM, all points,   Dücze, Turkey

Height models may have a good relative accuracy, but a limited absolute accuracy due to systematic problems of the images, as it is the case for CORONA height models where the GSD of 2m allows a high morphologic quality, but systematic image errors influence the absolute height values. With a comparison of the high absolute accuracy of TDM90, having limited morphologic details due to the point spacing of 90m, with a CORONA height model the systematic height errors can be determined and corrected without loss of the morphologic details of the CORONA height model.

5.5 Relative accuracy and morphologic quality

Closely neighbored points are correlated, causing the relative standard deviation of Z (RSZ) to be better as the absolute accuracy (figure 13), (2). For larger distances between height points the correlation is smaller, causing that RSZ will reach SZ. This fact influences the morphologic quality which is based on the relative accuracy.

```
RELATIVE STANDARD DEVIATION OF Z
      1    6.56                        *               +
      2    8.33                               *        +
      3    9.18                                   *    +
      4    9.58                                     *  +
      5    9.78                                      * +
      6    9.93                                       *+
      7   10.05                                       *+
      8   10.17                                        * +
      9   10.24                                        * +
     10   10.27                                        * +
```

Figure 13. Relative SZ as function of the point distance [m] – SPOT-6 DSM against TDM90
+ = SZ   * = relative SZ; distance of point groups = 80m (to be multiplied with line index)

$$RSZ = \sqrt{\frac{\sum DZi - DZj}{2 * nv}}$$

(2) Relative standard deviation (RSZ)

with nv = number of point combinations in the distance group
and DZi, DZj = closely neighbored height points

With the analyzed DEM contour lines can be generated. They are optimal for morphologic analysis. Of course with a point spacing of 5m and the high accuracy of LiDAR the corresponding contour lines (figure 14 left) are more detailed as for data sets with 27m point spacing (figure 14, 2nd and 3rd from left). AW3D30 has with 1 arcsec the same spacing as SRTM, nevertheless there are more morphologic details in AW3D30 and it is closer to the LiDAR contour lines. Even with 90m spacing TDM90 is close to the details of SRTM (Abb. 14, right).

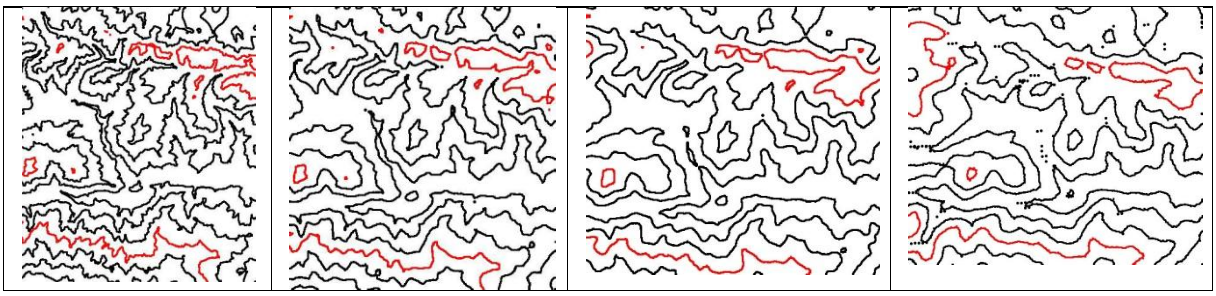


Figure 14. Contour lines with 50m equidistance, 6km x 5km, with different point spacing
LiDAR 5m   AW3D30 ~27m   SRTM ~27m   TDM90 ~90m

Gross errors in a height model cannot be avoided. They may influence the accuracy numbers strongly. Due to this a threshold for the respected height differences has been used. The

threshold has to be realistic to avoid a manipulation of the results – at least it should be 5 times SZ or better even 10 times SZ.
DEM-generation from aerial images is a standard procedure supported by GCPs and GNSS-coordinates of the projection centers avoiding orientation problems. Large format digital cameras today have only limited systematic image errors; this was not always the case (Spreckels, Schlienkamp & Jacobsen, 2007) are reporting about not negligible model deformations caused by systematic image errors. Special additional parameters were required for the UltraCam-D. This problem still exists today for mid-format cameras which have to be handled with self-calibration by additional parameters. Stepwise scanning cameras are not resulting in the required geometric quality of height models.

6. Conclusion

As mentioned in the introduction, the accuracy and quality of a height model is more complex as just to be described by one or two accuracy numbers. The analysis of a DEM has to be done by comparison with another DEM. The use of a limited number of ground control points instead of a reference DEM should be avoided. Ground control points are located on flat ground and do not present the DEM properly by avoiding rough and inclined area, so the analysis results would be too optimistic.
The evaluation has to be made in the same coordinate and datum system. Shifts between the reference and the compared DEM have to be determined and respected - in few cases also tilts are available.
The correct accuracy number has to be used – the Hannover program DEMANAL computes all above listed accuracy numbers and quality criteria. The threshold values CE90 or CE95 do present only the accuracy of the 10%, respectively 5% largest differences; nevertheless they can be used as quality criteria.
The evaluation cannot be based on the comparison of a DSM with a DTM – such results would be dominated by the height of the vegetation and the buildings. If a DTM is required from an original DSM, it has to be filtered and closed forest areas have to be excluded from the analysis, optimally made by a layer indicating the forest area. The comparison of a DSM from optical images or InSAR with a LiDAR DSM has limitations in forest areas due to different definition of the canopy height.
The evaluation should include the dependency of the accuracy from the terrain slope. Especially for InSAR-data in mountainous areas aspects have to be computed. An analysis of the frequency distribution of the height differences and a rough estimation of the influence of point interpolation should be included as well as the determination of the relative accuracy. The latter influences also the morphologic quality what can be checked with the generation of contour lines. In general a color coded presentation of the height differences is required; it shows areas with problems and may indicate systematic DEM errors. Systematic errors as Function of X, Y and Z have to be analyzed and may be respected by iteration.

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