

Accuracy check analysis of digital elevation model data results based on ICESat-2 ATL08 data

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Abstract

Traditional methods for verifying the accuracy of digital elevation model (DEM) primarily rely on acquiring high-precision checkpoint elevations through field surveys. However, such approaches are often impractical in remote or inaccessible regions. To address the above issues, this paper proposes an accuracy verification method for DEM data products using ICESat-2 ATL08 data. Referencing current surveying and mapping quality control standards, the methodology includes data acquisition, preprocessing, and experimental validation in challenging terrains. Experimental results demonstrate the feasibility and effectiveness of using ICESat-2 ATL08 data for independent accuracy assessment of DEM products in areas where conventional ground truth data is unavailable. This study provides a practical reference for applications requiring DEM validation under limited field measurement conditions.

1. Introduction

Digital Elevation Model (DEM) product describes the elevation information of the ground surface (Wang, 2022). With growing demands across fields such as land surveying, urban planning, environmental monitoring, disaster prevention, transportation, energy, and water resource management, the development of high-precision, high-resolution, and wide-coverage DEMs has become increasingly critical (Li, 2020).

Currently, the primary method for validating the accuracy of DEMs involves field-based acquisition of high-precision checkpoint, followed by comparative evaluation. However, such methods are often infeasible in remote or densely vegetated regions due to logistical challenges and the unavailability of reliable ground truth data. Consequently, traditional validation techniques are not fully applicable for assessing the quality of DEM products in these contexts. Given that DEM quality directly affects the reliability of derived analyses and the achievement of application objectives (Meng, 2020), it is essential to explore alternative accuracy verification methods.

This study investigates the potential of using ICESat-2 ATL08 data as a reference for DEM accuracy assessment. It analyzes the characteristics of ATL08 data, outlines the screening and preprocessing procedures, and adopts current surveying and mapping quality standards as a reference framework. Using a case study from a mountainous, forested, and rain-prone region with limited accessibility, we demonstrate and validate the proposed DEM accuracy verification method based on ICESat-2 ATL08. The results aim to provide a feasible solution for DEM quality control in areas lacking field-survey checkpoints and to provide a reference for future validation efforts.

2. ICESat-2 ATL08 Data Overview and Characteristics

2.1 Data Introduction

ICESat-2 was successfully launched on September 15, 2018, with scientific objectives that include: (1) Quantitatively assessing the impact of polar ice sheets on current and near-term

sea level change. (2) Quantify the regional characteristics of ice sheet changes, assess the mechanisms driving them, and improve ice sheet prediction models. (3) Estimate sea ice thickness and study energy, matter and moisture exchange between sea ice/ocean/atmosphere.

ICESat-2 provides 21 types of data (ATL01-ATL21), which are categorized into four levels: Level 1, Level 2, Level 3A, and Level 3B (Dong, 2021). Level-3 products (ATL06-ATL21) provide measurements such as glacier, ice cap height, sea ice height, vegetation canopy height, inland water body elevation and other information. Among them, ATL02-ATL10, ATL12, ATL13, ATL16 and ATL17 data can be downloaded free of charge.

On the basis of Level-1 data, the time-of-flight calculation and correction of each photon can be performed to obtain the 3D coordinates of each photon, i.e., Level-2 data. The ATL08 data were obtained by processing the ATL03 data. It aggregates and statistically processes data along the satellite's ground track using a 100-meter segment as the basic unit. ATL08 data are also freely accessible and widely used in vegetation and terrain studies due to their high spatial resolution and vertical accuracy.

2.2 Data Characterization

ICESat-2 data features small and dense laser footprints, enabling the acquisition of precise topographic surface information. Its applications span a wide range of fields, including ice sheet elevation measurement, sea ice thickness inversion, land elevation measurement, forest biomass estimation, and lake water level monitoring. After inspection and calibration, ICESat-2 released the data to the public, who can download it for free from the designated website (Cao, 2020).

However, due to factors such as atmospheric conditions and tides, the downloaded ICESat-2 ATL08 data contains errors with high variability and low accuracy, requiring preprocessing and filtering before it can be used as elevation check points for DEM. It is necessary to combine actual conditions with remote sensing imagery of the same location as the DEM (Google

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Maps can be used) and perform overlay analysis to remove forests, buildings, and other features from the ICESat-2 ATL08 data. The ICESat-2 ATL08 data should be filtered based on attribute parameters and project accuracy requirements to obtain useful ICESat-2 ATL08 data as accuracy check points. While some researchers have begun to explore ATL08 data validation workflows, detailed documentation and standardization of each processing stage remain limited. Further research is needed to establish comprehensive and reproducible methodologies for integrating ATL08 data into DEM quality assessment.

3. ICESat-2 ATL08 Data Processing

This study presents a structured method for processing ICESat-2 ATL08 data based on attribute parameters, enabling the accurate selection of reliable elevation checkpoints for validating digital elevation model (DEM) data. The method can be divided into three steps: data download, data processing, and data screening. The overall workflow is illustrated Figure 1.

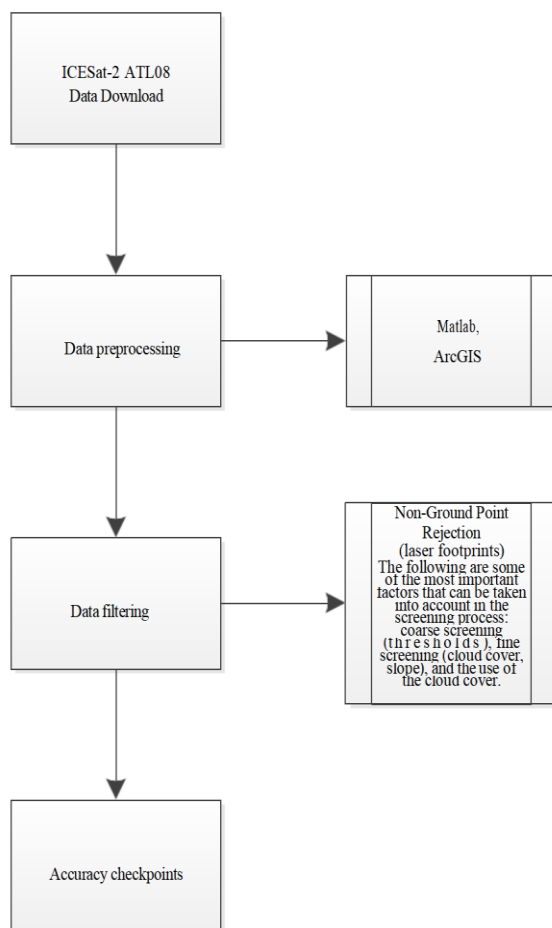


Figure 1. ICESat-2 ATL08 data processing scheme.

3.1 Data Download

Visit the official website of "NSIDC" at the following link: <https://nsidc.org/data/atl08/versions/6>. After opening the link, select "Explore Data". After opening the link, select "Explore Data", and then select "All Datasets" to view the interface of downloadable datasets. Select "ATLAS/ICESat-2 L3A Land and Vegetation Height" to access the data download screen. Use the "Data Access Tool" to download the data.

Set the latitude/longitude range and time range. Since ICESat2 data are observed continuously in the latitude direction, they are oriented north-south. There are no gaps between data products, and the latitude range should be set slightly smaller than what is actually needed, otherwise unnecessary data will be selected. Select "Large/Custom Orders" for download. The format of the downloaded data is a file with the suffix ".h5" (HDF5 file).

When downloading, the system will prompt users to register for an Earth Data account. After completing registration, users will need to log in to their Earth Data account.

3.2 Data Preprocessing

3.2.1 Data Integration: The six lasers in the ICESat-2 ATL08 data are three strong lasers and three weak lasers, labeled with l or r, respectively. Using MATLAB, the data for the six lasers will be obtained after each file with the suffix ".h5" and stored in files with the suffix ".txt". The content of the files with the ".txt" extension includes 11 parameters: point number, longitude, latitude, ICESat-2 ground elevation, reference DEM (Digital Elevation Model) elevation, elevation difference, slope, terrain marker, urban marker, cloud cover, and nighttime marker, etc. (Wang, 2021). This is shown in Table 1.

Parameters	Account for
h_te_interp	Interpolated surface elevations
h_te_mean	Divided into average surface photometric elevations
h_te_median	Score the median surface luminosity elevation
h_te_max	Score the maximum surface photometric elevation of the
h_te_min	is divided into minimum surface photometric elevations
dem_h	Reference DEM elevation of the point, with reference values from one of four data products: North Pole, GMTED, MSS, and South Pole
terrain slope	The ground slope along the track direction is calculated by linear fitting of the
the flag of a city	City symbols, 0 = non-city, 1 = city
cloud logo	Cloudiness flag, greater than 0 indicates the presence of clouds or aerosols, value range [0,10].
landmark	Quality check flag indicating whether the deviation from the reference DEM is above the threshold, 0 = below threshold, 1 = above threshold
black flag	Night Flag, 0 days 1 night

Table 1. Key parameters of ICESat-2 ATL08 data

Merge all files with extension ".txt" into one "excel" table. Partial contents are shown in Table 2.

h_interp	h_max	h_min	h_mean
32.575714	33.986012	32.100285	32.693398
33.347038	34.117252	32.904766	33.430481
33.342621	34.073605	32.84584	33.550503

Table 2. Partial table after data merging

3.2.2 "ArcGIS" Data Loading: Click the right mouse button and select "Properties" at "Layer" in the menu bar of "ArcGIS" software, and modify the coordinate system to "Geographic coordinate system: Coordinate system: WGS 1984", and the unit of the data to "Decimal": Coordinate system: WGS 1984", and the unit of the data to "Decimal". Ignore this step if the unit is already "decimal". Select "New Grid: Latitude/Longitude" in "Grid" (in general, the latitude interval is set to 30 degrees and the longitude interval is set to 10 degrees). Switch to the latitude/longitude grid view with "View" in the menu: Layout view" switches to the latitude/longitude grid view. After loading the "x, y, z coordinates", switch to "Layout View" to see the position of the laser footprint track in the latitude and longitude grid. In the "File" in the menu bar of the "ArcGIS" software use the left mouse button click to select "Add Data" and then add the "x and y data." Select the file with the suffix ".txt" that needs to be loaded. Set the "x, y, z" field to load all ICESat-2 ATL08 data in the range. Export a file with the suffix ".shp" from the "ArcGIS" software.

3.3 Data Screening

3.3.1 Data Filtering: The laser footprint diameter of ICESat-2 ATL08 data is 17 meters. Therefore, it is necessary to refer to the image with the same name, buffer the ICESat-2 ATL08 data into a 17-meter circle, and exclude non-surface ICESat-2 ATL08 data containing vegetation and buildings within the circle.

3.3.2 Coarse Filtering of Data: The ICESat-2 ATL08 data obtained in the above steps are coarsely filtered. Extract the median surface photometric elevation (h_{te_median}) and interpolated surface elevation (h_{te_interp}) from the ICESat-2 ATL08 data, calculate the difference with the reference elevation value (dem_h), and reject the elevation points with a difference greater than the threshold value (the elevation error required by the project's accuracy) as the coarse difference value.

$$|H_1 - H_3| \leq H_4; |H_2 - H_3| \leq H_4, \quad (1)$$

Where H_1 = median surface photometric elevation value
 H_2 = interpolated surface elevation value
 H_3 = reference elevation value
 H_4 = elevation error value required by project accuracy

3.3.3 Fine Screening of Data: By studying the factors affecting the measurement accuracy of ICESat-2 ATL08 data, some research findings can serve as a reference for screening ICESat-2 ATL08 data. ICESat-2 ATL08 data exhibit significant errors in steep slopes and areas with high cloud cover. ICESat-2 ATL08 data are influenced by atmospheric conditions and are related to cloud cover, necessitating further screening based on

cloud cover flags. When the cloud cover (cloud_flag) value is 3, data with cloud cover less than or equal to 20% can be retained. Elevation accuracy on slopes with low slope gradients and exposed ground is superior to that on slopes with high slope gradients and dense vegetation cover. Attribute parameters representing slope and cloud cover (terrain_slope, cloud_flag_atm) are extracted from ICESat-2 ATL08 data (Wang, 2021), and a refined screening method for ICESat-2 ATL08 data based on these attribute parameters is established in conjunction with actual conditions. Through research and analysis, when the slope (terrain_slope) value is 0.01 (approximately 0.57°), the elevation accuracy of ICESat-2 ATL08 data is better than 0.1m, making it suitable as reference validation data for accuracy evaluation. Therefore, ICESat-2 ATL08 data with cloud cover greater than 3 and slope greater than 0.01 were excluded to remove abnormal elevation values caused by steep slopes and cloud/fog obstruction. Subsequently, based on the task area range of the digital elevation model (DEM) data results, the actual usable and reliable ICESat-2 ATL08 data were selected as elevation accuracy verification points for the DEM.. This is shown in Figure 2.

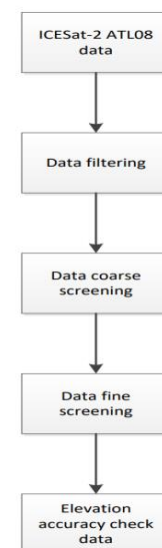


Figure 2. Elevation accuracy checkpoint data screening process.

4. Experiments and Analysis of Results

4.1 Experimental Design

The study area is located in a region characterized by tropical rainforest and tropical monsoon climates, featuring high annual rainfall, mountainous terrain, and dense vegetation. As shown in Figure 3, the absolute elevation error required for the DEM data accuracy in this area is 4 meters.

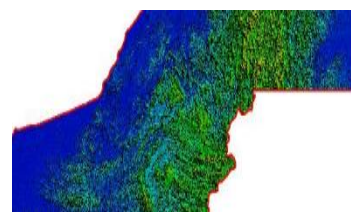


Figure 3. Spatial extent of DEM data coverage in the study area.

The DEM data used in this study are based on data from the LT-1 satellite, with a project accuracy requirement of an absolute elevation error of less than 4 meters. LT-1 is China's first synthetic aperture radar satellite constellation with interferometric measurement as its core mission. It consists of two satellites, A and B, both equipped with L-band synthetic aperture radar payloads. The constellation possesses all-weather, all-time, and multi-polarization imaging capabilities, making it applicable to fields such as geology, land management, seismology, disaster mitigation, surveying, and forestry. It primarily addresses global demand for deformation monitoring in key regions, high-precision digital elevation modeling, and the development of high-precision digital elevation modeling data. It can be applied to fields such as geology, land management, seismology, disaster mitigation, surveying, and forestry. It primarily addresses global demand for remote sensing information in fields such as deformation monitoring in key regions, high-precision digital elevation modeling, disaster emergency response, land surveying, global forest resource surveys, biomass inversion, and environmental monitoring.

According to the requirements of the national standard (GB/T 18316-2008 “Quality Inspection and Acceptance of Digital Surveying and Mapping Results”) (GB/T 18316-2008), it is necessary to inspect the elevation accuracy of DEM results. The nominal elevation accuracy of ICESat-2 data is 0.1 m, so it can be set as the true value for inspecting the DEM results of the task area. Since the nominal elevation of ICESat-2 data is 0.1 meters, it can be set as the true value for inspecting the DEM results in the task area. Due to various factors such as satellite orbital attitude, atmospheric conditions, terrain complexity, and tides, ICESat-2 ATL08 data downloaded using the method described in “Chapter 3.1” may still contain significant errors or invalid data. Therefore, it must undergo further processing steps such as format conversion, attribute analysis, and accuracy screening before it can be used as an accuracy verification point. The laser footprint diameter of the data is approximately 17 meters, with a spacing of 0.7 meters. Therefore, ICESat-2 ATL08 data outside the corresponding 17-meter diameter circle coverage area should be excluded according to the method described in “Chapter 3.3.” This is shown in Figure 4.



Figure 4. All ICESat-2 ATL08 data in the mission area.

Following the method in “Section 3.3,” the coarse screening process removes ICESat-2 ATL08 data with elevation differences greater than 4 meters. Considering the mountainous terrain, high rainfall, and heavy cloud cover in the mission area, the fine screening process is adjusted accordingly. The screening condition of cloud cover greater than 3 was retained, and nighttime data (night_flag=1) was selected to reduce atmospheric interference. When the slope is less than 5°, the elevation error of ATL08 is between 0.2 and 0.3 meters (Zheng, 2022), which can be used as reference validation data for accuracy evaluation. Therefore, the slope (terrain_slope) value is relaxed to 0.05 (approximately 2.86°), prioritizing data integrity while meeting the slope requirements for gentle slopes.

This is shown in Figure 5. After these screening steps, a total of 624 ICESat-2 ATL08 points were identified as valid checkpoints for accuracy evaluation.

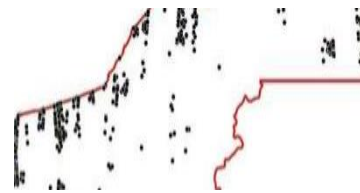


Figure 5. ICESat-2 ATL08 data filtered by elevation and attribute constraints.

To assess DEM accuracy, the filtered ICESat-2ATL08 data (with .shp suffix) was overlaid with the DEM dataset in ArcGIS. Using the “Extract Value to Points” function, corresponding DEM elevations were obtained for each ATL08 checkpoint, and calculate the elevation difference with the elevation of the same name of the screened ICESat-2 ATL08 data to check whether the accuracy of the DEM results is accurate or not. The accuracy of the DEM results meets the project accuracy requirements.

The error in absolute elevation between the screened ICESat-2 ATL08 data and the DEM should be less than 4 meters. For the points where the accuracy exceeds the standard, the reasons should be analyzed, the data accuracy should be checked, and the DEM results should be modified or regenerated to ensure that the accuracy meets the requirements.

4.2 Text Results

Comparing the maximum, minimum, and average values of the elevation of the filtered ICESat-2 ATL08 data and the digital elevation model elevation of the mission area, it can be seen that the difference between the two groups of data is small. This is shown in Table 3.

Analyzing indicators	ICESat-2 ATL08 Data elevation values	Mission area DEM Data elevation values
Maximum value/m	610.53	607.74
Minimum value/m	38.69	39.83
average value	137.62	138.37

Table 3. Comparison of maximum, minimum, and average elevation values in the mission area

Mean Error (Mean Error) and Root Mean Square Error (RMSE) were used to analyze and evaluate the accuracy of DEM in the mission area.

$$\text{Mean Error(ME)} = \frac{1}{n} \sum_{i=1}^n |x_i - y_i| \quad (2)$$

Where x_i = corresponding DEM elevation value
 y_i = ICESat-2 ATL08 data elevation values
 n = Number of ICESat-2 ATL08 data points

$$\text{Root Mean Square Error (RMSE)} = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - y_i)^2} \quad (3)$$

Where x_i = corresponding DEM elevation value
 y_i = ICESat-2 ATL08 data elevation values
 n = Number of ICESat-2 ATL08 data points

The histogram of elevation error distribution is used to represent the characteristics of elevation error distribution. This is shown in Figure 6.

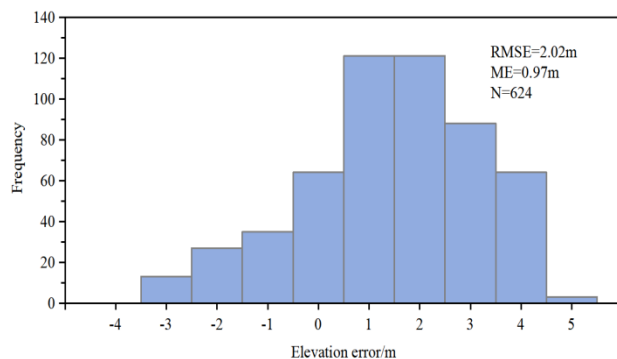


Figure 6. Histogram of elevation error distribution.

As shown in the figure, the elevation error distribution of the DEM in the task area follows a normal distribution, with 75% of the data points concentrated within the [0m, 3m] range, indicating a relatively small error margin.

The number of ICESat-2 ATL08 data points before screening was 4,363, and after screening, the number of data points was reduced to 624, resulting in a retention rate of 17.99%. The difference between the elevation values of the ICESat-2 ATL08 data and the elevation values of the DEM exceeds twice the absolute elevation error, which is defined as roughness. There are 16 roughness points, with a roughness rate of 2.5%, which are not included in the accuracy calculation. After calculation, the error of the DEM in the task area is 2.02 meters, the roughness rate is less than 5%, and the average error is 0.97 meters, meeting engineering requirements.

After checking, the rough spots are all located in mountainous areas with dense vegetation (mangrove forests and other vegetation with trees more than 10 meters high), and it is not possible to accurately judge the accuracy of ICESat-2 ATL08 data at the corresponding locations.

As shown in the Table 4. Further analysis was conducted using standard deviation (STD) analysis indicators to analyze the differences between the DEM elevation values of densely vegetated mountainous areas and non-densely vegetated mountainous areas in the task area and the elevation values of ICESat-2 ATL08 data. The standard deviation was calculated using the following formula.

$$\text{Standard Deviation (STD)} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n [(x_i - y_i) - ME]^2} \quad (4)$$

Where x_i = corresponding DEM elevation value
 y_i = ICESat-2 ATL08 data elevation value
 n = Number of ICESat-2 ATL08 data points

Mountainous areas with dense vegetation	STD/m	2.42
Non-mountainous areas with dense vegetation	STD/m	1.57

Table 4. Comparison of standard deviations in the mission area

Use the coefficient of determination (R^2) analysis indicator to analyze the degree of conformity between the elevation values of the DEM in the task area's densely vegetated mountainous regions and non-densely vegetated mountainous regions and the elevation values of the ICESat-2 ATL08 data. The coefficient of determination is calculated using the following formula.

$$\text{Coefficient of determination (R}^2\text{)} = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y}_i)^2} \quad (5)$$

Where y_i = ICESat-2 ATL08 data elevation value
 $\hat{y}_i$ = corresponding DEM elevation value
 $\bar{y}_i$ = Average ICESat-2 ATL08 data elevation value
 n = Number of ICESat-2 ATL08 data points

Mountainous areas with dense vegetation	R^2	0.65
Non-mountainous areas with dense vegetation	R^2	0.85

Table 5. Coefficient of determination in the mission area

As shown in the Table 5, the standard deviation of the DEM results in densely vegetated mountainous areas is greater than that in densely vegetated non-mountainous areas. In densely vegetated mountainous areas, R^2 is close to 1. This indicates that the accuracy of the DEM data results in densely vegetated non-mountainous areas is relatively reliable, and the elevation trends of the DEM data are highly consistent with those of the ICESat-2 ATL08 data.

In densely vegetated mountainous areas, the dispersion of the DEM results is relatively large, and there are differences in the elevation trends between the digital elevation data and the ICESat-2 ATL08 data, with R^2 decreasing to 0.65, indicating unstable elevation accuracy quality. Analysis shows that in densely vegetated mountainous regions, Landsat-1 signals cannot penetrate tall, dense vegetation, colliding with tree trunks and causing interference to contour lines in the area. Additionally, elevation values in some vegetated areas have not undergone elevation adjustment and do not reach ground points. Furthermore, existing research indicates that ICESat-2 ATL08 data errors increase with canopy height. Therefore, ICESat-2 ATL08 data lacks sufficient valid data in densely vegetated mountainous areas and relies on ground-based auxiliary data to enhance reliability.

5. Conclusions

This paper proposes a method for verifying the accuracy of digital elevation model (DEM) data results in the absence of available high-precision checkpoints., aiming to effectively control the quality of DEM data results. Referencing current surveying and mapping quality control standards, the methodology includes data acquisition, preprocessing, and experimental validation in challenging terrains. The approach utilizes ICESat-2 ATL08 data as reference and demonstrates its feasibility through a case study in a mountainous, densely vegetated region.

However, this method can only provide a certain reference for verifying the accuracy of DEM data results under the same terrain conditions and accuracy requirements as the task area. ICESat-2 ATL08 data varies across different regions and terrain conditions worldwide, and the screening criteria also differ. Further experiments will be conducted in the future, utilizing a large amount of DEM data from different regions and terrain conditions, to analyze the accuracy verification method for DEM data based on ICESat-2 ATL08 data. Using the open-source Copernicus DEM as test data to verify and analyze the accuracy of DEM will be the focus of future research.

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