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Bias-corrected rational polynomial coefficients for high accuracy geo-positioning of QuickBird stereo imagery

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ABSTRACT

The rational function model (RFM) is widely used as an alternative to physical sensor models for 3D ground point determination with high-resolution satellite imagery (HRSI). However, owing to the sensor orientation bias inherent in the vendor-provided rational polynomial coefficients (RPCs), the geo-positioning accuracy obtained from these RPCs is limited. In this paper, the performances of two schemes for orientation bias correction (i.e., RPCs modification and RPCs regeneration) is presented based on one separate-orbit QuickBird stereo image pair in Shanghai, and four cases for bias correction, including shift bias correction, shift and drift bias correction, affine model bias correction and second-order polynomial bias correction, are examined. A 2-step least squares adjustment method is adopted for correction parameter estimation with a comparison with the RPC bundle adjustment method. The experiment results demonstrate that in general the accuracy of the 2-step least squares adjustment method is almost identical to that of the RPC bundle adjustment method. With the shift bias correction method and minimal 1 ground control point (GCP), the modified RPCs improve the accuracy from the original 23 m to 3 m in planimetry and 17 m to 4 m in height. With the shift and drift bias correction method, the regenerated RPCs achieve a further improved positioning accuracy of 0.6 m in planimetry and 1 m in height with minimal 2 well-distributed GCPs. The affine model bias correction yields a geo-positioning accuracy of better than 0.5 m in planimetry and 1 m in height with 3 well-positioned GCPs. Further tests with the second-order polynomial bias correction model indicate the existence of potential high-order error signals in the vendor-provided RPCs, and on condition that an adequate redundancy in GCP number is available, an accuracy of 0.4 m in planimetry and 0.8 m in height is attainable.

1. Introduction

With recent advent of high resolution satellite imagery (HRSI) such as IKONOS and QuickBird, great efforts have been made in the applications of these remote sensing images in urban and environmental studies such as 3D shoreline extraction and coastal mapping (Li et al., 2002; Di et al., 2003a,b; Ma et al., 2003), DTM (Digital Terrain Model) and DSM (Digital Surface Model) generation (Toutin, 2004a,b; Poon et al., 2005), 3D object reconstruction (Baltsavias et al., 2001; Tao and Hu, 2002; Fraser et al., 2002; Tao et al., 2004), and national topographic mapping (Li, 1998; Holland et al., 2006). All these applications demand high-accuracy geo-positioning from HRSI. A critical issue is the choice of a sensor model for HRSI to acquire high-accuracy 3D object point determination. In general, sensor models are classified into two categories: physical sensor models and alternative generalized models (Tao and Hu, 2001). A physical sensor model, based on the collinearity condition, describes the rigorous imaging geometric relationship between the image point and the homologous ground point, with parameters of physical meanings. However, rigorous physical sensor models are complicated, and vary with different sensor types. Moreover, parameters used in the physical models are kept confidential by some commercial satellite image providers as they reveal the camera model information and metadata relating to the ephemeris and satellite attitude. These parameters thus may not be available to users. In contrast, the rational function model (RFM), one of the most popular generalized models, has drawn wide attention and investigation in the civilian photogrammetric and remote sensing community. The RFM supplied with commercial satellite image data with eighty rational polynomial coefficients (RPCs), expresses image coordinates as a ratio of two polynomials with variables of ground coordinates. In practice, the RFM is widely used to

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replace physical sensor models due to its capability of maintaining the accuracy of the physical sensor models, its unique characteristic of sensor independence, and real-time calculation. Since 1999, the RFM has been adopted by OGC (Open Geospatial Consortium) as part of the standard image transfer format (OGC, 1999).

Madani (1999) investigated the accuracy of the RFM solution using SPOT images and concluded that the RFM well described the SPOT imaging geometry. Dowman and Dolloff (2000) reviewed the RFM and studied the error propagation of the RFM for replacing physical sensor models. Yang (2000) studied the third-order and second-order RFMs with various denominators for SPOT imagery and obtained an accuracy of less than 0.2 pixels. Tao and Hu (2002) examined the inverse and forward RFM methods for 3D reconstruction with IKONOS stereo pairs, and found that the forward RFM achieved better reconstruction accuracy. Many other reports on the confirmation of RFM as a replacement model for both linear scanning sensors and frame cameras can be seen in Grodecki (2001), Hanley et al. (2002), Di et al. (2003c), Li et al. (2007) and Habib et al. (2007).

Although the RFM can theoretically provide an equivalent accuracy as physical sensor models, discrepancies exist between RPCs-derived coordinates and the true ones when the vendor-provided RPCs are directly used without the aid of ground control (Dial and Grodecki, 2002). Similar results were reported in Fraser and Hanley (2003), Noguchi and Fraser (2004), Wang et al. (2005), and Meng et al. (2007). These discrepancies could be modeled as biases in the object space or in the image space, and the biases could be subsequently corrected with a modest provision of ground control points (GCPs) (Dial and Grodecki, 2002). Furthermore, studies showed that bias correction in the image space tended to be more effective than in the object space (Fraser et al., 2002; Tao et al., 2002). Grodecki and Dial (2003) proposed the RPC block adjustment technique with an IKONOS image, and found that the RPC block adjustment achieved the same accuracy as the ground station block adjustment with the full physical camera model. The National Imagery and Mapping Agency (NIMA, now NGA, i.e. National Geospatial-Intelligence Agency) determined horizontal and vertical accuracies by averaging the differences between the derived photogrammetric points and the field surveyed GCPs for 12 stereo IKONOS pairs (Helder et al., 2003). Noguchi and Fraser (2004) reported that bias-corrected RPCs produced an average geo-positioning accuracy of sub-meter level for QuickBird Basic stereo images with a modest provision of GCPs in a test site located in Yokosuka, Japan. Through the experiments with IKONOS Geo products, Wang et al. (2005) demonstrated that with an appropriate correction model and GCP configuration, ground point errors were reduced from 5–6 m to 1.5 m horizontally and from 7 m to 2 m vertically.

In most studies mentioned above, biases in the image space or in the object space were modeled and corrected to refine RPCs-derived ground coordinates, while the original RPCs remained unchanged. Therefore, refined geo-positioning always needed to refer to the correction parameters. This would result in an awkward situation when the correction results could not be adopted by existing photogrammetric systems. In view of this problem, a few studies were conducted to examine the scheme of bias-corrected RPCs, which was to incorporate the bias correction into the original vendor-supplied RPCs (Hanley et al., 2002; Fraser and Hanley, 2003, 2005; Fraser et al., 2006). In Fraser's study, three choices of correction parameters were proposed to model the shift bias, shift and drift bias, and biases described by an affine transformation, respectively. The bias correction models were then tested for both IKONOS and QuickBird stereo images. In addition, the impact of the two scanning modes (i.e., the forward and the reverse scanning modes) on the geo-positioning accuracy were investigated (Fraser and Yamakawa, 2004; Baltsavias et al., 2005; Shaker, 2007). The reverse scanning mode, where the scan and orbital velocity vectors are approximately aligned and there is little rate of change of the sensor elevation angle (Fraser and Yamakawa, 2004), is regarded as a steady scanning mode. However, the forward scanning mode, where the scan is in the opposite direction to the satellite trajectory and there is larger rate of change of the sensor elevation angle, is not as steady as the reverse mode. For example, as reported in Fraser and Hanley (2005), for the reverse-scanned IKONOS imagery, due to its steady scanning mode, shift-only bias correction with only 1 GCP yielded sub-meter accuracy, while for the forward-scanned IKONOS imagery, standard low-order empirical models had a low accuracy because of the higher-order error sources such as perturbations in scan velocity. This is particularly true for the QuickBird imagery due to its unsteady orientation. Therefore, in this paper, the performance of bias-corrected RPCs will be further investigated with two separate-orbit QuickBird stereo imageries.

2. Bias-modeled RFM

RFM describes the relationship between an image point (l, s) and its point in the object space through a ratio of two cubic polynomials with variables of object space coordinates (B, L, H). It takes the general form as follows (OGC, 1999):

$$\begin{cases} l = \dfrac{P_1(B,L,H)}{P_2(B,L,H)} \\ s = \dfrac{P_3(B,L,H)}{P_4(B,L,H)} \end{cases} \tag{1}$$

where (l, s) are the normalized line and sample coordinates in the image space, (B, L, H) are the normalized geodetic latitude, longitude, and height in the object space.

The normalization of the coordinates in Eq. (1) is computed by (OGC, 1999):

$$\begin{cases} l = \dfrac{Line - LINE\_OFF}{LINE\_SCALE}, & s = \dfrac{Sample - SAMPLE\_OFF}{SAMPLE\_SCALE} \\ B = \dfrac{\phi - LAT\_OFF}{LAT\_SCALE}, & L = \dfrac{\lambda - LONG\_OFF}{LONG\_SCALE}, \\ H = \dfrac{h - HEIGHT\_OFF}{HEIGHT\_SCALE} \end{cases} \tag{2}$$

where *Line* and *Sample* are the image coordinates, *LINE_OFF* and *SAMPLE_OFF* are the offset values for the two image coordinates, and *LINE_SCALE and SAMPLE_SCALE* are the scale factors for the two image coordinates. Similarly, ϕ, λ and h are the geodetic latitude, longitude, and height in the object space, *LAT_OFF, LONG_OFF,* and *HEIGHT_OFF* are the offset values for the three ground coordinates, and *LAT_ SCALE, LONG_SCALE,* and *HEIGHT_SCALE* are the corresponding scale factors.

The RPC model provides a mathematical mapping from 3D object coordinates to 2D image coordinates. The vendor-provided RPCs are calculated from the physical imaging model without the aid of the ground control points. Owing to the errors in the direct measurement of sensor orientation, there exist biases in the RPC mapping. Therefore, taking biases into account, the bias-corrected RPC model is expressed as:

$$\begin{cases} Line + \Delta l = \dfrac{P_1(B,L,H)}{P_2(B,L,H)} \cdot LINE\_SCALE + LINE\_OFF \\ Sample + \Delta s = \dfrac{P_3(B,L,H)}{P_4(B,L,H)} \cdot SAMPLE\_SCALE \\ \quad + SAMPLE\_OFF \end{cases} \tag{3}$$

where Δl and Δs represent the discrepancies between the measured and the nominal line and sample coordinates, which can