Approximate Approaches to Geometric Corrections of High Resolution Satellite Imagery

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ABSTRACT The exploitation of different non-rigorous mathematical models as opposed to the satellite rigorous models is discussed for geometric corrections and topographic/thematic maps production of high-resolution satellite imagery (HRSI). Furthermore, this paper focuses on the effects of the number of GCPs and the terrain elevation difference within the area covered by the images on the obtained ground points accuracy. From the research, it is obviously found that non-rigorous orientation and triangulation models can be used successfully in most cases for 2D rectification and 3D ground points determination without a camera model or the satellite ephemeris data. In addition, the accuracy up to the sub-pixel level in plane and about one pixel in elevation can be achieved with a modest number of GCPs.

KEY WORDS remote sensing; rectification; polynomials; high resolution

CLC NUMBER TP751;P236

Introduction

In the last decade, many studies and researches were performed with rigorous and non-rigorous mathematical models to rectify the satellite line scanner imagery such as SPOT, MOMS-02 and IRS-1C. One of their goals is to find an appropriate mathematical model for accurate results.

For IRS imagery, despite the satellite ephemeris data and information about sensor model are available, practical approaches are preferred. The rigorous sensor model usually has some disadvantages such as the complexity of the model, the need of changing real time mathematical model for each different image sensor and the difficulties for selecting specialized proper software for multi sensor triangulation. In addition, the very long principal distance and the narrow angle of view comparing to the aerial photographs may make an orbital resection unstable. Due to these difficulties, practical approaches are preferred for geometric corrections of high-resolution satellite imagery (HRSI) and extracting accurate 2D and 3D terrain information.

1 High-resolution satellites

1.1 IRS 1C/1D technical specifications

As primary objectives of IRS satellites is to provide systematic and repetitive acquisition of data. IRS operates in a circular, sun-synchronous, near polar orbit with an inclination of 98.69°. With the stereo capabilities, the satellite can image the earth by a rotation of the whole PAN-camera up to ±26° across track viewing and with five-day revisit time at least. The swath width varied between 70 141 km and 804 km at nadir view for PAN, LISS-III, and WiFS images, respectively. The imaging with
the PAN camera consists of almost 12,000 pixels from three CCD lines. One main reason for the imaging with PAN camera is that the resulted images can be separated to three CCD-lines that there is no available CCD-line with 12,000 pixels and 7 micron meter pixel size. Each CCD-line has 4,096 pixels with a small overlap between the three CCD-lines, which make the effective size of the whole combination be 12,000 pixels. In general, the full PAN scene is delivered in three separated files, one file for each original CCD-sensor. Details about the IRS-1C satellite and its camera system, which is similar to IRS/1D, can be found in References [3] and [4].

1.2 IKONOS technical specifications

IKONOS satellite imageries are available within ±85° latitudes with two different levels of geometrically corrections. One is Geo product, which is imaged above 50° elevation angle for fast revisit time with pan ground sample distance (GSD) up to 1.2 m. The other is the Geo Ortho kit product, which has an elevation angle above 75° with pan GSD below 1 m, and includes polynomial rational coefficients (PRC) data as opposed to the rigorous mathematical model of the satellite. Table 1 illustrates the IKONOS product names and the corresponding accuracies in terms of circular error at 90% probability (CE90) and root mean square error (RMS).

| Product name | CE90/m | RMS/m | Associated scale map |
|--------------|--------|-------|----------------------|
| Geo          | 50.0   | 23.6  | 1:100,000           |
| Reference    | 25.4   | 11.8  | 1:50,000            |
| Pro          | 10.2   | 4.8   | 1:12,000            |
| Precision    | 4.1    | 1.9   | 1:4,800             |
| Precision Plus | 2.0   | 0.9   | 1:2,400             |

The rational polynomial coefficients RPCs (also termed Rational polynomial camera model (RPCM) or rational function model (RFM)) is used by space imaging (SI) company as opposed to the rigorous mathematical model. SI specifications showed that without ground corrections the horizontal accuracy is 50 m CE90% or 23.6 m RMS; however, when using RPCs model with GCPs, the accuracy can be improved to 4 m CE90% or 1.8 m RMS.

With the high stereo capability, IKONOS stereo principle based on along track technique as well as a capability of cross track, which can be rolled at distances of 725 km on either side of the ground track. Stereo pairs created from forward and backward looking (along track) ensure high quality collections because images are acquired under nearly the same conditions. However, the cross track technique provides opportunity to enhance the revisit frequency of the satellite up to daily frequency.

1.3 QuickBird technical specifications

Digital Globe’s QuickBird satellite provides a highest resolution (0.61 m and 2.44 m in PAN and multispectral modes, respectively) and the largest swath width (16.5 km at nadir) as well as largest on-board storage. Different processing levels have offered results ranging from raw data to orthorectified image maps. QuickBird imagery products are mainly yielded at two processing levels; basic imagery (Level 1) with the minimum amount of processing and standard imagery (Level 2) with standard radiometric and geometric corrections.

The basic imagery or Level 1 products are the least processed product with only radiometric and sensor corrections. In this level, the ground sample distance (GSD) which represents the image resolution varies from 61 cm (at nadir) to 72 cm (at 25° off-nadir look angle) for PAN mode and from 2.44 cm (at nadir) to 2.88 cm (at 25° off-nadir look angle) for the multispectral (QuickBird imagery product, product guide). However, the basic imagery is geometrically raw, a horizontal accuracy of 14 m RMSE (23 m CE90%) may be achieved when the data are processed and for this accuracy the topographic displacement effects are not taken into account. The GSD are presented as 70 cm with uniform pixel size. All standard products are supposed to have the same accuracy as in the basic imagery products after processing.
1. Technical comparison between different HRSI specifications

Many differences between IKONOS, QuickBird and IRS satellite systems can be presented; however, the main differences between the IKONOS-QuickBird systems and IRS system can be summarized in three main aspects. First, the inflexibility of the payload steering mechanism of IRS system compared with IKONOS and QuickBird systems led to limited acquisition of stereo IRS images. Second, the limited radiometric range (gray value) of the PAN sensor of IRS (only 6-bit) compared with IKONOS and QuickBird sensors (11-bit) may lead to saturation problems as will be discussed. Finally, the difference of the IRS satellite sensor architecture, which is composed of three linear arrays next to each other, from the IKONOS system with one linear array brings forth some difficulties for image triangulation process.

2 Test field

In the research work, the simulated data is usually used for the judgment of the mathematical model performance as a part of developing or establishing a new model, however, the conclusions on the performance of the model can only be made after using real data. The simulated imageries can be used in the first stages for model validation but it is not enough for sound conclusions because they themselves are created by the same model or by assumptions that they may not represent the real situation. Thus, the use of the real data is indeed necessary when we are talking about the development of mathematical models.

2.1 IKONOS images of Hong Kong

The data set used in this paper as an example comprises two IKONOS satellite images for Hong Kong region with different terrain types. The Hong Kong test field area is located in the central part of Hong Kong. Two images were available for this area, image 1 (Fig. 1) covered an area of 11.60 km × 10.28 km, which is a part of Hong Kong Island and Kowloon district, and image 2, in the same region covered an area of 6.62 km × 10.18 km and has a 2.5 km × 10.0 km overlap with the first image. The max ground elevation difference in the tested area is about 500 m. The central parts of the two images are nearly flat, while the northern and southern parts are mountainous.

The two images were not sold originally as stereo pair but as two single images. It means that the images were not delivered with the rational function models but the company submitted it with its Meta data files only. However, from the azimuth and elevation angles of the two images, it is obvious that the images were captured in along track and can be used as a stereo pair for the overlap area. From the two images specifications, the ratio of base to height (B/H) can be calculated and is equal to 0.87, which give us indication that the two images can be used geometrically as a stereo pair. Hong Kong test field has special characteristics due to the very tall buildings and great differences in elevation. These unique characteristics lead to some problems due to relief displacement and shadow from buildings. Therefore, we just consider the terrain surface regardless the buildings and all GCPs/checkpoints were chosen on the terrain surface and quite far from the residential areas. Fig. 1 shows the covered area and the GCPs distribution on the two images.

2.2 Hong Kong GPS work

Up to date, the most traditional source of GCP
for satellite imagery rectification has been from topographic maps and digitized tablet, however, with the launch of high-resolution satellites there may be other alternative methods for use. In general, the accurate rectification of the remote sensing imagery to a map projection relies on accurate source of ground control points. At the same time, the accuracy of ground control points should meet the need of resolution of the digital image. In Hong Kong, 1:1000 digital topographic maps are available, which means that accuracy of 0.5 m to 1.0 m can be achieved from extracting GCPs and it may match the images resolution. However, it was not useful for us to use it in our research work because in many cases we cannot find and match GCP positions on the image and the digital maps. In addition, 1.0 m accuracy from the extracted GCP can not be achieved when the source of the elevation values are one contour layer with major contour interval of 10 m and minor contour intervals of 2.0 m. These facts and principles lead us to use GCPs acquired by GPS instead of those acquired from digitized topographic maps due to its high accuracy.

For this project, a reference receiver located on one of Hong Kong Polytechnic University buildings was used as a base station when a rover receiver were moved for collecting the GCPs. Thirty-eight well-distributed ground control points were established by using two GPS Trimble sets system 4000 SSI and applying differential GPS techniques. First, the images were divided into several areas of interest. Alternative points were chosen in each area so that they were well distributed across the images and the stereo model. The natures of the observed points were landmarks, road intersections and some well-known features that can be identified easily on the image. All the GPS ground points were chosen to be located on the ground surface.

The final accuracy of all points is estimated to be of the order of 5cm in X and Y directions and 10 cm in Z direction. For some satellite images, rectification process will need just one to two meters positional accuracy by single frequency GPS unit without differential corrections. However, the necessity of the base station triangulations will still be compulsory for very high accuracy.

3 Used models

On the basis of previous research on IKONOS satellite, it is reasonable to assume that the sensor moves linearly in space, and that the attitude is almost unchanged. Furthermore, if the WGS84 UTM system is adopted as a reference system, the orientation angles can be regarded as constant and the flight path of the satellite as approximately straight. These characteristics let one abridge the collinearity equations between the satellite imagery and the ground points to simple formulas. For 2D transformation, five models were studied in this research using different numbers of ground control points. These models are generally available within most of remote sensing image processing systems. These models can be used to provide sufficient insight into the ground elevation effects on the metric integrity of the rectified images. The five 2D transformation models adopted for testing were four orders of 2D polynomials and eight-parameter projective model. The following sections discuss their characteristics.

3.1 Polynomial models

Polynomial models are usually used in the transformation between source file coordinates and map coordinates. The necessary transformation can be expressed in different orders of the polynomials based on the distortion of the image, the number of GCPs and terrain type. A first-order transformation is a linear transformation, such as scale, skew, rotation and change location. In most cases, first order polynomial is used to project raw imagery to a planar map for data covering small areas. Transformations of the second-order or higher are nonlinear transformations that can be used to convert Lat/Long data to planar or to correct nonlinear distortions such as Earth curvature, camera lens distortion.
The following equations are used to express the general form of the polynomial models.

**General 2D polynomials:**
\[
x = a_0 + a_1 X + a_2 Y + a_3 X^2 + a_4 Y^2 + a_5 XY + \cdots \tag{1}
\]
\[
y = b_0 + b_1 X + b_2 Y + b_3 X^2 + b_4 Y^2 + b_5 XY + \cdots \tag{2}
\]

**General 3D polynomials:**
\[
x = a_0 + a_1 X + a_2 Y + a_3 Z + a_4 X^2 + a_5 Y^2 + a_6 Z^2 + a_7 XY + a_8 XZ + a_9 YZ + \cdots \tag{3}
\]
\[
y = b_0 + b_1 X + b_2 Y + b_3 Z + b_4 X^2 + b_5 Y^2 + b_6 Z^2 + b_7 XY + b_8 XZ + b_9 YZ + \cdots \tag{4}
\]
where \(a, b\) are the model coefficients; \(X, Y\) are model parameters.

### 3.2 Eight-parameter projective model

Eight-parameter projective model expresses the relationship between two planes on the basis of perspective projection concepts. The basic elements of the perspective projection consist of the point of the perspective center, bundle of arrays through this point, and two different planes cut the bundle of arrays and do not contain perspective center. These two planes can be defined as image plane and the ground projected plane. The relationship between the two planes can be written as follows.

**Eight-parameter transformation model:**
\[
x = \frac{(a_1 X + a_2 Y + a_3)}{(a_4 X + a_5 Y + 1)} \tag{5}
\]
\[
y = \frac{(a_1 X + a_2 Y + a_3)}{(a_4 X + a_5 Y + 1)} \tag{6}
\]
where \(a_i\) is the model coefficient, \(x, y\) are the image's coordinates; \(X, Y\) are the object's plane coordinates.

### 3.3 Affine model

In this research, the straightforward eight-parameter affine model was used to confirm that it could reach the accuracy equivalent to that by rigorous sensor models. The adoption of an affine model as opposed to perspective projection model for satellite line-scanner imagery has been previously considered for both SPOT and MOMS-02 imagery, and the results showed that the affine model is quite robust and stable for image orientation and triangulation. The noteworthy benefit is that using the affine model we can save at least thirty percent on image prices by ordering stereo images without the need for the rational functions. Each observation of a GCP will give rise to a set of two affine condition equations derived from the relationship between the image coordinates and the GCP coordinates in the geocentric system. The two affine condition equations are as follows:
\[
x = A_1 X + A_2 Y + A_3 Z + A_4 \tag{9}
\]
\[
y = A_5 X + A_6 Y + A_7 Z + A_8 \tag{10}
\]
where \(x, y\) are the image coordinates, and \(X, Y, Z\) are the ground coordinates.

### 4 Results analysis

#### 4.1 2D image to object space transformation

Five 2D transformation models, four orders of polynomials and the projective model were used in this study due to their simplicity and availability within most of the remote sensing software packages to check its applicability for HRSI rectification. Furthermore, the use of a compensation plane with 2D transformation models is further studied when accurate planimetric results are sought and there is a difference in the terrain elevations.

To determine the errors in the image geo-referenced coordinates, the observed GPS WGS84 UTM ground coordinates were compared with the corresponding measured geo-referenced image coordinates. The absolute planimetric errors...
for all points was found between 1 m and 111 m in Y direction and 3 m to 32 m in X direction, depending on the points' elevations. As can be seen from the variation values in X and Y direction, Y direction contains the large amount of error as can be expected due to the along track capturing technique. The transformation process involved two main steps: ① model parameters were determined by using different numbers of GCPs and the least square adjustment; ② the transformed coordinates were calculated with the determined parameters. Since the two images in Hong Kong data set are quite similar with respect to the X and Y accuracy results, this paper presents the results of applying the 2D transformation models to image 1.

The 2D transformation comprised two tests. Firstly, the GCPs were utilized without being projected to a compensation plane. The number of GCPs varied from 6 to 18, while the remaining points were used as checkpoints. The results showed that in all cases, the total RMS errors ranged from 5.83 m to 8.34 m in X direction and from 14.47 m to 38.27 m in Y direction, and the projective model presented the best results. However, it can be seen that these 2D transformation models improve image accuracy but cannot verify accepted results’ accuracy. In a second test, all 3D ground point positions were projected to their equivalent positions on a compensation plane at an elevation of 200 m, which presented the mean elevation of the tested area. The projected coordinates were applied to the 2D models to check their accuracy. For control configurations starting from six up to eighteen GCPs and using the remaining points as checkpoints, the 2nd order polynomial produced best RMS errors with results of 0.46-0.29 m and 0.49-0.46 m in X and Y directions, respectively. However, the 4th order polynomial yielded slightly better results than the second order but it required at least sixteen GCPs. In all cases, the RMS error values are less than one pixel in both X and Y directions.

From these findings, it is remarkable that no significant effects in the total RMS errors were achieved when increasing gradually the number of the GCPs from 6 to 18. Thus a conclusion can be drawn that the most important factor is GCP quality rather than quantity for 2D rectification. The third and fourth order polynomials offered results similar to the second order polynomial, but with more GCPs (at least 10 and 16 GCPs, respectively).

### 4.2 3D ground points determination using affine model

This research is an attempt to evaluate the potential of IKONOS panchromatic sensor data using non-rigorous models. In the implementation of these models for orientation and triangulation process, sophisticated programs were developed for 3D ground point determination. The programs comprises a space resection, which is applied individually to each of the images making up the stereo pair, and a space intersection procedure, which generates the ground coordinates of the images with the aid of the least square adjustment. The least square solution solves the models’ equations to determine the orientation parameters of the left and right images. Stereo intersection is implemented independently to calculate the ground coordinates of conjugate points. Multiple sets of well-distributed GCPs were applied while the rest of the ground points were utilized as checkpoints.

In the implementation of the affine model for the IKONOS orientation and triangulation process, a particular program was developed, which comprises object to image space transformation in forward (resection) and inverse (intersection) forms. Multiple sets of four, six, eight, ten and twelve well-distributed GCPs were applied when the rest of the eighteen points were utilized as checkpoints.

In general, it can be seen from the results that the total RMS errors in X, Y and Z directions considerably decrease with the increase of the number of GCPs. For the control configuration of four well-distributed GCPs and fourteen checkpoints, the affine model produced 1.38 m, 1.98 m, 3.20 m RMS errors in X, Y and Z di-
rections, respectively, whilst the RMS error results improved significantly to 0.58 m, 0.63 m in X, Y directions and 0.98 m in Z direction when 12 GCPs were used. The accuracy of the model achieved by applying different sets of six to ten GCPs confirms the gradual improvement of the RMS errors of the checkpoints. In all cases the maximum residuals for the GCPs in the least square adjustment process was less than 5 cm, while it varied between 0.5 m to 2 m in X, Y directions and from 0.6 m to 3.5 m in Z direction for the checkpoints. The results obtained obviously showed that it is consistent with the expectation from photogrammetry experience.

An additional test was performed to examine the accuracy of the ground coordinates determination using the affine based program by generating DEM based on some extracted points and by comparing it with an existing one, produced from 1 : 5 000 scale maps. More than 300 well-defined points were digitized in the model region with the accuracy of image coordinates of more than half pixel. The measured points were applied to the affine program to compute its X, Y and Z ground coordinates using all available GCPs. When the generated DEM was compared with the existing one, the absolute height residuals varied between zero to five meters for the most part of the flat area on the image, while they ranged between zero to three meters for the hilly and mountainous areas. In order to treat the shortcomings of using the affine model in flat areas, some constraints, such as the seashore, were added to the model. The DEM was generated from all calculated (measured and constraint) points using the Kriging interpolation method and again was compared with the existing one. The resulting values of the latest DEM surpass those from the previous one in terms of height accuracy.

6 Conclusions

There is a distortion in the planimetric Geo-reference image coordinates delivered from the satellite depending on the ground point elevation level as can be expected from the imagery specifications. The ground points elevation should be cared about even we just rectify the image in 2D directions. The accuracy of the rectified coordinates is heavily affected by the elevation difference of the ground points. An accuracy of 0.5 m can be achieved by utilizing most of 2D transformation models after projecting the ground coordinates into a compensation plane. 3D affine model can be used successfully in most cases for 3D ground points determination without a camera model or the satellite ephemeris data. The accuracy up to the sub-pixel level in X-Y directions and about one pixel in Z direction can be achieved by using the eight-parameter affine model and a modest number of GCPs. Increasing the number of GCPs significantly improves the accuracy of the results when the affine model applied for an area with different terrain types.

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