Geometric Accuracy Assessment of Tie Point-Based RFM Refinement Using Bundle Adjustment Framework

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Abstract: Rational Function Model (RFM) are widely used for satellite image georeferencing. However, initial RFM parameters often contain geolocation errors due to orbit, attitude, and sensor modeling limitations. This study presents a bundle adjustment framework that refines RFM using tie points without external ground control points (GCPs). Multi-view experiments with two to seven images demonstrated that increased redundancy enhanced adjustment stability. The adjustment operated in a relative model space, and its effectiveness was validated using GCPs. Results showed that reprojection errors of tie points remained below 0.6 pixels, while independent check points showed errors under 0.8 pixels. Evaluation with GCPs confirmed reductions of 1–5 pixels in image-space errors compared to the original RFM. Furthermore, residual error patterns revealed systematic trends, suggesting potential for further correction. These findings indicate that referencing imagery with minimal GCPs could anchor the refined model to absolute coordinates, thereby reducing GCP dependence in large-scale correction workflows.

Keywords: RFM; Bundle adjustment; Relative correction; Satellite image; Self adjustment.

1. Introduction

High-resolution satellite image is indispensable for mapping, monitoring, and 3D reconstruction. Rational Function Model (RFM) is the standard georeferencing representation because they are sensor independent. However, RFM often contains systematic errors caused by orbit uncertainties, attitude errors, or imperfect initial sensor modelling. These errors typically range from several pixels in image space. Conventional geometric correction requires dense ground control points (GCPs), which are costly and difficult to scale. An alternative is to refine RFM through bundle adjustment using tie points. This approach enhances relative geometric consistency without external data. However, the solution remains in a relative model space rather than being anchored to absolute ground coordinates.

In this study, the emphasis is placed on evaluating how effectively tie-point-based bundle adjustment without external GCPs improves geometric accuracy. The assessment focuses on the degree of sub-pixel consistency that can be achieved and the role of multi-image redundancy in enhancing the stability of the refined model.

2. Methodology

In our study, we aim to refine RFM without relying on external data. The process consists of three main steps. First, reliable tie points are extracted from overlapping satellite images. Next, the RFM is refined through multi-image bundle adjustment. Finally, the geometric accuracy is evaluated using internal reprojection errors and independent check points.

Because no GCPs are introduced, tie points provide the only geometric constraints in our adjustment framework. They establish relative correspondences among overlapping images and form the basis for refining sensor orientation. Candidate image pairs are first screened according to viewing geometry, and only those with convergence angles greater than 15° are retained. Within valid overlap regions, features are detected using the Scale-Invariant Feature Transform (SIFT). The search is restricted to regions predicted by the initial RFM and further subdivided into grids to encourage uniform spatial coverage. Candidate matches are first filtered using descriptor thresholds. They are then refined with Random Sample Consensus (RANSAC). This procedure reduces mismatches and produced a well-distributed set of thousands of reliable tie points.

Refined RFMs are obtained through multi-image bundle adjustment. Each tie point observed in multiple images contributes a set of two-dimensional measurements, while its ground position is treated as an unknown. Projections from ground to image space are computed using initial RFM, and small affine corrections are applied to account for systematic biases. The adjustment minimizes the overall reprojection error of tie points using an iterative Gauss-Newton optimization. A conceptual diagram of this adjustment is shown in Figure 1, illustrating how multi-view tie points are linked to ground coordinates through the initial RFM and refined by affine bias corrections.

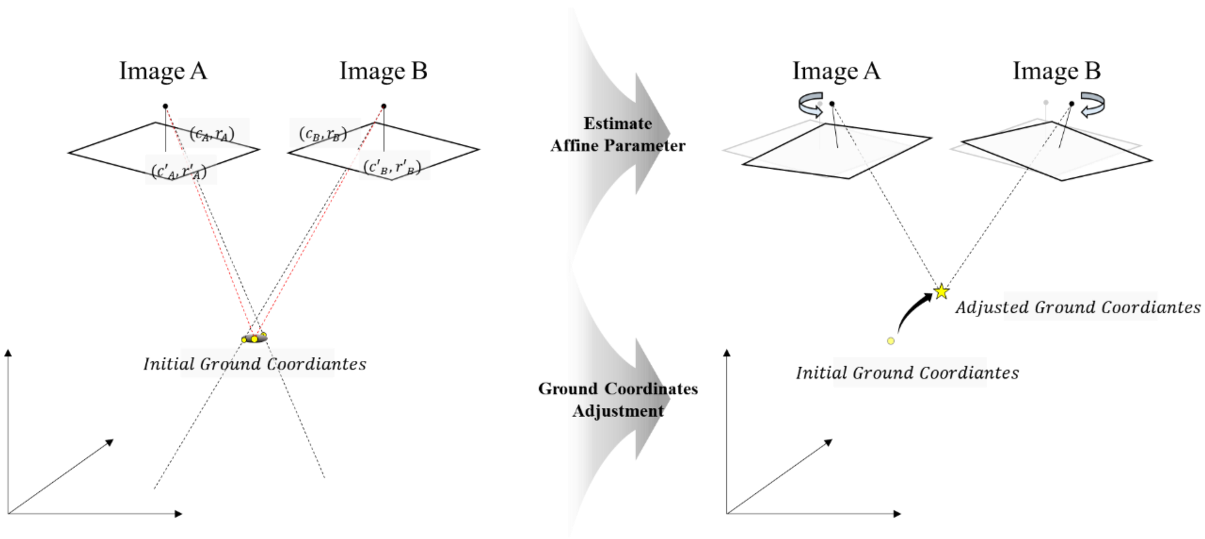

Figure 1. Conceptual diagram of the multi-image bundle adjustment.

To stabilize the adjustment solution, initial weights are not assigned uniformly but determined through pairwise residual statistics. Reprojection errors from each image pair are analysed to identify whether a given image consistently produces accurate or inaccurate correspondences. Based on this assessment, images with reliable behavior are assigned higher initial weights, while those contributing larger or unstable errors are down-weighted. During subsequent iterations, these weights are updated according to the refined residuals, allowing the adjustment to place greater emphasis on reliable observations. This pairwise-informed weighting scheme improves robustness and enabled faster convergence of the bundle adjustment.

The accuracy of the refined models is evaluated through three complementary strategies. Internal consistency is assessed by analysing the reprojection errors of the tie points used in the adjustment, providing a direct measure of geometric alignment. External accuracy is examined using independent check points that are not included in the adjustment process. In addition, a limited number of GCPs are employed to measure absolute accuracy and to confirm the extent to which the refined models reduce image-space errors compared to the original RFM.

3. Results and Findings

Bundle adjustment substantially improved the internal alignment of overlapping images. Across all experimental settings, the mean reprojection errors of tie points remained below 0.6 pixels. This confirms that the refinement removed most of the systematic shifts in the initial RFM and ensured stable sub-pixel consistency. The result is significant in that even without any external control, the internal geometry could be stabilized to a level that was sufficient for reliable downstream processing such as stereo matching or orthorectification.

Independent check points that were not included in the adjustment process also confirmed the external reliability of the refined models. Errors consistently remained below 0.8 pixels, which was comparable to the accuracy levels reported in previous GCP–based refinement studies. These results demonstrate that the refined RFMs provided not only internal consistency but also stable geometric accuracy in external evaluations. In addition, a limited number of GCPs were used to examine absolute positioning accuracy. The refined models reduced image-space errors by 1–5 pixels in most cases, although some scenes showed slight increases when images with large initial misalignments were included. This behavior was expected, as the bundle adjustment balanced residuals across all images in a virtual model space. Nevertheless, the overall trend was toward improved absolute accuracy rather than overfitting, confirming the robustness of the proposed refinement.

Table 1 provides detailed scene-level statistics for the seven-image configuration. Large initial misalignments in Image 2 and Image 4 were significantly mitigated, with errors reduced by more than 20–40 pixels. A few scenes, such as Image 1, showed slight increases in error, which could be attributed to the balancing nature of the bundle adjustment that distributed residuals across all images. Despite these minor variations, the overall RMSE decreased from 6.1 pixels to 3.3 pixels, underscoring both the effectiveness and robustness of the proposed refinement strategy.

Table 1. Scene-level error statistics for the seven-image configuration

Scene ID	Before Adjustment		After Adjustment	
	MAE (pixels)	RMSE (pixels)	MAE (pixels)	RMSE (pixels)
Scene 1	1.45	1.49	1.33	1.37
Scene 2	2.58	2.64	2.98	3.15
Scene 3	25.71	25.81	4.45	4.57
Scene 4	1.26	1.28	1.28	1.30
Scene 5	52.57	52.57	4.52	4.53
Scene 6	3.74	3.90	3.94	4.06
Scene 7	1.95	1.99	1.94	1.98

4. Conclusion

These experiments demonstrate that tie-point-based bundle adjustment could stabilise internal geometry to sub-pixel levels, even without external reference data. The refined RFMs also generalised well to independent check points, confirming their external reliability. When only a few GCPs were introduced, absolute positioning accuracy improved further, with image-space errors reduced by several pixels. Overall, the method provides a practical and scalable solution for large-scale geometric correction while reducing dependence on dense GCP networks.

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