Comprehensive Evaluation of the ICESat-2 ATL08 Terrain Product

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***Abstract*— Current spaceborne lidar Ice, Cloud, and Land Elevation Satellite (ICESat)-2 provides ATL08 product for global terrain height, whose quality properties are yet to be fully understood. This article performs a comprehensive evaluation on its quality by using 3-D elevation program (3DEP) digital elevation model (DEM) and hundreds of survey marks of two counties in the USA. The evaluation is carried out in terms of data specification, survey marks, land cover, season and time (day or night) of acquisition, incidence angle, and terrain slope. The ATL08 height errors are further modeled as a function of laser incidence angle and canopy coverage. It is found out the height from ATL08 product lies between the 3DEP DEM and true ground surface. The uncertainty of ATL08 height is 0.2 m for plain terrain, and 2 m for mountainous terrain where the majority of ATL08 segments are not useful for terrain extraction. The terrain height gets more underestimated by ATL08 products in regions with large terrain slope or incidence angle and more overestimated where the terrain is covered by dense canopy. Furthermore, seasonal variation of terrain height error can be as high as 0.8 m, while the impact of acquisition time is less than 0.3 m. We expect these findings to be informative for the utilization of ATL08 terrain product by worldwide users, and for the improvement of future ATL08 product.**

***Index Terms*— Accuracy, ATL08, canopy coverage, Ice, Cloud, and Land Elevation Satellite (ICESat)-2, incidence angle, land cover, seasonality, slope, terrain height, time of acquisition.**

I. INTRODUCTION

SPACEBORNE lidar remote sensing is an advanced technology to directly acquire the vertical dimension and thus to derive various height-related information for global scientific studies. Launched in 2003 by the National Aeronautics and Space Administration (NASA), Geoscience Laser Altimeter System (GLAS) onboard the Ice, Cloud, and Land Elevation Satellite (ICESat) provided worldwide lidar waveform data until October 2009 [1]–[3]. The primary purpose of ICESat was to determine interannual and long-term changes in polar ice-sheet volume (and inferred mass change) to a sufficient accuracy to assess their impact on global sea level [4]. As a follow-on of the ICESat laser altimetry mission, NASA launched ICESat-2 mission on September 15, 2018 primarily to measure changes in land ice elevation and sea-ice freeboard, and to enable the determination of vegetation canopy height globally [5], [6]. The instrument for height determination on the ICESat-2 observatory is the Advanced Topographic Laser Altimeter System (ATLAS). The design of ATLAS is based on the success and limitations of the GLAS aboard ICESat [5]. As illustrated in Fig. 1(a), a 532-nm laser light at a pulse repetition frequency of 10 kHz is split into six beams by the ATLAS, and the six primary beams have unequal energy, with three relatively strong beams and three relatively weak beams [5]. These six beams are arranged into three pairs of beams and are defined from left to right in the direction of travel as (ground track (GT) 1L, GT 1R, GT 2L, etc.) [5]. This configuration allows the measurement of the surface slope in both along and across track directions with a single pass and the measurement of height change from any two passes over the same site [5].

ICESat-2 provides several data products to the science community and general public [5], [7]. Among the products of ICESat-2, the Level 1B data product, denoted as ATL02, provides the ATLAS time of flight, ATLAS housekeeping data, and other data necessary for science data processing. The Level 2A data product, identified as ATL03, provides the latitude, longitude, and ellipsoidal height of photons detected by the ATLAS instrument. Based on the ATL03 data product, higher-level (Level 3A) surface-specific data products consist of glacier and ice sheet height, sea ice freeboard, vegetation canopy height, ocean surface topography, and inland water body height [5], [7]–[9].

Among all these Level 3A data products, ATL08 data product provides users with valuable terrain (ground surface including buildings) and canopy height information extracted from ATL03 with a global coverage. Instead of providing photon level information as ATL03 product, ATL08 provides height information at a fixed step size of 100m such that the canopy and terrain information are consistent in the along-track direction and ease the use of the final products. According to [6] and [7], ATL08 should have approximately 140 signal photons per 100-m segment over vegetated surfaces. Each ATL08 segment is provided with the canopy height (h_canopy) and terrain height. Fig. 1(b) demonstrates a track of ATL08 product including both canopy and terrain. The terrain parameters in ATL08 include the mean, minimum, maximum, median, standard deviation, mode, and skewness of the ground photons within each 100-m segment. In addition, ATL08 also has the height associated with the interpolated ground line at the midpoint of each 100-m segment (h_te_interp), and the best-fit terrain elevation at the midpoint of each 100-m segment (h_te_bestfit) [6]. The h_te_bestfit is

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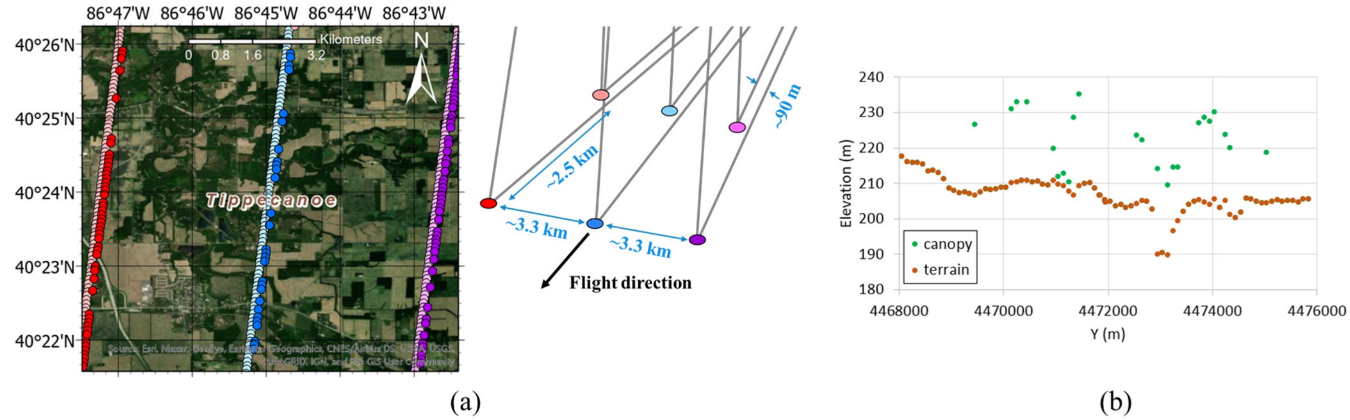

Fig. 1. ATLAS working principle. (a) ATL08 GT No.896 in Tippecanoe County and its beam footprints. (b) Canopy and terrain elevation profile of the beam GT 1L.

calculated by fitting a 1st-, 3rd-, and 4th-order polynomial to the labeled ground photons. A slope correction is applied to the linear fit, and the ground photons are weighted by distance to the mid-segment location. The final h_te_bestfit reported in the product is the one with the smallest standard deviation of fitting errors [6], [7]. Besides the terrain height information, canopy coverage (Landsat_perc) of each segment is also included in ATL08. This parameter provides the average percentage of the Landsat Tree Cover Continuous Fields (VCF, Version 3, Circa 2015 Landsat data) for each ATL08 100-m segment [6], [7].

As a newly global lidar product from ICESat-2, ATL08 product is significant for many scientific fields. To provide on-going and future studies with a comprehensive understanding of ATL08 product, the objective of this work is therefore to evaluate the quality of its terrain height thoroughly. The rest of this article is structured as follows. Section II reviews recent related works. Section III presents a brief introduction to the study areas and the data used to assess ATL08 product, including 3-D elevation program (3DEP) digital elevation models (DEMs), survey marks, and National Land Cover Database (NLCD) 2016 map. After describing the co-registration of different data sets, Section IV discusses the selection of the proper ATL08 terrain height, ATL08 segments, and the influential factors for assessment. Section V presents the evaluation results and discusses the quality of ATL08 products in terms of segments, overall height accuracy, height accuracy in terms of land cover, terrain slope, seasons, and time of acquisition. It also attempts to model ATL08 height errors as a bivariate function of canopy coverage and incidence angle. Section VI summarizes our main findings on the quality properties of the ATL08 terrain products.

II. Related Works

Several assessments on ATL03 product or ATL08 product have been accomplished. Before the launch of ICESat-2, Zhang and Kerekes [10] used Multiple Altimeter Beam Experimental Lidar (MABEL) to simulate the lidar data of ICESat-2 and extracted the ground and canopy returns. They found that the accuracy of extracted ground height would be better in smoother surfaces. Initial studies [7] were carried out with simulated ATLAS data generated from airborne lidar data with high point density over two distinctly different ecosystems (Tundra in Northern Alaska and dense forest in California). Three different frequencies of random noise were injected into the data to simulate three different solar background noise cases. The performances of h_te_interp and h_te_bestfit were analyzed. The initial results indicated that the mean and root-mean-square error (RMSE) residual of these two terrain heights would be close. The h_te_bestfit performed slightly better than h_te_interp except one background noise case in the Tundra region; and the average terrain residuals differences from airborne lidar truth is 0.61 ± 5.50 m for h_te_bestfit and 0.62 ± 5.52 m for h_te_interp [7]. Once the ICESat-2 data became available, Brunt *et al.* [11] compared the ICESat-2 ATL03 photon-based heights on a 750-km long ground-based traverse of the flat interior of the Antarctic ice sheet with reference to kinematic Global Navigation Satellite Systems (GNSS) surface height data using continuously operating Septentrio PolaRx5 receivers and PolaNt-x MF antennas, which were deployed on the smooth-riding rear-center of a sled. Based on this evaluation, they concluded that over the ice sheet interior ATL03 had an accuracy better than 5 cm with a precision better than 13 cm of surface height [11]. Xing *et al.* [12] assessed the performance of ATL03 product referred to a digital terrain model (DTM) at a 1-m resolution collected by an airborne lidar Goddard's LiDAR, Hyperspectral and Thermal imager (G-LiHT). They found that ATL03 would overestimate the elevation compared to the airborne lidar. The mean error and RMSE of all ground photons were, respectively, 0.3 and 0.75 m among a forested area in the City of Aiken, SC, USA [12]. Using ATL03 product of ICESat-2 and Landsat-based Global Surface Water Data Set (GSWD), Xu *et al.* [13] derived a bathymetric map of Lake Mead, USA with the dynamic area exceeding 235 km^2. The produced lake bathymetry achieved an accuracy of approximately 2 m in elevation with an R^2 of 0.97 with the reference to the airborne lidar data and ship/boat-based bathymetric data [13]. As for the accuracy of ATL08 product, Neuenschwander and Magruder [14] conducted a quantitative assessment of the canopy and terrain height (estimated median terrain height and best-fit terrain height) of a 110-km track of ATL08 over a vegetated site in Finland. With reference to airborne lidar data retrieved from the National Land Survey of Finland, the results indicated that the terrain residuals had a mean absolute error of less than 0.5 m (0.37 m for median, 0.39 m for best fit), and the RMSE for median terrain height and best-fit terrain height were 0.85 and 0.82 m, respectively [14]. More recently in 2020, Neuenschwander *et al.* [15] validated the terrain and canopy heights estimated from 11 months of ICESat-2 data using airborne lidar data collected in southern Finland. They discovered the accuracy of terrain height and canopy height from ATL08 products are influenced by snow presence, beam selection, season, and time of acquisition. The terrain heights from ATL08 product had a vertical error less than 0.75 m (mean = −0.07 m; mean absolute error = 0.53 m, RMSE = 0.73 m), and a positive bias (0.33 m) under the presence of permanent snow cover [15]. In the same year, Dandabathula *et al.* [16] evaluate 40 segments of ATL08 product in a semiarid region of India with reference to differential GPS (DGPS) survey points. The study area has a topography variation from flat to almost flat. In their research, the deviation of h_te_bestfit is in the range of 1–70 cm, and the accuracy of h_te_bestfit is better than 12 cm (RMSE) for segments represented by strong beams [16].

Of primary interest to the scientists is the accuracy of ATL08 terrain height derived from the ATLAS measurements. Benefit from the single-photon technology, ATLAS needs a lower energy laser power than other conventional lidar system and operates at high repetition rates leading to an improved along track resolution [17]. However, high sensitivity to photons makes solar background noise a big challenge to ATLAS. As such, relatively low laser energy may cause losing ground signal under dense forest and in situations where cloud cover obscures the terrain signal [7], [8]. In brief, the ATLAS photon-counting measurements are dependent on the laser energy, surface reflectance, solar conditions, and scattering and attenuation in the atmosphere [7], [8]. Despite all above evaluations indicated that ICESat-2 ATL08 held a submeter terrain accuracy, the vertical accuracy of terrain height is affected by many factors such as incidence angle [18], [19] and land cover [20], which has not been assessed in sufficient detail at a large spatial extent with diverse land covers since most of the reported studies were focused on glaciers. Moreover, the seasonality change of land cover (vegetation or trees) and time of acquisition (day or night) may affect the vertical accuracy of the ATL08 terrain height as well [15]. It is therefore necessary to perform a comprehensive assessment for ATL08 terrain height over a large spatial extent with varying land covers so that it can be subsequently utilized for extracting other trustworthy information beyond ice sheet, sea, and glaciers.

Based on previous analysis, our hypothesis is that the uncertainty of terrain height of ICESat-2 ATL08 product is dependent on canopy coverage, number of ground photons within each 100-m segment, topography, incidence angle, land cover, season, and data acquisition time. In this article, we choose Tippecanoe County, IN and Mendocino County, CA as our study areas, which are plain region and mountain region, respectively. The U.S. Geological Survey (USGS) 3DEP DEM [21] is regarded as the primary reference elevation. In addition, the 2016 land cover and land use maps produced by NASA [22] will be introduced for land cover related evaluation.

III. Study Areas and Data

A. Study Areas

Two full counties in the USA shown in Fig. 2 are chosen for evaluation. Tippecanoe County is located in the west-central portion of Indiana State in the USA about 35-km east of the Illinois state border. It is regarded as a representative of plain region for this study since its average slope is less than 2° and max elevation difference is about 110 m. According to the 2010 census, the county population was 172 780 and has a total area of 503.24 square miles (1303.4 square km), of which 499.81 square miles (1294.5 square km or 99.32%) is land and 3.44 square miles (8.9 square km or 0.68%) is water. Different from Tippecanoe County, Mendocino County is a county located on the northern coast of the California State. It is mostly mountains with an average slope larger than 6° and max elevation difference of 2100 m. It is regarded as a representative of mountain region for this study. As of the 2010 census, the county population was 87 841 and had a total area of 3878 square miles (10 040 square km), of which 3506 square miles (9080 square km, or 90.41%) is land and 372 square miles (960 square km or 9.59%) is water. These two study areas are within two ICESat-2 geographic granules (No. 02 and 06). The data were collected from December 2018 to February 2020 for Tippecanoe, and October 2018 to May 2020 for Mendocino. Tippecanoe has 5 unique tracks, while Mendocino contains 12 unique tracks. The data we aim to evaluate is the terrain height from ATL08 product Version 003. The density of the segments is quite similar for these two counties, 12.08 segments per square km for Tippecanoe and 9.56 segments per square km for Mendocino. Table I details the month, time (day or night), track ID, and the number of segments of the ATL08 data used in this study.

B. Reference Elevation Data

Two elevation data sources will be used as reference. Fig. 2 shows the USGS 3DEP DEM for the two counties. The 3DEP DEMs are produced from airborne lidar under the USGS National Geospatial Program. As shown in Fig. 2, the most recent (released in January 2020) Tippecanoe County 3DEP DEM is at a resolution of 2.5 ft (0.76 m) under the Universal Transverse Mercator (UTM) projection. Its horizontal datum is the North American Datum 1983 (NAD83), while its vertical datum is the North American Vertical Datum 1988 (NAVD88). As for Mendocino County, its 3DEP DEM is at 1-m resolution under the UTM projection and was released during 2017–2018. Its horizontal datum is the NAD83 and the vertical datum is the NAVD88. According to the specification

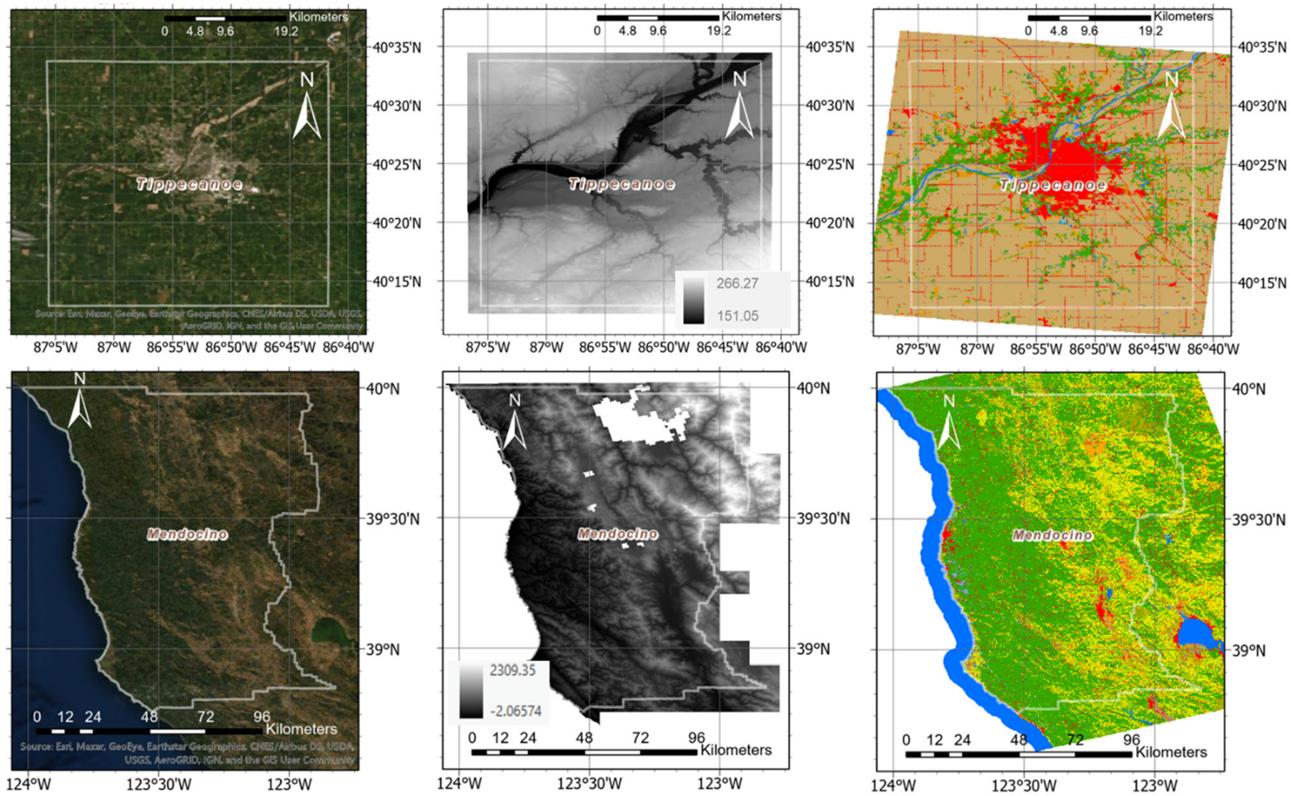

Fig. 2. Data sets of the two study areas. (Top) Tippecanoe County and (Bottom) Mendocino County as our study areas. (From left to right) Satellite imagery (Esri), USGS 3DEP DEM, and aggregated USGS NLCD 2016 maps.

TABLE I

SUMMARY OF ATL08 DATA PRODUCT IN THE STUDY AREAS

Year	Month	Tippecanoe county				Mendocino county			
		Track ID		# segments		Track ID		# segments	
		day	night	day	night	day	night	day	night
2018	Oct	\	\	\	\	\	486	\	4985
	Nov	\	\	\	\	570	547	1795	747
	Dec	\	1361	\	1809	1012	44, 989	3092	4666
2019	Jan	\	\	\	\	67, 509	486	3647	2526
	Feb	896, 919	896	963	2002	\	\	\	\
	Mar	1361	1361	1697	2	1012	\	42	\
	Apr	\	\	\	\	486	44	4211	11
	May	896, 919	\	1322	\	509,547,570,928	509	2379	1
	Jun	1361	3161	4	1121	989, 1012	1012	817	2040
	Jul	454	\	52	\	486, 509	509	4013	2081
	Aug	896	\	103	\	547, 928, 989	570, 951, 989	2711	2226
	Sep	1338, 1361	1338, 1361	1053	1027	44, 1012	1012	312	2846
	Oct	\	\	\	\	67, 486, 509	67, 486, 509	4503	7143
	Nov	896	896, 919	1618	687	547, 570, 951	570, 951	3474	2341
	Dec	\	1361	\	19	67	44, 67, 1012	3142	4228
2020	Jan	\	\	\	\	509	105, 128, 547	3683	4158
	Feb	896	896	414	1851	570	989	3333	3961
	Mar	\	\	\	\	1012	1012	2890	6
	Apr	\	\	\	\	486, 509	105, 486, 509	2693	4566
	May	\	\	\	\	547	547	336	411
Total		12	10	7226	8518	32	30	47073	48943

of the 3DEP provided by USGS, its vertical accuracy is 10 cm (1σ) in nonvegetated area and 15 cm (1σ) in vegetated area [21].

For any spaceborne lidar product, evaluation of its quality is challenging since nearly all reference data will have errors as well. When comparing the ATL08 product with the reference data, one should also consider the uncertainty of the reference data itself. To assure a reliable evaluation, we introduce the survey marks provided by the National Spatial Reference System (NSRS) of NOAA's National Geodetic Survey (NGS).

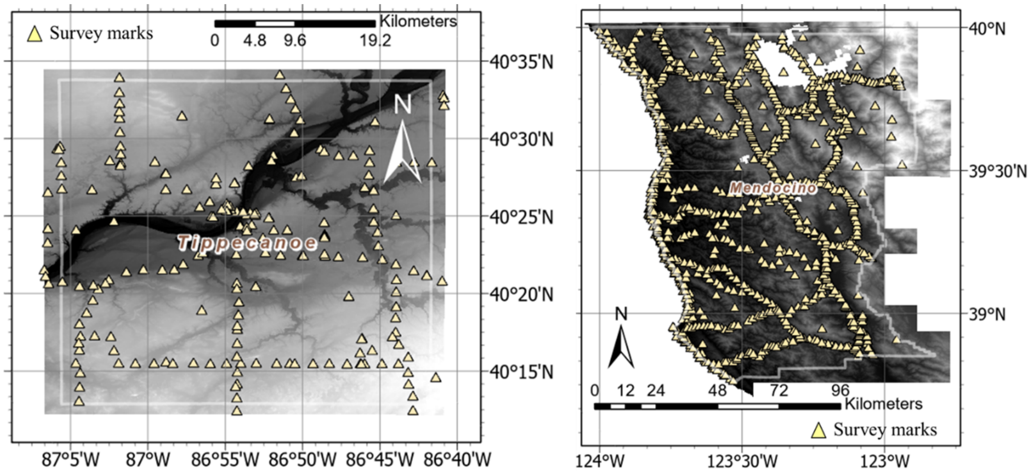

Fig. 3. Survey marks distribution in the study areas. (Left) Tippecanoe County and (Right) Mendocino County.

TABLE II
HEIGHT DIFFERENCES OF 3DEP DEM WITH REFERENCE TO SURVEY MARKS

County	# Survey marks (Inner 90%)	Mean (m)	Std. Dev (m)
Tippecanoe	161	0.039	0.377
Mendocino	918	0.435	1.774

The survey marks are mostly random in space and refer to permanent marks or disks placed in the ground or attached to a permanent structure with known latitude, longitude, or height information [23]. They will be used to make an independent assessment for the 3DEP DEM. It should be noted that these survey marks cannot be directly used for evaluating ATL08 product because both survey marks and ATL08 data are very sparse in space. We downloaded 234 and 1221 survey marks for Tippecanoe County and Mendocino County from NSRS. According to the information about NGS survey marks [23], “stability” index is an indicator as to whether the point is likely to move in space, either horizontally or vertically. When the “stability” equals “*D*” (the worst condition), the survey marks may have a questionable monument with unknown reliability. Thus, we discarded those survey marks whose stability index is “*D*,” resulting in 179 survey marks for Tippecanoe County and 1020 for Mendocino County, as shown in Fig. 3. We use the locations of these survey marks to extract the heights from 3DEP DEM and compare them with the heights of the survey marks. The height error of 3DEP DEM is then determined by cutting off the first 5% and last 5% of the height difference distribution between these two heights, which leads to 161 and 918 remaining survey marks, respectively, in Tippecanoe County and Mendocino County. Table II summarizes the statistics of the cleaned height differences. We find that the 3DEP DEM actually overestimates the height referred to the survey marks for both counties. As shown in Table II, the vertical accuracy of the 3DEP DEMs referred to the survey marks is below the normally expected 15 cm (30 cm at 95th percentile [21]) for vegetated area, i.e., 0.039 ± 0.377 m for Tippecanoe County and 0.435 ± 1.774 m for Mendocino County.

C. National Land Cover Data Set 2016

The vertical accuracy of ATLAS is related to land cover type. The 2016 National Land Cover Data Set [22] is regarded as supplementary data to assist our assessment. NLCD is produced based on Landsat-8 multispectral satellite images at 30-m resolution. Among a total of 18 land cover types for NLCD 2016 map [22], there are 16 nominal land cover types in our study areas. Their distribution is summarized in Table III. In this study, the four (4) different developed land cover types are merged into one (1) “developed land cover,” and three (3) different forest land cover are combined into one (1) “forest land cover.” We select the land cover types that have more than 2% of the total land cover for our evaluation. As such, four (4) land cover types for Tippecanoe County and four (4) land cover types of Mendocino County are participated in the assessment.

Table IV summarizes the mean and standard deviation of slopes for these land cover types in the order of percentage of the land cover from most to the least. Cultivated crops, which is the most common land cover in Tippecanoe County, has a very smooth topography. Whereas Forest, the most common land cover in Mendocino County, has a much rougher topography.

IV. STUDY DESIGN AND METHODS

A. Data Co-Registration

Since several different elevation data sets are involved in this study, it is necessary to co-register them correctly. Tippecanoe County and Mendocino County’s 3DEP DEM are in NAD83 horizontal datum with UTM projection, while the NLCD 2016 is in WGS84 horizontal datum with Albers projection. The ATL08 v003 product is in WGS84 horizontal datum without projection. As for the vertical datum, Tippecanoe County’s 3DEP DEM is in foot and referred to the NAVD88 vertical datum, while Mendocino County’s 3DEP DEM is in meter and referred to NAVD88. ATL08 terrain height is in meter above the WGS84 ellipsoid [7], [24]. We transform all data to NAD83 with the UTM projection. As for the ATL08 terrain height, it is transformed into

TABLE III

LAND COVER PERCENTAGE IN TIPPECANOE AND MENDOCINO COUNTIES FROM NLCD 2016. HIGHLIGHTED LANDCOVER TYPES ARE, RESPECTIVELY, AGGREGATED FOR EVALUATION. REMAINING LAND COVERS THAT ARE LESS THAN 2% (GRAYED) OF THE TOTAL AREA ARE EXCLUDED FROM EVALUATION

County	Open water	Open space (developed)	Low intensity (developed)	Medium intensity (developed)	High intensity (developed)
Tippecanoe	0.64	5.71	4.06	1.77	0.65
Mendocino	0.18	4.85	0.37	0.10	0.03
	Barren land	Deciduous forest	Evergreen forest	Mixed forest	Shrub
Tippecanoe	0.03	5.16	0.01	1.97	0.02
Mendocino	0.10	1.99	47.06	5.81	29.65
	Herbaceous	Hay	Cultivated crops	Woody wetlands	Emergent herbaceous wetlands
Tippecanoe	1.23	4.67	72.85	1.04	0.20
Mendocino	7.67	1.18	0.32	0.52	0.17

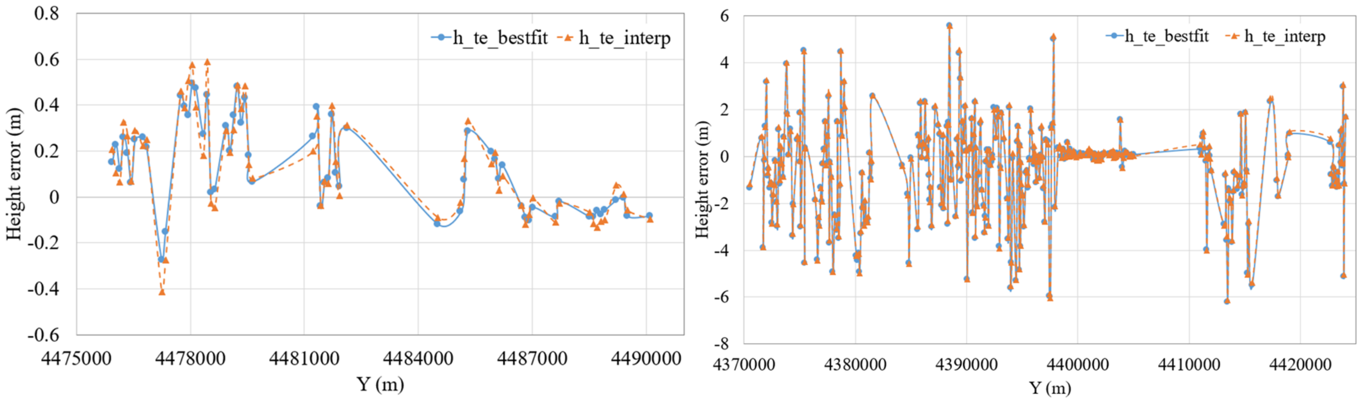

Fig. 4. Height errors of h_te_interp and h_te_bestfit with respect to 3DEP DEM. Track No.454 in (Left) Tippecanoe County and track No.44 in (Right) Mendocino County.

the orthometric height NAVD88 by subtracting the geoid height of each location from the ellipsoid height based on the NOAA's Vertical Datum Transformation v4.1 [25]. The calculated geoid heights have a mean of −34.879 m with a standard deviation 0.156 m for Tippecanoe County, and a mean of −29.928 m with a standard deviation 0.984 m for Mendocino County.

B. ATL08 Heights

The ATL08 product has two terrain heights: the best-fit terrain height (h_te_bestfit) and the interpolated height (h_te_interp) [6], [7]. Fig. 4 plots the ATL08 height errors of a track, i.e., the differences of the ATL08 heights with respect to the 3DEP DEM, for each county. The plots first illustrate that the two ATL08 heights are actually very close, with a relative difference 0.005 ± 0.087 m for Tippecanoe and 0.048 ± 0.073 m for Mendocino, respectively, for these two specific tracks.

Comparing to the 3DEP DEM along 17 tracks in total, the accuracy of the ATL08 h_te_bestfit is -0.011 ± 0.163 m for Tippecanoe County and -0.405 ± 1.829 m for Mendocino County. Similarly, the accuracy of the ATL08 h_te_interp is -0.008 ± 0.237 and -0.457 ± 1.897 m, respectively, for the two counties. Except one slightly worse mean (−0.011 m versus −0.008 m), the h_te_bestfit has a higher accuracy and smaller variation than the h_te_interp. This initial evaluation confirms the finding with simulated ICESat-2 data by Neuenschwander and Pitts in 2019 [7] that the h_te_bestfit is slightly better than the h_te_interp. As such, we will only evaluate the h_te_bestfit in the ATL08 product thereafter.

C. ATL08 Segments

Once the data are co-registered, elevation values are extracted from the reference 3DEP DEMs for each segment in all tracks of the ATL08 product. Then, the extracted elevation from the 3DEP DEM is subtracted from the ATL08 height, yielding the ATL08 height errors. It is noticed that some of these errors are significantly large, which shall not be included for a trustworthy assessment. As such, we need to exclude invalid segments and outlier segments, both of which have a poor confidence.

ATL08 product provides each segment with an uncertainty index "h_te_uncertainty" for the mean terrain elevation. This uncertainty index incorporates all systematic uncertainties

TABLE IV
TERRAIN SLOPES FOR MAJOR LAND COVERS

			Cultivated crops	Developed	Forest	Hay
Tippecanoe	Percentage (%)		72.85	12.19	7.14	4.67
	Slope (degree)	Mean	1.55	3.32	7.85	2.83
		Std. Dev	2.20	4.28	9.50	3.51
			Forest	Shrub	Herbaceous	Developed
Mendocino	Percentage (%)		54.86	29.65	7.67	5.35
	Slope (degree)	Mean	24.89	21.20	16.70	16.62
		Std. Dev	11.09	10.67	11.65	12.41

(e.g., timing, orbits, geolocation, etc.) as well as the uncertainty in photon identification [7]. An "invalid" value (3.4028E + 38) will be reported if the number of ground photons in the segment is $\leq 5\%$ of total number of signal photons per 100-m segment [6], [7]. Without a sufficient number of ground photons in a segment, the calculated terrain height has little confidence. Thus, the segments with the "invalid" value in the h_te_uncertainty attribute in the ATL08 product, noted as invalid segments, are eliminated from evaluation.

ATL08 product may also have large uncertainties when laser beams are reflected from irregular canopy and building roofs. After getting the differences between the ATL08 terrain height and the 3DEP DEM, we only keep the inner 90%, i.e., discarding the points that are in the first 5% and the last 5% of these differences. The remaining segments, thereafter regarded as normal segments, are retained for subsequent analysis. They will be assessed by calculating the mean, median, and standard deviation of the ATL08 height errors, i.e., the elevation differences between terrain height of ATL08 and 3DEP DEM, in terms of land cover, season, acquisition time, terrain slope, and incidence angle.

D. Influential Factors

Several factors will influence the ATL08 height accuracy. Seasonal change of vegetation and the time of acquisition have certain impact on the ATL08 height accuracy [15]. Different land cover has different impacts on height measurement. For example, water area and dense forest area have a great influence on the reflectance of lidar, which considerably affects the elevation accuracy. Moreover, height accuracy is correlated with the incidence angle, noted as θ, defined by the angle between the laser beam and the terrain surface normal [26]. The laser beam and the normal of terrain surface are regarded as unit vectors b° and s°, respectively. Both unit vectors can be determined by two angles, the angle α between the vector itself and nadir, and the angle ϕ between the projection of vector on horizontal plane and north (i.e., the azimuth). Under these definitions, the normal of terrain surface s° can be represented as $(\sin\alpha_s \sin\phi_s, \sin\alpha_s \cos\phi_s, \cos\alpha_s)$, and the laser beam b° is $(\sin\alpha_b \sin\phi_b, \sin\alpha_b \cos\phi_b, \cos\alpha_b)$. The incidence angle θ can then be inferred by the dot product of these two unit vectors, see the following equation:

$$\cos\theta = \sin\alpha_s \sin\alpha_b (\cos(\phi_s - \phi_b)) + \cos\alpha_s \cos\alpha_b. \quad (1)$$

The ϕ_s and α_s (slope) are calculated pixel by pixel for two counties based on the 3DEP DEM, while the ϕ_b and α_b of the laser beam are two parameters, off-nadir pointing angle (atlas_pa) and azimuth of the laser beam (beam_azimuth), provided in ATL08 for each segment.

To get a comprehensive assessment on the ATL08 accuracy, incidence angle θ and canopy coverage (Landsat_perc) are combined to analyze the vertical accuracy of the ATL08 product. The canopy coverage and incidence angle are summarized according to the binned height error. The height error bin is chosen as 0.04 m. Finally, the effects of canopy coverage and incidence angle on height error are modeled.

V. RESULTS AND DISCUSSION

This section first presents results from segment selection and then discuss the overall accuracy of the ATL08 terrain height. The distributions of their height errors with reference to 3DEP DEM are demonstrated and summarized. Second, major land cover types for Tippecanoe County and Mendocino County are selected, so that the statistics of height errors can be summarized accordingly. Third, ATL08 height errors are studied in terms of the season and time of acquisition. Finally, the effects of slope, incidence angle as well as canopy coverage to ATL08 height error are discussed and modeled for both counties.

A. Quality of Segments

Table V summarizes the statistics of invalid segments, outlier segments, and normal segments. As shown in Table IV, 54.86% of Mendocino County is forest land cover, thus it has much more invalid segments than Tippecanoe County (34% versus 2%) (see Table V). According to Table V, invalid segments for both counties are associated with a small number of ground photons (less than four ground photons in average). Furthermore, their canopy coverage (30.8% and 57.8%) is also significantly larger than the ones in outlier segments and normal segments. As shown in Fig. 5, the invalid segments are almost covered entirely by trees while the valid segments are not. It reveals the fact that few ground photons would be received by ATLAS due to the large canopy coverage, leading to an invalid segment.

In contrast, outlier segments are mostly locations with sufficient (up to over a hundred) number of photons (see Table V) including wrongly classified ground photons in

TABLE V
STATISTICS OF INVALID, OUTLIERS, AND NORMAL SEGMENTS

		County		Tippecanoe	Mendocino
Total number of segments				15,744	96,016
Invalid segments		Number of segments		315 (2%)	33,046 (34%)
		Number of ground photons	Mean	3.13	3.38
			Std. Dev.	9.76	2.7
		Canopy Coverage (*landsat_perc*) (%)	Mean	30.8	57.8
			Std. Dev.	17.26	16.6
		Slope (degree)	Mean	10.77	25.82
			Std. Dev.	11.04	11.05
Valid segments	Outlier segments	Number of segments		1,575 (10%)	6,298 (6%)
		Number of ground photons	Mean	157.07	16.6
			Std. Dev.	275.21	30.74
		Canopy Coverage (*landsat_perc*) (%)	Mean	13.08	50.29
			Std. Dev.	14.51	19.92
		Slope (degree)	Mean	7.11	27.41
			Std. Dev.	9.69	11.34
		h_te_uncertainty	Mean	4.82	65.69
			Std. Dev.	7.34	68.07
	Normal segments	Number of segments		13,854 (88%)	56,672 (59%)
		Number of ground photons	Mean	149.99	54.77
			Std. Dev.	139.85	73.27
		Canopy Coverage (*landsat_perc*) (%)	Mean	4.15	35.58
			Std. Dev.	7.95	20.85
		Slope (degree)	Mean	1.96	19.84
			Std. Dev.	2.79	11.37
		h_te_uncertainty	Mean	2.02	33.88
			Std. Dev.	2.14	45.56

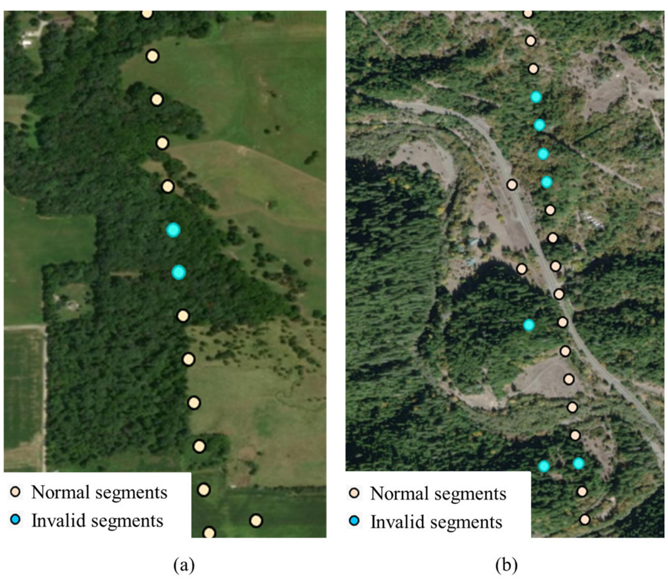

Fig. 5. Tracks of ATL08 terrain height with invalid segments in the study areas. (a) Tippecanoe County and (b) Mendocino County. The distance between two adjacent points (segments) along the track is 100 m.

ATL08. The left demonstration over Tippecanoe County in Fig. 6 shows an example of buildings causing an outlier segment that even has 174 ground photons. In this case, photons reflected from building roof are classified as ground photons by the Differential, Regressive, and Gaussian Adaptive Nearest Neighbor (DRAGANN) algorithm during ATL08 data production to find signal photons [7]. It is noticeable that the terrain height of ATL08 actually is the elevation of the surface including buildings rather than elevation of the bare Earth. Since Tippecanoe County has more population from 2010 Census (172 780 versus 87 841) and more developed land cover (12.19% versus 5.35% from Table IV), buildings cause significant outlier segments (10%) as shown in Table V. According to the information of outlier segments over Mendocino County in Table V and the right illustration of Fig. 6, another situation where outlier segments usually occur is the segments with high canopy coverage, rough topography and relatively small number of ground photons. Low number of ground photons are reflected from vegetated surface, coupled with complex topography; it is very challenging to accurately represent the peaks and valleys. As a result, the detected ground surface would be smoother than the true surface, causing a large height uncertainty. Considering all these, we purposely exclude building points as outliers due to the unpredictable uncertainty caused by the large footprint of 17 m [5], [7] of the ICESat-2 laser beam. As such, we are only evaluating the ground returns in the ATL08 products to assure the reliability of this study. After removing the invalid segments and the outlier segments, our remaining normal segments are actually the returns from the bare ground.

After excluding the invalid segments and outlier segments, the remaining normal segments are ground segments with the smallest canopy coverage (4.15% and 35.58% from Table V), smallest slope (1.96° and 19.84° from Table V), and sufficient number of photons. It should be noted that the value (score) of the index h_te_uncertainty in the ATL08 product can reflect the quality of the segments. For the outlier segments we selected, as shown in Table V, the mean and standard deviation of h_te_uncertainty are larger (4.82 ± 7.34 for Tippecanoe

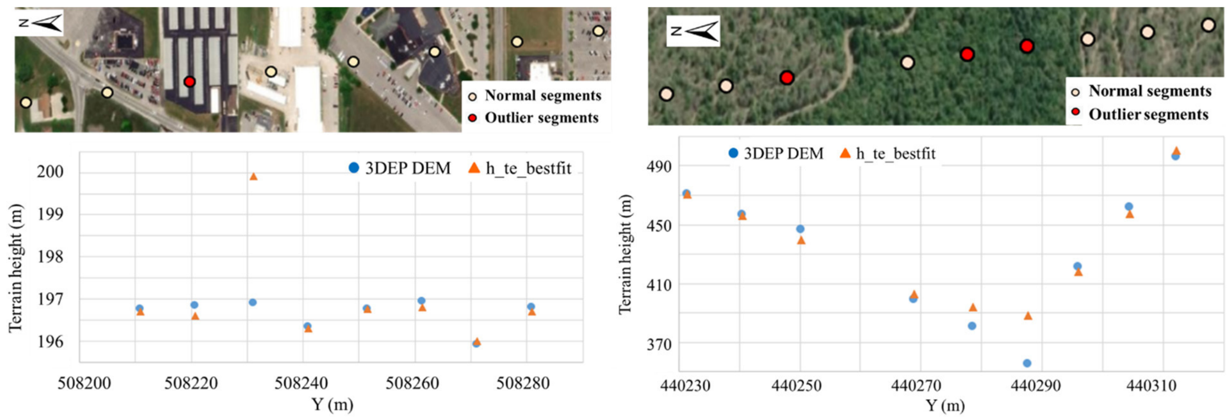

Fig. 6. Terrain height profiles of ATL08 and 3DEP DEM with outlier segments. (Left) Outlier segments resulting from buildings in Tippecanoe County. (Right) Outlier segments resulting from trees in Mendocino County.

TABLE VI
OVERALL VERTICAL ACCURACY OF ATL08 WITH REFERENCE TO 3DEP AND SURVEY MARKS

County	Reference	Mean μ (m)	Std. Dev. σ (m)	Median (m)	% in ($\mu \pm \sigma$)	% in ($\mu \pm 2\sigma$)
Tippecanoe	3DEP	-0.011	0.163	-0.011	80.6%	92.9%
	Survey Marks (calculated)	0.028	0.411	N/A	N/A	N/A
Mendocino	3DEP	-0.416	1.963	-0.191	75.7%	92.2%
	Survey Marks (calculated)	0.038	2.646	N/A	N/A	N/A

County, 65.69 ± 68.07 for Mendocino County) than for normal segments (2.02 ± 2.14 for Tippecanoe County, 33.88 ± 45.56 for Mendocino County). It is therefore concluded that h_te_uncertainty is a comprehensive parameter revealing uncertainty and confidence of an ATL08 segment. It can be used for ATL08 data processing and applications.

B. Overall Height Accuracy

After excluding the invalid segments and outlier segments, the distributions of the ATL08 height errors with respect to 3DEP DEM for both counties are presented in Fig. 7. Their overall vertical accuracy is summarized in Table VI. For Tippecanoe County, the ATL08 height error is −0.011 ± 0.163 m. These are in contrast to the statistics −0.416 ± 1.963 m in Mendocino County. For Tippecanoe County, 80.6% of the ATL08 height errors is within the range of 1σ, and 92.9% of it is within 2σ; these statistics are, respectively, 75.7% and 92.2% for Mendocino County. This is in contrast to the common 68%–95%–99.7% rule (with respect to 1, 2, 3σ) for normal distribution. Although the ATL08 height errors for both counties are more centralized (1σ) than the standard normal distribution, they also have longer tails, i.e., an abnormal amount of errors occur beyond 2σ. The percentage of larger errors ($>2\sigma$), 7.1% for Tippecanoe County, and 7.8% for Mendocino County are more than what a normal distribution suggests. Counting the facts that we have excluded outliers in the evaluation, it is a precautious reminder that the uncertainty of the ATL08 terrain height data is likely larger than one would normally expect.

Recalling the statistics from Table IV, the difference between vertical accuracy of the two counties can be analyzed in terms of terrain slope and land cover. Compared to Mendocino County, the vertical accuracy of the ATL08 product in Tippecanoe County has a better quality since 73.95% of it has a slope less than 2° and 72.85% of it is cultivated crops, which by definition is areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards [22]. Such a lower canopy over smoother terrain leads to the higher vertical accuracy (−0.011 ± 0.163 m) of ATL08 product in Tippecanoe County. In contrast, 54.86% of Mendocino County is covered by forest and 88.39% of its slopes is between 6° and 35°. The vertical accuracy of ATL08 terrain height becomes lower and less stable (−0.416 ± 1.963 m) due to the large elevation variation and dense forestry coverage.

Table VI suggests the terrain height of ATL08 product underestimates (being lower) the topography by 0.011 and 0.416 m, respectively, for Tippecanoe and Mendocino County. This needs to be explained and justified. As shown in Table II, 3DEP DEM exhibits an overestimation of the survey marks.

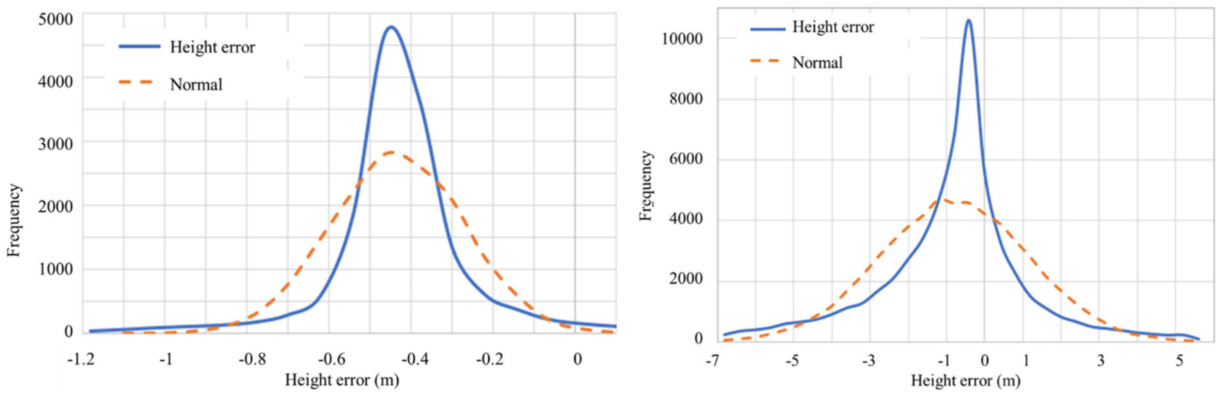

Fig. 7. Distribution of ATL08 height errors with respect to 3DEP DEM. (Left) Tippecanoe County and (Right) Mendocino County. For reference, the dash curves present the density function of the corresponding normal distribution.

Assuming the height error of ATL08 referred to 3DEP DEM (d_{A3}) and the height error of 3DEP DEM referred to survey marks (d_{3s}) are independent, the height error of terrain height for ATL08 product with reference to survey marks (d_{As}) can then be calculated through $d_{As} = d_{A3} + d_{3s}$. By applying error propagation to Tables II and VI, the mean of height error between ATL08 and survey marks is $\mu_{As} = \mu_{A3} + \mu_{3s}$, and the standard deviation of height error is $\sigma_{As} = \sqrt{\sigma_{A3}^2 + \sigma_{3s}^2}$. As such, the vertical accuracy of terrain height for ATL08 product referred to survey marks is summarized in Table VI.

Produced from lidar, ATL08 would overestimate the terrain height referred to survey marks. This overestimation is mainly caused by the mechanism of lidar. The elevation of terrain is determined by the photons reflected from objects on the ground, and noise photons are sourced from trees or atmosphere. It should be noted that the term "noise photon" is usually referred to solar background noise or instrument noise, while we also use it in this article for within-canopy photons or canopy photons that are misclassified to ground photons since we are focusing on terrain height of ATL08 product. Under this context, photons received by ATLAS would always be from the ground or above the ground surface, causing an overestimation of ATL08. Moreover, it is noticed that ATL08 overestimates the terrain height less than the 3DEP DEM does. This less overestimation is likely due to the processing algorithm for ATL08 production. According to [7], an iterative ground finding filter was applied to refine the initial results determined by using the ground photons found by the DRAGANN filter. The ground finding filter sets a lower bound and an upper bound. The lower bound is offset by 4 m below the median surface of the initial ground photons, while the upper bound is 1-m offset above the median surface. The photons lying between the bounds are defined as the refined ground photons. The refining algorithm is designed to choose the lower part of photons as refined ground photons. Thus, DRAGANN filter makes compensation to the overestimation of ATL08 terrain height, leading to a less overestimation. In summary, when evaluating the quality of the ATL08 data, the quality of the 3DEP DEM shall be taken into account as well. The ATL08 height is between 3DEP DEM surface and the true ground surface, with an offset less than 0.20 m above the ground.

C. Height Accuracy in Terms of Land Cover

The land cover type of each segment is extracted based on the NLCD 2016 map. Elevation accuracy in terms of land cover types is accomplished by calculating the mean and standard deviation of ATL08 height errors for each land cover type. As shown in Table IV, there are, respectively, four (4) major land cover types that are more than 2% of the two counties. Fig. 8 shows the statistics of the ATL08 height errors with respect to different land covers. The cultivated crops in Tippecanoe County has the most accurate elevation with an uncertainty 0.004 ± 0.131 m. This is the land cover type with the smoothest terrain according to Table IV. Similarly, for the Mendocino County, the ATL08 product has the best accuracy −0.528 ± 1.457 m for the herbaceous land cover, which as shown in Table IV holds the second smallest and stable slope (16.70°± 11.65°). This is very close to the smallest slope (16.62°± 12.41°) of the developed land cover. It can therefore be inferred that for those nonforest land covers without steep slope, such as cultivated crops and herbaceous, the ATL08 product has the most accurate terrain height. Furthermore, cultivated crops in Tippecanoe County is the area that has minimum effect from relief, building, and forest. Thus, its height error can be regarded as representative of the best quality of terrain height for ATL08 product. For those land covers whose slopes and canopy coverage are between the cultivated crops and forest, such as developed, hay and shrubs, their ATL08 height errors are similar to each other and fall between cultivated crops and forests.

For both counties, terrain height of the ATL08 product has the highest height uncertainty over forest. The forest with rough topography contributes to the poor precision of the ATL08 product in two ways. On the one hand, dense vegetation leads to a relatively low number of ground photons, which makes it difficult to represent the complex topography and smooths the terrain surface after filtering (for instance Fig. 6, right). On the other hand, noise photons are likely intermixed with signal photons as input to the ATL08 algorithm over

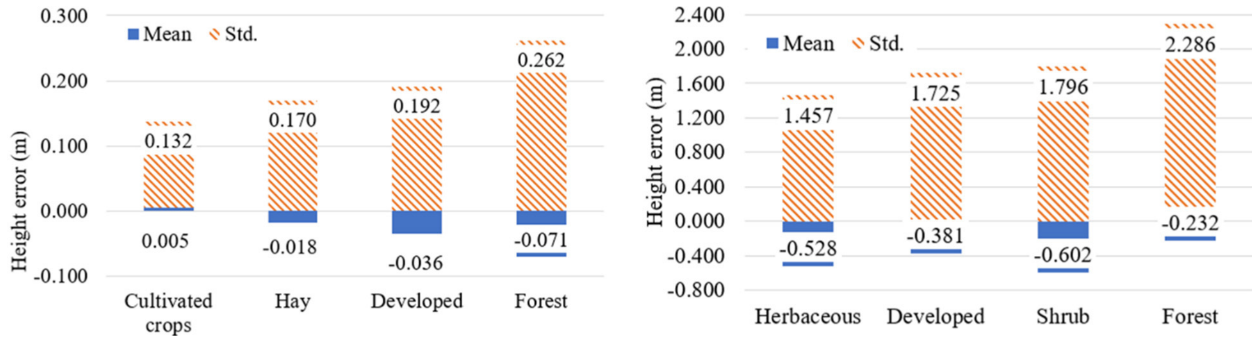

Fig. 8. Mean and standard deviation of ATL08 height errors with respect to 3DEP DEM summarized by land cover types. (Left) Tippecanoe County and (Right) Mendocino County.

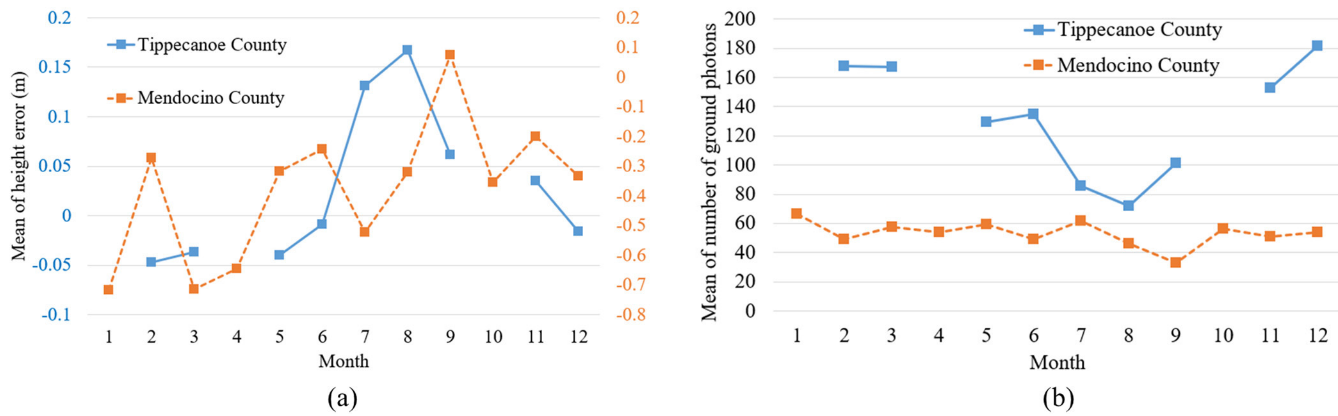

Fig. 9. (a) Seasonal variation of ALT08 height errors with respect to 3DEP DEM and (b) number of ground photons.

forest due to the complicated tree structure. Those noise photons were misidentified as either canopy or ground photons, which subsequently led to incorrect estimates of terrain height in ATL08 product. One noticeable value is the mean of height errors in Mendocino County (−0.232 m). Different from the mean of height errors in Tippecanoe, it is the "smallest" (less underestimate with reference to 3DEP DEM than other land cover) in Mendocino. Accuracy of terrain height is a big challenge in areas having dense vegetation where only a handful of photons are likely returned from ground with majority of reflections from within the canopy. It is expected that the detected ground surface in dense forest area would be drawn upward into the canopy inside [7]. The canopy coverage for the forest land cover in Mendocino is 52.96% ± 14.75%. The large canopy coverage of forest in Mendocino leads to its segments with an uplifted ground surface, which is below but closer to the 3DEP DEM compared to other land cover.

D. Seasonal Variation of Height Accuracy

Seasonable change of vegetation and trees may possibly result in visible variations in ATL08 height accuracy. To explore this, Fig. 9 presents the mean height error and mean number of ground photons by month for the two counties. As shown in Fig. 9(a), winter to spring (January to May) is the season when the ALT08 height is the most underestimated referred to 3DEP DEM. Fig. 9(b) also shows that ATL08 collects a slightly higher amount of ground photons in this season. After the summer (June–August), as the vegetation or tree grows, the number of reflected ground photons keeps decreasing and reaches the minimum in August for Tippecanoe County and September for Mendocino County. Grown vegetation and trees attribute to the low number of reflected ground photon as well as a lifted upward "terrain." Therefore, it can be seen from Fig. 9(a) that terrain height of ATL08 product becomes closer to ground from January to summer months, and the largest mean of height errors occurs in August for Tippecanoe County and September for Mendocino County when canopy/vegetation is fully developed. Received ground photons have decreased by 53.6% for Tippecanoe county and 42.1% for Mendocino County in August/September compared to the average received number of ground photons in spring, and the corresponding height error has increased by 508.4% (0.208 m) for Tippecanoe County and 114.0% (0.608 m) for Mendocino County. Mendocino County exhibits less seasonal effect on height error and received ground photons on account of the majority of evergreen forest in Mendocino County and majority of cultivated crops in Tippecanoe County (see Table III).

The seasonality of height error is attributed to the seasonal change of vegetation/forest on the ground. Nevertheless, it should be noted that the terrain height error change is in the range of 0.21 m for the Tippecanoe County and 0.79 m for the Mendocino County. The corresponding maximum photon count change is less than 60%. It presents relatively higher stability in subtropical area than in inland region.

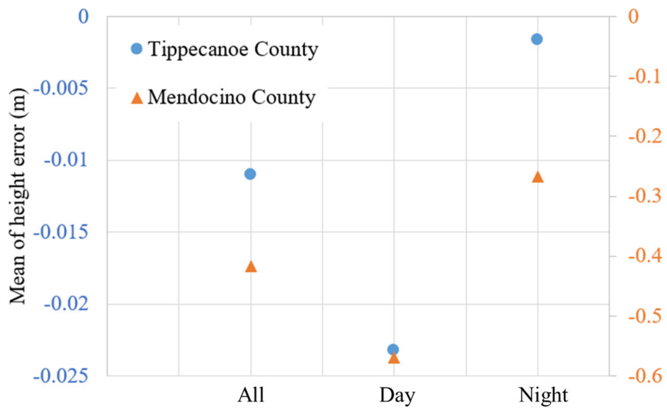

Fig. 10. Diurnal variation of ALT08 height errors with respect to 3DEP DEM.

E. Diurnal Variation of Height Accuracy

One of the difficulties in photon-counting lidar is to distinguish the noise photons from signal photons. The presence of solar background noise would impede or reduce the quality of the ground finding algorithm. As a result, night acquisitions should potentially result in a more accurate terrain height than day acquisitions [15]. After filtering the normal segments in terms of acquisition time, Fig. 10 shows their height accuracy for day acquisitions and night acquisitions. As expected, the night acquisitions yield a more accurate terrain height than day acquisitions. For Mendocino County, the mean of height errors is −0.57 m for day acquisitions and −0.27 m for night acquisitions (0.30-m difference). For Tippecanoe county, night acquisitions have the least height error −0.002 and −0.023 m for day acquisitions (0.022-m difference). Recalling Table V, the vegetation distribution and terrain type of Tippecanoe County is very different from Mendocino County which has a 35% mean canopy coverage and 20° mean slope, resulting in a much greater number of ground photons per segment for Tippecanoe county (mean 149) than Mendocino County (mean 54). These results indicate that the impact of acquisition time (day versus night) is actually very minor for regions with low canopy coverage and smooth terrain, since the number of received ground photons is large enough to detect a clearer ground surface even under the solar background noise in a daytime. On the other hand, for Mendocino County, which has much fewer received ground photons due to its dense canopy and complex topography, the diurnal variation yields more significant impact.

F. Height Accuracy in Terms of Slope

As a spaceborne lidar product, ATL08 height accuracy is affected by terrain slope. Fig. 11 demonstrates the relationships between the mean and standard deviation of ATL08 height errors and slope for different land covers. For Tippecanoe County, the mean of the ATL08 height errors is linearly dependent on the slope for developed, forest, and hay land cover with an R^2 larger than 0.80. The slightly small R^2 for cultivated crops land cover indicates that the mean ATL08 height error is not dependent on slope and has little change as the slope increases. For Mendocino County, the mean ATL08 height error is also found linearly dependent on slope for shrub and herbaceous with R^2 no less than 0.85, while the linear dependences for developed and forest are not very strong. Moreover, the standard deviation of ATL08 height errors is also found largely linearly dependent on slope in terms of land cover.

It can be seen from Fig. 11 that slope negatively affects the mean of height error and positively affects the standard deviation of height error. Furthermore, the vertical accuracy of ATL08 terrain product in plain region (Tippecanoe County) is less sensitive to slope compared to mountain region. While for the mountain region (Mendocino County), in which high relief and dense forest present, slope has a more significant influence on the ATL08 height accuracy, causing a larger coefficient than plain regions. To sum up, the ATL08 height uncertainty is linearly related to the terrain slope. The linear relationship gets steeper when the land cover becomes more complex.

G. Modeling the Height Errors

This section intends to model the ATL08 height errors with all factors under consideration. Fig. 12 shows the mean and standard deviation of height errors in terms of canopy coverage, laser beam incidence angle, and terrain slope. It is shown that the overall uncertainty (standard deviation and mean combined) of height errors increases as the canopy coverage increases. Similarly, for most of the height errors their uncertainty is positively related to the incidence angle and terrain slope, respectively. It should be noted that slope and incidence angles are dependent. Although slope is found related to the height accuracy of ATL08 product, it is the incidence angle that affects the height accuracy directly [18], [26]. Since the pointing angle of ATLAS is very small (less than 2°), the effect of slope to ATL08 height error is similar to the one of the incidence angle, as shown in Fig. 12. In addition, segments whose slopes are the last 5% of the slope distribution are excluded from the subsequent modeling. The cutoff slopes are 3.9° and 35°, respectively, for Tippecanoe County and Mendocino County. The resulting maximum incidence angles for remaining points are, respectively, 11.8° and 32.2°.

Based on the above analysis, we tried a second-order two variable polynomial model to model the ATL08 height error at first. These two variables are incidence angle and canopy coverage. The incidence angles are retrieved from the ATL08 data files segment by segment, while the canopy coverage in percentage is recorded in the ATL08 data files as well. The frequencies within bins of height errors are used as the weight of every sample data point during the modeling. Two modeling strategies are applied: a local model is determined for each county separately, while a global model is generated by combining the height errors of the two counties. Since the coefficients of θ^2 are as small as −0.02 and θ^2 (in radian) itself is also a small quantity, we discard the second order of the incidence angle in our final model. Fig. 13(a) and (b) plot the residuals for local models, while Fig. 13(c) shows the residual for the global model. In addition, local residuals from global model are plotted in Fig. 13(a) and (b) in square. Table VII lists the regression functions along with the statistics.

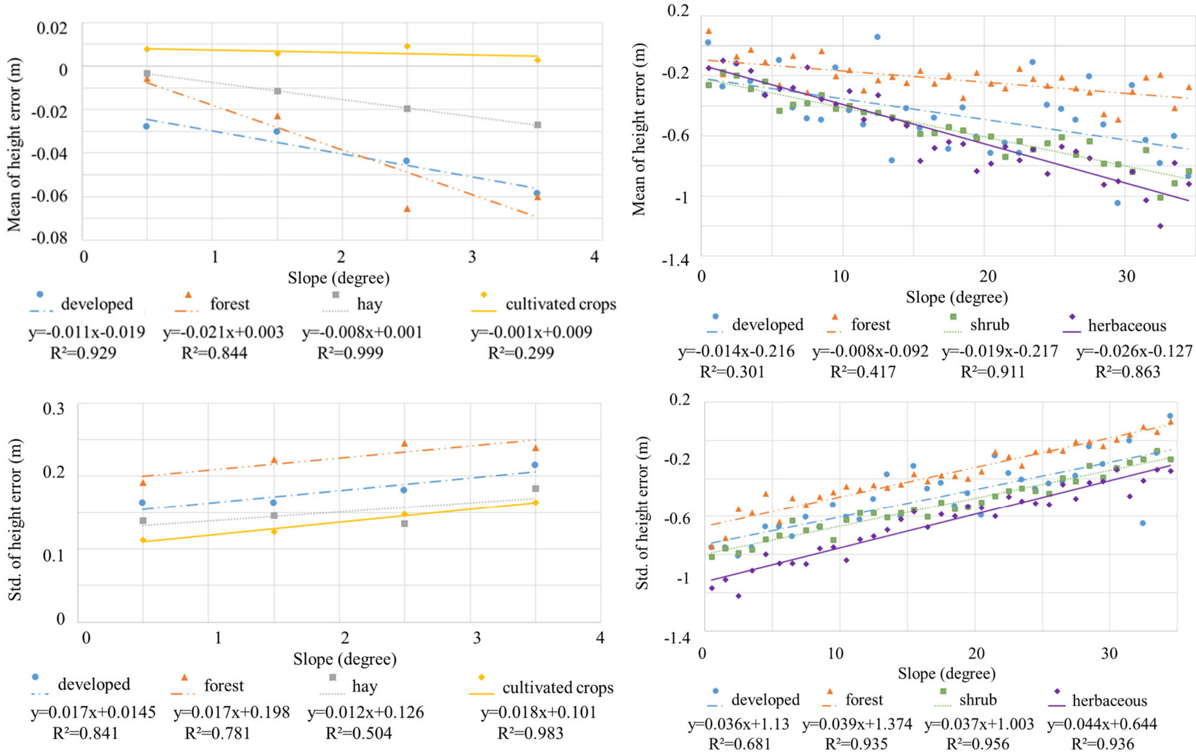

Fig. 11. (Top) Mean and (Bottom) standard deviation of the ATL08 height errors in terms of slopes for different land covers over the study areas. (Left) Tippecanoe County and (Right) Mendocino County.

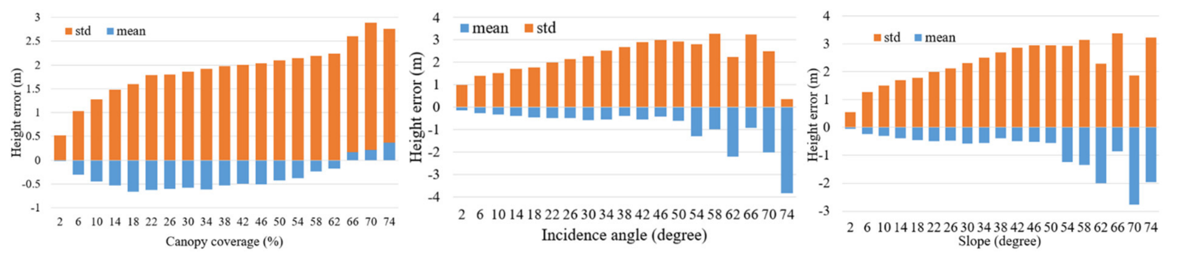

Fig. 12. Mean and standard deviation of the ATL08 height errors in terms of (from left to right) canopy coverage, incidence angle, and terrain slope.

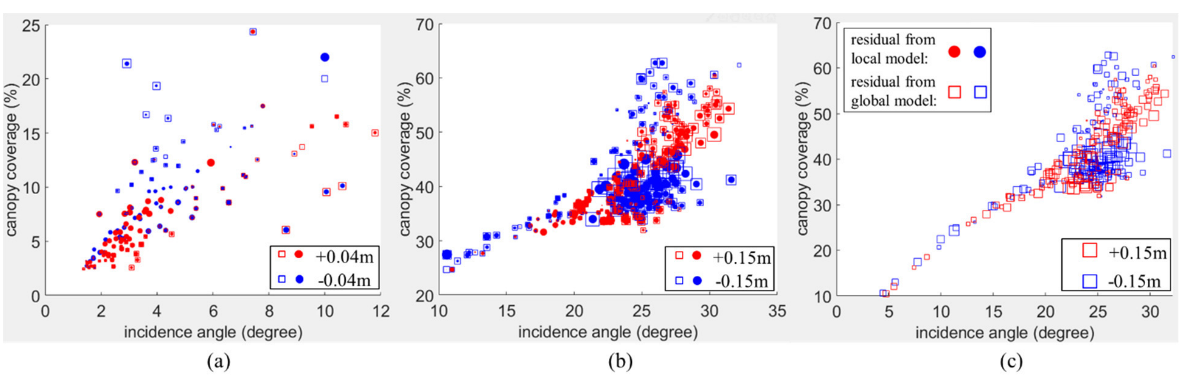

Fig. 13. Residuals for models of height error. (a) Local model in Tippecanoe County. (b) Local model in Mendocino County. (c) Global model over the combined data.

According to Table VII, the largest R^2 indicates that 66.6% of the height errors are well described by the global model. And from Fig. 13(c), it is shown that the residuals increase as canopy coverage and incidence angle increase. The global model performs better where the canopy coverage and incidence angle are small. Moreover, the local performance of the global model is obtained by applying it to the two counties separately, which leads to an RMSE of 0.025 m for Tippecanoe County and 0.078 m for Mendocino County. Fig. 13(a) and (b) shows that the local residuals from global model are slightly larger than residuals from the corresponding local model. Though the results from global model are not the same as the

TABLE VII
MODELS OF ATL08 HEIGHT ERRORS dh (IN m) AS A FUNCTION OF CANOPY COVERAGE p (IN %) AND LASER INCIDENCE ANGLE θ (IN °)

County	Model of ATL08 heigh error ($dh, in\ meter$)	R^2	RMSE (m)	
			Modeled	Predicted by global model
Tippecanoe	$-0.157 + 0.172\theta - 0.018p - 0.017p \cdot \theta + 0.002p^2$	0.322	0.012	0.025
Mendocino	$-3.279 - 0.533\theta + 0.319p + 0.001p \cdot \theta + 0.001p^2$	0.653	0.065	0.078
Combined	$0.017 - 0.778\theta + 0.031p + 0.06p \cdot \theta - 0.0003p^2$	0.666	0.058	N/A

local model, the RMSEs are close (0.025 m versus 0.012 m for Tippecanoe and 0.065 m versus 0.078 m for Mendocino). On the other hand, neither of the two local models can yield a satisfactory estimation for the other county.

It is noticeable that the best quality of terrain height for ATL08 we stated in Section IV-C is 0.005 ± 0.132 m for cultivated crops land cover. The height error with zero incidence angle and zero canopy coverage predicted by the global model is 0.017 m, which is consistent with the results above. From the global model, it is shown that the height error is positively affected by canopy coverage, and negatively affected by incidence angle. In other words, the increasing of both factors leads to a larger absolute height error of ATL08 product with reference to 3DEP DEM. A larger canopy coverage makes it more overestimate while a larger incidence angle makes it more underestimate.

VI. CONCLUSION

Timely and comprehensive evaluation for the ATL08 product is necessary due to limited current work. Our assessment extends to county scale at a size of hundreds of square kilometers and introduces land cover and incidence angle as influential factors. There are two heights in ATL08 product: h_te_bestfit and h_te_interp, this study confirms the previously reported simulated studies that their difference is as small as several centimeters. We thus chose the h_te_bestfit for our assessment.

In addition, we also carefully consider the quality of different ATL08 segments. It is found that ATL08 segments have different qualities due to several reasons. First and foremost, it is related to the number of ground photons. Segments labeled as invalid in h_te_uncertainty in the ATL08 file indicate insufficient ground photons within the segments. This study finds out that the number of invalid segments can be as high as 80% for forest land. For terrain modeling under forest, a significant majority of ATL08 product may not useful. In addition to these invalid segments labeled in the ATL08 products, they may still have outlier segments when comparing to the 3DEP DEM. These outliers usually happen where topography is rough, has dense vegetation, or where buildings exist. A large h_te_uncertainty value can reflect all such situations. It is therefore suggested that h_te_uncertainty of each segment should be carefully taken into consideration, especially for those with a relatively higher h_te_uncertainty than other segments.

Accuracy assessment is carried out for valid, outlier-free segments in the ATL08 products. We found the mean of height error of ATL08 terrain is less than 0.05 m in plain region and 0.5 m in mountain region below 3DEP, and the variance of the height error varies largely for different terrain (0.2 m for plain region and 2 m for mountain region). It is also noticed that the ATL08 height errors have a longer tail than normal distribution. Furthermore, through comparing terrain height of ATL08 product and 3DEP DEM against survey marks, respectively, we found that ATL08 product makes a less overestimation than 3DEP DEM, i.e., it is between 3DEP DEM surface and the true ground surface. The accuracy of ATL08 terrain height varies with land cover. The terrain height of ATL08 product performs best for cultivated crops land cover in plain region with less than 0.3-m-height error at 95% confidence level. The forest land cover has the least accuracy for plain region (0.6-m-height error at 95% confidence level) and mountain region (4.7-m-height error at 95% confidence level), and the uncertainty of ATL08 product in mountain region can be as eight times poor as the plain region. In addition, the seasonal grow and fall of vegetation and possible presence of snow have significant influence on the reflectance. We found the possible snow and absence of leaves in winter can lead to more ground photons than summer. Reflected ground photons received by ATLAS largely decrease by 54% for Tippecanoe county and 42% for Mendocino County after the growing season (June–August), leading to a less overestimated terrain height comparing to the winter season. The impact of season on height difference can be high as 0.8 m, while the time of acquisition has an influence less than 0.3 m. Moreover, the uncertainty (mean and standard deviation) of ATL08 products is largely linearly dependent on terrain slope for most land covers. However, the rate of change of this linear relationship is different, with regions of complex canopy having steeper relationship.

A bivariate polynomial of canopy coverage and incidence angle can be used to model the ATL08 height errors. Large incidence angle or large canopy coverage would lead to a higher uncertainty in ATL08 product. The incidence angle negatively influences the height error of ATL08 product, whereas the canopy coverage positively influences it. This study also shows a global model derived by combining the data of two diverse topographic areas can be used to satisfactorily predicate the quality in each local area, indicating the necessity of using large amount data to characterize the ATL08 height errors.

In summary, one should not expect that the terrain height of ATL08 product has the same accuracy over different areas. When the terrain height of ATL08 product is used, the impact of incidence angle (or terrain slope) and land cover type must be taken into consideration or significant impact may follow, especially for mountain region where the variance of the height error of ATL08 would be much larger than in plain region. Furthermore, it should be kept in mind that the terrain height provided by ATL08 product is the elevation of ground surface including the building height.

As a newly global lidar product from ICESat-2, ATL08 product is significant for many research in different fields. To provide future studies with a better understanding of ATL08 product, the quality of its terrain height is evaluated thoroughly in this study. Although a model describing the impact of incidence angle and canopy coverage is obtained, more data are necessary to improve the model reliability. Moreover, the canopy height of ATL08 product, which is critical for global biomass study, has not been discussed. Once the canopy height information at the time of data acquisition is available, further evaluation is certainly necessary.

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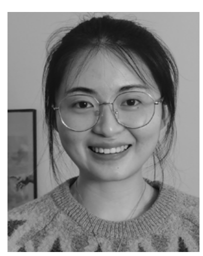

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