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# RELATIVE GEOMETRIC CORRECTION OF MULTIPLE SATELLITE IMAGES BY RIGOROUS BLOCK ADJUSTMENT

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**KEYWORD:** Satellite, Block adjustment, Tie point, Image matching, RFM.

**ABSTRACT:**

With the development of satellite imaging technology, many Earth observation satellites have been launched and almost all areas of the Earth are daily covered by satellite images. It is promising to utilize such images in change detection, monitoring, semantic classification, etc. To obtain geometric information on each pixel in images, Rational Polynomial Coefficients (RPCs) of a Rational Functional Model (RFM) are provided with satellite images. However initial RPCs may include geometric errors. Therefore, errors in initial RPCs must be corrected before utilization. In this study, we attempt to perform rigorous block adjustments for refining RFMs of overlapping satellite images without ground control points. Our rigorous block adjustment method operated based on automatically extracted tie-points within overlapping areas. It estimates the optimal adjustment coefficients of RPCs and ground coordinates of tie-points. We achieved relative geometric correction of multiple satellite images by transforming the images based on the estimated adjustment coefficients. As a result, an initial RFM model with an error of around 21.73 pixels was corrected to within 1 pixel, and the reprojection error of check points decreased to 0.87 pixels. We also confirmed that our method showed more accurate results than general image registration methods, such as 2D homography transformation.

## 1. INTRODUCTION

As a result of the increasing number of Earth observation satellites being launched, every part of the Earth is now daily covered by satellite imagery. These satellite images have been transformed into vast volumes of big data that hold immense potential for utilization. Furthermore, they can be processed into valuable time-series data that facilitates analysis such as monitoring and change detection. The starting point of such analyses relies on ensuring the accuracy of the conversion between image coordinates and ground coordinates. To ensure this accuracy, a preprocessing method is employed, which involves refining the Rational Functional Model (RFM) by adjusting the Rational Polynomial Coefficients (RPCs) using ground control points (GCPs) as the reference for ground coordinates. This allows for the alignment of satellite imagery with precise geospatial information (Son *et al*., 2021).
However, it is costly to prepare GCPs for each satellite image. Moreover, the process of identifying GCPs in the imagery and performing geometric correction in real-time consumes a significant amount of time compared to the generation of satellite imagery itself. For these reasons, the importance of relative geometric correction, which considers a transformation between satellite images using only tie-points without GCPs is rapidly increasing (Li *et al*., 2022).

There are two common methods used for the relative geometric correction of satellite images. One approach is based on image registration, where a 2D image transformation model is predefined and estimated using tie-points. The 2D image transformation models include translation, similarity, affine, homography transformation. When satellite images are captured at a nadir view where terrain-induced errors can be considered negligible, homography transformation is primarily used to describe the transformation relationship between satellite images. Homography transformation allows for accurate geometric correction by accounting for perspective distortions and projective transformations in the image (Zitova and Flusser, 2003). Another approach is based on block adjustment method. The image registration-based method considers satellite imagery as a two-dimensional image to estimate the transformation relationship. In contrast, the block adjustment-based method adjusts the given initial RPCs and re-estimates ground coordinates corresponding to tie-points or GCPs (Grodecki and Dial, 2003). The imagery is then projected onto the estimated complex terrain model, accounting for the variations in terrain. This method considers the three-dimensional nature of the scene and provides a more accurate geometric correction.

In this study, we performed a rigorous block adjustment method on multiple satellite images with overlapping areas to refine the initial RFM. This refinement was carried out using only automatically extracted tie-points. First, we extracted tie-points between the satellite images. For this purpose, we employed the Scale-Invariant Feature Transform (SIFT) algorithm. In the process, outliers of tie-points were removed through the Random Sample Consensus (RANSAC) algorithm. Next, we set up a mathematical model to describe the transformation relationships between image coordinates and ground coordinates. Finally, we performed rigorous block adjustment based on the mathematical model and estimated the RPC correction factors and ground coordinates of tie-point iteratively.

For the experiments, we used multiple high-resolution satellite images acquired from KOMPSAT-3A as input data. The satellite images were organized into four datasets. Each dataset consists of satellite images designed to have overlapping areas for relative geometric correction using tie-points. To evaluate the performance of the proposed relative geometric correction method, we manually extracted check points that were identifiable in the images. Using the image coordinates of these check points, we calculated the reprojection error, which measures the discrepancy between the reprojected positions and the actual positions of the points. In addition, we compared the block adjustment result with a homography transformation.

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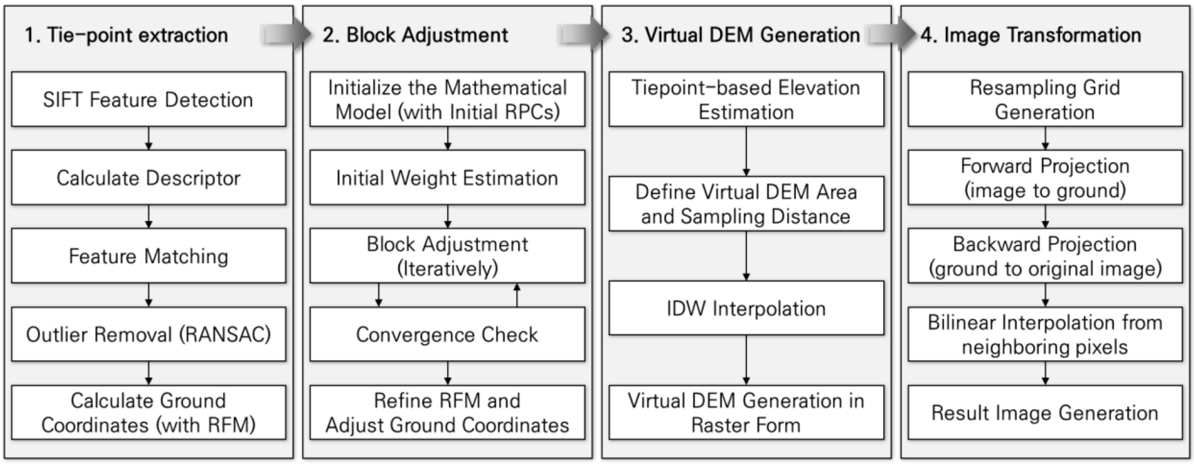


**Figure 1.** Flow chart of relative geometric correction

## 2. METHODOLOGY

To apply relative geometric correction, we need multiple satellite images with overlapping areas and their initial RPCs as input data. Our method comprises four main steps. Firstly, tie-point matching and filtering are performed to establish correspondence between keypoints in the image. Next, block adjustment is conducted and refines the initial RPCs and ground coordinates of tie-points. Subsequently, a virtual terrain model is generated, providing a three-dimensional representation of the image scene. Finally, the satellite images are projected onto the virtual terrain model, resulting in the generation of relative geometrically corrected images. The flow chart of our algorithm is depicted in Figure 1.

### 2.1 Tie-point Matching and Filtering

We perform tie-points matching and filtering. This involves identifying corresponding points between the satellite images. To perform tie-point matching, we used the SIFT algorithm, which is a robust feature detection and description technique that is invariant to changes in image scale, and rotation. It extracts distinctive keypoints from the satellite images and computes their descriptors, which capture the local image information. Additionally, SIFT offers sub-pixel accuracy in estimating the image coordinates of keypoints, further enhancing the precision of our relative geometric correction.

After obtaining keypoints and descriptors, we applied the RANSAC algorithm for tie-points filtering. The RANSAC is a robust estimation method used to eliminate outliers in the tie-point matching process. In our method, the RANSAC algorithm was based on the homography transformation model. We set the threshold for determining outliers to approximately 10 pixels. This threshold was chosen to allow for the extraction of a large number of tie-points with some terrain relief displacements. Setting a tighter RANSAC threshold would increase the likelihood of classifying tie-points extracted from complex terrains, structures and building as outliers, as the homography model assumes a flat 2D plane. The combination of SIFT and RANSAC algorithms enhances the accuracy and robustness of the tie-point matching process. It enables us to extract high-quality tie-points that serve as reliable references for the subsequent steps of the relative geometric correction method. Figure 2 shows a result using SIFT and RANSAC in obtaining reliable tie-points.

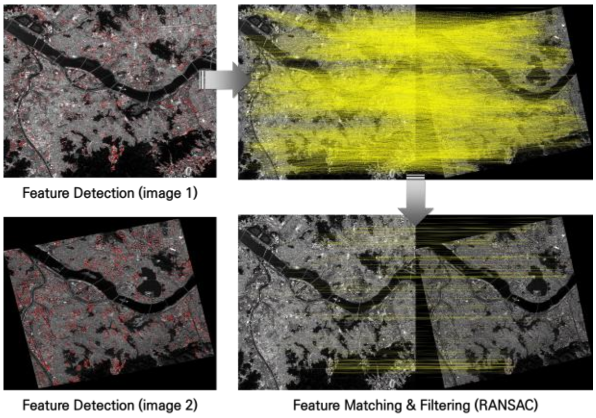


**Figure 2.** Example result of SIFT and RANSAC

### 2.2 Rigorous Block Adjustment Using Tie-points

To perform rigorous block adjustment, we need to establish a mathematical model based on RFM with RPCs (Equation (1)). The mathematical model describes the relationship between image coordinates and ground coordinates, incorporating a correction value to account for any systematic errors or biases present in the initial RPCs. Figure 3 provides a visual representation of the mathematical model used in our approach. As shown in Figure 3, our mathematical model represents the projection of ground coordinates onto image coordinates (unrefined RFM) using the initial RPCs. It also encompasses the computation and application of correction values on the image plane to estimate the corresponding image coordinates where the ground coordinates should be projected.

$$
\begin{aligned}
line &= \Delta line + Line(Lat, Lon, Hgt) + \nu_{line} \\
samp &= \Delta samp + Samp(Lat, Lon, Hgt) + \nu_{samp}
\end{aligned}
\tag{1}
$$

Where $line$ and $samp$ are measured line and sample coordinates of tie-points. $\Delta line$ and $\Delta samp$ are model correction functions in line and sample directions. $Line$ and $Samp$ are calculated line and sample coordinates using initial RPCs and ground coordinates of tie-points. $\nu_{line}$ and $\nu_{line}$ are random unobservable errors in line and sample directions.


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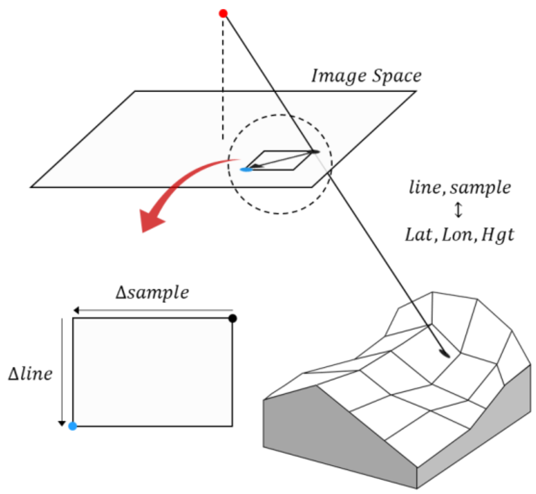


**Figure 3.** RFM mathematical model with correction value

The model correction functions in Equation (1) are derived from the error model present in the initial RPCs. In our proposed method, the correction functions are expressed in the form of an affine transformation model, as shown in Equation (2).

$$\begin{aligned} \Delta line &= a_0 + a_s \cdot samp + a_l \cdot line \\ \Delta samp &= b_0 + b_s \cdot samp + b_l \cdot line \end{aligned} \tag{2}$$

In Equation (2), the terms $a_0$ and $b_0$ represent parameters that absorb various sources of error. Specifically, $a_0$ accounts for in-track error, pitch attitude error, as well as the line component of principal point and sensor position errors. On the other hand, $b_0$ absorbs cross-track error, roll attitude error, and the sample component of principal point and sensor position errors. Additionally, $a_l$ and $b_l$ capture the effects of gyro drift during image scanning, while $a_s$ and $b_s$ absorb errors in the radial direction and interior orientation errors, such as lens distortion and focal length. These parameter values play a crucial role in the mathematical model for correcting the image coordinates and aligning them accurately with the ground coordinates.

Block adjustment can be performed on multiple satellite images having overlapping areas using the math model and tie-points. Compared to an image registration method, the block adjustment-based relative geometric correction is more suited for handling multiple satellite images. In the image registration-based method, finding a single reference image that accurately represents the entire dataset can be challenging. Additionally, pairwise registrations between individual images become increasingly computationally intensive and time-consuming with a growing number of images. In contrast, the block adjustment-based method is well-equipped to handle multiple images simultaneously. It optimizes the mathematical model with ground coordinates of tie-points. In the overlapping images, a relative positional relationship between images can be defined using the extracted tie-points which are measured image coordinates on those images (Figure 4)

The mathematical model in Equations (1) and (2) allows for the formulation of the observation equation in multi-image block adjustment, as shown in Equation (3). Tie-points are utilized as virtual adjustable ground coordinates (Latitude, Longitude, Height). As a result, two observation equations can be established for each image point (i) in the jth image, using the kth ground coordinate of a tie-point.

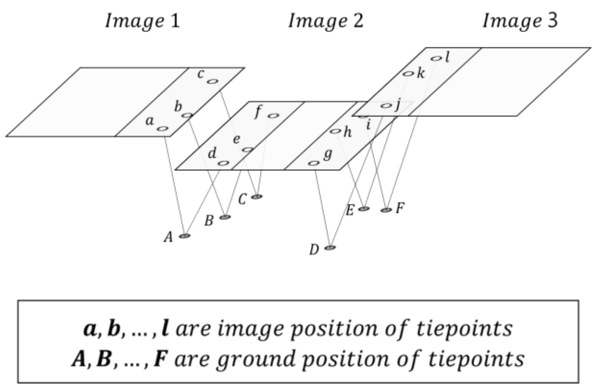


**Figure 4.** Relationship of multiple overlapping images

$$\begin{aligned} F_{line} &= -line_i^{(j)} + a_0^{(j)} + a_s^{(j)} \cdot samp_i^{(j)} \\ &\quad + a_l^{(j)} \cdot line_i^{(j)} + Line_i^{(j)}(Lat_k, Lon_k, Hgt_k) \\ F_{samp} &= -samp_i^{(j)} + b_0^{(j)} + b_s^{(j)} \cdot samp_i^{(j)} \\ &\quad + b_l^{(j)} \cdot line_i^{(j)} + Samp_i^{(j)}(Lat_k, Lon_k, Hgt_k) \end{aligned} \tag{3}$$

By applying Taylor Series expansion to Equation (3), it is possible to derive a linearized model represented by Equation (4). This linearized model can be solved using the least squares method, which allows for the estimation of solutions. In our proposed method, we utilize the least squares approach with initial constraints to guide the optimization process (Equation (5)). Through iterations, we iteratively estimate the solutions and covariance values to converge towards an accurate relative geometric correction. By incorporating the initial constraints and iteratively refining the parameters, our method ensures a more precise alignment and improves the overall accuracy of the relative geometric correction.

$$F_0 + dF_i + \varepsilon = 0 \tag{4}$$

$$\begin{bmatrix} w & 0 & 0 \\ 0 & \dot{w} & 0 \\ 0 & 0 & \ddot{w} \end{bmatrix} \begin{bmatrix} \dot{B} & \ddot{B} \\ I & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} \Delta x_{RFM} \\ \Delta x_{TP} \end{bmatrix} = \begin{bmatrix} w & 0 & 0 \\ 0 & \dot{w} & 0 \\ 0 & 0 & \ddot{w} \end{bmatrix} \begin{bmatrix} M_{mm} \\ M_{RFM} \\ M_{TP} \end{bmatrix} \tag{5}$$

In Equation (5), the variables $w$, $\dot{w}$ and $\ddot{w}$ represent weights for observations, image adjustment parameters, and ground coordinates of tie-points, respectively. These weights are applied in the weighted least squares method. $\dot{B}$ and $\ddot{B}$ denote the partial differentials of the objective function $F$ with respect to the adjustment parameters and tie-points. $\Delta x_{RFM}$ and $\Delta x_{TP}$ are iteratively estimates and changes from the initial values of adjustment parameters and tie-points. $M_{mm}$, $M_{RFM}$ and $M_{TP}$ are misclosures for the mathematical model, adjustment parameters and tie-points.

The evaluation of the estimation results in our method relies on the estimated residuals and the covariance matrix of residuals. The covariance matrix of residuals is calculated using Equation (6), as proposed by Mikhail and Ackermann (1976). Additionally, the estimated new weight for the next iteration can be computed using Equation (7). These calculations provide valuable information for assessing the accuracy and reliability of the estimated parameters and allow for iterative refinement in subsequent iterations of the rigorous block adjustment process.

$$C_{vv} = C_{LL} - BC_{\hat{p}\hat{p}}B^T \quad (6)$$

where

$$C_{\hat{p}\hat{p}} = (B^T C_{LL}^{-1} B)^{-1}$$

and

$$\hat{C}_{LL}^{-1} = \frac{v^T C_{LL}^{-1} v}{trace(C_{vv} C_{LL}^{-1})} \quad (7)$$

### 2.3 Virtual Terrain Model Generation

Following the rigorous block adjustment, the adjustment parameters of the refined RFM and ground coordinates of tie-points were computed for each image to achieve an optimal level of relative position accuracy between tie-points. This refinement process enhances the alignment of the images and ensures a more precise representation of their relative positions. Moreover, image transformation is employed to visually assess the relative positional accuracy and detect any potential image distortions. This step is crucial for generating reliable and visually coherent results, which are essential for the practical utilization of multiple satellite images.

Image transformation for relative geometry correction has been mainly described as image-to-image transformation such as affine transformation model and 2D homography. In our proposed rigorous block adjustment method, we refine the adjustment parameters of the RFM and adjust the ground coordinates of the tie-points. As a result, image transformation can be achieved by re-projecting the original images onto an orthogonal plane in a 3-dimensional space. To enable this 3-dimensional re-projection, it is necessary to define a 3D object space which we refer to as, virtual Digital Elevation Model (DEM), that serves as the reference for the re-projection process. To generate a virtual DEM, we utilized the ground coordinates of the adjusted tie-points and applied Inverse Distance Weighting (IDW) interpolation. IDW is a spatial interpolation method used to estimate values at unmeasured locations based on the weighted average of neighboring points, where the weights are inversely proportional to their distances from the target location. The formula for IDW shown as Equation (8). The IDW interpolation technique allowed us to estimate the elevation values at unsampled locations, creating a continuous representation of the terrain surface. By utilizing the adjusted tie-point information, we were able to generate a virtual DEM that accurately reflected the elevation variations across the study area.

$$Z' = \frac{\sum w_i \cdot z_i}{\sum w_i} \quad (6)$$

where

$$w_n = \frac{1}{distance^{power}}$$

$Z'$ represents the estimated height value at the target location, $z_i$ is the height value at the neighboring location. $distance$ is the distance between target and neighboring locations. $power$ is a power parameter that controls the influence of the neighborinbg points on the estimation.

### 2.4 Image Transformation with Refined RFM

For the generate result image of relative geometric correction of satellite images, image transformation was performed by applying image resampling method based on the relationship between the image coordinates and ground coordinates expressed in Equation (1). Image resampling is a technique used to resize or geometrically transform an image. During the image resampling step, it is necessary to define which pixel values from the original image should be used for each pixel in the transformed image. In our proposed method, we utilized the refined RFM model to perform the image transformation. The pixel values at the transformed image coordinates were determined by applying bilinear interpolation using the neighboring image coordinates from the original image.

Figure 5 shows the process of generating the result image using the refined RFM and the virtual DEM. As shown in Figure 5, our proposed method utilizes an inverse projection-based image resampling, where the resampling area is predefined and discretized into a grid.

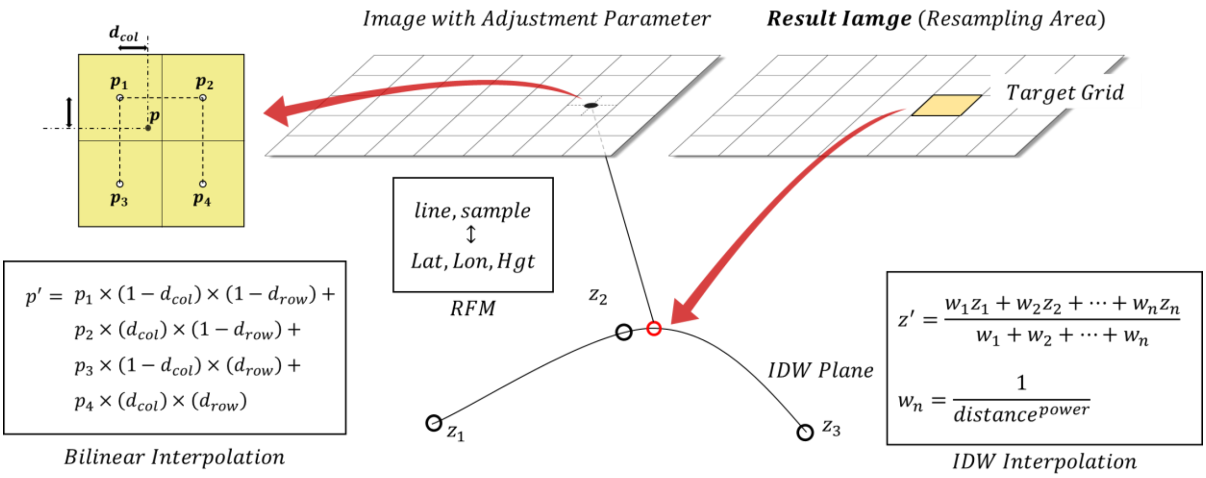


**Figure 5.** Image generation processing using Refined RFM and Virtual DEM with inverse projection


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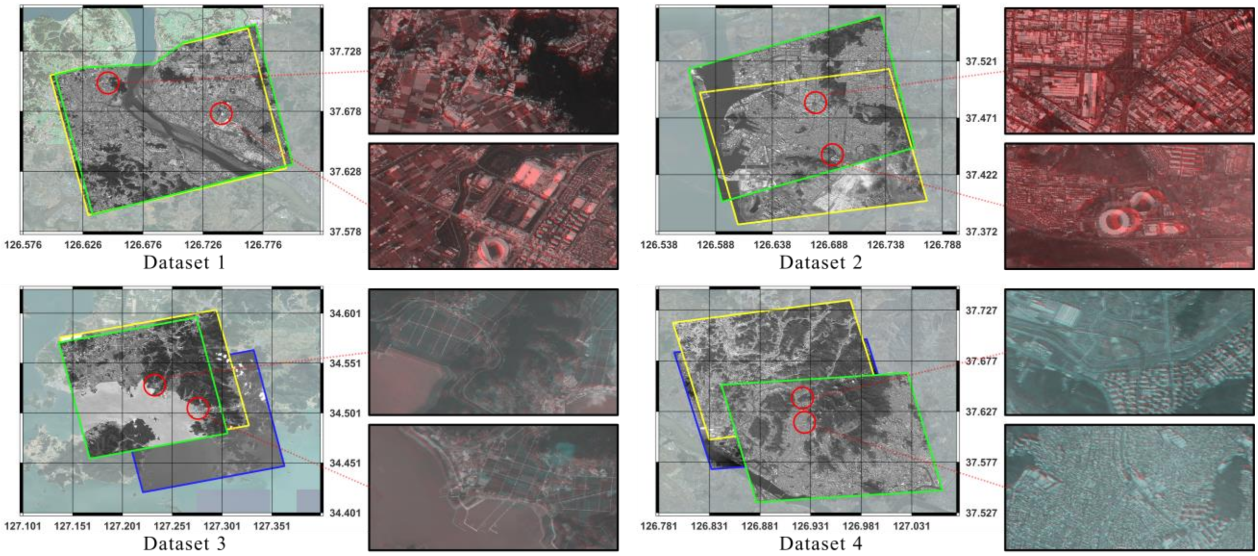


**Figure 6.** Locations and initial position error of used datasets

| Dataset | Date of Acquisition | Image Center Latitude | Image Center Longitude | Tie-point Number | Relative Error | Average BIE Angle | Average Convergence Angle |
|---|---|---|---|---|---|---|---|
| 1 | 2017.09.25 | 37.66915019 ° | 126.69710367 ° | 15,145 | 21.11 pixels | 58.64 ° | 3.48 ° |
| | 2017.10.30 | 37.67087524 ° | 126.70190406 ° | | | | |
| 2 | 2018.01.19 | 37.49371647 ° | 126.65767617 ° | 6,026 | 7.93 pixels | 62.21 ° | 22.05 ° |
| | 2018.01.27 | 37.47981407 ° | 126.66328898 ° | | | | |
| 3 | 2016.04.15 | 34.52600519 ° | 127.22197921 ° | 2,302 | 29.93 pixels | 80.28 ° | 16.37 ° |
| | 2016.08.19 | 34.49221006 ° | 127.27716224 ° | | | | |
| | 2016.12.31 | 34.53259921 ° | 127.23400772 ° | | | | |
| 4 | 2016.01.08 | 37.59898370 ° | 126.95392817 ° | 8,210 | 27.92 pixels | 59.52 ° | 16.30 ° |
| | 2017.02.15 | 37.63303289 ° | 126.91200926 ° | | | | |
| | 2017.02.24 | 37.66738170 ° | 126.90280595 ° | | | | |

**Table 1.** Properties of used datasets

## 3. EXPERIMENT

For the experiments, we constructed the datasets using multiple high-resolution satellite images obtained from the KOMPSAT-3A satellite. Each dataset consists of two or more images and is designed to have overlapping areas for tie-point extraction. The images were carefully selected to cover different geographical regions and capture various environmental conditions. Table 1 shows the properties of the KOMPSAT-3A image dataset used in these experiments. Figure 6 visually presents the satellite images used in our experiments, providing information on their actual locations, overlapping area. All satellite images used in the experimetns were processed at Level 1R, which involved radiometric and sensor distortion correction. It is worth noting that the experimental datasets initially exhibited significant relative errors, with an average of 21.73 pixels between the images within each dataset. The errors ranged from a minimum of 7.93 pixels to a maximum of 29.93 pixels.

To validate the performance of our proposed method, we established check points for each dataset. In the case of our relative geometric correction, the check points were not based on actual ground coordinates but rather visually identified corresponding points on the images. The extracted check points are used to calculate the re-projection error using the refined RFM. To calculate the re-projection error, the image coordinates are projected onto the ground, and then the projected ground coordinates are back projected onto another image. However, the RFM model, which interprets the relationship between image coordinates (2D) and ground coordinates (3D) in a homogeneous coordinate system, can only interpret the directionality from the image coordinates. Without an actual terrain model, direct projection onto ground is not possible. To address this, we utilized a pre-generated virtual DEM.

As shown in Table 1, we performed block adjustment using only tie-points for the four datasets. Table 2 presents the experiment results. The presented errors in Table 2 primarily focus on the reprojection error. The errors are further divided into two categories: the model error, which evaluates how well the sampled tie-points adhere to the model estimated using tie-points, and the check error, which represents the reprojection error of the extracted check points. Additionally, to provide further analysis of the performance of the proposed method, the error of the homography transformation model, which defines the transformation of the image in 3D space, is also presented. Since the height values of the actual points are not known, we used the "Height Offset" value in the initial metadata of the satellite image as a reference height to calculate the initial reprojection error of the check points.


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| Dataset | Tie-point Number | Initial Check Error | 2D homography | | Proposed Method (Rigorous Block Adjustment) | |
|---|---|---|---|---|---|---|
| | | | Model Error | Check Error | Model Error | Check Error |
| 1 | 15,145 | 21.11 pixels | 0.80 pixels | 0.91 pixels | 0.62 pixels | 0.71 pixels |
| 2 | 6,026 | 7.93 pixels | 3.66 pixels | 5.61 pixels | 0.32 pixels | 1.03 pixels |
| 3 | 2,302 | 29.93 pixels | 1.06 pixels | 1.03 pixels | 0.39 pixels | 0.70 pixels |
| 4 | 8,210 | 27.93 pixels | 3.93 pixels | 3.82 pixels | 0.37 pixels | 1.03 pixels |

**Table 2.** Relative geometric correction result with 2D homography and proposed method

As shown in Table 1, we performed block adjustment using only tie-points for the four datasets. Table 2 presents the experiment results. The presented errors in Table 2 primarily focus on the reprojection error. The errors are further divided into two categories: the model error, which evaluates how well the sampled tie-points adhere to the model estimated using tie-points, and the check error, which represents the reprojection error of the extracted check points. Additionally, to provide further analysis of the performance of the proposed method, the error of the homography transformation model, which defines the transformation of the image in 3D space, is also presented. Since the height values of the actual points are not known, we used the "Height Offset" value in the initial metadata of the satellite image as a reference height to calculate the initial reprojection error of the check points.

The result of the proposed method showed a model error ranging from a minimum of 0.32 pixels to a maximum of 0.62 pixels. In contrast, the model error of the homography transformation model ranged from a minimum of 0.80 pixels to 3.93 pixels. For the check error, the proposed method showed an average of approximately 0.87 pixels, with a minimum of 0.70 pixels and a maximum of 1.03 pixels. On the other hand, the homography model exhibited a check error of around 1 pixel for datasets 1 and 3, but for datasets 2 and 4, it showed higher values of 5.61 pixels and 3.82 pixels, respectively. These results indicate that the homography only estimates a single transformation model based on image coordinate alone, which does not adequately account for terrain relief errors present between the images.

The result of the relative geometric correction was obtained by applying the proposed rigorous block adjustment method and using the refined RFM with a virtual DEM. Figure 7 shows the images transformed using adjustment parameters estimated after the proposed method. As shown in Figure 7, when projecting the satellite images onto the ground using the unadjusted initial RFM, there are noticeable relative positioning errors present in all the datasets. To confirm that the initial error was corrected properly, the result image was enlarged for each dataset, and then the continuity of the object identified in the image was compared. The proposed block adjustment method successfully mitigated the positional errors of the initial RFM, resulting in improved alignment and coherence of the objects across the images, as demonstrated in Figure 7.

## 4. CONCLUSION

This paper proposed a method to solve the important problem of relative geometric correction of multiple satellite images. The proposed block adjustment method, which utilizes tie-points only, offers a solution to the complex process of adjusting errors in multiple images without precise ground control points. By establishing a mathematical model that defines the relationship between ground and image coordinates, our method achieves a high level of modelling accuracy through the iterative estimation of optimal weights. Experimental results using KOMPSAT-3A images with a 50 cm ground sampling distances demonstrated an average relative positional accuracy of 0.87 pixels.

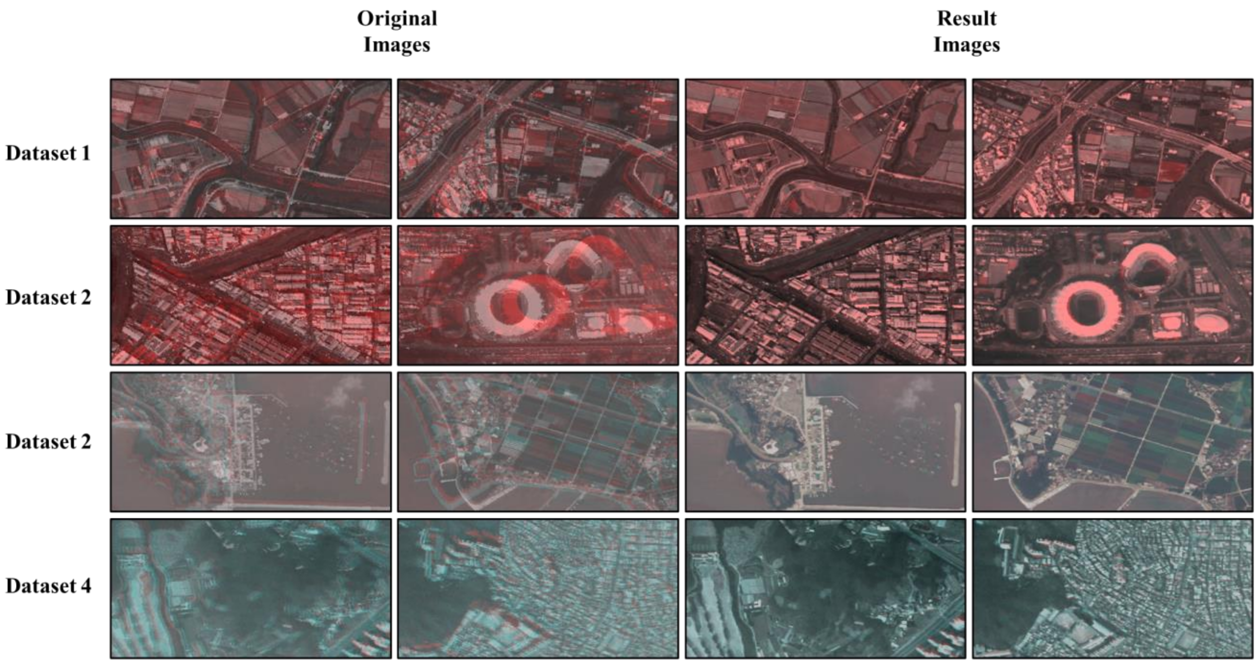


**Figure 7.** Result of relative geometric correction with proposed method

The corrected satellite images exhibit reduced discontinuity and improved alignment, enabling more reliable and accurate spatial analysis and interpretation. By accurately aligning multiple satellite images, our method could enhance the usability and utility of satellite imagery in various applications such as environmental monitoring, land cover mapping and analysis between heterogenous satellite images.

In conclusion, the proposed rigorous block adjustment method based on tie-points could provide a robust and efficient solution for relative geometric correction in multiple satellite images. With tie-points and refining the RFM parameters, our method effectively corrects the initial position errors and improves the overall accuracy and alignment of the images. This research would contribute to the advancement of satellite image processing and enables more accurate and reliable analysis of Earth observation data.

## ACKNOWLEDGEMENT

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