PRECISE MAPPING OF HIGH RESOLUTION SATELLITE IMAGES WITHOUT GROUND CONTROL POINTS

Taejung Kim *, Jaehoon Jeong

[a] Department of Geoinformatic Engineering, Inha University, 253 Yonghyun-Dong, Namgu, Incheon Korea
tezid@inha.ac.kr, Jung2174@inhaian.net

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ABSTRACT:

As one way of removing the requirement of ground control points (GCPs) for precise mapping of high resolution satellite images (HRSIs), this paper proposes to use existing low-resolution elevation dataset. We adapted DEM matching technique, originally proposed to solve absolute orientation of aerial images from perspective sensors, for establishing absolute orientation of HRSIs from pushbroom sensors without GCPs. We used a SPOT-5 stereo pair with the resolution of 2.5m and DTED level 2 data with grid spacing of 30 m for experiments. First, we established relative orientation for the pair. We showed that conventional relative orientation methods with tiepoints were not applicable to pushbroom-type images due to the intrinsic property of pushbroom geometry. We proposed to use pseudo GCPs, the artificial control points generated using existing elevation data and initial geometric models available from the satellite metadata, for relative orientation. Then, we proposed mathematical formulation of DEM matching for pushbroom images. From the image pair with relative orientation established, tiepoints and their 3D model coordinates were automatically generated. These were matched against the DTED level 2 data and the transformation between the model space and the object space was retrieved. We showed that by applying this transformation to the image pair we can establish absolute orientation of the left and right images. The major contribution of this paper is that we applied DEM matching to pushbroom images and that we verified the applicability of the existing elevation dataset available worldwide for precisely mapping HRSIs without external GCPs.

1. INTRODUCTION

In order to generate precise large scale maps from high resolution satellite images (HRSIs), it is necessary to reconstruct accurate geometric relationship between the image space and the object space. Traditionally, this task is performed by using ground control points (GCPs), the points with known ground coordinates, and measuring their corresponding image coordinates. The accuracy of the ground and image coordinates of GCPs governs the accuracy of map products of satellite images. In many applications, significant efforts are dedicated to acquire GCPs with sufficient accuracy. However, this GCP requirement makes the overall applications costly and time consuming. Moreover, there are areas or situations where GCPs of sufficient accuracy cannot be retrieved.

Due to these reasons, ways to alleviate the necessity of GCPs have been explored. Previously acquired GCPs were maintained and reused to solve geometric relationship of new images (Kim and Im, 2003). For aerial images additional sensors, such as GPS receivers and INS, were installed within imaging devices. Satellite platforms are equipped with more advanced sensors to provide accurate orbit and attitude information, often with more diligent ground operations to maintain high accuracy of satellite orbit prediction (Baudoin, 2004).

While the advancement of sensor or platform technologies can ease the requirement of GCPs, these technologies may not be sufficient to meet accuracy requirements of large scale maps. Nor they can contribute to reduce the overall mission costs. We argue that we still need to seek for photogrammetric approaches to precisely map HRSIs without GCPs. In this paper, we aim to achieve this goal by using existing low-resolution elevation dataset available globally.

DEM matching was proposed to replace the need of external control points with existing digital elevation models (DEMs) (Ebner and Strunz, 1988). DEM matching was originally proposed and has been demonstrated to solve absolute orientation of aerial images with perspective geometry (Rosenholm and Torlegard, 1988; Ebner et al., 1991; Ebner and Ohlhof, 1994). DEM matching technique was further extended to solve the problem of registration of 3D objects (Gruen and Akca, 2005). In this paper, we applied DEM matching to solve absolute orientation of HRSIs with pushbroom geometry. DEM matching in our case is still challenging. DEM matching has not been applied to HRSIs with pushbroom geometry. The resolution of images we are using (a few meters or finer) is much finer than that of the DEMs available (30m). The DEMs we use are not perfect but with many blunders and errors. In order to apply DEM matching, we first need to establish the relative orientation between image pairs, which is not a trivial process for pushbroom images.

We used a SPOT-5 stereo pair with the resolution of 2.5m and DTED level 2 data with grid spacing of 30 m for experiments. First, we established relative orientation for the pair. We will show that conventional relative orientation methods with tiepoints were not applicable to pushbroom-type images due to the intrinsic property of pushbroom geometry. We propose the concept of pseudo GCPs, the artificial control points generated using existing elevation data and initial geometric models

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* Corresponding author.

available from the satellite metadata. We will show how to construct and use pseudo GCPs for relative orientation. Then, we propose mathematical formulation of DEM matching for pushbroom images. From the image pair with relative orientation established, tiepoints and their 3D model coordinates will be automatically generated. These will be matched against the DTED level 2 data and the transformation between the model space and the object space will be retrieved. We will show that if we apply this transformation to the relative orientation models of the image pair we can establish absolute orientation of the left and right images.

The major contribution of this paper is that we applied DEM matching to pushbroom images and that we verified the applicability of the existing elevation dataset available worldwide for precisely mapping HRSIs without external GCPs.

2. DATASET USED

For experiments, a SPOT-5 stereo pair over Daejeon, Korea was used. See figure 1 for the left and right images and table 1 for their characteristics. GCPs for the pair were acquired by differential GPS measurements. They were used to check the accuracy of absolute orientation through the proposed method.

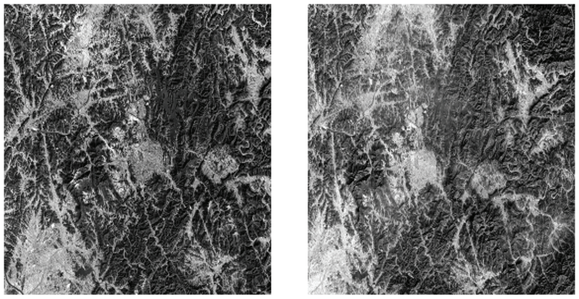

Figure 1. The SPOT-5 image pair used.

Table 1. The characteristics of SPOT-5 images

ID	Left	Right
Sensor	SPOT-5	SPOT-5
Spatial Resolution	2.5 m	2.5 m
Date of Acquisition	20 Dec 2003	11 Dec 2003
Tilt angle	18.49°	-25.53°
No. of GCPs	18	18

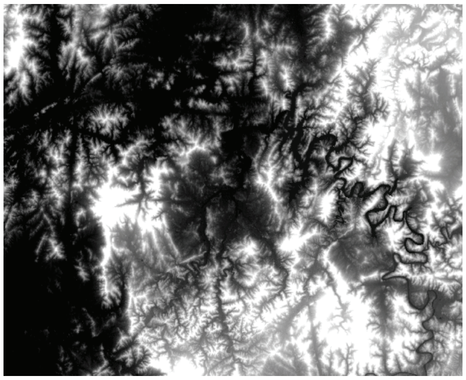

Figure 2. DTED level 2 data over Daejeon

For elevation dataset, DTED level 2 dataset over Daejeon area was used. Figure 2 shows the portion of DTED level2 dataset over the extent of the SPOT-5 images. Table 2 shows the technical specification of DTED level 2 data (NIMA, 2000). Note that the resolution of the DTED level 2 data (30m) is significantly coarser than that of SPOT-5 images used (2.5m). Also note that the horizontal and vertical error of the DTED level 2 dataset is also very large compared to the resolution of images used.

Table 2. The characteristics of the DTED level 2 data used.

DTED level	2
Datum	WGS84
Grid Spacing	1″ x 1″
Resolution	30 m
Horizontal accuracy (90% CE)	23m
Vertical accuracy (90% LE)	18m

3. RELATIVE ORIENTATION

In this paper, we used a rigorous sensor model to represent the geometric relationship between the object space and HRSIs. The following matrix equations were used (Kim and Dowman, 2006) for the left and right images.

$$\begin{pmatrix} X - X_S \\ Y - Y_S \\ Z - Z_S \end{pmatrix} = \lambda \mathbf{R}_{pv} \mathbf{R}_{rpy} \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} \tag{eq. 1}$$

where (X,Y,Z) the ground coordinates, (u_x, u_y, u_z) the coordinates of a look vector at a sensor frame, $\mathbf{R}_{pv}$ a rotation matrix defined by satellite position and velocity, $\mathbf{R}_{rpy}$ a rotation matrix defined by satellite attitude angles (roll, pitch and yaw) and λ a scale factor.

For relative orientation, we adjust orientation parameters of the right image so that a left look vector, right look vector and the base vector are coplanar. Depending on the modelling approach, one may choose the parameters to adjust (Kim and Dowman, 2006; Kim et al., 2007). Here, we chose to adjust position biases, drifts and attitude biases (Kim and Dowman, 2006).

In the conventional approach for relative orientation, one selects tiepoints, left and right images points corresponding to the same object points, and then adjusts orientation parameters using tiepoints through least squares estimation. However, in our previous experiments, this approach failed. When we used tiepoints only to adjust orientation parameters of the right image to meet the coplanar conditions, the solution diverged. Solution diverged with different orientation parameter sets. We also could not achieve relative orientation with collinear conditions. The reason was due to the intrinsic property of pushbroom images. As mentioned before, relative orientation is established when each tiepoint (or their object point) and the left and right projection centers constitute a triangle. For a number of tiepoints, the same number of triangles can be defined. For perspective images, all of these triangles share the same side, the side defined by the base vector. Relative orientation is the process of finding the base vector and orientation angles of the right image to best constitute triangles for given tiepoints. However, for pushbroom images, there is a separate base vector for each tiepoint. And moreover base vectors are almost parallel to each other and so are all triangles. Due to this property, relative orientation process with multiple tiepoints is analogous to use only one tiepoint for establishing relative orientation. One cannot define unique orientation parameters that meet the coplanar condition. Detailed results and analysis on this issue are to be reported elsewhere.

To solve relative orientation in this situation, we introduced the concept of ‘pseudo GCPs’ and devised the following procedures. From the satellite metadata provided with images, we can establish initial geometric models. Using initial models, we can calculate the positions of left image points for any ground points (X,Y,Z) acquired from the existing elevation dataset. Next, we can observe the positions of right image points that correspond to the left image points. We define the right image points and the ground points as pseudo GCPs. Using these pseudo GCPs, we adjust orientation parameters of the right image.

The concept of pseudo GCPs is illustrated in Figure 3. Figure 3 shows the left and right subimages for the same ground surface. The center of each subimage is the correct location for an object point (X,Y,Z) measured from DGPS surveying. The point A in each subimage is the image location of the object point (X,Y,Z) calculated by the initial geometric models. Due to the inaccuracy of initial models, they appear at different locations in the left and right subimages. Since we will not use GCPs, it is not possible to know the true image location for the point A. However, we can measure the image location of the right image that corresponds to the point A in the left image. We define the new right image points observed as pseudo GCPs for adjusting orientation parameters for the right image.

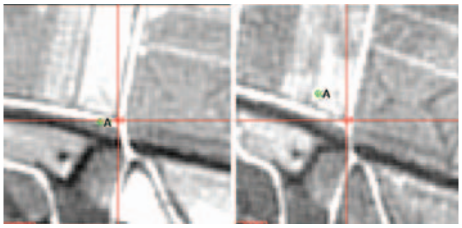

Figure 3. The concept of pseudo GCPs

From the DTED level 2 dataset, 50 object points were selected and 50 pseudo GCPs were generated as explained before. 30 pseudo GCPs were used for relative orientation and 20 used to check the accuracy of relative orientation. Table 3 shows the accuracy of initial geometric models and the relative models for the left and right images. The first two lines are results compared against true GCPs. The first line shows that the initial left and right model had errors in different magnitude and direction to each other. The second line shows that after relative orientation using pseudo GCPs, the accuracy of right model became similar to the left one. Note that only the right model is updated after relative orientation and that the accuracy of the left model remains unchanged. The last line is the accuracy checked against the 20 pseudo GCPs that were not used for adjustment. Using the updated model, we calculated the positions of right image points for given pseudo GCPs and compared them against the image point coordinates of the pseudo GCPs. There should be no Y parallex after relative orientation. The last line shows that Y parallex has been successfully removed.

Table 3. Accuracy of initial and relative models

	Left Error (pixel)			Right Error (pixel)		
	Col	Row	Mag.	Col	Row	Mag.
Initial model	6.10	1.47	6.27	9.28	7.86	12.16
Relative model	6.10	1.47	6.27	5.13	1.63	5.38
Relative model	-	-	-	1.54	1.01	1.84

Figure 4 shows the DEMs generated from automated stereo matching developed in-house (Lee at el., 2003) using the relative orientation models. Figure 3 supports that even though the model is not absolute, satellite epipolarity (Kim, 2000) has been recovered correctly through the proposed relative orientation procedures.

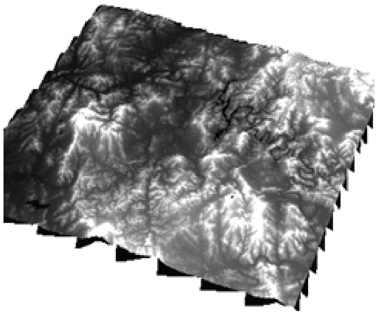

Figure 4. DEMs generated from relative models

4. DEM MATCHING AND ABSOLUTE ORIENTATION

Firstly, we will explain mathematical formulation of DEM matching for perspective images as originally proposed by (Ebner and Strunz, 1988). The relationship between two DEMs (or two 3D frames) can be defined by the 3D similarity transformation as below.

$$\begin{pmatrix} X \\ Y \\ H \end{pmatrix} = s\mathbf{R}\begin{pmatrix} x \\ y \\ h \end{pmatrix} + \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta H \end{pmatrix} \qquad \text{(eq. 2)}$$

where (X,Y,H) is the coordinates of a 3D point in an absolute coordinate (or in the absolute DEM), (x,y,h) the coordinates of a 3D point in a relative DEM, R a rotation matrix, (Δ X,Δ Y,Δ H) a shift between the two DEMs and *s* a scale factor. Let (x_k, y_k, h_k) be the k-th point in the relative DEM and $(\hat{X}_k, \hat{Y}_k, \hat{H}_k)$ the estimate of the k-th point in the absolute DEM using the above similarity transformation. The height difference v_k between the estimate and the actual point on the absolute DEM is

$$v_k = \hat{H}_k - H\left(\hat{X}_k, \hat{Y}_k\right), \qquad \text{(eq. 3)}$$

where *H(.)* is the height of a point on an absolute DEM.

DEM matching is the problem of adjusting the parameters for similarity transformation; s, Δ X,Δ Y,Δ H and rotation angles for R to minimize the sum of squares of height differences. Since this is a non-linear adjustment problem, the equation is linearized as below.

$$v_k = \hat{H}_k - H\left(\hat{X}_k, \hat{Y}_k\right) + dH_k - \frac{\partial H\left(\hat{X}_k, \hat{Y}_k\right)}{\partial X} dX_k - \frac{\partial H\left(\hat{X}_k, \hat{Y}_k\right)}{\partial Y} dY_k$$

where *dX*, *dY*, and *dH* are calculated based on eq. 2.

Next, we derive mathematical formulation for DEM matching for pushbroom images. For linear pushbroom images, the relationship between a relative and absolute frame can be derived as follows. Let eq. 1 be the relationship between the image points (u_x, u_y, u_z) and ground points (X,Y,Z) in a relative frame and the following equation be the relationship between the image points (u_x, u_y, u_z) and the ground points (X', Y', Z') in an absolute frame.

$$\begin{pmatrix} X' - X'_S \\ Y' - Y'_S \\ Z' - Z'_S \end{pmatrix} = \lambda' \mathbf{R}'_{pv} \mathbf{R}'_{rpy} \begin{pmatrix} u_x \\ u_y \\ u_z \end{pmatrix} \qquad \text{(eq. 4)}$$

Using eqs. 1 and 4, the following relationship holds between the relative and absolute frames for linear pushbroom images.

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = \frac{\lambda'}{\lambda} \mathbf{R}'_{pv} \mathbf{R}'_{rpy} \mathbf{R}^T_{rpy} R^T_{pv} \begin{pmatrix} X - X_S \\ Y - Y_S \\ Z - Z_S \end{pmatrix} + \begin{pmatrix} X'_S \\ Y'_S \\ Z'_S \end{pmatrix} \qquad \text{(eq. 5)}$$

The above equation can also be generalized as the similarity transformation in eq. 2. Therefore, we proved that the relationship between the relative and absolute DEMs for pushbroom images can be represented as a 3D similarity transformation.

However, the solution for eq. 3 has to be modified for pushbroom images taken from the satellites. Unlike perspective images, we use earth-centered coordinate frames for satellite images. DEM matching for earth-centered coordinate frames is linearized as below.

$$\begin{aligned} v_k = \hat{H}_k - H\left(\hat{X}_k, \hat{Y}_k\right) + \frac{dH_k}{dX} dX_k + \frac{dH_k}{dY} dY_k + \frac{dH_k}{dZ} dZ_k \\ - \frac{\partial H\left(\hat{X}_k, \hat{Y}_k\right)}{\partial X} dX_k - \frac{\partial H\left(\hat{X}_k, \hat{Y}_k\right)}{\partial Y} dY_k - - \frac{\partial H\left(\hat{X}_k, \hat{Y}_k\right)}{\partial Z} dZ_k \end{aligned}$$

Using the above formulation, DEM matching for pushbroom images was implemented. DEM matching was applied between the relative DEM shown in figure 4 and the DTED level2 dataset. From the relative DEM, 255 grid points were extracted. The quality of these grid points were visually checked by comparing their locations on the left and right images and by comparing their locations on the DTED level2 dataset. Among the 255 points 44 were found to be erroneous due to mismatch and removed.

The 211 grid points were used for DEM matching and the parameters for 3D similarity transformation were adjusted. The values converged were as below.

$$s = 0.99916, \omega = -1.0888 \times 10^{-6\circ}$$

$$\varphi = 8.1179 \times 10^{-6\circ}, \kappa = 7.3265 \times 10^{-6\circ}$$

$$\Delta X = 440.62m, \Delta Y = 664.89m, \Delta Z = 473.11m$$

We further proved whether the DEM matching process implemented was successfully converted relative orientation models into absolute orientation models. This was done by updating the left and right relative models by the 3D similarity transformation equations estimated through DEM matching. We checked the accuracy of the updated models with true GCPs. For this purpose, we derived mathematical formulation on how to update pushbroom models using 3D similarity transformation. Assume that eq. 1 is for relative orientation of the left image and eq. 2 has been achieved after DEM matching. We can update the image sensor model by combining the eqs. 1 and 2 together as below

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = s\mathbf{R}\lambda^L \mathbf{R}^L_{pv} \mathbf{R}^L_{rpy} \begin{pmatrix} u^L_x \\ u^L_y \\ u^L_z \end{pmatrix} + s\mathbf{R} \begin{pmatrix} X^L_S \\ Y^L_S \\ Z^L_S \end{pmatrix} + \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}$$

where the superscript *L* denotes parameters for the left image. New platform position of the left image can be updated as below

$$\begin{pmatrix} X'^L_S \\ Y'^L_S \\ Z'^L_S \end{pmatrix} = s\mathbf{R} \begin{pmatrix} X^L_S \\ Y^L_S \\ Z^L_S \end{pmatrix} + \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}.$$

New attitude angle of the left image can be determined from the new rotation matrix as below

$$\mathbf{R}'^L_{rpy} = \left(\mathbf{R}'^L_{pv}\right)^T \mathbf{R}\mathbf{R}^L_{pv} \mathbf{R}^L_{rpy}$$

where $\left(\mathbf{R}'^L_{pv}\right)^T$ is the transpose of the rotation matrix defined by the updated platform position and velocity vector.

The platform position and attitude are updated using the triangular relationship between the left look vector $\vec{l}$, right look vector $\vec{r}$ and the base vector $\vec{B}$:

$$\vec{B}' = \begin{pmatrix} X'^R_S - X'^L_S \\ Y'^R_S - Y'^L_S \\ Z'^R_S - Z'^L_S \end{pmatrix} = s\mathbf{R} \begin{pmatrix} X^R_S - X^L_S \\ Y^R_S - Y^L_S \\ Z^R_S - Z^L_S \end{pmatrix}.$$

Similar to the left image case, the attitude of the right image can be updated as below

$$\mathbf{R}'^R_{rpy} = \left(\mathbf{R}'^R_{pv}\right)^T \mathbf{R}\mathbf{R}^R_{pv} \mathbf{R}^R_{rpy}.$$

Table 4 shows the accuracy of absolute models acquired by updating the relative models with the similarity transformation. The accuracy of initial and relative models was also included for comparison. As before, 19 GCPs measured by DGPS surveying were used for accuracy check. The left and right models were successfully updated to have the pointing accuracy of round two pixels or better for the both images.

Table 4. Accuracy of absolute models

	Left Error (pixel)			Right Error (pixel)		
	Col	Row	Mag.	Col	Row	Mag.
Initial model	6.10	1.47	6.27	9.28	7.86	12.16
Relative model	6.10	1.47	6.27	5.13	1.63	5.38
Absolute model	0.56	1.06	1.20	1.40	1.58	2.12

Table 5 shows the accuracy of absolute models in 3D coordinate determination. Table 5 verified that the absolute models estimated in this way, 3D coordinates can be determined at the accuracy of around 4 meters or better without employing any GCPs. Compared to the spatial resolution of the DTED level2 dataset used for the experiments, the accuracy of absolute models achieved are remarkable.

Table 5. Accuracy of absolute models in 3D object space

	Horizontal Error (m)	Vertical Error (m)
Absolute model	3.91	4,35

5. CONCLUSIONS

This paper proposed to use existing low resolution elevation dataset to solve orientation problems of high resolution satellite images. We used a SPOT-5 stereo pair at 2.5m resolution as examples of high resolution images and a DTED level2 dataset at 30m resolution as examples of low resolution elevation dataset.

Firstly, we pointed out that relative orientation for pushbroom images cannot be established by tiepoints only and proposed new relative orientation procedures using the existing elevation dataset. We verified the validity of the proposed relative orientation process in various ways.

Then, we proposed mathematical formulation for DEM matching for pushbroom images and updating pushbroom sensor models from DEM matching. We verified that DEM matching applied in this formulation can establish absolute orientation of the left and right images in a rigorous way. It was possible to establish geometric model by the proposed method with a planemetric error better than 4 meters and a vertical error better than 5 meters from SPOT-5 images with the resolution of 2.5 meters.

The contributions of this paper include that we proved theoretically and experimentally that DEM matching can be used for mapping pushbroom images without GCPs. Digital elevation models with moderate grid spacing of 30 meters or better are available worldwide. The results of this paper indicate that it is possible to map high resolution satellite images without GCPs at the global scale.

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