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Epipolar resampling of linear pushbroom satellite imagery by a new epipolarity model☆

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ABSTRACT

This paper presents a practical epipolarity model for high-resolution linear pushbroom satellite images acquired in either along-track or cross-track mode, based on the projection reference plane in object space. A new method for epipolar resampling of satellite stereo imagery based on this model is then developed. In this method, the pixel-to-pixel relationship between the original image and the generated epipolar image is established directly by the geometric sensor model. The approximate epipolar images are generated in a manner similar to digital image rectification. In addition, by arranging the approximate epipolar lines on the defined projection reference plane, a stereoscopic model with consistent ground sampling distance and parallel to the object space is thus available, which is more convenient for three-dimensional measurement and interpretation. The results obtained from SPOT5, IKONOS, IRS-P5, and QuickBird stereo images indicate that the generated epipolar images all achieve high accuracy. Moreover, the vertical parallaxes at check points are at sub-pixel level, thus proving the feasibility, correctness, and applicability of the method.

1. Introduction

Epipolar resampling aims to generate rectified images so that the stereo disparities are parallel to one of the image axes, thus providing advantageous conditions for automatic image matching, digital elevation model (DEM) generation, and stereo measurement (Cochran, 1995; Ono et al., 1999; Hashimoto, 2000; Bang et al., 2003; Lee et al., 2003; Morgan, 2004; Kornus et al., 2006). As is well known, epipolar resampling is a well-established procedure for images captured by a frame camera (Zhang, 1998; Torr, 2002), as the rigorous epipolar geometry can be easily defined and the epipolar lines are in a simple, straightforward linear style. However, as the leading payload of high-resolution imaging satellites, linear array pushbroom scanners are characterized by their particularly distinct imaging principle and their diverse, complex physical structures in comparison with conventional frame cameras. That is, the image scenes are formed by stitching the one-dimensional (1D) scan lines captured as the sensor moves (Wolf and Dewitt, 2000). On the one hand, it is almost impossible to rigorously define the epipolar geometry of linear pushbroom satellite imagery, primarily because the determination of the accurate geometric relationship between object space and image space (i.e., sensor modeling) is difficult due to the adopted multi-center projection imaging mode. On the other hand, the resulting epipolar lines are actually not straight lines on the original image scenes, which brings complexity and difficulty to epipolar resampling. As a result, for satellite stereo imagery, the classical epipolar theory and methodology applied to single perspective frame-based imagery will no longer be feasible. Actually, epipolar resampling is the arrangement of epipolar lines based on a specific epipolarity model, so it is theoretically and practically significant to study the epipolarity model of linear pushbroom satellite stereo imagery.

In general, the existing epipolarity models can be categorized into two classes: (1) the models for finding epipolar curves in image space by image correspondence, and (2) the models for exploiting epipolar geometry based on a geometric sensor model. In the first category, the most often used model is the polynomial fit model (PFM), which was proposed and discussed to arrange the approximate epipolar curves of the SPOT cross-track stereo imagery in the late 1980s (Su, 2002). In the second category,

☆ A new method for generating approximate epipolar images from high-resolution linear pushbroom satellite stereo images based on the projection reference plane in object space.

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the Projection Trajectory based Epipolarity Model (PTEM) and the Parallel Projection transformation based Epipolarity Model (PPEM) are two typical examples. The Projection Trajectory (PT) based epipolar curve definition is most widely known and accepted for linear pushbroom satellite images (Alrousan et al., 1997), and can be extended to conventional frame-based images. Considerable effort has been expended on the PTEM and the major achievement has been the derivation of the mathematical form of the epipolar geometry from the rigorous sensor model based on collinearity equations (Kim, 2000; Bang et al., 2003; Zhao et al., 2008) and the simplified pushbroom sensor model (Lee and Park, 2002). Accordingly, the geometric properties of the theoretically non-straight epipolar lines can thus be visibly analyzed, providing constructive instructions to the epipolarity related applications of linear pushbroom satellite images. In recent years, PPEM has been studied and applied to epipolar resampling of high-resolution linear pushbroom satellite imagery (e.g., IKONOS, QuickBird, etc.) (Morgan et al., 2004a,b, 2006; Jaehong et al., 2006). Due to the small field of view (FOV) of this type of spaceborne linear pushbroom scanner, the perspective projection sensor model of such satellite images is first transformed to a parallel projection sensor model (Fraser and Yamakawa, 2004), and then the epipolar geometry parameters can be determined by at least four pairs of conjugate points, according to the property that the parallel projection stereo imagery holds a unified epipolar line direction. Finally the epipolar images are generated in a manner similar to the process of digital image rectification. The feasibility of PPEM used for epipolar resampling towards automatic DEM generation from high-resolution satellite images has already been investigated (Morgan, 2004; Habib et al., 2004).

Although the existing models described above have been used to generate approximate epipolar images of satellite stereo imagery, technical limitations still exist when the generality, applicability, and simplicity of these models are taken into account. For example, epipolarity models established from either coordinate polynomial fitting or image projection trajectories are without exception in a non-linear style and the derivation of these models needs a certain number of qualified conjugate image points or image orientation parameters, which brings the great complexity to the epipolar resampling process. Moreover, the applicability of PPEM is actually not fully universal because the model needs to work well under the condition that the sensor's FOV is small, and the degree of approximation of the parallel projection model to the perspective projection model relates to topographic conditions and terrain relief, roll angle of the scanner, as well as some other factors. Moreover, compared with the rigorous perspective projection model, although it only requires a small number of parameters to describe the sensor model of parallel projection images holding straight epipolar lines parallel with each other, it needs a certain number of well-matched conjugate image points, along with ground control points (GCPs) and sometimes the roll angle of the imaging sensor to decide the parameters for perspective to parallel projection transformation, as well as epipolar resampling (Morgan et al., 2006; Jaehong et al., 2006). And all of these to a large extent restrict the degree of applicability of the PPEM. Currently, how to produce a qualified epipolar image directly from the provided high-accuracy orientation data of satellite stereo images, especially from the rational polynomial coefficients (RPC) of the rational function model (RFM), is yet an unsolved problem (Zhao et al., 2008) in the application field of high-resolution satellite imagery.

Under these circumstances, our previous work (Hu et al., 2008) initially proposed an epipolarity model of satellite stereo imagery based on the Virtual Horizontal Plane (VHP) in object space. The feasibility of our original idea was validated using only the VHP-based epipolar resampling method to generate the approximate epipolar images of 5 m resolution panchromatic SPOT5-HRG stereo imagery. Therefore, the epipolarity model presented in our previous paper lacked depth and comprehensive analysis and validation. In addition, the concept of Virtual Horizontal Plane (VHP) is not very rigorous and understandable.

In this article, we aim to (1) investigate an epipolarity model for satellite stereo imagery based on the Projection Reference Plane (PRP) in object space, (2) develop a PRP-based method for epipolar resampling of linear pushbroom satellite images, (3) focus on universality of the method, by introducing various kinds of satellite images with different stereoscopic imaging modes and terrain conditions in the experiments, and finally (4) exploit some key factors that affect the accuracy of epipolar resampling results for optional technical routines and better performance of the epipolar resampling method. The newly proposed model needs no sensor model transformation as does PPEM, and needs no conjugate image points or ground control points (GCP) but just orientation data of satellite stereo images to decide the direction for epipolar rearrangement. Overall, the PRP-based method for epipolar resampling is more applicable and universal in practice.

The reminder of the paper is organized as follows. The next section introduces the principle and foundation of our PRP-based epipolarity model by recalling the geometric properties of epipolar curves of linear pushbroom satellite images, along with theoretical reasoning on practical image data. The following sections describe the workflow for generating the approximate epipolar images of pushbroom satellite stereo imagery based on the PRP in object space, followed by experimental results with accuracy assessment, further discussion, and finally the conclusions.

2. Principles

2.1. Sensor modeling for epipolar resampling

The effective epipolar resampling requires sound geo-locating accuracy of the geometric sensor models, so obtaining high-quality orientation parameters of satellite stereo images is a prerequisite. Today, rigorous geometric sensor modeling of linear array pushbroom satellite imagery is still a challenging task. The calculation of image coordinates based on the rigorous geometric sensor model (i.e., collinearity equations) requires the best scan line search, which adds a considerable amount of computation for stereo mapping and the production of DEMs and digital orthoimage models (DOMs). Besides, vendors of high-resolution commercial satellite images normally provide the end-users with the RPC parameters of the RFM instead of ephemeris and attitude parameters, as well as sensor information. It is demonstrated that the 0.01 pixel high fitting accuracy is totally possible with the 3rd-order form of the RFM, in comparison with the rigorous geometric sensor model (Yang, 2000). Therefore, the RFM can be a good replacement for the rigorous geometric sensor model in the epipolar resampling procedure with satellite stereo imagery. Sometimes the accuracy of the sensor-oriented RFM is not sufficient, and thus additional parameters for bias-compensation (Fraser and Hanley, 2003; Fraser et al., 2006) are calculated using a certain number of GCPs or image tie points in order to ensure a fairly desirable level of geo-positioning accuracy.

2.2. Epipolar geometry of linear pushbroom imagery

The epipolar geometry of traditional frame-based stereo imagery is classically elaborated in many archives of photogrammetry, and it is well known that the parallel epipolar lines can be obtained by projecting the original non-parallel epipolar lines