Research on the Precise Matching Method between Control Points and DSM

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Abstract: In the surveying and geographic information industry, it is extremely important to match control points to terrain data such as DSM. After matching the measurement control points with DSM,the position and elevation in the high-precision DSM digital model can be used to analyze and evaluate the quality of the measurement control points. Conversely, the coordinates of high-precision measurement control points can be used to correct the plane position and elevation in DSM, making them consistent with the coordinates of the control points and more accurately reflecting surface information.

This study mainly adopts a method that takes into account global elevation differences and can achieve matching between measurement control points and DSM while minimizing global elevation differences.The algorithm designed in this article is based on principles such as affine transformation,and effectively solves the main problem of traditional control point and DSM matching by measuring the root mean square error (RMSE)of elevation anomalies between control point data and DSM terrain data,achieving high-precision matching between measurement control points and DSM.The main research content of this article is as follows:

(1) We used satellite laser point cloud control point data and DEM terrain data released by the United States Geological Survey. After a brief introduction, we carried out preprocessing steps such as extracting high-precision control point data and converting the plane and elevation benchmarks of the two types of data.

(2) The experimental data was divided into three groups of test data, and the matching results were obtained using the designed matching method. The results were compared with the single point matching experimental group as a control. The analysis showed that the matching method that takes into account the minimum global elevation difference has a significant improvement in matching accuracy, and the improvement is related to the terrain characteristics of the study area.

Keywords: Digital Surface Model; Control points; Affine transformation; Global elevation difference; Root mean square error; LiDAR point cloud

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1. Introduction

1.1 Research background and significance

With the rapid progress of various high-resolution remote sensing satellite technologies in the world, the development of acquiring various high-resolution remote sensing image data has entered a new stage in recent years.It includes high resolution DSM 3D image data and high resolution laser point cloud control point data, which are the control point data and DSM terrain data studied in this paper. Although the resolution of the two is getting higher and higher with the development of satellite research, it is still difficult to obtain the real plane position of the

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control point, so it is still indispensable to achieve accurate matching between the two.After the horizontal control points are matched with the DSM, the high-precision coordinates of the control points can be used for correcting the elevation and plane position information in the DSM, so that the elevation and plane position information is consistent with the coordinates of the control points, and the surface information is more accurately reflected; and conversely, the high-precision elevation and plane information in the DSM can also be used for analyzing and evaluating the quality of the control points.

In terms of their data characteristics, DSM data has high geometric accuracy and rich details, but the degree of automation of related processing is not high; while the control point data, especially the laser point cloud LIDAR data, can directly provide three-dimensional coordinates, which is conducive to improving the degree of automation of processing and registering the two types of data.The texture information and the plane coordinate and elevation information of the research object target can be obtained at the same time, It is confirmed that it has a wide application prospect in the fields of ground object classification, target change detection and three-dimensional reconstruction.

To sum up, the matching of control point data and DSM data can improve the accuracy of spatial positioning, thereby improving the accuracy and reliability of geospatial data, and providing more reliable basic data for the application of geospatial data in the fields of terrain analysis, urban planning, environmental protection and governance. Therefore, the matching algorithm between DSM and GCPs needs to be constantly developed. In this paper, a method based on the root mean square error (RMSE) of elevation is proposed.As the reference datum, based on the principle of affine transformation, the method of matching DSM with control points considering the minimum difference of global elevation emerges as the times require, which is also the core content of this paper.

1.2 Research status of control point and DSM matching method

The 3D information of surface features can be obtained mainly through stereo pairs, laser point cloud and digital surface model (DSM). Stereo pairs and laser point clouds provide the point cloud data of the surface of the object, while DSM is a special orthophoto image of the surface elevation, which has the same format as the commonly used reference image and digital elevation model (DEM).Because of this characteristic of DSM, if DSM can be used to perform geometric correction on optical satellite images, it will not require major modifications to the existing satellite image processing process, and the accuracy of the images can be significantly improved.

There is a 3D-3D registration method based on point pair space transformation. On the basis of effective extraction of image feature points, the image point cloud is obtained by means of stereo matching or motion recovery structure, and then the image point cloud and LIDAR point cloud are registered according to the traditional point cloud registration method. Many scholars have proposed the consistent 4-point set method (4 point congruent sets, 4 PCs)., and a series of related improved algorithms, such as dynamic 4-point method (4PCS, D4PCS), super 4-point method (super4PCS) . These methods need to consider multiple parameters. DEM is a regular grid, and the minimum elevation difference method is proposed for the structural characteristics of the data, which does not require any tedious processing and is one of the most widely used methods in 3D terrain matching.The method has the advantages that feature points do not need to be extracted, and the relationship between the point pairs can be directly used for registration processing, but the method has the disadvantages that the calculation amount is large, because the method has higher requirements on a camera and calibration and has constraint conditions on the number of images, wrong matching point pairs are easy to occur, errors are also generated in the process of generating the point cloud through intensive matching, and the registration accuracy is reduced.Multi-beam laser point cloud data is presented in the form of two-dimensional narrow band, which can not extract the same feature points on the image as airborne or ground laser point cloud, so the traditional matching method is difficult to apply.

In order to improve the efficiency and reliability of matching, researchers have begun to consider building a database to manage the control point data. This means that the automation of the selection of control point data and the automatic matching with the target image are realized. This method can not only improve the efficiency of image matching, but also ensure the security of control point data. More importantly, it can realize the effective management and utilization of the results of the existing control points.Specifically, researchers can build a control point database, and add the image information and related description information of the local area of the corresponding control point to the database. When matching is needed, the system can quickly call the control points that meet the requirements in the control point database to match with the target image.

1.3 Research content and train of thought

Based On the research background and current situation of the matching method between GCPs and DSM, this paper uses coordinate transformation, affine transformation and the principle of correlation adjustment algorithm, takes the root mean square error (RMSE) of elevation as the metric, and adopts a method which takes into account the global elevation difference. The algorithm that can realize the matching of survey control points and DSM and minimize the global elevation difference (also called surface nesting matching algorithm in the following text)The method effectively solves the main problem of the matching between the traditional control points and the DSM at present, and realizes the high-precision matching between the measurement control points and the DSM.In this paper, we use the matching method which takes into account the minimum difference of global elevation, aiming at the control point data extracted from the ATL03 product obtained by ICESat-2 satellite and the DEM terrain data released by the United States Geological Survey, and use the single-point matching algorithm to analyze the accuracy of the results through comparative tests, using the elevation RMSE as a reference metric. The advantages and disadvantages of the surface matching method are verified and summarized. The main contents of this paper are as follows:

(1) Three groups of control point data extracted from ATL03 products obtained by ICESat-2 satellite are matched with the corresponding 1m resolution 3dep dem terrain data of the study area by using the control point and DSM matching method (surface nesting algorithm) which takes into account the minimum global elevation difference. The best nested model corresponding to the minimum RMSE is obtained.

(2) Using different matching algorithms to match the three groups of the same processing data, and obtain the RMSE value respectively, as a control test, comparing the matching results of the two different matching methods and the size of the RMSE value, analyzing and comparing the results, summarizing the advantages and disadvantages of the control points with the smallest global elevation difference and the DSM matching method.

2. Introduction of Experimental Data and Data Preprocessing Method

2.1 Introduction of experimental data

In this study, the control point data is extracted from the ATL03 product of ICESat-2 satellite after a series of preprocessing, covering the longitude and latitude coordinates and elevation information of the control point; The DSM data is from Elevation Products (3dep) published by the United States Geological Survey (USGS).DEM terrain data with 1m resolution is a kind of high-precision three-dimensional raster data.

The LiDAR DEM data in the United States can be downloaded from the website:https://apps.nationalmap.gov/downloader/ - /.The DSM terrain data used in this paper is the 3DEP 1m resolution DEM terrain data released by USGS downloaded from the above website, which is a kind of three-dimensional raster image data.

In September 2018, NASA launched the ICESat-2 satellite, a satellite carrying the Advanced Terrain Laser Altimetry System (advanced topographic laser altimeter system, ATLAS). The system uses lidar technology to respond to the ground. Unlike the conventional full-waveform lidar, ICESat-2 uses single-photon detection technology for the first time, which means that it can measure on the ground with the response capability of a single photon, thus greatly improving the data acquisition efficiency.

ATL03 product data is global geolocation photon data, This data set contains the altitude above the WGS84 ellipsoid (ITRF2014 reference frame), latitude, longitude, and time of all photons downlinked by the Advanced Terrain Laser Altimeter System (ATLAS) instrument on the Ice, Cloud, and Land Elevation Satellite (ICESat-2) observatory.The ATL03 product is designed to be the single source of all photon data and ancillary information required for advanced ICESat-2/ATLAS products. It therefore also includes spacecraft and instrument parameters and ancillary data, which are not explicitly required by ATL03.

The control point data used in this study is the high-precision photon control point data extracted from ATL03 products obtained by ICESat-2 satellite after preprocessing, including longitude, latitude and elevation data.

2.2 Data preprocessing

2.2.1 Method for extracting control points from satellite-borne laser point cloud based on ICESat-2

Spaceborne photon counting technology may encounter the situation that laser beams shine on flying targets or moving objects on the ground when collecting data. This multipath effect can result in the generation of multiple, inaccurate echo signals, which are also recorded. As a result, significant gross error point cloud data will be observed on the profile. Therefore, before using these data, the data must be preprocessed.To extract the laser point cloud control point data from the product data obtained by ICESat-2 satellite, the following preprocessing process is required to ensure that the elevation information of the surface and other targets can be accurately extracted from the received photon signals.

First of all, data collection should be carried out. Because the principle of photon counting lidar is to emit laser pulses and record the single photons returned. The arrival time of each photon is related to its distance from the lidar to the ground or other targets.

The second step is to start signal preprocessing. Because that raw data typically contain a large amount of background noise and artifacts, a signal pre-process step is required to remove and filter out these background noise and artifacts. Pre-processing steps include filtering out background noise (such as that caused by sunlight) and electronic noise. This may involve setting a threshold to retain only those photon events above a certain energy level.

The third step is signal detection and classification. This step is also the core step to extract the coordinates and elevations of the control points of the laser point cloud. Various algorithms such as sliding window techniques or density-based clustering algorithms such as DBSCAN are used to identify and separate groups of photons that may represent actual ground returns. In this step, the elevation positions of the photons can be estimated from their time tags.

The fourth step is the separation of ground points and non-ground points. That is, to distinguish between ground returns and non-ground returns (such as trees, buildings, etc.) By relevant algorithms. This usually involves comparing the heights at which the photons return to identify which photons are directly reflected from the ground.

After completing the above steps, related models and products can be generated, such as DEM digital elevation model or DSM digital surface model. Once the ground return photons are identified, the data can be used to construct a digital elevation model of the ground. This involves interpolating the point cloud data into a regular grid to form a continuous elevation surface.

The above is the process of extracting accurate control point data from ICESat-2 laser point cloud data by preprocessing. Compared with the airborne multi-beam laser point cloud, the satellite-borne laser point cloud data has higher flight altitude, longer orbit distance, higher coverage density along the orbit direction, and more information, but the returned energy is weaker, so it is necessary to study a suitable method to accurately eliminate the noise points of massive profile point cloud.

The DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm is used to process the trend components in the photon data.DBSCAN is a density-based clustering algorithm, which can identify data points with high enough density and treat them as a cluster, while low density areas can be treated as noise. "Detrend photon" "refers to the trend components in photon data, and DBSCAN can be used to identify and remove noise points outside these trend components.Using the above algorithm to complete the point cloud denoising, and then through the separation of ground points and non-ground points, the high-precision ground control point data can be extracted.

2.2.2 Plane datum transformation (to make the control points consistent with the plane coordinate datum of DSM)

Because the control point data used in this paper is the high-precision photon control point data extracted from ATL03 products obtained by ICESat-2 satellite after preprocessing, including plane longitude, latitude and elevation data. The external DSM terrain data used is the 3DEP 1m resolution DEM terrain data released by USGS and downloaded from the above website. The preprocessing process of point cloud photon control point data extracted from ATL03 product.

For these two kinds of data, they belong to different reference coordinate datum and elevation datum. See Table 2-1 below for the coordinate datum and other attributes of the two kinds of data.

Table 2-1 Datum Attributes of Control Point Data and DEM Data

Data group	Plane Datum	Elevation datum	Projection mode
Laser point cloud control point data	WGS84	Ellipsoid	No projection
DEM topographic data	NAD83	Quasi-geoid	UTM projection

It can be seen from the above Table 2-1 that the plane datum and elevation datum of the two data are different. The control point data extracted from the ATL03 product of ICESat-2 satellite is the longitude and latitude data with WGS84 as the plane datum, while the LiDAR DEM data of the United States is the NAD83 as the plane datum.

WGS84, or Global Geodetic System 1984, is a datum designated by the National Imagery and Mapping Agency of the United States Department of Defense. The WGS84 reference ellipsoid is used. The WGS84 coordinate system is a conventional terrestrial reference system CTS. The origin of the coordinate system is the center of mass of the earth, so it is a geocentric coordinate system. The coordinate system uses geodetic coordinates, namely longitude, latitude and elevation, to describe geographical location. It is a global universal geographic coordinate system and is widely used in various geographic applications and research fields.

NAD83, the North American Datum 1983, is a geographic coordinate system developed and maintained by the United States and Canada. It uses the GRS80 reference ellipsoid, which is similar to the WGS84 coordinate system and uses geodetic coordinates to describe geographic locations. The difference is that the reference ellipsoids of the two coordinate systems are different. The NAD83 coordinate system is more suitable for North America, and a set of datum points and coordinate system parameters suitable for North America are adopted.

(1) Projection conversion

For the control point data, because the point cloud photon control point data extracted by ATL03 product data preprocessing is not processed by projection, the plane coordinates of the control point data are directly described by geodetic coordinates longitude and latitude, namely B and L.

As for the American IiDAR DEM data downloaded from the Internet, it is the data processed by UTM projection, and the plane coordinates are described by X and Y of the rectangular coordinate system. Therefore, in order to unify the plane coordinate datum of the two kinds of data and realize the matching operation in the subsequent test process, it is necessary to unify the two kinds of data into the same coordinate system.

In this study, the processing method is to use UTM projection for the control point data, and the reference ellipsoid is projected into the plane to achieve the unification of the plane coordinates of the two kinds of data, so as to provide the data that can be directly matched for the subsequent matching test.

The UTM projection is the universal transverse-Mercator projection, which belongs to the transverse-equiangle-secant elliptical cylinder projection. Its projection cylinder is secant to the earth, and its plane right-angle system is the same as the Gaussian projection. The projection was proposed by the United States Military Bureau of Surveying and Mapping, and has been used as the projection datum of geodetic survey and topographic maps in many countries and regions in the world, and can also be used to obtain various topographic data.In order to control the deformation, the UTM projection usually uses the zonal projection method to divide the earth's surface area between 84 degrees north latitude and 80 degrees south latitude into north-south longitudinal zones according to longitude. The common zoning methods are 6 degrees zoning and 3 degrees zoning. In this paper, UTM projection conversion is realized by reading the longitude and latitude data of control points first, and then by programming the relevant function code.

(2) Ellipsoidal transformation

It can be seen from Table 2-1 that the reference ellipsoids of laser point cloud control point data and DEM terrain data are different. Therefore, in order to achieve a high degree of unity of the two kinds of data to achieve subsequent accurate matching, it is necessary to convert the WGS84 ellipsoid to the GRS80 ellipsoid.

The specific steps of the common ellipsoid conversion method are as follows:

Firstly, the geodetic coordinates under the WGS84 ellipsoid are transformed into Cartesian coordinates, that is, spatial rectangular coordinates. In this step, the conversion from BLH to XYZ can be realized through the relevant calculation formula.

In the second step, the Cartesian coordinates under the WGS84 ellipsoid are converted into the Cartesian coordinates under the GRS80 ellipsoid. Generally speaking, the difference between two reference ellipsoids lies in the origin of coordinates, the direction of coordinate axes, the shape and size of ellipsoids. Therefore, the "seven parameters" method can be used to complete the coordinate transformation between ellipsoids.

The "seven-parameter" conversion formula from WGS84 ellipsoid to GRS80 ellipsoid is shown in Figure 2-1:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{GRS80} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{WGS84} + \begin{bmatrix} s & r_z & -r_y \\ -r_z & s & r_x \\ r_y & -r_x & s \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{WGS84} + \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} \#(2-1)$$

Where, $\Delta X, \Delta Y, \Delta Z$ are three translation parameters (unit: m), r_x, r_y, r_z are three rotation parameters (unit: rad), and *s* are scale factors.

Finally, the obtained GRS80 Cartesian coordinates are converted into geodetic coordinates to realize ellipsoid conversion.

In this study, although different reference ellipsoid benchmarks are used for these two kinds of data, the parameter difference between the two kinds of reference ellipsoids is very small and can be ignored in this study, so ellipsoid conversion is not used in the subsequent test process.

2.2.3 Elevation datum conversion

It can be seen from Table 2-1 in 2.2.2 that the elevation datum of the control point data is different from that of the DEM topographic data, and the elevation of the control point is expressed as the ellipsoidal height corresponding to each laser photon, which belongs to the geodetic height with the ellipsoidal surface as the reference datum. The elevation datum of DEM topographic data is quasi-geoid, which belongs to normal height.

The ellipsoid height corresponding to the control point data, namely the geodetic height, *H* ,refers to the distance from the ground control point to the reference ellipsoid along the normal of the reference ellipsoid. The elevation in DEM topographic data, namely normal height, H_{normal} ,refers to the distance from the ground point to the quasi-geoid along the plumb line, which belongs to the normal height system.Because the average gravity value of the undetermined point in the orthometric system can not be accurately calculated, the normal gravity value of the undetermined point is generally used to replace the average value. Because the change of the gravity value is equivalent to the change of the elevation starting surface, the geoid becomes the quasi-geoid.

Therefore, in this study, in view of the elevation difference between the two kinds of data, we take the average value of the elevation difference between the elevation of all control points, that is, the geodetic height, and the corresponding elevation in the DEM data, that is, the normal height, as the elevation anomaly. The elevation conversion from the geodetic height of control points to the normal height of DEM terrain raster data can be realized through the elevation abnormal value. See Equation 2-1.ξ

$$H = H_{normal} + \xi \#(2-2)$$

In this study, because the area of the selected data is very small, it can be approximately considered that each point is the same as the elevation anomaly in the DEM data, that is, there is no change between different points, so the average elevation difference between the geodetic height and the normal height of the whole area is used as the elevation anomaly value in this paper. And then the conversion of the height datum is realized through the height abnormal value.

3. Matching Method of Control Points and DSM Considering the Minimum Difference of Global Elevation

3.1 Introduction

In this paper, a method based on the principle of affine transformation is adopted, which takes the root mean square error (RMSE) of elevation as the reference datum and takes into account the control points with the smallest global elevation difference to match the DSM. The introduction of the principle of this method is also the core content of this chapter. This chapter introduces the core algorithm of this paper, the control point and DSM matching method considering the minimum global elevation difference, which can also be called surface nesting matching method, and the principle of the algorithm and related formulas are mainly explained.

3.2 Matching method of control points and DSM considering the minimum difference of global elevation

3.2.1 Matching principle

The invention relates to a method for matching a control point and a DSM in consideration of the minimum global elevation difference, which is characterized in that according to the elevation abnormal value of the control point elevation and the DSM terrain data elevation, the control point elevation root mean square error (RMSE) is taken as the measurement, based on an affine transformation model covering translation and rotation, the elevation difference between the control point and the reference terrain data is minimized, A method for enabling the control points to be precisely matched with the DSM.The method supposes that the plane position of the external DSM terrain data is accurate, so the plane position of the control point can be corrected by using the accurate DSM terrain data, the coordinate conversion is realized by performing translation and rotation operations on the control point, the control point and the DSM data are subjected to registration, the corresponding optimal registration model when the elevation root mean square error value is minimum is obtained, Different rotation and translation parameters correspond to different nested models,Therefore, the matching method can also be called surface nesting method.

The core idea of this method is to treat the control points as a rigid body model and apply translation and rotation transformation to it, so that the control points can adjust their attitude and position in space and match with the digital surface model (DSM). The control point is regarded as a rigid body model, and the control point is no longer a fixed data, but a model that can be translated and rotated.The position of the control point can be adjusted by controlling the size of the translation parameter, or any control point can be selected as the rotation center, and the attitude of the control point can be adjusted by the rotation parameter. When rotating, it can operate in any posture in space. Through this method, the position and attitude of the control points in the space can be matched with the DSM according to different coordinate transformation parameters.The translation parameter mainly determines the spatial position of the control point, while the rotation parameter mainly determines the spatial attitude of the control point. The mathematical principle and calculation steps of this matching method are described in detail in Formula (3-1).

$$\begin{bmatrix} X_i \\ Y_i \\ h_i \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_i - x_0 \\ y_i - y_0 \\ h_i \end{bmatrix} + \begin{bmatrix} x_0 \\ y_0 \\ 0 \end{bmatrix} + \begin{bmatrix} \Delta x \\ \Delta y \\ 0 \end{bmatrix} \#(3\text{-}1)$$

Formula (3-1) is the coordinate obtained by translating and rotating the coordinate of the control point. Alternatively, the coordinate of the control point can also be obtained by only translating the coordinate of the control point. See Formula (3-2).

$$\begin{bmatrix} X_i \\ Y_i \\ h_i \end{bmatrix} = \begin{bmatrix} x_i - x_0 \\ y_i - y_0 \\ h_i \end{bmatrix} + \begin{bmatrix} x_0 \\ y_0 \\ 0 \end{bmatrix} + \begin{bmatrix} \Delta x \\ \Delta y \\ 0 \end{bmatrix} \#(3\text{-}2)$$

where X_i, Y_i, h_i are the coordinates of the control point after coordinate conversion, θ is the rotation parameter, Δx, Δy are the translation parameters, x_i, y_i are the corresponding control point coordinates in each pose, and x_0, $y_0$are the coordinates of the control point in the initial pose.

The control points after coordinate transformation are matched with the DSM, and the row and column number of each control point in the DSM and the corresponding DSM elevation value are calculated according to the plane coordinates of the control points after coordinate transformation by using the formula (3-2).

$$\begin{cases} row = \left[\dfrac{(Y_i - \min(Y_{DSM}))}{Resolution_x} \right] \\ col = \left[\dfrac{(X_i - \min(X_{DSM}))}{Resolution_y} \right] \\ h_{DSM} = f_{DSM}(row, col) \end{cases} \#(3\text{-}3)$$

Where, row and col are row and column numbers of the control point in DSM; x_i, y_i is the coordinate of the control point after coordinate transformation; $\min(X_{DSM})$, $\min(Y_{DSM})$ are the minimum values of abscissa and ordinate of DSM respectively; [*] is the integral function; $h_{DSM}$is the corresponding DSM elevation value.

Use the formula (3-4) to calculate the system error between the control point and the DSM elevation value, that is, calculate the average residual error between the control point elevation and the DSM elevation value, and take this value as the system error to correct the control point elevation, so as to eliminate the influence of the elevation system error on the subsequent solution.

$$\begin{cases} \varepsilon = \dfrac{h_i - h_{DSM}}{N} \\ \hat{h} = h_i - \varepsilon \end{cases} \#(3\text{-}4)$$

Where, ε is elevation system error; h_i is the elevation value of the control point; h_{DSM} DSM elevation value corresponding to each control point; $\widehat{h}$ is the elevation value of the control point after system error correction; N is the number of control points.

Construct a mathematical model to solve the coordinate transformation parameters of the optimal nesting with the root mean square error of elevation (RMSE) as the metric. See Formula (3-5) for the calculation formula of RMSE of elevation.

$$RMSE = \sqrt{\frac{\sum_i^N \left(\widehat{h_i} - h_{DSM}\right)^2}{N}} \# (3\text{-}5)$$

The coordinates of the control points are known. According to Formula (1), Formula (2), Formula (3) and Formula (4), the elevation RMSE is only related to the coordinate transformation parameters,, that is,$\theta, \Delta x, \Delta y$

$$RMSE = f(\theta, \Delta x, \Delta y) \# (3\text{-}6)$$

Therefore, when the minimum value of the ternary function is obtained, that is, the minimum value of the elevation RMSE, the value of the corresponding independent variable is the optimal nested coordinate transformation parameter. According to the mathematical model in the formula (3-6), the optimal nested coordinate transformation parameters are solved by the ergodic method. And perform coordinate transformation on that control points accord to the optimal nested coordinate transformation parameters, namely corresponding translation parameter and angle parameters, and matching the transformed coordinates with the DSM again, wherein the matching result is the optimal matching result. $f(\theta, \Delta x, \Delta y)$

3.2.2 Against reference method (single point matching)

It can be seen from above that the control point and DSM matching method considering the minimum global elevation difference is to perform the matching operation after the coordinate transformation of the control point completes the translation and rotation. For the matching process, the direct matching is to find the position of the row and column numbers in the corresponding DSM data model according to the coordinates of the control points.For the obtained laser point cloud control point data, each control point has different longitude, latitude and elevation, and has different row and column number positions in the corresponding DSM terrain data. Although the data in the DSM or DEM model and the data coordinate datum of the control point are different, they are one-to-one correspondence in the real surface position.The principle of single point matching is to calculate the grid position of different elevation points in the corresponding digital elevation model according to the longitude and latitude of different control points, that is, the specific row and column number position of the grid in the DEM model. The principle is to realize the one-to-one correspondence and matching between points.

Therefore, in this study, the control points and DSM single point matching method are selected to deal with the same data, and the matching method with the smallest global elevation difference is used as a reference test to analyze and verify the advantages and disadvantages of the matching method studied in this paper.

4. Matching Test and Analysis of Control Points and DSM

4.1 Matching algorithm implementation

4.1.1 Implementation process of single point matching method between control point and DSM

In this study, in order to better compare and analyze the effect and advantages of the designed control points and DSM matching method considering the minimum global elevation difference, a direct point-to-point single-point matching algorithm is adopted. By minimizing the sum of squares of the root mean square error, the specific row and column number position of the corresponding point in the corresponding DSM raster data is obtained according to the row and column number calculation formula, so as to achieve the precise matching between the control point data and the digital surface model (DSM).

In order to minimize the influence of different coordinate datum on the matching results, the coordinate systems of control points and DSM data are checked, and if they are inconsistent, they are converted into the same coordinate system. In order to facilitate the calculation, both of them are transformed into the plane coordinates of the UTM projection under the corresponding band sign. That is to say, through the transformation of coordinate system, the longitude and latitude data of the extracted control points are transformed into rectangular coordinate data, which is represented by X and Y.Then the row and column numbers of all the point data are obtained by reading in the dem three-dimensional grid data. Find the data index in line with the specified area range, extract the rectangular coordinates and elevation in line with the range, then obtain the resolution through the DEM terrain data, and use the relevant formula to calculate the row and column number of each control point in the corresponding DEM elevation data model.The elevation of each control point in the corresponding DEM model grid can be obtained through correlation calculation. The difference between the two data can be calculated by using the geodetic elevation of the control point and the normal elevation in the corresponding dem grid. The value obtained after averaging is the elevation anomaly value. Finally, the elevation RMSE value can be calculated by using the correlation formula through the elevation anomaly value.

4.1.2 Implementation process of matching method considering minimum global elevation difference (only translation)

In this paper, taking into account the smallest difference in the global height of the control points and DSM precise matching, is a matching method based on the principle of affine transformation and iterative algorithm, also known as the surface matching method, and the difference with the single point matching is that the control point data is not regarded as a fixed data model, but as a rigid model. Coordinate transformation of the control points based on translation and rotation parameters,Gets the coordinates of the control point after translation and rotation operations.Therefore, in the implementation process of the algorithm, there is a considerable part of the content similar to the single point matching. The matching process can also be realized by only translating the curved surface, that is, the coordinate transformation of the control points is based on a certain translation parameter, and finally the corresponding translation parameter value can be obtained when the RMSE is the minimum, so as to achieve the best matching effect.

The same as the implementation of the single point matching algorithm, after reading the preprocessed laser point cloud control point longitude, latitude and elevation data and the DEM terrain data, for the convenience of the subsequent calculation, the two are converted into the same coordinate system, that is, through the UTM projection, the UTM projection plane rectangular coordinates X, Y under the corresponding band number are obtained. Then continue to extract rectangular coordinates and elevations that fit the scope of the study.After this step is completed, for the smoothness and completeness of the subsequent programming implementation, a one-step operation can be performed, that is, dem oversampling. Calculate the row and column number after oversampling, and then use the row and column number after oversampling to calculate the DEM elevation value and residual value after translation. Here, the oversampling interval is set to 10, that is, the unit is 10×10. After the oversampling, the resolution after the oversampling is obtained, and the calculation of the row and column numbers is started. After the calculation is completed, the translation operation is started.

Setting the range of each shift to 5 pixel values, a matrix is created to store the DEM elevation values of the neighboring pixels of the photon in each row, where the first column represents a shift of five pixels to the left and five pixels to the top. In the same way, the matrix is created to store the residual between the photon and the DEM elevation value of the adjacent pixel in each row, and the first column represents the shift of five pixels to the left and five pixels to the top.And then enter a loop, traversing that photon in the X and y directions respectively through a double for loop representation, calculating to obtain the row and column numbers in the oversample DEM and the row and column numbers in the DEM, and then calculating to obtain the elevation value and the residual value of the DEM after translation and the elevation anomaly by using a formula.And finally, calculating the RMSE value, and finally obtaining the mathematical model of the coordinate transformation parameter during the optimal registration, namely the optimal registration model, which is the translation parameter corresponding to the minimum RMSE in the algorithm.

4.1.3 Implementation process of matching method considering minimum global elevation difference (translation and rotation)

Because the algorithm considering the minimum global elevation difference regards the control point as a certain rigid body model, the coordinate transformation based on translation and rotation parameters can be carried out on the control point. In the second matching algorithm mentioned above, we have realized the coordinate transformation operation of only translating the control point, and finally we can get the minimum RMSE after matching. Corresponding translation parameters in the X and y directions.Similarly, we can translate and rotate the control points at the same time to achieve coordinate transformation, and finally we can get the translation parameters and rotation parameters in the X and y directions corresponding to the minimum RMSE.

Similar to the previous two algorithms, at the beginning of the algorithm implementation, that is, after reading in the data, the two data types are converted into the data under the same coordinate system, that is, the projection plane rectangular coordinates X, Y under the UTM projection coordinate system, and then the plane rectangular coordinate index in the corresponding research range is found. In the process of algorithm implementation, the test data can be tested and displayed first.

The loop is then started to complete the nesting match.Because coordinate translation and rotation are need at that same time, a triple cycle is needed to be establish to complete the registration operation in the algorithm realization process, relative to the curved surface registration with only translation, the algorithm adds a loop, namely a traversal angle, the change value of the angle is in a very small range, aft the loop traversal, Because that longitude and latitude value of the geodetic coordinates are just store in the test data, the coordinate values after translation and rotation can be calculate,Then according to the coordinate values after translation and rotation, the dem index, namely the corresponding row and column number, is calculated, and after the index beyond the research range is processed, the final pixel elevation value is obtained.After the above calculation is completed, the elevation anomaly value and the RMSE are finally calculated, and after the loop is jumped out, the corresponding translation parameter and rotation parameter (angle value) are extracted and marked when the RMSE, namely the root mean square error, is minimum.

4.2 Comparison and analysis of test results

The first group of data is the DEM topographic data of the northeast area of Sandhills in the United States and the corresponding control point data extracted from the ATL03 product of ICESat-2 satellite after preprocessing. Figure 4-1 below is a scatter plot drawn by setting the first set of data as test data, where the abscissa is the abscissa X of the Cartesian coordinate system after the control point data is projected by UTM, the unit is 10^5 m, and the ordinate u is the elevation corresponding to the control point, that is, the geodetic height H, and the unit is m.

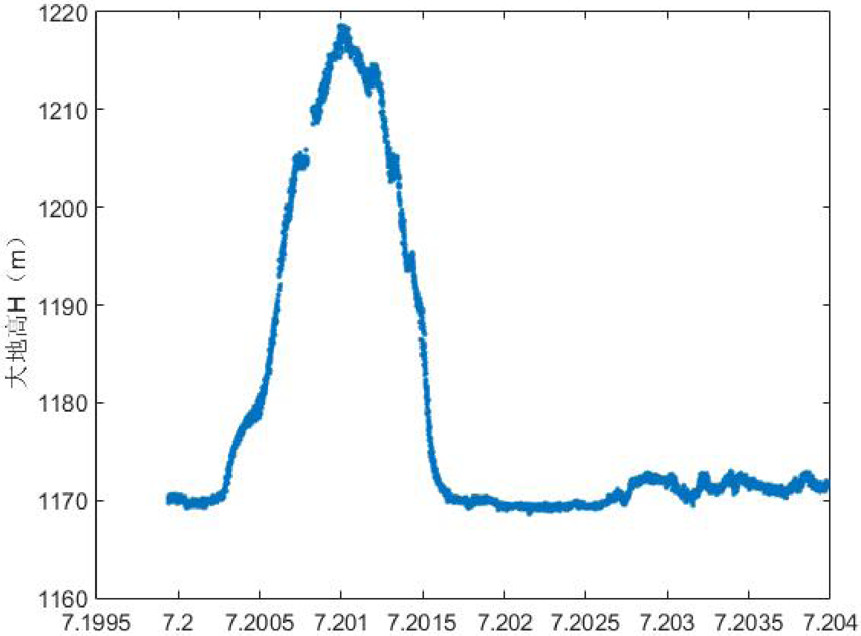

Figure 4-1 Scatter plot of the elevation change of the first set of test data

For the first group of test data, the following Figure 4-1 uses the surface registration algorithm to translate only the control points, and draws the relationship between the horizontal and vertical coordinate translation values and the RMSE. The horizontal coordinate is the translation amount of X, and the vertical coordinate is the translation amount of y. The RMSE gradually changes from blue to red from small to large. When the RMSE is the smallest (that is, when the color is the bluest), the corresponding X and y translation amounts are marked with circles in the figure, that is, X = 2.2m and y = 1.2m.

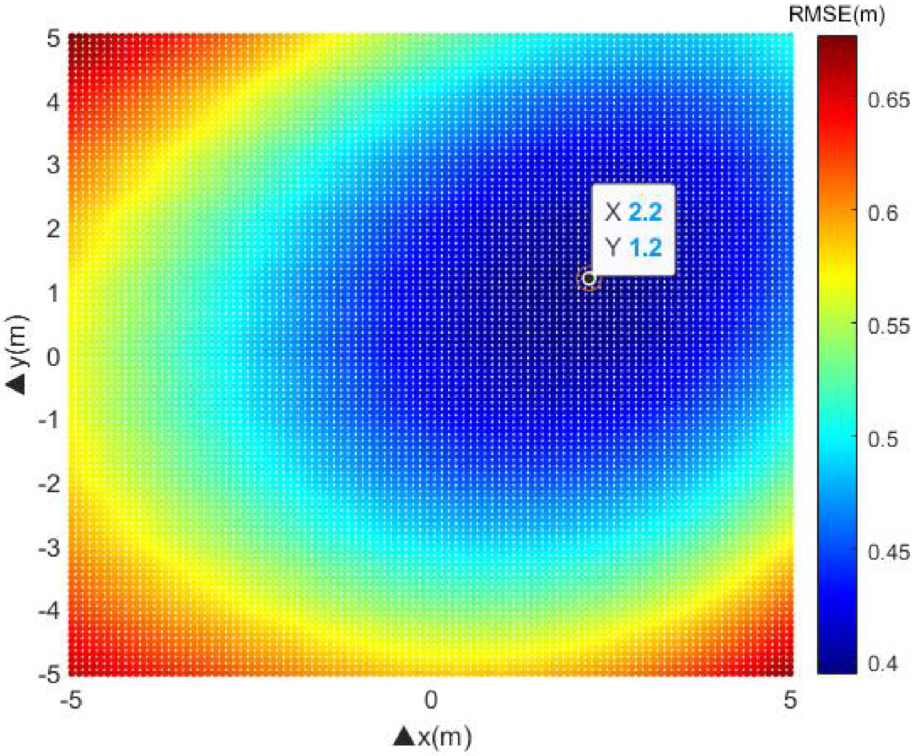

Figure. 4-2 Relationship between translation parameters and RMSE after surface matching (translation) (the first set of data)

For the first group of test data, the minimum value of RMSE is 0. 40 m in all the nested models by using the surface nesting algorithm and only translating the control points.

For the first group of test data, the following Figure 4-2 uses the matching algorithm with the smallest global elevation difference, namely the surface nesting matching algorithm, to perform translation and rotation operations on the control points, and draws the relationship between the horizontal and vertical coordinate translation values, the angle rotation values and the RMSE. The RMSE gradually changes from blue to red from small to large. When the RMSE is the smallest (that is, when the color is the bluest), the position is marked with a red dot in the figure, which represents the corresponding X, y translation and angle rotation when the RMSE is the smallest, that is, X = 4.2m, y = -0.9 m, angle = -0.052 °.

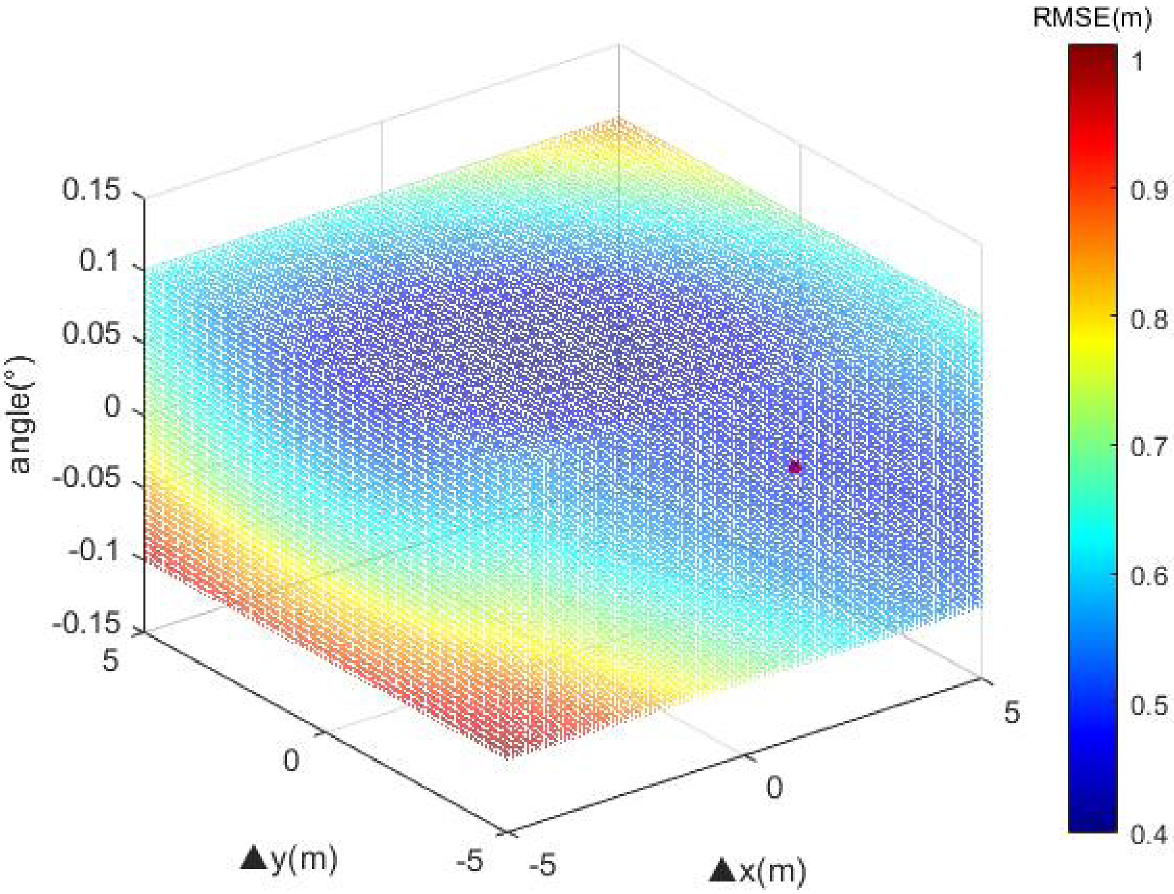

Figure. 4-3 Relationship between translation and rotation parameters and RMSE after surface matching (translation and rotation) (the first group of data)

For the first group of test data, the minimum value of RMSE is 0. 39 m by using the surface matching method with the minimum global elevation difference to translate and rotate the control points.

The second group of data is the high-resolution DEM topographic data of the southwestern Colorado area and the corresponding control point data extracted from the ATL03 product of ICESat-2 satellite after preprocessing. Figure 4-4 below is a scatter plot drawn by setting the second set of data as test data, where the abscissa is the abscissa X of the Cartesian coordinate system after the control point data is projected by UTM, the unit is 10^5 m, and the ordinate u is the elevation corresponding to the control point, that is, the geodetic height H, and the unit is m.

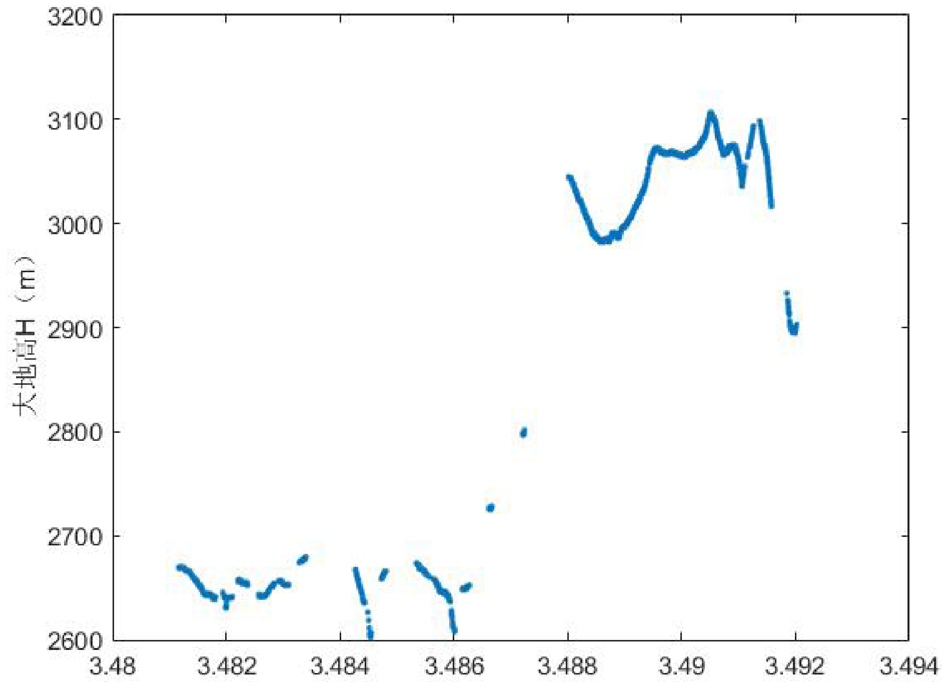

Figure 4-4 Scatter plot of the elevation change of the second set of test data

For the second group of test data, Figure 4-3 shows the relationship between the translation value of the horizontal and vertical coordinates and the RMSE, which is obtained by using the surface matching algorithm with the minimum global elevation difference and only translating the control points. The RMSE gradually changes from blue to red from small to large. When the RMSE is the smallest (that is, when the color is the bluest), the corresponding X and y translation amounts are marked with circles in the figure, that is, X = 5m, y = 2.6m

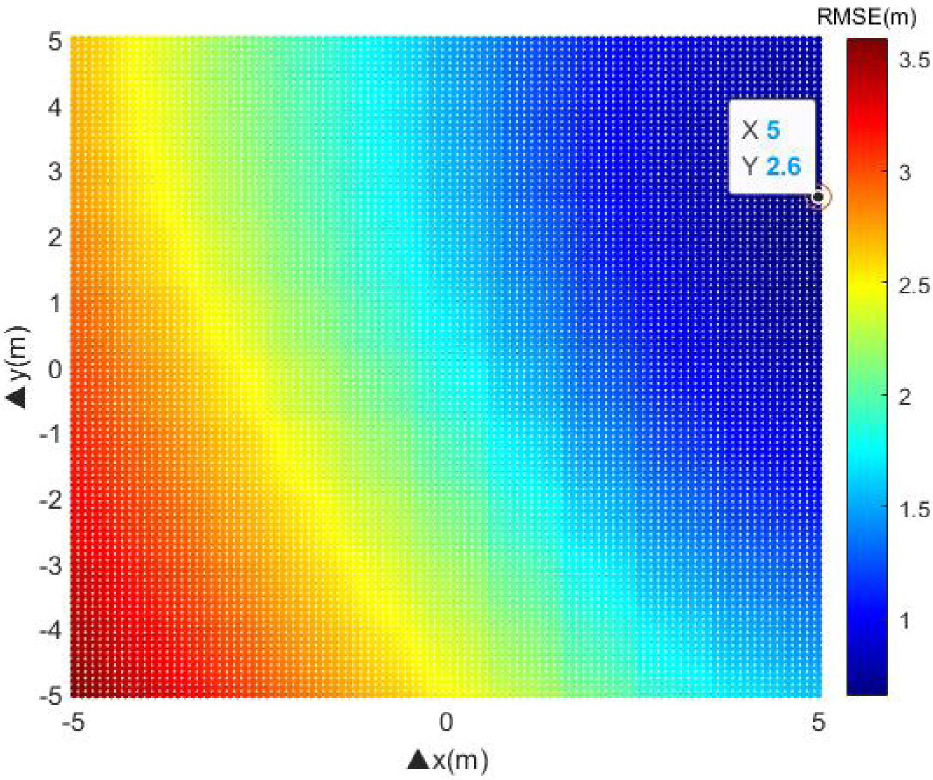

Fig. 4-5 Relationship between translation parameters and RMSE after surface matching (translation) (the second set of data)

For the second group of test data, the minimum value of RMSE is 0. 66 m in all the nested models obtained by using the surface nested matching method which takes into account the minimum global elevation difference and only translates the control points.

For the second group of test data, the following Figure 4-4 uses the surface registration algorithm to perform translation and rotation operations on the control points, and draws the relationship between the horizontal and vertical coordinate translation values, angle rotation values and RMSE. The RMSE gradually changes from blue to red from small to large, and the corresponding position is marked with a red dot in the figure when the RMSE is the smallest (that is, when the color is the bluest). This position represents the corresponding X, y translation and angle rotation at the minimum RMSE, i.e., X = 4.8 m, y = -2.6 m, angle = -0.014 °

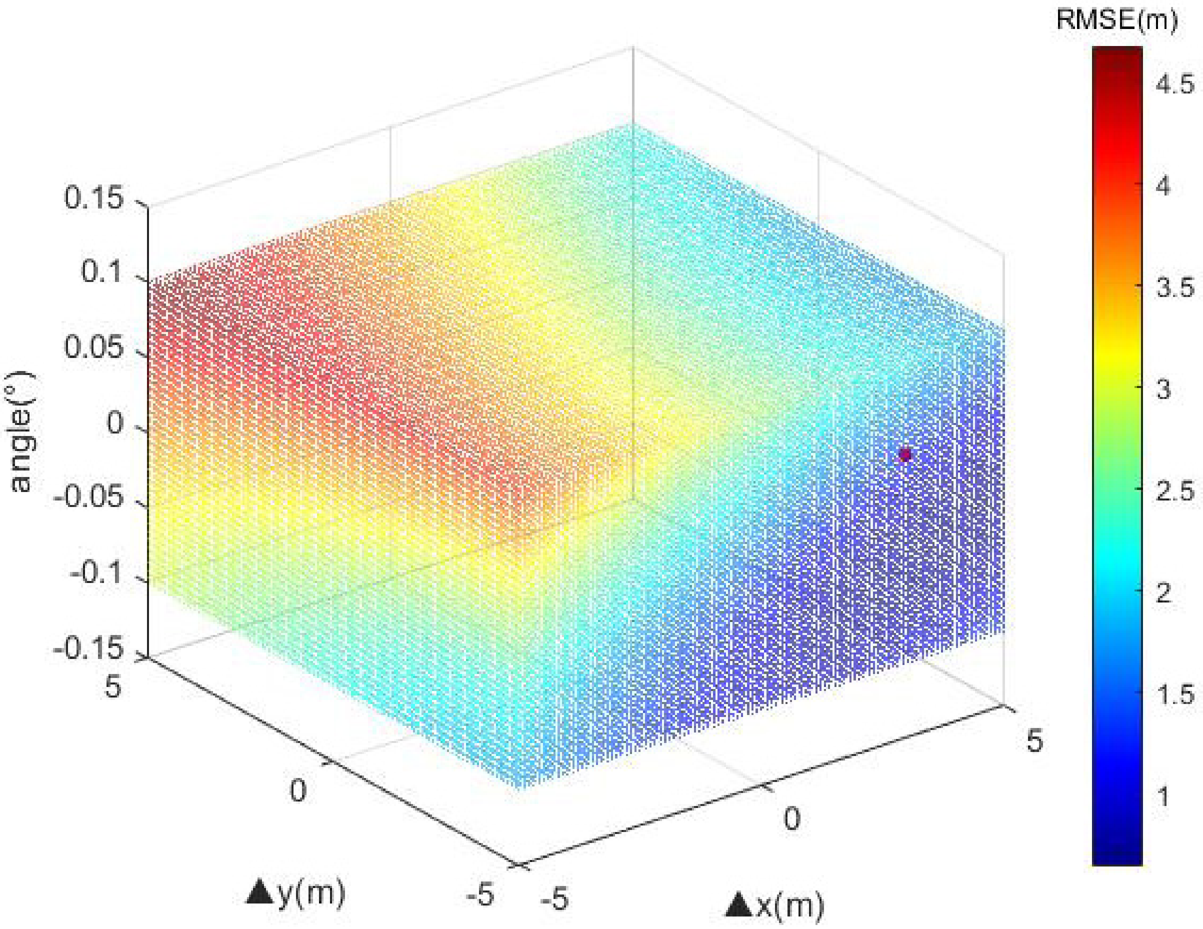

Fig. 4-6 Relationship between translation and rotation parameters and RMSE after surface matching (translation and rotation) (the second set of data)

For the second group of test data, the minimum value of RMSE in all nested models is a = 0. 65 m, which is obtained by using the surface nesting algorithm considering the minimum global elevation difference to translate and rotate the control points.

The third group of data is the high resolution DEM topographic data of the northwest New Mexico region and the corresponding control point data extracted from the ATL03 product of the ICESat-2 satellite after preprocessing. The following Figure 4- is the scatter diagram drawn by setting the third group of data as the test data, in which the abscissa is the abscissa X converted from the UTM coordinate projection, the unit is 10^5 m and the ordinate is the elevation corresponding to the control point, namely the geodetic height H, the unit is m.

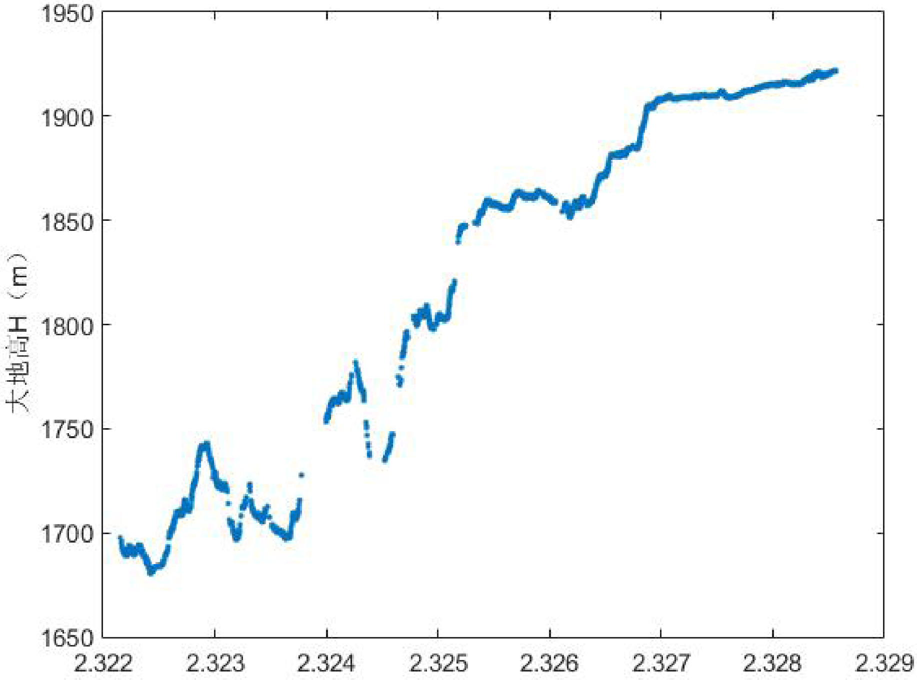

Figure 4-7 The third set of elevation scatter plots of test data

For the third group of test data, Figure 4-5 shows the relationship between the translation value of the horizontal and vertical coordinates and the RMSE, which is obtained by using the surface matching algorithm with the minimum global elevation difference and only translating the control points. The RMSE gradually changes from blue to red from small to large. When the RMSE is the smallest (that is, when the color is the bluest), the corresponding X and y translation amounts are marked with circles in the figure, that is, X = 0.2m, y = -1.7 m

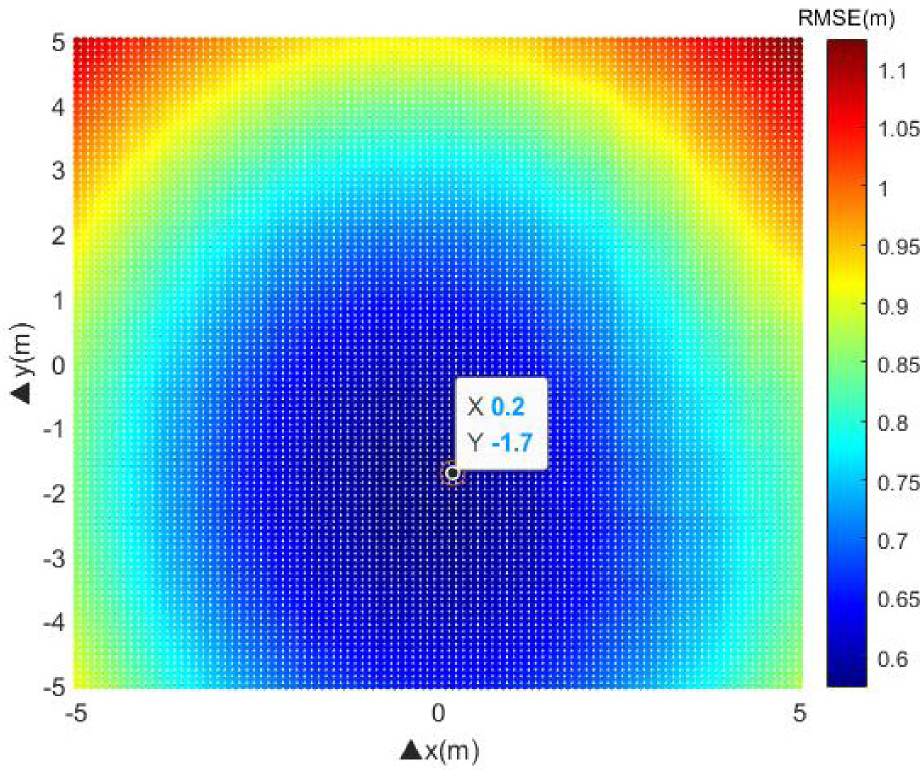

Fig. 4-8 Relationship between translation parameters and RMSE after surface matching (translation) (the third group of data)

For the third group of test data, the minimum value of RMSE is 0. 57 m, which is obtained by using the surface matching method considering the minimum global elevation difference and only translating the control points.

For the third group of test data, Figure 4-6 shows the relationship between the horizontal and vertical coordinate translation values, the angle rotation values and the RMSE obtained by using the surface registration algorithm to perform the translation and rotation operations on the control points. The RMSE gradually changes from blue to red from small to large. When the RMSE is the smallest (that is, when the color is the bluest), the amount of X, y translation and angle rotation should be marked, that is, X = -0.1m, y = 1.7 m, angle = 0.002 °.

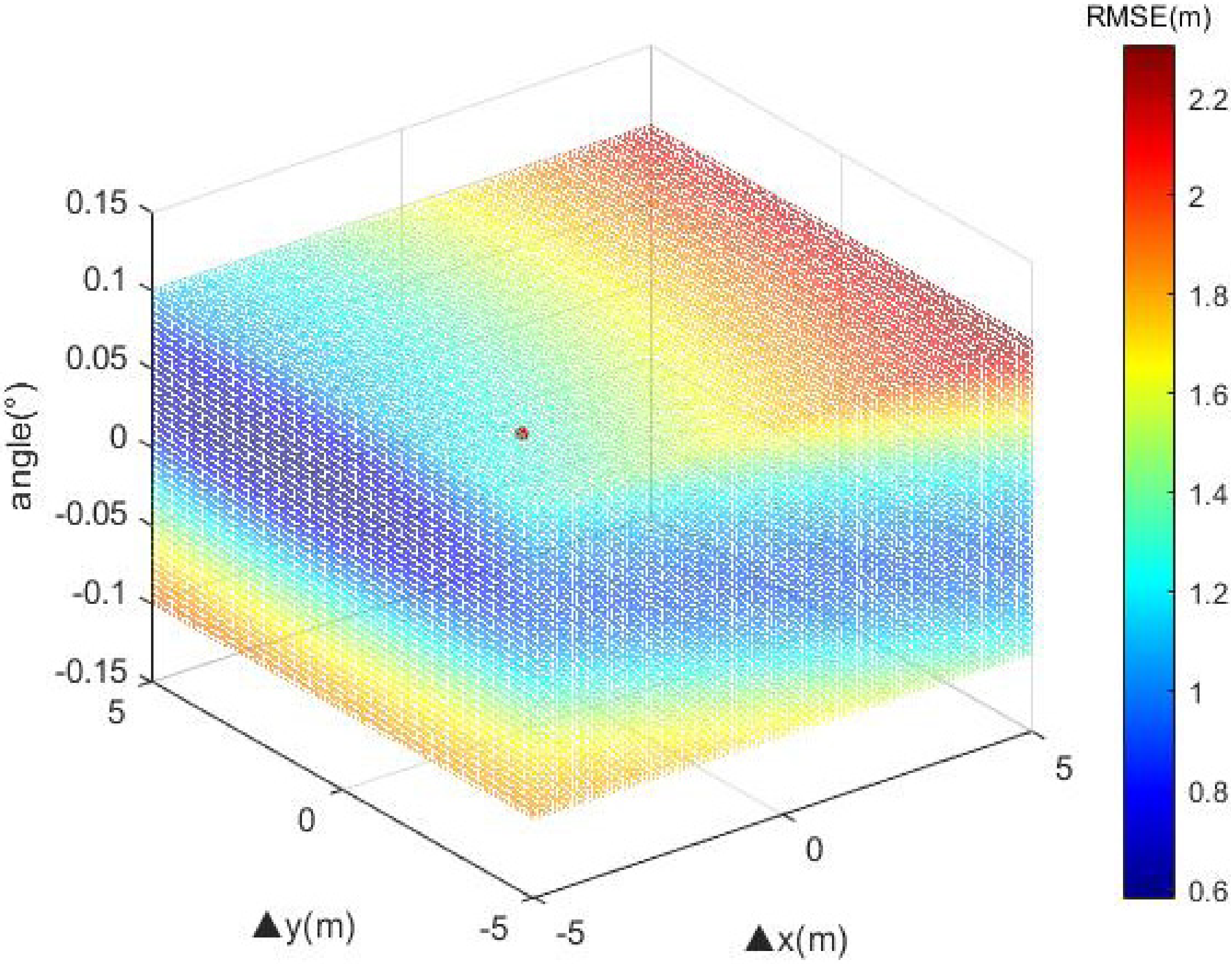

Fig. 4-9 Relationship between translation and rotation parameters and RMSE after surface matching (translation and rotation) (the third group of data)

For the third group of test data, the minimum value of RMSE is 0. 55 m in all the nested models by using the surface nesting algorithm to translate and rotate the control points.

The test results are analyzed and compared, and for three different groups of test data, the minimum root mean square error value corresponding to the best nested model obtained by using the control point with the minimum global elevation difference and the DSM matching method is reduced to a certain extent compared with the root mean square error value obtained by using the single-point matching method, It shows that the accuracy of the matching results has been improved to a certain extent. As shown in Table 4-1.

Table 4-1 RMSE of three groups of test data corresponding to three methods

Data group	Single Point Matching RMSE (m)	(Translation only) Surface Snapping Minimum RMSE (m)	(Translation plus Rotation) Surface Snapping Minimum RMSE (m)
First set of test data	0.43	0.40	0.39
Second set of test data	1.82	0.66	0.65
The third set of test data	0.62	0.57	0.55

An analysis of Table 4-1 above and Figure 1-9 above is as follows:

(1) First, the terrain of three groups of test data is analyzed. For three different groups of test data, it can be seen from the elevation change scatter diagram of the test data, i.e. Fig. 4-1, 4-4 and 4-7, that the elevation size and change of the area represented by the three groups of data are different, i.e. the change of terrain height and the average altitude are different.For the first group of test data and the third group of test data, compared with the second group of test data, the amplitude and rate of elevation change are smaller, and the average elevation is lower. In the height range of 1000-2000 m, the elevation change is more continuous, so the terrain is more flat; The second group of test data has a large fluctuation in elevation, and the average elevation is more than 3000 m, which is significantly higher than first group and the third group of test data.Therefore, we can get the second set of data. The average elevation of the study area is high and the terrain is undulating.

(2) For the first and third groups of test data, we can analyze and know that the root mean square error values of the two best matching models obtained by the two matching algorithms are less than root mean square error values obtained by the single point matching, whether only the control points are translated or translated and rotated at the same time, using the surface matching algorithm considering the global elevation difference.For the first group of test data, compared with the single point matching, the accuracy is improved by 8% when the control points are only translated, and by 9% when the control points are translated and rotated at the same time, which means that the accuracy is improved slightly.For the third group of test data, only the control point is translated, and the accuracy is improved by 9%, while the control point is translated and rotated at the same time, and the accuracy is improved by 11%, which is also relatively small.Combined with the test data elevation change scatter diagram of the first group of data and the third group of data and the previous analysis, it can also be seen that the elevation of this area is lower than average elevation, the terrain is less undulating, and it is relatively flat, so this result will be produced.

For the second group of test data, according to the final root mean square error values obtained by the three matching algorithms, we compare and analyze that the root mean square error values of the two best matching models obtained by the two surface matching algorithms are significantly less than root mean square error values obtained by the single point matching, and compared with the first group of test data and the third group of test data, The range of accuracy improvement has increased significantly.For the first group of test data, compared with the single point matching method, the accuracy is improved by about 64% when the control points are only translated, and the accuracy is improved by about 65% when the control points are translated and rotated at the same time, which shows that for the second group of test data, the matching effect is better and the elevation accuracy is improved more obviously by using the surface nesting matching method.Therefore, it can be concluded that for the second group of test data, the terrain factors of the study area have a greater impact on the accuracy of the matching results, and from the elevation scatter diagram of the second group of test data, it can be seen that the average altitude of the area is higher, the terrain is undulating, and the terrain changes greatly, so the final matching effect is better by using the control point data and DSM terrain data of the area.

At the same time, comparing the RMSE values of the control point elevation of the three groups of data, no matter which method is used, the RMSE of the second group of data is the largest, followed by the second group of data, and the RMSE of the third group of data is the smallest. Combined with the analysis of the three groups of data corresponding to the terrain of the study area, it can be seen that the control point elevation RMSE can reflect the surface relief of the study area to a certain extent.

The reason for the above results is that when we study the matching method, because there is a deviation between the plane position of the obtained control point and the plane position of the real surface, we assume that the plane position of the external DEM topographic data is accurate when we match it. When we use the elevation anomaly to correct it, if the surface of the study area is undulating, A small deviation in the plane location will result in a large value of the elevation deviation; whereas if the study area is relatively flat,The elevation deviation caused by the same plane position deviation will be relatively smaller.Therefore, after correcting the plane position of the control point in the undulating area, the elevation accuracy will be improved significantly, while the flat terrain effect will not be so significant.

As for the result that the precision improvement effect of the surface nesting method is more obvious than that of the single point matching method, the reason is that the single point matching directly uses the difference between each obtained control point and the corresponding dem grid elevation to calculate the elevation difference and the RMSE, and the plane position of the directly obtained control point is biased and inaccurate; The surface nesting method is to obtain the translation parameters and rotation parameters first, and then modify the plane position. Then the elevation difference between the control points and the corresponding dem grid is obtained, which takes into account the elevation difference of the whole study area, and it is more accurate to use the plane position of the control points after translation and rotation.

(3) Compared with the results of only translation, the RMSE values of the two matching algorithms of surface nesting with translation and rotation at the same time are reduced to a certain extent, which indicates that the matching accuracy has been improved to a certain extent, but the RMSE values obtained by the two methods are very small, that is, the accuracy improvement effect is not significant.

In this paper, the reason analysis of this result has not yet been clearly answered, and the specific reasons need to be analyzed. Considering the data acquisition method of ICESat-2 satellite, it is speculated that it may be related to the satellite orbit deviation, but it has not been verified.

4.3 Advantages and disadvantages of the method

Through the above test analysis and comparison, combined with the accuracy measurement standard of matching results in this paper, that is, the root mean square error (RMSE) of elevation, we can draw the following conclusions. For the control point and DSM matching method considering the minimum global elevation difference, as well as the single point matching method as a reference test group, the main advantages and disadvantages are as follows.

For the single-point matching algorithm as a contrast, the algorithm logic of the method is simple and direct, after preprocessing, the row and column numbers of the control points in the corresponding DSM terrain raster data are directly calculated by using a formula, but because the single-point matching does not correct the obtained plane positions of the control points, the plane positions of the control points used in the matching are not accurate, Therefore, the accuracy is obviously insufficient, and it is impossible to analyze and match a wide range of DSM data and dense control points, and the influence of terrain factors is not considered.

As To the surface nesting method studied in this paper, this method is based on the principle of affine transformation, and takes the control points as a rigid model that can be translated and rotated, and uses the best translation and rotation parameters obtained by iteration to modify the plane position of the control points. The systematic deviation in the plane and elevation directions between the control point and the DSM is fully considered, the root mean square error of the obtained best nested model is small,The method has high precision, is suitable for the matching between the control points and the DSM under any terrain, has a clear mathematical model, and the obtained matching result can be used for various purposes according to actual needs.At the same time, the efficiency of the algorithm is high, and it can be used for large-scale DSM and matching in the case of dense control points. However, this method does not fully consider the impact of random errors on the mathematical model, and for the laser point cloud control point data, if the random noise is not completely removed, the random errors will have a greater impact on the matching results and accuracy.

5. Summary and Outlook

5.1 Sum up

In the study of the matching method of DSM terrain data and control point data, the key factor to achieve accurate matching is to fully consider the impact of terrain characteristics on the real coordinates and elevation of control points, and to fully consider the systematic deviation in the direction of plane and elevation between control points and DSM.In order to maximize the value of terrain data and take into account the systematic deviation between the control points and DSM in the plane and elevation directions, this paper mainly uses a set of affine transformation principle-based, with the root mean square error (RMSE) of the control point elevation as the reference metric, through minimizing the elevation difference between the control points and the reference terrain data. The matching method of control points and DSM considering the minimum difference of global elevation.

The matching method between control points and DSM, which takes into account the minimum global elevation difference, can also be called surface matching method. The core of this method is to treat the control points as a rigid body model that can be translated and rotated.Coordinate transformation of the control points based on translation and rotation parameters is carried out to obtain the coordinates of the control points after translation and rotation operations, and the plane positions of the obtained control points are corrected according to different coordinate transformation parameters, so that the control points can be nested with a digital elevation model or a surface model in any posture and position in space.By traversing all the control points, many kinds of nested models can be obtained, wherein the model with the minimum root mean square error value is the best nested model, and the position of the control point corresponding to the model is also the closest position of the real surface position of the control point. The method takes the control point as the center, realizes the whole and whole nesting, and can effectively identify the association relationship between the control points. This association ensures that the control point data is linked to the Digital Elevation Model (DSM).Achieve precise registration and alignment between them.

As a reference test, the single point matching algorithm directly realizes the one-to-one correspondence between points through coordinate transformation and other preprocessing between different data models, that is, according to the longitude and latitude of different control points, through the calculation of related formulas and algorithm principles, the grid position of different elevation points in the corresponding digital elevation model is obtained. Finally, the one-to-one correspondence and matching between the points in the digital elevation or surface model and the control points are realized.

This paper mainly studies and adopts the precise matching algorithm between the control points and the digital elevation model, which takes into account the minimum difference of the global elevation. At the same time, the single point matching method between the control points and the DSM is used as a reference test method. For three groups of different regional data, two methods are used to deal with the same data, and the experimental results are obtained.The experimental results show that the matching method that takes into account the minimum global elevation difference, that is, the surface matching algorithm that combines the whole with the whole, is outstanding in the accuracy and stability of accurate matching, and its accuracy value (RMSE value in this paper)Compared with the first point to point single point matching algorithm, there is a significant degree of reduction, which shows that the surface nesting method greatly enhances the data reliability of GIS related data processing and analysis (in this paper, it refers to the matching of control points and DSM).We can clearly conclude that the curvature of the earth's surface is taken into account in the design of the surface registration algorithm, and through the integration of the affine transformation model, it ensures that the control points are aligned with the DSM in the local coordinate system with high accuracy. At the same time, similar research is also expanding step by step towards the future, and relevant personnel can conduct in-depth research on other application possibilities of this algorithm in order to expand its scope of application and enhance the performance of matching technology.

5.2 Insufficiency and prospect of experiment

In This paper, the surface nesting method is used to realize the precise matching between the elevation control points and the DSM data model, which takes into account the minimum global elevation difference between the control points and the DSM data model, and takes the RMSE of the elevation control points as the reference metric, by minimizing the elevation difference between the control points and the reference terrain data, combined with affine transformation and related adjustment algorithms. In order to obtain the accuracy of the results of different matching methods and related comparative analysis,As well as the advantages and disadvantages of each method in the practical application process.However, there are still some deficiencies in the research work of this paper, which can be improved in the follow-up research and in-depth study, so as to achieve a matching algorithm with higher accuracy and more advantages:

(1) This paper only realizes the research of surface registration matching method for the time being. When the global elevation difference of the control points is the smallest, the matching is carried out to obtain the best registration model to achieve the surface registration of the control points and the DSM data, and other higher precision matching methods are not realized. At the same time, the used control point data only use the on-board laser point cloud data of ICESat-2 satellite. The DSM terrain data used is only LiDAR DEM terrain data in the United States.Other types of data have not been used to verify the accuracy of different methods, and there is a lack of extensive application verification for various types of data in the practical application process.Further improvement can integrate more adjustment algorithm principles, such as joint block adjustment and six-tuple relaxation method, to achieve a more accurate matching algorithm, and can also use other types of satellites or methods to obtain control point data, carry out relevant preprocessing, and obtain the final matching results and verification.

(2) This paper has not yet used more error evaluation indicators to measure the matching effectiveness, nor has it fully considered the impact of random errors on the accuracy of matching results, and then evaluated the matching effectiveness in an all-round way, and therefore there is a lack of steps such as intelligent optimization of matching algorithms based on this evaluation. Further improvement can be achieved by fusing the local least squares method (LML) and the genetic algorithm (GA).And that like, specifically, the parameter of the affine transformation model can be refined and correct through the least square iteration, so as to minimize the elevation difference between the control point and the reference terrain, and realize the accurate refinement and optimization of the matching result, thereby significantly improving the matching accuracy.

(3) The experimental data sources used in this paper focus on the satellite-borne laser photon data obtained from the middle and high latitudes of the Northern Hemisphere, lacking the research and verification of the data in other parts of the world. Although the matching method studied in this paper takes into account the influence of terrain slope on photon location and matching results, no corresponding solution has been proposed.In future research, researchers can focus on verifying and analyzing the geolocation accuracy of ATLAS data in other parts of the world, and develop a correction model based on terrain, slope and other factors to improve the geolocation accuracy of ICESat-2 and the matching accuracy between control points and DSM terrain data.

(4) Compared with the results of only translation, the accuracy of the matching results obtained by the two matching algorithms of surface nesting with translation and rotation at the same time has been improved to a certain extent, but the RMSE values obtained by the two methods are very small, that is, the accuracy improvement effect is not significant. However, this paper does not get an accurate answer to this phenomenon, and the specific

reasons need to be analyzed. Considering the data acquisition method of ICESat-2 satellite, it is speculated that it may be related to the satellite orbit deviation, but it has not been verified.

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