Results on the Refinement of DEM Using Iteratively Generated Orthoimage from SPOT Stereo pairs

SPOT 衛星画像の反復処理によるオルソ画像を利用した
digital elevation modelの作成

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Abstract: Iterative Orthophoto Refinement (IOR) approach is based on the assumption that left and right orthophotos, generated from the same source of DEM, should be identical. It is an efficient process not only to correct or refine existing DEMs but also to generate a new DEM. In this study we adopted and modified the original IOR concept used in the aerial photographs and applied the method to a pair of stereo SPOT images. Experiments were conducted to refine two existing DEMs (DTED Level 1 and SPOT-derived DEM) using IOR approach. Results showed that 2 or 3 iterations were enough to refine existing DEMs to meet the criteria of positional accuracy.

1. Introduction

Automatic DEM (Digital Elevation Model) extraction process has been widely implemented on most of current digital photogrammetric systems. The digital approach has much more benefits in producing DEM through the digital correlation matching techniques than manual process. Correlation method, however, may contain many sources of matching errors if the images have undetectable features, repeated micro structures, linear edges, and so on (Lemmens, 1988). Also these errors may be significant especially when the geometric and radiometric conditions of stereo images are quite different. These error sources lead not only to degrade DEM accuracy, but also to require correction procedure for the mismatched parts in the post-processing. DEM editing is very labor-intensive work, since this has been generally conducted by the operator using the computer or analytical stereo-plotter. Therefore, automatic error correction technique has been strongly desired to reduce the...
Many studies related to DEM correction have been done mainly in the field of the aerial photography. In order to correct DEM effectively and quickly, Schenk (1989) proposed the DEM generation using iteratively rectified images. Norvelle (1996) used Iterative Orthophoto Refinement (IOR) approach to correct elevations. Lobonc (1996) provided the theoretical and computational background for elevation correction. He demonstrated the practical aspect of IOR using GDE DPW 750 with aerial photographs. Since SPOT satellite imagery has quite different geometric and radiometric characteristics from aerial photos, we may need to consider other approaches to correct SPOT-derived DEM. Especially, when a user wants to generate a dense DEM (about 2 pixel post interval) using SPOT-PAN image, it is difficult to effectively eliminate the blunders created during the image matching processes.

In this study, we modified 3D modeling and orthoimage generating procedure in the aerial IOR concept and applied them to the spaceborne SPOT imagery. To do this, left and right SPOT orthoimages were generated from the stereo-pairs using the existing DEM by digital differential rectification approach. Iterative orthoimage matching was applied to calculate the parallaxes that were used to correct elevation. Experiments were conducted on the test site (part of SPOT GRS 305-277) to demonstrate the feasibility of IOR for the refinement of an existing DEM and SPOT-derived DEM through iteration.

2. IOR Process

2.1 IOR Concept

IOR concept is based on the assumption that two (left and right) orthoimages, which are generated from the same source of DEM, should be identical. In this case we assume that there are no errors on the DEM caused by the errors in the ground control points and exterior orientation parameters. The accuracy of ground control points used in the study is about 5-10 m. This accuracy still can cause the positional errors in the resulting orthoimages. Therefore, orthoimages generated from left and right images may still have parallaxes due to errors in the exterior orientation parameters and errors in the height of source DEM.

To perform IOR, the amount of elevation correction should be computed considering the parallaxes between the pair of stereo orthoimages. The calculation is repeated until all the parallaxes are smaller than the predetermined threshold. The parallaxes between stereo orthoimage pairs result from two sources of errors. One is the error from 3-D modeling process. This kind of error is considered as a systematic error after 3-D modeling process, and thus cannot be eliminated. By regarding this, we decided to use the threshold value as the one which was greater than the errors from 3-D modeling (bundle adjustment) process.

Figure 1 schematically depicts the procedure for DEM refinement used in this study. First, the 3-D modeling (bundle adjustment) process is performed to compute exterior orientation parameters of input SPOT imagery. We used second-order polynomial equations for image acquisition time in the colinearity equation of SPOT scenes and the resulting equations can be written as follows:

\[
F(t) = 0 \\
+ \frac{m_{11}(X_i - X_{le})}{m_{31}} + \frac{m_{12}(Y_i - Y_{le})}{m_{32}} + \frac{m_{13}(Z_i - Z_{le})}{m_{33}} = 0 \\
G(t) = y_i \\
+ \frac{m_{21}(X_i - X_{le})}{m_{31}} + \frac{m_{22}(Y_i - Y_{le})}{m_{32}} + \frac{m_{23}(Z_i - Z_{le})}{m_{33}} = 0
\]

(1)

In Equation(1), f is the focal length and t is the acquisition time for a line (perpendicular to the flight direction). \( m_{is} \) represents the elements of the rotation matrix at time t. \( X, Y, Z \) are the ground coordinates, and \( X_{le}, Y_{le}, Z_{le} \) means the position of the exposure center at time t. Since the second-order polynomial function was used to represent...
Figure 1. Iterative DEM refinement procedure

Each orientation parameter, for example, $X_L$, could be expressed as follows.

$$X_L = X_0 + X_1 t + X_2 t^2$$

As a result of the above process, 18 newly introduced orientation parameters need to be computed.

Stereo orthoimage pairs are generated through the digital differential rectification process using SPOT stereo pairs and a source DEM is to be refined accordingly. The amount of correction for each DEM point is computed using the parallaxes between the two orthoimages. If all the corrected values for terrain heights are less than predetermined threshold, refinement steps are stopped not to perform further correction. If not, the refinement process is iteratively applied until the above condition is fully satisfied.

The threshold value to terminate the iteration procedure needs to be well defined and thus unnecessary iterations are not performed. Considering all aspects of the positional accuracy, it is reasonable to state that a DEM cannot be refined better than the 3-D modeling accuracy. We defined two forms of threshold values in the 3-D modeling of SPOT images by computing the CEP(Circular Error Probable) and LEP(Linear Error Probable) of the GCPs (Ground Control Points).

2.2 Orthoimage Generation

In order to generate an orthoimage by differential rectification, a source image, the results of 3-D modeling (exterior orientation parameters), and the DEM are required. Differential rectification can be done by the direct or indirect method dependent on the direction of coordinate transformation (Chen and Lee, 1993). We used the indirect approach to create orthoimage and the concept is depicted in Figure 2.

As shown in equation (1), $t$ can be computed for a given ground coordinate $(X, Y, Z)$. We used the Newton–Raphson method to compute the acquisition time corresponding to a given ground coordi-
Figure 2. Indirect approach for differential rectification

Acquisition time is computed repeatedly until $|t_{n+1} - t_n|$ is absolutely small relative to the precision using Equation 3.

$$t_{n+1} = t_n - \frac{F(t_n)}{F'(t_{n+1})}$$

Using the two image coordinates of left and right SPOT images, we computed the ground coordinates and calculated the image coordinates indirectly.

Those obtained image coordinates may not be the same as the original image coordinates due to the errors occurred during 3-D modeling. But once they are computed, one-to-one correspondence exists between the ground coordinate and the image coordinate space with Equation 1. Therefore, in ideal situation DEM as a result of the IOR process has only one error source caused by the error in 3-D modeling.

2.3 Elevation Correction

The relationship between the orthoimage matching error and the DEM error is depicted in Figure 3. Assume that a height error ($d_H$) exists between the DEM surface and true surface at ground location $P(X_L, Y_L)$. Due to this height error, true surface point $P$ can not be located at $(X_L, Y_L)$ on the orthoimage generated from left scene. Instead, surface point $Q'$ is appeared at $(X_L, Y_L)$ on it. Likewise, $Q'$ cannot be located at $(X_R', Y_R')$ on the orthoimage from right scene. It may be appeared at $(X_R, Y_R)$ instead. Therefore, when there exists a height error at a certain geographic location, the parallax

Figure 3. Relationship between DEM and orthoimage
caused by this height error also exists between the two orthoimages from left and right scenes. The height errors can be detected by observing these parallaxes. Furthermore, the height error at that location can be estimated with the amount of the parallaxes. In Figure 3, \( d_H \) should be computed for correcting the height error at ground position \( P \). Since the true terrain surface is not known, the height error of DEM at \((X_L, Y_L)\) is estimated using parallax between two ground points on orthoimages and the \( B/H \) (Base Height) ratio as follows.

\[
d_H = d_X \cdot \frac{H - Z_L}{B}
\]  

(4)

In Equation 4, \( d_H \) cannot be computed, since \( Z_L \) and \( d_X \) are also unknowns. So, we replaced \( d_H' \) as an estimator of \( d_H \), and the following computation was performed.

\[
d_H' = d_X' \cdot \frac{H}{B}
\]  

(5)

d_{X}' in Equation 5 represents the parallax between two ground points on stereo orthoimage pairs. Considering the nominal height of SPOT satellite, \( H - Z_L \) can be simplified as \( H \) because \( Z_L \) is negligible compared to \( H \). Furthermore, \( y \)-parallax is also negligible due to the acquisition mechanism of SPOT HRV (\( y \)-parallax is relatively much smaller than \( x \)-parallax). Performing all these processes stepwise, height errors on DEM can be repeatedly corrected using iteratively generated orthoimages as described in Figure 1.

3. Study area and Data Description

Study area (SPOT GRS 305-277) is about \( 10\text{km} \times 10\text{km} \) in the ground shown in Figure 4. Two types of DEMs were generated to conduct experiments, i.e., DEM 1 from the DTED Level 1 and DEM 2 from SPOT stereo pairs acquired in 1987.

DEM 1 was used to investigate whether coarse DEM could be refined into a finer DEM through IOR method. DEM 2 was used to figure out whether IOR approach could be applied to the existing sparse DEM. To test the feasibility of IOR process for DEM 2, another SPOT stereo pairs acquired in 1995 were used in the experiment. The characteristics of two sets of SPOT images are summarized in Table 1. DEM 2 was generated by automatic correlation matching with 5 pixel interval (Brockelbank, 1991).

A reference DEM was created by the analytical plotter using 1: 30,000 scale aerial photography with 5 m post spacing and resampled with 20m to use as a reference DEM.

4. Experiments

The positional accuracy of refined DEM was analyzed by covariance analysis using reference DEM. RMSE (root mean square error) for each

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<th>Usage</th>
<th>Main Characteristics</th>
<th>Left Image</th>
<th>Right Image</th>
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DEM spacing was calculated accordingly.

Parallaxes between the two orthoimages were also analyzed for each iteration. The parameters used for covariance analysis and orthoimage matching are given in Table 2. Two sets of stereo orthoimage were produced based on the DEM 1 and the DEM 2. For each set the x parallax was extracted to correct the each corresponding DEM. Results of iterative refinements of DEM 1 and 2 are shown in Figure 5 and 6. It can be easily identified that the distinct refinement were made as the iteration goes. The reduction of x parallax for each iteration process is also depicted in Figure 7 through Figure 10.

Table 2. Parameters for covariance analysis and orthoimage matching

<table>
<thead>
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<th>Parameters</th>
<th>Covariance Analysis</th>
<th>Orthoimage Matching</th>
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<td>interval</td>
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As shown in the pattern of parallaxes in Figure 7 and 9, most parallaxes were reduced to smaller than 1 pixel. Considering the 3-D modeling error is around 10m, the resultant accuracy after IOR could be considered to be close to the modeling accuracy. As shown in the above result, most parallaxes were gradually reduced to less than 1 pixel. This means that the errors of orthoimages due to the height errors of DEM are gradually eliminated so that the pair of orthoimages becomes identical through IOR process. As shown in Figure 8 and 10, both horizontal and vertical accuracies, i.e. CEP and LEP are generally improved by IOR process. As a result, we observed that 2 or 3 iterations were enough to refine
5. Conclusions

By performing experiments by applying the IOR approach to SPOT imagery, we could reach the following conclusions:

1) The accuracy and precision of SPOT derived DEM and DTED can be improved by applying IOR process. The possibility of improvement was demonstrated by implementing IOR for SPOT imagery.

2) IOR had little effects on the improvement of the DEM quality, when the quality of original DEM was sufficiently good. Actually, there existed relatively smaller changes in DEM quality by IOR for the DEM 2 than DEM 1.

3) If the time interval between two stereo images is big, various errors may be included during the image matching process. IOR approach, however, was effectively used to improve the resultant DEM quality. It was shown that IOR could be used as a tool for correction and/or refinement of DEM produced by the SPOT imagery.

References


