A Feature Based Generic Model for Georeferencing of High Resolution Satellite Imagery

FARHAD SAMADZADEGAN[1], SARA SAEEDI[1], TONI SHENK[2]
[1]Dept. of Surveying and Geometrics, Faculty of Engineering,
University of Tehran,
North Amir-Abad- Faculty of Engineering -Tehran,
IRAN

[2]Dept. of Geomatics,
Ohio State University,
USA

Abstract: - Geo-referencing through rectification remains to be one of the challenging problems in remote sensing and various imagery applications such as image pose estimation, image to Object Registration and 3D map generation. Rigorous mathematical models with the aid of satellite ephemeris data can present the relationship between the image space and object space. With government funded satellites, access to calibration and ephemeris data allowed the development of these models. However, for commercial high-resolution satellites, these data have been withheld from users, and therefore alternative empirical rectification models have been developed. In general, most of these models are based on the use of control points. Visibility and uniqueness of distinct control points in the input imagery limit use of this feature for robust Georeferencing procedure and provide a catalyst for the development of algorithms based on other image features. Recent advances in digital photogrammetry and Remote sensing mandate adopting higher-level primitives such as control linear features for replacing traditional control points. Linear features can be automatically extracted from the image space. On the other hand, object space control linear features can be obtained from an existing GIS layer containing 3D vector data such as road network, or from terrestrial Mobile Mapping Systems.

In this paper, we present a new model named the Line Based Generic Model (LBGM), for Georeferencing of High Resolution Satellite imageries. The model has the flexibility to either solely use linear features or control point to define the image transformation parameters. As with other empirical models, the LBGM does not require any sensor calibration or satellite ephemeris data. Synthetic as well as real data have been used to check the validity and fidelity of the model, and experimental results proved the feasibility and robustness of LBGM approach, especially when compared to those obtained through traditional point based transformation models.

Key-Words: - Geo-referencing, Generic Sensor Model, Linear Feature, High-resolution, Satellite Imagery

1 Introduction

Point based math models have been, for several decades, used extensively in photogrammetry and remote sensing for sensor orientation, image rectification and terrain modeling. They are driven by connecting points in the image space and the corresponding points in the object space using rigorous or generic mathematical models. However, under many circumstances accurately identifying discrete conjugate points may not be possible. Unlike point features, which must be explicitly defined, linear features have the advantage that they can be implicitly defined by any segment along the line. In the era of digital imagery, linear features can be easily identified in the image by many automatic extraction tools and in object space, they can be obtained from an existing GIS database, hardcopy maps, and terrestrial mobile mapping systems (using for instance kinematics GPS techniques). Therefore, using linear features becomes an advantage, especially because they add more information, increase redundancy, and improve the geometric strength of adjustment [6].

Mulawa and Mikhail [12] present the concept of linear features in photogrammetric tasks in which linear features and photogrammetric observations are combined in the formulation. Kanok [8] and Mikhail and Kanok [10] have used an independent set of linear feature descriptors to present the relationship between image space and object space. The method is based on the observation that any ray from the perspective center passing through a point on the image line must intersect the object line. In their approach, the standard point-based collinearity equations were replaced by line-circle based ones. Instead of the regularly used two collinearity equations, a single equation is established to ensure the coplanarity of a unit vector defining the object space line, the vector from the perspective center to a point on the object line, and the vector from the perspective center to a point on the image line. Furthermore, coordinate transformations are implemented on the basis of linear features. In this case, feature descriptors are related instead of point coordinates.

Nevertheless, in the absence of sensor calibration and satellite orbit information, there are several limitations in applying such techniques to High Resolution Satellite Imagery (HRSI). Some of these limitations are:

a) All those presented are based on rigorous mathematical models which require sensor and system parameters that are withheld from the HRSI user community;

b) When using linear features, rather than point features, conventional photogrammetric rules may not be appropriate [10];

c) Most of these models are valid for the projective geometry imagery of a photograph which is not exactly the case for linear array sensor imagery;

d) The models become quite complicated when modified for the geometry and time dependency characteristics of linear array scanners;

e) Numerical problems could be encountered because of the initial approximation; and finally,

f) Constraints improve accuracy of the adjustment and increase the redundancy in estimation but each constraint adds an additional parameter to the adjustment and multiple constraints may lead to over parameterization [6].

To date, there has been a substantial body of work dealing with non-rigorous mathematical models (such as rational functions, affine, polynomial, and DLT models) to circumvent the absence of satellite information and to rectify HRSI (see for example [2, 3]). These models are point based and have focused on two main aspects concerning accuracy: the accuracy attainable in image rectification, and the accuracy of DTM extraction by stereo spatial intersection. All reports demonstrate that the models described in them produce acceptable results.

It is obvious that linear features can be used with rigorous mathematical models but “Can linear features be used with non-rigorous mathematical models in order to circumvent the absence of satellite information and maintain satisfactory results?” This research answers the question with the development of a generic sensor model named the Line Based Generic Model (LBGM). With the LBGM, most of the problems of using linear features with the present generation of rigorous models have been overcome. The model can either solely use linear features as well as use control points to define the image transformation parameters. The underlying principle of the model is that the relationship between line segments of straight lines in the image space and the object space can be expressed by a rational model relationship.

2 The Mathematical Model

Successful exploitation of linear features in georeferencing of HRSI requires consideration of the following two major aspects: 1- the mathematical representation of linear features in image and object space, and, 2- the mathematical modeling of the relationship between the two spaces.

2.1 The Mathematical Representation of Linear Features

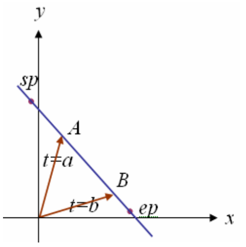
There are different approaches for representing linear features in both image and object space. Straight lines and free form lines are examples of such representation. Various forms of equations can represent straight and free form lines in two and three-dimensional spaces. In this work, we briefly describe about some methods for line representation in 2D or 3D spaces.

2.1.1 Line Representation in 2D Space

The best known Representation methods for parametric line in 2D space are Cartesian-parametric and polar-parametric form.

- **Cartesian-Parametric Form of 2D Lines**

In this representation, a line can defined with a point laid on this line and the direction vector. This form of representation doesn’t provide a unique definition of line (Figure 1).



Fig, 1: 2D Line Representation in the form of Cartesian Parametric

$$l(t)=\begin{bmatrix} x(t) \\ y(t) \end{bmatrix},$$
$$a \le t \le b \qquad (1)$$
$$x = x_{sp} + (x_{ep} - x_{sp})t$$
$$y = y_{sp} + (y_{ep} - y_{sp})t$$

In the above equations, t is the variable line parameter, (x_{sp}, y_{sp}) are the start point coordinates and (x_{ep}, y_{ep}) are the end point coordinates of line.

- **Polar-Parametric Form of 2D Lines**

In this representation, a line can defined with a length that is the minimum distance from line to the origin of coordinate system (ρ) and an angle between x-axis and line perpendicular from origin to the considerable line (θ).(Figure 2)

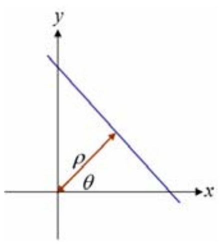


Fig. 2: 2D Line Representation in the form of Polar Parametric

$$x = \rho \cos\theta - t \sin\theta$$
$$y = \rho \sin\theta + t \cos\theta \qquad (2)$$

2.1.2 Line Representation in 3D Space

The main methods for parametric line representation in 3D space, are Cartesian-parametric and polar-parametric form. In this section have a quick look on these equation.

- **Cartesian-Parametric Form of 3D Lines**

In this representation, a line can defined with a point laid on this line and the direction vector in three dimension space. This form of representation doesn't provide a unique definition of line (Figure 3).

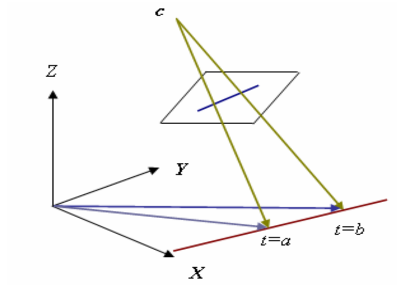


Fig. 3: 3D Line Representation in the form of Cartesian Parametric

$$L(t)=\begin{bmatrix} X(t) \\ Y(t) \\ Z(t) \end{bmatrix}, \; a \le t \le b \qquad (3)$$
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{SP} \\ Y_{SP} \\ Z_{SP} \end{bmatrix} + t \begin{bmatrix} X_{EP} - X_{SP} \\ Y_{EP} - Y_{SP} \\ Z_{EP} - Z_{SP} \end{bmatrix}$$

In the above equations, t is the variable line parameter, (X_{SP}, Y_{SP}, Z_{SP}) are the start point coordinates and (X_{EP}, Y_{EP}, Z_{EP}) are the end point coordinates of line.

- **Polar-four Parametric Form of 3D Lines**

In this representation, a line can defined with four parameters: Two angular parameters (φ, θ) that define the line orientation and two positional parameters (x_0, y_0) that are the position of the intersection of the line with a plane perpendicular to it. This provides a unique line representation (Figure 1) [13].

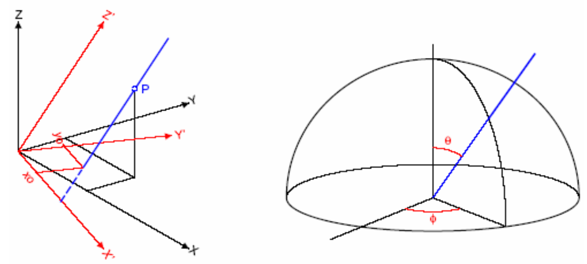


Fig. 4: 3D Line Representation in the form of Polar four Parametric

Any point laid on the line can be expressed according to equation (4).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_0 \cos\phi\cos\theta - y_0 \sin\phi + z \sin\theta\cos\phi \\ x_0 \sin\phi\cos\theta + y_0 \cos\phi + z\sin\theta\sin\phi \\ -x_0 \sin\theta + z\cos\theta \end{bmatrix} \qquad (4)$$

2.2 The Mathematical Representation of the Relationship Between the two Spaces

Successful exploitation of the high accuracy potential of HRSI depends on the ability of the mathematical formulation of the relationship between image and object space. In this direction, the requirement for the development of an efficient 2D/3D comprehensive sensor model formulation for various satellite images is a real challenge and has been investigated by different research groups [1, 13, 14, 15]. Mathematical formulations presented in these research works, may be divided into two main groups of *rigorous sensor models* (RSMs) and *generic sensor models* (GSMs).

RSMs reconstruct the spatial relations between remotely sensed imagery and the ground scene based on conventional collinearity equations. The method is highly suited to frame type sensors. Non-linear effects caused by lens distortion, film shrinkage or atmospheric effects are dealt with either by additional parameters or by a priori refinement process. The RSM models have proved to be quite appropriate for the sensor modeling provided that the influential physical factors are available with the required accuracy, (see for example [1]) .

However, in practice, these models have several limitations and drawbacks [1, 9, 15]. GSMs are presented as a sophisticated solution for overcoming the RSMs limitations.

GSMs use a set of general polynomials (or ratio of them) to establish the connection between images and object spaces. Formally, they equate *x* (row) and *y* (column) image coordinates to coefficients of some polynomials (often, first, second or third order) in *X*, *Y*, and *Z* object coordinates (typically latitude, longitude, and elevation):

$$\begin{cases} x_n = \dfrac{P_1(X_n,Y_n,Z_n)}{P_2(X_n,Y_n,Z_n)} = \dfrac{\sum_{i=0}^{m1}\sum_{j=0}^{m2}\sum_{k=0}^{m3} a_{ijk} X_n^{\,i} Y_n^{\,j} Z_n^{\,k}}{\sum_{i=0}^{m1}\sum_{j=0}^{m2}\sum_{k=0}^{m3} b_{ijk} X_n^{\,i} Y_n^{\,j} Z_n^{\,k}} \\ \\ y_n = \dfrac{P_3(X_n,Y_n,Z_n)}{P_4(X_n,Y_n,Z_n)} = \dfrac{\sum_{i=0}^{m1}\sum_{j=0}^{m2}\sum_{k=0}^{m3} c_{ijk} X_n^{\,i} Y_n^{\,j} Z_n^{\,k}}{\sum_{i=0}^{m1}\sum_{j=0}^{m2}\sum_{k=0}^{m3} d_{ijk} X_n^{\,i} Y_n^{\,j} Z_n^{\,k}} \end{cases} \tag{5}$$

where m_1, m_2, m_3 are maximum term orders of *X*, *Y* and *Z* components respectively, $p_1,\ldots,p_4$ are the transformation parameters and x_n, y_n, X_n, Y_n and Z_n are the normalized image and object coordinate given by the following equations:

$$x_n = \frac{x - x_0}{x_s},\quad y_n = \frac{y - y_0}{y_s},$$
$$X_n = \frac{X - X_0}{X_s},\ Y_n = \frac{Y - Y_0}{Y_s},\ Z_n = \frac{Z - Z_0}{Z_s} \tag{6}$$

where x_0 and y_0 are the offset values for the image coordinates; x_s, y_s are scale values; X_0,Y_0 and Z_0 are the offset values for the object coordinates and X_s, Y_s and Z_s are their corresponding scale values. A detailed description on this normalization process can be found in [9].

3 Proposed Method for the Line Based Generic Model (LBGM)

Georeferencing process aims to register image to object to achieve improved accuracies and better inference about the environment. An effective image Georeferencing methodology must deal with an effective transformation function that mathematically describes the mapping function between the images and object.

In this paper we use rational function for establish the relation between images and object space. The dominator for rational function in *x* and *y* component are equal. So we have these equations:

$$x = \frac{P_1(X,Y,Z)}{P_2(X,Y,Z)}\ ,\quad y = \frac{P_3(X,Y,Z)}{P_4(X,Y,Z)}\ ,$$
$$P_2(X,Y,Z) = P_4(X,Y,Z) \tag{7}$$

The next step is mathematically describes constraints for ensuring the correspondence of conjugate primitives. As mentioned earlier, the registration primitives, straight lines, will be represented by their end points, which need not be conjugate.

After applying the transformation function on the line segment in the input image (*AB*), Equation (8) mathematically describes the necessary constraint for one of the end points of the line segment (*a* or *b*) in the reference data (Figure 5).

$$F = x'\,cos(\theta) + y'\,sin(\theta) - \rho = 0 \tag{8}$$

where (ρ, θ) are the polar coordinates representing the line segment *cd* in the image, and

(x', y') are the transformed coordinates of point *a* in the object after applying the transformation function. Another constraint of the form in equation (8) can be written for point *b* along the line segment in the object (Figure 5).

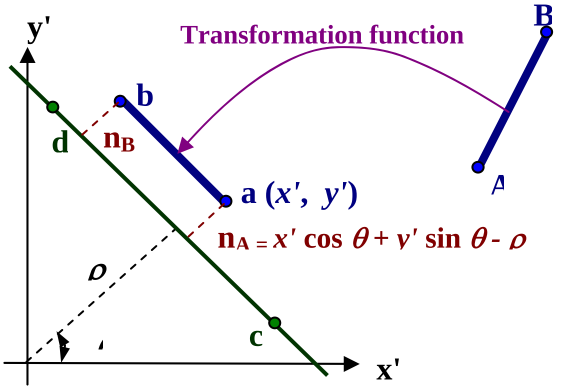


Fig. 5: Similarity constraints using straight-line segments.

3.1 Proposed LBGM Strategy

The lines $l_{sp\text{-}ep}$ and $L_{SP\text{-}EP}$ are used for displaying conjugate lines in image and object space respectively (Figure 6). These two lines can be defined by any two points along the line segment in image and object space. Suppose that point $sp=(x_{sp}, y_{sp})$ and $ep=(x_{ep}, y_{ep})$ are two points on the $l_{sp\text{-}ep}$ in image space and $SP=(X_{SP}, Y_{SP}, Z_{SP})$ and $EP=(X_{EP}, Y_{EP}, Z_{EP})$ are two points on the $L_{SP\text{-}EP}$ in object space.

$$l_{sp-ep}(x_{sp}, y_{sp}, x_{ep}, y_{ep}) \approx L_{SP-EP}(X_{SP}, Y_{SP}, Z_{SP}, X_{EP}, Y_{EP}, Z_{EP}) \quad (9)$$

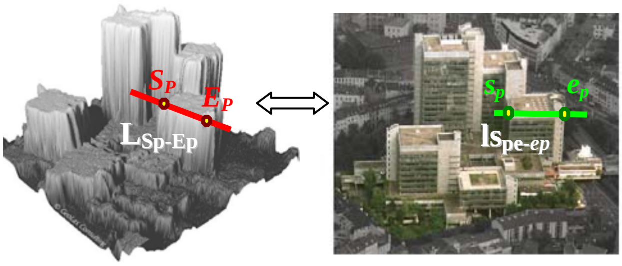


Fig. 6: LIDAR data and corresponding aerial image

It is worth mentioning that points *sp*, *ep* and *SP*, *EP* in image and object spaces are not conjugate points, but the lines they lie on are conjugate lines. So we have these equations:

$$\begin{cases} x_{Sp} \neq \dfrac{P_1(X_{SP}, Y_{SP}, Z_{SP})}{P_2(X_{SP}, Y_{SP}, Z_{SP})} \\ \\ y_{Sp} \neq \dfrac{P_3(X_{SP}, Y_{SP}, Z_{SP})}{P_4(X_{SP}, Y_{SP}, Z_{SP})} \end{cases}, \qquad 10$$

$$\begin{cases} x_{Ep} \neq \dfrac{P_1(X_{EP}, Y_{EP}, Z_{EP})}{P_2(X_{EP}, Y_{EP}, Z_{EP})} \\ \\ y_{Ep} \neq \dfrac{P_3(X_{EP}, Y_{EP}, Z_{EP})}{P_4(X_{EP}, Y_{EP}, Z_{EP})} \end{cases}, \qquad 11$$

For be able to solve orientation problem, must be establish equation in above equations. For overcome to this tree strategies will be considered.

$$\begin{aligned} & l_{sp-ep} \prec\!=\!\succ L_{S_P-E_P} \\ & s_p, e_p \prec\!=\!\succ L_{S_P-E_P} \\ & l_{sp-ep} \prec\!=\!\succ S_P, E_P \end{aligned} \qquad 12$$

First case says that using line equation in image and object spaces. This cause singularity in normal matrix, because many points on corresponding lines in two spaces will be true in the equations. So this case can't solve the line based orientation problem. The second case suggests selecting a point on image line and using line representation in object space. In this case solving the orientation problem will be very difficult or nearly impossible. Because of the equations versus unknowns will be nonlinear and need to initial values for unknowns. The rational coefficients has no geometric interpretation so the estimation of initial values for these parameter is difficult and if these initial values don't near to real values may cause normal equations don't convergence. So we use third case as an optimum solution.

3.2 Proposed Mathematical Model

As mentioned before, final mathematical model will be in below form:

$$F = \frac{P_1(X, Y, Z)}{P_0(X, Y, Z)} \cos\theta + \frac{P_3(X, Y, Z)}{P_0(X, Y, Z)} \sin\theta - \rho = 0 \Rightarrow \qquad 13$$

$$F = P_1(X, Y, Z)\cos\theta + P_3(X, Y, Z)\sin\theta - \rho \cdot P_0(X, Y, Z) = 0$$

For each line in image two line parameters (ρ, θ) are known. This can be calculated by using Hough transform or by consider at least 2 points of line and fit polar-parametric models to it. The object coordinate of any arbitrary point on the 3D line can be considered and used as (X, Y, Z). So in the equations (13) the rational coefficients are as unknowns. Each point laid on the line provides one equation. On each line the maximum points that can be used are equal two. This equation is linearized versus to unknown. So it can be solved easily.

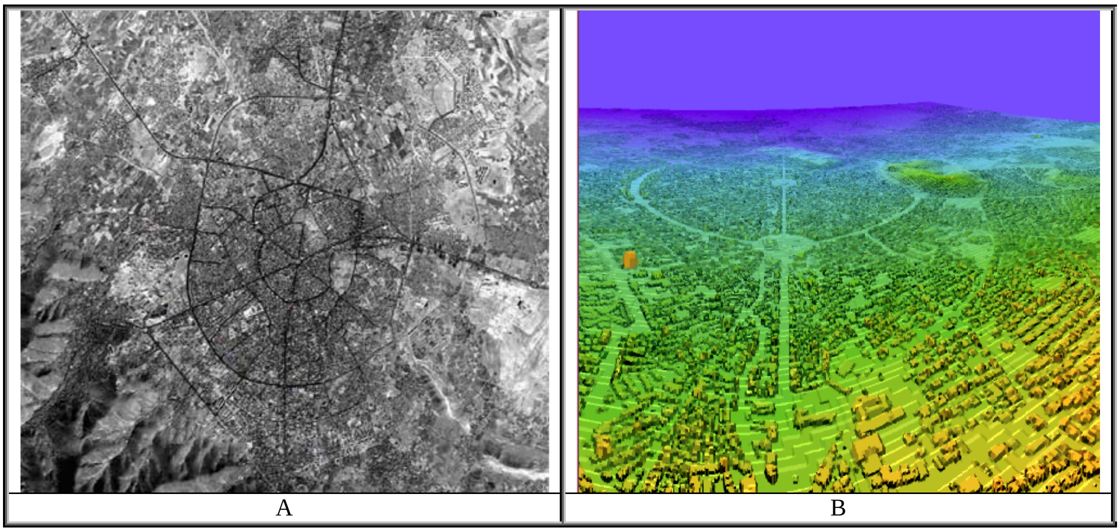


Fig. 7: (A) IKONOS Geo panchromatic image used for the evaluation of the proposed LBGM, (B) the corresponding 3D view of the area.

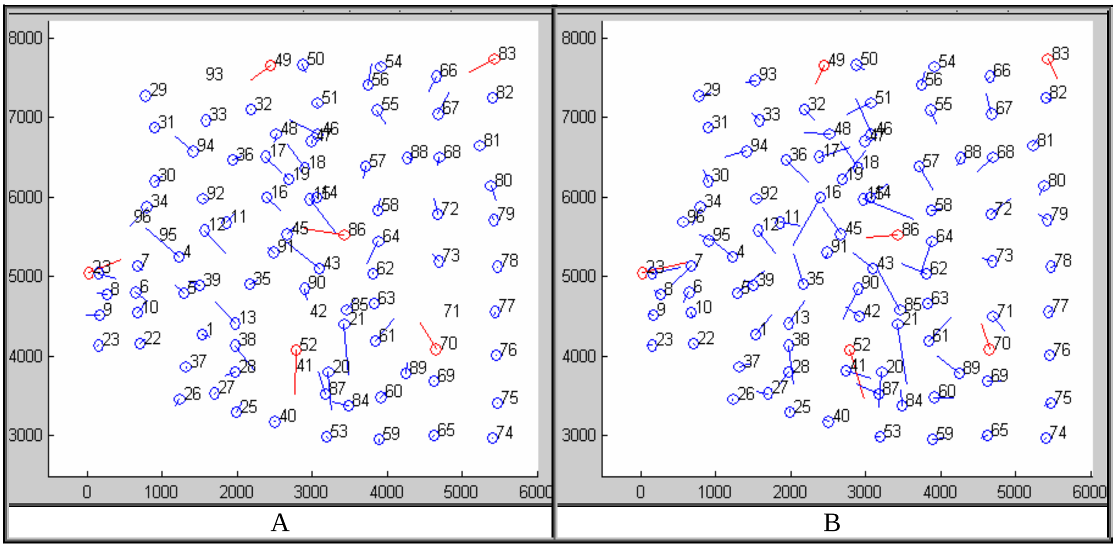


Figure 8. Residual vectors in image space, (A) using LBGM and (B) Point based method

4 Experimental Results

The potential of the proposed method for the line based generic model are evaluated through comprehensive experimental tests conducted on a wide variety of satellite imageries. In this paper the tests are conducted on Geo panchromatic IKONOS image with ground resolution of about 1 meter, which lies within the category of pushbroom type imageries with flexible structure. The test image was taken over the city of Hamadan, Iran on 10th of October, 2004. The relief variation in the area is in the range of 1700m to 2050m above sea level (ASL). To match with the resolution and accuracy of the image, the ground control points (GCPs), ground control lines (GCLs) and check points were extracted from 1:1000 scale maps. The expected control features accuracy is about ±30 centimeters according to the common mapping standards. Figure 7 shows the IKONOS image, the distribution of the check points and 3D view of the area generated from the corresponding digital map data-set.

4.1 Evaluation Strategy

To evaluate the optimization capability of our proposed approach, the following strategy is adopted. The line based generic modeling of the satellite imageries, were implemented; the transformation coefficients were calculated, using the already measured values of the GCPs, GCLs and incorporated into their respective mathematical models. The corresponding image coordinates of check points, control points in point based approach and points laid on the lines were computed with back projection, according to the mathematical models. The residual values between the measured image coordinates of the check points and their respective computed values in image space were then determined. The number of the measured GCPs and GCLs in the way selected that degree of freedom in orientation problem using points and using lines will be the same. The following sections report the results of the tests.

4.2 Performance Evaluation

In this section, the RMSE error on check points, and control points in image space calculated (Table 1). Also the residual vectors for each point will be displayed. In figures 8 the left part belongs to transformation parameters using LBGM and right part belong to transformation parameters using point based Method. The red points are check and blue points are showed control points and the points that laid on the lines (in line based approach).

Table 1: RMSE in image space in mm unit

	RMSE of Proposed LBGM			RMSE of Point Based Model		
	x	y	x,y	x	y	x,y
Control Point	0.150	0.180	0.234	0.209	0.223	0.306
Check Point	0.648	0.410	0.767	0.329	0.328	0.464

5 Conclusion and Future Work

The Feature Based Transformation Model is proposed for the georeferencing of high-resolution satellite imagery. This is an attempt to establish a new model, which can deal with linear features and/or linear features with a number of Point features. In this model, most of the problems encountered in previous models using linear features have been overcome. In addition, sensor calibration and satellite orbit information are not required.

Experiments with synthetic and real data have been conducted and the results prove the applicability of the new model for image rectification. It is a very simple model which is time independent, can be applied to images from any linear array sensor, does not require any information about sensor or any initial approximation values.

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