THE DEVELOPMENT OF AN ACCURATE DEM EXTRACTION STRATEGY FOR SATELLITE IMAGE PAIRS USING EPIPOLARITY OF LINEAR PUSHBROOM SENSORS AND INTELLIGENT INTERPOLATION SCHEME

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ABSTRACT

This paper describes a strategy to extract accurate Digital Elevation Models (DEMs) from satellite image pairs. In general, extracting DEMs consists of camera modeling, stereo matching, editing and interpolation. Because of the unique geometry and radiometric characteristics of satellite image pairs, methods developed for aerial or perspective image pairs cannot be applied. The proposed strategy employs a stereo matching algorithm taking the epipolarity of linear pushbroom sensors and scene geometry into account and an optimal interpolation scheme for satellite images. Using 100m-resolution Digital Terrain Elevation Data (DTED) by NIMA, USA and 60m-resolution DEM generated from digitized contours produced by National Geography Institute, Korea, we assess the performance of our strategy in comparison with other commercial software packages on two 60km×60km SPOT panchromatic stereo image pairs. Based on results, DEMs from our strategy have 25.5m RMS (Root Mean Squares) errors for Boryung area, Korea, and 33.6m for Seoul area, Korea, while DEMs from PCI have 44.7m and 61.1m, respectively and DEMs from Intergraph have 50.8m for Boryung area.

1 INTRODUCTION

The generation of Digital Elevation Models (DEMs) from remotely sensed images is an important task for various applications such as three-dimensional Geographic Information System (GIS), cell planning, environment monitoring, virtual reality and so on. DEMs from satellite images have several advantages over aerial images: 1) A scene covers large and restricted area. 2) Satellite images are a digital data so that the automation for extracting DEMs can be archived. 3) In recently, a number of remote sensing satellites have been launched and it is becoming easier to get in hands. Despite of these advantages, generating DEMs from satellite images suffers from shortcomings – accuracy, coverage and computation time (Lee *et al.,* 2000).

Extracting DEMs involves the following steps: camera modeling, stereo matching, editing and interpolation. Camera modeling is a step estimating the sensor position and orientation parameters during the seconds required to capture images. Stereo matching finds corresponding points in stereo image pairs (Lee *et al.,* 2000). The elevation data generated by camera models and corresponding points can be erroneous. In automatic editing, these errors are corrected using a statistical model (Kim *et al.,* 1999). After these steps, the elevation data do not provide a complete spatial coverage. A complete coverage may be obtained by interpolating scattered elevation data.

Ever since computers become available, many researchers have tried to generate DEMs automatically from satellite images. Brockelbank and Tam (1991) compares the techniques to extract accurate elevation information from SPOT stereo satellite images. Tateishi and Akutsu (1992) explains a method to produce a relative DEMs from SPOT image pairs without GCPs. AI-Rousan *et al.* (1997) tests and validates DEMs extraction module in PCI EASE/PACE system commonly used. However, in our opinion, most of these methods do not consider geometric and radiometric characteristics of satellite images or adapt the model for aerial or perspective images.

In this paper, we propose a DEM extraction strategy considering the geometric and radiometric characteristics of satellite images. A stereo matching algorithm based on epipolarity and scene geometry is used (Lee *et al.,* 2000) and an optimal interpolation scheme for satellite images are selected after various interpolation schemes are studied (Kim *et al.,* 1999). Adapting these two methods, robust and accurate extraction of DEMs can be achieved from satellite images.

In section 2, stereo matching based on epipolarity and scene geometry is described. Section 3 analyzes various interpolation schemes. In section 4, the quality of DEMs from our strategy is assessed using truth DEMs in comparison with other commercial software packages.

2 STEREO MATCHING BASED ON EPIPOLARITY AND SCENE GEOMETRY

2.1 Epipolarity of linear pushbroom sensors

Generally, epipolar geometry can be established in general stereo images and is a very useful clue in processing satellite images to improve processing time and accuracy. We have proved that there exists a unique epipolar geometry for linear pushbroom satellites that is different from that for perspective images (Kim, 1999). We have derived a epipolarity for linear pushbroom sensors based on Orun and Natarazan's (1994) camera model.

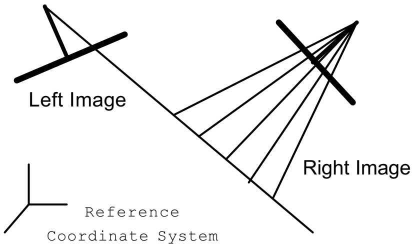

Figure 1. Epipolar geometry between stereo images.

Epipolar geometry can be described as follows: the identical point of one point in a left (or right) image lies on a unique curve in a right (or left) image. As shown in figure 1, suppose a beam of light is projected from a left camera center through a point on a left image. Each point lying on the beam can be uniquely mapped into a right image as a point. The points form a curve on a right image. The curve is defined as an epipolar curve and the equation of the curve derived from Orun and Natarazan's model is shown below (Kim, 1999).

$$y_r = \frac{A_1 x_l + A_2 y_l + A_3}{(A_4 x_l + A_5 y_l + A_6)\sin Q(x_r) + (A_7 x_l + A_8 y_l + A_9)\cos Q(x_r)}$$

where (x_l, y_l) and (x_r, y_r) are the coordinates of left and right image points, respectively, A_1~A_9 are parameters that can be acquired from the camera model and Q(x_r) is a quadratic polynomial of x_r (See Kim, 1999 for detail).

Even if the epipolar curve can be defined by a non-linear equation, it can be linearized in short segments (within 10~20 pixels) for computational efficiency (Kim, 1999). It means that the problem finding conjugate pairs can be converted to one-dimensional searching problem. This search space is called local support regions (Lee *et al.,* 2000). Eventually, the computation time can be minimized drastically and the accuracy can be increased.

2.2 Scene geometry

Because of the difference in incidence angles between a left and right image, unit areas on the ground are represented by patch with different sizes. In order to make similarity (or correlation) value calculated from two patches meaningful, patches in a left and right image should cover the same area on the ground. Taking these into account, patch shapes – patch ratio and patch rotation – based on scene geometry are carefully used.

Let us assume the geometry as shown in figure 2. Let "*a*" be the incidence angle in a left image and "*b*" be the incidence angle in a right image, then patch ratio can be represented as *Patchratio = cos(b)/cos(a)* (Lee *et al.,* 2000).

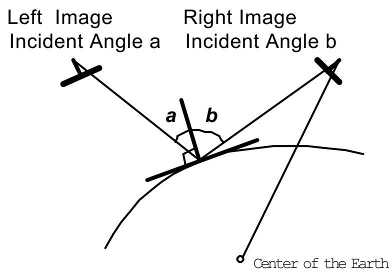

Figure 2. Scene geometry at image acquisition time.

In addition to that, different incidence angles make the orientation of a left and right image different from each other. For perspective images, the whole images are rotated to make the orientation of a left and right image identical. This process is called as "epipolar resampling". This process, however, cannot be applied to linear pushbroom images since epipolarity for such images are not represented by linear equations (Kim, 1999). For such images, individual patches shall be rotated to make the orientation of left and right patches identical (Lee *et al.,* 2000). Since we know epipolar curves in a left and right image, rotating a patch can be done easily by to make parallel to an epipolar curve (or line). If the slope of a epipolar line in a left image is L_a, the angle θ between epipolar line and column axis is $\theta = arctan(L_a)$. The rotation of a left patch can be represented by the following affine transformation.

$$X_{new} = \cos\theta * dx - \sin\theta * dy + X_o$$
$$Y_{new} = \sin\theta * dx + \cos\theta + dy + Y_o$$

where (X_o, Y_o) is the image coordinate of the center of a patch, (dx, dy) is the distance between the element in a patch and the center of a patch. The rotation of a right patch can be expressed similarly.

2.3 Stereo matching strategy

Matching starts from determining patch shapes and orientations described previous sections. For a given left patch, a right patch is defined at a point within a local support region and these two patches are compared each other to calculate a similarity value. The point having the highest similarity value is selected as a corresponding point for a given left point. We have employed a zero-mean normalized cross correlation for the similarity measure (Lee *et al.,* 2000).

For completeness of DEMs, it is required to match points well-distributed over stereo pairs. For this, a region growing approach is employed. Matching starts from initial seed points selected by a user or generated automatically from GCPs. These points are considered as match candidates and matching applies to one of them. When matched, its four neighbor points are considered as match candidates. Matching continues for other match candidates until there are no match candidates left. Through this region growing, it is possible to match entire scenes.

In summary, we now describe the stereo matching strategy based on epipolarity and scene geometry (Lee *et al.,* 2000)

1. Set up camera model of a left and right image using GCPs.
2. Select initial seed points.
3. Select a match candidate and find its epipolar curves in a left and right image.
4. Estimate a local support region and patch shapes based on epipolar curve and scene geometry
5. Find a maximum correlation point by calculating similarity values with respect to all points in a local support region in a right image.
6. If a correspondence point is found, select its neighbor points as match candidate points.
7. For such neighbor points, calculate image coordinates of corresponding right points.
8. Repeat Step 3 ~ 7 until there are no match candidate points left.

3 OPTIMAL INTERPOLATION

3.1 Interpolation schemes commonly used

Many interpolation schemes for elevation data have been studied (Desmet, 1997, Carlson and Foley, 1991). Most of these schemes, however, do not deal with real elevation data but use a test data set with less than 100 elements. To determine the optimal interpolation scheme for satellite images, five interpolation schemes commonly used are evaluated using real elevation data from automatic stereo matching.

Five interpolation methods are listed below (Kim *et al.,* 1999).

- Gaussian: elevation on a grid is calculated from the statistical properties of a terrain $(x_o)=\Sigma\omega_i \cdot \mathrm{H}(x_i)$, where a weight function is given by $\exp[-(x_i-x_o)^2/\sigma^2]$.
- Minimum curvature: the minimum curvature interpolation minimizes the curvature of a surface that is formed by interpolated elevations.
- Kriging: elevation on a grid is calculated from the statistical properties of a terrain $(x_o)=\Sigma\omega_i \cdot \mathrm{H}(x_i)$, where optimal weights for interpolating the elevation at x_o are determined from variogram describing the spatial variation of terrain.
- Multiquadric: elevation on a grid is calculated from the statistical properties of a terrain $(x_o)=\Sigma\omega_i \cdot \mathrm{H}(x_i)$, except that a basis function is given as $\mathrm{Q}_i(x,y) = \mathrm{sqrt}((x-x_i)^2+(y-y_i)^2+\mathrm{R}^2)$.
- Modified Shepard: elevation on a grid is calculated from quadratic basis functions and inverse-distance weights are used.

To test the interpolation method on the real elevation data from automatic stereo matching result, two regions are selected: one is smooth region and the other is rough. The parameters for each interpolation schemes are determined so that they perform best with input data. The accuracy is assessed by comparing DEMs from each schemes with truth DTED produced by NIMA, USA. The results are summarized in table 1.

Kriging and Gaussian interpolation scheme performed best. The error of Kriging was 37.8m and 44.4m, and that of Gaussian is 36.5m and 44.5m for two regions, respectively. Additional comparison shows that Gaussian interpolation scheme is superior. Since Kriging is exact interpolation, errors in stereo matching results appear unfiltered in the interpolation output. These errors, however, are smoothed out in Gaussian interpolation scheme (See figure 3).

	Accuracy (RMS, meter)	
	Smooth region	Rough region
Gaussian	36.55m	44.54m
Minimum curvature	39.32m	46.74m
Kriging	37.84m	44.37m
Multiquadric	40.54m	49.66m
Modified Shepard	39.04m	45.44m

Table 1. Quality assessments of interpolation schemes performed using automatic stereo matching results.

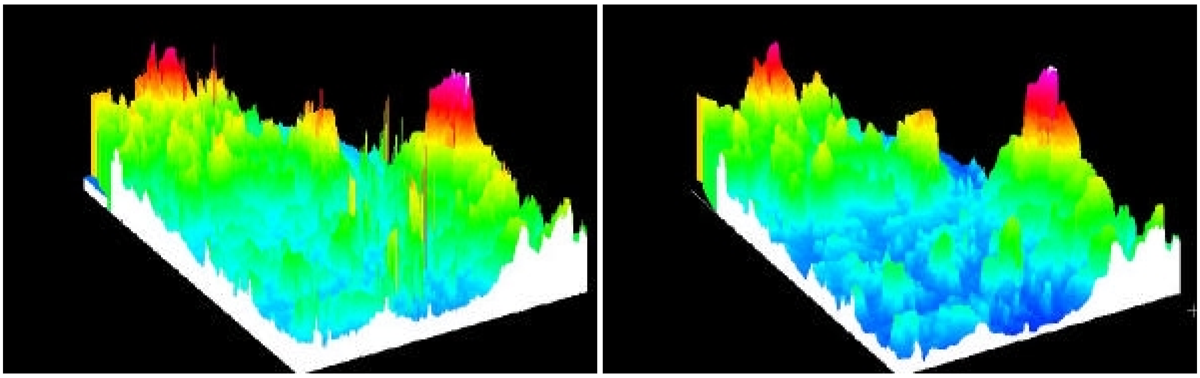

Figure 3. Three-dimensional view of DEMs over 30km × 40km region by Kriging (left) and by Gaussian (right).

3.2 Optimum interpolation strategy

Although Gaussian interpolation scheme shows satisfactory results, unrealistic elevation, unfortunately, can be introduced in large regions where stereo matching fails. This can be explained using the concept of 'center of gravity (COG)' and 'empty center index (ECI)' (Kim *et al.,* 1999). The COG of scattered input points comprises the average of two-dimensional coordinates. ECI is the mean distance of scattered input points from the center of interpolation. If COG is greater than a threshold or if normalized ECI is too far from 0.5, interpolation is regarded as failure.

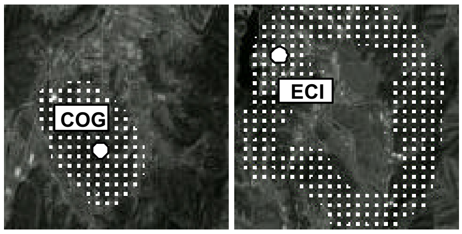

Figure 4. Concepts of 'center of gravity' (left) and 'empty center index' (right).

Without correcting for COG, boundaries of matched regions will have incorrect elevation. Even if the COG criterion is satisfied but stereo matching fails over a small hill, the hill will not be correctly represented after interpolation. Thus, the ECI criterion that may be regarded as a one-dimensional version of COG in radial direction is also needed. The result of using COG/ECI criteria exhibits correct boundaries of matched regions.

In summary, due to errors in stereo matching, Gaussian interpolation scheme shows satisfactory results for satellite images. Also, to prevent interpolation on large regions where stereo matching fails, COG and ECI within each search regions of interpolation are used as a rejection criterion. Through this strategy, DEMs can be effectively generated from satellite images.

4 EXPERIMENTS AND RESULTS

We will show experiments with two 60km×60km SPOT panchromatic stereo image pairs including ocean, rivers, urban and mountain, etc. (See figure 5 and 6). Table 2 shows the scene information on SPOT images used. GCPs are collected using a GPS receiver whose accuracy is less than one meter. For the quantitative assessment of DEMs, we prepare two truth DEMs: 1) 100m-resolution Digital Terrain Elevation Data (DTED) generated by NIMA, USA. 2) 60m-resolution DEM generated from digitized contours produced by National Geography Institute.

Figure 5. SPOT Left (left) and Right (right) scenes over Boryung area.

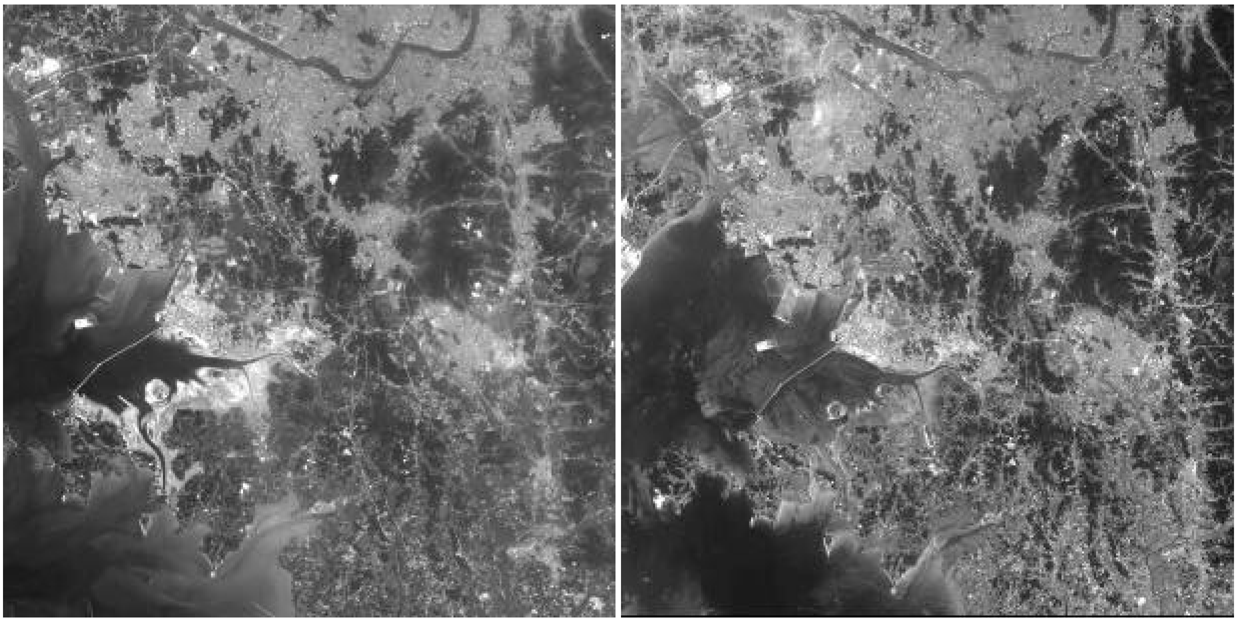

Figure 6. SPOT Left (left) and Right (right) scenes over Seoul area.

	Boryung area, Korea		**Seoul area, Korea**	
	Left image	Right image	Left image	Right image
Scene size	6000×6000	6000×6000	6000×6000	6000×6000
Viewing angle	-25.8’	-0.4’	-16’	2.2’
Acquisition time	March, 1, 1997	November, 15, 1998	May, 5, 1998	August, 24, 1997

Table 2. SPOT Panchromatic Scene Information

The performance of our strategy (we will refer our strategy to “Valadd-Pro” from now on) and other commercial software packages is summarized in table 3 and 4. The commercial software packages, unfortunately, have large errors in ocean and river parts (See figure 7 and 8). Therefore, in the first one, we have compared DEMs automatically generated by Valadd-Pro, PCI and Intergraph with truth DEMs. In the second, we have excluded ocean parts from DEMs by Valadd-Pro, PCI and Intergraph, and have compared with truth DEMs.

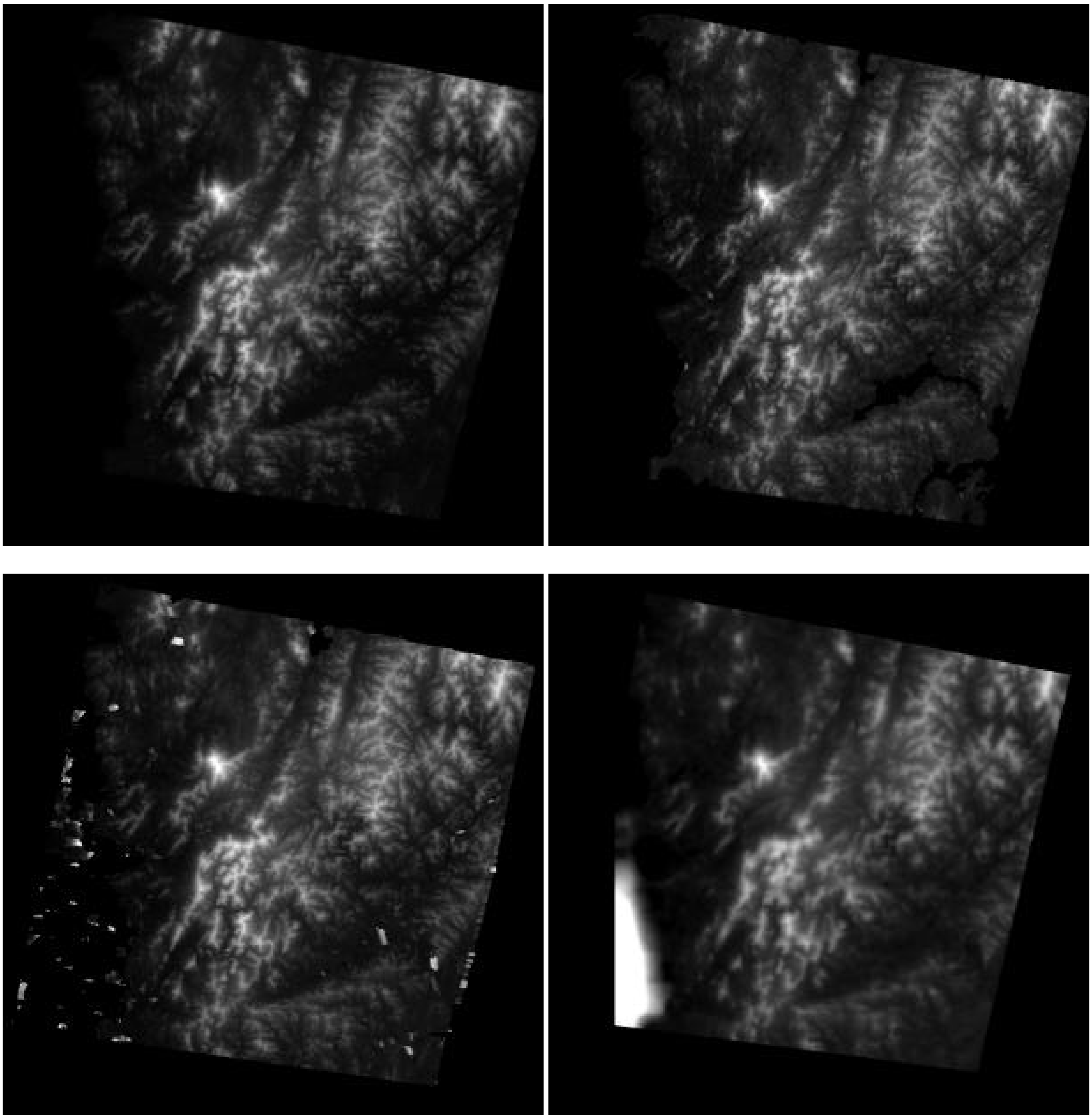

Figure 7. The truth DEM over Boryung (top left). A DEM over Boryung By Valadd-Pro (top right). A DEM over Boryung By PCI (bottom left). A DEM over Boryung By Intergraph (bottom right).

	Boryung area, Korea				
	Including ocean parts		Excluding ocean parts		
DTED	Mean error	RMS error	Mean error	RMS error	Exec. time
Valadd-Pro	9.68m	22.83m	9.68m	22.45	35m
PCI	36.0m	60.6m	36.0m	44.7	1h 52m
Intergraph	32.1m	281.9m	32.1m	50.8	3h 15m
Digitized DEM	Mean error	RMS error	Mean error	RMS error	Exec. time
Valadd-Pro	1.1m	–	1.1m	22.3m	–
PCI	30.0m	–	30.0m	38.8m	–
Intergraph	-0.5m	–	-0.5m	50.0m	–

Table 3. The comparison among DEMs by Valadd-Pro, DEMs by PCI and DEMs by Intergraph over Boryung area

	Seoul area, Korea				
	Including ocean parts		Excluding ocean parts		
DTED	Mean error	RMS error	Mean error	RMS error	Exec. Time
Valadd-Pro	–	33.6m	19.1m	33.6 m	40 m
PCI	–	110.0m	38.0m	61.1m	2h 25m

Table 4. The comparison among DEMs by Valadd-Pro, DEMs by PCI and DEMs by Intergraph over Seoul area

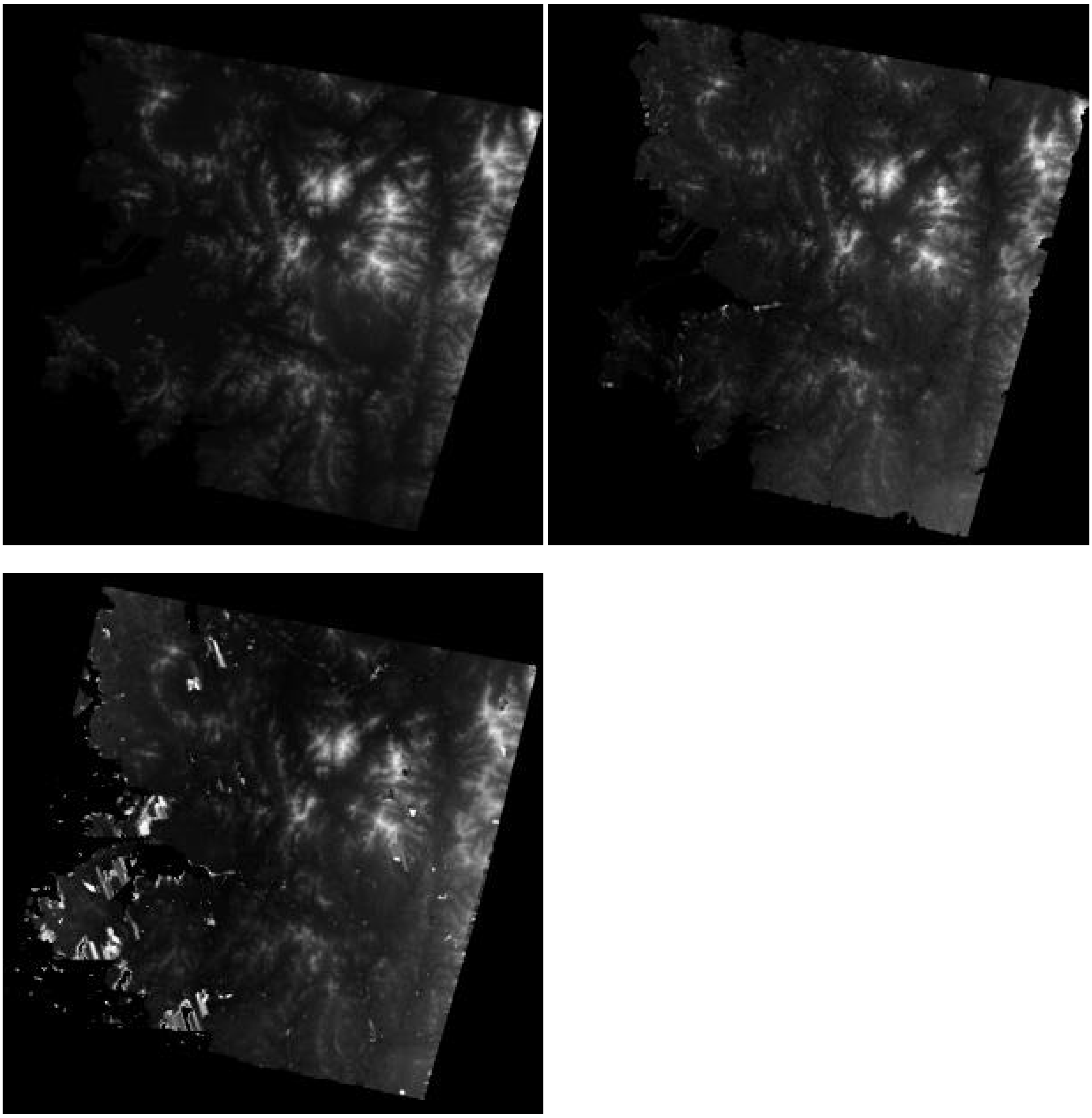

Figure 8. The truth DEM over Seoul (top left). A DEM over Seoul by Valadd-Pro (top right). A DEM over Seoul by PCI (bottom left)

As shown in the tables, our strategy produces DEMs whose accuracy and execution time are much better than that of other commercial software packages. Figure 7 and 8 show DEMs generated from our strategy and from other commercial software packages for Boryung and Seoul area, Korea. As shown in the figures, DEMs from PCI require manual editing to remove errors appeared as bright spot. DEMs from Intergraph are too much smoothed out so that the exactness of DEMs is low. In particular, DEMs from commercial software packages have many errors over oceans. The accuracy of DEMs from commercial software packages, even after the removal, is much lower than that of DEMs from our strategy. PCI and our strategy are performed in an Intel Pentium II Platform. However, since Intergraph is installed on a different platform, execution time taken is meaningless.

Through these experiments, we conclude that we achieve a more accurate and fast DEM generation compared to some commercial software packages.

5 CONCLUSIONS

We have addressed the accurate and robust strategy to extract accurate DEMs from satellite image pairs. In this strategy, firstly, a stereo matching algorithm based on epipolarity and scene geometry is adapted. Secondly, an optimal interpolation scheme considering the radiometric characteristics of satellite images is used. By these techniques, we can increase the accuracy of DEMs and minimize the computation time. Also, we can achieve the satisfactory coverage.

Our current and future research is focused on applying the strategy we proposed here to high-resolution satellite images. Since these images are a linear pushbroom type, we expect our strategy should work. We will report the results of such experiments.

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