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Automatic Generation of a SPOT DEM: Towards Coastal Disaster Monitoring

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Abstract : A DEM (digital elevation model) is generated from a SPOT panchromatic stereo-pair using automated algorithms over a 8 km × 10 km region around Mokpo city. The aims are to continue the accuracy assessment over diverse conditions and to examine the applicability of a SPOT DEM for coastal disaster monitoring. The accuracy is assessed with respect to three reference data sets: 10 global positioning system records, 19 leveling data, and 1:50,000 topography map. The planimetric error is 10.6m r.m.s. and the elevation error ranges from 12.4m to 14.4m r.m.s.. The DEM accuracy of the flat Mokpo region is consistent with that over a mountainous area, which supports the robustness of the algorithms. It was found that coordinate transformation errors are significant at a few meters when using the data from leveling and topographic maps. The error budget is greater than the requirements for coastal disaster monitoring. Exploiting that a sub-scene is used, the affine transformation improves the accuracy by 50% during the camera modeling.

Key Words : digital elevation model, SPOT, error reduction, disaster monitoring

1. Introduction

Automatic generation of a digital elevation model (DEM) is an important issue because of diverse utilities of a DEM and, when compared with manual processes, anticipated reduction in the production cost. Automatic DEM generation, especially using satellite images, draws continuous efforts (e.g., Al-Rousan *et al.*, 1997; Krupnik, 2000) mainly because of frequent imaging, global coverage and low cost. Though still lacking the accuracy and the amount of extracted information in comparison to the traditional aerial photogrammetry, the advent of ever higher-resolution satellite images attempts to diminish the deficiency.

In these contexts, new algorithms are developed which include the epipolairty for satellite images, adaptive matching and intelligent interpolation (Lee *et al.*, 2000, hereafter Lee00's algorithms). The performance of the new algorithms has been assessed with respect to topography maps a few times: on two SPOT full-scene areas (Lee *et al.*, 2000) and on a KOMPSAT

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Electro-Optical Camera (EOC) image pair (Im and Kim, 2001). Such assessment is subject to potential inaccuracy in the reference data due to their being out-dated, thus absolute assessment is needed. So far, absolute assessment has been made on one SPOT full-scene (Kim and Lee, 2000, Kim00 hereafter) over the mountainous Donghae area. It is essential to test the performance over diverse terrains and different conditions for scene acquisition. In particular, the terrain slope and the tilt angle of a camera may affect the performance of automatic DEM generation. The terrain slope causes the layover effect and distorts an image. The image resolution would vary according to the tilt angle. In this paper, by accuracy assessment using GPS (global positioning system) and leveling data over a flat Mokpo area, it is intended to test the robustness of Lee00's algorithms.

The second objective of this paper is to examine how useful a SPOT DEM would be for coastal disaster prevention. The study area, Mokpo, is a coastal city with the elevation over a large area of the city within 10 m from the sea level. Moreover, the tidal variation is as large as 3m. In such a situation, an accurate DEM is essential for estimation of flood damages or prediction of inundated areas. Because civil properties are involved, the DEM has to be very accurate, and perhaps the only viable solution at present would be aerial imaging. For example, the accuracy of satellite DEMs ranges 6 – 22m r.m.s. for SPOT (Al-Rousan *et al.*, 1997; Krupnik, 2000; Kim00) and 14 m for EOC (Im and Kim, 2001). Nevertheless it would be still be useful to test the limit of spaceborne imaging because of its merit and improvements in image resolution. The primary merits are the frequent and regular imaging. The merits would be important around Mokpo area where man-made changes such as construction and land reclamation are fast.

Noting that the accuracy of a satellite DEM would not be sufficient for the coastal application, accuracy improvement is necessary. One possibility for the improvement is to use sub-images. Within sub-images, the errors due to approximation in sensor model may be smaller. For example, the sensor's position and attitude can be approximated to a second-order polynomial of time (Gugan and Dowman, 1988). The model can be reduced further by approximating that the sensor attitudes in pitch and roll do not vary in time (Orun and Natarajan, 1994). Temporal variations in the sensor parameters would be smaller within a sub-image than within a full-scene, thus possibly reducing the approximation errors.

2. Data and Method

1) SPOT images

The path and row numbers of the SPOT panchromatic pair are 305 and 280 for the reference left scene and 304 and 280 for the target right scene (Fig. 1). The left scene was taken at 11:22am on May 5, 1999 at 8.8° tilt and the right scene was at 11:34am on May 20, 1999 at +7.6°tilt. The tilt angles for Donghae were −13° and 26°. Reflectance over land differs between the two images due to the collection geometry (the configuration made by the camera and the Sun). Over the sea, specular reflection is found on the left image. The test site is around Mokpo city area of 8 km × 10 km large, defined by 126°21′ – 126°29′, 34°43′ – 34°50′ in Tokyo Mean datum.

2) Preparation of GPS Records

GPS measurements provide the check points

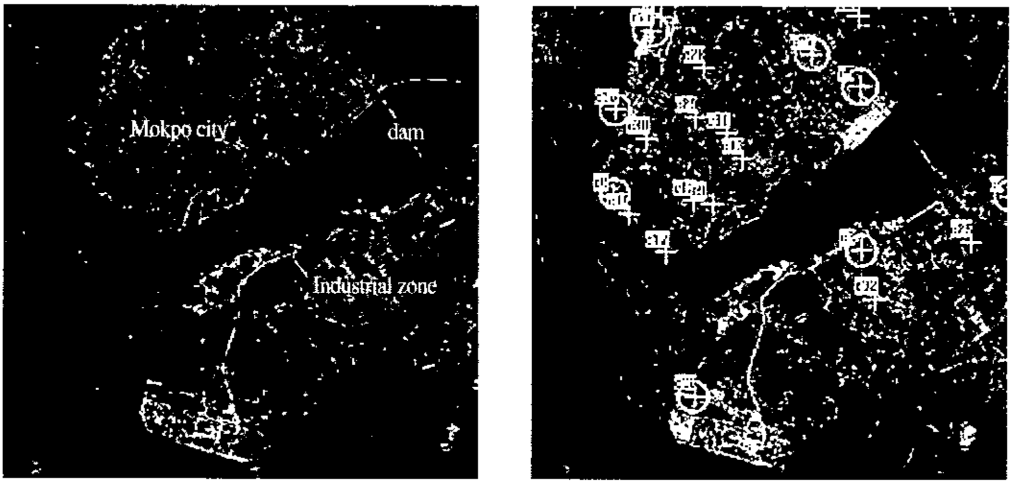

Fig. 1. SPOT stereo-images and 21 GPS records. 8 GCPs for sensor modeling are marked by circles.

for absolute accuracy assessment and the ground control points (GCP) for sensor modeling. The philosophy in designing the GPS measurement locations follows that in Kim00: to obtain the statistical significance in the mean elevation error. The target of the mean error budget is set to 5m. Since the tidal variation in the test region is about 3 m, elevation changes greater than 5m would be due to some other causes such as floods thus has to be identified. That is, mean errors larger than 5m cannot be tolerated thus should be significantly meaningful. Taking 20m as the typical level of s.d. error of Lee00's algorithms (Lee *et al.*, 2000), the required number of check points is 16 to achieve the statistical significance of the mean error. Including additional 6 records for control points and a few redundancies, 25 GPS measurements are planned. Out of 16 check points, 13 are located inland because along the coast there are 19 leveling data. The layout of GPS measurements are summarized in Table 1.

Table 1. Design of the numbers and locations of the GPS measurements. 3 GPS records are discarded after measurement.

	GPS measurements	Leveling data
Control points	9	0
Check points (coast)	3	19
Check points (inland)	13	0

Trimble Pro XR receiver is used and each point is surveyed for 10−15minutes at single carrier mode. With this configuration, the nominal accuracy is 0.7m r.m.s. with Namwon and Kwnagju as the reference stations for differential GPS. For more details of the differential GPS processing and fine tuning, one may refer to Kim00. The fine tuning produces accuracy of each GPS record assessed by the vector propagation model, and 20 out of the 21 GCPs are accurate better than 10m (Fig. 2).

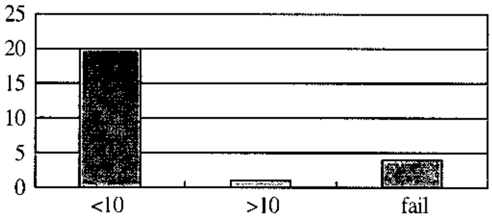

Fig. 2. Distribution (ordinate, in the number of records) of GPS records with respect to their measurement accuracy (abscissa, in meter).

3) Sensor Model

The sensor model by Orun and Natarajan (1994) is used. GPS records with high measurement accuracy and even distribution over the image are selected as control points. Experimented by increasing the number of the GCPs from 6, the sensor model accuracy converged with more than 7 GCPs (Fig. 3). For even distribution of GCPs over the scene, the number of GCPs are chosen to 8 (Fig. 1). Normalization of the coordinates of the GPS records is applied during the sensor model but does not improve the accuracy (Kim, 2001).

4) DEM Generation

For the details of the DEM generation procedures one may refer to Lee *et al.* (2000). The environments for application to Mokpo are as follows. 58 tie points are extracted for stereo-matching. The match window over which the correspondence of the stereo-pair is computed has the size of 25 × 25 pixels. Stereo-matching is performed at every 5-pixel at the threshold on the correlation of 0.5. The interpolation gives a 1-pixel resolution DEM. The interpolation radius is set to 1800 m with only 10 nearest interpolants are counted. The details of the intelligent interpolation are as follows (Kim *et al.*, 2000): thresholds on center-of-gravity/empty-center-index are 0.6 and 0.8 respectively; empty holes less than 6000 pixels large are filled; land segments less than 500 pixels large are regarded as noise.

3. Accuracy Assessment

1) Qualitative Examination

The SPOT DEM is shown in Fig. 4. The mountains and hills in Mokpo city and Daebul industrial zone are correctly shown. The highway running NW-SE direction is clearly identifiable. The topography in Daebul industrial zone is erroneous: the elevation is shown below zero in Fig. 4a but the truth is between 0−10m. The errors in the zone is greater than elsewhere (Fig. 4b). The main reason for the error would be mismatches. The industrial zone is characterized by flat grassland due to low occupancy of factories. With Lee00's area-based matching, the consequent homogeneity leads to mismatches as in farmland. Large errors are inevitable where there are few GCPs, such as on the eastside of the dam or the northeastern boundary (not shown). One solution would be to use feature-based matching. Since the zone is outside the Mokpo city, the main concern

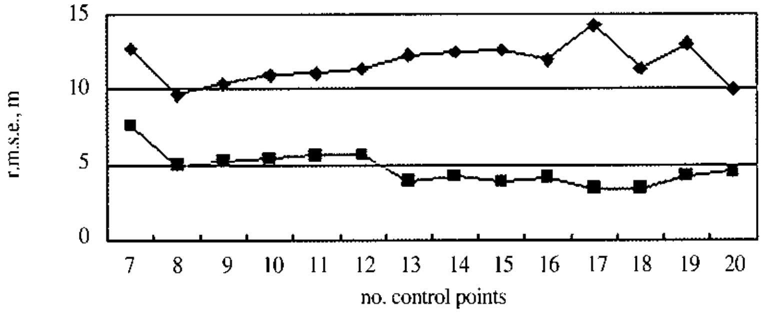

Fig. 3. Sensor model accuracy: before residual remove (diamond) and after (square). 21 GPS records are divided into control and check points.

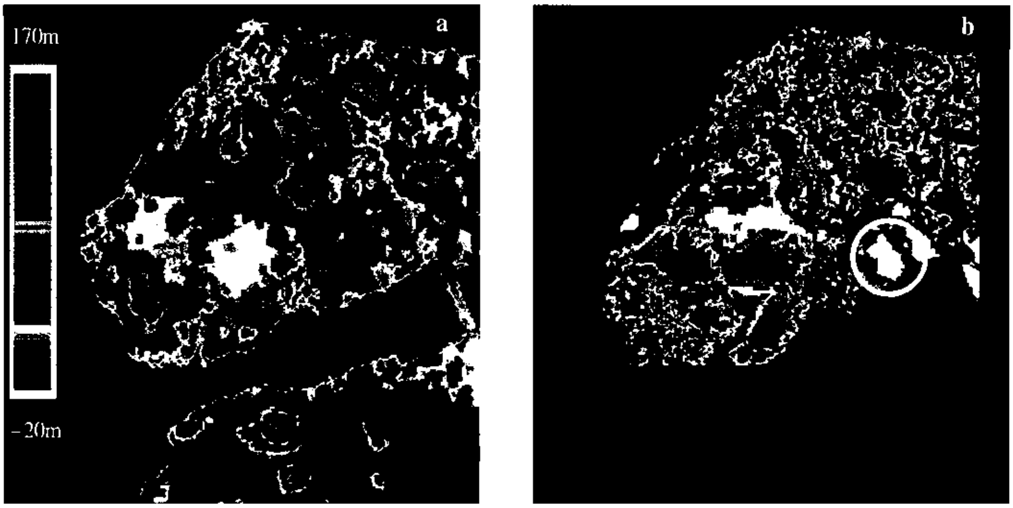

Fig. 4. DEMs over Mokpo area: (a) DEM with orthometric height (b) difference: DEM-topography map. The pseudo-coloring in (b) is the same as that in (a), but ranging between-30 m and 30 m.

of this research, no solution is implemented.

2) Quality Assessment (QA) with respect to GPS Measurements

13 GPS check points are used (unmarked ones in Fig. 1) out of 16 planned ones (Table 1). The planimetric error is 10.6m r.m.s. (Table 2) and the elevation error reaches 14.6m r.m.s.. Full details of the accuracy assessment procedures can be found in Kim00. The accuracy is comparable with those in Donghae region against 38 records: w.r.t. GPS records, 10.3m and 12.0in planimetry and elevation (Kim00). What differs is the large mean difference: in Donghae region the mean differences are less than 0.5m and 2.1m in planimetry and elevation. It is yet clear what is the cause of the large mean difference: all the GPS records are fine-tined and the only errors should all be random.

Table 2. Accuracy assessment w.r.t. 10 GPS measurements

	Difference in meter (SPOT DEM-reference)	
	mean	r.m.s.
In latitudinal direction	2.5	11.0
In longitudinal direction	8.5	10.2
In elevation	13.4	14.6

Further analysis of the error in Mokpo DEM shows the signal dependence (Fig. 5). Ideally if the dependence stems from any physical cause, the dependence may be removed by, for example, a linear modeling. In such a case, the GPS comparison may support the hypothesis that sub-scenes produce better accuracy. At present the cause of the large mean error or the dependence is not clear. Also the use of more GPS check points are highly desired to confirm the dependence. It, however, may as well be that the r.m.s. error

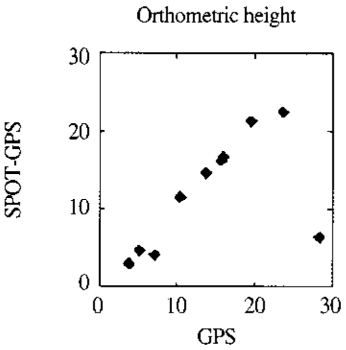

Fig. 5. Signal dependence of the elevation error(units in meter).

of~10m is the limit of the accuracy attainable from SPOT images: the errors in planimetry, and consequently elevation, are subject to the precision in manual positioning of the GPS records onto an image, thus is subject to about 10m error (see Section 7 of Kim00 for fuller discussion).

3) QA with respect to leveling data

The leveling data are measured in May 1998, provided by Ministry of Marine Affairs and Fishery, and is given relative to Inchon Mean Sea Level (Mokpo Min. Marine Affairs Fishery, 1998). There are 21 measurements and, excluding 2 in an island, 19 data are available for comparison (Fig. 6). The mean and r.m.s. error are 7.5m and 12.8m (Table 3). The r.m.s. error is comparable with that assessed w.r.t. GPS (Table 2). Mean error is smaller than the GPS comparison. Coordinate transformation error may be one of the causes of the mean error difference: the leveling data are given relative to Tokyo Mean datum while the SPOT DEM is to WGS84 datum. When the orthometric height in Tokyo Mean datum is transformed to WGS84, that in WGS84 is shown higher by 0.2 (near Inchon), 1.87 (near Mokpo) and 3.36 (near Busan). Such level of difference is plausible because only the small number of leveling data, 38 records, are incorporated (Hongsik Yoon, personal communication 2001). The coordinate transformation is performed using 7 parameter Bursa-Wolf model (Lee, 1997). Correction of the coordinate transformation error would act to increase the mean error in the leveling data QA, reducing the difference in the mean error between the GPS and level data QAs. Other reasons for the mean error between the GPS and level data QAs include errors in geoid (Choi, 1998) and the leveling data themselves[1].

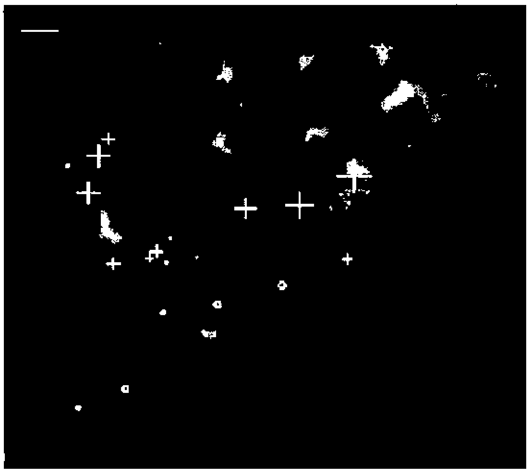

Fig. 6. Comparison between the SPOT DEM (gray background) and the leveling data. The locations of the leveling data are marked by cross (when the DEM height is greater leveling height) and circle (vice versa). The sizes of the marks indicate that of the difference. The size of the cross at the top-left comet corresponds to 30m error.

Table 3. Elevation accuracy w.r.t. the leveling data and the 1:50,000 topography map.

Reference data	Difference in meter (SPOT DEM reference)	
	mean	r.m.s.
Leveling data	7.5	12.8
Topography map	4.4	14.2

Interesting features in the spatial distribution of error in Fig. 6 are (1) errors are larger in Mokpo city side than in Daebul industrial zone side and (2) positive errors are found in Mokpo city region while negative errors are in Daebul area. However, such linear trend is not removed in the final DEM: for such removal, the accuracy of the leveling data and the coordinate transformation has to improve and also more leveling-type data are needed over the whole study area.

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[1] It is probable that leveling data in general possess errors of several meters large (HongSik Yoon, personal communication 2001).

4) QA with respect to Topography Data

The 1:50,000 topography map updated in 1995 is used as a reference and the difference map is shown in Fig. 4b. The difference map is shown only over Mokpo city area because, elsewhere, lack of control points leads to large errors.

The mean and r.m.s. errors are 4.4m and 14.2m (Table 3). A part of the error may be attributed to that in coordinate transformation as explained earlier. The map is posted on WGS84 datum, while its source is 1:5,000 topographic map which is given in Tokyo Mean datum. In Mokpo city downtown the error is maintained to less than 10 m. On the other hand, large blobs of positive errors are found (marked by the gray circle in Fig. 4b). A probable cause is the blunder propagation during stereo-match (Kim and Lee, 2001) because of weak texture in the reclaimed land in Hadang district.

The accuracy assessment with respect to the three reference data sets can be summarized as follows:

- The r.m.s. error in elevation ranges from 12.8m to 14.6m. This is consistent with 12.5m, the accuracy of Lee00's algorithms in the Donghae region (Kim00), despite the different terrain types and view angles. The consistency supports the robustness of Lee00's algorithms. The accuracy is comparable also with those of commercially available digital photogrammetric workstations (Krupnik, 2000).
- The mean elevation error of 4.4m to 13.4m is larger than that from GPS comparison in Donghae region (2.1m). If the cause of the mean error is identified and the error can be removed, it would support that the use of sub-scene improves the DEM accuracy.
- When the leveling data and the topographic map are used as reference, errors in coordinate transformation and the geoid data can contribute a few meters to the mean error.

4. Error Reduction

In this section, the possibility of reducing the error in SPOT DEM is probed. The primary motivation is to reduce the error budget to below 5m-the magnitude of sea level changes in this region. The attempts are focused on improving the sensor modeling. Initially normalization of the coordinates of the GPS records is applied but it does not improve the accuracy (Kim, 2001). Then the residual between the truth coordinate from GPS (X_{tr}, Y_{tr}, Z_{tr}) and the coordinate estimated by Orun and Natarajan's sensor model ($\hat{X}$, $\hat{Y}$, $\hat{Z}$) is modeled by a simple affine matrix. Removal of the residual, which produces $\tilde{X}$, $\tilde{Y}$, $\tilde{Z}$ is supposed to improve the sensor model. Expressed in matrix forms, the procedures are:

$$\begin{bmatrix} X_{tr} \\ Y_{tr} \\ Z_{tr} \end{bmatrix} \approx \begin{bmatrix} X_{tr} \\ Y_{tr} \\ Z_{tr} \end{bmatrix} = \begin{bmatrix} a11 & a12 & a13 \\ a21 & a22 & a23 \\ a31 & a32 & a33 \end{bmatrix} \begin{bmatrix} \hat{X} \\ \hat{Y} \\ \hat{Z} \end{bmatrix} + \begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix}$$

To estimate 12 affine parameters a minimum of 4 sets of GPS records are required. The estimation is performed by varying the number of GPS sets from 6 to 21.

In Mokpo sub-images, the residual removal method works well: the sensor model error is halved (Fig. 3), whereas over full-scenes the improvement is weak (Seoul) or little (Boryung, Fig. 7). On sub-images the affine method models the residual better: the affine method is a linear modeling while the residual is non-linear, therefore sub-images are more suitable for the linear approximation. In Fig. 7, it should be noted that when the number of model GCPs is greater

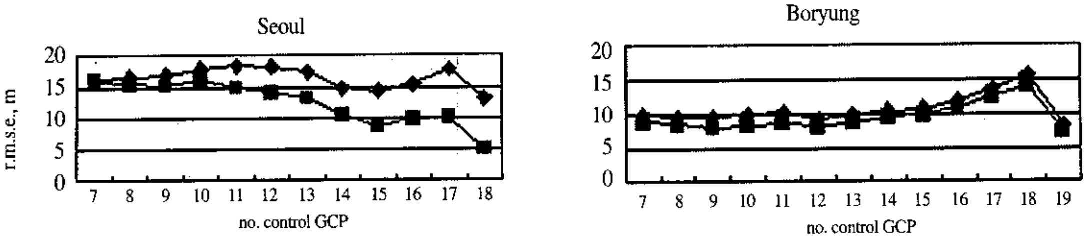

Fig. 7. Camera model accuracy: before residual remove (diamond) and after (square).

than~16, the check GPS points become less than 3 and the statistics are not meaningful. Despite the error budget has been reduced in Mokpo, however, the affine parameters are unrealistic. For example, the magnitudes of the shift parameters are as large as those of X_{tr}, Y_{tr}, Z_{tr}. Tested in a different coordinate, in latitude, longitude, elevation coordinate, the shift in elevation still turns out to be as large as 200m. Consequently, when the affine parameters are applied to the stereo-matched result, the error in the consequent elevation increases. More research is needed to obtain more sensible affine parameters.

5. Conclusions

A DEM is generated automatically from a SPOT panchromatic stereo-pair using the automated algorithm over a 8km × 10km region around Mokpo city. The aims are two-fold: (1) to continue the accuracy assessment over various terrain types and scene acquisition conditions and (2) to examine the applicability of a SPOT DEM for coastal disaster monitoring.

The accuracy is assessed with respect to three reference data sets: 10 global positioning system records, 19 leveling data, and 1:50,000 topography map. The planimetric error is 10.6m r.m.s. and the elevation error ranges from 12.4m to 14.4m r.m.s.. The DEM accuracy of the flat Mokpo region is consistent with that over a mountainous area, which verifies the robustness of the automatic algorithm. Large mean errors are found and, if the cause of the mean error is identified and the error can be removed, it would support that the use of sub-scene improves the DEM accuracy. Care should be taken when the coordinate transformation is used during the validation because it may introduce several meters of bias.

The error budget is greater than the requirements for coastal disaster monitoring. To reduce the error, it is modeled by the affine transformation during the camera modeling and the camera model accuracy improves by 50%. Further studies are required to extend the error reduction method to the DEM generation steps.

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