Assessment of the rectification accuracy of IKONOS imagery based on two-dimensional models

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High-resolution satellite images have become a reality after several high-resolution satellites, such as IKONOS and QUICKBIRD, were launched with 1 m and 0.61 m resolution, respectively, in panchromatic mode. These satellites may change the ordinary concepts of producing varied-scale maps, especially of urban areas, which are now normally based on aerial photographs. This paper focuses on two main issues: first, the attainable geometric accuracy of the digital maps generated from IKONOS satellite imagery by using different two-dimensional transformation models; secondly, the effect of variations in the elevation of the terrain on the resulting overall accuracy.

Two typical cases were selected for this research and the attainable accuracy of the checkpoints versus the number and distribution of the ground control points (GCPs) was studied further. The first case is a relatively flat area in the city of Zagazig in Egypt, where the total variation in elevation is about 7 m in the area covered by the image. The second case is a hilly area of Hong Kong, with about 450 m variation in terrain elevation. The two-dimensional models used for the evaluation process include different orders of polynomials and projective models. Moreover, the determination of the effect of land topography, the selection of the best two-dimensional model and the optimum number of GCPs are all investigated in detail. Based on the results obtained, it can be concluded that variations in terrain elevation significantly affect the accuracy of rectification. To achieve better rectification accuracy, ground points should be projected onto a compensation plane for hilly terrain, but they can be used directly without projection on flat terrain. Accuracy up to less than 1 m can be achieved by using most of the 2D-transformation models after projecting ground points onto a compensation plane or onto flat terrain.

1. Introduction

The making of precise digital maps of urban areas from satellite imagery has become one of the main goals for researchers. This is the case especially in the last two years, during which Space Imaging and DigitalGlobe launched their IKONOS and QuickBird satellites, respectively. For several decades, due to its high accuracy and flexible schedule, airborne photography has been the primary technique employed in producing national map products (Li et al. 1998). However, it cannot map areas that airplanes cannot reach and its mapping frequency is constrained by the limits of flight planning (Li et al. 2000). Now, in the era of high-resolution satellites, the
accuracy required of medium, small-scale maps is achievable, with the possibility of frequently mapping an area without the need to deal with special flight planning and scheduling involved when using aerial photographs.

In the last decade, many studies used rigorous and non-rigorous mathematical models to rectify the satellite linear array scanner imagery, such as SPOT, MOMS-02 and IRS-1C/D. One of the main goals of these studies was to find the appropriate mathematical model to produce precise and accurate maps. To date, the studies published about IKONOS and other satellites have focused on two main aspects: the accuracy attainable in ortho-image generation (Fraser 2000, Hanley and Fraser 2001), and Digital Terrain Model (DTM) extraction concerning 3D positioning from stereo spatial intersection (Shi and Shaker 2003).

El-Manadili and Novak (1996) suggested Direct Linear Transformation (DLT) for the geometric modelling of SPOT imagery. The original proposal for the DLT model appears in Abdel-Aziz and Karara (1971). Since then, various DLT methods have been introduced. The DLT model does not need the parameters of the interior orientation and ephemeris information; the results are based only on the ground control points (GCPs). This is helpful for the geometric correction of the new high-resolution satellite images, especially if the sensor model and the ephemeris information are unavailable. Okamoto et al. (1998) proposed an affine transformation model after converting the original perspective imagery into an affine projection plan. The method was applied to SPOT stereo scenes of level 1 and 2 and it yielded good results.

Furthermore, Ono et al. (2000) tested the 2D affine projective model with SPOT, and proved that ortho-imagery to one pixel ground accuracy can be produced using ground control and DTM data. In 1986, Gugan suggested an orbital parameter model based on collinearity equations. He expanded it by two orbital parameters to model the satellite’s movements along the path and the Earth’s rotation. The same model was adopted successfully by Valadan Zoej and Petri (1998) and applied to SPOT level 1A and 1B, MOMS-02 and IRS-1C imagery (Valadan Zoej and Foomani 1999).

After IKONOS was launched, adoptions of such non-rigorous models, rather than the rigorous collinearity equations, become a necessity where the camera model and precise ephemeris data are withheld from the user community. Hanley and Fraser (2001) tested the metric integrity of IKONOS experimentally. They achieved the kind of sub-pixel ground point accuracy that can be gained from medium-resolution push-broom satellite sensors. In many respects, high metric integrity images are required for some application approaches, such as affine projection and DLT, as a means of both ascertaining the planimetric positioning and evaluating the sensor linearity. Various evaluation schemes are assessed in this paper on the relationship between the geometric accuracy versus the number of GCPs, and the accuracy versus different models in two different cases. The best 2D model and the optimum number of GCPs were identified for the rectified IKONOS images based on the two test cases. The vector map that was generated is also presented.

### 2. Mathematical models of 2D transformation

Mathematically, the rectification process of high-resolution satellite images is a 2D transformation problem. Many 2D transformation models can be used, such as polynomials, similarity, affine and projective models. In this research, five models
were utilized due to their simplicity and availability within most of the remote sensing software packages. These include the first- to fourth-orders of polynomials. In addition, the projective model was utilized to check the metric integrity of the images. The five transformation models adopted for testing can be presented as follows:

- first- to fourth-order polynomial

\[
X_0 = \left( \sum_{i=0}^{t} \right) \left( \sum_{j=0}^{t} \right) a_{i-j} \times X_i \times Y_j
\]

(1)

\[
Y_0 = \left( \sum_{i=0}^{t} \right) \left( \sum_{j=0}^{t} \right) b_{i-j} \times X_i \times Y_j
\]

(2)

where the subscript \( k = \frac{i \times i + j}{2} + j \), \( t \) is the order of the polynomial (here \( t = 1 \) to 4), \((X, Y)\) are the input image coordinates and \((X_0, Y_0)\) are the rectified image coordinates (ERDAS Imagine 1999).

- the projective models

\[
x = \frac{(a_1X + a_2Y + a_3)}{(a_4X + a_5Y + 1)}
\]

(3)

\[
y = \frac{(a_6X + a_7Y + a_8)}{(a_4X + a_5Y + 1)}
\]

(4)

where \((x, y)\) are the image coordinates and \((X, Y)\) are the object plane coordinates.

Due to the fact that the object control points lay at different elevations, object coordinates may need to be projected to a compensation plane. Details of these will be discussed in the next sections. The following two equations are used to calculate the corrections of the coordinates in an easterly direction \((\Delta X)\) and a northerly direction \((\Delta Y)\).

\[
\Delta X = \Delta Z \sin \alpha / \tan \varepsilon
\]

(5)

\[
\Delta Y = -\Delta Z \cos \alpha / \tan \varepsilon
\]

(6)

where \( \alpha \) is the satellite azimuth angle, \( \varepsilon \) is the satellite elevation angle and \( \Delta Z \) is the elevation difference between the points and plane of control.

3. Test fields, images and GCPs

3.1 Test fields and images

This paper evaluates the potential attainable geometric accuracy of rectified IKONOS images based on GCPs derived from a global positioning system (GPS) and different 2D transformation models. The study focuses on the effect of the elevation of the GCPs into their planimetric position. Thus, two different datasets with different elevation differences were used: one with a flat area and another with higher elevation differences.
The test fields comprise two datasets. The first test field is a relatively flat area for the city of Zagazig in Egypt. The image extends 11.16 km × 11.09 km. The central part of the image is mostly urban areas of the city and the other parts are predominantly rural areas with land used for agriculture. The maximum elevation difference is about 7 m in the covered area of the image. Figure 1 illustrates the covered area of the image and the distribution of the ground points, while table 1 contains the technical specifications of the scene.

The second test field is a hilly area of Hong Kong. The image covered 11.64 km × 10.28 km. The image includes three parts—Kowloon peninsula to the north, Hong Kong Island in the southern part of the image and the middle part covered by water. The ground elevation range varied between 0 m to about 500 m. Most of the image is made up of urban areas, except for the areas close to the border, which are nearly all comprised of hills. Figure 2 and table 1 show the image features of Hong Kong, the observed GCPs and the technical specifications of the image.

This variation of the datasets and test fields is fairly reasonable for many reasons.
First, one of the research goals is to check the effects of terrain variation on the resulting accuracy. Secondly, these models need to be validated for different cases. For example, the test field for Hong Kong has special characteristics, due to the presence of very tall buildings and high differences in elevation. These unique characteristics can lead to some problems caused by relief displacement and shadows from buildings. In this study, the surface of the terrain—regardless of the buildings—was mainly considered. Thus, all GCPs/checkpoints were chosen to be on the surface of the terrain and quite far from residential areas.

On the other hand, from Zagazig image technical specifications, it is clear that the image is near to nadir. One can detect that from the acquired nominal ground sample distance (GSD) in cross and along the scan track, which is less than 0.9 m, and from the sensor collection elevation angle. This means that almost no relief displacement problems are found in the image, especially when it is known that almost no tall buildings are found in that area and that the maximum elevation difference is less than 7 m. In addition, the Sun azimuth and elevation angles for the image beside the area specifications lead to almost no shadow problems.

### 3.2 Ground control points

The most traditional sources of GCPs for the rectification of satellite imagery are topographic maps and digitized tablets (Smith and Athinson 2001). However, the launch of high-resolution satellites may lead to the use of other alternative methods. In general, accurate rectification of the remote sensing imagery to a map projection depends on having an accurate source of GCPs. At the same time, the accuracy of the GCPs should match the resolution of the digital image (Smith and Athinson 2001).

In Hong Kong, 1:1000 topographic digital scale maps are available, which means that an accuracy of 0.5 m to 1.0 m can be achieved from extracting GCPs and that

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**Table 1.** Technical specifications of IKONOS images used in the experiment.

<table>
<thead>
<tr>
<th></th>
<th>Zagazig city image</th>
<th>Hong Kong image</th>
</tr>
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<tbody>
<tr>
<td>Processing level</td>
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<td>Standard geometrically corrected</td>
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<td>Zone number</td>
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<td>50 N</td>
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<td>Acquired nominal GSD (m):</td>
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<td>cross scan</td>
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<tr>
<td>along scan</td>
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<td>0.91</td>
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<tr>
<td>Nominal collection elevation (°)</td>
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<td>Nominal collection elevation (°)</td>
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</tr>
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<td>Sun elevation angle (°)</td>
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<td>23 November 2000</td>
</tr>
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<td>Coverage area</td>
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<td>22.26249919° to 22.35721210° N</td>
</tr>
<tr>
<td></td>
<td>31.44390809° to 31.56184163° E</td>
<td>114.11396605° to 114.22652104° E</td>
</tr>
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</table>
the accuracy may match the resolution of the images. However, it was not possible to use this approach in this study because, in many cases, GCP positions on the image cannot be matched with the digital maps. In addition, a 1.0 m accuracy from the extracted GCPs cannot be achieved when the source of the elevation values is one contour layer with a major contour interval of 10 m and minor contour intervals of 2.0 m.

Due to the consideration of a higher accuracy, these facts and principles led to the use of GCPs acquired by GPS instead of digitized topographic maps. Thirty-eight well-distributed GCPs were collected by GPS; some of these points were pavement corners and others were road intersections or intersections between roads and canals. The base lines did not exceed 5 km and the occupation time was about 20 minutes for each point. Figures 3 and 4 show the collection of one of the GCPs from the Hong Kong test field and its identification on the image.

For the Zagazig image, 13 well-defined and distributed ground points were observed by means of the GPS technique. The coordinates of each GCP were
Figure 3. Identification of GCPs on the image.

Figure 4. GCPs collection.
determined using Leica system 300 GPS. Two receivers were used: one as a base station on one known point and the other one on the other points. Measures of X, Y and Z coordinates were recorded at 10 s intervals for about 45 minutes, with at least four satellites available for each point. Most of the observed GCPs are road intersections or intersections between roads and canals. The GPS position data were corrected by post-processing using Ski-Pro software. In all cases, coordinates from GPS measures were provided as WGS84 Datum and UTM projection and the accuracy of the processed GCPs is less than 5 cm. Photographs and full description cards were made for the computer digitizing process for these points.

4. Rectification results and analysis

With regard to Space Imaging technical specifications for the IKONOS Geo product, a planimetric accuracy of 50 m 90%CE (Circular Error) and 23.6 m associated rms errors are expected for a Geo product (Space Imaging 2001). However, this accuracy does not account for the effects of terrain displacement, which depends on geometry and elevation uncertainty and can amount to several hundred metres. The five 2D transformation models, with different numbers of GCPs, were used for the two test fields to identify a model which can offer the highest rectification accuracy for IKONOS imagery.

First, the Zagazig IKONOS image was utilized with first- and second-order polynomials and an eight-parameter projective model, as most popular models available in most of the remote sensing and image processing software packages. Coupled with this fact, the lack of knowledge about the algorithms used for IKONOS geometric correction encouraged use of these models, which provide sufficient insight into the metric integrity of the IKONOS imagery. Due to the lack of ground points, no orders higher than the second order of polynomials were used with this image. Cases with different numbers of GCPs (from four to ten) were configured and the rest were used as checkpoints. Figures 5(a)–(c) show the results in terms of the rms errors of the checkpoints. From the results obtained, it was found that an accuracy of less than 1 m in both the X and Y directions could be achieved by utilizing most of the used 2D transformation models with a modest number of GCPs. This means that no significant perturbations in the sensor system can be observed. Furthermore, the minor variation between the results of the models indicates that no significant first- or higher-order systematic errors existed in the satellite sensor. In addition, one can conclude that the benefit of having a narrow field of view (0.93°) is perceptible, as the wider-angle sensors had significant nonlinear image perturbations from the lens projective distortions. The results show that there is no need to project the GCPs onto a compensation plane when the difference in the elevation is less than 7 m, as indicated in the Zagazig case study. The eight-parameter projective model yields the best results, about 0.5 m with ten GCPs. Figure 6 presents the vector map generated from the Zagazig image after the rectification process.

Secondly, the Hong Kong image was studied further to test the necessity of using a compensation plane with 2D transformation models when accurate planimetric results are sought and there is a higher difference in terrain elevations. To determine the errors in the geo-referenced image coordinates due to relief displacement, the observed GPS WGS84 UTM ground coordinates were compared with the corresponding measured geo-referenced image coordinates. The absolute planimetric errors for all points were found to be between 1 m and 111 m in the Y
Figure 5. Zagazig data set rms errors in (a) the X direction, (b) the Y direction and (c) the total errors.
direction and from 3 m to 32 m in the X direction, depending on the elevation of the points; the higher the point the greater the error value. One can see from the variation in error values in the X and Y directions that the Y direction contains a large number of errors. This can be expected due to the along-track image capturing technique. The transformation process involved two main steps: (a) model parameters were determined by using different numbers of GCPs and the least-square adjustment technique; then (b) the transformed coordinates were calculated based on the determined parameters.

Five 2D transformation models, first- to fourth-order polynomials and the projective models were used in this part of the test, as the number of GCPs are sufficient. The 2D transformation process comprised two tests. First, the GCPs were utilized without being projected to a compensation plane. The number of GCPs used varied from 6 to 18, while the remaining points were used as checkpoints. In all cases, the resulting rms errors present discrepancies in the checkpoints; the total rms errors ranged from 8.34 m to 5.83 m in the X direction and from 38.27 m to 14.47 m in the Y direction, and the projective model presented the best results. It is obvious that these 2D transformation models improve the accuracy of the rectified images but cannot verify accepted accuracy.

In the second test, the positions of all ground points were projected to their equivalent positions on a compensation plane. Different elevation levels for the compensation plane were used, and no differences in the results could be remarked. Therefore, an elevation of 200 m was chosen to present the mean elevation of the tested area. Using equations (5) and (6) and with the aid of the azimuth and elevation angles of the sensor, the projected coordinates were calculated and applied to the 2D models to check the accuracy of the results. Figures 7(a)–(c) summarize the results yielded from the transformation process when utilizing a different
Figure 7. Hong Kong data set rms errors in (a) the X direction, (b) the Y direction and (c) the total errors.
number of GCPs. For control configurations, starting from six up to 18 GCPs and using the remaining points as checkpoints, the second-order polynomial produced the best rms errors, with results varying between 0.46 m and 0.29 m and 0.49 m and 0.46 m in the X and Y directions, respectively. However, the fourth-order polynomial yielded slightly better results than the second-order polynomial, but it required at least 16 GCPs. In all cases, the rms error discrepancy values were less than 1 m in both the X and Y directions.

From these results, it is remarkable that no significant effects in the total rms errors were achieved when the number of GCPs was gradually increased from 6 to 18. This led to the conclusion that the most important factor for 2D IKONOS image rectification is GCP quality rather than quantity. The third- and fourth-order polynomials offered results similar to the second-order polynomial, but with more GCPs (at least 10 and 16, respectively). The noteworthy point of the results is that the second-order polynomial, which is available in most remote sensing software, produces almost the best results when the ground coordinates are projected onto a compensation plane. This finding confirms that, after projecting ground coordinates onto a compensation plane or in the case of flat terrain, IKONOS imagery does not have a higher order of distortions. Thus, any low level polynomial can be used to rectify the images. However, the second-order polynomial is highly preferable and presents the best results because it may cover any additional perturbations due to lens distortion or sensor motion. Finally, one can conclude that projecting GCPs to a compensation plane should be done before IKONOS images are geometrically corrected, when there is a great difference in elevation.

5. Conclusions

This paper presents an experimental assessment of various 2D transformation models for IKONOS satellite images. The assessment includes identifying the most suitable 2D transformation model(s) for image rectification and evaluating the factors that affect the accuracy of the rectification, such as variations in terrain elevation within the imaged area and the number of GCPs.

According to the experiments in this study, the results show that the accuracy of the rectified coordinates is affected heavily by the difference in elevation of the ground points. For higher accuracy results, when there is a significant difference in terrain elevation levels, GCPs should be projected onto a compensation plane before 2D transformation models are utilized. This should be done in order to reduce the considerable effect of relief displacement in the area covered by the image.

Furthermore, in the case of flat terrain or after projecting ground points to a compensation plane, the second-order polynomial model gives the best image rectification results (less than 0.5 m accuracy) with a modest number of GCPs (six points), while an accuracy of less than 1 m can be achieved by utilizing most 2D transformation models. In most of the cases, when applying most of the 2D transformation models, no significant improvement for image rectification results could be obtained by simply increasing the number of GCPs. A good distribution of the GCPs is even more beneficial to improving accuracy than a dense but poor spatial distribution of the GCPs.

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