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Accurate direct georeferencing of aerial imagery in national coordinates ☆

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ABSTRACT

In aerial photogrammetry, data products are commonly needed in national coordinates, and, in practice, the georeferencing is often performed in the required national map projection frame directly. However, as a map projection frame is not Cartesian, some additional corrections are necessary in the georeferencing process to take account of various map projection distortions. This paper presents a new map projection correction method for the direct georeferencing of aerial images in national coordinates, which comprises of three consecutive steps: (1) a rough intersection to predict ground point coordinates in the Cartesian space; (2) calculating map projection corrections; and (3) a fine intersection. Benefiting from the explicit estimation of ground positions in the Cartesian space, our new method can directly adopt the accurate map projection distortion model that was previously developed for the direct georeferencing of airborne LiDAR data in national coordinates. Simulations show that the correction residuals of our new method are smaller by one order of magnitude than those of the previous best approach while their computational costs are at the same level, and even in an extreme scenario of 8000 m flight height above ground, the maximum error of our method is only several centimeters, which can be safely neglected in practical applications.

1. Introduction

Benefiting from the continuous improvement of GPS/INS hardware and integrated navigation technology, the exterior orientation parameters (EOPs) of aerial imagery can be directly and accurately acquired by an onboard position and orientation system (POS), and can be used for scene restitution directly (Yastikli and Jacobsen, 2005a; Legat, 2006). This georeferencing method, which is called direct georeferencing (DG), has gained increasing attention in the photogrammetry community because it does not need the field work of measuring ground control points and a bundle adjustment, and it can therefore greatly reduce data acquisition and processing costs (Skaloud, 2002; Cramer et al., 2012). However, as being an extrapolation method, DG is particularly sensitive to systematic and random errors (Yastikli and Jacobsen, 2005a,b).

Aerial photogrammetric products are typically needed in national coordinates and, accordingly, in practice, DG is often conducted in the required national frame directly (Zhang and Shen, 2013a). However, as a national frame is not Cartesian but rather defined by a national datum and a conformal map projection, the DG process in national coordinates is inevitably affected by a number of map projection distortions, which should be carefully corrected to acquire accurate DG results (Ressl, 2001; Yastikli and Jacobsen, 2005a,b; Legat, 2006; Zhang and Shen, 2013a,b).

Many map projection correction methods were developed for the DG of aerial imagery in national coordinates, and so far any of them was designed for correcting a specific distortion factor only (either the earth curvature distortion or length distortion. The earth curvature distortion and length distortion refer to the height difference and the horizontal length difference between a ground point and its corresponding projected point in the local level frame defined by the perspective center as the anchor point, respectively. The former is independent upon the map projection and the latter

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is not. For more details on the properties of these two distortion factors, please see Legat (2006), or Zhang and Shen (2013a)). To our best knowledge, all sophisticated earth curvature correction methods adopt a similar strategy that modifies image coordinates (Wang, 1990; Mikhail et al., 2001; Mugnier et al., 2004; Legat, 2006; Kraus, 2007; Zhao et al., 2014). The correction methods for the length distortion, on the other hand, are more diversified. Corrections can be added to flight heights (Ressl, 2001; Legat, 2006), focal lengths (Ressl, 2001; Yastikli and Jacobsen, 2005a,b), image coordinates (Zhang and Shen, 2013b), or ground heights (Zhang and Shen, 2013b).

Existing map projection correction methods were evaluated by a number of researchers using simulated (Legat, 2006; Zhang and Shen, 2013b; Zhao et al., 2014) or real data (Skaloud and Legat, 2008), and they were proven to be capable of substantially improving DG accuracies in national coordinates. However, simulation results also indicated that the residuals of these methods cannot be entirely neglected. By analyzing the equation derivations of previous map projection correction algorithms, it can be found that their performance is not fully satisfied for two main reasons: (1) the map projection distortion model used is not very accurate, e.g., the angle distortion (it contains three parts: the skew-normal distortion, the normal-section-to-geodesic distortion, and the arc-to-chord distortion. For more details please see Zhang and Shen (2013a)) is not considered in previous studies; (2) an average terrain elevation is adopted in widely used non-iterative earth-curvature-correction methods to approximate real ground heights.

In this paper, we present a new map projection correction method for the high-precision DG of aerial imagery in national coordinates. Different from previous studies, ground coordinates in the Cartesian space are explicitly estimated in our algorithm, and an accurate map projection distortion model can then be adopted and the ground height approximation can also be avoided.

The remainder of this paper is organized as follows. In Section 2, we introduce some background on the DG problem. Then, Section 3 presents our new map projection correction method. Finally, we provide experimental results and conclude the paper in the last two sections.

2. Geometric basis

2.1. Differences between direct georeferencing of imagery and LiDAR data

If technical details not required for this solution, such as the calibration parameters of imaging sensors and the mounting parameters between different sensors (i.e., lever arms and boresight angles), are ignored, the DG models of aerial imagery and airborne LiDAR data in a Cartesian frame can be written as

$$\boldsymbol{T}_{\text{grd}}^{\text{img}} = \boldsymbol{T}_{\text{eo}} + \boldsymbol{T}_{\text{dg}}^{\text{img}} = \boldsymbol{T}_{\text{eo}} + s\boldsymbol{R}_{\text{eo}}\boldsymbol{T}_{\text{sensor}}^{\text{img}} \tag{1}$$

and

$$\boldsymbol{T}_{\text{grd}}^{\text{LiDAR}} = \boldsymbol{T}_{\text{eo}} + \boldsymbol{T}_{\text{dg}}^{\text{LiDAR}} = \boldsymbol{T}_{\text{eo}} + \boldsymbol{R}_{\text{eo}}\boldsymbol{T}_{\text{sensor}}^{\text{LiDAR}} \tag{2}$$

respectively. The superscripts img and LiDAR refer to optical image data and LiDAR data, respectively; $\boldsymbol{T}_{\text{grd}}$ represents the column vector constituted by a ground coordinate; $\boldsymbol{T}_{\text{eo}}$ and $\boldsymbol{R}_{\text{eo}}$ refer to the 3D vector and 3×3 rotation matrix formed by linear and angular EOPs, respectively; $\boldsymbol{T}_{\text{dg}}$ refers to the DG vector (Zhang and Shen, 2013a); s is the scale factor of a bundle ray; and $\boldsymbol{T}_{\text{sensor}}$ is the sensor observation vector and can be given by

$$\boldsymbol{T}_{\text{sensor}}^{\text{img}} = \begin{bmatrix} x \\ y \\ -f \end{bmatrix} \tag{3}$$

and

$$\boldsymbol{T}_{\text{sensor}}^{\text{LiDAR}} = \boldsymbol{R}_{\text{scan}} \begin{bmatrix} 0 \\ 0 \\ -r \end{bmatrix} \tag{4}$$

for aerial images and airborne LiDAR data, respectively, where (x, y) is the image coordinate, f is the focal length, r is the range observation, and $\boldsymbol{R}_{\text{scan}}$ refers to the scan angle matrix (Baltsavias, 1999).

By comparing Eqs. (1) with (2), it can be seen that either the DG process of aerial images or airborne LiDAR data can be expressed as an addition operation between the vectors $\boldsymbol{T}_{\text{eo}}$ and $\boldsymbol{T}_{\text{dg}}$. However, since a camera does not possess range measurement capability like a LiDAR instrument, $\boldsymbol{T}_{\text{dg}}$ cannot be directly derived from the information in a single image.

2.2. Direct georeferencing in national coordinates

The DG model in a national map projection frame can be written as

$$\boldsymbol{T}'_{\text{grd}} = \boldsymbol{T}_{\text{eo}} + \boldsymbol{T}_{\text{dg}} + \Delta(\boldsymbol{T}_{\text{eo}}, \boldsymbol{T}_{\text{dg}}) = \boldsymbol{T}_{\text{grd}} + \Delta(\boldsymbol{T}_{\text{eo}}, \boldsymbol{T}_{\text{dg}}) \tag{5}$$

where $\boldsymbol{T}'_{\text{grd}}$ and $\boldsymbol{T}_{\text{grd}}$ refer to the ground coordinates in the national map projection frame and in the Cartesian space, respectively; Δ refers to the map projection distortion, which is a very complicated function of $\boldsymbol{T}_{\text{eo}}$ and $\boldsymbol{T}_{\text{dg}}$ (Zhang and Shen, 2013a) and is schematically shown by the coordinate difference between G (G_1 or G_2) and G′ in Fig. 1.

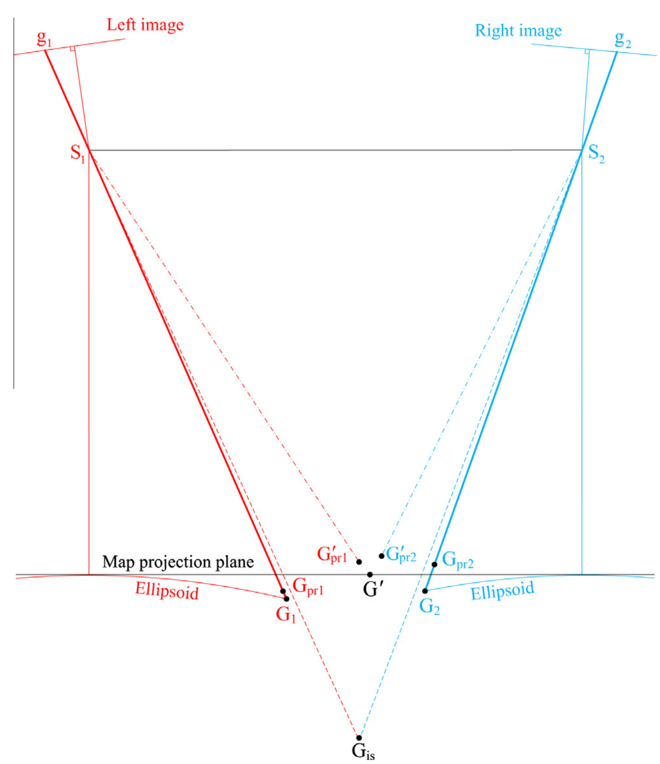

Fig. 1. A two-view geometry in a national map projection frame. G′ is a ground point in national coordinates, and G_1 and G_2 are the corresponding ground positions in the Cartesian space with respect to the perspective centers S_1 and S_2, respectively, where the subscripts 1 and 2 refer to the left and right images, respectively; G_{pr1} and G_{pr2} are the predicted ground positions in the Cartesian space, and G'_{pr1} and G'_{pr2} are their corresponding map projection positions, respectively; G_{is} is the result of a space intersection in national coordinates without correcting any map projection distortions; and g_1 and g_2 are the image points in the left and right images, respectively.