A NEW EPIPOLARITY MODEL BASED ON THE SIMPLIFIED PUSHBROOM SENSOR MODEL

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ABSTRACT:

This paper addresses the epipolar geometry of linear pushbroom imagery. Two images of a single scene are related by epipolar geometry which contain all geometric information and is essential for the three dimensional reconstruction of the scene in computer vision and remote sensing. It is told that the epipolar geometry of the linear pushbroom sensor is different from that of the perspective one. In this paper, we propose an epipolarity model which does not require the ephemeris data but shows high performance (in accuracy, processing time, etc.). We also quantitatively analyse various epipolarity models such as the epipolar geometry of perspective and aerial imagery, the one by Gupta and Hartly and the one based on the Orun and Natarajan sensor model. To analyze the accuracy of the proposed epipolarity model and others, we quantitatively measure the distance between the truth point and epipolar lines on two types of linear pushbroom images; SPOT and KOMPSAT. The results show that the epipolarity model based on the Orun and Natarajan sensor model is more accurate than that of perspective sensor and by Gupta and Hartly because the ephemeris data of the satellite image is applied. The proposed epipolarity model shows a high accuracy similar to that of the Orun and Natarajan sensor model without the ephemeris data. Our epipolarity model will be very useful when the ephemeris data are not available such as IKONOS images or are not accurate.

1. INTRODUCTION

In general, two or more images of a single scene are related by the so-called epipolar geometry. Since the epipolar geometry contains all geometric information that is necessary for establishing correspondence, it is commonly used for the extraction of three-dimensional information in computer vision, photogrammetry and remote sensing.

The epipolar geometry means that a point (*a*) in the image is mapped to the point on the known linear line (epipolar line) or non-linear curve (epipolar curve) in the other image (refer figure 1). In case of aerial and perspective imagery, the epipolar geometry is mathematically well founded and widely used in computer vision and aerial photogrammetry [Zhang, 1998]. In case of linear pushbroom imagery, however, the epipolar geometry is modelled as very complex non-linear equations and, based on the reviews, depends on the sensor model. It is also told, but not proved, that the epipolar geometry of perspective imagery cannot be applied to linear pushbroom imagery [Kim, T. 2000]. Details of the epipolar geometry are described in section 2.

In this paper, we propose a new epipolarity model based on the simplified pushbroom sensor model, proposed by Gupta and Hartly, which does not require the ephemeris data but show high performance (processing time, accuracy, etc.). We also verified the accuracy of the proposed epipolarity model in comparison with other models for linear pushbroom imagery; (1) the epipolarity model of perspective and aerial imagery, (2) the one by Gupta and Hartly and (3) the one based on the Orun and Natarajan sensor model.

For the quantitative analysis of the epipolarity models, we used 20 ground control points, measured using GPS receiver, as modelling points and 30 conjugate pairs, accurately extracted by an experienced operator, as independent checking points on two types of linear pushbroom imagery, SPOT and KOMPSAT stereo image pairs.

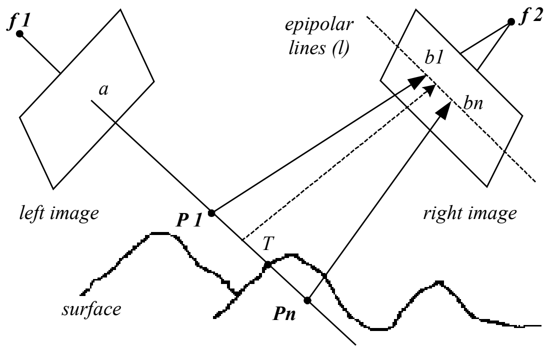

Figure 1. The relation among sensor, image and objects.

Based on the results, the epipolarity model of perspective imagery and by Gupta and Hartly show the mean accuracy below 1 pixel although the error on several checking points was large. The epipolarity model based on the Orun and Natarajan sensor model is more accurate than that of perspective imagery and by Gupta and Hartly. The accuracy of the proposed epipolarity model is considerably high and similar to that of the epipolarity model based on the Orun and Natarajan sensor model although the ephemeris data is not applied. It can be effectively applicable to the imagery which do not provide the ephemeris data such as IKONOS or when the quality of the ephemeris data is low.

In section 2, the epipolarity models for perspective imagery and linear pushbroom ones are reviewed. Section 3 describes our proposed epipolarity model. In section 4, the results of experiments are shown and discussed.

2. VARIOUS EPIPOLARITY MODELS

EPIPOLAR GEOMETRY OF PERSPECTIVE AND AERIAL IMAGERY

The epipolar geometry of perspective and aerial imagery is mathematically well founded and has been extensively studied in computer vision and aerial photogrammetry. In these images, the epipolar geometry is modeled as a 3x3 singular matrix called as a fundamental matrix shown below.

$$\begin{pmatrix} x_r & y_r & 1 \end{pmatrix} \begin{pmatrix} f_{11} & f_{12} & f_{12} \\ f_{21} & f_{22} & f_{23} \\ f_{31} & f_{32} & f_{33} \end{pmatrix} \begin{pmatrix} x_l \\ y_l \\ 1 \end{pmatrix} = 0$$

Where, (x_l, y_l) and (x_r, y_r) is the coordinates of each image points and the matrix has only seven degrees of freedom.

The matrix can be represented as below.

$$k_1 x_r + k_2 y_r + k_3 = 0$$

Where,

$k_1 = f_{11}x_l + f_{12}y_l + f_{13}$,

$k_2 = f_{21}x_l + f_{22}y_l + f_{23}$,

$k_3 = f_{31}x_l + f_{32}y_l + f_{33}$.

This equation implies that a point in the one image is projected to points on the line called epipolar line in the other image. By selecting over 7 conjugate pairs, this matrix can be calculated using various numerical solutions such as, Gauss-Jordan, LU decomposition and Singular value decomposition [Zhang, 1998]. To increase the accuracy of the modelling, the extensive research such as the normalization of input data or the rank2 constraints, etc., is performed.

EPIPOLAR GEOMETRY BASED ON THE GUPTA AND HARTLY SENSOR MODEL

In case of linear pushbroom sensor, differently from perspective sensor, its position and attitude change during the acquisition moment. Hence, its modeling called as a sensor model is very difficult and computationally expensive. By assuming the linear movement and the constant attitude of sensor, Gupta and Hartly propose a simplified pushbroom model[1], which can be calculated from ground control points without the ephemeris data. They also described its epipolarity model.

The epipolar geometry by Gupta and Hartly is represented as a 4x4 singular matrix called as LP fundamental matrix as against that of perspective imagery. This matrix is shown below.

$$\begin{pmatrix} x_r & x_r y_r & y_r & 1 \end{pmatrix} \begin{pmatrix} 0 & 0 & f_{13} & f_{14} \\ 0 & 0 & f_{23} & f_{24} \\ f_{31} & f_{32} & f_{33} & f_{34} \\ f_{41} & f_{42} & f_{43} & f_{44} \end{pmatrix} \begin{pmatrix} x_l \\ x_l y_l \\ y_l \\ 1 \end{pmatrix} = 0$$

Where, (x_l, y_l) and (x_r, y_r) is the coordinates of each image points and it contains no more than eleven degrees of freedom. Similar to that of perspective imagery, the solution can be acquired using over 11 corresponding points.

This matrix can be represented as below.

$$k_1 x_r + k_2 x_r y_r + k_3 y_4 + k_4 = 0$$

Where,

$k_1 = c_1 y_l + c_2$,

$k_2 = c_3 y_l + c_4$,

$k_3 = (c_5 x_l + c_6) y_l + (c_7 x_l + c_8)$,

$k_4 = (c_9 x_l + c_{10}) y_l + (c_{11} x_l + c_{12})$.

From this equation, we can certain that the epipolar geometry by Gupta and Hartly is represented as a hyperbola curve, called as an epipolar curve. This means that a point in the image is mapped to points on the non-linear curve, differently from that of perspective imagery, in the other image. We must note the fact that it is represented as first-order polynomials for along-track and across-track, respectively. Similar to that of perspective imagery, the solution can be calculated from a set of corresponding points using numerical solutions. In general, this non-linear equation is approximated as a piece-wise linear-line for the practical use.

EPIPOLAR GEOMETRY BASED ON THE ORUN AND NATARAJAN SENSOR MODEL

As explained previously, the position and attitude of linear pushbroom sensor changes during the acquisition moment. Orun and Natarajan model the position as second-order polynomials, the yaw variations as second-order polynomials, and the pitch and roll angles as constants in the attitude[2]. Differently from the Gupta and Hartly sensor model, the Orun and Natarajan sensor model necessarily needs ground control points and the ephemeris data for the calculation. Although this sensor model is mathematically complex and computationally expensive, its accuracy is high. Most of commercial software packages are based on this sensor model as well [Orun and Natarajan, 1994].

The epipolar geometry based on the Orun and Natarajan sensor model is represented as a mathematical equation shown below [Kim, 2000].

$$y_r = \frac{k_1 x_l + k_2 y_l + k_3}{(k_4 x_l + k_5 y_l + k_6)\sin Q(x_r) + (k_7 x_l + k_8 y_l + k_9)\cos Q(x_r)}$$

Where, (x_l, y_l) and (x_r, y_r) are the coordinates of each image points, respectively, k_1~k_9 are constants and $Q(x_r)$ is a quadratic polynomial of x_r.

[1] In this paper, we will call this model as the Gupta and Hartly sensor model.

[2] In this paper, we will call this model as the Orun and Natarajan sensor model

In this equation, we can find that the epipolar geometry of the Orun and Natarajan sensor model is a hyperbola-like equation. Although this model is considerably accurate, the ephemeris data is necessarily required. Therefore, this epipolarity model cannot be applied to images if the ephemeris data is not provided, for example IKONOS or its accuracy is low. Similar to that of the Gupta and Hartly sensor model, it is approximated as a linear line for the practical use.

3. PROPOSED EPIPOLARITY MODEL

In this section, we propose another epipolarity model based on the Gupta and Hartly sensor model, which does not require the ephemeris data but show high performance (processing time, accuracy, etc.). To derive the epipolarity model between two images (called as left and right image, respectively), let the Gupta and Hartly sensor model for each images be shown as below.

$$x_l = A_0X + A_1Y + A_2Z + A_3$$
$$y_l = \frac{A_4X + A_5Y + A_6Z + A_7}{A_8X + A_9Y + A_{10}Z + A_{11}} \quad (a)$$
$$x_r = B_0X + B_1Y + B_2Z + B_3$$
$$y_r = \frac{B_4X + B_5Y + B_6Z + B_7}{B_8X + B_9Y + B_{10}Z + B_{11}} \quad (b)$$

In the left pusbroom model (*a*), equations can be represented about *X* and *Y* as below.

$$X = \frac{(k_1y_l + k_2)Z + (k_3x_ly_l + k_4x_l + k_5y_l + k_6)}{i_1y_l + i_2}$$
$$Y = \frac{(j_1y_l + j_2)Z + (j_3x_ly_l + j_4x_l + j_5y_l + j_6)}{i_1y_l + i_2} \quad (c)$$

Where, k_1~k_6, i_1~i_2 *and* j_1~j_6 are constants.

By applying (*c*) to the right pushbroom model (*b*), we can write the right pushbroom model as below.

$$(m_1y_l + m_2)Z = m_3x_ry_l + m_4x_r + m_5x_ly_l + m_6x_l + m_7y_l + m_8$$
$$y_r = \frac{(n_1y_l + n_2)Z + (n_3x_ly_l + n_4x_l + n_5y_l + n_6)}{(n_7y_l + n_8)Z + (n_9x_ly_l + n_{10}x_l + n_{11}y_l + n_{12})}$$

Where, m_1~m_8 and n_1~n_{12} are constants.

Combining two equations, we can derive a new equation as shown below.

$$y_r = \frac{(c_1y_l^2 + c_2y_l + c_3)x_r + (c_4x_l + c_5)y_l^2 + (c_6x_l + c_7)y_l + (c_8x_l + c_9)}{(d_1y_l^2 + d_2y_l + d_3)x_r + (d_4x_l + d_5)y_l^2 + (d_6x_l + d_7)y_l + (d_8x_l + d_9)}$$

Where, (x_l, y_l) and (x_r, y_r) are the coordinates of each image points, respectively and c_1~c_9 and d_1~d_9 are constants.

This is our proposed epipolarity model and can be written as below.

$$k_1x_r + k_2x_ry_r + k_3y_4 + k_4 = 0$$

Where,

$k_1 = c_1y_l^2 + c_2y_l + c_3,$

$k_2 = d_1y_l^2 + d_2y_l + d_3,$

$k_3 = (d_4x_l + d_5)y_l^2 + (d_6x_l + d_7)y_l + (d_8x_l + d_9),$

$k_4 = (c_4x_l + c_5)y_l^2 + (c_6x_l + c_7)y_l + (c_8x_l + c_9).$

The proposed epipolarity model is a non-linear hyperbola curve and similar to that by Gupta and Hartly in section 2.2. However, differently from that by Gupta and Hartly, the along-track (y_l) is represented as second-order polynomials in the proposed model. If we ignore the second term (y_l^2), we can sure that the proposed model becomes the one by Gupta and Hartly. As against that of Gupta and Hartly, the proposed epipolarity model can be represented as a 4x6 matrix shown below.

$$(x_r, x_ry_r, y_r, 1)\begin{pmatrix} 0 & f_{12} & 0 & f_{14} & f_{15} & f_{16} \\ 0 & f_{22} & 0 & f_{24} & f_{25} & f_{26} \\ f_{31} & f_{32} & f_{33} & f_{34} & f_{35} & f_{36} \\ f_{41} & f_{42} & f_{43} & f_{44} & f_{45} & f_{46} \end{pmatrix}\begin{pmatrix} x_ly_l^2 \\ y_l^2 \\ x_ly_l \\ y_l \\ x_l \\ 1 \end{pmatrix} = 0$$

Where, (x_l, y_l) and (x_r, y_r) are the coordinates of each image points, respectively. The proposed epipolarity model can be calculated using only conjugate pairs without ground control points and the ephemeris data.

4. EXPERIMENTAL RESULTS

The proposed epipolarity model is verified using two types of linear pushbroom imagery; SPOT "Taejon" and "Boryung" panchromatic images and KOMPSAT "Taejon" and "Nonsan" EOC (Electro-optical) images over Korea. The resolution of SPOT is 10 meters and its swath is 60 kilometers. The resolution of KOMPSAT is 6.6 meters and its swath is 17 kilometers. Details of scenes are summarized in table 1.

The performance of the proposed epipolarity model is compared with those of three other models; (1) the epipolarity model of perspective and aerial imagery, (2) the one by Gupta and Hartly and (3) the one based on the Orun and Natarajan sensor model described in section 2.1, 2.2 and 2.3, respectively.

20 conjugate pairs taken from 20 ground control points are used to calculate the epipolarity model of perspective and aerial images and the one by Gupta and Hartly. The proposed

Table 1. The information of SPOT and KOMPSAT stereo image pairs

		SPOT Boryung	SPOT Taejon	KOMPSAT Taejon	KOMPSAT Nonsan
Left Scenes	Acquisition time	Mar. 1 1997	Nov. 15 1997	Mar. 9 2000	May 1 2000
	Viewing angle	-25.8	4.2	26.0	19.456
Right Scenes	Acquisition time	Nov. 15 1998	Oct. 14, 1997	Mar. 1 2000	April 28 2000
	Viewing angle	0.6	25.8	-4.0	-12.305

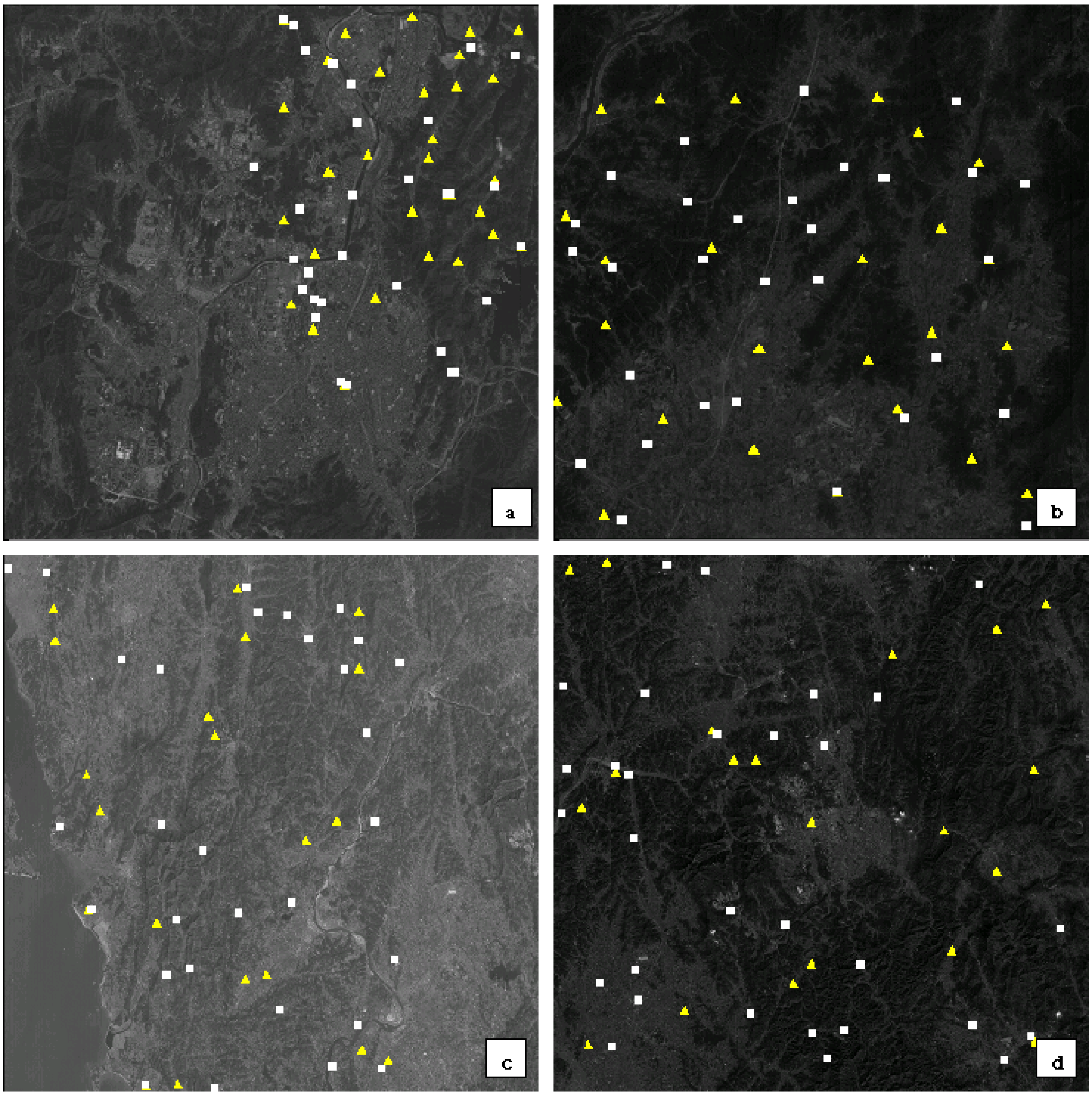

Figure 2. The distribution of modeling and checking points (Modeling : triangle, Checking, rectangular). (1) KOMPSAT Taejon, (2) KOMPSAT Nonsan, (3) SPOT Taejon, (4) SPOT Boryung

epipolarity model is computed using 20 ground control points and the one based on the Orun and Natarajan sensor model is acquired from the ephemeris data of the satellite images and 20 ground control points.

For the quantitative assessment of the accuracy, we devise a robust method which measure the minimum distance between the truth point and the epipolar lines. Except the epipolar geometry of perspective imagery, the epipolar geometry is represented as a non-linear curve in other models. To apply this measure, we estimated a non-linear curve as a linear one because a non-linear curve can be regarded as a linear line in locally [Kim, 2000]. We take 30 corresponding points, accurately extracted by an experienced operator, as independent checking points. The checking and modelling points are distributed to entire images as shown in figure 2.

The results are summarized in table 2. The errors of 30 independent checking points are shown in figure 3, 4, 5 and 6. As shown in the results, the epipolarity model of perspective and aerial imagery and by Gupta and Hartly show the average accuracy below 1 pixel although the errors on several checking points are large. We think that the epipolarity model of perspective imagery can be applicable to linear pushbroom imagery. To clarify the results, more experiments are necessary using various linear pushbroom images. The epipolarity model based on the Orun and Natarajan sensor model show high accuracy than that of perspective images and by Gupta and Hartly. However, this model cannot be computed without the ephemeris data. The accuracy of the proposed epipolarity model is considerably high and similar to that based on the Orun and Natarajan sensor model although the ephemeris data is not applied. The proposed model is also not so computationally expensive. It means that the proposed epipolarity model can be effectively applicable to the imagery which do not provide the ephemeris data such as IKONOS or when the quality of the ephemeris data is low. In this experiments, the proposed epipolarity model is derived using ground control points. However, it can be acquired from only conjugate pairs as described in section 3.

5. CONCLUSIONS

In this paper, we proposed a new epipolarity model which does not require the ephemeris data but show high performance (accuracy, processing time, etc.). We also quantitatively analyzed various epipolarity models to verify the applicability for linear pushbroom imagery.

The analysis of the proposed epipolarity models and others are performed using two types of linear pushbroom imagery; SPOT and KOMPSAT. The results show that the proposed epipolarity model can model the epipolar geometry of linear pushbroom

images although the ephemeris data is not used. It means that the proposed epipolarity model is effectively applicable to the

linear pushbroom imagery which does not provide the ephemeris data because of various reason for example IKONOS, etc.

In this paper, we verified the proposed epipolarity model on two types of linear pushbroom imagery; SPOT and KOMPSAT. However, we think that the proposed model will work in other types of linear pushbroom images. Our future research is focused on applying the proposed and other models to the reconstruction of the digital elevation model. We will report results of such experiments in the future.

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Table 2. Performance analysis for each epipolarity models (in pixels)

		Perspective Epipolarity model	Gupta and Hartly Epipolarity model	Proposed Epipolarity model	Orun and Natarajan Epipolarity model
SPOT Boryung	MEAN	0.309	0.358	0.275	0.240
	STD. D	0.190	0.223	0.178	0.177
	RMS	0.363	0.422	0.327	0.298
SPOT Taejon	MEAN	0.716	0.924	0.299	0.504
	STD. D	0.669	0.701	0.222	0.392
	RMS	0.981	1.160	0.373	0.639
KOMPSAT Nonsan	MEAN	0.509	0.519	0.528	0.505
	STD. D	0.377	0.452	0.340	0.336
	RMS	0.634	0.689	0.629	0.607
KOMPSAT Taejon	MEAN	0.537	0.568	0.521	0.498
	STD. D	0.267	0.365	0.302	0.244
	RMS	0.600	0.676	0.602	0.554

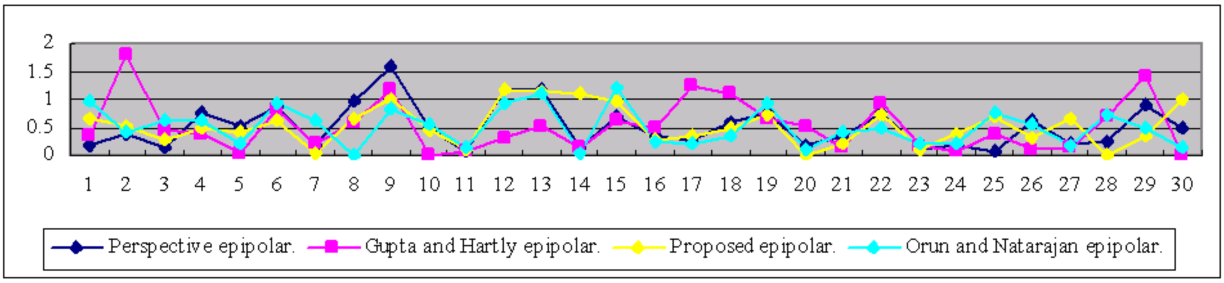

Figure 3. The errors for each independent checking points in SPOT Boryung area (in pixels)

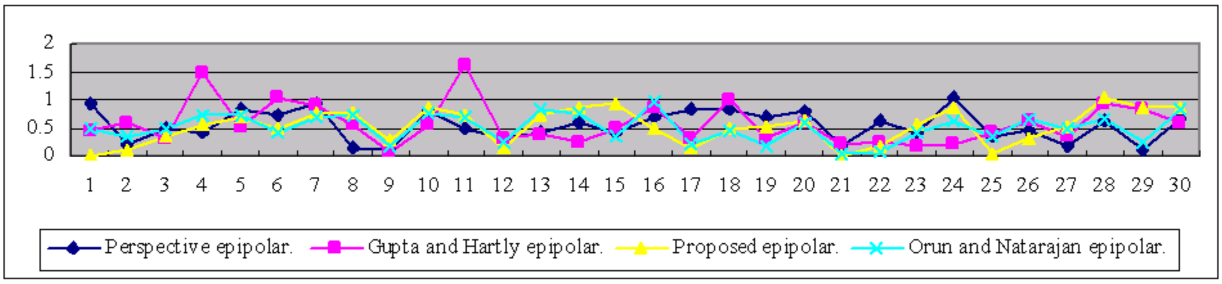

Figure 4. The errors for each independent checking points in SPOT Taejon area (in pixels)

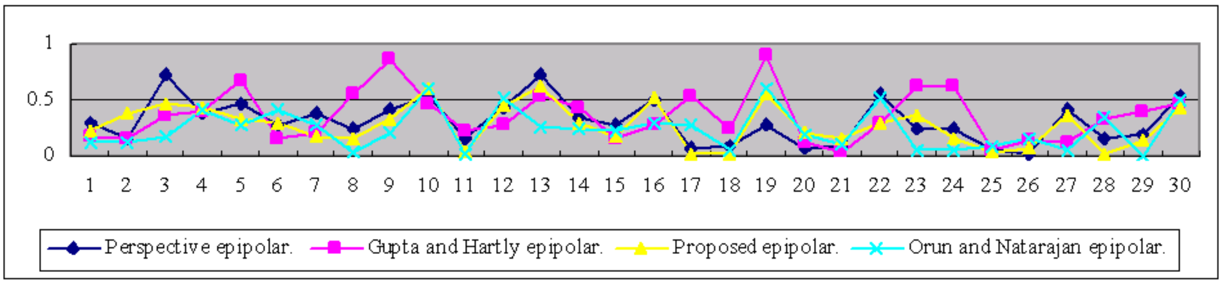

Figure 5. The errors for each independent checking points in KOMPSAT Nonsan area (in pixels)

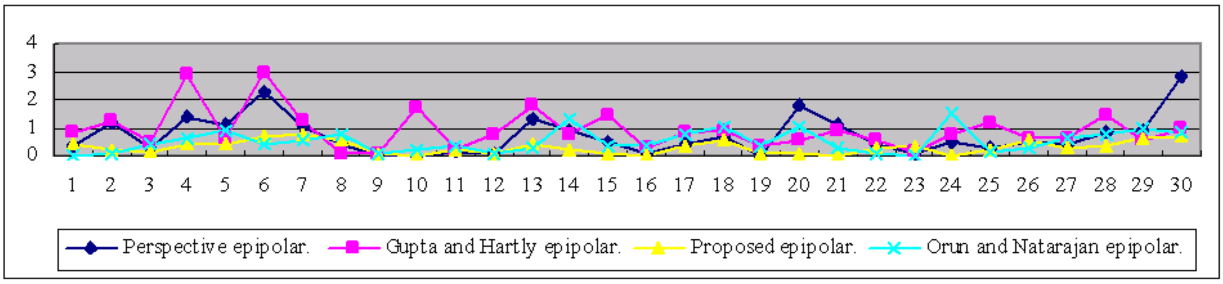

Figure 6. The errors for each independent checking points in KOMPSAT Taejon area (in pixels)