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Extraction Strategy for ICESat-2 Elevation Control Points Based on ATL08 Product

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***Abstract*—ICESat-2 can obtain high-precision three-dimensional measurement information of targets and has a unique advantage in determining global elevation control points. However, due to the influence of the atmospheric environment, target characteristics, hardware equipment, and other factors, its elevation accuracy is not highly reliable, and not all data points can be used as control points. To obtain high-precision elevation control points from ICESat-2 data products, an extraction strategy that combines the accuracy and location requirements for control points was developed based on the ATL08 product. Multiple attribute parameters were incorporated into the extraction procedure, including terrain factor information, segment elevation information, cloud confidence flag, surface coverage data, topographic photon quantity, and photon height difference information. The extraction approach was then performed and analyzed using experimental data from the Hanzhong area in Shanxi province and the Songshan area in Henan province. In the experiments, the root-mean-square error (RMSE) of the extracted data points in two areas were both about 0.5 m and could reach 0.3 m after eliminating gross error points caused by surface changes and misclassification. The results suggest that the developed strategy takes into account the point location requirements of control points, can overcome the influence of complex terrain and ground objects and significantly improve the overall accuracy of obtained control points. Therefore, the proposed extraction strategy can support the establishment of the global elevation control point database and promote the application of ICESat-2 data in land surface surveying and mapping.**

***Index Terms*—Spaceborne Laser Altimeter, ICESat-2, ATLAS, ATL08, Elevation Control Point, Ground Photon Ratio**

I. INTRODUCTION

WITH the rapid development of laser technology (e.g., single-photon, multi-beam, micro-pulse, and high-frequency), space-borne laser technology has gradually matured, providing all-day high-precision three-dimensional target measurements, and has gradually become one of the leading technologies in earth observation science [1]. The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2), launched by NASA on 15 September 2018, is the world's first multi-beam, single-photon counting, laser altitude measurement satellite equipped with the Advanced Topographic Laser Altimeter System (ATLAS). ATLAS can obtain denser three-dimensional point cloud data for targets with low energy consumption, high detection sensitivity, and high repetition rates, which is one of the main development directions in future space-borne laser altimeters [2,3]. Running for nearly four years, ICESat-2 has obtained large amounts of laser cloud data covering the world and could provide vital data support in various studies, including land surface surveying and mapping [4-6], sea ice elevation measurement [7-9], forest biomass estimation [10-12], and lake water level detection [13-15]. In terms of land surface surveying and mapping, due to the limitation of ground spatial resolution, ICESat-2 data is mainly used as elevation control points for joint processing with optical remote sensing images and existing topographic results [1].

Height measurement accuracy is an important factor affecting ICESat-2 data application. In flat areas, the measurement accuracy of ICESat-2 elevation data can reach 0.1 meters [16,17]. However, due to various factors in laser transmission, including atmosphere, cloud layer, surface reflectance, and hardware dynamic response range, the accuracy of laser ranging and the reliability of elevation are significantly constrained [18]. In addition, the ATLAS' low-energy pulse and high sensitivity may bring considerable noise. The accuracy of ICESat-2 measured data needs further testing and verification.

Since the launch of the ICESat-2 satellite, the evaluation of its data accuracy has been an important research direction. Numerous scholars [19-22] have analyzed its accuracy from different perspectives. For instance, Zhu et al. [20] assessed the accuracy of ICESat-2 ATL08 terrain estimates using airborne lidar data and concluded that the accuracy of data acquired at night is better than that obtained during daytime. They also found that the accuracy from non-vegetation-covered areas is better in vegetation-covered areas, and the accuracy of winter data for vegetation-covered areas is better compared to those acquired during the summer. Tian et al. [21] performed a comprehensive evaluation of the quality of the ATL08 product using high precision digital elevation model (DEM) and survey marks. They analyzed various factors affecting its accuracy, including canopy coverage, number of ground photons within each 100-m segment, topography, incidence angle, land cover, season, and data acquisition time.

In the study of precision evaluation, many factors affect the precision of height measurements. In addition, due to the low spatial resolution of the ground, the available information is limited in the data processing. Therefore, in the absence of high-precision external reference data, extracting high-precision control points from ICESat-2 data products would be difficult, especially in areas with complex terrain and surface features. There have been few studies on high-precision control point extraction. For example, Zhang et al. [6] studied the joint adjustment of laser data and image data and proposed the extraction of laser control points from ATL03 data products using high-precision DEM obtained by remote sensing image matching, combined with classification information (isurf parameters) and noise information (conf parameters). Their proposed method requires an external DEM, and the extraction results mainly depend on the quality of the external DEM data. To eliminate dependence on external reference data, Wang et al. [5] developed a method for extracting global elevation control points from ATL08 data products based on built-in reference elevation data and laser attribute information, including slope, cloud cover, and observation time. However, the applicability of their method is limited in areas with complex terrain due to fewer attribute factors considered. Based on Wang's method, Zheng et al. [23] added quality inspection before data processing in order to preliminarily screen the data using three parameters: the number of ground photons within each 100-m segment, the difference between the median elevation and the interpolated elevation, and the difference between the median elevation and the built-in reference elevation. Their approach enhances the adaptability of the algorithm to a certain extent and improves the stability and precision of the obtained control points. However, their proposed technique mainly uses DEM and average error to evaluate the accuracy of data processing without considering the actual application requirements of control points. Therefore, taking into account the location requirements of control points, their approach needs to be further studied on extracting high-precision control points from ICESat-2 data products in complex scenes without external reference data.

In order to obtain high-precision ICESat-2 elevation control points without external reference data, an extraction strategy based on the ATL08 product was designed based on the comparative analysis of the characteristics of ATL03 and ATL08 products, combining the accuracy and location requirements of control points. This approach extensively uses multiple attributes, including terrain factor information, segment elevation information, cloud confidence flag, surface coverage data, topographic photon quantity, and photon height difference information. The extraction results were analyzed with experimental data from the Hanzhong area in Shanxi province and the Songshan area in Henan province. The corresponding research results and developed extraction strategy can support expanding the applications of laser altimetry data and establishing the global elevation point database.

II. ATLAS Data Product

ATLAS is carried on ICESat-2 satellite with an orbital altitude of 500 km and emits green laser pulses with a wavelength of 532 nm to the ground at a repetition rate of 10 kHz; it can obtain overlapping footprints with an orbital interval of approximate 0.7 m and a diameter of approximate 17 m [25]. Each transmitted laser pulse is split by a diffractive optical element in ATLAS to generate six individual beams arranged in three pairs (Figure 1). The beams within each pair have different transmit energies (‘weak’ and ‘strong,’ with an energy ratio between them of approximately 1:4) and are separated by 90 m in the across-track direction [22,23]. The beam pairs are separated by ~3.3 km in the across-track direction, and the strong and weak beams are separated by ~2.5 km in the along-track direction [26].

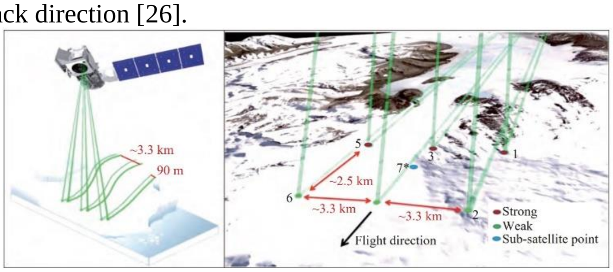


Fig. 1. ATLAS beams distribution sketch map [27]

The data acquired by ATLAS is processed into 22 data products (ATL00-ATL21) [25]. Among them, the ATL03 is the global geolocated photon cloud after various geophysical corrections are introduced, providing the latitude, longitude, ellipsoidal height, and classification (signal or noise) of photons detected by the ATLAS instrument [25]. ATL08 is extracted from the ATL03 data after filtering and classification, which contains heights for both terrain and canopy at 100 m segments in the along-track direction and other descriptive parameters derived from the measurements [26,27]. Both have accurate location information and can be used as basic data for control point extraction. For this paper, ATL08 was selected as basic data for the following reasons. In terms of data quality, ATL03 is a collection of all photon points, including a huge amount of noise points and non-terrestrial photon points (control points are generally located on land), which is detrimental to the subsequent data extraction. In terms of data processing efficiency, the amount of data and photons of ATL03 is much larger than ATL08 for the same area (Table 1), so the efficiency of data reading and processing is lower. In terms of data information, ATL08 contains more descriptive parameters (e.g., surface roughness, slope, canopy height, and coverage), which can provide more information support for the control point extraction.

TABLE 1
Data Volume Comparison of ATL03 and ATL08 Product

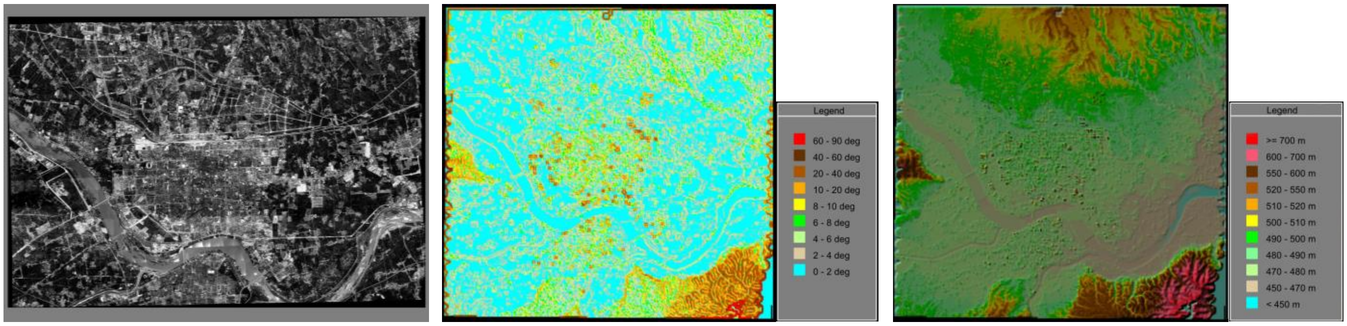
Acquisition Time	Product Code	Number of Photons	Data Volume
2021.11.17(night)	ATL03	24595981	569 MB
	ATL08	84290	121 MB
2021.11.27(day)	ATL03	118644423	2512 MB
	ATL08	145450	217 MB

III. Attribute Analysis and Experiment

The ATL08 product contains subgroups for land and canopy height segments and beam and reference parameters. These attribute information can assist in laser point extraction processing, including segment elevation, terrain factor parameters, surface coverage information, photon quantity parameters, accuracy description parameter, cloud confidence flag, and photon height difference information. In order to evaluate the effect of attribute information on extraction processing, high-precision terrain data from the Hanzhong area in Shaanxi province and the Songshan area in Henan province were collected as benchmark data for experimental analysis.

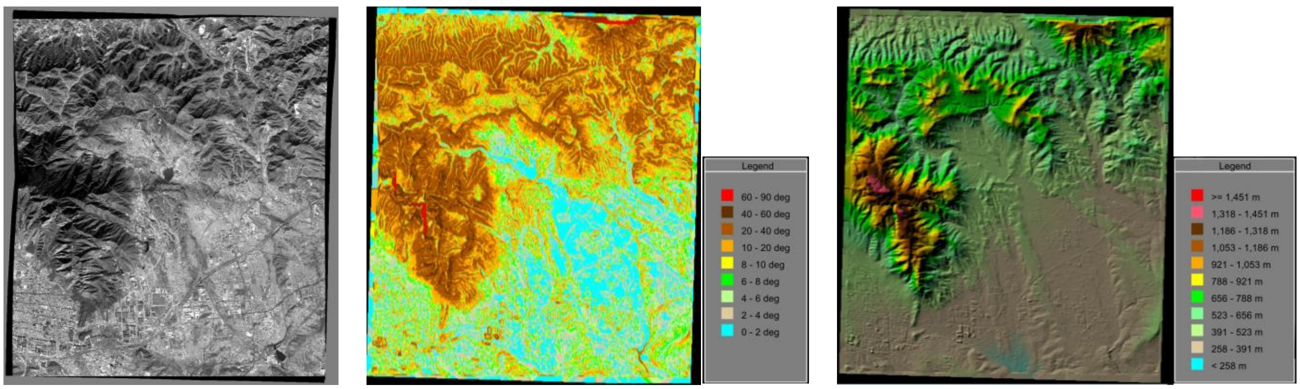
A. Experimental Data

The Hanzhong experimental area is located in the urban area of Hanzhong city and is covered mainly by buildings, vegetation, rivers and roads. The schematic diagram of its aerial image is shown in Figure 2 (a). The Hanzhong experimental area extends about 15 km from north to south and 16 km from east to west. Its topography is mainly flat to hilly, having an average slope is less than 2° and a maximum elevation difference of about 300 m. The schematic diagram of its slope data is shown in Figure 2 (b). The airborne LiDAR technology was used to obtain high-precision 3D laser point cloud data in the experimental area, producing terrain data with a grid resolution of 0.2m. After evaluating the precision of terrain data using 120 control points, the elevation RMSE was calculated to be about 0.08m. The schematic diagram of the terrain data is shown in Figure 2 (c).



(a) Aerial image (b) Slope data (c) Terrain data

Fig. 2. Schematic Diagrams of the Hanzhong experimental area



(a) Satellite image (b) Slope data (c) Terrain data

Fig. 3. Schematic Diagrams of the Hanzhong experimental area

The Songshan experimental area is located in Dengfeng city and is mainly covered by buildings, vegetation, and roads. The schematic diagram of its satellite image is shown in Figure 3 (a). The Songshan experimental area spans about 17 km from north to south and 16 km from east to west. The area is hilly and mountainous, with an average slope larger than 8° and a max elevation difference of about 1000 m. The schematic diagram of its slope data is shown in Figure 3 (b). Combining worldview-2 satellite images (the spatial resolution is about 0.5 m) and measured control points, the terrain data was produced with a grid resolution of 2 m. The precision of terrain data was evaluated using 99 control points, and the RMSE of elevation was calculated to be about 0.33m. The schematic diagram of terrain data is shown in Figure 3 (c).

The main goal of the experiment is not to evaluate the accuracy of the ATL08 product but rather to obtain elevation control points. The elevation control point requires high precision and easy interpretation. The benchmark terrain data used in this experiment is a digital surface model (DSM), not a digital elevation model (DEM), for two main reasons. First (reason in accuracy), the accuracy of some control points obtained using the DEM is low. Whether benchmark data or space-borne laser altimetry data, the elevation of buildings and vegetation regions in DEM are obtained through interpolation, and the accuracy of control points in such regions is relatively low. Second (reason in interpretation), some control points obtained using DEM are difficult to interpret and apply in practical projects. If DEM is used as benchmark data, the extracted control points may be located in vegetation and building regions. In practical engineering applications, such control points are difficult to interpret and apply due to the occlusion of buildings and vegetation.

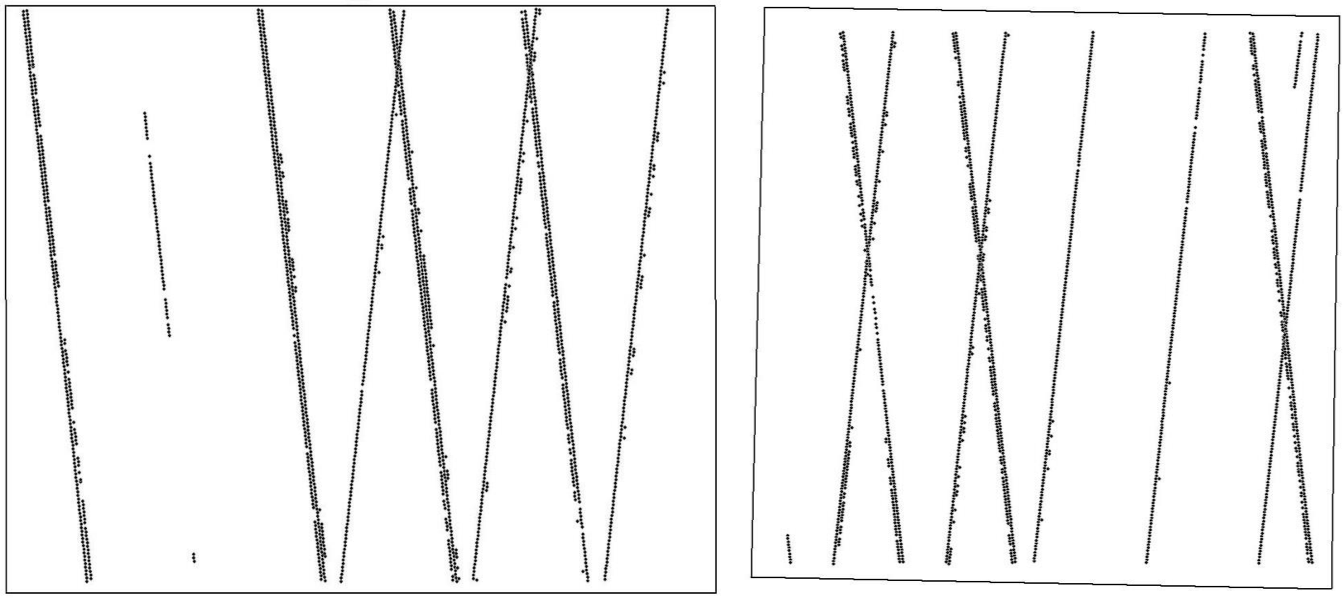
Using the longitude and latitude ranges of the experimental areas, the corresponding ATL08 products were downloaded from the website (https://nsidc.org/data/icesat-2/) and are shown in Table 2. The distribution of ATL08 data in the experimental areas is presented in Figure 4.

ATL08 data is discrete point cloud data, while the benchmark terrain data is regular grid data. Therefore, it is necessary to co-register them first when using the datum data to evaluate the filtered ATL08 data. Considering the high precision of benchmark data used in this experiment, the registration method based on geographical coordinates [21] was adopted, which is commonly used in ATL08 data precision evaluation research. This unifies the coordinate system of two data types and determines the corresponding relationship based on the coordinate information. The ATL08 product is in the WGS84 horizontal datum without projection (geographic coordinate system in degrees), while the ATL08 terrain height is in meters above the WGS84 ellipsoid [26]. The benchmark data were converted to the above coordinate system to achieve registration in this experiment.

TABLE 2

Correspondence of Experimental Areas and ATL08 Products

Experimental Area	Product Name
Hanzhong Area (4 tracks)	ATL08_20200304080716_10480602_005_01.h5 ATL08_20200603034708_10480702_005_01.h5 ATL08_20200901232654_10480802_005_01.h5 ATL08_20210322015509_13451006_005_01.h5
Songshan Area (5 tracks)	ATL08_20210120042542_04151006_005_01.h5 ATL08_20210529100909_10021102_005_01.h5 ATL08_20210621210921_13601106_005_01.h5 ATL08_20210730071259_05601202_005_01.h5 ATL08_20210920164918_13601206_005_01.h5



(a) Hanzhong Area (b) Songshan Area

Fig. 4. Schematic Diagrams of Laser Data Distribution. The black border indicates the range of the experimental area; Black dots represent ATL08 data points.

B. Attribute Analysis

1. Segment Elevation Information

Segment elevation information mainly contains land elevation values and reference terrain height. The land elevation value refers to various height values calculated by using all ground photon elevation values in the segment, including mean terrain height (h_te_mean), minimum terrain height (h_te_min), maximum terrain height (h_te_max), median terrain height (h_te_median), interpolated terrain surface height (h_te_interp), and best-fit terrain elevation (h_te_best_fit). According to the analysis and research of [28], the best-fit terrain elevation has good accuracy and can be used as the terrain elevation value for the segment. It refers to the best-fit terrain elevation at the mid-point location of each 100 m segment and is determined by selecting the best of three fits (linear, 3rd order and 4th order polynomials) to the terrain photons and interpolating the elevation at the mid-point location of the 100 m segment [26]. The reference terrain height is also a built-in data of ATL08 product, which is recorded in parameter dem_h; its value for each segment is determined using the "best" DEM available based on the data location. The DEM is taken from various ancillary data sources: MERIT, GIMP, GMTED, and MSS [26]. The difference between the terrain elevation value (h_te_best_fit) and the reference terrain height value (dem_h) reflects the precision of data points to a certain extent and can be used for preliminary screening of ICESat-2 data points [5,18].

To evaluate the supporting effect of dem_h on screening treatment, different thresholds were used to screen ATL08 products according to the difference between the dem_h and h_ te_best_fit values. First, the data points with height differences greater than the threshold were removed as gross errors. Second, the accuracy of the remaining data points was evaluated by the benchmark terrain data. Finally, the remaining data points were tallied, and the RMSE, maximum value (MAX), and standard deviation (STD) of their accuracy were calculated. The specific statistical results are shown in Table 3.

From the experimental results, the RMSE showed a downward trend as the height difference threshold decreased. However, the rate of decline was slow, and the RMSE fluctuated when the height difference threshold was small. The variation trend of STD was also similar to the RMSE. When the height difference threshold was reduced, MAX decreased marginally. In terms of the remaining points, the decrease in the height difference threshold resulted in a sharp decline in the number of remaining points.

Based on the preliminary analysis, the main reasons for these trends are as follows. First, the accuracy and reliability of dem_h are not high. Second, because the acquisition time of DEM and laser altimetry data is different, some ground surfaces could have changed. Third, the value of dem_h comes from the DEM, while the benchmark data is from the DSM; the height differences may be due to vegetation and buildings. Fourth, the accuracy of laser altimetry data is low due to the influence of the atmospheric environment, complex targets, and data processing. Therefore, the reference terrain height can only be used for preliminary screening to eliminate large gross errors.

2. Terrain Factor Parameters

Terrain factor parameters that can be used in extraction processing mainly include the slope of terrain within the segment (terrain_slope) and the skew of terrain height for the segment (h_te_skew). The terrain_slope is computed from a linear fit of the ground photons, estimating the rise [m] in relief over each segment [100 m]; e.g., if the slope value is 0.04, there is a 4 m rise over the 100 m segment [26]. The influence of slope on laser elevation accuracy is particularly noticeable (laser elevation accuracy decreases significantly with the rise in slope) [5], so terrain_slope is one of the important bases for preliminary screening. The h_te_skew is calculated based on the ground photon elevation value in the segment, which reflects the symmetry of the elevation value distribution. The value affects the accuracy of data interpolation to a certain extent and can be used as one of the bases for advanced screening.

TABLE 3
Statistical Table of Filter Results Based on Height Difference

Threshold	Hanzhong Area				Songshan Area			
	RMSE	MAX	STD	Number	RMSE	MAX	STD	Number
+∞	8.29 m	80.43 m	7.54 m	1850	12.79 m	207.03 m	10.89 m	1829
50 m	7.61 m	78.83 m	6.71 m	1846	11.59 m	107.88 m	9.59 m	1825
40 m	7.61 m	78.83 m	6.71 m	1846	10.81 m	71.22 m	8.73 m	1819
30 m	7.34 m	78.83 m	6.45 m	1841	10.27 m	71.22 m	8.24 m	1800
20 m	7.03 m	78.83 m	6.19 m	1823	9.65 m	69.68 m	7.80 m	1738
10 m	6.27 m	78.83 m	5.61 m	1743	8.38 m	69.68 m	7.12 m	1437
5 m	5.97 m	78.83 m	5.45 m	1525	7.32 m	69.68 m	6.51 m	998
2 m	6.18 m	78.83 m	5.82 m	953	7.97 m	69.68 m	7.48 m	477
1 m	5.60 m	77.33 m	5.28 m	517	6.77 m	47.25 m	6.37 m	259
0.5 m	5.07 m	51.61 m	4.73 m	249	9.03 m	47.25 m	8.62 m	122

TABLE 4
Statistical Table of Filter Results Based on Slope

Threshold	Hanzhong Area				Songshan Area			
	RMSE	MAX	STD	Number	RMSE	MAX	STD	Number
0.5	8.23 m	80.43 m	7.49 m	1847	11.55 m	207.03 m	9.70 m	1758
0.4	8.21 m	78.83 m	7.48 m	1843	11.39 m	207.03 m	9.63 m	1691
0.3	8.13 m	78.83 m	7.42 m	1832	11.23 m	207.03 m	9.58 m	1589
0.2	8.05 m	78.83 m	7.36 m	1821	11.09 m	207.03 m	9.55 m	1399
0.1	7.65 m	78.83 m	7.02 m	1757	9.10 m	69.68 m	7.66 m	1048
0.08	7.32 m	78.83 m	6.67 m	1727	9.00 m	69.68 m	7.66 m	949
0.06	7.09 m	78.83 m	6.44 m	1664	8.60 m	69.68 m	7.43 m	813
0.04	6.87 m	78.83 m	6.22 m	1531	7.93 m	69.68 m	6.86 m	642
0.02	6.68 m	78.83 m	6.13 m	1293	8.18 m	69.68 m	7.13 m	390
0.01	6.51 m	78.83 m	6.00 m	987	8.73 m	69.68 m	7.82 m	224

To evaluate the supporting effect of terrain_slope on screening treatment, different slope thresholds were used to screen ATL08 products. First, the data points with slopes greater than the threshold were removed as gross errors. Second, the accuracy of the remaining data points was evaluated by the benchmark terrain data. Finally, the number of the remaining data points was counted, and the RMSE, MAX and STD of their accuracy were calculated. The specific statistical results are shown in Table 4.

For RMSE, as the height difference threshold decreased, the RMSE exhibited a downward trend. However, when the slope threshold was small, the RMSE fluctuated in the Songshan experimental area with more complex terrain. The variation trend of STD was largely consistent with the RMSE. For the MAX, the values were mainly unchanged since the maximum value is mainly from tall buildings and the terrain near buildings is generally flat and insensitive to the slope.

when the slope threshold was decreased, the number of remaining data points had a downward trend, and the extent of the decline was closely related to the change in terrain. The slope can better reflect the topographic relief. However, due to the influence of buildings and vegetation, it did poorly in the screening process when used alone, based on accuracy indicators (e.g., RMSE and MAX). Since the terrain_slope value is calculated based on the ground photon elevation in each segment, the value reflects the topographic relief in the laser scanning direction rather than the overall topographic relief within the segment, weakening its supporting role in screening to a certain extent.

3. Surface Coverage Information

Reference landcover for segment (segment_landcover) is the main parameter to describe the surface coverage information; the landcover classes and class codes can be found in the reference [26]. The segment_landcover value comes from the 2019 Copernicus Landcover 100m discrete landcover product. Considering that the spatial resolution of the data source is low and the acquisition time of the data source is different from the laser altimetry data, the reliability of segment_landcover is limited and can only be used as a basis for further advanced screening.

4. Photon Quantity Parameters

Photon quantity parameters mainly include the number of ground photons (n_te_photons), the number of canopy photons (n_ca_photons), the number of top canopy photons (n_toc_photons), and the quality flag for the distribution of terrain photons (subset_te_flag). Ground photon is the basis for calculating land elevation, and the accuracy of land elevation will be affected when there is an insufficient number of ground photons in the segment. The ground photon ratio (ratio_te_photons) is the ratio of ground photons to all signal photons in the segment, which can reflect the surface coverage to a certain extent; its value can be calculated by Equation 1. The subset_te_flag divides the 100 m segment into five sub-segments (every 20 m is a sub-segment); flags (-1, 0, 1) are placed on each sub-segment (-1: no data within the sub-segment available; 0: no ground photons within the sub-segment; 1: ground photons within sub-segment), indicating the quality distribution of identified ground photons within each 100 m segment. And this flag can be used as a basis for further advanced screening.

$$ratio\_te\_photons = \frac{n\_te\_photons}{n\_te\_photons + n\_ca\_photons + n\_toc\_photons} \quad (1)$$

To evaluate the supporting effect of ratio_te_photons on the screening treatment, different ratio thresholds were used to screen ATL08 products. First, data points with ratios less than the threshold were removed as gross errors. Second, the accuracy of the remaining data points was evaluated by the benchmark terrain data. Finally, the number of the remaining data points was counted, and the RMSE, MAX and STD of their accuracy were calculated. The specific statistical results are shown in Table 5.

TABLE 5
Statistical Table of Filter Results Based on Ground Photon Ratio

Threshold	Hanzhong Area				Songshan Area			
	RMSE	MAX	STD	Number	RMSE	MAX	STD	Number
0.05	6.47 m	80.43 m	5.97 m	1647	12.25 m	207.03 m	10.52 m	1770
0.1	5.86 m	78.83 m	5.39 m	1572	7.47 m	107.88 m	6.75 m	1124
0.2	5.72 m	78.83 m	5.36 m	1410	5.34 m	69.68 m	4.78 m	829
0.3	5.04 m	77.33 m	4.76 m	1249	5.25 m	69.68 m	4.78 m	623
0.4	4.78 m	77.33 m	4.56 m	1085	4.32 m	31.25 m	3.92 m	498
0.5	4.21 m	77.33 m	4.04 m	920	4.00 m	31.25 m	3.64 m	375
0.6	2.30 m	19.69 m	2.15 m	767	3.59 m	26.95 m	3.27 m	269
0.7	2.31 m	17.11 m	2.15 m	604	2.52 m	16.39 m	2.34 m	181
0.8	1.91 m	15.84 m	1.79 m	427	2.59 m	16.39 m	2.46 m	107
0.9	1.89 m	15.84 m	1.78 m	284	0.79 m	3.35 m	0.78 m	50

Based on the statistical results, when the ratio threshold increased, the RMSE, MAX, and STD of the two experimental areas showed a downward trend, while the overall accuracy of the remaining data points was greatly improved. This means that the ground photon ratio is able to adapt to the changes in terrain and ground objects and performs well in the screening process. However, based on the RMSE, even if the ratio threshold reaches 0.9, a gap remains between the accuracy of the remaining data points and the requirements of the control points. Also, there are only a few remaining data points. The results suggest that relying solely on the ground photon ratio to obtain ideal screening results would be difficult in areas with complex terrain and ground objects.

5. Accuracy Description Parameter

The accuracy description parameter mainly refers to the uncertainty of ground height estimates (h_te_uncertainty) and includes all systematic uncertainties (e.g., geolocation, pointing angle, timing, radial orbit errors) and the uncertainty from errors of identified photons; the calculation formula for h_te_uncertainty can be found in reference [26]. Therefore, h_te_uncertainty is a comprehensive parameter revealing the uncertainty and confidence of an ATL08 segment and can be used for ATL08 data processing and applications [21].

To evaluate the supporting effect of h_te_uncertainty on the screening treatment, different uncertainty thresholds were used to screen ATL08 products. First, data points with uncertainty exceeding the threshold were removed as gross errors. Second, the accuracy of the remaining data points was evaluated by the benchmark terrain data. Finally, the number of the remaining data points was counted, and the RMSE, MAX and STD of their accuracy were calculated. The specific statistical results are shown in Table 6.

From the statistical results, with the decrease in the uncertainty threshold, the RMSE, MAX and STD exhibited a downward trend in both experimental areas, and the overall accuracy of the remaining data points improved. However, the RMSE fluctuated in the Songshan area with complex terrain when the uncertainty threshold was small, and the number of remaining points also dropped sharply. The results suggest that relying solely on the uncertainty of ground height estimates would make it difficult to obtain ideal screening results.

6. Cloud Confidence Flag

The cloud confidence flag comes from the ATL09 product and indicates the number of cloud or aerosol layers identified in each 25Hz atmospheric profile [26]. If the flag exceeds 0, aerosols or clouds could be present. The existence of clouds and aerosols in the atmosphere mainly affects the accuracy of laser ranging and the number of photons reaching the ground [29]. Therefore, for accuracy description and photon quantity parameters, the cloud confidence flag is generally used as one of the bases for further advanced screening processing.

7. Photon Height Difference Information

The photon height difference information is the photon height above the interpolated ground at the photon's location and is recorded in the attribute as parameter ph_h. The photon height difference information near the data point reflects the surface elevation change near the data point and can be used as one of the bases for further advanced screening processing.

The height difference of the five signal photons closest to the data point was used as the photon height difference information of the data point. Therefore, when the photon height difference information is assumed to be the parameter diff_h_photons, it is a row matrix recording five height difference values and can be obtained by the GPS time in ATL08 products.

TABLE 6
Statistical Table of Filter Results Based on Uncertainty of Ground Height Estimates

Threshold	Hanzhong Area				Songshan Area			
	RMSE	MAX	STD	Number	RMSE	MAX	STD	Number
1000	6.37 m	80.43 m	5.91 m	1634	8.69 m	107.88 m	7.76 m	1324
100	6.35 m	80.43 m	5.89 m	1622	7.04 m	107.88 m	6.26 m	1244
50	5.82 m	78.83 m	5.36 m	1551	5.46 m	69.68 m	4.65 m	1093
30	5.77 m	78.83 m	5.36 m	1468	5.42 m	69.68 m	4.75 m	919
20	5.80 m	78.83 m	5.45 m	1337	5.40 m	69.68 m	4.79 m	795
10	5.80 m	78.83 m	5.53 m	974	5.46 m	69.68 m	4.99 m	557
6	4.41 m	77.33 m	4.19 m	659	6.20 m	69.68 m	5.71 m	366
4	2.87 m	20.59 m	2.67 m	525	5.51 m	28.04 m	4.81 m	218
2	2.67 m	15.84 m	2.45 m	263	4.92 m	16.39 m	4.13 m	75
1	2.73 m	14.81 m	2.51 m	131	5.52 m	16.39 m	4.61 m	18

IV. Strategy Design and Experiment

The previous attribute analysis and experiments suggest that it would be difficult to obtain ideal screening results solely relying on a single attribute, especially in areas with complex terrain and ground objects. Only by combining more attributes and comprehensive screening can a sufficient number of high-precision data points be obtained. Therefore, an extraction strategy was developed based on various attribute information and included preliminary and advanced screening procedures. The photon quantity parameter (ratio_te_photons) and photon height difference information (diff_h_photons) were used to extract control points for the first time, which greatly improves the accuracy and reliability of the extraction results. The feasibility and effectiveness of the proposed approach were evaluated using the Hanzhong and Songshan experimental areas.

A. Strategy Design

Considering the reliability of each attribute in ATL08 products and the correlation between attributes, a high-precision extraction strategy for ICESat-2 elevation control points was designed based on various attribute information. The proposed strategy considers different influencing factors (e.g., laser transmission environment, ground target characteristics) and includes eight screening steps. The specific process is shown in Figure 5, and the detailed steps are as follows:

1. Filtering based on h_te_uncertainty: When the number of terrain photons is insufficient, h_te_uncertainty will be given an invalid value (3.4028235E+38). Data points with invalid values of h_te_uncertainty are screened out as gross errors.

2. Filtering based on dem_h: The elevation difference threshold is usually set according to the accuracy of the reference DEM. In this experiment, the elevation difference threshold was set according to the accuracy of SRTM (Shuttle Radar Topography Mission). The RMSE of SRTM elevation is about 16 m. In general, twice the RMSE value is the accuracy range in the actual measurement project, which can be loosened to 1.5-2 times in difficult areas. Therefore, the height difference threshold is generally 30 m (about twice the RMSE value) and 50 m (about triple the RMSE value) in difficult areas. The difference between dem_h and h_te_best_fit is calculated, and data points whose elevation difference exceeds the threshold are removed as gross errors.

3. Filtering based on terrain_slope: The slope threshold is set according to the accuracy requirements of control points and the area's terrain condition. In flat areas (slope <2°), ICESat-2 has better measurement accuracy. According to the triangle transformation relationship, the terrain_slope value corresponding to a 2° slope is about 0.03. Therefore, the slope threshold is generally 0.03; in difficult areas, 0.05 is taken as the slope threshold according to the principle of appropriately loosening the range. Data points with slopes greater than the threshold are removed as gross errors.

4. Filtering based on n_te_photons and ratio_te_photons: The lower limit of ground photon ratio is set according to the surface coverage and the required number of control points; data points whose ratio are less than the lower limit are eliminated as gross errors. To ensure the accuracy of fitting terrain elevation, the ratio threshold is generally 0.6 (0.5 in difficult areas), which is an empirical value. Then, the lower limit of the number of ground photons is set, and data points with ground photons less than the lower limit are removed as gross errors. Too low a number of ground photons would not be conducive to the calculations of accurate terrain elevation. Therefore, 50 is taken as the number threshold for ground photons, which is an empirical value.

5. Filtering based on h_te_uncertainty and h_te_skew: The RMSE of h_te_uncertainty and h_te_skew is calculated for all remaining data points. Taking twice the RMSE value of h_te_uncertainty as the uncertainty threshold, data points with uncertainty exceeding the threshold are removed as gross

errors. Then, taking triple the RMSE value of h_te_skew as the skew threshold, data points with skew greater than the threshold are removed as gross errors.

6. Filtering according to subset_te_flag: Under the same conditions, the more uniform the distribution of terrain photons in the segment, the higher the accuracy of the corresponding data points. Therefore, data points with five flags of subset_te_flag greater than -1 and the middle three flags equal to 1 are retained; the rest are eliminated as gross errors.

7. Filtering according to cloud_flag_atm and segment_landcover: Considering the influence of clouds and aerosols on the accuracy, data points with cloud_flag_atm greater than 2 are removed as gross errors. Considering the location requirements for control points, data points located in forests and waters according to segment_landcover are removed as gross errors.

8. Filtering according to diff_h_photons: The elevation difference threshold is set based on the area's surface condition and the accuracy requirements for control points. According to the slope threshold setting analysis, the flat area refers to the area where the terrain_slope value is less than 0.03. Therefore, 3 m is taken as the threshold based on the terrain_slope value. Data points with five parameters of diff_h_photons less than the threshold are retained, and the rest are eliminated as gross errors.

After the eight-step screening process, the low-precision data points caused by the terrain, ground objects, and other factors are eliminated, guaranteeing the accuracy of the remaining data points and improving the reliability of control points. For areas with flat terrain and simple ground objects, good results can be obtained even after the preliminary screening. But for areas with complex surfaces, advanced screening is necessary to ensure the reliability of control points.

The strategy provides calculation methods or empirical values for various thresholds. In general, for areas with flat terrain and simple ground objects, the thresholds should be adjusted as much as possible to screen control points with higher accuracy. For areas with complex terrain and surface features, the thresholds should be adjusted as much as possible to ensure that a sufficient number of control points can be screened.

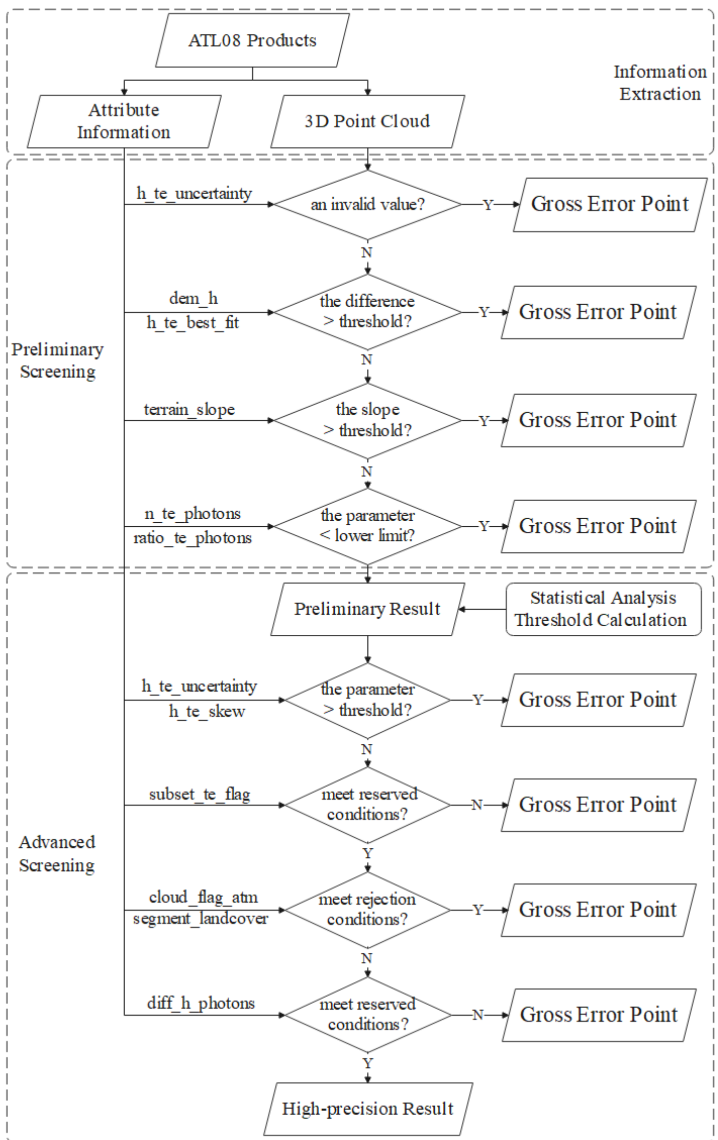


Fig. 5. Flowchart of the Elevation Control Points Extraction Strategy

TABLE 7
Statistical Table of Elevation Control Points Indicators During Extraction Process

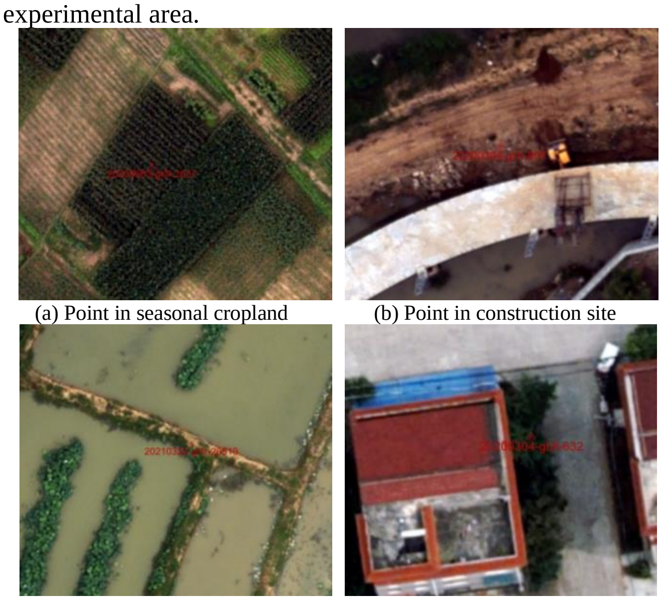
Step	Hanzhong Area			Songshan Area		
	RMSE	MAX	Number	RMSE	MAX	Number
0	8.29 m	80.43 m	1850	12.79 m	207.03 m	1829
1	6.37 m	80.43 m	1634	8.69 m	107.88 m	1324
2	5.99 m	78.83 m	1632	7.50 m	71.22 m	1317
3	6.02 m	78.83 m	1355	5.32 m	69.68 m	611
4	2.08 m	19.69 m	555	1.55 m	9.10 m	159
5	2.06 m	19.69 m	520	1.42 m	9.10 m	151
6	1.74 m	17.11 m	502	1.42 m	9.10 m	147
7	1.13 m	13.88 m	402	0.71 m	2.83 m	120
8	0.54 m	4.28 m	329	0.53 m	2.61 m	96

B. Experiment and Analysis

The extraction results were analyzed and verified using experimental data from the Hanzhong area in Shanxi province and the Songshan area in Henan province; relevant thresholds were adjusted based on the characteristics of the experimental area. Since the terrain in the Hanzhong experimental area was relatively flat, with more high-precision data points, the thresholds were adjusted to improve the screening requirements to obtain higher precision control points. The terrain in the Songshan experimental area was more complex and with fewer high-precision data points. Therefore, the threshold was adjusted to reduce the screening requirements to increase the number of control points. To accurately analyze the extraction process, the RMSE, MAX, and number of remaining data points were calculated after each screening step; the detailed results can be found in Table 7.

In terms of RMSE after preliminary screening, the RMSE for the remaining data points in the Hanzhong experimental area was 2.08 m. Since the experimental area was located in an urban area with relatively complex ground objects, further advanced screening was needed. The RMSE for the control points was 0.54 m after the advanced screening. In the Songshan experimental area, the RMSE of the remaining data points after the preliminary screening was 1.55 m. Since the experimental area was located in a mountainous region with relatively complex terrain, further advanced screening was necessary. The RMSE for the control points after the advanced screening was 0.53 m. In general, for areas with more complex terrain and ground objects, the RMSE can reach about 2 m after preliminary screening and about 0.5 m after further advanced screening. Ground photon ratio screening had the greatest improvement in accuracy, which was consistent with the results of the attribute analysis experiment.

In terms of MAX, after eight steps of screening, there were still 14 data points with an error of more than 1 m in the Hanzhong experimental area, while the MAX was 4.28 m. In the Songshan experimental area, there were still six data points with an error of more than 1 m, and the MAX was 2.61 m. These large error data points were superimposed on the image and terrain data and were analyzed together with their attribute information. There were two main reasons why these data points with large errors were not removed. First was due to the changes in terrain and ground objects at the location of data points, such as points located in seasonal croplands (as shown in Fig. 6 (a)), sites under construction (as shown in Fig. 6 (b)), and intermittent rivers and ponds (as shown in Fig. 6 (c)). The large errors were caused by the inconsistency between the acquisition times of the benchmark data and the laser data, and the terrain and ground features at the data point location have changed significantly. This was the main cause of the large-error data points in the Hanzhong experimental area. The second was the misclassification of signal photons. Signal photons on low plants and low-ancillary facilities near buildings (as shown in Fig. 6 (d)) had been misclassified as terrain photons. The participation of non-terrain photons in terrain fitting resulted in large errors for these data points. This problem occurred in areas with complex terrain and was the main reason for the large errors in the Songshan experimental area. After excluding the gross errors caused by these two reasons, the RMSE of the remaining data points reached 0.30 m in the Hanzhong experimental area and 0.38 m in the Songshan experimental area.

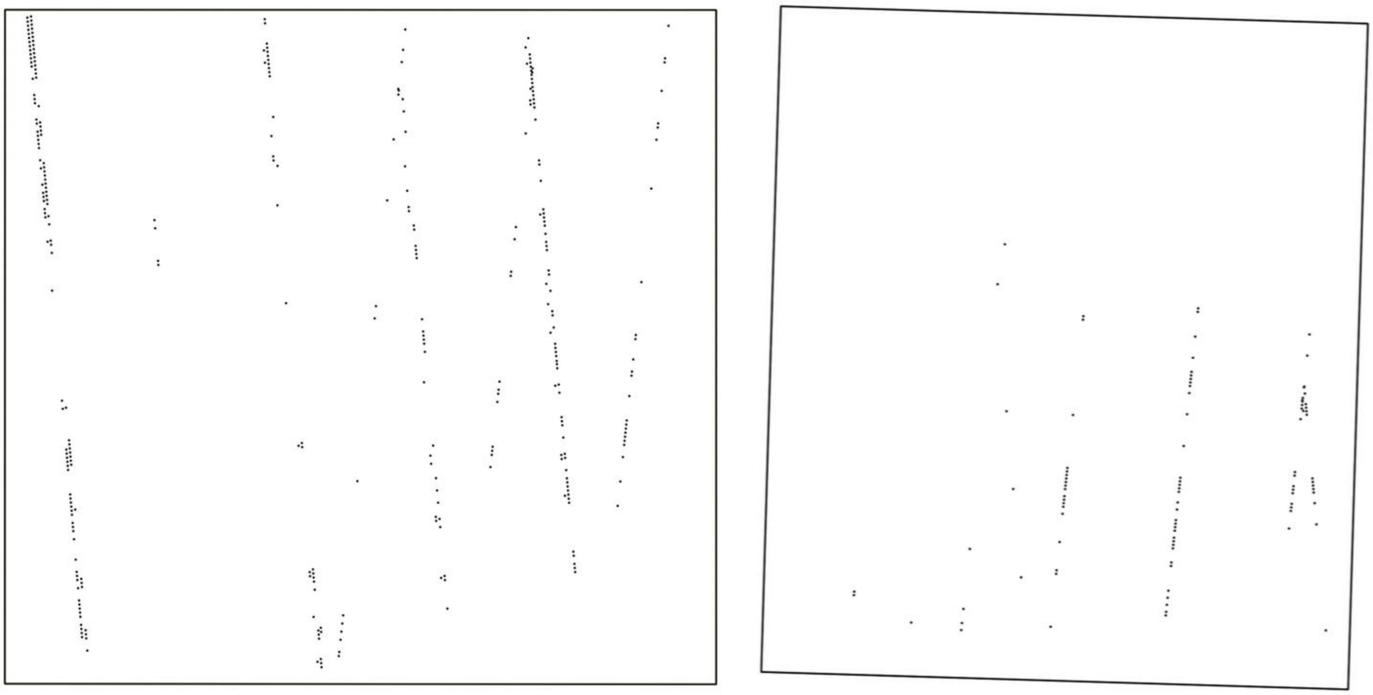


(a) Point in seasonal cropland (b) Point in construction site

(c) Point in intermittent pond (d) Misclassification point

Fig. 6. Location schematic diagram of data points with large error. The benchmark data corresponding to all data points in the figure was acquired in July 2019. The red triangle in the figure is the location of the data point, and the red character is the point number (e.g.,20210322-gt1r-20519, and “20210322” means that the data point was acquired on 22 March 2021).

In terms of the remaining data points, 329 data points were left in the Hanzhong experimental area after eight steps of screening, and the distribution is shown in Figure 7 (a). The figure shows that the density of the remaining data points is high, and the distribution is relatively uniform. The Songshan experimental area had 96 remaining data points after eight screening steps, and the distribution is presented in Figure 7 (b). The figure shows that the remaining data points are mainly distributed in the flat area, with few points in the mountainous regions. This is because fewer high-precision data points can be found in mountainous areas due to complex terrain and less exposed ground (mountainous areas are generally dominated by vegetation).



(a) Hanzhong Area (b) Songshan Area

Fig. 7. Schematic Diagrams of Laser Control Point Distribution. The black border indicates the range of the experimental area; Black dots represent the remaining control points.

V. Conclusion and Prospect

Space-borne laser altimetry technology has the advantages of being free from geographical restrictions and having high accuracy in measuring global elevation control points. However, due to the complexity and variability of terrain and ground objects, coupled with the low spatial resolution between orbits, the available information in space-borne laser altimetry data is limited, and the reliability of various attribute information in data products is not high. Therefore, how to extract high-precision elevation control points from Space-borne laser altimetry data is still a highly challenging problem. This paper developed a high-precision elevation control point extraction strategy based on ATL08 products by comprehensively utilizing various attribute parameters. Then, two typical experimental data were used to evaluate the feasibility and effectiveness of the extraction strategy. And main conclusions are as follows:

1. From the perspective of the accuracy index, the extraction strategy significantly improves the overall accuracy of obtained control points without external data support, which can be used to support the establishment of a global elevation control point database.

2. From the location of the obtained control points, this strategy can not only improve the accuracy of the control points but also take into account the location demand of the control point application, which is of great significance for promoting the engineering application of space-borne laser altimetry data.

3. From the distribution of extraction results, the extraction strategy can overcome the influence of complex terrain and ground objects and obtain dense control points with a relatively uniform distribution, which is of great significance for promoting the large-scale application of space-borne laser altimetry data in land surface surveying and mapping.

Based on the conclusions and the current development and applications in laser altimetry technology, the following aspects should be explored in subsequent studies:

1. Future studies should look into combined processing using stereo-mapping satellite images to further improve the accuracy of the screening process. The RMSE in laser data is improved after extraction. However, in terms of the MAX, there are still data points with low accuracy in the filtered data points, while the stereo mapping satellite image has good internal consistency. Combined processing can further reduce large-error data points and significantly improve the MAX index.

2. Deep learning methods should be introduced in future control point extraction studies. Many factors affect the laser data elevation accuracy, and there is a certain correlation between the various attributes of laser data. There is no strict causal relationship but a more correlated relationship in the screening process. Deep learning can be introduced to extract control points, accounting for the complexity of terrain and ground features and highlighting the algorithm's generalization.

3. Further research should be conducted on automated

interpretation for laser altimetry control points. Interpretation is crucial in control point application. This study used DSM data, taking into account the influence of ground object occlusion on the interpretation of control points, which supports automated interpretation. In the future, we will look into the automated interpretation of laser altimetry control points in combination with data-matching technology.

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1.The data resolution of the airborne data and spaceborne data is different, further refine how to match the two-kind data. What is the resolution of ATL03 and ATL08 data product?

Indeed, registration is very important for the joint processing of two types of data; and it is necessary to co-register them firstly, when using the datum data to evaluate the filtered ATL08 data. Considering the high precision of benchmark data used in this experiment, the registration method based on geographical coordinates was adopted, which is commonly used in ATL08 data precision evaluation research.

ATL03 is a collection of all photon points; Theoretically, its spatial resolution is consistent with the design value of ATLAS (the orbital resolution is about 0.7 m; The beams within each pair are separated by 90 m in the across-track direction; The beam pairs are separated by ~3.3 km in the across-track direction, and the strong and weak beams are separated by ~2.5 km in the along-track direction). In practice, the resolution of ATL03 product is also affected the atmospheric environment and target characteristics.

ATL08 is extracted from the ATL03 data after filtering and classification, which contains heights for both terrain and canopy at 100 m segments in the along-track direction; therefore, its orbital resolution is about 100 m (In practice, due to the impact of noise, sometimes it is more than 100 m), and the resolution in the across-track direction is the same with ATL03 product.

2.Test Site should be described more, especially coverage and slopes in test site.

Yes, the description of the test site is improved. For the coverage of test site, the aerial image or satellite image is added on the basis of the text description; in the term of slope, the average slope of the test site is calculated based on the datum data, and the slope map is drawn.

3. In Table 4, what is Slope threshold units? why start with 0.5?

The slope here refers to the attribute terrain_slope in ATL08 product. The terrain_slope is computed from a linear fit of the ground photons. It estimates the rise [m] in relief over each segment [100 m]; e.g., if the slope value is 0.04, there is a 4 m rise over the 100 m segment.

According to topographic classification standard in slope (flat: slope < 2°; hilly :2° ≤slope < 6°; mountainous :6° ≤ slope <25°), When the slope is greater than 25 °, the terrain belongs to high mountains. The laser data point in high mountains area is low in accuracy, and does not meet the location requirements of elevation control points. According to the triangle transformation relationship, the terrain_slope value corresponding to slope 25 ° is about 0.5. This is the main reason for starting from 0.5.

4.The slopes of the two study areas are obviously different. Is it reasonable to compare them together?

Indeed, the slopes of the two study areas are obviously different. The average slope of Hanzhong experimental area is less than 2° ; It is regarded as a representative of plain and hilly region for this study. The average slope of Songshan experimental area is larger than 8° ; It is regarded as a representative of hilly and mountainous region for this study. These two typical experimental data are used to analyze and estimate the adaptability of various parameters in extraction strategy, not to compare them.

6.In Table, why are the thresholds of steps 2, 3 and 4 different?

The terrain and ground objects of the two experimental areas are very different, so it is difficult to obtain ideal results by using the same set of parameters to process. Therefore, it is necessary to adjust the parameters appropriately according to t the characteristics of the terrain and ground objects in the experimental area. In fact, not only the thresholds in steps 2, 3 and 4 are different, but also the thresholds set according to the RMSE information of the remaining data points in the following steps are different.

7.Whether the threshold of each step needs to be changed in other research areas, so as to reduce the robustness of the strategy.

According to the relationship between various influencing factors of point accuracy and attribute parameters of the data point, the strategy mainly includes qualitative parameters, quantitative parameters and adaptive parameters. Qualitative parameters (e.g., segment_landcover, cloud_flag_atm) do not need to be adjusted. For quantitative parameters, this strategy provides two sets of thresholds (empirical value); One set is suitable for ordinary areas, and the screening requirements are higher in order to obtain higher precision control points; The other set is applicable to difficult areas, and the screening requirements are lower in order to obtain more control points. Adaptive parameters are set according to the RMSE information of the remaining data points.

8.Sunlight is the main factor that affects noise photons. It is suggested to supplement how the strategy threshold changes during the day and night, and explain the reasons. Strong and weak beams also need to be supplemented.

Indeed, sunlight will cause a lot of noise, which will affect the noise removal process. Currently, according to literature [3] in references, the noise removal process can remove about 98% noise; ATL08 is a product after noise removal. Therefore, this strategy based on ATL08 product can ignore the impact of acquisition time (day versus night). In fact, the impact of acquisition time is usually studied in the accuracy evaluation of ATL08 product (Details can be found at literature [20,21] in references).

According to the study of accuracy evaluation in laser data product, energy intensity in laser beam mainly affects the probability of photons being detected by the instrument, and then affects the number of photons reaching the ground. The ground photon ratio in the extracting strategy can express the influence of energy intensity (strong versus week) to a certain extent.

9. At the end of the first paragraph, the authors said that "ICESat-2 data is mainly used as elevation control points for joint processing with optical remote sensing images and existing topographic results" without any reference. Authors could provide more detailed information such as how the quality of control points influences the joint processing (like topographic correction or other processes).

"In terms of land surface surveying and mapping, ICESat-2 data is mainly used as elevation control points for joint processing with optical remote sensing images and existing topographic results"; This content is described in overview articles (literature [1]). Therefore, the reference has been added after this sentence.

The influence of the quality of control points on the joint adjustment belongs to another research content, which is related to many factors such as the precision, distribution, number of control points, and the size, terrain, internal consistency (terrain data or image data) of the survey area. This problem is an important direction for our next research.

Specific contents can be found in corresponding papers, such as: Tang Xinming, Liu Changru, Zhang Heng, et al. GF-7 Satellite Stereo Images Block Adjustment Assisted with Laser Altime- try Data[J]. Geomatics and Information Science of Wuhan University,2021,46(10): 1423-1430. Li Guoyuan, Tang Xinming, Zhou Ping, et al. Laser Altimetry Data Processing and Combined Surveying Application of ZY3-03 Satellite [J]. Infrared and Laser Engineering,2022,51(05):441-449.

10. Multiple methods can support the calculation of these descriptive parameters, such as slope and canopy height. The difference in calculating methods may lead to different results and influence the corresponding analysis. I suggested authors consider this issue and provide more details about the calculation of derivative parameters.

Indeed, Multiple methods can support the calculation of these descriptive parameters, and the difference in calculating methods may lead to different results. These descriptive parameters are built-in parameters in ATL08 products, and their calculation methods can be found in the product description document (literature [26]). There are many attribute parameters used in this paper; for the parameters that are directly extracted and used with clear meaning (such as surface coverage information, cloud confidence flag), a simple description and reference are used to introduce them; For parameters inconsistent with the conventional meaning(such as slope), a detailed description of the calculation method is added; For parameters that need to be calculated with other information (such as ground photon ratio), their calculation formulas are listed.

11. I do not think two reasons here can explain why they use DSM instead of DEM. In my opinion, the points on the canopy are unstable, especially since the benchmark and ATL data are collected at two different times. The changes in canopy could be the main factor that significantly influences the RMSE or other accuracy indexes.

The DEM product filters the buildings and vegetation information, while the DSM product keeps them; and this is the main difference between them. Indeed, the points on the canopy are unstable. Therefore, the points on the canopy cannot be used as elevation control points and should be removed as gross errors in the processing. At present, there are many ancillary facilities (such as elevators, vents, solar energy) on the top of buildings, and the surface of building top is uneven. Therefore, the points on the building also cannot be used as elevation control points and should be removed as gross errors in the processing. If the points on the building or canopy are retained as control points in the processing, using DSM to evaluate the point accuracy can find this problem. If using DEM to evaluate the obtained control points accuracy in the processing, the RMSE or other accuracy indexes may be good, but some of the obtained points not meet the point location requirements of the elevation control point and cannot be used as elevation control points.

12. I think the most significant issue is the consistency of benchmark data and ATL08 data. In other words, these two datasets should be all DSMs or DEMs and then the comparison between these two datasets is valid. In addition, the collecting time could also be discussed. Especially for natural above-ground objects such as trees, the difference in season can lead to large elevation deviations in datasets collected by UAVs and also satellites. The explanation of this paragraph is hard to be understood which should be rewrote.

If Our purpose is to evaluate the accuracy of ATL08 products, I agree that the most significant issue is the consistency of benchmark data and ATL08 data. But Our purpose is to obtain elevation control points, not to evaluate the accuracy of ATL08 products; and the elevation control points require high precision and easy interpretation (Not all data points with high accuracy can be used as control points). From the requirement of high precision, the accuracy of some control points obtained using the DEM is low. Whether benchmark data or space-borne laser altimetry data, the elevation values of buildings and vegetation region in DEM are obtained through interpolation, and the accuracy of control points in such regions is relatively low. From the requirement of easy interpretation, some control points obtained using DEM are difficult to interpret and apply in practical projects. If DEM is used as benchmark data, the extracted control points may be located in vegetation and building regions. In practical engineering applications, such control points are difficult to interpret and apply due to the occlusion of buildings and vegetation.

13. What is the reference terrain height value? Data collected by yourself or DEMs mentioned in the next sentence? Line 37-46. I agree that the above process can filter points with large errors, but I do not think the reasons provided by the authors are valuable. For the first reason, authors should clarify the specific accuracy and quality of DEMs providing dem_h. If the accuracy and quality of these DEMs are not high enough, the above process would be invalid. For the third reason, I am a little confused about why you compare dem_h from DEMs and benchmark data. The above process calculates the difference between dem_h from DEMs and h_te_best_fit from ATL08 instead of the benchmark data. I hope the authors could provide more detailed clarification.

One of the characteristics of this design strategy is that it does not rely on external data; The reference terrain height is also a built-in data of ATL08 product, which is recorded in parameter dem_h. Its value for each segment is determined using the "best" DEM available based on the data location; The DEM is taken from various ancillary data sources: MERIT, GIMP, GMTED, and MSS. The above is the main description about parameter dem_h in ATL08 product document (literature [26]). At present, these DEMs have not been released publicly, and we have no reliable information about these DEMs. I believe that although there is no accurate information about these DEMs, the accuracy of these DEMs should be better than the published global DEM data (such as SRTM); Otherwise, NASA will choose to use the public DEM data.

However, the accuracy of these DEMs is not high enough to be used as the benchmark data to extract control points. Therefore, dem_h can be used as reference information to remove gross errors, as did References 5 and 23.

This experiment is based on dem_ h (DEM data) to extract control points, and the evaluation screening results are based on the benchmark data (DSM data); The purpose of comparing the dem_ h and the benchmark data is to analyze the reasons for the poor extraction results.

14. I suspect that it is not necessary to use all parameters to achieve filtering. Based on the preliminary experiments, it is clear the terrain and ground photon ratio play significant roles in this filtering process. The authors also clarify that "this is because fewer high-precision data points can be found in mountainous areas due to complex terrain and less exposed ground". I think it is possible to do a significant assessment of parameters and remove useless parameters to further improve the reasonable efficiency of your method.

In fact, in the initial experiment, a small number of efficient parameters are combined to extract control points; but there were always some gross error points in the extraction results that could not be filtered out; Then, I extracted a total of 46 parameters that may be helpful for screening processing, and repeatedly combined various parameters to experiment; Finally, 11 parameters are retained, and the extraction strategy was developed.

In my opinion, there are three main reasons why it is difficult to obtain ideal results with a few efficient parameters. First, according to the research results of ATL08 product accuracy evaluation, there are many factors that affect the accuracy of data points, and a few parameters cannot cover all interference factors. Second, the reliability of these attribute parameters is not high, such as the terrain_slope (it reflects the topographic relief in the laser scanning direction, rather than the overall topographic relief within the segment), ground photon ratio (it will be affected by the misclassification of photons). Third, the observation objects (land) are complex and changeable (It's not as simple as ice and snow). The characteristics of the observation object has an important impact on the observation accuracy. Therefore, in order to obtain reliable extraction results, it is necessary to combine multiple parameters.

15. It is unclear whether the method is applicable in large scales.

In terms of threshold setting, for large areas with large topographic relief, the threshold setting method for difficult areas is recommended; If it is necessary to further improve the accuracy of extraction control points, it is recommended to use global public DEM data to simply partition large regions according to terrain, and then adopt different threshold strategies for different regions.

16. A detailed introduction of the ATLAS data products is not needed. A brief introduction of ATL03 and ATL08 data products is enough. Description in section II. ATLAS Data Product should be deleted.

ATLAS Data Product was deleted, and the description of ATL03 and ATL08 data products is modified.

17. The analyses on the results need to be improved. e.g., taking the data with large error as example for illustration, adding figures, etc. to increase the credibility of the analysis.

In the part of experimental result analysis, the REMS is mainly analyzed based on the statistical data in Table 7; For maximum value analysis, the sample data points with large error are added (as shown in Fig. 6); In terms of the remaining data points, the analysis is mainly based on the distribution of obtained control points in Figure 7.