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Correcting bias in the rational polynomial coefficients of satellite imagery using thin-plate smoothing splines

Xiang Shen [a,b,c], Bin Liu [d], Qing-Quan Li [a,*]

[a] Key Laboratory for Geo-Environmental Monitoring of Coastal Zone of the National Administration of Surveying, Mapping and Geo-Information & Shenzhen Key Laboratory of Spatial-temporal Smart Sensing and Services, Shenzhen University, Nanhai Road 3688, Shenzhen 518060, PR China
[b] Beijing Key Laboratory of Urban Spatial Information Engineering, Beijing 100038, PR China
[c] College of Information Engineering, Shenzhen University, Nanhai Road 3688, Shenzhen 518060, PR China
[d] State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth (RADI), Chinese Academy of Sciences, Beijing 100101, PR China

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ABSTRACT

The Rational Function Model (RFM) has proven to be a viable alternative to the rigorous sensor models used for geo-processing of high-resolution satellite imagery. Because of various errors in the satellite ephemeris and instrument calibration, the Rational Polynomial Coefficients (RPCs) supplied by image vendors are often not sufficiently accurate, and there is therefore a clear need to correct the systematic biases in order to meet the requirements of high-precision topographic mapping. In this paper, we propose a new RPC bias-correction method using the thin-plate spline modeling technique. Benefiting from its excellent performance and high flexibility in data fitting, the thin-plate spline model has the potential to remove complex distortions in vendor-provided RPCs, such as the errors caused by short-period orbital perturbations. The performance of the new method was evaluated by using Ziyuan-3 satellite images and was compared against the recently developed least-squares collocation approach, as well as the classical affine-transformation and quadratic-polynomial based methods. The results show that the accuracies of the thin-plate spline and the least-squares collocation approaches were better than the other two methods, which indicates that strong non-rigid deformations exist in the test data because they cannot be adequately modeled by simple polynomial-based methods. The performance of the thin-plate spline method was close to that of the least-squares collocation approach when only a few Ground Control Points (GCPs) were used, and it improved more rapidly with an increase in the number of redundant observations. In the test scenario using 21 GCPs (some of them located at the four corners of the scene), the correction residuals of the thin-plate spline method were about 36%, 37%, and 19% smaller than those of the affine transformation method, the quadratic polynomial method, and the least-squares collocation algorithm, respectively, which demonstrates that the new method can be more effective at removing systematic biases in vendor-supplied RPCs.

1. Introduction

The georeferencing of high-resolution satellite imagery can be conducted by two different approaches: the physical sensor model and the generic sensor model (Poli and Toutin, 2012; Zhang et al., 2015). The former approach is directly built on the collinearity condition, which depicts the geometric relationship between image and object coordinates rigorously by exterior and interior orientation parameters as well as some inter-sensor calibration parameters (Jeong and Kim, 2015; Kim and Jeong, 2011). The latter one, which is commonly constructed by a polynomial or a ratio of two polynomials, is a convenient mathematical approximation to the physical sensor model (Fraser et al., 2006; Fraser and Yamakawa, 2004; Shaker, 2008). The advantage of using a generic rather than a physical sensor model is that its geometric form is independent of the distinct characteristics of different sensors, which facilitates the data processing of high-resolution satellite imagery (Toutin, 2011). In addition, all the technical details relating to cameras and satellite orbits can be safely concealed, which is demanded by some commercial satellite image vendors (Zhang et al., 2015).

The Rational Function Model (RFM), which is defined as a ratio of two cubic polynomials, is currently the most popular generic

* Corresponding author.
E-mail address: liqq@szu.edu.cn (Q.-Q. Li).

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sensor model used in the field. A great number of researches have reported that the RFM can be utilized for high-precision geopositioning of pushbroom satellite images (Aguilar et al., 2012; Alkan et al., 2013; Di et al., 2003b; Fraser et al., 2006; Poli and Toutin, 2012; Tao and Hu, 2001b), and it can also replace physical sensor models in the data processing of satellite SAR (Synthetic Aperture Radar) (Sekhar et al., 2014; Toutin, 2012; Zhang et al., 2010, 2012a, 2011) and aerial frame photographs (Ma, 2013).

Limited by the inaccurate measurement of satellite orbits and attitudes, the Rational Polynomial Coefficients (RPCs) provided by image vendors are often biased, and the resulting errors in the image space typically range from several pixels to tens of pixels (Jiang et al., 2015; Nagasubramanian et al., 2007; Teo, 2011). The bias correction of vendor-provided RPCs is therefore required in the photogrammetric processing of high-precision satellite images, and it has been continuously studied almost since the RFM was introduced to the remote sensing community (Di et al., 2003a; Fraser and Hanley, 2003; Hong et al., 2015; Tong et al., 2010).

A large number of studies have been conducted to correct the bias in vendor-provided RPCs. Almost all previous methods employ lower-order polynomials in error modeling. Some popular bias models in the literature are the translation model, the shift and drift model, the conformal transformation model, the affine transformation model, and the quadratic polynomial (i.e., the second-order polynomial) model (Fraser and Hanley, 2005; Teo, 2011; Topan, 2013; Wang et al., 2005; Xiong and Zhang, 2009). Many researchers have compared these models using a variety of high-resolution satellite imageries, such as QuickBird (Hong et al., 2015; Tong et al., 2010; Xiong and Zhang, 2011), IKONOS (Grodecki and Dial, 2003; Wang et al., 2005), IRS-P6 (Nagasubramanian et al., 2007), KOMPSAT-2 (Jeong and Kim, 2015), GeoEye-1 (Aguilar et al., 2012, 2013), and WorldView-1/2 (Alkan et al., 2013; Teo, 2011), and most of them have reported that the affine transformation model commonly yields the best performance and the quadratic polynomial model can obtain comparable results when sufficient Ground Control Points (GCPs) are available. Given that the field survey of GCPs is inherently laborious and time consuming, researchers have also developed some cost-efficient algorithms that adopt other reference data, such as topographic maps (Oh and Lee, 2015) and digital elevation models (Oh and Jung, 2016).

Although lower-order polynomial based models have been demonstrated to be capable of efficiently correcting systematic errors in vendor-provided RPCs, there is still plenty of room to further improve the accuracy. In a very recent work, Li et al. (2014) introduced the least-squares collocation algorithm to tackle the RPC bias-correction problem. Their results showed that strong spatially-correlated errors existed in the RPC data of QuickBird, and the least-squares collocation method performed much better than the affine transformation and the quadratic polynomial methods in terms of accuracy and reliability.

In this paper, we propose an alternative approach for the bias correction of RPCs by using the thin-plate spline technique. The thin-plate spline is known as a powerful tool for modeling irregular deformations specified by point correspondences, and it has been applied successfully in a variety of image processing and computer vision applications, e.g., image warping and non-rigid image registration (Bookstein, 1989; Rohr et al., 2001; Ross and Nadgir, 2008; Sotiras et al., 2013). As a nonparametric model, the thin-plate smoothing spline is more powerful and flexible than parametric polynomial models in data fitting (Wahba, 1990), which benefits accurate correction of complex RPC distortions caused by orbit perturbations and other related factors.

The remainder of this paper is organized as follows. Section 2 first gives some basic concepts of the RFM. Then, Section 3 introduces the construction of the thin-plate spline model and the formulas for estimating the smoothing parameter. Finally, we provide experimental results and analysis in Section 4 and conclude our work in the last section.

2. The rational function model

The rational function model describes the geometric relationship between a ground point and its corresponding image point through a ratio of two cubic polynomials (Fraser et al., 2006; Tao and Hu, 2001a; Zhang et al., 2012b). Its general form is defined as

$$\begin{aligned} y_n &= \frac{P_1(\varphi_n,\lambda_n,h_n)}{P_2(\varphi_n,\lambda_n,h_n)} \\ x_n &= \frac{P_3(\varphi_n,\lambda_n,h_n)}{P_4(\varphi_n,\lambda_n,h_n)} \end{aligned} \tag{1}$$

where $(\varphi_n, \lambda_n, h_n)$ refer to the normalized latitude, longitude, and height of a ground point, respectively; (x_n, y_n) are the normalized sample and line coordinates of the corresponding image point, respectively; P_1, P_2, P_3 and P_4 represent third-order polynomials.

The RPCs provided by image vendors are directly derived from satellite ephemeris and attitude data by using the terrain-independent method (Fraser and Hanley, 2003; Li et al., 2014). Limited by the imperfect performance of navigation sensors, the vendor-supplied RPCs are often systematically biased. The most commonly-used and effective solution for bias compensation is to add some corrections to the image coordinates (Hong et al., 2015; Teo, 2011; Wang et al., 2005). In almost all previous studies, the corrections are modeled by a low-order polynomial of the image coordinates, e.g., the translation model (using a zero-order polynomial) and the affine transformation model (using a first-order polynomial).

3. The thin-plate smoothing spline model

The Thin-Plate Spline (TPS) has been widely used in image warping and other image processing operations that require the modeling of non-rigid deformations (Bookstein, 1989; Sotiras et al., 2013). In this paper, we introduce the thin-plate spline technique to solve the RPC bias-correction problem. The following parts of this section provide the details of the TPS algorithm.

3.1. Constructing a thin-plate spline

The general form of the TPS function is given by (SAS Institute Inc., 2015; Wahba, 1990)

$$f(x,y) = \alpha[x \quad y \quad 1]^T + \sum_{j=1}^{m} \delta_j \psi(r_j) \tag{2}$$

with r_j the Euclidean distance

$$r_j = \sqrt{(x - x_j)^2 + (y - y_j)^2} \tag{3}$$

and $\psi()$ the Radial-Basis-Function (RBF) kernel

$$\psi(r) = r^2 \log(r^2) \tag{4}$$

where (x, y) are the coordinates of an arbitrary point in the image space, (x_j, y_j) are the measured image coordinates of the jth GCP, m is the number of GCPs, and α and $\delta = (\delta_1, \delta_2, \ldots, \delta_m)$ are the coefficients (row vectors) that need to be estimated by minimizing the following quantity (Green and Silverman, 1993; Wood, 2003).

$$E(f) + \lambda R(f) \tag{5}$$

with $E(f)$ the error measure

$$E(f) = \sum_{j=1}^{m} \|z_j - f(x_j, y_j)\|^2 \tag{6}$$