Comparative Analysis and Evaluation of Various Mathematical Models for Stereo IKONOS Satellite Images

Nagawa ELASHMAWY, Yasser ELMANADILI and Hazem BARAKAT, Egypt

Key words: Satellite images, IKONOS, stereo, sensor modeling

SUMMARY

This paper presents two mathematical models for stereo IKONOS imagery restitution and summarizes the results of their assessment using the first stereo pair acquired in Egypt over an area in the south-east of Cairo. A well distributed set of 25 ground points was selected on the stereo images and then surveyed using differential GPS static technique. These points were then divided into control and check points for the evaluation of the two models.

Most of the mathematical models incorporated in the software packages that were used in this research (ERDAS OrthoBase, PCI OrthoEngine, Z/I Imaging SSK) are based on the rational function model (RFM). This model uses the rational polynomial coefficients (RPCs) supplied with the images, since IKONOS precise sensor and orbit parameters are not released by the satellite company. An alternative model was also presented based on the Affine transformation between the 2D image coordinates and the 3D ground coordinates. A computer program was developed to implement the 3D Affine projection mathematical model.

Several experiments were performed to evaluate the two mathematical models for both single and stereo IKONOS images. Results of the experiments were presented and comparisons were carried out. It was found that sub-meter horizontal accuracy and 1.3-1.7m vertical accuracy can be obtained using either the refined RFM model or the 3D Affine projection model for the stereo images.

Finally, conclusions and recommendations for further research were presented especially regarding the development of rigorous modeling approaches for stereo high resolution satellite images with available precise sensor information such as QuickBird.

Comparative Analysis and Evaluation of Various Mathematical Models for Stereo IKONOS Satellite Images

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ABSTRACT

The recent availability of stereo high resolution satellite images has encouraged many researchers to investigate the potential gain in large scale topographic map production from stereo images. Several mathematical models were introduced in recent researches and were also included in some of the commercially available software packages. This paper presents two mathematical models and summarizes the results of their assessment using a stereo pair of IKONOS images over an area in the south-east of Cairo. The IKONOS stereo pair was acquired for the first time in EGYPT, as was shown from the satellite company archive at the time of acquisition (13 July 2003). A well distributed set of 25 ground points was selected on the stereo images and then surveyed using differential GPS static technique. These points were then divided into control and check points for the evaluation of the two models.

Most of the mathematical models incorporated in the software packages that were used in this research (ERDAS OrthoBase, PCI OrthoEngine, Z/I Imaging SSK) are based on the rational function model (RFM). This model uses the rational polynomial coefficients (RPCs) supplied with the images, since IKONOS precise sensor and orbit parameters are not released by the satellite company. An alternative model was also presented based on the Affine transformation between the 2D image coordinates and the 3D ground coordinates. A computer program was developed to implement the 3D Affine projection mathematical model.

Results of the experiments with the RFM model for stereo images, without any control points, showed a horizontal accuracy of 3.0-3.6m and vertical accuracy of 6.0-6.9m. When using ground control points with the RFM model, the results improved to 1.1-1.2m in horizontal accuracy, and 1.7-2.0m in vertical accuracy. It was found that only one control point is sufficient for the improvement of the results of the RFM model since only a shift in the ground coordinates is needed to be compensated for. The 3D Affine projection model provided a horizontal accuracy of 1.3m and vertical accuracy of 2.5m using 8 control points while accuracies of 0.9 horizontally and 1.3m vertically were achieved using 20 control points. This showed the effectiveness of such a model especially when the RPCs and/or commercial software packages are not available for users.

Finally, conclusions and recommendations for further research were presented especially regarding the development of rigorous modeling approaches for stereo high resolution satellite images with available precise sensor information such as QuickBird.

1. INTRODUCTION

One of the most important elements of the topographic information is the terrain elevation data. In these days of digital era, it is important to acquire the topographic and terrain elevation data in digital format since it is easier to be accessed, mobilized and used comparing to other formats. Although the terrain data are essential, unfortunately, there are no accurate up-to-date large-scale topographic digital maps covering the whole country of Egypt. Thus, generating an accurate Digital Terrain Model (DTM), as a digital representation of the large scale topographic maps to be used in different applications, is a necessity.

Applying pohotogrammetric modeling techniques to stereo satellite images is one of the efficient techniques for topographic data acquisition and production. Using stereo high-spatial resolution satellite images, dense and accurate DTM can be produced. The stereo IKONOS images, with one meter spatial resolution, have been available lately. Recently, many researchers have examined stereo IKONOS in different countries; however, no such experimental studies nor evaluation and assessment have been done in Egypt. Therefore, it is required to evaluate the capability of using high-resolution stereo satellite images in producing digital terrain models for Egypt.

The goal of this research is the selection of the most suitable mathematical model for IKONOS stereo images restitution in order to be used for the production of large scale digital maps, DTM, and orthoimages. To accomplish the objective of this research, the following procedures are implemented:

- Acquiring stereo IKONOS satellite images for a study area.
- Studying the various mathematical models for IKONOS satellite stereo image restitution, and analyzing the specific requirements for each mathematical model by developing computer programs and using commercial software packages.
- Assessing the results of the different mathematical models based on high accurate ground control and check points.
- Studying the effect of the number and distribution of ground control points on the restitution results.

The paper describes the mathematical models that can be used for IKONOS sensor modeling for stereo images. Each mathematical model is assessed using the obtained images and the acquired ground points. Several computer programs are developed and also commercial software packages are used. Furthermore, comparisons between the different models lead to the selection of the most accurate mathematical model. Finally, conclusions and recommendations are summarized.

2. MATHEMATICAL MODELS FOR STEREO IKONOS

In order to calculate the parameters of the transformation between image and ground coordinates, a mathematical model for satellite sensor orientation is required. There are mainly two types of sensor models; physical and generalized models (Tao et al., 2000). The physical model parameters represent the physical imaging process of the sensor. Thus, they are more rigorous and provide more accurate results. However, developing the physical models requires information about the sensor itself and its imaging parameters, which are not always available. On the other hand, the generalized sensor models are independent of both the sensor parameters and platforms types. Therefore, the generalized sensor models are more common to be used in mapping community (Tao et al., 2000). Even though generally the generalized models are less accurate than rigorous physical models, in some cases the accuracy of the results using generalized models can be as close as those obtained when using the rigorous physical models (McGlone, 1996) and (Fraser, 2000).

For IKONOS stereo images, the sensor physical parameters are derived from the satellite ephemeris and attitude data without using ground control points. The satellite ephemeris data are determined using on-board GPS receivers and sophisticated ground processing of the GPS data. The satellite attitude is determined by optimally combining star tracker data with measurements taken by the on-board gyros. Since the IKONOS satellite imagery vendor, SpaceImaging Company, has not released the satellite ephemeris data, no physical mathematical model can be established. Therefore, some generalized generic mathematical models are needed to substitute the physical models for IKONOS Imagery restitution (Hu et al., 2004) as will be described in the following subsections.

2.1 Rational Function Model (RFM)

A generalized model that is widely used is the Rational Function Model. In the past few years, the Rational Function model has come into widespread use within the intelligence community. This imaging geometry model uses ratios of two 3rd order polynomial functions to compute the image coordinates. All four polynomials are functions of the three ground coordinates. Each polynomial has 20 terms, although the coefficients of some polynomial terms are very small (McGlone, 1996) and (Fraser, 2000). The IKONOS satellite image company, SpaceImaging, computes the rational polynomial coefficients (RPCs) for each image and distributes these data with the images. Since rational polynomial considers heights into geometric correction, it is more adequate than 2D polynomials and thin plate mathematical models. It can be considered as the best choice when there is no information about the image and then a rigorous modeling cannot be used (as in the case of IKONOS satellite imageries). (PCI, 2001) The capabilities of the Rational Function Model (RFM), which is considered as a generic sensor model, has been tested and examined. The validation of this model has been tested in several researches with aerial photography data and satellite imageries (Tao et al., 2000). The RFM can be represented as follows,

$$
\begin{aligned}
x &= \frac{p1(X,Y,Z)}{p2(X,Y,Z)} = \frac{\sum_{i=0}^{m1}\sum_{j=0}^{m2}\sum_{k=0}^{m3} a_{ijk} X^i Y^j Z^k}{\sum_{i=0}^{n1}\sum_{j=0}^{n2}\sum_{k=0}^{n3} b_{ijk} X^i Y^j Z^k} \\
y &= \frac{p3(X,Y,Z)}{p4(X,Y,Z)} = \frac{\sum_{i=0}^{m1}\sum_{j=0}^{m2}\sum_{k=0}^{m3} c_{ijk} X^i Y^j Z^k}{\sum_{i=0}^{n1}\sum_{j=0}^{n2}\sum_{k=0}^{n3} d_{ijk} X^i Y^j Z^k}
\end{aligned}
\quad (1)
$$

Where,

x, y	image coordinates,
X, Y, Z	ground coordinates,
$a_{ijk}, b_{ijk}, c_{ijk}, d_{ijk}$	polynomial coefficients (total 80),
$m_1, m_2, m_3, n_1, n_2, n_3$	0- 3, where $i+j+k \leq 3$.

The polynomial coefficients are called rational polynomial coefficients (RPCs). In general, distortions caused by optical projection can be represented by ratios of first-order terms, while corrections such as earth curvature, atmospheric refraction, and lens distortion etc., can be well approximated by second-order terms. Some other unknown distortions with high order components can be modeled using a RFM with third-order terms (Tao et al., 2000).

2.2 3D Affine Projection Model

A generalized model that is independent of the sensor geometry and the platform is the polynomial model. It is a simple and computationally fast model. Also, it is more applicable for flat areas, where the relief displacement does not influence the results significantly. In this case, it can be represented as 1st order polynomial model which is also known as 2D Affine transformation. It is one of the most common techniques for 2D satellite image rectification. On the contrary, in the hilly or mountainous areas, 3D polynomial models are required. Therefore, another generalized model that is proposed in this research is the 3D Affine projection model. The standard formulation of the 3D Affine projection model is expressed as a linear transformation from 3D object space (X, Y, Z) to 2D image space (x, y) (Dare, 2004) and(Yamakawa and Fraser, 2004), as follows,

$$\begin{aligned} x &= a_0 + a_1 X + a_2 Y + a_3 Z \\ y &= b_0 + b_1 X + b_2 Y + b_3 Z \end{aligned} \qquad (2)$$

Where,

x, y	image coordinates,
X, Y, Z	ground coordinates,
$a_0, a_1, a_2, a_3, b_0, b_1, b_2, b_3$	3 Parameters describing rotation, 2 Parameters describing translation in X and Y, and 3 Parameters describing non-uniform scaling (in X and Y directions) and skew distortion.

The 3D Affine projection equations can be understood in various ways. It can be interpreted as a 3D similarity transformation (including 7 parameters) followed by a skew parallel projection, or as a 3D to 3D Affine transformation (including 12 parameters) followed by an orthogonal projection (thus eliminating *z* coordinate equation with its 4 parameters). The 3D Affine model is a further generalized form, which allows affinity (non-uniform scaling and skew distortion) in the image to object space transformation (Yamakawa and Fraser, 2004).

3. DATA SET DESCRIPTION

3.1 Study Area and Stereo IKONOS Images Acquisition

In the previous decades, satellite images were used for small and medium scale topographic mapping. Currently, the IKONOS satellite, which has the stereoscopic capability, can be used for large scale topographic mapping. A stereo pair of IKONOS imagery, for a particular area in the south-east part of Cairo that contains different ground features and variety of topography is obtained by the Survey Research Institute (SRI). Figure 1 shows the selected study area within the IKONOS Image footprint over Cairo.

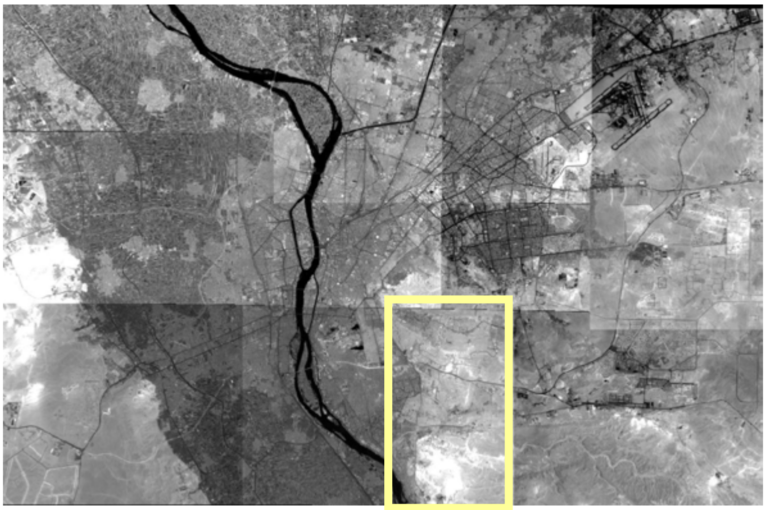


Figure 1: Footprint of IKONOS Image over Cairo

The selected area is around 11.5km long by 8.5km width, covering an area of 100 km^2 in the south-east part of Cairo. The study area includes various topographic features; it contains main roads such as the Ring Road and the Autostrad, urban area, hilly area of Mokatam, and a part of the eastern desert.

The acquired data are stereo IKONOS panchromatic satellite images, with 1m resolution, covering the study area as shown in Figure 2. It was the first stereo pair of IKONOS images acquired over Egypt in 13 July 2003, as was shown in the satellite company archive at that time. The stereo images are obtained as Reference Stereo Product (standard geometrically corrected processing level) which is the least processed stereo images available by the satellite company, Space Imaging. These data are delivered in GeoTiff format with text files containing the Rational Polynomial Coefficients (RPC) for each image. These RPCs are important for rectifying IKONOS satellite images using Rational Function Model instead of the rigorous models that require the ephemeris data of the satellite orbit, which have not been released yet by the satellite company.

From the metadata supplied file, the Base to Height ratio of the stereo images was calculated using the nominal collection elevation angles of the two images. The nominal collection elevation angles are 71.51° and 75.82° for forward and backward images, respectively, thus the base to height ratio equals to 0.58.

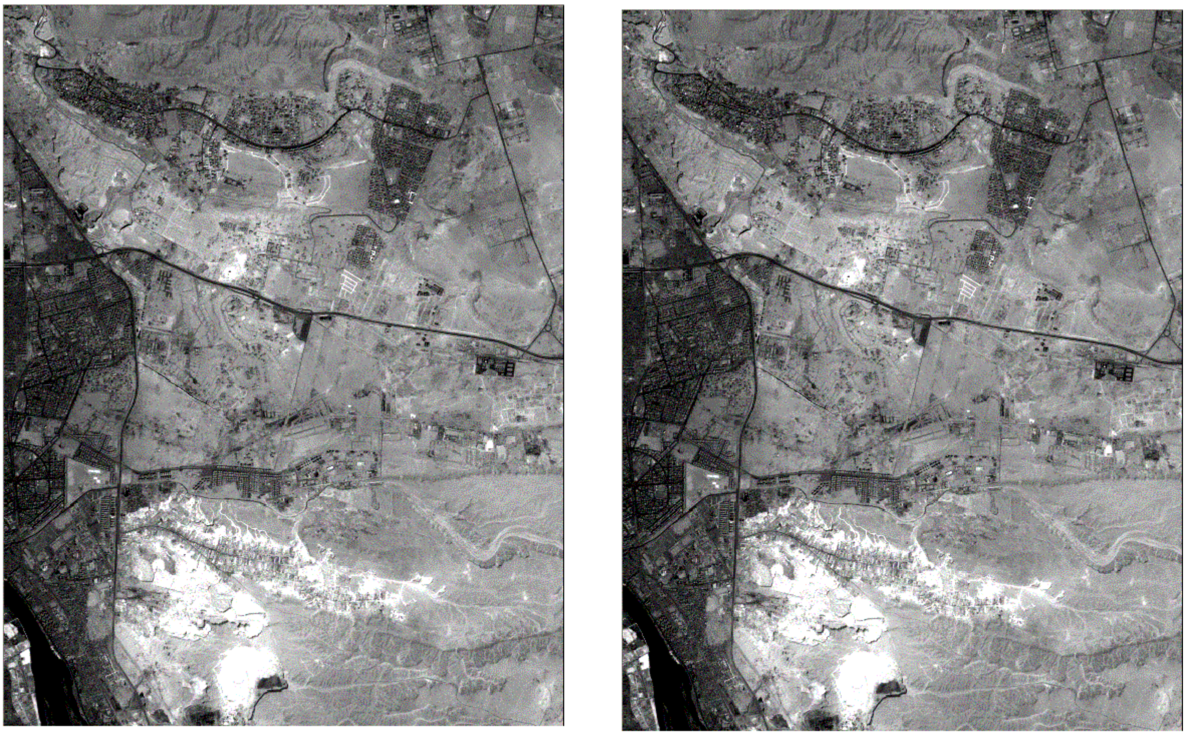


Figure 2: Stereo IKONOS Image for the Study Area

3.2 Ground Points Collection

For stereo IKONOS satellite images restitution and for evaluating the various mathematical models described above, collection of ground control and check points is needed. One of the fastest and accurate techniques is the Global Positioning System (GPS). Some criteria were taken into consideration in the selection process of the ground points. For example, before selecting the point locations on the ground, the best well-identified points on the images were selected such that they were well distributed all over the common area of the stereo images. These locations were easily identifiable; mostly corners of buildings, corners of fences/walls and some road intersections. However, in few cases, because of lack of man-mad features; less-ideal intersections of tracks had to be selected. Since the images are geo-referenced, the selected locations of the ground points were approximately provided; within 12m horizontal accuracy, according to Space Imaging publication (Space Imaging, 2002).

Static differential GPS technique was used for measuring the ground point coordinates, as it is the most accurate technique. Two well identified points of the High Accuracy Reference Network (HARN), provided by the Egyptian Survey Authority (ESA), near the study area, were chosen to act as reference stations. Other 3 stations within the study area boundaries were established to be used as reference stations in the proceeding work. Three GPS survey crews worked for the measurements of ground point coordinates with at least one GPS receiver remained over the reference station the whole work session, while the other established points were observed for at least 45 minutes by the other two crews.

The observed data were processed and resulted in the determination of 25 distinct ground points with an accuracy of about 10 cm horizontally and 20 cm vertically. Figure 3 shows the distribution of the final ground points on the study area, which were divided into control and check points. The geographic coordinates with ellipsoidal heights were transformed and projected on the UTM projection and the orthometric heights based on the existing geoid model, EGM96 were calculated. The height of the ground points ranges from 30 to 300 m above the Mean Sea Level (M.S.L.).

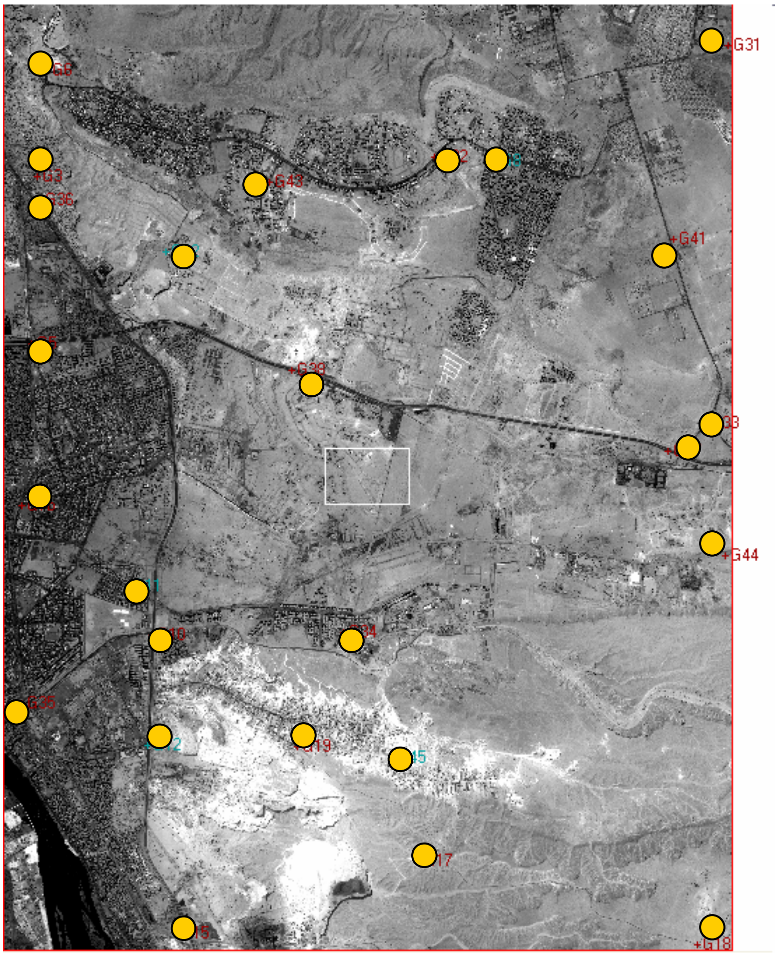


Figure 3: Ground Points Distribution Over the Study Area

4. RESULTS AND ANALYSIS

Several experiments were performed to apply the above mentioned mathematical models (the RFM and the 3D Affine projection), described in section 2, for the IKONOS images; both as stereo and single images. The RFM model equations, as shown in subsection 2.1, need a large number of ground control points (minimum 40) to calculate the 80 RPCs. Since it is not practical to have such large number of control points, and since the RPCs are already supplied by the image vendor, a robust and sophisticated software package was needed to apply the RFM model. Therefore, the RFM model was applied using commercial software packages; PCI Geomatica OrthoEngine, ERDAS Imagine OrthoBase, and Z/I Imaging (Intergraph) SSK. As for the 3D Affine projection model, a least squares adjustment computer program was developed using MatLab in order to apply the model equations, shown in subsection 2.2.

Before studying and evaluating the mathematical models for image restitution, the accuracy of the acquired IKONOS images was checked by locating the twenty-five ground points on the images and comparing their coordinates to the GPS observations. It was found that the RMSE for the horizontal residuals were 14.4m, and 17.4m for the first and second images, respectively. These values were compared to the nominal horizontal accuracy values published by Space Imaging for Reference Stereo images of 11.8m RMS (Space Imaging, 2002).

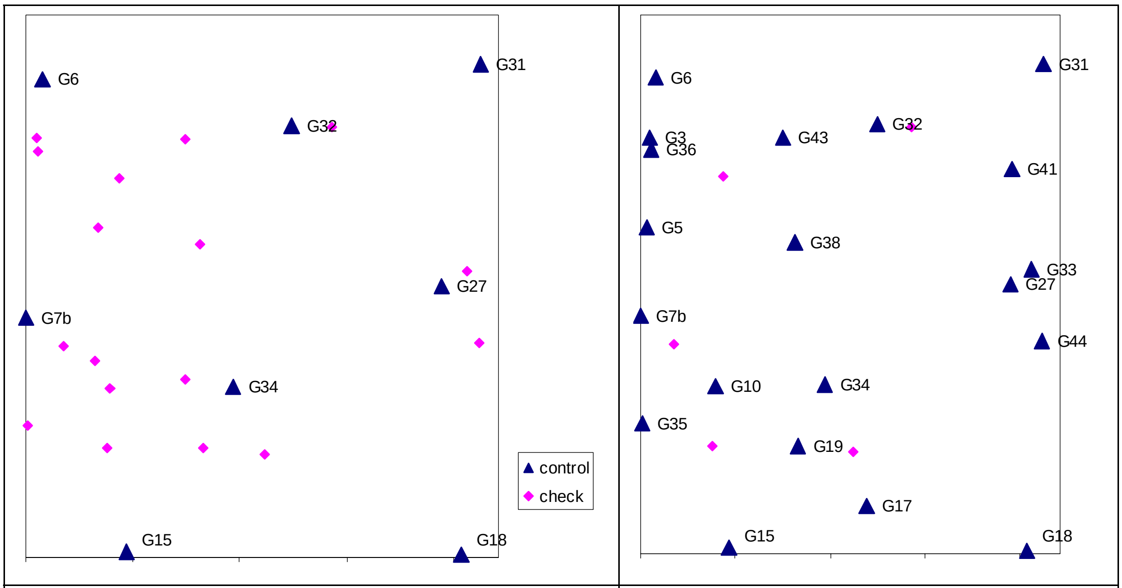
4.1 Evaluation of Rational Function Model for IKONOS Images

The IKONOS imagery vendor, Space Imaging, adopts the Rational Polynomial Coefficients (RPCs) scheme in order to deliver the imaging geometry model instead of providing the interior and exterior orientation geometry of the IKONOS sensor and other physical parameters associated with the imaging process. The RPCs are calculated by Space Imaging from the satellite ephemeris and attitude data instead of releasing the ephemeris data themselves. Therefore, the RFM model is implemented by most of the commercial software packages in order to use the supplied RPCs and also since a rigorous physical sensor model can not be developed due to the lack of the ephemeris files. These software modules deal with IKONOS satellite images by reading the RPC files and applying the RFM model to orient the IKONOS imageries.

The first experiment with the RFM model was performed on each single image using PCI OrthoEngine software package. Table (1) presents the RMSE values for the differences in X and Y coordinates for 17 check points (CPs), as shown in Figure 4 (a), using the RFM model without any ground control points (GCPs). The results show a moderate accuracy, taken into consideration that no GCPs were used, especially for the first image. However, it can be noted that there are a large error in the Y direction (Satellite orbital pass, i.e., image acquisition direction). The results show average horizontal accuracy figures (RMSE XY) that are similar to those published by Space Imaging of 4.25m, (Dial and Grodecki, 2003).

Table (1): RMSE (m) for 17 CPs using RPCs without GCPs for IKONOS Single Images

Image 000			Image 001		
X	Y	XY	X	Y	XY
2.68	4.13	3.48	1.32	8.26	5.91



(a) **8 GCPs / 17 CPs**	(b) **20 GCPs / 5 CP**

Figure 4: Distribution of Ground Control (GCPs) and Check Points (CPs)

The second experiment with the RFM model was performed on the stereo images using Z/I Imaging SSK and ERDAS OrthoBASE software packages. The RMSE values for the differences in X, Y and Z coordinates for the same 17 CPs are listed in Table (2) using the RFM model without any GCPs. It is clear that considerably accurate results were obtained for this case of stereo IKONOS images using RPCs without any GCPs. It shows that the RFM model is appropriate for the areas where there is a difficulty of collecting ground control points. In addition, although the measured image and ground coordinates were the same for both software programs, their results were slightly different. However, both were compatible with results published by Space Imaging for Reference Stereo product which are 3.0m horizontal accuracy and 6.4m vertical accuracy (Dial and Grodecki, 2003).

Table (2): RMSE (m) for 17 CPs using RPC without Control Points for IKONOS Stereo Images using ERDAS OrthoBase and Z/I Imaging SSK

Software	X	Y	XY	Z
ERDAS OrthoBase	**2.67**	**3.39**	**3.05**	**6.88**
Z/I Imaging SSK	**3.53**	**3.69**	**3.61**	**5.97**

Finally, it is clear that the results obtained for the stereo images are more accurate than those obtained for the single images as expected. Furthermore, stereo images provide vertical measurements as well.

4.2 Refined Model

The Rational Polynomial Coefficients (RPCs) are estimated utilizing the physical IKONOS camera model, known only to Space Imaging, without using any ground control points (GCPs). The physical orientation parameters are derived from the satellite ephemeris and attitude. The satellite ephemeris is determined using on-board GPS receivers and sophisticated ground processing of GPS data. The satellite attitude is determined by optimally combining star tracker data with measurements taken by the on-board gyros (Hu et al., 2004). Therefore, it is expected that the modeling accuracy will be improved when using GCPs in the RFM model. Each software package applies its own method for refining the RFM model either by applying polynomials or Affine transformation for the image coordinates. The following equations provide the form of the refined RFM model using first order polynomials (Affine) transformation (Hanley and Fraser, 2004).

$$\begin{aligned} x + a_0 + a_1 x + a_2 y &= \frac{F_1(X,Y,Z)}{F_2(X,Y,Z)} \\ y + b_0 + b_1 x + b_2 y &= \frac{F_3(X,Y,Z)}{F_4(X,Y,Z)} \end{aligned} \qquad (3)$$

Where

x and *y*	image coordinates,
F_i	third-order polynomial functions of object space coordinates *X*, *Y* and *Z*,
a_i and b_i	coefficients of Affine transformation.

The refined RFM model was first applied, using PCI OrthoEngine, for each single image with different number of GCPs (8 and 20). Table (3) presents the RMSE values for the differences in X and Y for 17 and 5 CPs, as shown in Figure 4 (a, b). The results are more accurate than those obtained without any control points (see Table (1)). However, there is no large improvement of the results when greater number of GCPs is used.

Table (3): RMSE (m) for CPs using RFM for Single Images with different Number of GCPs

No. GCPs	No. CPs	Image 000			Image 001		
		X	Y	XY	X	Y	XY
8	**17**	**1.59**	**1.83**	**1.71**	**1.58**	**0.96**	**1.31**
20	**5**	**1.51**	**1.29**	**1.40**	**1.44**	**0.98**	**1.23**

The refined RFM model was then applied for the stereo images, using both software packages; Z/I Imaging SSK and ERDAS OrthoBASE. Table (4) lists the RMSE (in meter) for the differences of the 17 CPs in X, Y and Z coordinates using the refined model with 0th, 1st, and 2nd order polynomials using ERDAS Imagine, while Table (5) lists the RMSE values for the same 17 CPs using Z/I SSK software which implement the refined model with Affine transformation. Different numbers of GCPs were used; starting with 8 GCPs and then reducing them to only one GCP.

Table (4): RMSE (m) for 17 CPs using the 0th, 1st, and 2nd Order Polynomial with Refined RFM Model, using ERDAS OrthoBase

No. GCPs	0th order				1st order				2nd order			
	X	Y	XY	Z	X	Y	XY	Z	X	Y	XY	Z
0	**2.67**	**3.39**	**3.05**	**6.88**								
1	**1.18**	**1.11**	**1.14**	**2.09**								
2	**1.10**	**1.12**	**1.11**	**2.07**								
4	**1.09**	**1.31**	**1.21**	**1.93**	**1.60**	**1.84**	**1.72**	**2.26**				
8	**1.15**	**1.17**	**1.16**	**2.94**	**1.33**	**0.92**	**1.14**	**4.26**	**1.52**	**1.62**	**1.57**	**5.01**

Table (54): RMSE (m) for 17 CPs using Affine Transformation with Refined RFM Model, using Z/I Imaging SSK

No. GCPs	RMS			
	X	Y	XY	Z
0	**3.53**	**3.69**	**3.61**	**5.97**
1	**0.82**	**1.25**	**1.06**	**1.72**
2	**0.71**	**1.32**	**1.06**	**1.71**
4	**0.76**	**1.29**	**1.06**	**1.83**
8	**0.87**	**1.36**	**1.14**	**2.16**

Compared with the case without any GCPs (No. of GCPs equals 0), the results are significantly improved when using GCPs. It is clear that increasing the GCPs from one to 8 points does not improve the accuracy. Thus, the refined RFM model can yield accurate results with only a single ground control point. This confirms that there is only a shift (or a bias) in the supplied RPCs since they are estimated without using any GCPs (Fraser, 2003), (Hanley et al., 2002), (Grodecki et al., 2002) and (Fraser & Hanley, 2003). Therefore, one control point was sufficient to compensate for the shift.

Additionally, increasing the order of the polynomials for refining the RFM model, as shown in Table (4), provided less accurate results. This confirms that there is mainly a shift in the supplied RPCs and, hence, the refinement RFM model should be applied using just the 0th order polynomial.

4.3 3D Affine Projection Model

A computer program was developed using MatLab, applying least-squares adjustment technique, to implement the 3D Affine projection model equations, as described in section 2.2, which transform the 3D object space to 2D image space.

The results of the 3D Affine projection model for the single images are presented in Table (6) for several number of CPs and using various number of GCPs. It can be seen that there is an improvement in the results as the number of GCPs is increased. Also, the results are similar to those obtained by the refined RFM model (in Table (3)).

Table (6): RMSE (m) for CPs using 3D Affine Projection Model for Single Images with Different Number of GCPs

No. GCPs	No. CPs	Image 000			Image 001		
		X	Y	XY	X	Y	XY
8	**17**	**2.14**	**0.94**	**1.65**	**1.70**	**1.52**	**1.61**
20	**5**	**1.60**	**0.91**	**1.30**	**1.21**	**0.95**	**1.09**

In the case of stereo images, the developed program applied the 3D Affine equations for the two stereo images, thus , four equations were written for each ground control point with just three unknowns (X,Y, and Z Ground coordinates), as follows:

$$\begin{aligned} x &= a_0 + a_1 X + a_2 Y + a_3 Z \\ y &= b_0 + b_1 X + b_2 Y + b_3 Z \\ x' &= c_0 + c_1 X + c_2 Y + c_3 Z \\ y' &= d_0 + d_1 X + d_2 Y + d_3 Z \end{aligned} \quad (4)$$

Where,

x, y, x', y'	Image coordinates in the 1st and 2nd images, respectively.
X, Y, Z	Ground Coordinates
$a_0, \ldots, b_3$ and $c_o, \ , d_3$	3D Affine parameters for the 1st and 2nd images, respectively.

Table (7) lists the results when using the 3D Affine projection model for the stereo images in the case of 8, 12, 16, and 20 GCPs with different number of CPs. It is obvious from the table that increasing the number of GCPs improves the results significantly. The results are slightly more accurate than the refined RFM model results (see Table (4) and (5)), however larger number of GCPs is required. In addition, the distribution of the GCPs and CPs will greatly affect the results of the 3D Affine projection model.

Table 4): RMSE (m) for CPs Using 3D Affine Projection Model for Stereo Images with Different Number of GCPs

No. of GCPs	No. of CPs	X	Y	XY	Z
8	**17**	**1.54**	**1.05**	**1.31**	**2.51**
12	**13**	**1.45**	**0.77**	**1.16**	**2.58**
16	**9**	**1.10**	**0.89**	**1.00**	**1.70**
20	**5**	**1.05**	**0.72**	**0.90**	**1.29**

The 3D Affine projection model is suitable for IKONOS Geo-products, which are delivered without the supplied RPCs, and/or for cases where commercial software packages are not available for the users.

It can be concluded from the results, in Table (5) and Table (7), that the most accurate figures, which can be obtained from stereo IKONOS of around 1 pixel (or less) in X and Y, and 1.3-1.7 pixels in Z, using the refined RFM model with one or two control points or using the 3D Affine projection model with 16-20 control points.

5. CONCLUSIONS AND RECOMMENDATIONS

1. The Rational Function Model (RFM) is straight forward; however, it requires commercial software packages that support RPCs files. The model is sensor independent and supports non-iterative solution for the real time restitution.
2. The RFM model, using RPCs files supplied by satellite company, can be used for stereo IKONOS orientation without GCPs.
3. The RFM model provides more accurate results when using just one GCP which compensates for the bias/shift in the supplied RPCs.
4. The 3D Affine projection model provides the most accurate results. However, it is greatly affected by the number, distribution and quality of GCPs.
5. The 3D Affine projection model is found to be the most suitable model since it recognizes that for satellite imagery, as the field of view becomes small and narrow, high correlation developed between EO parameters, and a parallel projection is approached instead of perspective projection. It is sufficiently applicable to along-track stereo imaging configurations of narrow-angle 1m resolution imagery.
6. Sub-meter accuracy in (X and Y) and 1.3-1.7m in (Z) can be achieved for the Stereo IKONOS imagery triangulation process using two mathematical models; the refined RFM and 3D Affine.
7. More accurate results for Stereo IKONOS sensor modeling can be achieved with higher precision image point measurements and better identification of GCPs.
8. More investigation of the studied/developed sensor models of RFM and 3D Affine are needed for other stereo IKONOS images over various study areas with different terrain types.
9. It is recommended to apply and evaluate the 3D Affine projection model for other recent satellite images, whether single or stereo, such as SPOT5 and QuickBird.
10. Modifications to the 3D Affine projection model need to be studied, by applying relief correction (projection of GCPs on a reference height plane), similar to orthorectified image generation technique for a single image (Shaker et al., 2002).
11. Rigorous mathematical models for other stereo high-resolution satellite images with available sensor parameters (ephemeris information), such as QuickBird, need to be developed and compared with the RFM and 3D Affine Models.

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BIOGRAPHICAL NOTES

Nagwa ElAshmawy, Researcher and Head of Photogrammetry and Remote Sensing Department, Survey Research Institute, National Water Research Center, Ministry of Water Resources and Irrigation, Cairo, Egypt.
Yasser ElManadili, Associate Professor, Surveying and Photogrammetry Division, Public Works Department, Faculty of Engineering, Cairo University, Cairo, Egypt.
Hazem Barakat, Associate Professor, Surveying and Photogrammetry Division, Public Works Department, Faculty of Engineering, Cairo University, Cairo, Egypt.

CONTACTS

Dr. Hazem Barakat
Faculty of Engineering
Cairo University
Giza, Cairo
EGYPT.
Tel.: +202 3055050
Fax.: +202 3055400
Email: hazem_barakat@yahoo.com