

COMPARATIVE TESTES OF MATHEMATICAL MODELS FOR ACCURACY POTENTIAL OF POINT MEASUREMENTS IN IKONOS GEO IMAGE

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ABSTRACT:

The number of high resolution satellite sensors for mapping applications is growing fast. Successful exploitation of the high accuracy potential of these systems depends on good mathematical models for the sensor modelling. High resolution image data increases the need for higher accuracy data modelling. The satellite orbit, position, attitude angles and interior orientation parameters have to be adjusted in the geometrical model to achieve optimum accuracy with the use of minimum number of Ground Control Points (GCPs). But most of high resolution satellite vendors do not intend to publish their sensor models and ephemeris data. At present, however, the necessary camera model and precise ephemeris data for Ikonos have not been published. There is consequently a need for a range of alternative practical approaches for extracting accurate terrain information from Ikonos imagery.

Geopositioning accuracy of Ikonos panchromatic Geo image is investigated in this paper. Rational functions, the DLT, SDLT, 2D projective equations, polynomials, 3D affine, multiquadric functions and thin plate spline methods have been applied in tests with Ikonos Geo image.

Also orbital parameters of Ikonos satellite have been estimated and an orbital parameter model has been expanded that cover the Ikonos Geo image. This Ikonos rigorous model uses basic information from the metadata and image file. This is followed by the results of various geometric accuracy tests carried out with Ikonos Geo image using different parameters (9, 12, 15) and combination of control and check points. The test area cover parts of West of Iran. For determining GCPs and independent check points (ICPs), 3D digital maps was used. Taking into account the quality of GCPs, for the Ikonos Geo, an optimal accuracy of 0.9 m was achieved using the orbital parameter model.

1. INTRODUCTION

After the successful launch and deployment of Ikonos-2 satellite in September 24, 1999, EROS-A1 in December 5, 2000, QuickBird-2 in October 18, 2001, SPOT5 in May 4, 2002 and OrbView 3 in June 26, 2003, the era of commercial high resolution earth observation satellites for digital mapping had began. Successful exploitation of the high accuracy potential of these systems depends on a comprehensive mathematical modeling of the imaging sensor. An orbital parameter model can be applied to stereo space imagery in order to determine exterior orientation parameters. Unfortunately the ancillary data (position, velocity vectors and angular rates) of the satellite platform have not been provided with Ikonos imagery, therefore alternative ways of camera modeling need to be employed. Recently, several 2D and 3D approaches have been reported to tackle this issue (Valadan and Sadeghian, 2003a, Sadeghian and Delavar, 2003; Dowman and Tao, 2002; Fraser et al., 2002a, 2002b; Valadan et al., 2002; Hanley and Fraser, 2001; Sadeghian et al., 2001a, 2001b; Tao and Hu, 2001, 2002). They do not require interior orientation parameters or orbit ephemeris information. The image to object space transformation solution is based only upon ground control points (GCPs). This is an advantage for processing the new high resolution satellite imagery (HRSI). In this paper the possibility of using non-rigorous and rigorous sensor models for 2D ground point determination from Ikonos Geo image is investigated.

2. ORIENTATION MODELS

At this writing, Space Imaging has refused to release information on the sensor model for Ikonos, as well as data on the precise in-flight position and attitude of the imaging sensor. This means that a large number of photogrammetric parameters are unknown and not readily determinable from the imagery alone. The very long focal length and narrow angle of view (0.93°) and swath (~11 km) will likely make an orbital resection unstable, and even if many GCPs and several images are used, an accurate solution might not be possible. There is consequently a need for a range of alternative, practical approaches for extracting accurate 2D and 3D terrain information from HRSI. In the following discussion, Rational functions, the DLT, SDLT, 2D projective equations, polynomials, 3D affine, multiquadric functions and thin plate spline method are evaluated as potential approximate sensor models to substitute for the rigorous physical sensor model. Also in this paper the possibility of using a rigorous model (orbital parameter modelling) for ground point determination were explored and investigated (Valadan and Sadeghian, 2003b). The orbital parameters and ephemeris data have been approximated from meta data, image file and celestial mechanics. These parameters then have been used in the orbital parameter modeling.

2.1 Rational Functions

Under the model, an image coordinate is determined from a ratio of two polynomial functions, in which the image (x,y) and ground coordinates (X,Y,Z) have all been normalized (OGC, 1999):

$$x = P1(X,Y,Z)/P2(X,Y,Z) = \frac{\sum_{i=0}^{m1} \sum_{j=0}^{m2} \sum_{k=0}^{m3} a_{ijk} X^i Y^j Z^k}{\sum_{i=0}^{n1} \sum_{j=0}^{n2} \sum_{k=0}^{n3} b_{ijk} X^i Y^j Z^k}$$

$$y = P3(X,Y,Z)/P4(X,Y,Z) = \frac{\sum_{i=0}^{m1} \sum_{j=0}^{m2} \sum_{k=0}^{m3} c_{ijk} X^i Y^j Z^k}{\sum_{i=0}^{n1} \sum_{j=0}^{n2} \sum_{k=0}^{n3} d_{ijk} X^i Y^j Z^k}$$

(1)

For example RFM with 14, 17 and 20 terms are as follows:

Rational with 14 terms:

$$x = \frac{a_0 + a_1X + a_2Y + a_3Z + a_4XY}{1 + c_1X + c_2Y + c_3Z + c_4XY} \quad (2)$$

$$y = \frac{b_0 + b_1X + b_2Y + b_3Z + b_4XY}{1 + c_1X + c_2Y + c_3Z + c_4XY}$$

Rational with 17 terms:

$$x = \frac{a_0 + a_1X + a_2Y + a_3Z + a_4XY + a_5Z}{1 + c_1X + c_2Y + c_3Z + c_4XY + c_5XZ}$$

$$y = \frac{b_0 + b_1X + b_2Y + b_3Z + b_4XY + b_5XZ}{1 + c_1X + c_2Y + c_3Z + c_4XY + c_5XZ} \quad (3)$$

Rational with 20 terms:

$$x = \frac{a_0 + a_1X + a_2Y + a_3Z + a_4XY + a_5XZ + a_6YZ}{1 + c_1X + c_2Y + c_3Z + c_4XY + c_5XZ + c_6YZ}$$

$$y = \frac{b_0 + b_1X + b_2Y + b_3Z + b_4XY + b_5XZ + b_6YZ}{1 + c_1X + c_2Y + c_3Z + c_4XY + c_5XZ + c_6YZ} \quad (4)$$

The rational function method (RFM) maps three-dimensional ground coordinates to image space for all types of sensors, such as frame, pushbroom, whiskbroom and SAR systems. The direct linear transformation (DLT), self calibration DLT (SDLT), 3D affine, 2D projective equations and polynomials are specialized forms of the RFM, and we now consider these models.

2.1.1 Direct Linear Transformation (DLT)

Eleven linear orientation parameters define the relationship between 2D image space and 3D object space:

$$x = \frac{a_0 + a_1X + a_2Y + a_3Z}{1 + c_1X + c_2Y + c_3Z}, \quad y = \frac{b_0 + b_1X + b_2Y + b_3Z}{1 + c_1X + c_2Y + c_3Z} \quad (5)$$

2.1.2 Self Calibration Direct Linear Transformation (SDLT)

Twelve linear orientation parameters define the relationship between 2D image and 3D object space:

$$x = \frac{a_0 + a_1X + a_2Y + a_3Z}{1 + c_1X + c_2Y + c_3Z} + a_4xy, \quad y = \frac{b_0 + b_1X + b_2Y + b_3Z}{1 + c_1X + c_2Y + c_3Z} \quad (6)$$

2.1.3 3D Affine Transformation

Eight parameters define the relationship between the object and image spaces:

$$x = a_0 + a_1X + a_2Y + a_3Z, \quad y = b_0 + b_1X + b_2Y + b_3Z \quad (7)$$

2.1.4 2D Projective Transformation

Eight parameters define the relationship between the object and image planes:

$$X = \frac{a_0 + a_1X + a_2Y}{1 + C_1X + C_2Y}, \quad Y = \frac{b_0 + b_1X + b_2Y}{1 + C_1X + C_2Y} \quad (8)$$

2.1.5 2D Polynomials

The model describes the relationship between image and object space independent of the sensor geometry:

$$X = \sum_{i=0}^{m1} \sum_{j=0}^{m2} a_{ij} x^i y^j \quad \text{and} \quad Y = \sum_{i=0}^{m1} \sum_{j=0}^{m2} b_{ij} x^i y^j \quad (9)$$

In the above functions x,y are the coordinates on the image; X,Y,Z are the coordinates on the ground; and a_i, b_i, c_i, d_i are transformation parameters.

2.2 Radial Basis Function Methods

Radial basis functions, such as Hardy's multiquadric functions (MQs) and reciprocal multiquadrics (RMQs), thin plate splines (TPS) and variations of these methods offer ready alternatives to conventional rational function and polynomials methods for image to object space transformation where many of GCPs are available. The radial basis function methods involve the solution of an equation system with the same number of unknown parameters as GCPs. Thus, we have a perfect fit for all GCPs.

2.2.1 Multiquadric Approach (MQ)

This discussion is limited to the 2D case where radial basis functions may be constructed as a linear combination of the following equations for x and y:

$$\sum_{j=1}^N a_j h_j(x_i, y_i) + \sum_{j=1}^M b_j q_j(x_i, y_i) = X_i \text{ and } Y_i \quad i = 1, \dots, N$$

$$\sum_{i=1}^N a_i q_j(x_i, y_i) = 0, \quad j = 1, \dots, M \quad (10)$$

where N is the number of GCPs and M is the number of terms in a bivariate polynomial. The basis for the MQ and RMQ, may be expressed as follows :

$$h(x, y) = \sqrt{(d^2 + c^2)} \text{ and } h(x, y) = 1/\sqrt{(d^2 + c^2)} \quad (11)$$

Where d is the distance between a point (x, y) and a neighbouring point, and c is the MQ parameter. The effect from a given point to all equidistant points is the same, being expressed as a translation of the radial function h . A polynomial is first used to model the general geometric image to object transformation and an interpolating function is then used to separately fit the resulting vectors of residuals in X and Y at each control point. Weights can be assigned to each control point and the effect of local distortions measured GCPs are calculated using an interpolating matrix developed from the distance between GCPs. Matrix formulations of the MQ, which is particularly suited to the rectification of remote sensing images of large scale and locally varying geometric distortions, are given in Ehlers.

2.2.2 Thin Plate Splines (TPS)

Thin plate splines are analogous to the bending of an infinitely thin plate when subjected to point loads X and Y at locations (x, y) . The formulation of TPS basis function may be given as:

$$h(x, y) = d^2 \log d \text{ or } h(x, y) = d^2 \log d^2 \quad (12)$$

Derived functions in TPSs have minimum curvature between control points, and become almost linear at large distances from the GCPs. The influence of individual GCPs is localized, and diminishes rapidly away from their locations. In order to represent a warping transformation accurately, TPSs should be constrained at all extreme points of the warping function.

2.3 Orbital Parameter Model

An orbital parameter model can be applied to the pushbroom images in order to determine their exterior orientation parameters. An orbital resection method has been developed to model continuous changing of position and attitude of the sensors by finding the orbital parameters of the satellite during the period of its exposure of the image. A bundle adjustment has been developed to determine these parameters using GCPs. This program has been already tested for SPOT Level 1A and 1B stereo pairs (Valadan and Petrie, 1998) as well as, MOMS-O2 stereo images (Valadan, 1997) and IRS-1C stereo pairs (Valadan and Foomani, 1999).

The well known collinearity equation relates the points in the CT object coordinate system to the corresponding points in the image coordinate system. The relationship between these two coordinate systems is based on three rotations using combinations of the Keplerian elements mentioned above but computed with respect to the CT system using the transformation parameters between the CT and CI systems, plus three rotations, ω , φ , κ , for the additional undefined rotations of the satellite at the time of imaging. The off-nadir viewing angles of the linear array sensor must also be included as angle α and β . The following equations will then result:

$$\begin{bmatrix} x_i - x_0 \\ y_i - y_0 \\ -c \end{bmatrix} = SR \begin{bmatrix} X_i - X_0 \\ Y_i - Y_0 \\ Z_i - Z_0 \end{bmatrix} \quad (13)$$

where

$$R = R_2(\alpha)R_1(\beta)R_3(\kappa)R_2(\varphi)R_1(\omega)R_2((f + \omega_p) - \pi/2)R_1(\pi/2 - i)R_3(\Omega - \pi)$$

and

S : is the scale factor;

α, β : is the cross-track and along-track viewing angles;

x_i, y_i : are the image coordinates of object point i ;

x_0, y_0 : are the image coordinates of principal point;

X_i, Y_i, Z_i : are the object coordinates of image point i ;

X_0, Y_0, Z_0 : are the coordinates of the position of the sensor's perspective centre in the CT system;

c : is the principal distance \approx focal length of the linear array imaging system, and

R_j : defines the rotation around the j axis, where $j=1, 2$ or 3 .

Because of the dynamic geometry of linear array systems, the positional and attitude parameters of a linear array sensors are treated as being time dependent. The only available measures of time are the satellite's along-track coordinates. Thus the major components of the dynamic motion, the movement of the satellite in orbit and the Earth rotation are modelled as linear angular changes of f and Ω with respect to time, defined as f_1 and Ω_1 . Thus:

$$\begin{aligned} f_i &= f_0 + f_1 x, \\ \Omega_i &= \Omega_0 + \Omega_1 x \end{aligned} \quad (14)$$

where,

f_i and Ω_i : are the true anomaly and the right ascension of the ascending node of each line i respectively;

f_0 and Ω_0 : are the true anomaly and the right ascension of the ascending node with respect to a reference line, for example the centre line of the scene; and

f_1 and Ω_1 : are the first values for the rates of change of f_i and Ω_i .

During the orientation of a pushbroom image, nine parameters of the orientation $(f_0, \Omega_0, a, i, f_1, \Omega_1, \omega_0, \varphi_0, \kappa_0)$ find the position in space of the satellite and its sensor system and its crude attitude. Considering the attitude of a scan line as a reference, the attitude parameters ω, φ , and κ of the other lines can therefore be modelled by a simple polynomial based on the along-track (x) image coordinates as follows:

$$\begin{aligned} \omega &= \omega_0 + \omega_1 x + \omega_2 x^2 \\ \varphi &= \varphi_0 + \varphi_1 x + \varphi_2 x^2 \\ \kappa &= \kappa_0 + \kappa_1 x + \kappa_2 x^2 \end{aligned} \quad (15)$$

2.3.1 Orbital Parameter Modeling of Ikonos Geo Image

The Keplerian elements $(f_0, \Omega_0, a, e, \omega_p)$, in-flight position (X_0, Y_0, Z_0) and viewing angle of the imaging sensor were approximated from meta data, image file, image acquisition geometry and celestial mechanics (Sadeghian, 2002).

A simpler and more pragmatic approach was implemented by the authors to convert Geo image to the corresponding raw image form. A comparison of the raw and Geo image shows one major difference in terms of geometry. As noted previously, the number of pixels per line in the raw image is 13500, while in this Geo image it is more than 13500. It is because off-nadir view angle of the image and the image has been rectified and resampled in such a way that each pixel has a pixel size of 1 m on the ground. With due attention to this difference, a procedure was devised and implemented by authors to carry out the required conversion.

The size of the Geo image (rectangle) is different from that of the corresponding raw image. Two coefficients are now computed to enable the final image to have the same size (13500 * 13500 pixels) in two directions as a raw image. These coefficients are used to produce the pixel and line coordinates of each point respectively from the following expressions:

Coefficient for the p coordinate = 13500/total number of pixels in each line

Coefficient for the l coordinate = 13500/total line of pixels in each scene

It will be seen that this procedure is somewhat akin to that of an affine transformation. However, additional displacements were introduced into the Geo imagery by the original corrections for each curvature/panoramic distortion. These displacements occur predominantly in the cross-track (y) direction and, since they are approximately symmetrical about the image center line, parameters adjusting the attitude as a function of the cross-track image coordinates should give a good correction for these displacements by replacing the terms in equation (3) by a term for this purpose, which leads to the following equations:

$$\begin{aligned}\omega &= \omega_0 + \omega_1 x + \omega_2 y^2 \\ \varphi &= \varphi_0 + \varphi_1 x + \varphi_2 y^2 \\ \kappa &= \kappa_0 + \kappa_1 x + \kappa_2 y^2\end{aligned}\quad (16)$$

Where x and y are the image coordinate. These equations have been incorporated in the procedure to transform the Geo image coordinates to their raw image form.

3. THE HAMEDAN IKONOS TESTFIELD AND IMAGE MENSURATION

The Ikonos Geo panchromatic image employed covered an 11 x 15 km area of central Hamedan city in the west of Iran. It was acquired on 7 October 2000 with a 20.4° off-nadir angle and 47.4° sun elevations. Carterra Geo products are georectified, which means that they are rectified to an inflated ellipsoid and selected projection, in this case UTM on the WGS84 datum. No terrain-correction model is applied so these images are only rectified, as opposed to orthorectified. The stated accuracy of the Carterra Geo products is specified as 50 m CE90 exclusive of terrain displacement (Grodecki and Dail, 2001). In this investigation, the

elevation within the Ikonos test area ranged from 1700 m to 1900 m. The GCPs/ICPs (Independent Check Points) for the tests were extracted from NCC-product digital maps, which employed a UTM projection on the WGS84 datum. In this instance the mapping scale was 1:1000, with the compilation have been carried out using 1:4000 scale aerial photographs. The selected GCPs/ICPs in the imagery were distinct features such as building and pools corners, and wall and roads crossings, etc. The image coordinates of the GCPs/ICPs were monoscopically measured using the PCI EASI/PACE software system. These image measurements were then input into the least-squares adjustment computations, for the parameters of the DLT, SDLT and 3D affine as well as into the calculations for the orbital parameter model.

4. PRACTICAL EVALUATION

Non-rigorous transformation computations were carried out with software written by the first author. Least squares determinations of the parameters of each orientation model were carried out using all available GCPs, namely 34 also 20 and 7 for the Ikonos image. The ground coordinates of ICPs were then determined utilizing the derived parameters and the differences between the photogrammetrically determined and map-recorded ground positions then formed the basis of the accuracy assessment phase. Tables 1,2,3 and 4 show summaries of the root mean square error (RMSE) obtained for the series of object point determinations, for the Ikonos image using polynomials (4, 5 and 6 terms), 2D projective, 3D affine, DLT, SDLT, rational (14, 17 and 20 terms), multiquadric (3,6 and 10 terms) and TPS. Where ΔPI is represented as the square root of sum of ΔE and ΔN squares.

Table 1. ΔPI , RMSE values achieved in UTM coordinates of the Ikonos data, using polynomial equations

Method	GCPs Number	ICPs Number	Control Points	Check Points
			$\Delta PI(m)$	$\Delta PI(m)$
4 Term	34	20	4.24	3.30
	20	34	4.52	4.02
	7	47	1.39	6.61
5 Term	34	20	3.95	3.22
	20	34	4.16	3.73
	7	47	1.37	6.46
6 Term	34	20	1.31	1.56
	20	34	1.35	1.62
	7	47	1.30	9.90

Table 2. ΔPI , RMSE values achieved in UTM coordinates of the Ikonos data over the Hamedan project area

Method	GCPs Number	ICPs Number	Control Points	Check Points
			$\Delta PI(m)$	$\Delta PI(m)$
2D Projective	34	20	4.17	2.95
	20	34	4.45	3.20
	7	47	1.74	4.41
3D Affine	34	20	1.02	0.97
	20	34	0.96	1.04
	7	47	0.91	1.10
DLT	34	20	0.95	0.95
	20	34	0.90	0.97
	7	47	0.59	1.90
SDLT	34	20	0.85	0.98
	20	34	0.82	0.96
	7	47	0.32	2.69

Table 3. Δ PI, RMSE values achieved in UTM coordinates of the Ikonos data using rational equations

Method	GCPs Number	ICPs Number	Control Points	Check Points
			Δ PI(m)	Δ PI(m)
14 Term	34	20	0.87	0.90
	20	34	0.83	0.94
	7	47	0.00	4.36
17 Term	34	20	0.85	0.98
	20	34	0.80	0.91
	7	47	-	-
20 Term	34	20	0.84	0.98
	20	34	0.76	1.22
	7	47	-	-

Table 4. Δ PI, RMSE values achieved in UTM coordinates of the Ikonos data over the Hamedan project area.

Method	GCPs Number	ICPs Number	Control Points	Check Points
			Δ PI(m)	Δ PI(m)
Multiquadric 3 Term	34	20	0.00	3.26
	20	34	0.00	3.97
	7	47	0.00	6.62
Multiquadric 6 Term	34	20	0.00	1.31
	20	34	0.00	1.34
	7	47	0.00	9.91
Multiquadric 10 Term	34	20	0.00	1.32
	20	34	0.00	1.35
	7	47	0.00	-
TPS	34	20	0.00	1.46
	20	34	0.00	1.36
	7	47	0.00	6.38

Table 5. Δ XY, residuals in WGS 1984 coordinates for the control and check points on the Ikonos Geo image corrected with 9, 12 and 15 parameters and using equation 15 and with 15 parameters and using equation 16, over the Hamedan project area.

Method	GCPs Number	ICPs Number	Control Points	Check Points
			Δ XY(m)	Δ XY(m)
9 Parameters	34	20	2.71	2.72
	20	34	2.98	2.65
	7	47	5.35	5.00
12 Parameters	34	20	34	20
	20	34	20	34
	7	47	7	47
15 Parameters	34	20	2.36	2.35
	20	34	2.55	2.32
	7	47	2.87	3.12
15 parameters for Geo image corrected	34	20	1.01	1.31
	20	34	1.15	1.10
	7	47	0.97	2.13

A bundle adjustment program implementing the mathematical model outlined in Part 3.3.1, written by the second author in Borland C++ for Windows and run on a PC, has been used to

carry out the accuracy tests of the Ikonos Geo image. The bundle adjustment program is very flexible and the number of exterior orientation parameters can be reduced from 15 to 9 as a result of removing the quadratic and linear terms of the polynomials which model the change of the conventional rotation parameters (i.e. ω , ϕ and κ) with respect to time. The results of the bundle adjustment when using 3 combinations of control points and check points for the Hamedan test field are given in Table 4. The result of adjustment using equation (16) are stated in tables 4 and 5. As can be seen in Tables 4 and 5 using equation 16 yields better results than using equation 15. Also, the results show increased improvement for 15, 12 and 9 parameters equation respectively. However, from the practical test, equivalent RMSE values for independent check points in terms of the UTM coordinate system for 20 GCPs and 34 ICPs are given in table 6.

Table 6. R.m.s.e. values of the errors at the residual errors in the GCPs/ICPs in terms of both the WGS 1984 geocentric coordinate system and the UTM coordinate system on the Ikonos Geo image corrected with 15 parameters and using equation 16, over the Hamedan project area.

Method	Control Points (n=20)	Check Points (n=34)
	Δ PI (m)	Δ PI(m)
Orbital parameter	0.97	0.89

5. CONCLUSION

In this paper the accuracy potential of Ikonos Geo image was investigated. Rigorous models are not always available for satellite sensor orientation, especially for images from high resolution satellites such as Ikonos. Unlike the rigorous physical sensor model, non-rigorous models such as RFM, DLT, SDLT, 3D affine and RBF models need no knowledge of the sensor model, or of orbit ephemeris and platform orientation parameters. Applications of these models to remotely sensed imagery acquired by Ikonos satellite indicate that relatively accurate geopositioning can be obtained through provision of ground control points.

High resolution data increase the need for higher accuracy of data modelling. In order to accurately model the imaging geometry of high resolution flexible pointing images such as Ikonos-2, EROSA-1, Quickbird-2, SPOT 5 and OrbView 3, we can use orbital parameter model. In this paper the flexibility and favourable accuracy of the orbital parameter model approach has been demonstrated with Ikonos Geo image and the method should be equally useful for other high resolution satellite imaging systems. This investigation has shown that Ikonos Geo imagery has high geometric integrity. When distinct object features such as building corners or roads crossings are used, an accuracy of better than 1 m can be achieved for Ikonos Geo with orbital parameter model. That accuracy is within the accuracy of Ikonos Precision Plus product.

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