Geometric Accuracy Testing of Geo-Rectified Images using Orbital Parameter Model and Rational Function Model

Somayeh Yavari
M. Sc. Student
Faculty of Geodesy and Geomatics Engineering, K. N. Toosi University of Technology, Tehran, IRAN
yavari_sa@yahoo.com

Mohammad Javad Valadan Zoej
Assistant Professor
Faculty of Geodesy and Geomatics Engineering. K. N. Toosi University of Technology, Tehran, IRAN
valadanzouj@kntu.ac.ir

Saeid Sadeghian
Assistant Professor
National Cartographic Center (NCC), IRAN
sadeghian@ncc.neda.net.ir

Abstract: This paper proposes a model to extract 3D spatial information from the geo-rectified images which their geometry at the time of imaging has been lost. Based on this model, first the geo-rectified image is converted back to its geometry at the time of imaging. Then the Orbital Parameter Model is implemented to the resulted image to extract high accurate 3D spatial information from the image. The developed model has been tested on geo-rectified images such as SPOT L1B, and IKONOS Geo images taken over two test areas in Iran. This is followed by the results of various geometric accuracy tests carried out using different parameters and combination of control and check points. For the IKONOS Geo and SPOT L1B, the sub-pixel accuracy was achieved using the Orbital Parameter Model. Later the results of the developed model have been compared with Rational Function Model (RFM) results.
Keywords: Geo-rectified images, Orbital Parameter Model, Rational Function Model

1. Introduction

In recent decades, the issue of accurate 2D and 3D spatial data exploitation from high resolution space images are considerable in photogrammetry community. As known, to extract accurate spatial information, a mathematical model is needed. These models classified to two branches: rigorous models such as orbital parameter model and non-rigorous models such as Rational Function Model. Rigorous models are more accurate and also needs less Ground Control Points (GCPs) than non-rigorous models. Some papers have been published on different approaches (Dowman, 1991; Fraser & Shao, 1996; Radhadevi et al, 1998; Valadan Zoej & Petrie, 1998). However, the main problem of using rigorous models such as orbital parameter model is their need to raw image with ephemeris data, where some High Resolution Satellite Image (HRSI) vendors do not intend to release these data. Instead they provide the users with geo-rectified images with minimum information about the movement of the satellite in its orbit. It means the lack of geometry at the time of imaging which makes it very difficult to use rigorous models such as orbital parameter model for geometric correction of these images. As a result, most of investigators offer non-rigorous model, such as Rational Function Model (RFM) to be used.

This paper outlines briefly RFM as well as orbital parameter model used in this research. Then, the results of each model when testing on SPOT L1B, and Ikonos-Geo image are given and compared.

2. Test Area and Materials

One SPOT-4 Level 1B stereo-pair, covering a part of Zanjan Province in the west part of Iran, was acquired on 14 May and 21 June 2000, for the purpose of this research project. The cross-track angles for the left and right images of SPOT stereo pair are +24 and -26.4 degrees respectively. For this project, 35 well distributed Ground Control Points (GCPs) were established using differential GPS techniques. The accuracy of these points is estimated to be less than 1m.

An IKONOS Geo Panchromatic image was also employed covering an area of 11*15 km^2 of central Hamedan city in the west of Iran. It was acquired on 7 October 2000 with an off-nadir angle of 20.4^o and 47.4^o sun elevation. The elevation within the IKONOS test area ranged from 1700m to 1900m.The ground control points and check points were extracted from 1:1000 scale digital maps produced by National Cartographic Center (NCC) using 1:4000 scale aerial photographs. The image coordinates of control and check points were monoscopically measured using Geomatica software package. For this image, 68 Ground Control Points (GCPs) were selected from the test image. The points are distinct features such as buildings, and pool corners, wall and road junctions.

3. Mathematical Models

A rational function model and an orbital parameter model applied on the images used in this project. A brief describtion of these models are given in the followings.

3.1. Rational Function Model

In this model the image coordinates is determined from the ratio of two polynomials "Eq. (1)":

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

$$y = \frac{P3(X,Y,Z)}{P4(X,Y,Z)} = \frac{\sum_{i=0}^{m1}\sum_{j=0}^{m2}\sum_{k=0}^{m3} c_{ijk} X^i Y^j Z^k}{\sum_{i=0}^{n1}\sum_{j=0}^{n2}\sum_{k=0}^{n3} d_{ijk} X^i Y^j Z^k} \tag{1}$$

where

$$P1(X,Y,Z) = a_0 + a_1 X + a_2 Y + a_3 Z + a_4 XY + a_5 XZ + a_6 YZ + a_7 X\verb|^|2 + ... + a_{19} Z\verb|^|3 \tag{2}$$

where (x,y) are normalized image coordinates and (X,Y,Z) are normalized object coordinates.
The normalization equation can be describe as (OGC,1999):

$$x_n = \frac{x - x_o}{x_s} \qquad y_n = \frac{y - y_o}{y_s} \tag{3}$$

where:

x , y : are image coordinates,
x_0 , y_0 : are shift value for image coordinates,
x_s , y_s : are scale values for image coordinates,
x_n , y_n : are normalized image coordinates.

The same equations can be used for object coordinates normalization. In rational function model, it is important to normalize both image and object coordinates. This causes less computational input error, leading to better accuracy. RFM can be solved on two methods: Terrain-Independent (use the satellite parameters and sensor model with no GCPs) and Terrain-Dependent (that use only GCPs to compute the unknown parameters).

Since, for Geo-rectified images (such as IKONOS Geo) precise ancillary data is not available, therefore, in this paper the Terrain-Dependent forward rational function model (with different denominator (P2#P4) for the equations) is investigated. In first step the unknown parameters are calculated (Tao and Hu, 2001) and in the second step object coordinates are calculated using intersection method.

3.2. 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 tested already for SPOT Level 1A and 1B stereo pairs (Valadan and Petrie, 1998), MOMS-02 stereo images (Valadan, 1997), IRS-1C stereo pair (Valadan and Foumani, 1999), and Ikonos image (Valadan and Sadeghian, 2003).

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 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 "Eq. (4)" will then result:

$$\begin{pmatrix} x_i - x_0 \\ y_i - y_0 \\ -c \end{pmatrix} = S\ R \begin{pmatrix} X_i^g - X_0 \\ Y_i^g - Y_0 \\ Z_i^g - Z_0 \end{pmatrix}_{CT} \tag{4}$$

where

$$R = R_1(\alpha)R_2(\beta)R_3(\kappa)R_2(\varphi)R_1(\omega)R_2((f+\omega_p)-\frac{\pi}{2})R_1(\frac{\pi}{2}-i)R_3(\Omega-\pi) \tag{5}$$

α	: is the cross-track viewing angle,
β	: is the along-track viewing angle,
κ, φ, ω	: are additional undefined rotations of the spacecraft at the time of imaging,
f, i, ω_p, Ω	: are the true anomaly, orbital inclination, argument of perigee, and right ascension of the ascending node respectively,
x_i , y_i	: are the image coordinates of the image point i,
x_0 , y_0	: are the image coordinates of the principal point,
X_i^g , Y_i^g , Z_i^g	: are the coordinates of the image point I in the Conventional Terrestrial (CT) coordinate system,
X_0 , Y_0 , Z_0	: are the coordinates of the position of the sensor's perspective centre in CT coordinate system,
c	: is the principal distance,
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 sensor 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 modeled as linear angular changes of f and Ω with respect to time, defined as f_1 and Ω_1:

$$\begin{aligned} f_i &= f_0 + f_1 x \\ \Omega_i &= \Omega_0 + \Omega_1 x \end{aligned} \tag{6}$$

where

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

During the orientation of a pushbroom image, nine parameters of the orientation (f_0, Ω_0, a, i, f_1, Ω_1, ω_0, φ_0, κ_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, κ, and of the other lines can therefore be modeled by a simple polynomial based on the along-track (x) image coordinates as "Eq. (7)":

$$\begin{cases} \omega = \omega_0 + \omega_1 x + \omega_2 x^2 \\ \varphi = \varphi_0 + \varphi_1 x + \varphi_2 x^2 \\ \kappa = \kappa_0 + \kappa_1 x + \kappa_2 x^2 \end{cases} \tag{7}$$

In Geo-Rectified images, the Keplerian elements(f_0, Ω_0, a, e, ω_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).

Based on this model first of all the Geo-Rectified image is converted back to its geometry at the time of imaging. Then the Orbital Parameter Model is implemented to the resulted image to extract high accurate 3D spatial information from the image. A comparison of the raw and Geo image shows one major difference in terms of geometry, the number of pixels per line are different in raw and Geo images, because the rectified image is resample to unique space but in raw image because of off-nadir view angle this spaces are not same. To solve this problem, two coefficients computed to enable the final image to have the same size in two directions as a raw image. These coefficients are used to procedure the pixel and line coordinates of each point. 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 "Eq. (8)":

$$\begin{cases} \omega = \omega_0 + \omega_1 x + \omega_2 y^2 \\ \varphi = \varphi_0 + \varphi_1 x + \varphi_2 y^2 \\ \kappa = \kappa_0 + \kappa_1 x + \kappa_2 y^2 \end{cases} \tag{8}$$

4. Geometric Accuracy Test of SPOT-4 and Ikonos Imagery over the Test Areas Using RFM and Orbital Parameter Model

The results of RFM, where the dominators are considered to be different, on SPOT L1B and IKONOS Geo images are shown in Tables 1 and 2. Table 1 presents the ΔX, ΔY, ΔZ residuals in WGC 1984 coordinates for SPOT L1B image over the Zanjan project area when 20 Ground Control Points (GCPs) and 17 Independent Check Points (ICPs) have been used.

Table 1. ΔX, ΔY, ΔZ residuals in WGC 1984 coordinates for SPOT L1B image over the Zanjan project area (20 GCPs and 17 ICPs) using RFM

No. of terms	GCP Right Image (in pixel)			GCPs Left Image (in pixel)			ICPs Right Image (in pixel)			ICPs Left Image (in pixel)			ICPs (in meter)			
	Δx	Δy	Δxy	Δx	Δy	Δxy	Δx	Δy	Δxy	Δx	Δy	Δxy	ΔX	ΔY	ΔZ	ΔXY
9	0.56	0.65	0.86	0.44	0.60	0.74	1.18	0.68	1.36	0.99	1.12	1.50	10.6	10.1	9.49	14.70
11	0.60	0.62	0.86	0.38	0.45	0.59	1.14	0.73	1.36	0.92	1.11	1.44	10.6	9.75	9.17	14.44
13	0.74	1.25	1.45	0.40	0.40	0.57	1.23	1.02	1.60	0.94	1.13	1.47	11.5	10.5	10.8	15.62
15	0.23	0.85	0.88	0.31	24.1	24.1	1.42	1.01	1.74	1.10	2.45	2.69	14.1	12.8	13.3	19.12
17	0.20	3.70	3.70	0.43	0.56	0.70	3.77	1.14	3.94	2.31	1.58	2.80	14.9	13.6	13.7	20.26
19	0.04	0.10	0.11	0.07	0.59	0.59	2.97	2.68	4.00	1.64	1.31	2.10	38.5	16.9	22.9	42.12
21	0.01	0.00	0.01	0.00	0.00	0.00	2.01	1.56	2.55	2.30	3.25	3.98	25.0	12.9	18.4	28.21

Table 2 shows the ΔX, ΔY, ΔZ residuals in WGC 1984 coordinates for Ikonos Geo image over the Hamedan project area when 35 Ground Control Points (GCPs) and 37 Independent Check Points (ICPs) have been used.

Table 2. ΔX, ΔY, ΔZ residuals in WGC 1984 coordinates for Ikonos Geo image over the Hamedan project area (35 GCPs and 37 ICPs) using RFM

No. of terms	GCPs (in pixel)			ICPs (in pixel)			ICPs (in meter)		
	Δx	Δy	Δxy	Δx	Δy	Δxy	ΔX	ΔY	ΔXY
9	0.51	0.38	0.63	0.92	0.49	1.04	0.92	0.49	1.04
11	0.49	0.38	0.62	0.92	0.49	1.05	0.92	0.49	1.05
13	0.57	0.37	0.68	0.99	0.48	1.10	0.99	0.48	1.10
15	0.97	0.36	1.03	1.05	0.50	1.16	1.05	0.50	1.16
17	0.49	0.34	0.60	0.96	0.50	1.08	0.96	0.50	1.08
19	0.85	0.35	0.91	6.02	0.52	6.05	8.26	0.52	8.28
21	2.23	0.87	2.39	10.64	8.02	13.33	3.80	2.18	4.38

The residual errors (ΔX, ΔY, ΔZ) at the 20 ground control points as well as 17 independent check points after the application of the bundle adjustment program based on orbital parameter model for SPOT L1B stereo pair are given as RMSE values and are summarized in Table 3. As can be seen from this Table, good results have been achieved using this stereo image. The graphical analyses of these results using vector plots of the errors occurring at each individual GCP and independent check point show that the residual errors are random and free from systematic effects.

Table 3. ΔX, ΔY, ΔZ residuals in WGC 1984 coordinates for SPOT L1B image over the Zanjan project area (20 GCPs and 17 ICPs) using orbital parameter model

Method	GCPs (meter)			ICPs (meter)		
	ΔX(m)	ΔY(m)	ΔXY(m)	ΔX(m)	ΔY(m)	ΔXY(m)
15 parameter for Geo image corrected	3.63	3.56	5.07	6.91	5.29	5.92

The residual errors in terms of ΔX, ΔY, ΔZ in WGS 84 coordinates at the 35 GCPs and 37 ICPs after implementing orbital parameter model for Ikonos Geo image are summarized in Table 4. As can be seen again from this Table, good results have been achieved using this stereo image. The vector plots of the errors occurring at each individual GCP and independent check point show that the residual errors are random and free from systematic effects.

Table 4. ΔX, ΔY, ΔZ residuals in WGC 1984 coordinates for Ikonos Geo image over the Hamedan project area (35 GCPs and 37 ICPs) using orbital parameter model

Method	GCPs (meter)			ICPs (meter)		
	ΔX(m)	ΔY(m)	ΔXY(m)	ΔX(m)	ΔY(m)	ΔXY(m)
15 parameter for Geo image corrected	0.73	0.71	1.01	0.73	0.83	1.10

Comparing the results given in Tables 3 and 4 with the results given in Table 1 and 2 shows that the residual errors obtained from the orbital parameter model are better than the results obtained from the rational function model. This shows the efficiency of the orbital parameter model proposed in this paper. However, from the practical test, the 35 GCPs and 37 ICPs coordinates in WGS 84 convert to UTM coordinate system and the results shown in table 5.

Table 5. RMSE in UTM coordinate system for Ikonos Geo image over the Hamedan project area (35 GCPs and 37 ICPs) using orbital parameter model

Method	GCPs (meter)			ICPs (meter)		
	ΔE(m)	ΔN(m)	ΔPl(m)	ΔE(m)	ΔN(m)	ΔPl(m)
15 parameter for Geo image corrected	0.80	0.30	0.85	0.80	0.40	0.89

5. Conclusions

This paper presented a rigorous mathematical model based on orbital parameters for correction of the geo-rectified images such as Ikonos Geo where the geometry of image at the time of imaging is lost and minimum information regarding the satellite movement in its orbit is available. The model is tested on SPOT L1B and Ikonos Geo over two test areas in Iran. The results obtained from the presented orbital parameter model have been then compared with the results of rational function model. The orbital parameter model can achieve sub-pixel accuracy where RFM give the results with an accuracy of about one pixel.

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