Analysis of free large Area covering Elevation Models and Improvement by ICESat-2

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ABSTRACT:

With TDX-EDEM (EDEM), AW3D30, SRTM and ASTER GDEM-3 (GDEM) global or nearly global free elevation models are available, which are in several countries more accurate than the Digital Elevation Models (DEMs) of the national survey administrations. All these DEMs have a point spacing of 1 arcsecond, which corresponds to ~31 m at the equator. EDEM, based on the TanDEM-X satellite combination, is the latest one, available since 2024. All named DEMs were analysed against reference aerial LiDAR DEMs in four test areas – Mountain, Rolling, Flat and City to gain an overview of their characteristics and accuracy. All these DEMs exhibit systematic errors that depend on the type of data acquisition and the terrain slope. Using ICESat-2 elevation profiles, these systematic errors can be reduced, thus improving the DEMsTo exclude areas with high vegetation, built-up areas, and water surfaces, an exclusion layer is required. The major improvement by ICESat-2 can be reached through a Z-shift of the DEMs determined by comparing the DEMs with ICESat-2 data. Only in few cases a correction by tilt or higher order systematic errors was justified. The best results were achieved with EDEM; only in steep mountainous and in built-up areas, AW3D30, corrected by ICESat-2, has advantages. SRTM and GDEM DEMs are not as good and should no longer be used.

1. Introduction

1.1 Systematic elevation errors of DEMs

Systematic elevation errors of the freely global DEMs can be determined by comparing with reference DEMs, such as the airborne LiDAR data used. However, if precise reference is available, the information value of freely global DEMs is limited. In some countries, such qualified DEMs do not exist, and the freely global DEMs may be more accurate than the DEMs of surveying authorities.

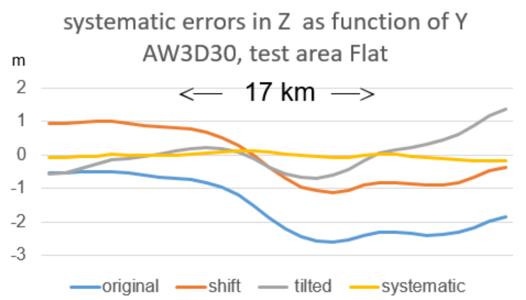


Figure 1. Systematic DEM errors of AW3D30 against LiDAR DEM

As shown in Figure 1, systematic errors may be caused by a constant height shift (shift), a model tilt (tilted), or a higher order deformation (systematic). In case of Figure 1, a higher order of correction is required to largely eliminate the systematic errors. This can vary depending on the type of elevation model and the test site; therefore, it is necessary to check the individual deformations. The systematic elevation errors can also be eliminated using ICESat-2 ATL08 data, which are freely available worldwide or in mountainous areas filtered and averaged ATL03-data.

1.2 Test sites and used global elevation models

The freely available elevation models used, TDX-EDEM (EDEM), AW3D30, SRTM and ASTER GDEM-3 (GDEM), are Digital Surface Models (DSM) with the height of the visible surface, while the used reference LiDAR model is a Digital Terrain Model (DTM) with the height of the bare ground. For the analysis, areas with high vegetation, buildings, and water surfaces must be excluded. The four used test areas have already been used before, for the analysis of the elevation models TDM90, AW3D30, SRTM and ASTER GDEM-3 (Jacobsen, Passini 2021). TDM90 is being replaced by TDX-EDEM, which is also based on TanDEM-X-data, but now – like the other DEMS – has a point spacing of one arcsecond. Furthermore, EDEM is improved through additional measurements and improved orientation. TDX-EDEM comes together with a Land Cover Map (LCM). The LCM can be used for areas of exclusion affected by high vegetation, buildings, and water surfaces. This is more detailed than the manually generated areas for exclusion used by (Jacobsen, Passini 2021) and leads to improved results. For the analysis of different terrain types, the four test sites Mountain, Rolling, Flat and City, are used (Figure 2), for which reference airborne LiDAR data are available.

TDX-EDEM, available since 2024, is based on the German TanDEM-X interferometric synthetic aperture radar (InSAR) constellation (Rizolli et al., 2017), (Gonzáles et al., 2020), (Gonzales et al., 2024). With the Shuttle Radar Topographic Mission (SRTM) in 2000 by NASA in collaboration with the USGS (Gesch et al., 2014) the SRTM DSM was generated. ASTER GDEM-3 is based on image matching using optical stereo image combinations of the Japanese satellite TERRA ASTER having a Ground Sampling Distance (GSD) of 15 m and was finally improved in August 2019 (ASTER 2019). This optical DEM was improved by the Japanese tri-stereo satellite camera ALOS PRISM. ALOS PRISM, which operated from 2006 to 2011, had a GSD of 2.5m and a better base-to-height-ratio of up to 1.0 (Tadono et al., 2014, Takaku et al., 2014).

Figure 2. Location test sites in Texas, USA, in Google Earth

Although more free digital terrain models (DEMs) are available worldwide, these were not considered because they do not have comparable accuracy and/or a lower resolution.

2. Analysis of free DEMs based on LiDAR

Before analyzing the influence of the systematic image errors, the original accuracy of the analyzed DEMs is examined in open area, without influence of vegetation, buildings, and water surfaces. A point spacing of 1 arcsecond corresponds to 30.86 m in north-south direction and, at a mean latitude of 30° for the test sites, to 26.73 m in east-west direction, or an average spacing of 28.8 m. The loss of accuracy due to interpolation in open area over 28.8m was analyzed using the Hannover program ZANAL. The influence of a horizontal shift of the DEMs proved to be negligible.

2.1 Test site Mountain

The Mountain test area contains no vegetation, buildings and water surfaces, so no area had to be excluded. The influence of interpolation over a distance of 30 m using bilinear interpolation in the rough mountainous area amounts to a root mean square error of 5.55 m, and thus dominates the determined accuracy values of the analyzed DEMs. In sub-areas with a terrain inclination of less than 5.7°, the accuracy loss by interpolation is limited, resulting in higher accuracy (Table 1, lower part).

Original DEMs against airborne LiDAR reference Test area **Mountain** average slope = 0.46 (24.7°)				
Data set	RMSZ	bias	SZ	NMAD
ASTER-GDEM	12.72	-5.22	11.60	11.53
SRTM	10.67	-1.45	10.57	9.87
AW3D30	4.71	.2,31	4.10	2.80
TDX-EDEM	6.38	-1.55	6.18	5.32
For sub-areas with inclination < 0.1 (5.7°)				
ASTER-GDEM	8.17	-2.12	7.89	6.54
SRTM	5.81	-1.86	5.50	3.76
AW3D30	2.63	-1.59	2.09	1.28
TDX-EDEM	3.45	-1.93	3.23	2.67

Table 1. Accuracy of DEMs in relation to LiDAR reference [m]

	SZ	NMAD
GDEM	$3.76 + 9.21 * \tan \alpha$	$2.40 + 12.86 * \tan \alpha$
SRTM	$5.14 + 9.55 * \tan \alpha$	$6.15 + 12.15 * \tan \alpha$
AW3D30	$2.30 + 4.07 * \tan \alpha$	$1.94 + 3.24 * \tan \alpha$
EDEM	$2.85 + 6.07 * \tan \alpha$	$1.95 + 6.35 * \tan \alpha$

Table 2. Z-accuracy as function of terrain inclination [m]
SZ = standard deviation in Z, NMAD =Normalized Median Absolute Deviation (Höhle and Höhle, 2009)

The accuracy as function of the terrain slope (Table 2) shows the dominating influence of the terrain slope.

2.2 Test site Rolling

With the exception of test site Mountain, all other test sites require an elimination of the not open area. The test site Rolling is not as rough, so the root mean square loss of accuracy by interpolation over 30 m is just 0.40 m.

Original DEMs against LiDAR reference in open area Test area **Rolling** average inclination = 0.039 (2.2°)				
Data set	RMSZ	bias	SZ	NMAD
ASTER-GDEM	5.61	-4.65	3.14	2.89
SRTM	2.95	-2.03	2.14	1.94
AW3D30	2.02	-1,58	1.26	0.90
TDX-EDEM	1.10	-0.33	1.05	0.86
For sub-areas with inclination < 0.1 (5.7°)				
ASTER-GDEM	5.52	-4.61	3.04	2.84
SRTM	2.91	-2.01	2.10	1.92
AW3D30	1.99	-1.61	1.21	0.88
TDX-EDEM	1.00	-0.28	0.96	0.68

Table 3. Accuracy of DEMs in relation to LiDAR reference [m]

	SZ	NMAD
GDEM	$5.47 + 5.07 * \tan \alpha$	$5.85 + 4.09 * \tan \alpha$
SRTM	$2.88 + 1.65 * \tan \alpha$	$1.80 + 2.10 * \tan \alpha$
AW3D30	$2.00 + 0.14 * \tan \alpha$	$1.94 + 0.04 * \tan \alpha$
EDEM	$0.97 + 2.74 * \tan \alpha$	$0.94 + 1.97 * \tan \alpha$

Table 4. Z-accuracy as function of terrain inclination [m]

The average inclination of 2.2° and the limited loss of accuracy by interpolation for the test site Rolling result to quite better results for test site Rolling (Table 3). Results for terrain inclination below 5.7° are not far away from the overall accuracy. The dependency on the tangent of the terrain slope (Table 4) is limited.

2.3 Test site Flat

Original DEMs against LiDAR reference in open area Test area **Flat** average inclination = 0.035(2.0°)				
Data set	RMSZ	bias	SZ	NMAD
ASTER-GDEM	6.39	4.17	4.84	4.16
SRTM	2.80	-1.52	2.35	2.26
AW3D30	2.08	-1.42	1.52	1.49
TDX-EDEM	0.72	0.31	0.65	0.48
For areas with inclination < 0.1 (5.7°)				
ASTER-GDEM	6.40	4.17	4.85	3.73
SRTM	2.79	-1.51	2.34	2.23
AW3D30	2.07	-1.41	1.51	1.49
TDX-EDEM	0.70	0.32	0.63	0.46

Table 5. Accuracy of DEMs in relation to LiDAR reference

The test site Flat is less rough as test site Rolling, therefore the root mean square loss of accuracy by interpolation over 30 m is only 0.26 m. The accuracy as function of the terrain slope does not show a remarkable dependency of the slope.

2.4 Test site City

The test site City is flat, but even with the area of exclusion based on the EDEM land cover map, the influence of buildings and single trees cannot be completely eliminated (Tab. 5). The root mean square loss of accuracy by interpolation over 30 m reaches 0.68 m. This also reflects in the computed terrain inclination with 3.2°.

Original DEMs against LiDAR reference in open area Test area **City** average inclination = 0.059 (3.2°)				
Data set	RMSE	bias	SZ	NMAD
ASTER-GDEM	6.53	-5.95	2.70	2.76
SRTM	4.18	-3.21	2.68	2.46
AW3D30	3.67	-3.49	1.15	0.89
TDX-EDEM	2.17	-0.92	1.97	1.76

Table 6. Accuracy of DEMs in relation to LiDAR reference

Due to the flat area, no dependence on the terrain inclination is apparent.

2.5 Discussion of DSM accuracy related to airborne LiDAR reference data

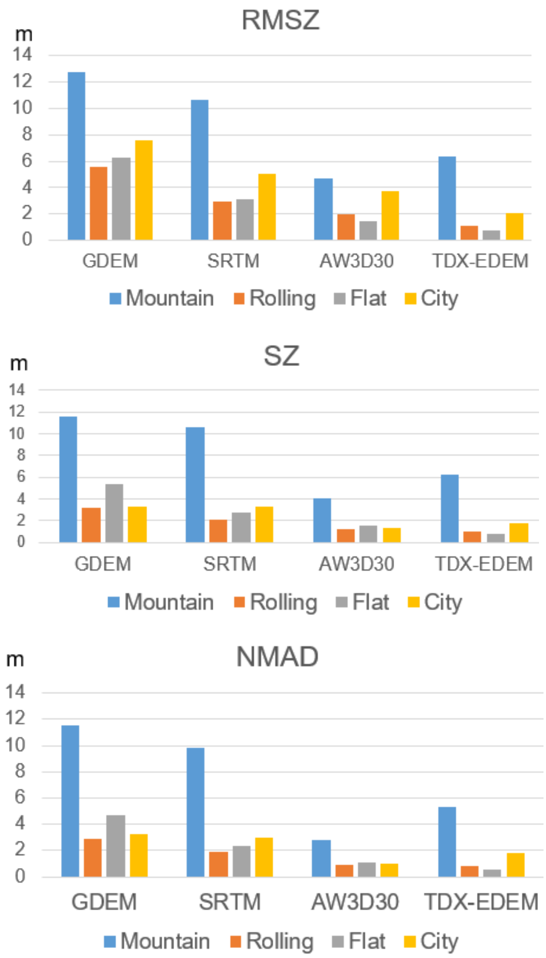


Figure 3. Accuracy of DEMs related to LiDAR

ASTER-GDEM-3 and SRTM are significantly not as good than AW3D30 and TDX-EDEM (Fig. 3), (Tables 1 to 5. This is also evident in other areas examined by the author. The orientation accuracy of TDX-EDEM is better than that of AW3D30. However, TDX-EDEM is affected in mountainous and in built-up areas by radar layover and foreshortening. In other areas, TDX-EDEM delivers significantly better results than AW3D30.

3. Improvement through ICESat-2

A dominating deviation of freely available global DEMs is the bias or systematic height error. The bias, as well as the model tilt and higher order DEM deformation, can be determined and respected by using ICESat-2 LiDAR profile data.

3.1 ICESat-2 data

ICESat-2 carries with ATLAS a single photon LiDAR profiler whose beam is split into six sub-beams. Three pairs, each consisting a weak and a strong beam, have a distance on the ground perpendicular to the orbit of approximately 3.3 km, while the distance between the pairs of weak and strong beams across to orbit is 90 m (https://icesat-2.gsfc.nasa.gov/space-lasers).

The ICESat-2 ATL03 and ATL08 *.h5 data sets are freely available at https://search.earthdata.nasa.gov. ATL03.h5 and ATL08.h5 data have been downloaded. Single photon object information is included in ATL03 product, while the ATL08 product filters and averages the object heights over every ~ 100m in orbital direction (https://nsidc.org/data/icesat-2). The *.h5 files were converted to ASCII *.csv files using the free software PHOREAL (copyright 2020 from the University of Texas at Austin). The selection of the required data of the ASCI-files has been made with own software. Using the PHOREAL program, the ATL03 data are filtered and fitted to ATL08 data. (Neuenschwander et al., 2024) report a SZ=0.25 cm for ATL08 in flat terrain. However, the horizontal accuracy is specified as 6.5 m. This corresponds to SZ=3 m at a terrain inclination of 24.7° in the mountainous terrain. With an absolute accuracy of 25 cm in flat open area, the accuracy of the freely available global DEMs can be improved.

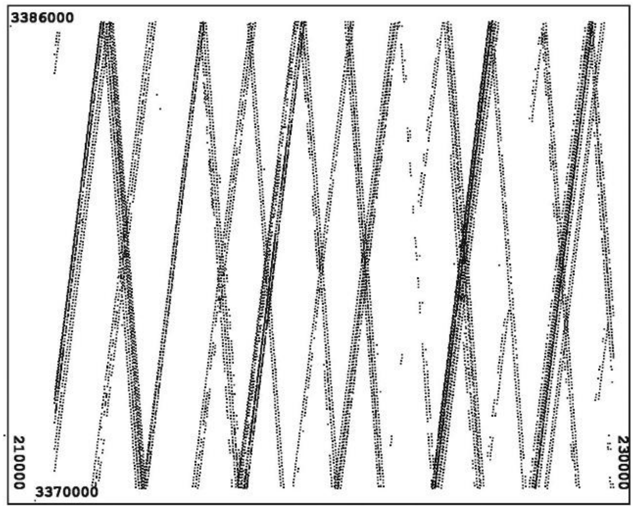


Figure 4. ICESat-2 ATL08-data in test site Flat (20 km x 16 km)

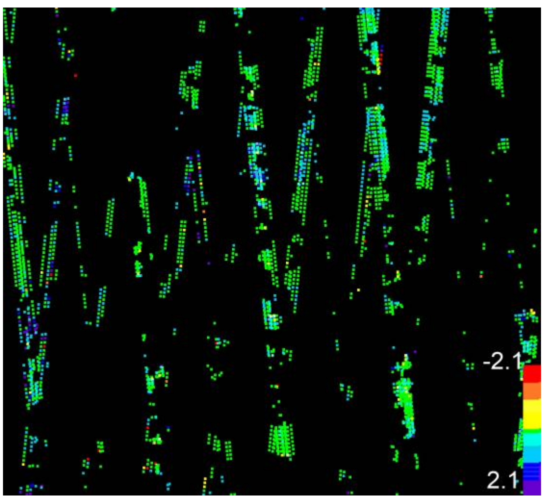


Figure 5. Color-coded differences LiDAR-ICESat2, open area of test site Rolling

A comparison of the ICESat-2 ATL08-data with airborne LiDAR data in the open area of test site Rolling (Figure 5) yielded in RMSZ of 0.54 m, a bias of 0.24 m, SZ of 0.57 m, and NMAD of 0.18 m. For normal distributed differences, SZ and NMAD have the same value. SZ is based on the square sum, while NMAD is based on the median. If SZ is significant larger than NMAD, this is due to a higher number of larger differences than corresponding to normal deviation, for example, caused by not excluded vegetation like shown by blue spots in Figure 5. However, this has only a minor influence on the bias. The determination of systematic height errors primarily is influenced by the bias and its accuracy.

The density of the ICESat-2 ATL08 points is sufficient to determine the systematic height errors.

3.2 Test site Rolling

The Rolling test site has an average slope of 2.2°. This corresponds to an influence of the horizontal uncertainty to the vertical component of 0.25 m. With the accuracy of the vertical component for the ATL08 points of also 0.25 m, an accuracy of 0.35 m is expected for ATL08 points corresponding to (Neuenschwander et al., 2024), (Neuenschwander, A., Magruder, L, 2016).

A comparison of the ICESat-2 ATL08 data in open terrain with the airborne LiDAR reference yielded in the following values: RMSZ=0.62 m, bias=0.24 m, SZ=0.57 m and NMAD=0.18 m. The large difference between SZ and NMAD indicates that not all points not belonging to the open area are excluded by the area of exclusion. The systematic height error (bias) of 0.24 m is as expected and the NMAD, which takes off the bias, is slightly better than expected.

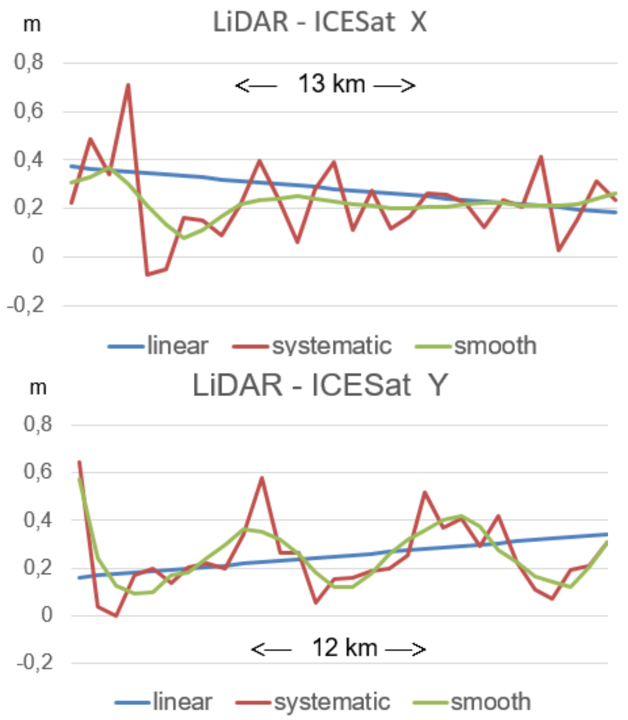


Figure 6. Systematic differences between airborne LiDAR and ICESat-2 ATL08, test site Rolling, as function of X and Y

The systematic differences between the airborne LiDAR reference and ICESat-2 ATL08 (Fig. 6 and 7) are within the expected range. In Figure 6, the smoothened systematics have to be taken into account due to some remaining effects of parts not belonging to the open area.

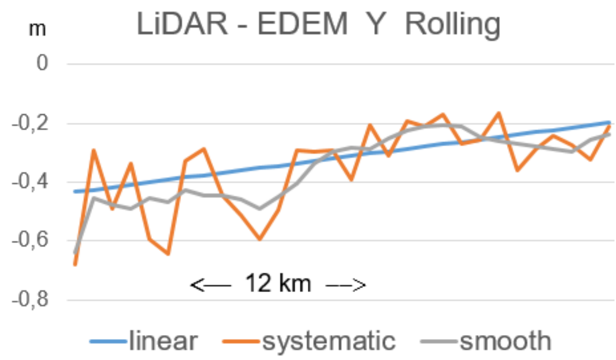


Figure 7. Systematic differences between airborne LiDAR and EDEM, test site Rolling

EDEM	RMSZ	bias	SZ	NMAD
LiDAR	1.10	-0.33	1.05	0.86
ICESat-2	1.22	-0.57	1.08	0.86
LiDAR, improved by Z-shift	1.10	0.24	1.07	0.86
LiDAR, improved by tilt	1.07	0.11	1.07	0.85

Table 7: Test site Rolling, with EDEM compared to airborne LiDAR, compared to ICESat-2, and compared to LiDAR after improvement by Z-shift and also tilt computed with ICESat-2 [m]

AW3D30	RMSZ	bias	SZ	NMAD
LiDAR	2.02	-1,58	1.26	0.90
ICESat-2	2.24	-1.85	1.27	0.98
LiDAR improved by Z-shift	1.25	0.27	1.27	0.90

Table 8: Test site Rolling, with AW3D30 compared to airborne LiDAR, compared to ICESat-2, and compared to LiDAR after improvement by Z-shift computed with ICESat-2 [m]

SRTM	RMSZ	bias	SZ	NMAD
LiDAR	2.95	-2.03	2.14	1.94
ICESat-2	3.07	-2.16	2.18	1.71
LiDAR improved by Z-shift	2.52	-0.58	2.14	1.94
LiDAR improved by tilt	2.20	0.29	2.18	1.97

Table 9: Test site Rolling, with SRTM compared to airborne LiDAR, compared to ICESat-2, and compared to LiDAR after improvement by Z-shift and also tilt computed with ICESat-2

ASTER-GDEM	RMSZ	bias	SZ	NMAD
LiDAR	5.61	-4.65	3.14	2.89
ICESat-2	5.58	-4.51	3.30	2.79
LiDAR improved by Z-shift	3.05	-0.58	3.14	2.89

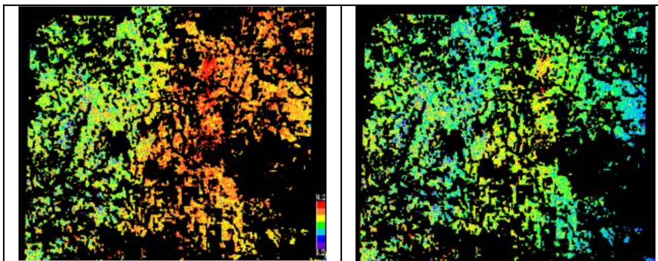
Table 10: Test site Rolling, with ASTER-GDEM compared to airborne LiDAR, compared to ICESat-2 and compared to LiDAR after improvement by Z-shift computed with ICESat-2 [m]

Tables 7 to 10 show the accuracy figures of the analysed freely global DEMs compared to the reference airborne LiDAR, against ICESat-2 ATL08 data, and the DEMs corrected by Z-shift and tilt against ICESat-2. The correction by the elevation shifts based on ICESat-2 for all four DEMs reduced the RMSZ, but not the standard deviation and NMAD. EDEM and SRTM benefit from an additional model tilt determined by ICESat-2, this was not the case for AW3D30 and ASTER GDEM. An improvement by systematic height differences determined by ICESat-2 did not result in a further reduction of the elevation differences against LiDAR reference. This means, that the improvements are limited mainly to the absolute orientation of the DEMs.

3.3 Test site Flat

The average terrain inclination of test site Flat is 2°, which corresponds to 3.5 %. This is not really the terrain undulation, but is influenced by remaining vegetation, which is not eliminated by the area of exclusion based on the EDEM Land Cover Map.

In test area Flat significant systematic elevation deviations are noticeable with AW3D30 (Figures 1 and 8). This is evident in the color-coded height differences of AW3D30 compared to reference LiDAR, as well as in the systematic errors. The reason for this is clearly shown in Figure 9. AW3D30 uses all available stereo models acquired by ALOS. Up to 10 "stacks" are used on right hand side, while only 2 up to 4 "stacks" are used on left hand side. The boundary between both sub-areas is clearly visible in Figures 8 and 9.



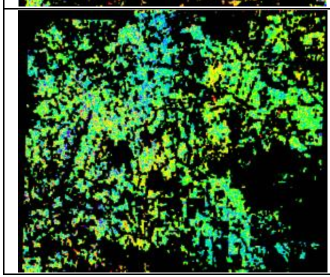


Figure 8. Colour coded height differences of AW3D30 against LiDAR reference

Upper left: original differences
Upper right: after tilt
Lower left: after correction by higher order systematic errors

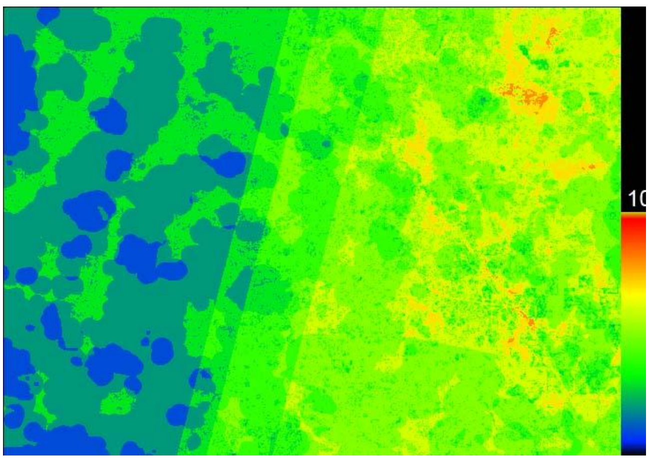


Figure 9. Number of "stacks" used for AW3D30 in test area Flat

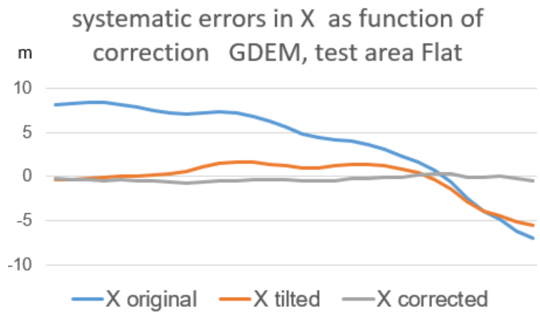


Figure 10. Systematic errors of ASTER-GDEM against airborne LiDAR in test area Flat in X-direction, originally (original), after tilt correction (X tilted) and after correction by higher-order systematic errors (X corrected)

The systematic errors can be eliminated by height correction, as shown in Figure 1.

EDEM	RMSZ	bias	SZ	NMAD
LiDAR	0.72	0.31	0.65	0.48
ICESat-2	0.62	0.16	0.60	0.59
LiDAR improved by Z-shift	0.67	0.15	0.65	0.48

Table 11: Test site Flat, with EDEM compared to airborne LiDAR, compared to ICESat-2, and compared to LiDAR after improvement by Z-shift computed with ICESat-2 [m]

AW3D30	RMSZ	bias	SZ	NMAD
LiDAR	2.08	-1.42	1.52	1.49
ICESat-2	2.23	-1.90	1.17	1.28
LiDAR improved by Z-shift	1.59	0.48	1.52	1.49
LiDAR improved by tilt	1.37	-0.13	1.36	1.19
LiDAR improved by systematic	1.31	0.21	1.30	1.11

Table 12: Test site Flat, with AW3D30 compared to airborne LiDAR, compared to ICESat-2, and compared to LiDAR after improvement by shift, tilt and also higher order systematic errors computed with ICESat-2 [m]

SRTM	RMSZ	bias	SZ	NMAD
LiDAR	2.80	-1.52	2.35	2.26
ICESat-2	2.43	-1.29	2.06	1.68
LiDAR improved by Z-shift	2.36	-0.23	2.35	2.26

Table 13: Test site Flat, with SRTM compared to airborne LiDAR, compared to ICESat-2, and compared to LiDAR after improvement by Z-shift computed with ICESat-2 [m]

ASTER GDEM	RMSZ	bias	SZ	NMAD
LiDAR	6.39	4.17	4.84	4.16
ICESat-2	6.54	4.42	4.82	4.86
LiDAR improved by Z-shift	4.85	-0.23	4.85	4.17
LiDAR improved by tilt	4.19	-0.95	4.08	3.57
LiDAR improved by systematic	3.95	0.62	3.90	3.65

Table 14: Test site Flat, with GDEM compared to airborne LiDAR, compared to ICESat-2, and compared to LiDAR after improvement by Z-shift, tilt and also higher order systematic errors computed with ICESat-2 [m]

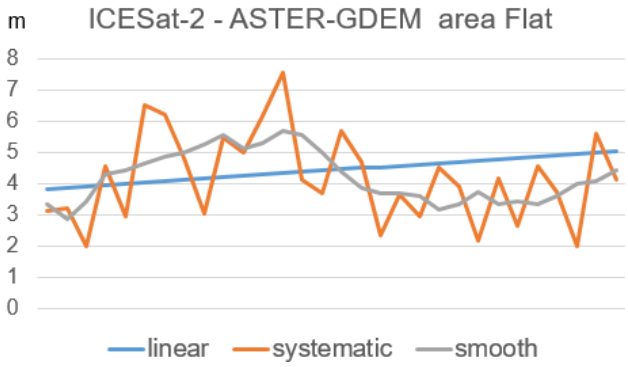


Figure 11. Linear, systematic and smoothened systematic errors in Y-direction of ASTER-GDEM related to ICESat-2 data

In test site Flat the best results were achieved by improving AW3D30 and also ASTER-GDEM by higher order systematic errors based on the differences compared to ICESat-2. The smoothened systematic errors were used for the correction. The smoothening is based on a moving average of the used 30 groups used in each coordinate direction, averaging between 5 and 11 neighbouring groups. The systematic errors in X- and in Y-direction are not correlated, allowing a determination in both components independently. For the more precise EDEM and AW3D30, the average of the 5 neighboured groups is used, while for the less precise SRTM and ASTER-GDEM, the average of the 11 neighbouring groups is used. For EDEM and SRTM, the best results were achieved by a Z-shift related to the ICESat-2 data. The less optimal results are not listed in Tables 7 to 14. Airborne LiDAR is generally used to determine the accuracy, but not for the improvement, since the availability of LiDAR, renders the free global elevation models unnecessary.

3.4 Test site City

Figure 12. Test site City (Google Earth), suburb of Houston

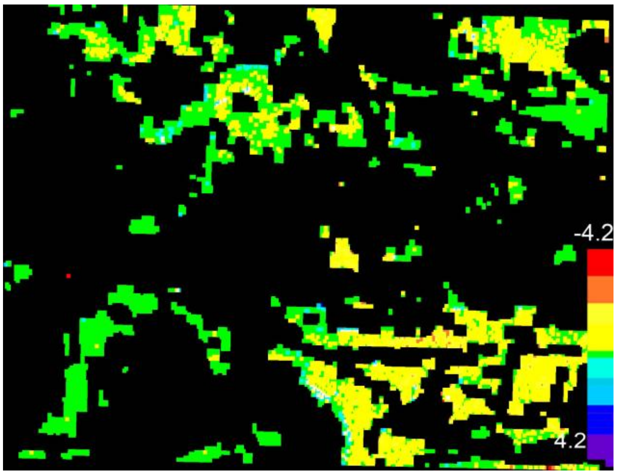


Figure 13. Colour-coded Difference of TDX-EDEM, test site City, black = extended area of exclusion (LCM2)

The test site City (Figure 12) is flat. However, the average terrain inclination is computed with 3.2°, which corresponds to 1.7 m over 30 m distance, if the original Land Cover Map (LCM) is used as area of exclusion. If the LCM is extended by 30 m into the "open area" as LCM2 (Figure 13), the average inclination is reduced to 1.4°. This demonstrates that such an extension is required to avoid an influence of buildings. This LCM2 was used for the whole test site City.

EDEM	RMSZ	bias	SZ	NMAD
LiDAR	2.17	-0.92	1.97	1.76
ICESat-2	2.20	-1.34	1.89	2.10
LiDAR improved by Z-shift	1.76	0.30	1.73	1.77

Table 15: Test site City, with EDEM compared to airborne LiDAR, compared to ICESat-2, and compared to LiDAR after improvement by Z-shift computed with ICESat-2 [m]

AW3D	RMSZ	bias	SZ	NMAD
LiDAR	3.67	-3.49	1.15	0.89
ICESat-2	3.99	-3.61	1.71	1.07
LiDAR improved by Z-shift	1.43	0.03	1.43	0.95

Table 16: Test site City, with AW3D30 compared to airborne LiDAR, compared to ICESat-2, and compared to LiDAR after improvement by Z-shift computed with ICESat-2 [m]

SRTM	RMSZ	bias	SZ	NMAD
LiDAR	4.18	-3.21	2.68	2.46
ICESat-2	4.01	-2.95	2.71	2.49
LiDAR improved by Z-shift	3.41	-0.56	3.37	2.89

Table 17: Test site City, with SRTM compared to airborne LiDAR, compared to ICESat-2, and compared to LiDAR after improvement by Z-shift computed with ICESat-2 [m]

ASTER-GDEM	RMSZ	bias	SZ	NMAD
LiDAR	6.53	-5.95	2.70	2.76
ICESat-2	6.53	-5.87	2.85	2.58
LiDAR improved by Z-shift	4.17	-1.93	3.70	3.84

Table 18: Test site City, with GDEM compared to airborne LiDAR, compared to ICESat-2, and compared to LiDAR after improvement by Z-shift computed with ICESat-2 [m]

In test site City some remaining impacts of buildings and artificial changes of the ground surface cannot be completely avoided even with the extended area for exclusion (Figure 13). Furthermore some areas with individual small houses are not included in the Land Cover Map, used as area of exclusion.

As in the other test areas, the absolute orientation accuracy of EDEM is significantly better than that of the other DEMs. However, with the Z-shift correction determined by ICESat-2, an improvement is possible for EDEM, but it is considerably more important for the other DEMs (Tables 15 – 18). With the Z-shift correction AW3D30 reaches even a higher accuracy than EDEM in built-up areas.

3.5 Test site Mountain

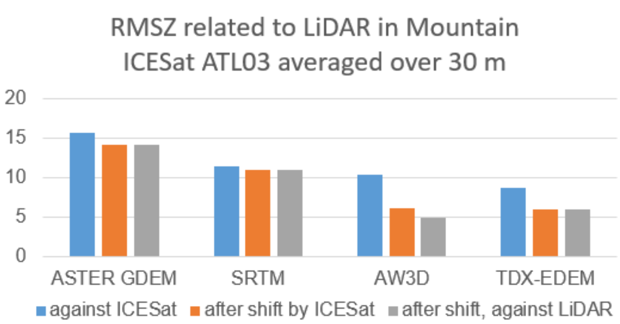


Figure 14. Accuracy of the DEMs in test site Mountain and improvement by ICESat-2 ATL03, filtered and averaged over 30m

The test site Mountain has an average slope of 24.7°. As mentioned in section 2.1, bilinear interpolation results in an accuracy loss of 5.55 m at a spacing of 30 m and 10.86 m over 100 m spacing. The accuracy loss when interpolating over 100m, corresponding to the spacing of ATL08 data, is unsatisfactory for correcting the systematic elevation errors of the free height models. For this reason, the program ICEFILTAV was developed to filter and average the ATL03-data over a selectable distance.
Figure 14 shows the original accuracy of the analyzed DEMs compared to ICESat-2 ATL03, filtered and averaged over 30m by the ICEFILTAV program in blue, the accuracy after shift correction by ICESat-2 against ICESat-2 data in red, and the accuracy after the shift correction compared to aerial LiDAR reference in gray. As mentioned earlier, ASTER GDEM 3 and SRTM are not as accurate as AW3D 30 and TDX-EDEM. SRTM ultimately exhibits root mean square differences of 4.95m and TDX-EDEM 6.06 m. Normally, TDX-EDEM is more accurate than AW3D30; however, Radar foreshortening and layover in steep mountains with in average slope of 24.7°, as well as in built-up areas, affect the accuracy of TDX-EDEM. Higher accuracy, as shown by the interpolation over 30 m with 5.55 m is not to be expected due to the rough terrain. The slightly better result reached by AW3D30 is just a random result.

4. Conclusion

The comparison of the analysed DEMs with the airborne LiDAR data (Figure 3) highlights the problems of the DEMs based on InSAR in steep mountains and built-up areas with foreshortening and layover. The limited horizontal accuracy of ICESat-2 of 6.5m at a mean terrain inclination of 24.7° results in a vertical uncertainty of 2.75 m. Therefore, ICESat-2 ATL08 is not suitable for improving DEMs in the very steep mountainous regions. In general, ASTER-GDEM-3 and SRTM are not as good as TDX-EDEM and AW3D30 and should no longer be used.

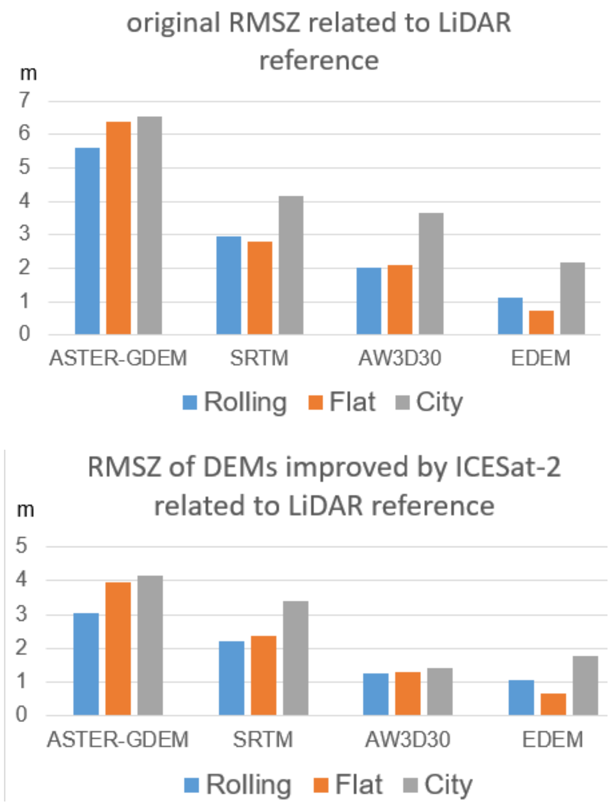


Figure 15b. RMSZ of the DEMs in relation to airborne LiDAR - originally and after improvement by ICESat-2 ATL08 data

Even without correction by ICESat-2 TanDEM-X EDEM exhibits the best orientation accuracy. However, with ICESat-2 data, the RMSZ of EDEM could be improved by approximately 12%, and that of AW3D30 by 49%, this due to the lower accuracy of the DEM orientation of AW3D30. ASTER-GDEM-3 improved by 40% and SRTM by 20%, but even with correction by ICESat-2, they do not reach the quality of EDEM and AW3D30 (Figure 15).

In test site Mountain, the influence of the rough terrain is clearly noticeable. Here, ASTER GDEM 3 improves with the filtered and averaged ATL03-data by 11%, SRTM by 5%, AW3D30 by 52%, and TDX-EDEM by 31%. The significant improvement achieved with AW3D30 can be explained by the not so good orientation accuracy of the optical data in mountainous terrain. In test site Mountain the uncertainty of the correction is higher, which makes improvement through tilt correction and higher-order systematic errors more difficult.

In general, with the exception of mountains, shifting the DEM heights based on ICESat-2 ATL08 data improves the accuracy, verified by airborne LiDAR. For test site Rolling EDEM and SRTM got a slightly higher correction by DEM tilt, while AW3D30 and GDEM got a better improvement even by higher degree systematic errors. The question now arises as to what type of correction is required for an optimal result. This can be determined by examining the systematic errors (Figures 1 and 10). Both figures show significant deformations in systematic errors, indicating the need for a higher correction level. A similar principle applies to the required tilt, which is indicated by the strong tilt of the systematic errors. In case of doubt, the similar results in Tables 12 and 14 preclude any issue.

The main influence of the ICESat-2 correction is the absolute accuracy. The relative accuracy, especially shown by the NMAD, is less affected by the ICESat-2 corrections.

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