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Development of a Coordinate Transformation method for direct georeferencing in map projection frames

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ABSTRACT

This paper develops a novel Coordinate Transformation method (CT-method), with which the orientation angles (roll, pitch, heading) of the local tangent frame of the GPS/INS system are transformed into those (omega, phi, kappa) of the map projection frame for direct georeferencing (DG). Especially, the orientation angles in the map projection frame were derived from a sequence of coordinate transformations. The effectiveness of orientation angles transformation was verified through comparing with DG results obtained from conventional methods (Legat method[1] and POSPac method[2]) using empirical data. Moreover, the CT-method was also validated with simulated data. One advantage of the proposed method is that the orientation angles can be acquired simultaneously while calculating position elements of exterior orientation (EO) parameters and auxiliary points coordinates by coordinate transformation.

These three methods were demonstrated and compared using empirical data. Empirical results show that the CT-method is both as sound and effective as Legat method. Compared with POSPac method, the CT-method is more suitable for calculating EO parameters for DG in map projection frames. DG accuracy of the CT-method and Legat method are at the same level. DG results of all these three methods have systematic errors in height due to inconsistent length projection distortion in the vertical and horizontal components, and these errors can be significantly reduced using the EO height correction technique in Legat's approach. Similar to the results obtained with empirical data, the effectiveness of the CT-method was also proved with simulated data.

1. Introduction

GPS/INS systems have been widely equipped with frame cameras, line scanning sensors, LiDAR, SAR, etc. in airborne remote sensing for many years. With GPS/INS, the position of the *inertial measurement unit* (IMU) in the global reference frame and its orientation, which is usually described with respect to the local tangent frame (*l*-frame), can be effectively determined. If the position and orientation are employed for direct georeferencing (DG) in the map projection frame (*p*-frame), two important issues need to be addressed, including (1) transforming the orientation angles of the *l*-frame into those of the *p*-frame (Bäumker and Heimes, 2001; Legat, 2006; Ressl, 2002), and (2) calibrating the three-axis boresight misalignment between the sensor and IMU (Jacobsen and Wegmann, 2001; Mostafa, 2001; Skaloud and Schaer, 2003).

The boresight misalignment calibration of cameras can be performed in either in-flight or terrestrial mode (Mostafa and Schwarz, 2001). The boresight angles can be determined with an accuracy at the same level with GPS/INS absolute accuracy or better by bundle block adjustment (Cramer and Stallmann, 2002; Honkavaara, 2004; Skaloud and Schaer, 2003). In calibrating boresight misalignment, intensive studies have been carried out, so no further discussions are provided in this paper. Regardless of the boresight misalignment calibration error and other systematic errors, the reliability and precision of sensor orientation transformation directly determine DG accuracy in the *p*-frame. Thus, it is essential to ensure the soundness and effectiveness of the orientation transformation.

With the conventional methods, orientation angles can be transformed from the *l*-frame by a sequential rotation matrix and a compensation matrix (in this paper, this is called as

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[1] Legat method: Klaus Legat published the paper "Approximate direct georeferencing in national coordinates" in 2006. He presented a method to calculate the attitude matrix and perspective center (PC) coordinates in national mapping frame. This method is termed Legat method in this paper.

[2] POSPac method: The method is presented by Applanix POSPac software technical note (Hutton and Savina, 1997). It is implemented in the POSEO module of POSPac software.

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Compensation Matrix method (CM-method)). There are three similar approaches (detailed in Section 2.2) in previously published papers that could be categorized under the CM-method. In this paper, we propose a novel approach for the direct calculation of orientation angles in the *p*-frame by coordinate transformation (herein referred to as the Coordinate Transformation method (CT-method)), with which the compensation matrix is not required. It is an alternative means of calculating orientation angles.

As shown in the Helmert transformation, the 7-parameters shared by two frames, including translations, rotations, and scale factor, can be calculated from two sets of coordinates at several points in the two coordinate frames (Kong et al., 2001). Exterior orientation (EO) angles in the *p*-frame are the rotation angles between the image space frame and the *p*-frame, so they can be calculated in view of similarity transformation of several homonymous points in the two frames. Based on the above method, the derivation in transforming orientations of GPS/INS *l*-frame into those of the *p*-frame is presented. With this method, orientation angles (omega, phi, kappa) in the *p*-frame can be calculated as long as map projection coordinates of perspective center (PC) and several auxiliary points have been determined.

The structure of this paper is as follows. Next section reviews conventional methods for calculating EOs in the *p*-frame, and introduces the CT-method as an alternative means. Section 3 validated the proposed CT-method through comparing the DG results derived from the CT-method EOs, POSPac EOs, and Legat method EOs with the help of empirical and simulated data. Finally, Section 4 concludes this paper.

2. Methods

In this section, definitions and descriptions of the terms associated with reference frames and map projections are presented in Section 2.1. Then, three conventional methods, the Bäumker method, Legat method, and POSPac method, are described in Section 2.2, and the proposed CT-method is detailed in Section 2.3.

2.1. Reference frames and map projections

The terms associated with reference frames and map projections are presented following Legat (2006)'s definitions and descriptions (see Table 1). All frames are assumed to be right-handed.

2.2. Compensation Matrix method

Approach 1: Bäumker method (Bäumker and Heimes, 2001). Bäumker and Heimes presented a method to calculate orientation angles in the *p*-frame in 2001. To eliminate the effects of the Earth's curvature and meridian convergence effect in the *p*-frame, a compensation matrix is applied (Bäumker and Heimes, 2001). First, the flight block center is computed, and then a *l*-frame is built with the block center as its origin. Then, all the orientation angles are transformed to the *l*-frame, and finally, the *l*-frame is transformed to the *p*-frame through the compensation matrix. It can be expressed by

$$R_c^p(\omega,\varphi,\kappa) = R_{l'}^p R_{l_0}^{l'} R_e^{l_0} R_l^e R_b^l R_c^b \tag{1}$$

where $R_c^p(\omega,\varphi,\kappa)$ is the rotation matrix of EO orientation angles (omega, phi, kappa) in the *p*-frame by which the orientation angles can be calculated; $R_{l'}^p = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix}$ is a matrix to correct the orientations of coordinate axes in the l'-frame and the *p*-frame; $R_{l_0}^{l'} = \begin{bmatrix} 1 & e_v & -e_e \\ -e_v & 1 & e_n \\ e_e & -e_n & 1 \end{bmatrix}$ is the compensation matrix for Earth curvature and meridian convergence from flight block center *l*-frame to the PC l'-frame, l_0 represents the *l*-frame whose origin is the flight block center; $e_v = (\lambda_i - \lambda_0^{GK})\sin\phi_i$ is an approximate formula to compensate meridian convergence, within which λ_i is the PC longitude, ϕ_i is the PC latitude. λ_0^{GK} is central meridian longitude of the projection zone, and *GK* is an abbreviation of Gauss–Kruger. $e_e = \phi_i - \phi_0$ and $e_n = -(\lambda_i - \lambda_0)\cos\phi_i$ compensate for Earth curvature, within which ϕ_0 is the flight block center latitude, and λ_0 is the flight block center longitude. $R_e^{l_0}$ is the rotation matrix that defines the transformation from *e*-frame to the flight block center *l*-frame; R_l^e is the rotation matrix defining the transformation from the PC *l*-frame to the *e*-frame; R_b^l is the rotation matrix defining the relative orientation of the IMU body frame (*b*-frame) to the PC *l*-frame defined by the sequence of rotations such as roll, pitch, and heading (Φ, Θ, Ψ); R_c^b is the fixed rotation matrix defining the transformation from the *c*-frame to the *b*-frame which was utilized to compensate for boresight misalignment.

Approach 2: Legat method (Legat, 2006). Legat presented a method to calculate the attitude matrix and PC coordinates in the national *p*-frame. Compared with the Bäumker method, it is unnecessary to compute the block center and transform the *l*-frame of the PC into the *l*-frame of the block center. The orientation angles can be directly transformed into the *p*-frame via a compensation matrix which corrects only for meridian convergence, and some other rotation matrices are supplemented for transforming them to the national datum. The transformation method can be expressed by

$$R_c^p(\omega,\varphi,\kappa) = R_{l'}^p R_{\bar{l}}^{l'} R_n^{\bar{l}} R_e^n R_l^e R_b^l R_c^b \tag{2}$$

where $R_{\bar{l}}^{l'} = \begin{bmatrix} \cos(\gamma_{PC}) & \sin(\gamma_{PC}) & 0 \\ -\sin(\gamma_{PC}) & \cos(\gamma_{PC}) & 0 \\ 0 & 0 & 1 \end{bmatrix}$ is the approximate compensation matrix for meridian convergence from the PC $\bar{l}$-frame to the

Table 1
Overview of the required frames.

Frames	Abbreviation	Description
Local tangent frame	$l, \bar{l}$	This frame is the local level frame which is tangent to the reference ellipsoid, *l* stands for the adoption of WGS84 ellipsoid. $\bar{l}$ stands for the adoption of the national ellipsoid
IMU body frame	*b*	Realized by the triad of accelerometers within an INS
Camera frame	*c*	Defined by the principal axes of a camera
Earth-centered Earth-fixed (ECEF) frame,	*e*	Earth-centered Earth-fixed (ECEF) frame, realized by a variant of the International Terrestrial Reference Frame (ITRF)
Geodetic coordinate system	*g*	In geodetic coordinates the Earth's surface is approximated by an ellipsoid and locations near the surface are described in terms of latitude, longitude and height
Eccentric Earth-fixed frame	*n*	Eccentric Earth-fixed frame, defined for the national datum
Map projection frame	*p*	An object mapping frame established by preservation of a metric property for the appointed datum, spanned by the grid east-, north-, and up-axes (ENU)
Auxiliary local tangent frame	l'	Its three axes are parallel to the local map projection frame, but their pointing directions are not the same