ACROSS-TRACK IMAGING ACCURACY ANALYSIS AND RESEARCH OF HIGH RESOLUTION SATELLITE IMAGERY IN METROPOLITAN AREA

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ABSTRACT:

High Resolution Satellite Imagery (HRSI) is now being used more and more in city development. The geometric correction of HRSI is the basis of all the image process work for other application such as acquisition and updating of topographic data. This paper first discusses the background and details of Rational Function Model (RFM) which describes the coordinates in image space and object space, and then two different schemes in both object space and image space are introduced. With different parameters, four kinds of accuracy improvement models in both spaces are put forward and discussed, respectively. Conclusion is drawn that with more well distributed Ground Control Points (GCPs), high geo-positioning accuracy can be obtained up to about 0.6 meter in plane direction and 0.7 meter in height direction for QuickBird across-track stereo imagery in Metropolitan Area.

1. INTRODUCTION

With the development of urbanization and increasing changes of infrastructure in city area, the high efficiency acquisition and updating of urban basic topographic data (UBTD) are now becoming more and more important. Many research institutes have been studying the capability of HRSI for development and construction of urban area due to comparable resolution compared with aerial imagery.

The launch of IKONOS initialled the new era of earth observation and digital mapping from commercial HRSI (Li 1998). Due to the advantages such as high resolution, short revisit time, and wide swath, HRSI is a valuable and cost effective data acquisition tool for a variety of mapping and GIS applications (Habib, Shin et al. 2007; Li, Zhou et al. 2007; Qiao et al. 2007). Both the IKONOS and QuickBird can provide along-track stereo imagery which is obtained at almost the same time and with the same orbit, and many research applications are based on along-track stereo imagery. However, along-track stereo imagery is not economic for mapping and applications compared with across-track stereo imagery. For example, the cost of along-track QuickBird stereo images is about 2 to 3 times than that of across-track stereo images, making it imperative that detailed research is given on positioning accuracy with across-track stereo imagery (Tao et al.; Qiao et al. 2007) .

The positioning models of HRSI mainly include rigorous sensor model (RSM) and RFM. The RFM has been used more and more in practice as an alternative to the RSM because of its sensor independent and easy calculation. Much more research work has been found in detail concerning the positioning model and the accuracy of RFM. Li (1998) discussed the potential accuracy of IKONOS imagery for national mapping products with satellite pushbroom CCD linear arrays. Di et al. (2003) presented the geometric processing of IKONOS along-track stereo imagery with the test data elevation range from 170m to 230m along the southern shore of Lake Erie, and achieved an RSME of 1.2 m, 0.9 m and 1.6 m in X, Y, Z directions. Zhou and Li (2000) demonstrated the potential accuracy of ground points using simulated IKONOS along-track stereo image data, and found that the ground point accuracy is 3 m (X and Y) and 2 m (Z) with 24 GCPs, and 12 m (X and Y) and 12 m (Z) without GCPs. Li et al. (2007) investigated the accuracy in 3D geo-positioning achieved by integrating IKONOS and QuickBird along-track stereo imagery with an elevation range between -29.7 and 31.9 m in south Tampa Bay, Florida. Fraser et al. (2006) examined RFM block adjustment to yield sub-pixel geo-positioning accuracy using along-track QuickBird stereo image pairs and three multi-image IKONOS blocks with elevation range differences from 50 m to 1280m, and accuracy was obtained in along-tack direction 0.7 to 1 m, across-track 0.4-0.6 m, and height 06-1.0 m. Habib et al. (2007) conducted rigorous and several approximate sensor models to investigate the accuracy of ground coordinates over the city of Daejeon, South Korea, where terrain height variation is about 300 meters, using along-track IKONOS stereo imagery, and an accuracy of 2-3 m were achieved.

However, existing work mainly focus on the test areas including mountainous and urban regions, which have distinct height difference, while little work has been conducted in planar metropolis, where very low relief and complex features are considered to be the main obstacles in imagery positioning process. Research is carried out based on the above situations as precondition in this paper.

2. RFM AND UPDATING SOLUTIONS WITH ADDITIONAL GCPS

2.1 RFM

The RFM are described in detail in Tao and Hu (2001) and Grodecki and Dial (2003). Here is a brief introduction.

The RFM, as expressed in equation 1, provides a direct mapping from 3D object space coordinates (usually offset normalized latitude, longitude, and height) to 2D image coordinates (usually offset normalized line and sample values).

$$r = \frac{P_1(X,Y,Z)}{P_2(X,Y,Z)} \qquad c = \frac{P_3(X,Y,Z)}{P_4(X,Y,Z)} \tag{1}$$

where r and c are row and column coordinates and P_i ($i = 1,2,3,4$) are third-order polynomial functions of object space coordinates X, Y, Z that transforms a point from the objects space to the image space. There are 39 Rational Polynomial Coefficients (RPCs) in each equation, including 20 in the numerator and 19 in the denominator, and they are usually provided by satellite image providers.

Tao and Hu (2002) derived a least-squares solution to the RFM and comprehensively evaluated and analyzed the results of numerous tests with different data sets.

2.2 Updating RPCs with Additional GCPs

GCPs are required for the elimination of biases, and a lot of research has been done on this respect. Hu and Tao (2002) used batch iterative least-squares method and an incremental discrete Kalman filtering method to update or improve the existing RFM solutions when additional GCPs are available. Robertson (2003) assessed the absolute geometric accuracy of a sample set of QuickBird products using a full photogrammetric block adjustment.

According to Wang et al. (2005), basically, there are two kinds of schemes to improve the geo-positioning accuracy of RFM with additional GCPs, object space and image space. There are four different models defined in both spaces to refine the RPC-derived ground coordinates. They are translation model, scale and translation model, affine model, and second-order affine model. Here are some basic mathematical principles of the models.

2.2.1 Geometric Correction in Object Space

The four geometric correction models are shown as equation 2-5 as below,

$$\begin{cases} P = a_0 + X \\ L = b_0 + Y \\ H = c_0 + Z \end{cases} \tag{2}$$

$$\begin{cases} P = a_0 + a_1 X \\ L = b_0 + b_1 Y \\ H = c_0 + c_1 Z \end{cases} \tag{3}$$

$$\begin{cases} P = a_0 + a_1 X + a_2 Y + a_3 Z \\ L = b_0 + b_1 X + b_2 Y + b_3 Z \\ H = c_0 + c_1 X + c_2 Y + c_3 Z \end{cases} \tag{4}$$

$$\begin{cases} P = a_0 + a_1 X + a_2 Y + a_3 Z + a_4 XY + a_5 XZ + a_6 YZ + a_7 X^2 + a_8 Y^2 + a_9 Z^2 \\ L = b_0 + b_1 X + b_2 Y + b_3 Z + b_4 XY + b_5 XZ + b_6 YZ + b_7 X^2 + b_8 Y^2 + b_9 Z^2 \\ H = c_0 + c_1 X + c_2 Y + c_3 Z + c_4 XY + c_5 XZ + c_6 YZ + c_7 X^2 + c_8 Y^2 + c_9 Z^2 \end{cases} \tag{5}$$

where (P, L, H) are the GCP coordinates, (X, Y, Z) are the corresponding coordinates from RPC solution. (a_i, b_i, c_i) are the transformation coefficients. Geometric correction in object space is the coordinate conversion from coordinate system defined by RPCs-derived ground points to the coordinate system defined by GCPs. In translation model, the translation (a_0, b_0, c_0) are added to achieved the improved ground coordinates (P, L, H) and at least one GCP is needed for computation. Non-homogeneous scale distortions are corrected using additional scale factors (a_1, b_1, c_1) in the scale and translation model. Higher scale distortions can be estimated and eliminated in the affine transformation and second-order affine transformation models, respectively. In practice, the image points (r, c) of each GCP can be measured from the image, and the RFM triangulation is then applied for the derivation of ground coordinates (X, Y, Z). The least square adjustment is then employed for the calculation of optimal estimates of the transformation parameters when the over-determined equations are established using the (X, Y, Z) and the corresponding (P, L, H) coordinates. The Check Points (CkPs) are used to estimate the root mean square error (RMSE) for each model by compare the differences of their known and calculated ground coordinates from the transformation parameters.

2.2.2 Geometric Correction in Image Space

The geometric correction in image space is also referred to as the bias-compensated RFM (Fraser and Hanley 2003; Fraser and Hanley 2005) Incorporation of image shift and drift terms into the basic model of Equation 6 yields a bias-compensated RFM, which takes the form:

$$\begin{aligned} r + a_0 + a_1 r + a_2 c + a_3 rc + a_4 r^2 + a_5 c^2 &= \frac{P_1(X,Y,Z)}{P_2(X,Y,Z)} \\ c + b_0 + b_1 r + b_2 c + b_3 rc + b_4 r^2 + b_5 c^2 &= \frac{P_3(X,Y,Z)}{P_4(X,Y,Z)} \end{aligned} \tag{6}$$

Within this formulation there are four choices of additional parameter sets: 1) a_0, b_0, which affect an image coordinate translation; 2) a_0, a_1, b_0, b_1 , which model shift and drift; 3) $a_0, a_1, a_2, b_0, b_1, b_2$, which describe an affine transformation;4) $a_0, a_1, \ldots a_5, b_0, \ldots, b_5$, which describe a second-order affine transformation. The additional parameters can be solved using the multi-image, multi-point bundle adjustment developed by Fraser and Hanley (2003). For each GCP, the image coordinates (r, c) can be obtained by measurement, the parameters (a_i, b_i) and ground points (X, Y, Z) of CkPs can be determined simultaneously by the bundle adjustment incorporating the GCPs and CkPs. The CkPs are then used for the accuracy estimation.

3. STUDY SITE AND DATA SET

3.1 Study Area and QuickBird Across-track Stereo Imagery

The study area is shanghai metropolitan area, China, latitude ranges from 31°08′52.8″ to 31°17′59.6 ″, longitude from 121°25′28.9″ to 121°36′49.0 ″, the elevation range between 12 and 14 m, very low relief within about 3 meters, total area is about 300km^2 .Two QuickBird basic images were collected in Feb and May 2004 by DigitalGlobe in Shanghai area, China, making a pair of across-track stereo imagery. The scan directions were both forward. The satellite azimuth and elevation angles for imagery were provided in the metadata files. The convergent angle was calculated according to the equation in Li et al. (2007):

$$\cos\delta = \sin\alpha_1 \sin\alpha_2 + \cos\alpha_1 \cos\alpha_2 \cos(\theta_2 - \theta_1) \quad (7)$$

where δ is the convergent angle, α_i and θ_i ($i = 1,2$) are the nominal azimuth and elevation angles, respectively. The location of QuickBird imagery when taking images was illustrated in Figure 1. Some information regarding the images are shown in table 1, including data, time, view angle, off nadir angle, pixel resolution. DigitalGlobe has provided both the panchromatic and multispectral imagery with resolution of 0.7 meter and 2.8 meters respectively. The two panchromatic ones with resolution of 0.682 m and 0.717 m were chosen as the test images due to their high resolution and convenience for measuring the GCPs of GPS survey.

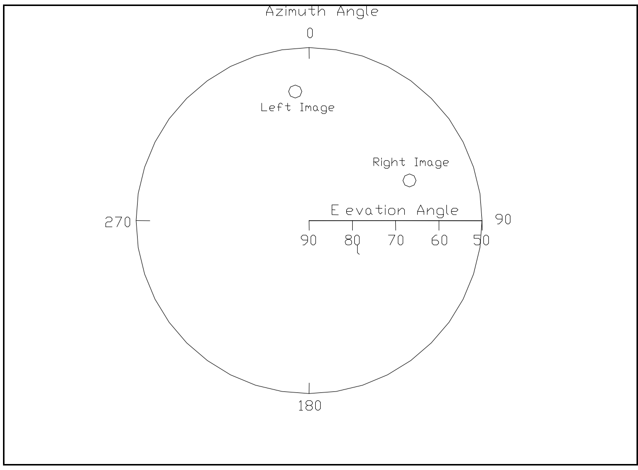


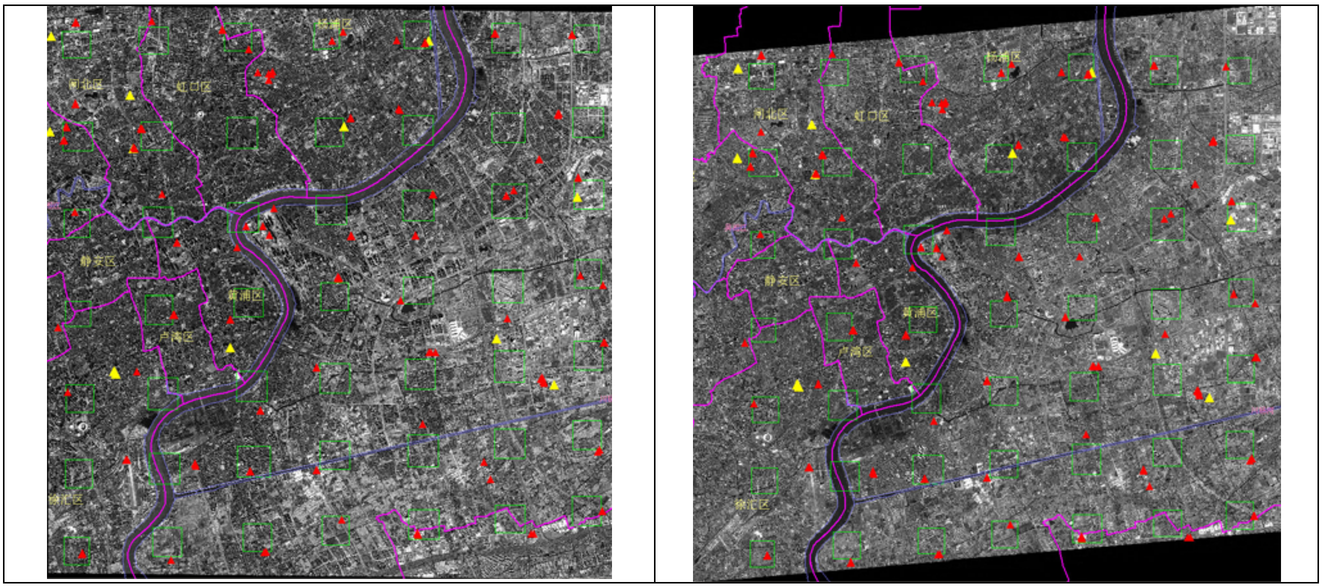
Figure 1. Location of QuickBird Imagery when taking images

	Left Image	Right Image
Acquisition Date	15 Feb 2004	5 May 2004
Acquisition Time	02:30:28	02:26:18
Scan Direction	Forward	Forward
Image Size (pixels*pixels)	27552 × 25776	27552 × 25952
Along-Track View Angle (º)	19.8	14.6
Cross-Track View Angle (º)	-5.5	19.6
Off Nadir View Angle (º)	20.6	24.4
Pixel Resolution (m)	0.682	0.717
Satellite Azimuth Angle (º)	353.9	60.4
Satellite Elevation Angle (º)	68.2	64.0
Convergent Angle (º)	25.9	

Table 1. Some Information of QuickBird Across-track Stereo Imagery

3.2 GCPs Collection

The high accuracy GCPs were obtained by GPS field survey in Shanghai urban area. The imagery obtained by DigitalGlobe was raw data without any geometric correction, thus distortion existed compared with topographic map and hard for GCP selection. The initial geometric correction was performed remote sensing software ERDAS and GIS software Emap-information developed by Emap Corporation. The field survey was issued with the aid of Shanghai Virtual Reference Station (VRS) provided by Shanghai Surveying and Mapping Institute. There were two types of GPS survey points considering the low relief in Shanghai urban area, the ground GPS survey and the building roof GPS survey. In general, the whole area was divided into 7*7=49 small survey districts. Each survey district was selected at least one GCP for the ground GPS survey according to concrete conditions, and totally 179 points were obtained in this type. 20 building roof GPS survey points were collected from different buildings whose height ranges from 30 to 420 m. The RMSE for the GPS survey points was 0.05 m. The initial geometric correction pair and distribution of GPS survey points and districts are illustrated in Figure 2



(a) (b)

Figure 2. The QuickBird across-track stereo imagery and the distribution of GPS survey points. (a) left (Feb) image of the stereo pair. (b) right (May) image of the stereo pair. The red triangles represent the ground GPS survey points, the yellows ones the building roof survey points. The green rectangles are the 49 districts designed for selection of GPS survey points.

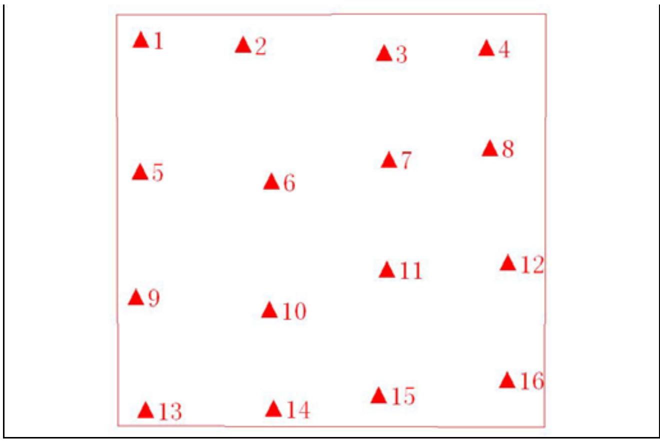


Figure 3. GCPs distribution on ground in QuickBird imagery.

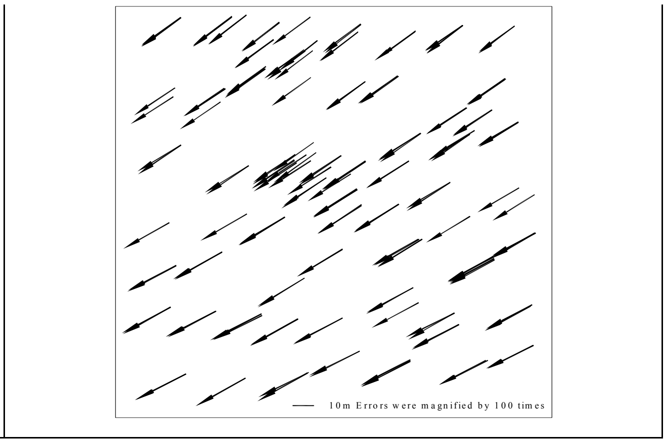


Figure 4. Vector graphics of discrepancies between the RPC generated and GCP coordinates in horizontal direction. The errors were exaggerated 100 times.

3.3 Results with updated RPCs using GCPs

Conclusion can be drawn that there are some systematic errors with the RPC provided by DigitalGlobe from the results above. The horizontal error is about 23 meters; the height error is about 16 meters. To get a better 3D coordinates, GCP must be added to the RFM. To study the importance of different configurations of GCPs, a typical 16 distributed GCP configuration are employed as Figure 5. Different combinations of the number and distribution of GCPs are tested to find the patterns and effectiveness of the configurations.

3.3.1 Accuracy improvement in object space

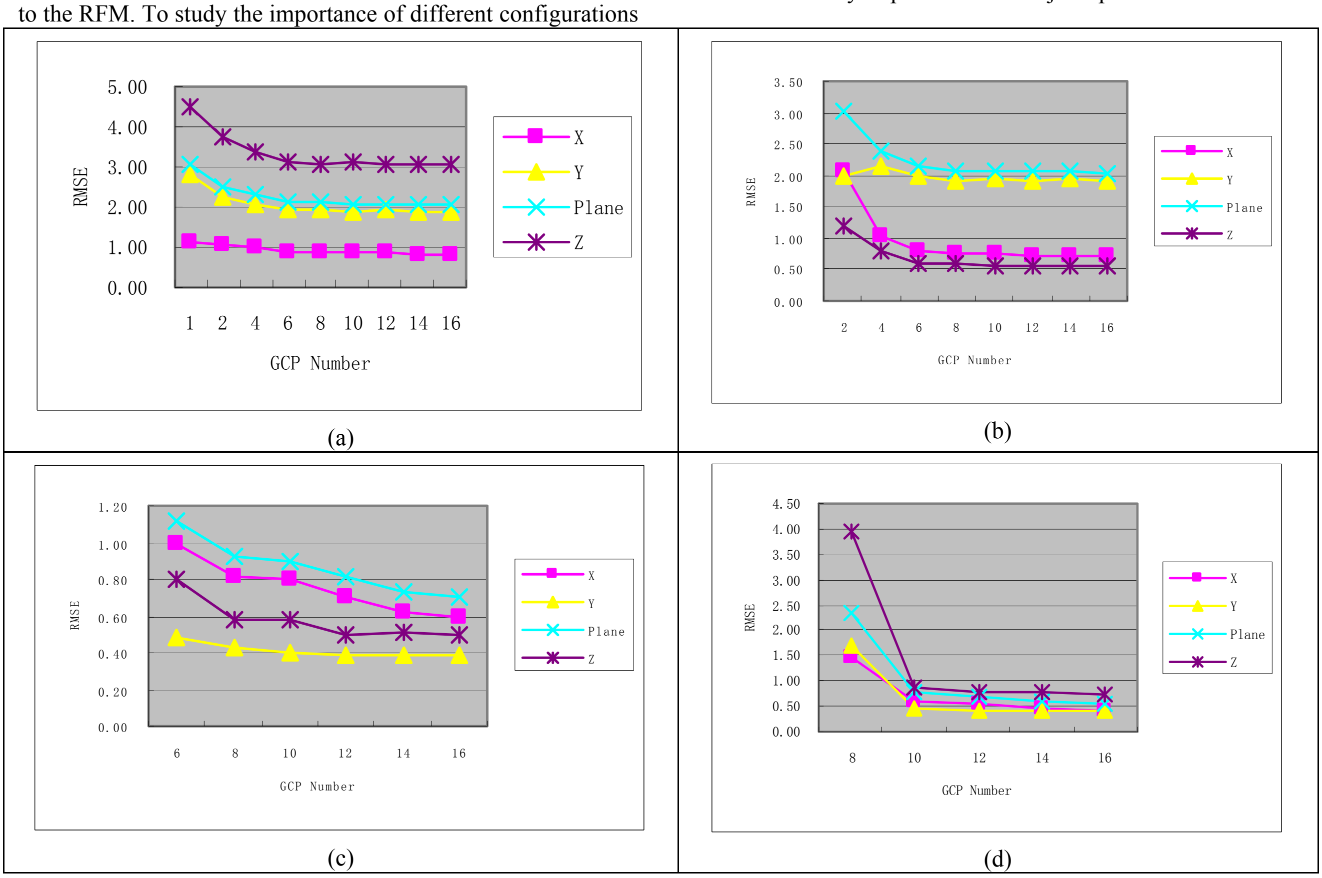


Figure 5. Figures of Accuracy with different GCP Number in object space:
(a) .translation model; (b) scale and translation model; (c) affine model; (d) second-order affine model.

- Translation Model: At least 1 GCP is needed for this model, and there is no adjustment during calculation. The plane accuracy is about 3 m for 2 m as the best, height accuracy ranges from 3 m to 5 m with 3 m for the best. Translation model in object space is not sensitive to GCP number, and addition of GCP cannot improve accuracy significantly. When the GCP number reaches 6, the accuracy is sensitive to the GCPs distribution and addition.

- Scale and Translation Model: If only GCPs are employed without redundancy, their distribution affects plane accuracy greatly mainly because the calculation error by the small denominator during solution. Rotation of the coordinates by 45 degrees can solve this problem and get stable solutions. Standardization is employed in the calculation to convert all the input data between -0.5 and 0.5, which can reduce the calculation error caused by big difference of data. The plane accuracy is 2 m to 5 m with 2 m for the best, while height accuracy is within 0.6 m. Increase of GCP number does not count much when the number is more than 6.
- Affine Model: At least 4 GCP are needed in affine model, and adjustment is needed when the GCP are redundant. Results with only 4 GCP are not stable. When GCP number is more than 8, accuracy is not sensitive to the GCP number. About 0.7 m in plane direction can be achieved when 16 well distributed GCP are employed, and the height accuracy is about 0.5 m.
- Second-order Affine Model: 10 GCP are needed for the model, and this is the most unstable model. One cannot get stable solutions when the GCP is 10, 12, 14, respectively, which means it has high requirement for GCP distribution. For this model, if the square items of height in plane direction equations are omitted (Equation 8.), the solution would be more stable, the right figure is the result of this simplified model. We can learn from the figure that for this model, with 16 well distributed GCP, the plane accuracy is within 0.6 m, and height accuracy is also within 0.6 m.

$$\begin{cases} P = a_0 + a_1X + a_2Y + a_3Z + a_4XY + a_5XZ + a_6YZ + a_7X^2 + a_8Y^2 \\ L = b_0 + b_1X + b_2Y + b_3Z + b_4XY + b_5XZ + b_6YZ + b_7X^2 + b_8Y^2 \\ H = c_0 + c_1X + c_2Y + c_3Z + c_4XY + c_5XZ + c_6YZ + c_7X^2 + c_8Y^2 + c_9Z^2 \end{cases} \quad (8)$$

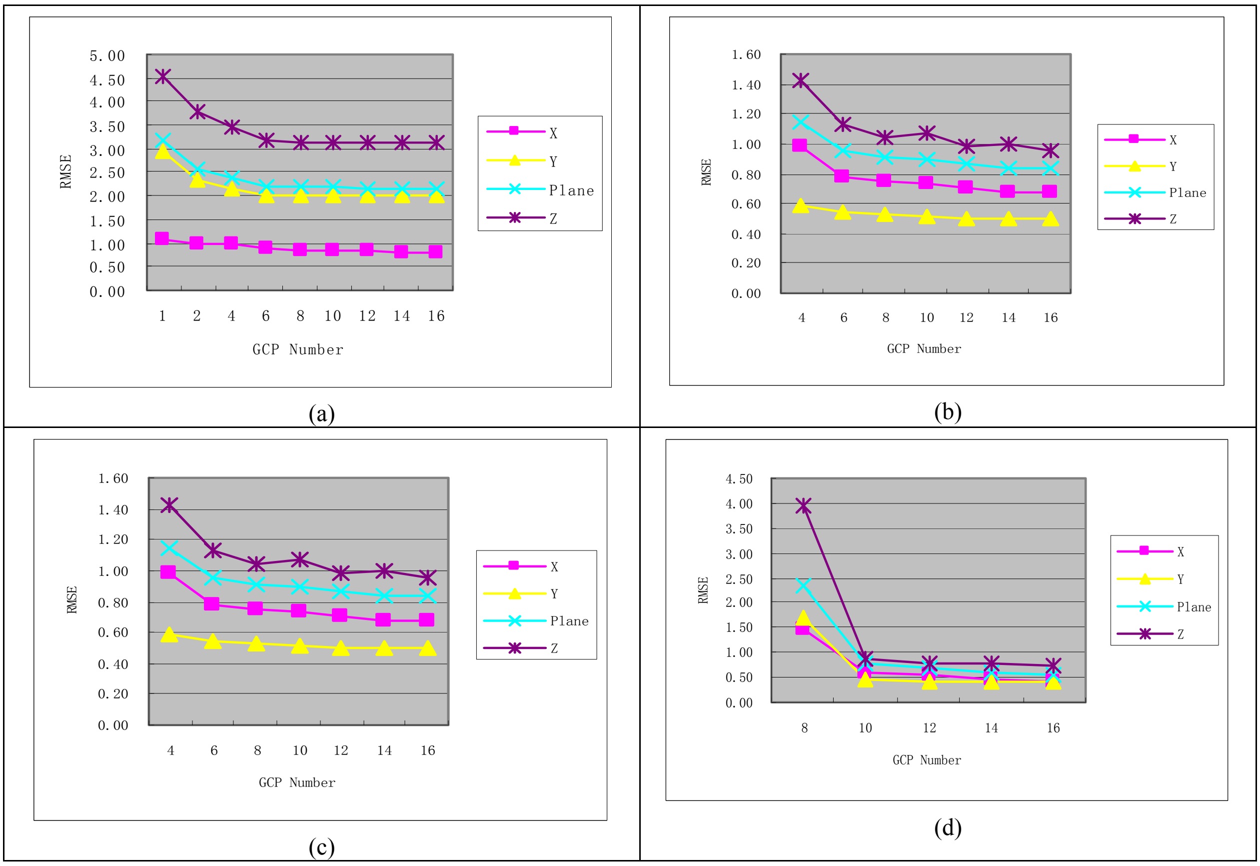


Figure 6. Figures of Accuracy with different GCP Number in image space:
(a) .translation model; (b) scale and translation model; (c) affine model; (d) second-order affine model.

3.3.2 Accuracy improvement in image space

- The translation model is the simplest model and the minimum GCP number is 1. Providing one GCP, the accuracy is about 3 meters in plane direction and 4.5 meters in height direction. Accuracy improves when more GCPs are available. With 6 or more GCPs available, accuracy in both directions are stable, about 2.2 m in Plane direction and 3.2 m in height direction can be achieved. The accuracy in latitude direction is much better than that in longitude direction. High accuracy can be obtained when the GCPs are in the middle of the test region.
- The minimum GCP number for translation and scale model is 2 and iterative calculation is needed for the solution of this model. When 2 GCPs are used in this model without redundancy, accuracy is about 6 meters in plane direction and 16 meters in height, thus for this model redundancy is necessary. With the increase of GCP number, accuracy in plane direction can achieve about 1 meter. With more than 8 GCPs, the accuracy in plane direction can be less than 1 m, up to about 0.85 m, and the height direction is about 1 meter. The maximum error in plane direction is about 2.5 meter and slightly less than that in height direction which is about 2.7 meter.
- 3 GCPs are necessary for the affine model with iteration needed for the solution. However, accuracy is also not satisfying when only 3 GCPs are used in this model without redundant number. With one more GCP, the accuracy is much better, about 1 meter in plane direction and 1.5 meter in height

direction. The general accuracy of this model is about 0.8 meter in plain direction with slightly more than 0.7 meter for the best, 0.9 to 1.6 meters in height direction with 0.9 meters for the best.

- The second order affine model is the most complex model with 6 GCPs for the solution at least. The solution with only 6 GCPs available are instable, affected much by the distribution of the GCP, thus not suitable for the accuracy improvement. When 8 GCPs are used, the solution is much better with about 2 meters in plane direction and 4 meters in height. With more than 4 redundant GCPs, this model provides better accuracy than the models above, but at the same time this model is also less stable than others. With 16 GCPs distributed evenly in the test region, the highest accuracy can be obtained for this model with 0.56 meter in plain direction and 0.75 meter in height direction.

4. CONCLUSIONS

This paper presents experimental results of a study on accuracy assessment based on QuickBird across-track stereo imagery using GCPs and different transformation models applied on RFM in both object space and image space. Two QuickBird images acquired in the Shanghai area at different time and highly accurate GPS survey points as GCPs are used in the experiment. Different methods and GCPs distribution patterns are tested. From the analysis above we can conclude that although the QuickBird across-track stereo imagery was collected at different time, they can still meet the DigitalGlobe's 23CE90 standard. The addition of GCP distributed on both ground and the top of buildings greatly improved the positioning accuracy. Analysis of the results obtained by both object and image space models using different numbers and distributions of GCP shows that, with the same redundancy of conditions, the second-order models achieved better accuracy. If some modifications are conducted to the second-order models by removing some quadratic terms from plane and height for reducing their correlation, the number of GCP required by the geometric model could be less while maintaining comparable accuracy. The positioning accuracy has been achieved with the plane direction 0.7 meter and height direction 0.6 meter in the sample spots of the whole test region.

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