Journal of the Korean Society of Remote Sensing, Vol. 14, No.3, 1998, pp.232~249

# Towards the development of an accurate DEM generation system from KOMPSAT-1 Electro-Optical Camera Data

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# 다목적 실용위성 1호기 EOC카메라 영상으로부터 DEM 추출을 위한 시스템개발에 관한 고찰

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## Abstract

The first Korean remote sensing satellite, Korea Multi-Purpose Satellite (KOMPSAT-1), is going to be launched in 1999. This will carry a 7m resolution Electro-Optical Camera (EOC) for earth observation. The primary mission of the KOMPSAT-1 is to acquire stereo imagery over the Korean peninsular for the generation of 1:25,000 scale cartographic maps. For this mission, research is being carried out to assess the possibilities of automated or semi-automated mapping of EOC data and to develop, if necessary, such enabling tools. This paper discusses the issue of automated digital elevation model (DEM) generation from EOC data and identifies some important aspects in developing a DEM generation system from EOC data. This paper also presents the current status of the development work for such a system. The development work will be described in three parts of sensor modelling, stereo matching and DEM interpolation. The performance of the system is shown with a SPOT stereo pair. A DEM generated from commercial software is also presented for comparison. The proposed system seems to generate promising results.

## 요 약

1999년도에 최초의 원격탐사용 국적위성인 다목적 실용위성 1호기가 발사된다. 이 위성에는 해상도 7m영상을 촬영할 수 있는 EOC 카메라가 탑재될 예정이며 이 위성의 주 임무는 이러한 EOC 카메라를 이용하여 1:25,000 축적의 지도제작이 가능한 한반도 전역의 스테레오 영상을 취득하는 것이다. 이 주임무를 위해 EOC 영상으로부터 1:25,000 축적지도제작의 가능성 확인 및 관련 소요기술 개발을 위한 연구과제가 진행 중에 있다. 본 논문에서는 그중에서 특히 EOC 영상으로부터 수치표고모형을 추출하는 문제에 관하여 논의하고자 한다. 먼저 위성영상으로부터 수치표고모형을 제작하는 시스템의 개발에 있어 요구되는 사항들에 관하여 논의한다. 또한 이를 위하여 현재 진행 중인 시스템 개발상태를 보고하고 개발과정에서 수행한 각종 알고리즘들의 성능평가 및 결론을 논의한다. 그리고 SPOT 위성영상을 이용, 상용 소프트웨어와 개발 중인 시스템에서 추출한 수치표고모형을 비교하여 개발 중인 시스템의 성능을 중간진단한다.

## 1. Introduction

Topographic mapping from satellite images is an important application of remote sensing data. This is also the primary mission of the KOMPSAT–1 (Korea Multi–Purpose Satellite), the first Korean remote sensing satellite to be launched in 1999. The KOMPSAT–1 carries a 7m–resolution Electro–Optical Camera (EOC) and is missioned to collect stereo imagery over the Korean peninsula for generation of 1:25,000 scale maps. For this mission, research is being carried out to assess the possibilities of automated or semi–automated cartographic mapping using EOC data and to develop, if necessary, such enabling tools.

Many technologies as well as various ground–support information are required for the generation of cartographic maps from satellite images. Some technologies are implemented in commercial software and can be used for such a purpose. Some are implemented but seldom used in practice. Some are not implemented at all. For the last two kinds new technologies must be developed. In particular, the authors felt that technologies for DEM generation were so. A DEM is very essential information for topographic mapping of satellite images. Several commercial software packages offer modules for automatic, semi–automatic or manual DEM generation. However, fully automatic DEM generation modules are not very often used because of many reasons[1]. A DEM may also be extracted from existing contour maps. It is, however, not easy to find a so–extracted DEM at a sufficient resolution and with a sufficient accuracy for 1:25,000 scale map generation. Moreover, the authors do not follow the idea of using DEMs obtained from

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[1] See the section 2 for explanation.

existing maps to create new maps.

This paper will describe the work being carried out to develop a system for automated DEM generation from EOC data. For the development of such a system, various sensor models for linear pushbroom cameras, adaptive least squares stereo matching algorithms and several DEM interpolation software modules have been newly developed or implemented. The proposed system is still under development and this paper will report on the intermediate achievements. Firstly, this paper will discuss the issue of automated DEM generation from EOC data and identify several important aspects in developing a system for such DEM generation. Secondly, this paper will report the current status of the development work in sensor modelling, stereo matching and DEM interpolation. Finally, a result of DEM generation will be presented using a SPOT stereo pair. A DEM generated by commercial software will also be shown for comparison and the performance of the proposed system will be discussed.

## 2. A consideration for DEM generation from the EOC data

Figure 1 shows an example of a processing chain for 1:25,000 scale digital map generation from EOC data. Once stereo images are obtained from the EOC, they need to be radiomatrically rectified to take into account different responses of electronic circuits in the camera and other irregularities related to the brightness values stored in CCD cells of the camera. After this, ground control points are measured for the area of interest. These points are used for sensor (or camera) modelling to reconstruct the geometry between the sensor and the object space at imaging. Stereo matching is then applied to the stereo pair to generate conjugate points, which can be converted into 3D coordinates using a sensor model. The resulting points are interpolated into grids with desired spacing for DEM generation.

This DEM can then be used to eliminate distortions due to sensor instability, the Earth curvature and height relief in the original images and hence to generate an ortho-image (ortho-rectification). An ortho-image can be regarded as a photographic map. For generation of digital maps, mapping features are extracted from an ortho-image and vectorised. These feature vectors can constitute layers of a digital map after ingesting the required auxiliary data as their attributes

Within the processing chain, this paper will discuss issues on sensor modelling, stereo matching and DEM interpolation, which are represented as shaded boxes in the figure.

In the generation of a DEM for a 1:25,000 scale map, the first consideration could be the accuracy of the processes involved. In the ASPRS's mapping standard (1990), the horizontal

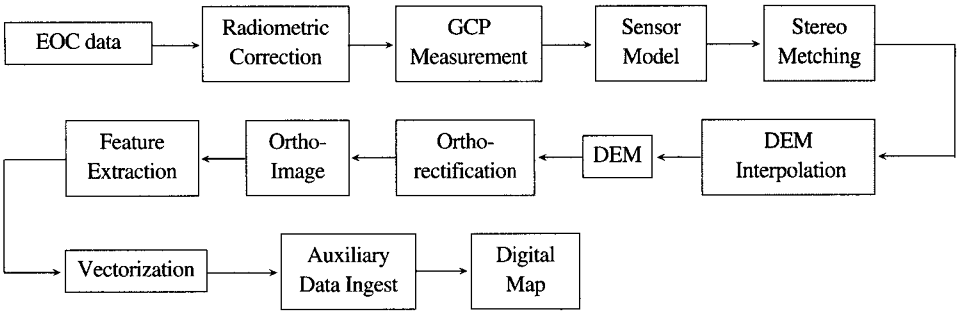

Fig. 1. An example of a processing chain for digital map generation from EOC data

accuracy requirements for such maps in class 1 are defined to have a maximum root mean square error of 6.25m and in class 2, a maximum root mean square error of 12.5m. In Korean standard, the horizontal accuracy is defined as a maximum root mean square error of 10m (Yeo et al., 1998). Vertical accuracy is generally defined as a maximum root mean square error of 1/3 of contour spacing.

To meet these requirements, a lot of accuracy constraints are needed on the processes involved; a stable platform, reliable imaging devices, accurate ground measurements and so on. An accurate sensor model is one of them. In order to reduce errors in geo–referencing of a point of an image or in height estimation of a conjugate point pair in stereo images, the geometry of a sensor, a platform and the Earth at imaging must be understood precisely. An accurate sensor model is also essential for the efficiency of DEM generation, i.e., in order to use fewer ground measurements while maintaining the accuracy of a DEM.

An other consideration is the mechanism of acquiring stereo pairs of the KOMPSAT–1. Although the geometry of the three–line CCD (and the generation of stereo pairs in the same track) would be ideal for cartographic mapping (Fritsch et al., 1998), the KOMPSAT–1 is designed to generate a stereo pair in different tracks, i.e. using across–track tilting mechanism. This mechanism may involve a significant time delay between images in a stereo pair and impose on a stereo pair the problem of serious brightness inconsistency. This also implies that one may have to face the presence of undesirable clouds and hazes in a stereo pair since it is generally not easy to have a cloud–free spaceborne images. This across–track stereo imaging also overrules the famous "linear epipolarity" for a stereo pair, which has been used for long in the field of photogrammetry dealing with aerial images. The SPOT is a very well–known satellite generating stereo pairs of this kind. Due to the above difficulties, automatic DEM generation modules available in commercial software are seldom used for SPOT data[2]. A stereo matching algorithm has to be designed to deal with such difficulties.

Another consideration is the processing time for DEM generation. Generally, stereo matching processes are very computationally expensive and take several tens of milli-seconds for height estimation of one point (Kim and Choi, 1997). In order to have a reasonable processing time, one has to derive an intelligent scheme for DEM generation. For this, efficient DEM interpolation techniques may be required. Such techniques can reduce the time for interpolation, which could take several hours in worst cases. More importantly, if such techniques can maintain the same accuracy of a DEM with a smaller number of sample points, stereo matching can be applied less and hence the total number of computation reduced. The authors feel that this important aspect has not been considered carefully (Kim, 1998). In most commercial software, this process is done in a simplest manner (or not known to the authors).

Accurate ground measurements, resampling schemes for ortho-rectification and extraction of mapping features from images are also important aspects in 1:25000 scale map generation. However, this paper will focus on DEM generation part and these aspects will not be discussed here.

## 3. The current status of the development work at the SaTReC

### 1) Sensor modelling of linear pushbroom cameras

As mentioned before, sensor models contribute the overall accuracy of a DEM significantly. It is even more so for images from linear pushbroom-type sensors, such as the EOC, since the principal point of such a sensor is not fixed during imaging periods. Due to this, linear pushbroom sensor models are generally regarded as complicated. There has been several models proposed for such sensors but as McGlone (1996) has rightly pointed out, there have not been any rigorous performance comparisons between different sensor models proposed nor the agreements made on an optimal sensor model for DEM generation among the research community. There is a need of further research on this issue.

Many sensor models proposed so far adapted the well-established sensor model for aerial photographs, which is based on collinearity equations. The position of principal point or sensor platform is modelled as a polynomial function of time. Gugan (1987) has proposed one such model and Gugan and Dowman (1988) further improved. They modelled the position and

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2) This observation is based on personal conversations with the staffs of the Korean Army Mapping Center.

attitude of sensor platform as second-order polynomials of time. Similarly Konecny et al. (1987) modelled the position of satellite as first-order polynomials of time and the attitude as second-order ones. Orun and Natarajan (1994) has found out that the Gugan and Dowman's model possessed highly correlated parameters and proposed a modified model by assuming the pitch and roll angle of the platform constant and the yaw angle and the position as second-order polynomials of time.

In order approaches, a complete orbit of the platform was modelled rather than the track of the platform during imaging period. Salamonowicz (1986) has proposed one such model for Landsat images. Westin (1990) has also proposed a similar model but with the assumption of circular orbit. Recently, Gupta and Hartley (1997) has proposed a direct linear transform model similar to those used for aerial images (Longuet-Higgins, 1981). This model was formulated based on the assumption that the attitude of the platform is constant and the platform moves along a straight path.

For the development of accurate sensor models for the EOC, three models were selected from the literature for performance analysis. These are Gugan and Dowman's collinearity-based model, Orun and Natarajan's modified collinearity-based model and Gupta and Hartley's direct linear transform model. A new sensor model was also developed based on accurate satellite orbit modelling (Shin and Lee, 1997).

Figure 2 shows the geometry between the sensor and the object space used for the Gugan and Dowman's model and the Orun and Natarajan's model.

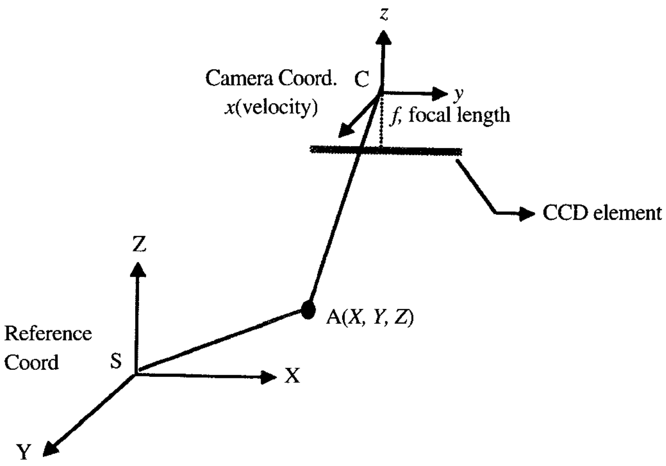

Fig. 2. A geometry between the sensor and the object space

Collinearity equations for linear pushbroom sensors can be modified from its original form for aerial photographs as follows

$$x = 0 = -f\frac{r_{11}(X-X_C)+r_{21}(Y-Y_C)+r_{31}(Z-Z_C)}{r_{13}(X-X_C)+r_{23}(Y-Y_C)+r_{33}(Z-Z_C)}$$

$$y = -f\frac{r_{12}(X-X_C)+r_{22}(Y-Y_C)+r_{32}(Z-Z_C)}{r_{13}(X-X_C)+r_{23}(Y-Y_C)+r_{33}(Z-Z_C)}$$

where $(X_C,\ Y_C,\ Z_C)$ is the coordinates of the origin of a camera coordinate system **C** in a reference coordinate system **S** at time $t$. $r_{11} \sim r_{33}$ are coefficients of a rotation matrix **R**, which rotates the camera coordinate system **C** to be aligned with the reference coordinate system **S**. $(X,\ Y,\ Z)$ is the coordinates of an object point in **S**. The rotation matrix **R** can be represented by the pitch ($\phi$), roll ($\omega$) and yaw ($\kappa$) angles as

$$\mathbf{R} = \begin{pmatrix} \cos\phi\cos\kappa & -\cos\phi\sin\kappa & \sin\phi \\ \sin\omega\sin\phi\cos\kappa+\cos\omega\sin\kappa & -\sin\omega\sin\phi\sin\kappa+\cos\omega\cos\kappa & -\sin\omega\cos\phi \\ -\cos\omega\sin\phi\cos\kappa+\sin\omega\sin\kappa & \cos\omega\sin\phi\sin\kappa+\sin\omega\cos\kappa & \cos\omega\cos\phi \end{pmatrix}$$

The Gugan and Dowman's model assumes the position of the platform $(X_C,\ Y_C,\ Z_C)$ and the attitude $(\phi,\ \omega,\ \kappa)$ as

$$\begin{aligned} X_s &= X_0+a_1t+b_1t^2 \\ Y_s &= Y_0+a_2t+b_2t^2 \\ Z_s &= Z_0+a_3t+b_3t^2 \\ \kappa &= \kappa_0+a_4t+b_4t^2 \\ \phi &= \phi_0+a_5t+b_5t^2 \\ \omega &= \omega_0+a_6t+b_6t^2 \end{aligned}$$

The Orun and Natarajan's model assumes $\phi$ and $\omega$ to be constant and other parameters as the above equations. The Gupta and Hartley's model relates the images coordinates $(u,v)$ and the coordinates of an object point $(X,\ Y,\ Z)$ by a $3 \times 4$ projection matrix **M** as below

$$\begin{pmatrix} u \\ vw \\ w \end{pmatrix} = \mathbf{M} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$

where $w$ is a scale factor.

The newly developed sensor model uses rigorous orbit models and the Earth reference models. It also uses the coordinate system developed for satellite orbit and attitude control. Since the formulation of the newly developed camera model is lengthy, this paper will not reproduce such formulation. The exact formulation can be referred to Shin and Lee (1997).

Table 1. A summary of performance analysis of the four sensor models

| | Gugan & Dowman's | Orun & Natarajan's | Gugan & Hartley's | Shin & Lee's |
|---|---|---|---|---|
| Minimum no. of GCPs required | 8 points | 6 points | 4 points | 3 points |
| Major advantage | – | Accurate sensor models are established | No scene-specific information is required | Accurate model with small no. of GCPs |
| Major disadvantage | High correlation between estimation | Scene header information is required | Highly inaccurate for independent check points | Information on satellite orbit dynamics is required |

These four models were tested using SPOT images and ground control points obtained from 1:50,000 topographic maps[3]. Table 1 summarizes the results. As Orun and Natarajan has pointed out (1994), there exists high correlation between the along-track position of the platform ($X_C$) and the pitch angle ($\phi$) and between the across-track position ($Y_C$) and the roll angle ($\omega$) in the Gugan and Dowman's model. Due to this, an accurate sensor model could not be established. The test results supported the Orun and Natarajan's approach to remove such correlation. The Orun and Natarajan's model produced accurate results although the position and attitude of the platform obtained through their sensor model did not describe the true position and attitude.

The Gupta and Hartley's model has an advantage since their model requires little information on the platform and sensor. For given modelling points, this model produced successful results with little errors. However, the test results have shown that this model had serious errors for independent check points. It seems that this model tunes its estimation parameters only for modelling points. A $3 \times 4$ matrix is not sufficient to model linear pushbroom sensors. This is contradictory to the claims of Gupta and Hartley (1997).

The newly developed model also produced accurate results and showed robust performance with the presence of errors in modelling points or in measurements. However, this model requires very detailed information on satellite orbit coordinate systems, orbit dynamics and the Earth reference model.

Based on the performance analysis, it was concluded that the Orun and Natarajan's model and the newly developed model could be used as sensor models for linear pushbroom cameras.

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[3] Because details of performance analysis will be appeared in a separate paper, this paper will mention the results and conclusions obtained from the analysis.

These two models are currently being tested further to decide the optimum one in carrying out the KOMPSAT-1 mission with the EOC data. Most commercial software packages uses modified collinearity-based models similar to that of Orun and Natarajan's.

### 2) Stereo matching

Stereo matching is a crucial process to determine the overall performance of DEM generation. In order to generate a DEM, stereo matching must produce conjugate points densely distributed over the area of interest. Also, stereo matching needs to generate accurate results and to be robust to brightness inconsistency between stereo images.

Since the publication of the first computational model of human stereopsis (Marr and Poggio, 1979) there have been a lot of stereo matching techniques proposed to solve correspondence problems in many different applications. In topographic mapping, stereo matching techniques are considered to have a potential to replace traditional techniques to retrieve height information. However, the existing stereo matching techniques are somewhat lack of mechanisms to maintain accuracy and robustness. Research is being carried out actively to tackle this problem.

Generally, stereo matching techniques are classified into feature-based and area-based stereo matching according to the nature of objects that stereo matching is applied to. Feature-based matching applies correspondence problems to image features generated by some intelligent feature detection operators (Foerstner, 1994). PMF algorithm (Pollard et al., 1985) is a very well-known feature-based matching algorithm. Area-based matching applies correspondence problems to image points using the brightness values stored in the points.

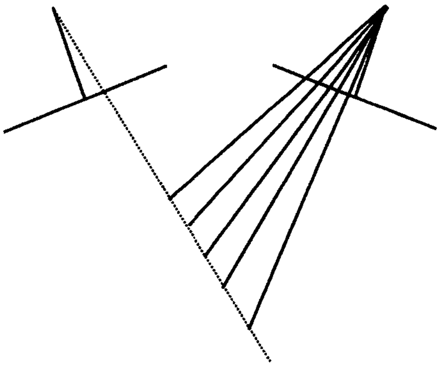

Fig. 3. The epipolar constraint

Area–based matching can be further divided into simple correlation matching and least squares correlation matching according to correlation schemes (Lemmens, 1988).

An important factor of stereo matching to determine the quality of a DEM is the mechanism to apply matching to the area of interest rather than the nature of objects. This is due to the requirement of dense height measurements distributed over the area of interest. For such mechanisms, relaxation (Barnard and Thompson, 1980, Pollard et al., 1984), dynamic programming (Maitre and Wu, 1988) and the use of epipolar constraint (Zhang et al., 1995) have been used.

In particular, the use of epipolar constraint has been used widely for stereo matching of aerial or laboratory images where there is one fixed principal point per one image. It is well–known that there exists the property of "epipolarity" between the left and right images in a stereo pair. "Epipolarity" can be stated as this: one point in the left (or right) image is mapped onto a unique curve in the right (or left) image. Figure 3 illustrates the epipolarity constraint. Suppose a beam of light is projected from the left camera center through a point in the image (the dashed line in the figure). Individual points lying on this beam can be mapped into the right image as points. If such points in the right image are combined, these will form a curve on the right image. This curve is called as an epipolar curve of the point in the left image. The corresponding point in the right image will always lie on the epipolar curve.

For aerial or laboratory images, it is very well known that epipolar curves are represented as lines. Hence when searching for a conjugate point in the right image for a given point in the left image, the search can be limited on the corresponding epipolar line (Zhang et al., 1995). This epipolar constraint can reduce the 2D search problem to 1D.

It is, however, not easy to derive epipolar curves for images from linear pushbroom sensors. Epipolar curves for such images are not represented as lines but in the form of non–linear equations. Due to this complicacy, some have concluded that there is no exact epipolar curves in such images (Otto, 1988). Otto and Chau (1991) has proposed a stereo matching algorithm without using the epipolar constraint and instead they used a region growing scheme similar to that used in region segmentation. Other stereo matching algorithms proposed use the epipolar constraint but with an assumption that epipolar curves for linear pushbroom images can be approximated as lines (Tateishi and Akutsu, 1992, Al–Rousan et al., 1997).

In order to develop a stereo matching algorithm for the EOC data, various stereo matching algorithms were tested. Test results indicated that feature–based matching such as the PMF could not generate as dense height measurement as required for DEM generation and that simple correlation matching could be a candidate but could not deliver appropriate quality control measures. Test results favored the use of least squares correlation matching (Kim and Lee, 1997).

Accordingly, a stereo matching algorithm was developed based on adaptive least squares correlation matching proposed by Gruen (1985). This algorithm is an iterative process and at each iteration, correlation between the left and right patch is computed and the shape of the right patch updated. This algorithm required 30*msec* to match one point and had a pull-in range of 3 to 4 pixels (Kim and Choi, 1997). This algorithm requires, at the beginning of matching, several seed points generated manually. After matching seed points, this algorithm utilizes the earlier match results to generate initial approximations for next match candidates, which are adjacent to the earlier match points.

An appropriate mechanism to apply matching over the area of interest is still under development. So far, Otto and Chaus algorithm which does not use the epipolar constraint has been implemented. A new mechanism which does use exact epipolar curves is also under development. To increase accuracy and robustness of match output, reliable match quality measures have been investigated (Kim et al., 1998). So far quality measures based on patch distortion, patch correlation and a fuzzy-based decision making have been developed (Lee et al., 1998). However, any concrete conclusion on the optimal mechanism for matching has not been made yet.

### 3) DEM interpolation

A DEM consists of regular spaced grids in a reference coordinate system and to each grid, height is assigned accordingly. The output from stereo matching is a list of points in 3D coordinates. These points, however, are scattered over the area of interest and not aligned with the desired regularly spaced grids. Interpolation is required to assign height on the grids from the scattered 3D points.

Interpolation can be divided into two kinds according to its characteristics (Lee, 1996). The first kind is smooth interpolation, which produces smooth height distributions among neighboring grids. The second one is exact interpolation, which assigns exact height of a sample point to a grid when the locations of the grid and the sample point coincide. A DEM created from smooth interpolation looks better as the DEM appears smooth. A DEM created from exact interpolation may look weird when the number of sample points is much less than that of grids but produces more accurate results.

For DEM interpolation techniques, four methods were compared; moving window averaging, Gaussian interpolation, nearest neighborhood interpolation and kriging (Kim, 1998). The first two are smooth interpolation and the third one exact interpolation. The last one is exact as well as smooth interpolation.

Moving window averaging assigns height to a grid by averaging height of the points located within a window centered on the grid with a given size. Gaussian interpolation can be considered as weighted moving window averaging, where weights are determined by a Gaussian function and the distance between the point and the grid. A formulation of Gaussian interpolation can be written as

$$\hat{H}(x_0) = \frac{\sum_{i=1}^{n} w(x_i - x_0) H(x_i)}{\sum_{i=1}^{n} w(x_i - x_0)}, \quad w(x) = \exp\left(-\frac{x^2}{\sigma^2}\right)$$

where $\sigma$ determines the width of a Gaussian curve. Nearest neighborhood interpolation assigns height to a grid as height of the sample point whose location is the nearest to the grid. Kriging can also be considered as weighted moving window averaging, where weights are determined by unbiased minimum variance estimation using correlation values between sample points (Wackernagel, 1995).

Test results with the four interpolation methods have shown that kriging produced the most accurate DEMs at all times (Kim, 1998). Nearest neighborhood interpolation produced the second most accurate DEMs when the number of sample points used for interpolation was more than 15% of the number of grids. When the number of sample points was less than 15%, Gaussian interpolation produced the second most accurate DEMs. Kriging, however, was the slowest among the four and required six minutes to generate a DEM with 800 × 600 number of grid points, whereas the fastest interpolation (nearest neighborhood interpolation) required half a minute to produce a DEM with the same size. The other two required slightly more time than nearest neighborhood interpolation.

Although kriging is the slowest interpolation method, the processing time is not significant compared with the time required for stereo matching. Therefore, it was concluded that kriging should be used for DEM interpolation.

## 4. An intermediate result of DEM generation from the proposed system

The proposed system has been tested with JERS and SPOT data and more tests will be carried out. Here, an intermediate result will be presented to assist the readers understandings on the issues the paper has discussed and the functionality of the proposed system.

Figure 4 shows the SPOT stereo pair used for a test. The left image was taken at 11:23 on October 20th, 1997 and the right at 11:12 on May 22nd, 1998. The tilt angle for the left image was 13.2° to the east and for the right one 10.2° to the west. The corresponding base–to–height ratio was about 0.4. Unfortunately, the quality of the right image was very bad. The image was very heavily contaminated by clouds and hazes. The quality of this stereo pair is not ideal for matching and such a pair should be replaced, if possible, to one in good quality for sensible DEM generation. However, one may face this situation when capturing stereo pairs with the EOC. Since DEM generation from this pair could be a real challenge for any DEM generation systems, the proposed system was tested with this pair.

Figure 5 shows the results of stereo matching from the proposed system. The adaptive least squares correlation algorithm together with the Otto and Chau's region growing mechanism was used for the test. Any human intervention was not involved in during stereo matching except for the identification of a few initial conjugate points. Blank regions in the figure represent the regions where match failed or match regions did not grow. The regions covered by clouds remain as blank, which indicates that the system did not produce positive false errors due to clouds. However, it is a little bit disappointing to observe the blank regions near the corners of the scene.

Using kriging, the stereo matching results in figure 5 were converted into a DEM. (see figure 6). Blank regions colored as black in figure 6 are those regions where there were no match points. This DEM seems to reproduce details of terrain patterns in many parts. However, it has some

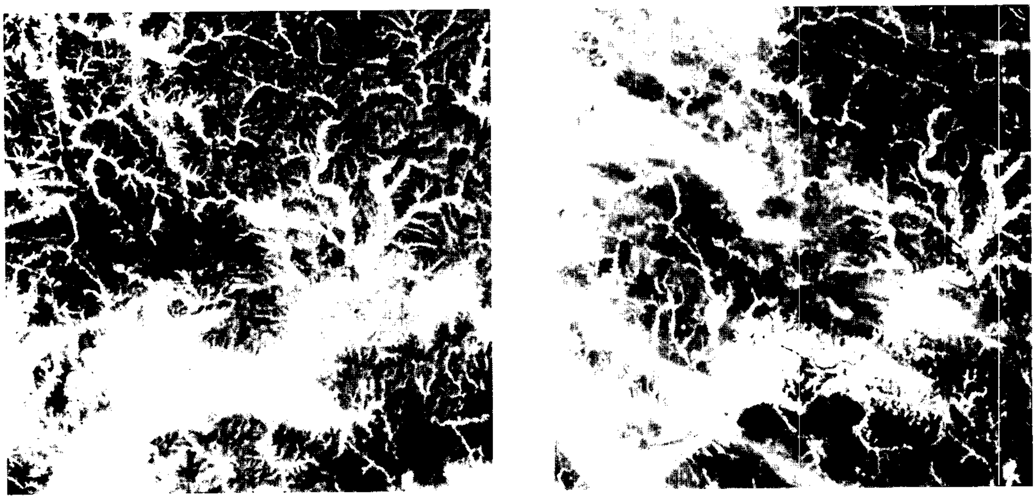

Fig. 4. A SPOT stereo pair used for tests

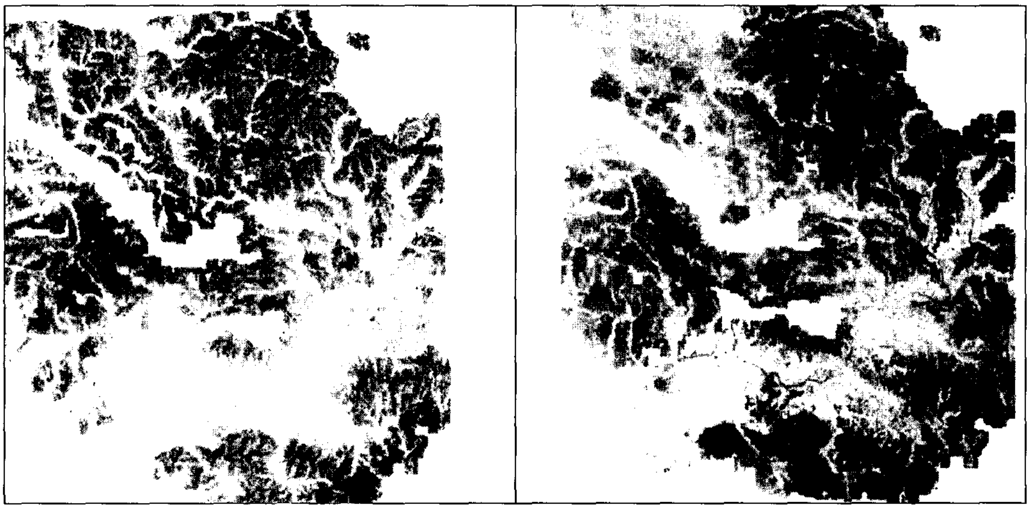

Fig. 5. The results of stereo matching

Fig. 6. A DEM created by the proposed system.

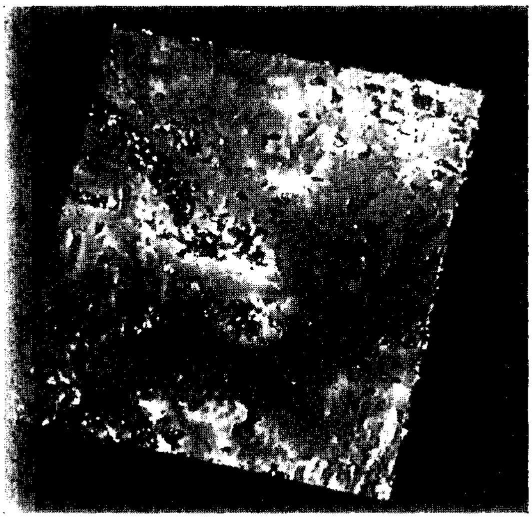

Fig. 7. A DEM created by PCI

erroneous peaks, which seems to come from errors in stereo matching output. Figure 7 shows a DEM generated from the same stereo pair using commercial software (PCI). The DEM in the figure 7 appears to have better coverage than the DEM in figure 6. This indicates that stereo matching modules in the PCI works better than those in the proposed system, in particular, at corners of the scene. The DEM in the figure 7 also has many erroneous peaks. It also has errors for the areas covered by clouds, whereas the DEM in figure 6 remained blank. This may indicate that stereo matching modules in the PCI software are sensitive to positive false errors due to clouds.

Since the stereo pair used was not in good quality, the DEMs in both figures were not in good quality either. However, it seems that the proposed system produced a comparable result to the commercial software. Although the DEM from the proposed system had less coverage than the one from the PCI software, this did not include cloudy and hazy regions where errors were likely to occur. A quantitative quality assessment of the two DEMs has yet to be carried out.

## 5. Conclusions and future work

This paper has shown the current status of the development of a DEM generation system from EOC data. The development is focused to tackle some expected difficulties due to the characteristics of EOC data. This paper discussed such difficulties and the approaches adopted in the proposed system. This paper divided the description of the development work into three parts of sensor modelling, stereo matching and DEM interpolation. In each part, this paper tried to explain the importance, brief literature review and current research trends of each topic.

As a paper to describe a DEM generation system as a whole, a large amount of detailed mathematical formulations and test results data are omitted. Instead, this paper tries to give the philosophy of the development of the proposed system.

The work described here is still in progress. Further efforts are required for finalizing stereo matching mechanisms and for integrating the three individual modules into a system. Overall system performance shall be analyzed with real EOC images and ground truth data.

## Acknowledgments

The work presented here is supported by the Ministry of Science and Technology of the Government of Korea. The authors appreciate Dr. Dongseok Shin for his work on the DEM development using the PCI software.

## Reference

Al-Rousan, N., Cheng, P., Petrie, G., Toutin, Th., Valadan Zoej, M.J., 1997, "Automated DEM

Extraction and Orthoimage Generation from SPOT Level 1B Imagery", *Photogrammetric Engineering and Remote Sensing*, 63(8):965-974

ASPRS, 1990, ASPRS Accuracy Standards for Large-Scale Maps, *Photogrammetric Engineering and Remote Sensing*, 56(7):1068-1070

Barnard, S.T., and Thompson, W.B., 1980, "Disparity Analysis of Image", *IEEE Trans. on Pattern Analysis and Machine Vision*, 2(4):333-340

Foerstner, W., 1994, "A Framework for Low Level Feature Extraction", Lecture Notes in Computer Science, *Computer Vision ECCV94 (Proc. Of Third European Conference on Computer Vision)*, 801:383-394, (ed.) J-O. Eklundh

Fritsch, D., Hahn, M., Kiefner, M. and Stallman, D., 1998, "Comprehensive Ground Truth Evaluation of MOMS-2P DTM Reconstruction", Proc. of ISPRS *Commission III symposium on Object Recognition and Scene Classification from Multispectral and Multisensor Pixels*, pp. 325-330, Columbus, Ohio, July 6-10

Gruen, A.W., 1985, "Adaptive Least Squares Correlation: A Powerful Image Matching Techniques", *South African Journal of Photogrammetry, Remote Sensing and Cartography*, 14(3):175-187

Gugan, D.J., 1987, "Practical Aspects of Topographic Mapping from SPOT Imagery", *Photogrammetric Record*, 12(69):349-355

Gugan, D.J. and Dowman, I.J., 1988, Accuracy and Completeness of Topographic Mapping from SPOT Imagery, *Photogrammetric Record*, 12(72):787-796

Gupta, R., and Hartley, R., 1997, Linear Pushbroom Cameras, *IEEE Trans. PAMI*, 19(9):963-975

Kim, T., 1998, "Comparisons of Various DEM interpolation Techniques", *Proc. of International Symposium on Remote Sensing (14th Fall Symposium of KSRS)*, pp.163-168, Kwangju, Korea, September 16-18

Kim, T. and Choi, S.D., 1997, "Selection of an Optimum Patch for an Area-Based Stereo Matching Algorithm", *Proc. of IGARSS 97*, vol. IV, pp. 1492-1494, Singapore, 4-8 August

Kim, T., Park W. and Lee, H.Y., 1998, "For Better Automation in DEM Generation from Satellite Images: Fuzzy Logic Approach for the Determination of Match Quality", *Proc. of ISPRS Commission III symposium on Object Recognition and Scene Classification from Multispectral and Multisensor Pixels*, pp. 127-131, Columbus, Ohio, July 6-10

Kim, T., and Lee, H-K., 1997, "Development of a New Patch-Based Stereo Matching Algorithm for Extraction of Digital Elevation Model from Satellite Imagery", *Journal of the Korean Society of Remote Sensing*, 13(2):121-132, (written in Korean)

Konecny, G., Lohmann, P., Engel, H. and Kruck, E., 1987, "Evaluation of SPOT Imagery on Analytical Photogrammetric Instruments", *Photogrammetric Engineering and Remote Sensing*, 53(9):1223-1230

Lee, Y.C., 1996, "A Study on the Interpolation Characteristics of the Scattered Geographic Data according to the Gridding Methods", *Journal of the Korean Society for Geo-Spatial Information System*, 4(2):173-180, (written in Korean)

Lee, H.Y., Kim, T., and Lee, H.K., 1998, More Efficient Method for Determination of Match Quality in Adaptive Least Square Matching Algorithm, Proc. of *International Symposium on Remote Sensing (14th Fall Symposium of KSRS)*, pp. 274-279, Kwangju, Korea, September 16-18

Lemmens, M.J., 1988, "A Survey on Stereo Matching Techniques", *Int. Archives of Photogrammetry and Remote Sensing*, 27(3):11-23, 1988

Longuet-Higgins, H.C., 1981, "A Computer Algorithm for Reconstructing a Scene from Two Projections", *Nature*, 293:133-135

Marr, D., and T. Poggio, 1979, "A Computational Theory of Human Stereo Vision", Phil. Trans. Royal Society, London, B-204:301-328

Maitre, H., and Wu, Y., 1989, "A Dynamic Programming Algorithm for Elastic Registration of Distorted Pictures based on Autoregressive Model", *IEEE Trans. on Acoustics, Speech, and Signal Processing*, 37(2):288-297

McGlone, C., 1996, "Sensor Modeling in Image Registration", *Digital Photogrammetry-An Addendum to the Manual of Photogrammetry*, edited by Greve, C., published by ASPRS, chapter 5, pp. 115-123

Orun, A.B. and Natarajan, K., 1994, "A Modified Bundle Adjustment Software for SPOT Imagery and Photography: Tradeoff", *Photogrammetric Engineering and Remote Sensing*, 60(12)1431-1437

Otto, G.P., 1988, "Rectification of SPOT Data for Stereo Image Matching", *Archives of the 16th Congress of International Society for Photogrammetry and Remote Sensing*, pp. 635-645, Kyoto, Japan, 1-10 July

Otto, G.P., and Chau, T.K., 1989, "A Region Growing Algorithm for Matching of Terrain Images", *Image and Vision Computing*, 7(2):83-94

Salamonowicz, P.H., 1986, "Satellite Orientation and Position for Geometric Correction of Scanner Imagery", *Photogrammetric Engineering and Remote Sensing*, 56(4):491-499

Pollard, S.B., Mayhew, J.E.W., and Frisby, J.P., 1985, PMF: A Stereo Correspondence Algorithm Using a Disparity Gradient Limit, *Perception*, 14:449-470

Shin, D. and Lee, Y-R., 1997, "Geometric Modelling and Coordinate Transformation of Satellite-Based Linear Pushbroom-Type CCD Camera Images", *Journal of Korean Society of Remote Sensing*, 13(2):85-98

Tateishi, R., and Akutsu, A., 1992, "Relative DEM Production from SPOT Data without GCP", *Int.*

*Journal of Remote Sensing*, 13(14):2517-2530

Wackernagel, H., 1995, "Multivariate Geostatistics", *Springer-Verlag*

Westin, T., 1990, Precision Rectification of SPOT ˈmagery, *Photogrammetric Engineering and Remote Sensing*, 56(2):247-253

Yeo, H-S., Han, D-Y., and Park K-H., 1998, "A Study on Producing Maps from Simulated KOMPSAT Ortho-Images", *Proc. of International Symposium on Remote Sensing (14th Fall Symposium of KSRS)*, pp. 331-341, Kwangju, Korea, September 16-18

Zhang, Z., Deriche, R., Faugeras, O., and Luong, Q-T., 1995, "A Robust Technique for Matching Two Uncalibrated Images through the Recovery of the Unknown Epipolar Geometry", *Artificial Intelligence*, 78(1995):87-119