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Geolocation error tracking of ZY-3 three line cameras

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ABSTRACT

The high-accuracy geolocation of high-resolution satellite images (HRSIs) is a key issue for mapping and integrating multi-temporal, multi-sensor images. In this manuscript, we propose a new geometric frame for analysing the geometric error of a stereo HRSI, in which the geolocation error can be divided into three parts: the epipolar direction, cross base direction, and height direction. With this frame, we proved that the height error of three line cameras (TLCs) is independent of nadir images, and that the terrain effect has a limited impact on the geolocation errors. For ZY-3 error sources, the drift error in both the pitch and roll angle and its influence on the geolocation accuracy are analysed. Epipolar and common tie-point constraints are proposed to study the bundle adjustment of HRSIs. Epipolar constraints explain that the relative orientation can reduce the number of compensation parameters in the cross base direction and have a limited impact on the height accuracy. The common tie points adjust the pitch-angle errors to be consistent with each other for TLCs. Therefore, free-net bundle adjustment of a single strip cannot significantly improve the geolocation accuracy. Furthermore, the epipolar and common tie-point constraints cause the error to propagate into the adjacent strip when multiple strips are involved in the bundle adjustment, which results in the same attitude uncertainty throughout the whole block. Two adjacent strips—Orbit 305 and Orbit 381, covering 7 and 12 standard scenes separately—and 308 ground control points (GCPs) were used for the experiments. The experiments validate the aforementioned theory. The planimetric and height root mean square errors were 2.09 and 1.28 m, respectively, when two GCPs were settled at the beginning and end of the block.

1. Introduction

High-accuracy geolocation is a key factor for integrating multi-temporal multi-sensor high-resolution satellite images (HRSIs) for national and even global monitoring and mapping. Even though the geolocation accuracy has been improved to within several meters, ground control points (GCPs) are required for image orientation. Two different strategies are used for orientation in photogrammetry: directly estimating the sensor model with GCPs and compensating the integrated sensor error (Di et al., 2014; Heipke, 1997; Heipke et al., 2002; Muller et al., 2012). Directly estimating the sensor model utilizes GCPs to estimate the orientation parameters with a given sensor model, while the position and attitude data are used to estimate the initial value. Owing to the innovative orbit and attitude-determination techniques, methods for compensating the integrated sensor orientation are widely used for HRSI orientation with both the rigorous sensor model (RSM) and the rational function model (RFM), and these methods achieve remarkable accuracy with fewer GCPs (Fraser and Ravanbakhsh, 2009; Grodecki and Dial, 2003; Li et al., 2011; Teo, 2011). In this paper, we mainly focus on the method of compensating the integrated sensor error.

The geolocation error of HRSIs depends on the exterior orientation parameter (EOP) errors, interior orientation parameter (IOP) errors, and imaging geometry of the stereo camera. The variance-covariance matrix is a powerful tool to assess the accuracy of the geolocation. Topan and Kutoglu (2009) used the figure condition method to assess the georeferencing accuracy of a single scene with affine projection. Li et al. (2009) showed that the geolocation error depends on the convergence angle of stereo images. In addition to the convergence angle, the bisector elevation and asymmetry angle are important considerations for interpreting the stereo geometry (Dolloff and Theiss, 2012). To quantitatively estimate the positional accuracy of satellite stereo pairs, the modified convergence, bisector elevation, and asymmetry angles were investigated by Jeong and Kim (2016). Tang et al. (2015b) analysed comprehensive planar and vertical errors with independent error sources for ZY-3. In theory, the error ellipsoids statistically represent the geolocation error. However, the physical explanation of

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geolocation uncertainty is still ambiguous for stereo pairs. In this paper, we will build a quantitative framework for analysing the geolocation error of a stereo pair, in which three-axes of the error ellipsoid are determined with the line-of-sight (LoS) uncertainty in the orthogonal coordinates. This contribution will help to understand the specifications of geolocation accuracy, typically in terms of CE90 (circular error at 90% confidence) or LE90 (linear error at 90% confidence).

Owing to the available EOPs, the direct orientation is a possible method to obtain the object coordinates with conjugate points. However, the EOP errors cause the LoS to be biased from the true position and direction. To compensate the EOP errors, bundle adjustment, with or without GCPs, is the most powerful tool. In the airborne case, the free-net bundle adjustment could improve the accuracy in image space with tie points for integrated sensor orientation (Heipke et al., 2002; Khoshelham, 2009). However, the EOPs of HRSIs are correlated because of the very narrow field of view (FoV) and stably dynamic imaging system. The change of EOP errors of HRSIs is still unknown when bundle adjustment without GCPs, also named as free-net bundle adjustment in this paper, is performed. In compensating the integrated sensor error perspective, the free-net bundle adjustment would adjust the compensation parameters to make all corresponding rays intersect with each other. It is equivalent to the photogrammetric relative orientation with the initial value of 'seven parameters,' because there are no GCPs involved and the rays are still biased. In this paper, we will investigate the degree of freedom of the free-net bundle adjustment for HRSIs.

Compared to frame cameras, HRSIs suffer from an ill-conditioned normal equation for block bundle adjustment, because the very narrow FoV and dynamic imaging system causes images between the strips to have a very small convergence angle and the images in the same strip to have parallel rays. To utilize the stability of HRSI, the images in the same strip usually are treated as a unit (Fraser and Ravanbakhsh, 2011; Pan et al., 2016a). However, the constraint between the strips is rarely studied with a rigorous sensor model. Lutes and Grodecki (2004) used an azimuth-elevation block adjustment model with only two offset parameters to analyse the error propagation of IKONOS Geo products. The geolocation error of adjacent strips have large discrepancies as shown in ALOS (Ravanbakhsh et al., 2012), IRS-P5 (d'Angelo and Reinartz, 2012), and ZY-3 (Zhang et al., 2015). With analysis of the error propagation, we will prove that the roll and pitch angle compensation model could reduce the discrepancy, and the result is independent to the overlap between the adjacent strips.

To pursue higher geolocation accuracy for ZY-3, we track the geolocation error with different orientation strategies, including direct orientation, free-net bundle adjustment, and bundle adjustment with GCPs. A quantitative frame is proposed to analyse the impact of EOP errors on the geolocation accuracy. To understand the error compensation procedure, the epipolar constraint is studied with relative orientation. After that, the bundle adjustment is used to further reduce the EOP errors, and we elaborate on how error propagation affects three line cameras (TLCs) and the constraints between adjacent strips. Owing to the high geolocation of ZY-3, ~10 m, the yaw angle is not significant compared with the roll and pitch angle, and the major errors could be modelled with the shift and drift compensation model on the pitch and roll angles (Pan et al., 2016a). Therefore, the drift compensation model is used as the EOP error model, and two adjacent strips of ZY-3 with 308 GCPs of field survey data are used for the experiments.

This paper is structured as follows. In Section 2, the geolocation error frame of a HRSI is proposed. Two simplified rays with nadir viewing are first introduced, following the general condition. The error compensation is presented in Section 3, in which the relative orientation, bundle adjustment, and error propagation are explained. In Section 4, experiments are described. Finally, the summary and concluding remarks are presented in Section 5.

2. Geolocation error of HRSIs stereo

The geolocation error of HRSIs depends on the EOP errors, IOP errors, picking-point (matching) errors, and imaging geometry. The errors can be simplified as the LoS error, as they can be modelled by the change in the LoS. Owing to the precise orbit determination, a centimetre-level position error is negligible for photogrammetric applications with a meter-level ground sample distance. The routine geometric calibration reduces the IOP error to sub pixels, which is the same level as the picking-point errors. However, the attitude uncertainty might be introduced by heat effects during the imaging process (Pan et al., 2016a). In this section, the influence of the LoS uncertainty is used to study the geolocation error.

2.1. Geolocation error in the epipolar coordinate system

To simplify the derivation, a stereo with two rays is analysed. The two rays S_1P and S_2P meet at P with angles θ_1 and θ_2, where S_1 and S_2 are the imaging positions. According to the stereo geometry, the epipolar coordinate system is built, whose X-axis is the baseline, the Z-axis passes though the ground point P and perpendicular to the baseline in the S_1S_2P plane, and the Y-axis is determined by the right-hand rule. The angle between the ray and the perpendicular of the baseline is within $[-\pi/2, \pi/2]$, and the flight direction is positive. Therefore, the θ_1 of the forward ray is positive, and the θ_2 of the backward ray is negative, as shown in Fig. 1.

The LoS uncertainty could be divided into two directions: the base direction $\Delta\alpha$ and the cross base direction $\Delta\beta$. Owing to the LoS uncertainty, the two rays, S_1P_1 and S_1P_2, may not intersect in three-dimensional space. In photogrammetry, a least squares estimation is used to calculate the position with minimum square of residual in the image space (Mikhail et al., 2001). In this paper, we simplify this solution to find the height H, in which the distance between P_1 of S_1P and P_2 of S_2P is minimum. The calculated object coordinate is then equal to the mean value of the two points, if they are of equal weight, as P′ in the larger version of Fig. 1. Then, the calculated ground point P′ is biased from P (0, 0, h) in three directions $[\,\delta X \quad \delta Y \quad \delta Z\,]$.

The ray from S_1 would intersect the Z-plane H at P_1, whose coordinate is (X_1, Y_1, H). At the same time, the ray from S_2 meets Z-plane

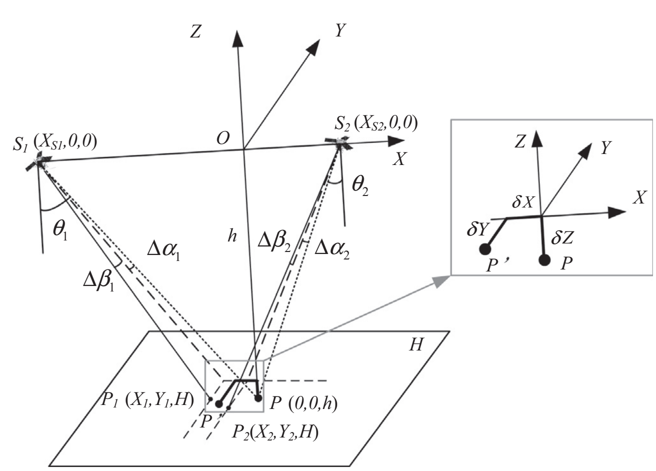

Fig. 1. Schematic diagram of geolocation error in the epipolar coordinate system. Owing to LoS uncertainty, the calculated object point P′ is biased from the true position P in three directions.