

Article

Geometric Accuracy Assessment of Large-Scale ZY-3 Imagery Based on Inter-Image Consistency

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Highlights

What are the main findings?

- A consistency-driven accuracy assessment framework using free-network tie points avoids ground control reliance.
- Higher inter-image consistency correlates with improved positioning accuracy; local inconsistencies may amplify errors.

What are the implications of the main findings?

- Provides a practical solution for large-area ZY-3 geometric accuracy assessment without ground control points.
- Enables the characterization of error propagation behavior to guide image processing and quality control.

Abstract

Geometric accuracy assessment is a fundamental prerequisite for the application of high-resolution optical satellite imagery, yet it remains particularly challenging in the absence of ground control points. This study proposes a consistency-driven accuracy assessment framework for ZY-3 satellite imagery that systematically bridges the conventional separation between block adjustment and accuracy evaluation. The framework is built upon a unified geometric error model that accommodates both inter-image consistency assessment and absolute accuracy evaluation within a common mathematical formulation. Recognizing the inherent uncertainties of publicly available reference data, a hierarchical validation chain is established: the Google Earth (GE) and Shuttle Radar Topography Mission (SRTM) datasets are first validated against WorldView imagery to bound their intrinsic errors, and subsequently employed as references for ZY-3 accuracy assessment. This design enables the simultaneous evaluation of planimetric accuracy, vertical accuracy, and inter-image consistency without reliance on ground control points. Experimental validation conducted on 1368 ZY-3 scenes covering a study area of 1.9 million km² yields a planimetric RMSE of 3.33 m and a vertical RMSE of 4.27 m. The results demonstrate that higher inter-image consistency empirically correlates with improved absolute positioning accuracy, and that the proposed framework not only reliably evaluates geometric quality but also provides diagnostic insights that can inform proactive adjustment strategies. The proposed method



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thus offers a practical and transparent solution for the geometric accuracy detection and enhancement of large-area ZY-3 satellite imagery.

Keywords: ZY-3 satellite imagery; geometric accuracy assessment; inter-image consistency; free-network adjustment; hierarchical validation

1. Introduction

Compared with traditional aerial imagery, optical satellite imagery offers distinct advantages including broader single-scene coverage, stable imaging geometry, and relatively low acquisition costs [1]. Owing to their high spatial resolution, inherent stereoscopic mapping capability, and superior geolocation accuracy, optical remote sensing satellite images have emerged as the predominant method for acquiring large-scale geographic information resources [2]. Internationally, satellites such as the SPOT series, IKONOS, QuickBird, WorldView series, and Pleiades series have been successively launched [3], achieving substantial progress in multi-angle imaging and stereo observation techniques [4–6]. Since 2012, China has deployed the Resources Satellite Three (ZY-3) series satellites, enabling global, wide-area optical stereo image acquisition at meter-level resolution through forward, backward, and nadir viewing configurations [7]. Under uncontrolled conditions (i.e., without ground control points—GCPs), block adjustment of ZY-3 imagery has been reported to achieve horizontal and vertical geolocation accuracies at approximately the 10 m level [8]. Furthermore, by introducing a limited number of high-quality GCPs, the positioning accuracy can be improved to better than 5 m in both horizontal and vertical directions [9]. These results demonstrate that block adjustment is an effective approach for improving the geometric accuracy of ZY-3 imagery; however, they also highlight the necessity of reliable accuracy verification methods, particularly for large-area datasets acquired without ground control [9].

To achieve stereoscopic mapping by using optical remote sensing satellite imagery, it is imperative to enhance and rigorously validate the positioning accuracy of such imagery. Aerial triangulation represents one of the predominant methodologies for improving geometric accuracy in optical remote sensing satellite images [10]. In 2003, Grodeki pioneered the rational function model (RPC/RFM)-based block adjustment for IKONOS imagery [5], and subsequent studies extended this framework to satellites such as QuickBird, SPOT-5, and ZY-3 [4,6]. Owing to its flexibility and sensor-independence, the RPC-based approach has gradually replaced rigorous physical sensor models in large-scale satellite image adjustment. Ground control points (GCPs) constitute the fundamental basis for geometric correction of optical satellite images, with their quality exerting direct influence on ultimate positioning accuracy [11,12]. Conventional GCP acquisition through field surveying proves cost-prohibitive and impractical for remote regions [13,14]. Consequently, the lack of reliable ground control has become a major limiting factor in large-area satellite image adjustment and accuracy evaluation.

To address the limitations of GCP-dependent geometric correction, numerous studies have explored the use of publicly available geospatial datasets as alternative or auxiliary control sources. Elevation products such as Shuttle Radar Topography Mission (SRTM) and ICESat have been incorporated as vertical constraints in block adjustment [15–17], while high-resolution imagery from Google Earth (GE) has served as planimetric reference data [16]. Joint adjustment strategies using multi-source satellite data have also been investigated to strengthen network geometry and reduce systematic errors [17]. Consequently,

extensive research has been conducted to evaluate the positioning accuracy characteristics of these datasets.

SRTM generally exhibits good stability and internal consistency, yet its vertical accuracy is strongly influenced by terrain relief and land cover [18–22]. Elevation errors may exceed 15 m in glacier-covered or steep mountainous regions but can reach decimeter to centimeter levels in flat or gently undulating terrain [23–26]. GE, one of the most widely used geospatial data platforms, exhibits spatially and temporally varying positioning accuracy [27–29]. Its planimetric RMSE has improved from approximately 16.9 m for imagery around 2000 to about 6.1 m for more recent products [30–33].

Overall, existing studies demonstrate that public geospatial datasets can effectively support block adjustment and accuracy evaluation of optical satellite imagery in the absence of dense GCPs. Nevertheless, the inherent uncertainties and spatial heterogeneity of these reference datasets complicate the direct interpretation of geometric accuracy results, especially for large-area satellite image blocks. Moreover, most existing accuracy verification methods rely primarily on sparse external reference points, which may be insufficient to fully characterize spatially varying errors across extensive adjustment networks.

In large-area satellite block adjustment, abundant tie points and strong overlap connectivity naturally establish dense inter-image constraints. However, existing studies have primarily treated free-network adjustment and accuracy evaluation as two independent stages—the former for geometric improvement, the latter for final quality reporting. A systematic investigation that bridges these two stages, by establishing an empirical linkage between inter-image consistency and absolute positioning accuracy and by embedding an uncertainty-aware hierarchical reference validation into a unified error model, remains conspicuously absent.

To fill this gap, this paper proposes an integrated framework for the geometric accuracy detection and enhancement of large-area ZY-3 satellite imagery based on inter-image consistency analysis. The novelty of this study is threefold.

First, we systematically investigate the empirical linkage between inter-image consistency accuracy, derived from free-network adjustment, and the absolute positioning accuracy of the adjusted ZY-3 imagery. Our results demonstrate that consistency metrics convey meaningful empirical information about absolute accuracy, thereby establishing a basis for using consistency measures as internal indicators of geometric quality. The necessary distinction between internal precision and external accuracy is explicitly maintained throughout the analysis.

Second, we construct an uncertainty-aware evaluation framework with a unified geometric error model. Unlike conventional approaches that employ reference data, such as GE and SRTM, as de facto ground truth, the proposed framework defines a generic error formulation that is mathematically common to both internal consistency assessment and absolute accuracy evaluation, and instantiates it separately with image-to-image comparisons and image-to-reference comparisons. The reference datasets themselves are validated against WorldView imagery prior to their use in ZY-3 accuracy assessment. This hierarchical verification design enables explicit acknowledgment and bounding of the uncertainties introduced by reference-data spatial variability, yielding accuracy estimates that are both realistic and defensible, with planimetric and vertical accuracies reaching the single-meter level.

Third, beyond serving as a post hoc quality reporting tool, the proposed framework demonstrates that the insights gained from consistency-based evaluation can inform and guide the adjustment process itself, contributing actively to the enhancement of geometric positioning accuracy for large-scale satellite imagery.

Collectively, this study bridges the conventional gap between adjustment and evaluation by proposing a unified error model that accommodates both internal consistency and absolute accuracy assessment. The explicit delineation of both the potential and the limitations of consistency-based verification—particularly the irreducible uncertainties arising from unrefined reference imagery and the spatial variability of publicly available datasets—provides a robust and transparent methodology for large-scale satellite image quality control in the absence of dense GCPs.

The structure of this paper is as follows. Section 2 introduces the proposed methodology and the datasets used in this study. Section 3 provides the experimental results and a comprehensive analysis. Section 4 provides a discussion. Section 5 gives the conclusions.

2. Methods

The proposed framework for geometric accuracy assessment comprises four main stages, as illustrated in Figure 1: (1) image data analysis, (2) inter-image geometric consistency assessment, (3) absolute positioning accuracy evaluation using external reference data, and (4) integrated geometric accuracy interpretation.

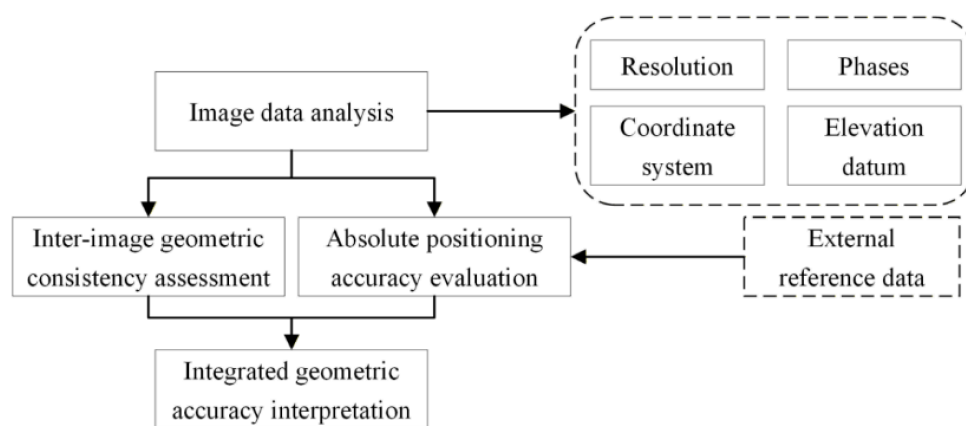


Figure 1. Geometric Accuracy Assessment Framework.

First, the fundamental characteristics of the ZY-3 imagery, including spatial resolution, acquisition time, coordinate reference system, and elevation datum, are analyzed to ensure compatibility with candidate reference datasets. Second, the geometric consistency between overlapping image scenes is quantitatively evaluated by statistically analyzing object-space coordinate differences derived from homologous tie points. Third, based on the results of image data analysis, appropriate external reference datasets are selected to assess the absolute planimetric and elevation positioning accuracy of the satellite imagery. Finally, the overall geometric accuracy of the ZY-3 image dataset is comprehensively evaluated by jointly considering the inter-image consistency results and the absolute positioning accuracy statistics.

This framework enables large-scale geometric accuracy verification without relying on ground control points, and provides insight into both internal geometric quality and external positional reliability of the adjusted imagery.

2.1. Image Data Analysis

2.1.1. Spatial Resolution and Temporal Consistency

Prior to geometric accuracy assessment, the spatial resolution and acquisition time of the target satellite imagery are analyzed. To reduce scale effects and temporal misregistration, reference datasets are selected based on explicit quantitative criteria. First, the spatial resolution ratio between the reference and target imagery is constrained within a

range of 0.5 to 2.0, meaning the ground sample distance of the reference must not deviate by more than $\pm 50\%$ from that of the target. Second, the temporal baseline, defined as the difference in acquisition dates between the reference and target imagery, is limited to a maximum of 3 years, provided that no significant land-cover changes, such as snow cover, flooding, or vegetation senescence, occur within this interval. Adhering to these strict thresholds minimizes systematic errors caused by surface dynamics and multi-scale effects, thereby ensuring the robustness and comparability of the subsequent geometric accuracy evaluation.

If multiple reference datasets satisfy these criteria, priority is given to the one with the spatial resolution and acquisition date closest to those of the target dataset. For datasets that exceed the temporal threshold but are otherwise irreplaceable, they may still be considered, provided that no significant land-cover changes are observed relative to the target imagery.

2.1.2. Coordinate Reference System and Elevation Datum

To eliminate systematic discrepancies arising from inconsistent spatial reference definitions, it is essential to first establish the coordinate reference system and vertical datum of the ZY-3 satellite imagery, and subsequently align all reference datasets with this common framework.

The native spatial reference of the ZY-3 imagery is determined first. This involves identifying the type of coordinate reference system, which is typically either a geographic coordinate system or a projected coordinate system. For projected coordinate systems, the specific projection is specified, such as the Universal Transverse Mercator or Gauss–Krüger projection, and the underlying reference ellipsoid is recorded. The vertical datum is then classified as either ellipsoidal heights or orthometric, respectively normal, heights. If ellipsoidal heights are used, the defining ellipsoid is noted; if normal heights are adopted, the associated quasi-geoid model is identified.

Once the reference framework of the ZY-3 imagery is fully characterized, each reference dataset is examined for consistency. Where the coordinate reference system or vertical datum of a reference dataset differs from that of the ZY-3 imagery, rigorous transformations are applied to bring it into alignment. Horizontal coordinate transformations are performed using standard methods available in widely adopted commercial geographic information system software, such as ArcGIS 10.8. Depending on the nature of the mismatch, appropriate transformation procedures are selected, for example, a seven-parameter Helmert transformation when converting between different projected coordinate systems, or a datum transformation based on a Molodensky model when the underlying ellipsoid differs. Vertical datum conversions are carried out by applying the relevant geoid or quasi-geoid undulation grids, such as the EGM2008 global geoid model, to convert orthometric or normal heights into ellipsoidal heights as required. All transformation parameters and source geoid models are documented to ensure full reproducibility.

Through this systematic procedure, all reference datasets are unified into the coordinate reference system and vertical datum of the ZY-3 imagery, thereby removing systematic spatial reference inconsistencies as a prerequisite for rigorous multi-source accuracy assessment.

2.2. Geometric Error Model

The geometric quality assessment of ZY-3 satellite imagery relies on quantifying discrepancies between object-space coordinates derived from different sources. This section defines a unified error model that serves as the common foundation for both the internal consistency evaluation and the absolute positioning accuracy assessment described in subsequent sections.

2.2.1. Object-Space Coordinate Derivation

For any ZY-3 image scene with valid rational polynomial coefficients, a homologous image point p_1 with image-space coordinates (x_1, y_1) can be back-projected to object space through photogrammetric forward intersection, yielding a three-dimensional object-space position $P_1(X_1, Y_1, Z_1)$. When the same ground point is observed in multiple images, each scene independently produces an object-space solution. The image-space coordinates are in pixels, while all object-space coordinates and error metrics are in meters.

2.2.2. Generic Error Definition

Let $P_1 = (X_1, Y_1, Z_1)$ and $P'_1 = (X'_1, Y'_1, Z'_1)$ denote two object-space coordinate solutions for the same ground point. These two solutions may originate from any combination of image-derived coordinates and external reference data, provided that both refer to the same ground position and are independently obtained. The coordinate differences between the two solutions are defined as given in Equation (1):

$$\Delta X_1 = X_1 - X'_1, \Delta Y_1 = Y_1 - Y'_1, \Delta Z_1 = Z_1 - Z'_1. \quad (1)$$

The corresponding planimetric and elevation errors are given by Equation (2):

$$d_{xy,1}^{\text{con}} = \sqrt{(\Delta X_1)^2 + (\Delta Y_1)^2}, d_{z,1}^{\text{con}} = |\Delta Z_1|. \quad (2)$$

Equations (1) and (2) constitute the generic error model applied throughout this study. The interpretation of P_1 and P'_1 varies depending on the specific assessment being conducted, as detailed in Sections 2.3 and 2.4.

2.3. Inter-Image Consistency Accuracy Assessment

During satellite image block adjustment, adjacent image scenes must maintain a minimum overlap of 10% to establish robust geometric constraints. These constraints are primarily formed through the matching of homologous tie points in overlapping regions. In this study, tie point matching was performed using PixelGrid 8.0.3, a photogrammetric software system developed by the Chinese Academy of Surveying and Mapping. PixelGrid implements a multi-image matching algorithm based on scale/rotation-invariant features, combined with multi-baseline and multi-feature matching strategies. The algorithm integrates feature-based and gray-based matching approaches within a hierarchical coarse-to-fine framework, with sub-pixel refinement for high-precision tie point extraction. By combining point and linear features, the multi-feature strategy balances local and global image information, enhancing matching robustness in areas with varying texture conditions. This approach has been validated for processing both Chinese (ZY-3, Gaofen) and international (IKONOS, GeoEye, WorldView) satellite imagery.

To maximize the reliability of tie points for consistency evaluation, a multi-stage quality control workflow was designed and implemented. First, initial correspondences were generated using sub-pixel matching to achieve precise image-space localization. Second, outlier correspondences were identified and removed through geometric consistency checks, using epipolar constraint residuals and re-projection errors as rejection criteria. Third, in regions where automatic matching produced insufficient or unreliable results, additional homologous points were manually introduced and visually verified. Fourth, following the initial block adjustment, the spatial distribution and residual errors of all tie points were systematically reviewed, and supplementary points were added where the existing point configuration was inadequate. This hierarchical procedure ensures that only tie points meeting predefined quality standards are retained for consistency evaluation.

After the above quality control procedures, the retained tie points were used to assess inter-image consistency. Based on the number and spatial distribution of the retained tie points, three scenarios may occur in overlapping image regions:

- (a) Adequate tie point quantity with strong inter-image geometric consistency;
- (b) Adequate tie point quantity with poor inter-image geometric consistency;
- (c) Insufficient tie point quantity, rendering reliable consistency assessment infeasible.

For scenarios (a) and (b), the inter-image consistency accuracy can be directly evaluated using statistical measures. In scenario (c), additional homologous points are manually introduced to reassess the inter-image consistency until a reliable determination can be made.

Notably, for this consistency evaluation, any systematic errors in the RPCs that are common to adjacent overlapping scenes tend to cancel out in the relative comparison; the consistency error therefore primarily reflects scene-to-scene geometric disagreement rather than absolute RPC inaccuracies.

2.3.1. Consistency Error Computation

As illustrated in Figure 2, let S_a and S_b denote two ZY-3 image scenes with overlapping coverage. A homologous point p_1 is identified within the overlapping region of the two scenes. The image-space coordinates of p_1 in scenes S_a and S_b are denoted as (x_{a1}, y_{a1}) and (x_{b1}, y_{b1}) , respectively.

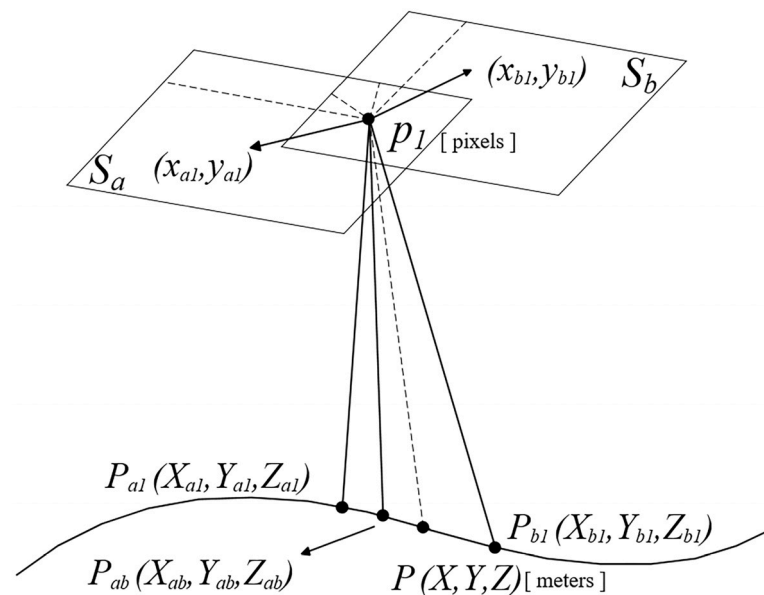


Figure 2. Geometric error model for consistency and absolute positioning accuracy assessment. Dashed line represents the ideal ground position of point p_1 assuming zero error.

For two overlapping ZY-3 image scenes S_a and S_b , the object-space solutions of a homologous tie point p_1 are denoted as $P_{a1}(X_{a1}, Y_{a1}, Z_{a1})$ and $P_{b1}(X_{b1}, Y_{b1}, Z_{b1})$. Applying the generic error model defined in Section 2.2.2, the consistency error at each tie point is obtained by substituting P_1 and P'_1 in Equations (1) and (2) with the independently derived object-space solutions P_{a1} and P_{b1} from the overlapping scenes. This substitution is valid because both solutions refer to the same ground point and are derived from geometrically independent RPC models. The resulting consistency errors are denoted as $d_{xy,i}^{con}$ and $d_{z,i}^{con}$.

2.3.2. Statistical Evaluation

For n homologous tie points across the overlap, the root-mean-square errors of planimetric and elevation consistency are computed as Equations (3) and (4):

$$\text{RMSE}_{xy}^{\text{con}} = \sqrt{\frac{1}{n} \sum_{i=1}^n (d_{xy,i}^{\text{con}})^2}. \quad (3)$$

$$\text{RMSE}_z^{\text{con}} = \sqrt{\frac{1}{n} \sum_{i=1}^n (d_{z,i}^{\text{con}})^2}. \quad (4)$$

In addition to RMSE, descriptive statistics such as the mean value and maximum value of the consistency errors are computed to further characterize the distribution of inter-image geometric consistency. The mean values are defined in Equation (5):

$$\bar{d}_{xy}^{\text{con}} = \frac{1}{n} \sum_{i=1}^n d_{xy,i}^{\text{con}}, \quad \bar{d}_z^{\text{con}} = \frac{1}{n} \sum_{i=1}^n d_{z,i}^{\text{con}} \quad (5)$$

These statistical indicators provide a quantitative measure of the internal geometric consistency between overlapping image scenes. When applied to all overlapping image pairs within a large-area block adjustment, the resulting consistency statistics enable comprehensive evaluation of geometric quality at both the scene level and the regional network level.

2.4. Absolute Positioning Accuracy Assessment

Absolute positioning accuracy is evaluated by comparing object-space coordinates derived from the ZY-3 imagery with independent reference data, following the generic error model established in Section 2.2. This assessment is conducted at two complementary levels: single-scene absolute accuracy and integrated block absolute accuracy.

2.4.1. Absolute Positioning Accuracy of Single-Scene Images

For a check point with reference position $P(X, Y, Z)$ obtained from external datasets, the object-space solution P_{img} from a single ZY-3 scene is compared directly. Applying Equations (1) and (2), P_1 and P'_1 are substituted by P_{img} and P , yielding the single-scene absolute planimetric error d_{xy}^{abs} and elevation error d_z^{abs} . The validity of this substitution rests on the independence of the two coordinate sources: P_{img} is derived solely from the ZY-3 RPC model, while P originates from an independent reference dataset.

2.4.2. Integrated Absolute Positioning Accuracy of the Image Block

As illustrated in Figure 2, when multiple overlapping images participate in free-network block adjustment, a multi-image forward intersection yields an integrated object-space solution P_{ab} for each check point. The absolute positioning error of the block-adjusted solution is evaluated by comparing P_{ab} with the reference position P , again following the generic error definition of Equations (1) and (2). The planimetric error $d_{xy,\text{ab}}^{\text{abs}}$ and elevation error $d_{z,\text{ab}}^{\text{abs}}$ of the block-adjusted solution are computed accordingly.

For a set of validation points distributed across the study area, the RMSE and descriptive statistics of $d_{xy,\text{ab}}^{\text{abs}}$ and $d_{z,\text{ab}}^{\text{abs}}$ are computed to quantify the overall absolute geometric accuracy achieved by the block-adjusted ZY-3 imagery.

It should be noted that the consistency RMSE (Section 2.3) and the absolute RMSE defined here quantify fundamentally different aspects of geometric quality—internal precision versus external accuracy. In the following, we examine whether an empirical relationship exists between these two metrics.

3. Experiment

The experiments in this section are designed to validate the effectiveness of the proposed inter-image consistency-based geometric accuracy detection framework. In particular, the experiments aim to demonstrate (1) the reliability of the mathematical preprocessing adopted in the method, (2) the rationality of the stereo intersection strategy, (3) the feasibility of using free-network tie points as independent checkpoints, and (4) the relationship between inter-image consistency accuracy and absolute positioning accuracy.

3.1. Dataset

3.1.1. Image Data

The study area is located in a broad region of the Americas and covers approximately 1.9 million km². The terrain is predominantly hilly, accounting for roughly 61% of the total area, while plains represent only 7% and are concentrated in the central part, where the lowest elevation descends to about 170 m in the north-central portion. Mountainous terrain constitutes 32% of the area, distributed mainly along the eastern and western margins, and reaches a maximum elevation of approximately 1000 m in the southeastern corner. The mean slope is approximately 3.53°. This composition reflects a predominantly rugged landscape, and the distortions induced by topographic relief pose considerable challenges for geometric accuracy assessment.

This study employed 1368 ZY-3 satellite images acquired in a three-line-array configuration consisting of forward-, nadir-, and backward-looking views. The imagery was collected primarily by the ZY-3-01 and ZY-3-02 satellites. Over 90% of the images were obtained between March and December 2020, while a small number of scenes dating back to July 2012 were included to fill coverage gaps within the study area. All images, regardless of acquisition year, share identical sensor specifications and product formats, ensuring compatibility within the block adjustment.

The ZY-3-01 imagery accounts for 40% of the dataset, providing a nadir ground sample distance (GSD) of 2.1 m and forward/backward GSDs of 3.5 m. The ZY-3-02 imagery contributes the remaining 60%, with forward and backward GSDs improved to 2.5 m.

All images were ordered as Level 1 products with rational polynomial coefficients and were transformed into the WGS-84 coordinate system prior to adjustment. Block adjustment was performed without ground control points. A total of 32,332,862 tie points were automatically matched for the free-network solution. After adjustment, the resulting ZY-3 imagery is referenced to the WGS-84 geographic coordinate system, with ellipsoidal heights relative to the WGS-84 ellipsoid.

The root-mean-square error of the image residuals was 0.313 pixels in the longitudinal direction, 0.420 pixels in the latitudinal direction, and 0.524 pixels in the combined direction. As shown in Table 1, approximately 72.45% of all tie points exhibit residual errors below 0.5 pixel, and approximately 93.06% fall within the 1.0-pixel threshold. The proportion of tie points with residuals exceeding 2.0 pixels is negligible (only 0.002%). This distribution indicates that the vast majority of tie points achieve sub-pixel consistency accuracy, demonstrating the high internal geometric stability of the ZY-3 imagery after free-network block adjustment.

Table 1. Statistical of Residuals Distribution at Tie Points in Free Network Adjustment Imagery Data.

Range of Error	Number of Tie Points	Proportion (%)
below 0.5 pixel	23,360,264	72.45
0.5 to 1 pixels	6,645,986	20.61
1 to 1.5 pixels	1,716,272	5.32
1.5 to 2 pixels	518,913	1.61
greater than 2 pixels	627	0.002

3.1.2. Reference Data

GE imagery and SRTM digital elevation model data were employed respectively as reference datasets to conduct statistical analysis of the plane positional accuracy and elevation accuracy for the Experimental ZY-3 Mapping Satellite.

High-resolution imagery from GE was used as the planimetric reference. The nominal spatial resolution is approximately 0.5–0.7 m, varying by region and zoom level. In this study, imagery at a zoom level corresponding to a ground resolution of approximately 2 m was used, referenced to the WGS84 coordinate system with ellipsoidal heights. The GE imagery consists of multi-temporal scenes acquired between approximately 2017 and 2019. These images were selected to ensure basic consistency in land-cover features with the ZY-3 imagery, with preference given to scenes acquired as close in time as possible, following the criteria established in Section 2.1.2.

SRTM 3 data were used as the elevation reference. The SRTM 3 product has a spatial resolution of 3 arc-seconds (approximately 90 m at the equator), with horizontal datum WGS84 and vertical datum EGM96. The data were acquired in February 2000 during the SRTM mission. To ensure vertical datum consistency with the ZY-3 imagery, the SRTM data (EGM96) were transformed to the EGM2008 vertical datum using the relevant geoid undulation grids, following the procedure described in Section 3.2.

We adopted a hierarchical validation strategy, whereby the first-stage assessment aimed to ascertain whether the GE imagery and SRTM datasets exhibit anomalous accuracy degradation within or in the vicinity of the study area. To this end, two separate assessments were conducted using high-resolution WorldView reference imagery. First, an urban area adjacent to the experimental research region was selected to evaluate the planimetric positional accuracy of GE imagery. Second, a topographically representative area spanning flat to hilly terrain, with landform characteristics consistent with those of the main study area, was chosen near the research site to evaluate the vertical accuracy of the SRTM dataset.

The WorldView reference imagery used in this study consisted of WorldView-2 standard stereo pairs (Level 2A, with accompanying rational polynomial coefficients, RPCs) acquired between 2017 and 2018. It should be explicitly noted that these images were not rigorously refined using in situ ground control points. According to the sensor's nominal accuracy specifications, the positioning accuracy under such unrefined conditions is approximately 3–5 m (CE90/LE90). Consequently, these unrefined WorldView-2 images may themselves introduce a source of error into the subsequent accuracy assessment of the GE and SRTM datasets.

In assessing the planimetric positional accuracy of GE imagery using WorldView reference imagery, as illustrated in Figure 3, 27 well-defined ground control points (GCPs) were identified across both datasets, and coordinate difference statistics were performed. Statistical analysis yielded RMSE of 2.40 m in the longitudinal direction, 3.60 m in the latitudinal direction, and a combined planimetric RMSE of 4.32 m.

A flat-to-hilly terrain region exhibiting terrain characteristics consistent with the study area, was selected to evaluate SRTM elevation accuracy using WorldView imagery, as illustrated in Figure 4, 27 well-defined ground control points (GCPs) were identified across both datasets, and coordinate difference statistics were performed. Statistical analysis yielded RMSE of 2.40 m in the longitudinal direction, 3.60 m in the latitudinal direction, and a combined planimetric RMSE of 4.32 m. The assessment yielded RMSE of 4.63 m and a maximum error of −10.58 m.

The results indicate that the GE and SRTM data over the study area are free from anomalous degradation or systematic gross errors. The planimetric deviation of GE (4.32 m) and the vertical deviation of SRTM (4.63 m) fall within the accuracy range typically reported for ZY-3 imagery, supporting the usability of these reference datasets.

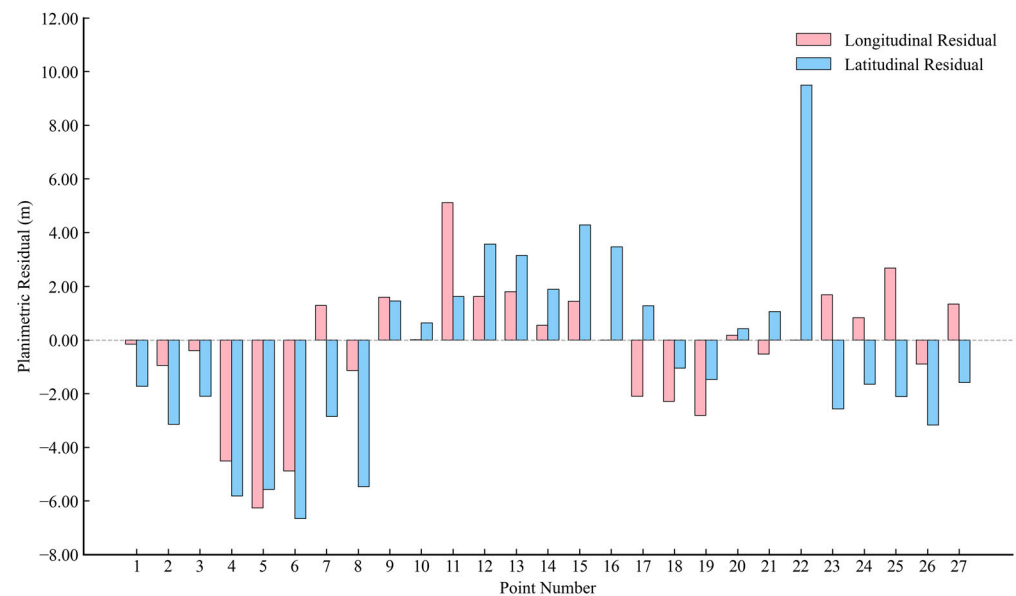


Figure 3. Distribution Characteristics of Residuals in GE Positioning Accuracy Assessment.

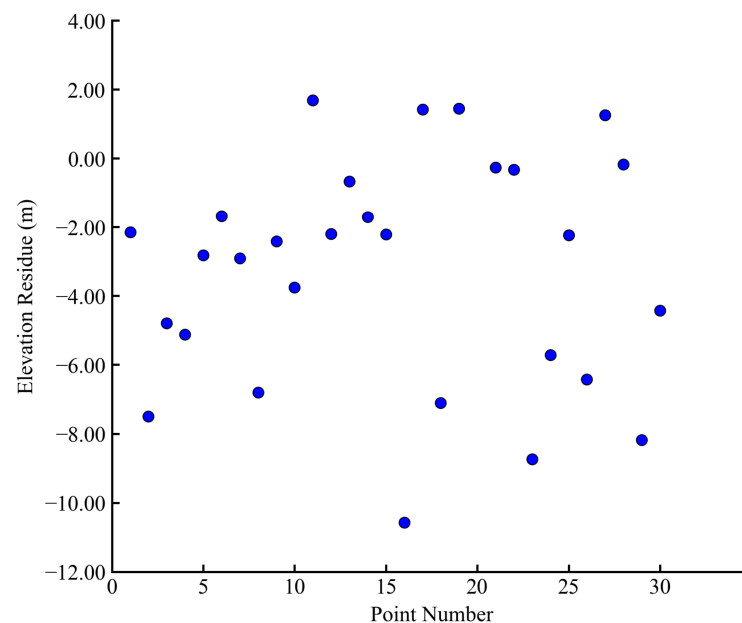


Figure 4. Distribution of Elevation Residuals in SRTM Accuracy Assessment. Each dot represents the residual value of one validation point.

This statistical conformity with independently validated product populations, achieved through relative comparison combined with multi-source cross-validation rather than absolute accuracy verification, supports the usability of these datasets. Subsequently, the second stage of the hierarchical validation strategy was carried out: the GE imagery and the SRTM digital elevation model data were adopted as the planimetric and vertical references, respectively, for the statistical accuracy assessment of the ZY-3 satellite imagery.

3.2. Validation of Height Datum Unification and Mathematical Preprocessing

To ensure that the proposed consistency-based geometric accuracy detection method reflects actual geometric performance rather than artifacts introduced by preprocessing, the influence of height datum unification and interpolation strategies must first be evaluated. The ZY-3 imagery and GE reference data are provided in the WGS-84 ellipsoidal height

system, whereas SRTM elevation data are referenced to the normal height system. Consequently, height datum transformation is required prior to elevation accuracy evaluation.

In this study, elevation anomalies were computed using the EGM2008 geoid model to transform SRTM normal heights into ellipsoidal heights. Since object-space coordinate differences constitute the core metric of the proposed consistency analysis, four interpolation strategies—Bi-Quadratic, Bi-Linear, Triangulation, and Nearest neighbor—were evaluated to quantify the uncertainty introduced during anomaly computation.

The maximum difference among the four interpolation-derived height anomaly values at individual points was 0.61 m, and the RMSE across all 80 validation points was 0.14 m, as summarized in Figure 5. Considering that the vertical positioning accuracy of ZY-3 imagery after free-network adjustment is at the meter level, the uncertainty introduced by interpolation strategy selection is negligible relative to the overall error budget. This result demonstrates that the adopted height datum unification procedure does not obscure or bias the subsequent consistency-based geometric accuracy analysis. Accordingly, bilinear interpolation was employed in the following experiments.

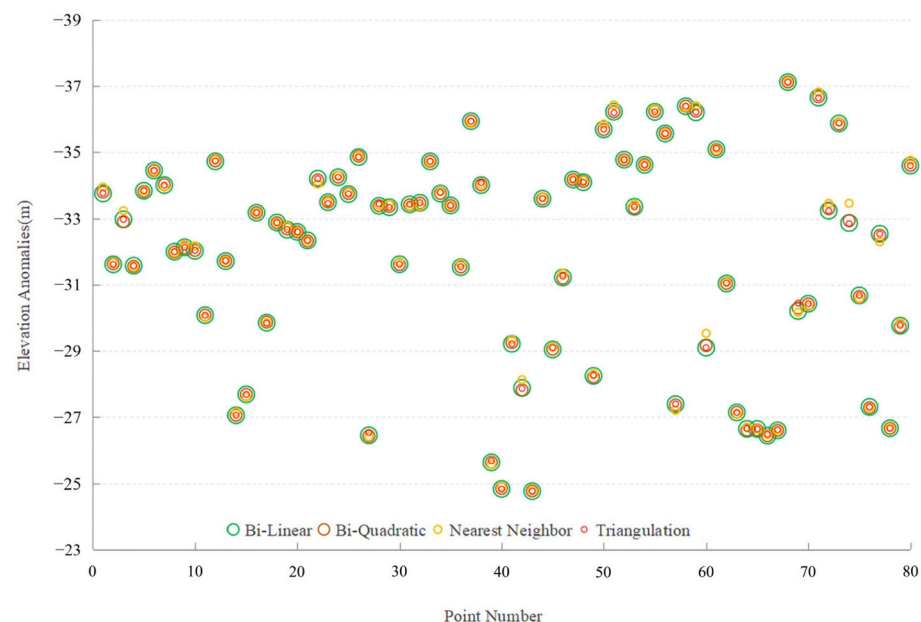


Figure 5. Discrepancy Distribution of Anomalous Elevation Values Using Different Interpolation Methods.

3.3. Verification of Consistency-Based Accuracy Detection Method

3.3.1. Effect of Stereo Intersection Strategy on Consistency Accuracy

The imaging data acquired by the ZY-3 include forward-, backward-, and nadir-looking views, enabling multiple stereo intersection configurations. In the proposed consistency-based geometric accuracy detection framework, the choice of stereo intersection strategy directly affects the stability and interpretability of object-space consistency estimation. Although photogrammetric theory suggests that intersection accuracy may increase with the number of participating images, additional views may introduce redundancy and instability in large-scale consistency analysis. Therefore, this experiment is designed to validate whether a two-view (forward–backward) intersection strategy is sufficient and appropriate for the proposed method.

Using the consistency detection approach described in Section 2.3.1, eighty locations were uniformly selected within overlapping image regions. Object-space coordinates were first estimated using a two-view forward–backward stereo intersection. The resulting mean consistency errors are 2.41 m in the longitudinal direction, 2.78 m in the latitudinal direction,

and 4.18 m in elevation. Subsequently, object-space coordinates were independently estimated using a three-view (forward–backward–nadir) intersection. For this configuration, the corresponding mean consistency errors are 2.44 m, 2.99 m, and 4.18 m, respectively.

To quantitatively evaluate the difference between the two intersection strategies, object-space coordinate discrepancies were computed at each location, with the distribution of discrepancies summarized in Figure 6. The corresponding RMSE of the coordinate differences is 0.18 m in the longitudinal and 0.35 m in the latitudinal directions. In the elevation direction, the RMSE of the coordinate differences is 0.03 m. These discrepancies are negligible relative to the meter-level geometric accuracy of ZY-3 imagery after free-network adjustment.

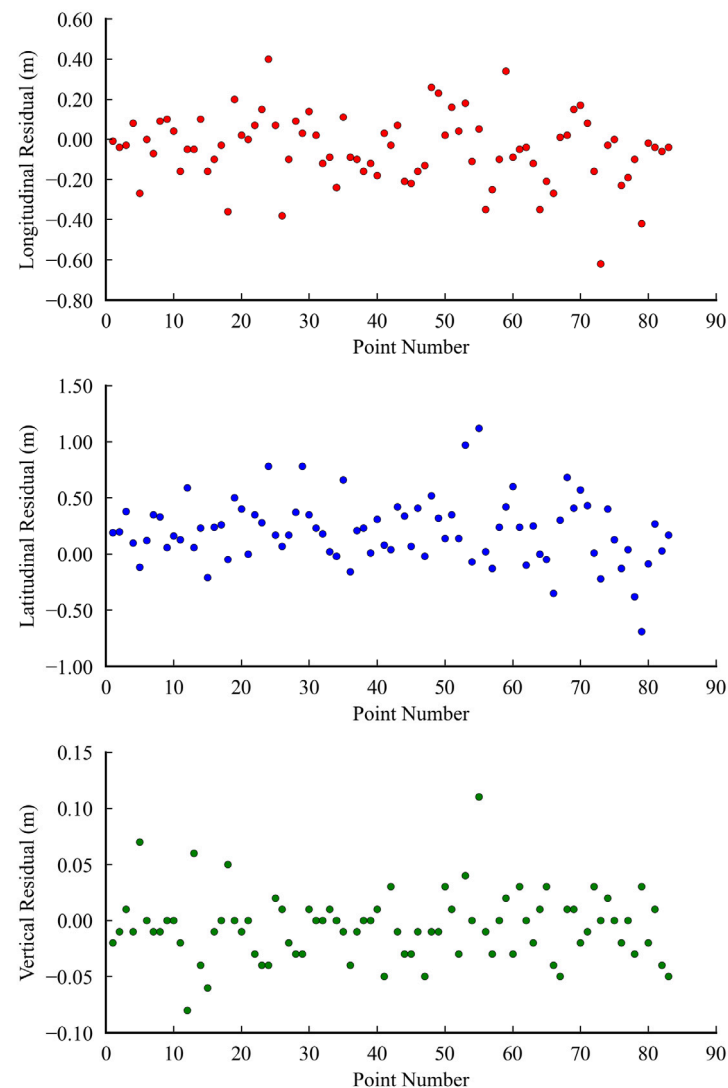


Figure 6. Coordinate Differences of Identical Points in Distinct Intersection Modes. Each dot represents the residual value of one validation point.

The results demonstrate that two-view and three-view intersection strategies yield nearly identical object-space coordinates in the context of consistency analysis. Moreover, two-view intersection exhibits more stable edge behavior within overlapping regions, which is advantageous for inter-image consistency evaluation. This experiment confirms that the forward–backward two-view intersection strategy provides sufficient geometric reliability for the proposed consistency-based accuracy detection method while

avoiding unnecessary redundancy. Accordingly, the two-view intersection strategy was adopted for subsequent consistency and geometric accuracy analysis.

3.3.2. Utilizing Free-Network Tie Points as Independent Checkpoints for Consistency Accuracy Evaluation

This experiment is designed to validate a core methodological contribution of this study: the feasibility of using tie points generated from free-network adjustment as independent checkpoints for inter-image consistency accuracy evaluation. Unlike conventional geometric accuracy assessment approaches that rely on external GCPs, the proposed method exploits the internal geometric constraints of the image network to achieve large-area, control-point-free accuracy detection.

The experimental dataset consists of 1368 ZY-3 image scenes, each comprising forward-, backward-, and nadir-looking views, resulting in a total of 5288 overlapping image edges. Following the consistency accuracy evaluation procedure described in Section 2.3, inter-image consistency accuracy was systematically quantified for every overlapping image pair using tie points obtained from free-network matching.

As illustrated in Table 2, across all 5288 overlapping edges, the RMSE of longitudinal consistency accuracy is 1.61 m, with a maximum deviation of 8.34 m. The lateral consistency accuracy demonstrates an RMSE of 1.67 m and a maximum deviation of 5.82 m. For elevation consistency accuracy, the RMSE is 2.20 m, with a maximum deviation of 10.87 m.

Table 2. Consistency Accuracy Test Results in the Experimental Area.

Consistency Accuracy	RMSE (m)	Maximum Deviation (m)
Longitudinal	1.61	8.34
Lateral	1.67	5.82
Elevation	2.20	10.87

These statistical results indicate that free-network tie points provide stable and spatially consistent geometric constraints across large-scale image networks. More importantly, the consistency accuracy distributions derived from these internal checkpoints exhibit coherent spatial patterns, demonstrating that reliable inter-image consistency assessment can be achieved without reliance on external control data. This experiment confirms that tie points generated through free-network adjustment can effectively serve as independent checkpoints for consistency accuracy evaluation, thereby validating the practicality and scalability of the proposed GCP-free geometric accuracy detection framework.

3.4. Image Geometric Accuracy Assessment

3.4.1. Assessment of Absolute Geometric Accuracy After Free-Network Adjustment

This experiment is conducted to validate the absolute geometric accuracy of ZY-3 imagery after free-network adjustment and to assess whether the proposed consistency-based detection framework yields positioning accuracy results that are reliable at the regional scale. Unlike conventional accuracy evaluation approaches that rely on field-surveyed ground control points, this experiment adopts public geospatial datasets as independent references to verify the effectiveness of the proposed method.

As shown in Table 3, 80 independent check points were used for validation. Planimetric positioning accuracy was evaluated using high-resolution GE imagery, and elevation positioning accuracy was assessed using SRTM elevation data. The differences in object-space coordinates between the adjusted ZY-3 imagery and the reference datasets were computed for each checkpoint.

Table 3. Statistical summary of absolute positioning accuracy and inter-image consistency accuracy at the 80 validation points.

Metric	RMSE (m)	Mean (m)	Max (m)	Min (m)	Std (m)
Planimetric Absolute Error (vs. GE)	3.33	2.61	10.38	0.30	2.08
Elevation Absolute Error (vs. SRTM)	4.27	3.22	14.90	0.11	2.82
Planimetric Consistency Error	3.24	2.92	8.56	0.24	1.43
Elevation Consistency Error	2.65	2.45	5.89	0.37	1.02

Note: For consistency metrics, the value at each checkpoint is derived from the RMSE of all tie points within the overlapping region covering that checkpoint.

To provide a comprehensive statistical overview of both absolute positioning accuracy and inter-image consistency metrics at the checkpoint level, Table 3 summarizes the RMSE, mean, maximum, minimum, and standard deviation of the four accuracy indicators computed over the 80 validation points: planimetric absolute error (validated against GE), elevation absolute error (validated against SRTM), planimetric consistency error, and elevation consistency error (derived from adjacent ZY-3 image pairs). The complete dataset of all 80 checkpoints is provided in Supplementary Table S1.

The overall planimetric RMSE reported in Table 3 is 3.33 m. To provide a more detailed characterization, the planimetric positioning accuracy was also evaluated separately in the longitudinal and latitudinal directions, yielding RMSE values of 2.05 m and 2.63 m, respectively, with corresponding maximum errors of 8.09 m and 9.01 m. In the elevation direction, the RMSE reaches 4.27 m, with a maximum error of 14.90 m.

The distribution of checkpoint-level errors (Table 3) indicates that the majority of checkpoints fall within the expected accuracy range. The standard deviations are substantially smaller than the maximum errors for both planimetric and elevation components, confirming that the reported maximum values represent isolated extreme cases rather than typical performance. This distribution pattern supports the conclusion that the free-network adjustment achieves consistent meter-level positioning accuracy across the majority of the study area.

Inspection of the checkpoint-level errors suggests a tendency for larger horizontal errors to occur more frequently in the central and eastern portions of the study area, while larger elevation errors appear more frequently in the northern and eastern portions.

These results demonstrate that, even in the absence of ground control points, free-network adjustment combined with the proposed consistency-based accuracy detection framework achieves meter-level positioning accuracy that is consistent with the reported geometric performance of ZY-3 imagery.

More importantly, this experiment establishes a reference baseline for subsequent comparative analysis between absolute positioning accuracy and inter-image consistency accuracy. By quantifying absolute geometric accuracy using independent reference data, the proposed framework enables a unified interpretation of consistency-based indicators and conventional positioning accuracy metrics, thereby providing a foundation for analyzing error propagation and spatial distribution characteristics in the following sections.

3.4.2. Comparative Analysis of Planimetric Positioning Accuracy and Planar Consistency Accuracy

This experiment aims to investigate the relationship between planimetric positioning accuracy and inter-image planimetric consistency accuracy, and to evaluate whether consistency-based indicators provide additional diagnostic information beyond conven-

tional absolute accuracy metrics. Such analysis is essential for validating the effectiveness of the proposed consistency-based geometric accuracy detection framework.

For each validation point, the differences in the longitudinal and latitudinal components between the reference coordinates and the free-network adjustment results were computed. The planimetric positioning accuracy error (ds) at each point was calculated using Equation ($ds = \sqrt{dx^2 + dy^2}$). In parallel, the planimetric consistency accuracy was statistically evaluated based on the RMSE of consistency errors derived from all tie points within the overlapping region of adjacent ZY-3 image pairs covering that validation point. This approach ensures that each checkpoint's consistency metric reflects the statistical geometric quality of the local overlapping region rather than the potential noise of an individual tie point.

As illustrated in Figure 7, the data points exhibit a wide scatter with no discernible global trend. The correlation analysis yields a coefficient of determination (R^2) of 0.00019 ($p > 0.05$), which quantitatively confirms the absence of a statistically significant linear relationship between the two variables.

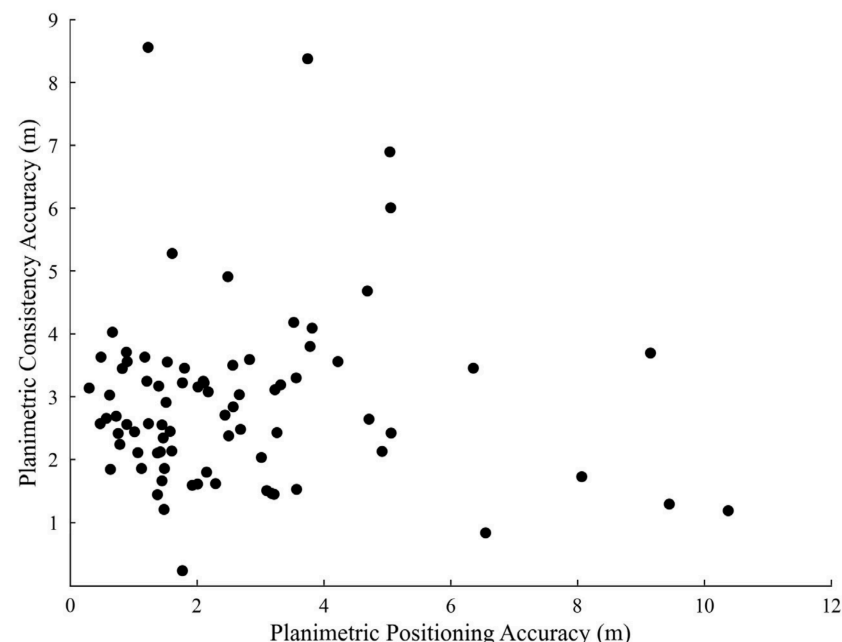


Figure 7. Scatter Plot of Planimetric Positioning Errors versus Planimetric Consistency RMSE at the 80 Validation Points.

This near-zero correlation does not contradict the regional-scale observation that areas with generally better consistency tend to exhibit improved positioning accuracy; rather, it highlights that this relationship is not a deterministic one-to-one mapping at the point level. The absence of a global linear trend reflects the modulating effects of local factors—including error cancellation between overlapping observations, systematic bias propagation through the adjustment network, and inherent uncertainties in the reference data—which collectively obscure any simple correspondence across the entire validation set. These interpretations are further elaborated in Section 4.2, where the spatial heterogeneity of the consistency–accuracy relationship is systematically examined.

However, notable discrepancies are observed at the point level. Several validation points exhibit relatively small planar positioning errors while simultaneously showing large planar consistency errors in the corresponding image pairs. This phenomenon indicates that high absolute positioning accuracy at individual points does not necessarily imply strong inter-image geometric consistency. In such cases, opposing error directions from

adjacent images may lead to partial error cancellation in absolute positioning accuracy computation, thereby masking underlying geometric inconsistencies.

Figure 8 illustrates the point No. 72 from ZY-3 imagery. Within this figure, the central point represents the location on the GE high-resolution reference image. The left point indicates the projected position of the homologous point from the northern scene image onto the GE image, while the right point shows the projected position of the homologous point from the southern scene image. The significant discrepancy between these projected points results in a large inter-scene consistency error for the satellite imagery. Notably, the error directions observed in the two scene images are opposite to those in the reference GE image. When calculating the planar positioning accuracy according to the methodology outlined in Section 2.3.2, the opposing error directions lead to error averaging. Consequently, the overall planimetric positioning accuracy error of the satellite image is reduced.



Figure 8. Satellite image at point No. 72.

These results demonstrate that planimetric consistency accuracy captures geometric characteristics that cannot be fully revealed by absolute positioning accuracy alone. By jointly analyzing planimetric positioning accuracy and consistency accuracy, the proposed method enables the identification of latent geometric instability and error propagation effects, thereby providing a more comprehensive evaluation of planimetric geometric accuracy in ZY-3 imagery.

3.4.3. Comparative Analysis of Elevation Positioning Accuracy and Elevation Consistency Accuracy

This experiment aims to investigate the relationship between elevation positioning accuracy and inter-image elevation consistency accuracy, and to evaluate whether consistency-based indicators provide additional insight into vertical geometric performance beyond conventional absolute accuracy metrics. This analysis further validates the capability of the proposed consistency-based framework to characterize error propagation behavior in the vertical direction.

For each validation point, the elevation positioning accuracy error (dz) was computed as the vertical discrepancy between the reference elevation and the free-network adjustment result. In parallel, elevation consistency accuracy was derived from the RMSE of consistency errors of all tie points within the overlapping region of adjacent ZY-3 image pairs covering that validation point, following the same approach as described in Section 3.4.2.

As illustrated in Figure 9, the data points exhibit a wide scatter with no discernible global trend. The correlation analysis yields a coefficient of determination (R^2) of 0.00375 ($p > 0.05$), quantitatively confirming the absence of a statistically significant global linear relationship between vertical consistency and absolute elevation accuracy.

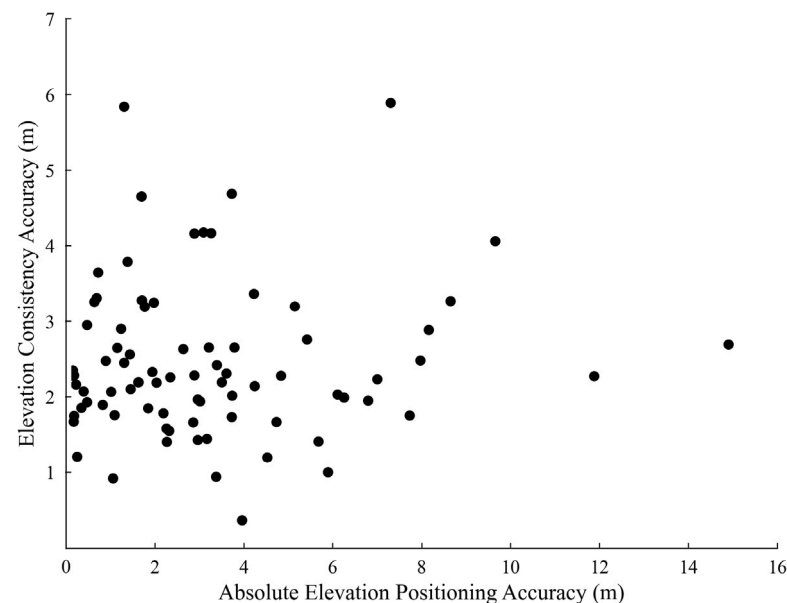


Figure 9. Scatter Plot of Absolute Elevation Errors versus Elevation Consistency RMSE at the 80 Validation Points.

This near-zero correlation does not contradict the qualitative observation that certain areas with favorable consistency tend to achieve reasonable elevation accuracy; rather, it underscores that the vertical consistency–positioning relationship is not deterministically linked at the point level. The weak global association reflects the modulating effects of local factors—including error cancellation between overlapping observations, systematic bias propagation through the adjustment network, and inherent uncertainties in the reference data—which collectively obscure any simple correspondence across the entire validation set. These issues are further examined in Section 4.2, where the spatial heterogeneity of the consistency–accuracy relationship is discussed in detail.

These observations suggest that elevation positioning accuracy and elevation consistency accuracy do not exhibit a one-to-one correspondence at the point level. In certain cases, local error cancellation effects may lead to satisfactory absolute elevation accuracy despite poor inter-image consistency. Conversely, systematic inconsistency across adjacent images may gradually propagate and manifest as elevation positioning errors in surrounding regions rather than at the same location.

These results demonstrate that elevation consistency accuracy captures vertical geometric instability that cannot be fully explained by absolute elevation positioning accuracy alone. By jointly analyzing elevation positioning accuracy and inter-image consistency accuracy, the proposed method enables the identification of latent error propagation patterns in the vertical direction, thereby providing a more comprehensive and interpretable evaluation of elevation geometric accuracy in ZY-3 imagery.

4. Discussion

4.1. Empirical Relationship Between Consistency and Absolute Positioning Accuracy

The results of this study reveal a clear empirical association between inter-image consistency accuracy and the absolute positioning accuracy of ZY-3 imagery after free-

network block adjustment. Regions with higher inter-image consistency, as indicated by lower consistency RMSE values, generally exhibit better absolute positioning accuracy. This finding suggests that consistency metrics, which are generated intrinsically during free-network adjustment without the need for external reference data, can serve as meaningful internal indicators of geometric quality.

The underlying mechanism of this association can be understood from the perspective of error propagation in block adjustment. When tie points are abundant and evenly distributed within overlapping regions, the resulting geometric constraints enforce strong coherence between adjacent scenes. This internal coherence reduces local geometric discrepancies, thereby limiting the accumulation of errors across the block and contributing to improved absolute positioning accuracy. Conversely, regions with sparse or unevenly distributed tie points exhibit weaker consistency and are more susceptible to local error amplification.

However, it must be emphasized that the relationship observed in this study is empirical rather than deterministic. Although the overall trend is statistically robust, the extent to which consistency metrics can directly predict absolute positioning accuracy on a point-by-point basis remains to be quantified. Establishing a quantitative functional relationship linking consistency errors to absolute positioning errors across the entire adjustment network constitutes an important direction for future investigation.

4.2. Spatial Heterogeneity of the Consistency–Accuracy Relationship

Although the overall association between consistency and accuracy is robust at the regional scale, the spatial correspondence between consistency error patterns and absolute positioning error fields is not strictly one-to-one. Local discrepancies arise from the interplay of at least three interacting factors:

- (a) Error cancellation between overlapping observations. In regions with multiple overlapping scenes, random errors in individual observations may partially cancel during the adjustment process, producing favorable consistency metrics without necessarily reflecting the true absolute accuracy at every point.
- (b) Systematic bias propagation through the adjustment network. The absence of absolute ground control allows systematic biases to propagate through the tie-point network. Depending on the geometry and connectivity of the block, these biases may accumulate in certain directions, leading to spatially coherent offsets that are not fully captured by consistency metrics alone.
- (c) Uncertainty inherent in the reference data. The SRTM and GE datasets used for accuracy assessment exhibit non-negligible spatial heterogeneity in both vertical and planimetric accuracy, as further quantified in Section 4.3.

These factors collectively indicate that the consistency–positioning relationship is spatially heterogeneous and context-dependent. A deeper understanding of this heterogeneity would require mechanistic analysis of how consistency errors propagate through large-scale adjustment networks and influence the spatial distribution of positioning errors.

4.3. Implications of Reference-Data Uncertainties for ZY-3 Accuracy Assessment

The reported ZY-3 accuracy metrics—a planimetric RMSE of 3.33 m and a vertical RMSE of 4.27 m—were derived using GE and SRTM as reference datasets, and must therefore be interpreted in light of the inherent uncertainties of these references. These reference-data uncertainties constitute a limiting baseline error that propagates into the ZY-3 accuracy evaluation. Notably, the reported ZY-3 planimetric RMSE of 3.33 m and vertical RMSE of 4.27 m both fall within the respective uncertainty ranges of the reference data. This indicates that, under the given reference-data conditions, the total observed

discrepancy between the ZY-3 products and the references is of the same order as the reference-data uncertainties themselves. Consequently, the ZY-3 free-network adjustment achieves an accuracy level that is at least comparable to the quality of the available reference data. Disentangling the ZY-3 sensor and processing errors from the reference-data errors more precisely would require higher-grade reference data, such as field-surveyed GCPs, which were unavailable for this large study area.

The inherent variability of the reference data is precisely one of the contributing factors to the local discrepancies discussed in Section 4.2, further reinforcing the need for cautious interpretation of the consistency–positioning relationship, especially in complex terrains where reference-data accuracy may degrade substantially.

4.4. Limitations and Future Work

While this study provides new insights into the relationship between inter-image consistency and absolute positioning accuracy, certain limitations should be acknowledged. These limitations also point to promising directions for future research.

First, as noted in Section 4.1, the relationship between consistency and absolute accuracy, although statistically evident at the regional scale, remains empirical rather than deterministic. Future work should therefore pursue quantitative modeling of this relationship at both local and regional scales, enabling consistency metrics to serve not only as qualitative indicators but also as direct predictors of absolute positioning accuracy.

Second, as discussed in Section 4.2, the spatial heterogeneity of the consistency–accuracy relationship arises from the interplay of error cancellation, systematic bias propagation, and reference-data variability. A mechanistic investigation of how consistency errors propagate through large-scale adjustment networks and shape the spatial distribution of positioning errors would substantially advance the understanding of this heterogeneity.

Third, the accuracy estimates reported in this study are constrained by the baseline uncertainties of the publicly available reference datasets, as quantified in Section 4.3. Acquiring higher-grade reference data, such as field-surveyed GCPs or LiDAR-derived control points, would enable a more precise separation of ZY-3 sensor and processing errors from reference-data errors, thereby refining the absolute accuracy assessment.

Addressing these issues would enhance both the interpretability and the practical utility of consistency-based geometric accuracy verification for large-area satellite imagery, advancing it from an empirical diagnostic tool toward a fully quantitative and mechanistically grounded quality control framework.

5. Conclusions

Based on the geometric accuracy analysis of the entire test area, this study utilizes Google high-resolution imagery and SRTM data as reference datasets. Eighty inspection points were selected to conduct plane geometric accuracy and elevation positioning accuracy assessments. The RMSE of plane positioning accuracy is 3.33 m, while the RMSE of elevation precision is 4.27 m. Previous studies indicate that employing field GPS survey points to evaluate the plane and elevation accuracy of ZY-3 satellite free-network adjustment results yields corresponding RMSE values ranging from 5 to 13 m. The accuracy assessment reported here follows a hierarchical verification chain in which WorldView imagery served as the primary reference to validate the GE and SRTM datasets, and these validated datasets were subsequently used to assess the ZY-3 imagery. The unrefined condition of the primary reference imagery and the spatial variability of the GE and SRTM data together introduce an irreducible level of uncertainty into the evaluation. Consequently, the accuracy values presented should be interpreted as the best achievable estimates given the available reference data. Given that the reference data employed in this study exhibit in-

herent accuracy limitations relative to GPS-measured points, the findings remain consistent with field conditions.

These findings demonstrate that when free network adjustment yields favorable consistency accuracy for satellite images, the adjusted ZY-3 imagery achieves positioning accuracy consistent with established research. This prior work demonstrates that leveraging inter-image constraints within defined ranges through ground control-free regional network adjustment enhances the overall positioning accuracy of large-scale imagery.

Therefore, the research presented in this paper is capable not only of accurately assessing the geometric positioning accuracy of wide-area remote sensing satellite images but also facilitates improvements in the geometric positioning accuracy of such imagery.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/rs18152509/s1>.

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