ACCURACY EVALUATION OF ICESAT-2 ATL08 IN FINLAND

Xu Wang [1], Xinlian Liang [1] *

[1] State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan, China-(wangxu0920, xinlian.liang) @whu.edu.cn

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ABSTRACT:

ATL08 is level-3A land and vegetation height product of ICESat-2 data, which recorded the terrain elevation and surface height parameters at 100 m fixed-length along the ground track. It has been used widely not only in vegetation monitoring at large scale, but also in improving the accuracy of satellite stereo mapping, so, the accuracy of ATL08 product is the precondition of its application. Although some studies have evaluated the terrain and canopy height retrieval accuracy of ATL08, it is still not comprehensive that most studies focus on the accuracy in vegetation area. In this study, the performance on terrain and surface height retrieval of ATL08 was evaluated both in forested and non-forested area based on DEM and ALS data in Finland. A total of 6,682,846 and 3,980,235 segments were used to evaluate the accuracy of terrain and surface height retrieval, respectively. The result showed that, firstly, terrain elevation retrieval from ICESat-2/ATLAS is accurate, e.g., sub-meter level both in forested and non-forested area and slope was an important factor affecting the accuracy of terrain retrieval, while, surface height retrieval was low accurate, e.g., the RMSE of surface height retrieval were more than 5 m. Secondly, the accuracy of terrain elevation retrieval in non-forested area was slightly higher than that in forested area showed by MAE and RMSE. Finally, the accuracy of surface height retrieval in forested area was higher than that in non-forested area, and it should be emphasized that there is a significantly difference on RMSE% between forested and non-forested area. The study indicated that the terrain elevation retrieval from ATL08 is relative reliable and recommended to use when the accuracy is not strictly required, while, the use of surface height should be considered carefully and avoid to use low accuracy observation.

1. INTRODUCTION

Ice Cloud and land Elevation Satellite-2 (ICESat-2) was launched in September, 2018. At present, the onboard Advanced Topographic Laser Altimeter System (ATLAS) has collected nearly 5 years of Earth Observation (EO) data at a global scale. The data collected by ATLAS was processed into different levels of products, among which the Land and Vegetation Height (ATL08) Product estimated the height of terrain and canopy in a 100m fix-length along the ground track (Neuenschwander et al. 2021). The ATL08 product can be used to estimate the state of vegetation at regional or national scales, independently or fused with other remote sensing data (Liu and Popescu 2022; Liu et al. 2022; Luo et al. 2023; Nandy et al. 2021; Narine et al. 2019; Silva et al. 2021; Wu and Shi 2022), or be used to improve the accuracy of satellite stereo mapping with no ground elevation control points (Li et al. 2021; Osama et al. 2022; Shang et al. 2022).

The accuracy of ATL08 data is the foundation of its application. Therefore, a few previous studies evaluated the accuracy of terrain and canopy height and analysed their impact factors. (Neuenschwander et al. 2020) quantified the accuracy of terrain and canopy height collected by ICESat-2/ATLAS in southern Finland. (Liu et al. 2021) validated the accuracy of terrain and canopy retrievals for Global Ecosystem Dynamic Investigation (GEDI) and ICESat-2 ATL08 product in 40 sites distributed in the U.S. (Malambo and Popescu 2021) evaluated ATL08 terrain and canopy height agreement with reference data in U.S., across the 12 sites including 6 major biomes. These studies reported the capabilities and limitations of ATL08 product in forested areas at large scale and different kinds of ecosystems.

ATL08 product also was demonstrated that can be used as a height reference for the global digital elevation models (Osama et al. 2022). The accuracy of terrain retrieval was evaluated dependently in some studies. (Wang et al. 2019) evaluated terrain retrieval accuracy form ATL03 data in U.S, and the factors, including signal-to-noise ratio (SNR), slope, vegetation height and vegetation cover, affecting the accuracy of terrain retrieval were analysed under different kinds of land cover. (Zhu et al. 2022) evaluated the accuracy of terrain retrieval derived from ATL08 product in Spain using 24 months observation. (Zhao et al. 2022) points out that ICESat-2 data has potential that can be used in the urban change monitoring and three-dimensional morphology. These studies validated the terrain retrieval accuracy derived from ATL08 product and provided the recommendations for the use and application of ICESat-2 data.

Although the above studies evaluated the accuracy of terrain and canopy derived from ATL08 data in different regions, the performance of ATLAS sensor has not been adequately evaluated. For example, the accuracy of terrain and surface height in non-forested area was rarely considered.

This study evaluated the accuracy of the terrain and surface height from ATL08 data in the forest and non-forest covered areas in Finland, in order to reveal the reliability of the satellite Lidar observations and its different properties over different land-cover conditions.

In this study, the surface was used instead of the canopy to describe the relative height to the ground under all types of land

* Corresponding author

cover and land use, although the relative height to the ground has been conventionally defined as canopy in the ATL08 product no matter what type of land cover it is.

2. MATERIAL AND METHODOLOGY

2.1 Study area

In this study, ATL08 data in Finland was used to evaluate the accuracy of terrain and surface height. Finland is selected as the study area because, firstly, ICESat-2 has a relatively dense footprint coverage in Finland in comparison with low-latitude regions since the ICESat-2 has a near-polar orbiting orbit and Finland locates in the high latitude region. Secondly, Finland has good reference data for the evaluation of satellite Lidar data. Airborne laser scanning (ALS) data and digital elevation model (DEM) data cover the whole country. Finally, previous studies (Neuenschwander et al. 2020) have been conducted in southern Finland which can be compared with the result of our study and verify the conclusion.

2.2 ATL08 product and pre-processing

ICESat-2 ATL08 product (Version 4) recorded terrain elevation, surface (canopy) height and other parameters such as ancillary data, satellite orbit and quality assessment, et al.

ATL08 data requires a pre-processing step for the accuracy evaluation, including the selection of cloud-free observations, coordinate reference and elevation datum transformation, and segment boundary calculation.

Firstly, the same terrain and surface (canopy) height indicators derived from ATL08, e.g., *h_te_median* and *h_canopy*, were selected, to compare with previous study (Neuenschwander et al. 2020). In a segment, *h_te_median* is the median height of terrain photons, and *h_canopy* is the 98% height of surface (canopy) photons. Due to the influence of observation conditions, there were possible invalid values that should be eliminated. The *layer_flag* in ATL08 product that represents the existence of clouds or blowing snow was used to filter out data with cloudy observation.

Secondly, since the datum of ATL08 product and reference data were different, the datum of ATL08 product was strictly transform to the datum from the WGS84 to EUREF-FIN35 system based on the Nordic Geodetic Commission 2020 (NKG2020) transformation. The officially recommended FIN2005N00 geoid model (Bilker-Koivula 2010) was used to transform ellipsoidal EUREF-FIN heights to N2000.

Finally, although the segment width varied in different studies, for comparison with previous studies (Neuenschwander et al. 2020), this study used the 11m segment width. The next and current segment in the same ground track were used to calculate the slope of the segment. Based on the size, slope and position of the segment, the coordinate of the segment boundary can be calculated.

After pre-processing described above, ATL08 data was divided into forest cover class and non-forest cover class for evaluating the accuracy of ATL08 product in forested area and non-forested area. The *segment_landcover* parameter, a flag indicating the land cover of segment in ATL08 product, was used to classify the segments into forest cover class and non-forest cover class. The value of *segment_landcover* from 0 to 16 means 17 kinds of land cover. In this study, evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, mixed forest and woody savanna indicated by *segment_landcover* were considered as a forest cover class, and other land cover classes besides the above were considered as a non-forest cover class.

2.3 Reference dataset and pre-processing

DEM data and ALS data distributed by National Land Survey (NLS 2018) in Finland were selected as reference data to evaluate the accuracy of terrain and surface height derived from ATL08, respectively. DEM product from NLS with 2m spatial resolution was used to evaluate the accuracy of terrain retrieval from ICESat-2 data, since ALS data in some regions were missing.

Outliers in ALS data were firstly removed based on point-distribution-analysis method (Liang et al. 2011) along elevation distribution. Digital surface model (DSM) and DEM were then generated from ALS data. The normalized digital surface model (nDSM) was generated by subtracting DEM from DSM was used to evaluate the accuracy of surface height retrieval with 2m spatial resolution.

The reference data were sampled as same method as ATL08 product, in order to compare with terrain and surface height derived from ATL08. For terrain height, the median value of elevation extracted in DEM in a segment was regard as reference value to ATL08 median terrain elevation (*h_te_median*). For surface height, the 98% height was extracted in nDSM in a segment was regard as reference value to ATL08 surface height (*h_canopy*).

2.4 Method of accuracy evaluation

The errors of the terrain and surface height defined in this study was the observation value minus the reference value, as shown in (1) and (2).

$$e_{terrain} = h\_te\_median_{ATL08} - h\_te\_median_{DEM} \tag{1}$$

$$e_{surface} = h\_canopy_{ATL08} - h\_canopy_{nDSM} \tag{2}$$

Three indicators including bias, mean absolute error (MAE), root mean square error (RMSE) were selected in this study to evaluate the accuracy of terrain and surface height. For the evaluation of the surface height accuracy, the relative RMSE (RMSE%) was also selected. The formulas of accuracy indicators were shown in (3) to (6).

$$bias = \frac{1}{n} \times \sum_{i=1}^{n} e_i \tag{3}$$

$$MAE = \frac{1}{n} \times \sum_{i=1}^{n} |\, e_i \,| \tag{4}$$

$$RMSE = \sqrt{\frac{1}{n} \times \sum_{i=1}^{n} e_i^2} \tag{5}$$

$$RMSE\% = \frac{RMSE}{\overline{h_{ALS}}} \times 100\% \tag{6}$$

3. RESULT

3.1 Terrain accuracy

Gross errors need to be eliminated due to the difference between ATL08 and reference data collection times and some unknow factors. In this study, observation with error distributed outside three times the standard deviation was excluded. Finally, the range of terrain errors was from -3.91m to 3.78m and 6,682,846 segments were selected to evaluate the accuracy of ATL08 terrain retrieval, in which 81.5% and 18.5% of segments were from forest and non-forest classes, respectively. The error distributed was shown in Figure 1.

In order to further evaluate the accuracy of terrain retrieval in forested, non-forested area and the whole study area, three accuracy indicators, including bias, MAE, and RMSE, were calculated which were listed in Table 1. The bias, MAE, and RMSE of the terrain height over the whole study area were 0.0 m, 0.46 m, 0.72 m, respectively.

In forested area, the bias, MAE, and RMSE of terrain retrieval were -0.02 m, 0.47 m, and 0.73 m, respectively, and the observations number are about 5.45 million. Table 1 also listed the results from the reference study (Neuenschwander et al. 2020) as it had a similar study area and forested area definition. It should be noted that the definition of errors in reference study is opposite to this study. The definition of errors in reference study was reference value minus observation value, while, that in this study following the definition in surveying that observation value minus reference value. This point needs to be noted especially when comparing the bias between two evaluation results. In non-forested area, the bias, MAE, and RMSE of terrain retrieval were 0.07 m, 0.44 m, 0.67 m, respectively, and the observation number was about 1.24 million.

Indicators	Total	Forest	Non-Forest	Reference
Bias (m)	0.00	-0.02	0.07	-0.07
MAE (m)	0.46	0.47	0.44	0.53
RMSE (m)	0.72	0.73	0.67	0.73
Observation (million)	6.68	5.45	1.24	0.91

Table 1 Accuracy of ATL08 terrain height

3.2 Surface accuracy

A total of 3,980,235 segments were selected to evaluated the accuracy of ATL08 surface height retrieval. The distribution of surface retrieval error was shown in Figure 2. For the evaluation of surface height, RMSE% was supplied as an accuracy indicator, since it represents the percentage of the deviation between observation value and true value to true value in surface height retrieval.

The segment number in the surface accuracy evaluation was notably smaller than the terrain evaluation. The number of valid values is different in surface height and terrain elevation retrieval. That is the reason for the different observations number of terrain and surface in the evaluation result.

Four accuracy indicators, including bias, MAE, RMSE, RMSE%, were calculated to further evaluated the accuracy of surface height retrieval in forested, non-forested and the whole area, as listed in Table 2.

The bias, MAE, RMSE and RMSE% of the surface height over the whole study area were -0.36 m, 3.51 m, 5.12 m and 36.82%, respectively, and the observation number was about 3.98 million. In forested area, the bias, MAE, RMSE and RMSE% were -0.53 m, 3.46 m, 5.07 m and 34.91%, respectively, and the observation number was about 3.59 million. In the non-forested area, the bias, MAE, RMSE and RMSE% were 1.21 m, 3.98 m, 5.57 m and 67.47%, respectively, and the observation number was about 0.39 million.

Indicators	Total	Forest	Non-Forest
Bias (m)	-0.36	-0.53	1.21
MAE (m)	3.51	3.46	3.98
RMSE (m)	5.12	5.07	5.57
RMSE%	36.82	34.91	67.47
Observation (million)	3.98	3.59	0.39

Table 2 Accuracy of ATL08 surface height

4. DISCUSSION

4.1 Terrain accuracy

The accuracy of terrain retrieval in forested are in this study was compared with a reference study carried out in southern Finland (Neuenschwander et al. 2020). Although the amount of the observations in this study was significantly larger than, i.e., the observations number was about 6 times as that in reference study and the duration of data collection in this study was 3 times as that in reference study, the accuracy of the terrain height in forested areas was similar as the reference study that the differences of bias and MAE were 9 cm and 6 cm, respectively, and the RMSE of forest class in this study is same as reference study, i.e., both were 0.73 m.

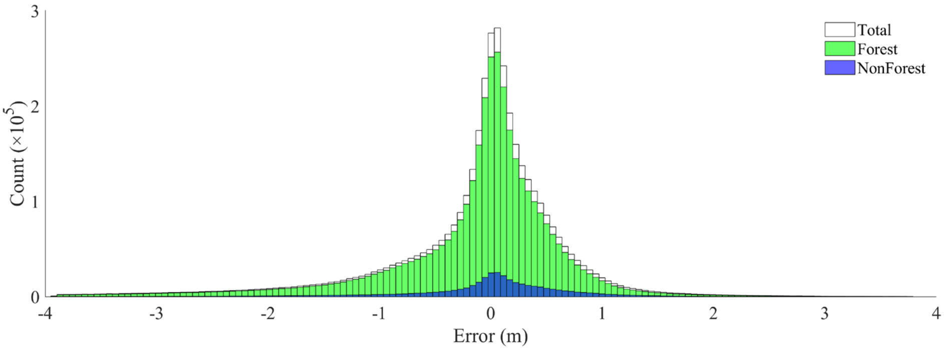

Figure 1 The distribution of the terrain errors stratified by forested and non-forested area.

Since forest coverage in Finland is more than 75% of land area (Finland 2022), the observation number in forested area is about 4 times as that in non-forested area in terrain accuracy evaluation. Although the accuracy of the terrain retrieval in ATL08 product was accurate, the accuracy in non-forested area was slightly higher than that in forested area. The reason for this phenomenon may be that the forest covered the ground, reducing the accuracy of terrain retrieval in forested area.

Slope is another important factor to terrain retrieval accuracy. In order to reveal the impact of slope on terrain retrieval, observations were divided into two level based on slope from ATL08 product that segment slope less than 15° was considered in gentle terrain, and segment slope greater than 15° was considered in steep terrain.

The three accuracy indicators, including bias, MAE and RMSE, were calculated in two slope levels separately in the whole study area which were shown in Figure 3. The result showed that the accuracy of terrain retrieval in gentle ground was obviously higher than that in steep ground. Due to the dominant number of observations in gentle ground, the evaluation result in the whole study area was similar to that in flat areas.

4.2 Surface accuracy

The accuracy of surface height retrieval was obviously lower than that of terrain retrieval. It can be clearly seen in the error distribution in Figure 1 and Figure 2 that the error of terrain retrieval was roughly within the range of -4 m to 4 m, while that of surface height retrieval was roughly within the range of -25 m to 25 m. In addition, terrain retrieval was more concentrated than the error distribution of surface height retrieval.

The accuracy in forested area was higher than that in non-forested area. Surface heights in forested and non-forested area were underestimate and overestimated, respectively. The canopy was underestimated 0.53m in the forested area which may be caused by the top of canopy photons missing sampled in forested area due to the ATLAS sampling method (Neuenschwander and Magruder 2016), while, the surface height was overestimated 1.21m in non-forested area, and the reasons for this phenomenon need further explorations.

Another point that is worthy of discussing is the RMSE and RMSE% in surface height retrieval between forested and non-forested area. Although the difference of RMSE between the whole, forested, and non-forested areas were not significant, the RMSE% in non-forested area was far greater than that in forested area, approximately 33%. This indicated that the average surface height in non-forested area is much lower than that in forested area.

Due to the high forest coverage in Finland, the observation number in forested area was 9 times as that in non-forested area. Despite the difference of RMSE% between forested and non-forested area was huge, the RMSE% of the whole study area was similar with the forested area as dominant observations were in forested area.

5. CONCLUSION

This work evaluated the performance of ATL08 product in terrain and surface height retrieval under different land cover and land use in Finland. 33 months ATL08 data was used to evaluate the accuracy of terrain and surface height retrieval stratified by forested and non-forested area. Evaluation results in reference study were also used to compared with that calculated in this study.

The results of this work indicated that the terrain height retrieval from ICESat-2 Lidar is accurate, i.e., at sub-meter level, in both forest and non-forest areas. This indicated that terrain retrieval from ATL08 is relative reliable and recommended to use when the accuracy is not strictly required. Although terrain retrieval is accurate from ATL08, the accuracy in non-forested area was slightly higher than that in forested area. This may be caused by the coverage of forest, reducing the accuracy of terrain retrieval in forested areas. This study also reported that the slope is an important factor affecting the accuracy of terrain retrieval. The terrain retrieval error was significantly higher in areas with a slope greater than 15° than that with a slope less than 15°.

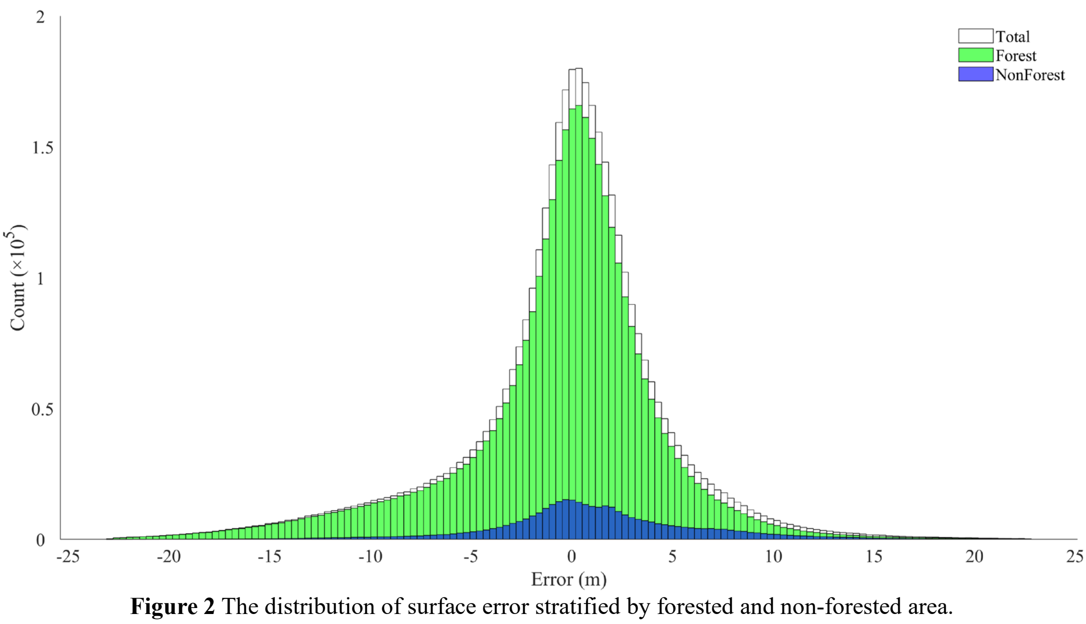

Figure 2 The distribution of surface error stratified by forested and non-forested area.

In addition to evaluate the accuracy of the terrain height measurements, this work also quantitatively evaluated the accuracy of the surface height retrieval and revealed that the surface height measurements are less accurate than terrain measurements, i.e., the RMSE of the surface height in the forested, non-forested, and whole study area was similar at 5.07 m, 5.57 m and 5.12 m, respectively.

For terrain retrieval, observations collected in flat area was recommended to use since its high accuracy. For surface height retrieval, it is worth of noting that the accuracy of surface height retrieval was highly affected by observation conditions. It should be avoided the low accuracy observation when using surface height retrieval form ATL08.

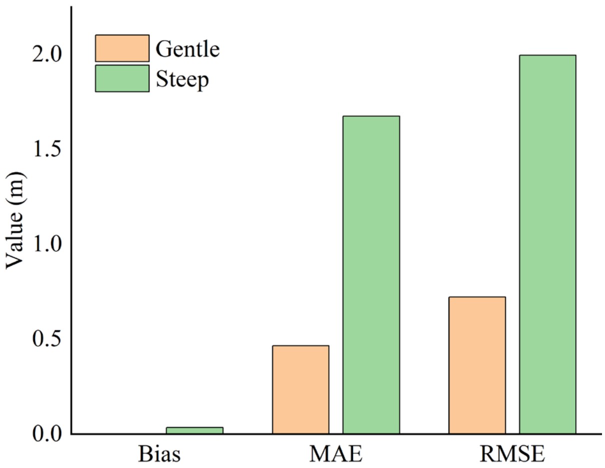

Figure 3 Terrain retrieval accuracy stratified by slope

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