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Geometric integration of high-resolution satellite imagery and airborne LiDAR data for improved geopositioning accuracy in metropolitan areas

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ABSTRACT

High-resolution satellite imagery (HRSI) and airborne light detection and ranging (LiDAR) data are widely used for deriving 3D spatial information. However, the 3D spatial information derived from them in the same area can be inconsistent. Considering HRSI and LiDAR datasets taken from metropolitan areas as a case study, this paper presents a novel approach to the geometric integration of HRSI and LiDAR data to reduce their inconsistencies and improve their geopositioning accuracy. First, the influences of HRSI's individual rational polynomial coefficients (RPCs) on geopositioning accuracies are analyzed and the RPCs that dominate those accuracies are identified. The RPCs are then used as inputs in the geometric integration model together with the tie points identified in stereo images and LiDAR ground points. A local vertical constraint and a local horizontal constraint are also incorporated in the model to ensure vertical and horizontal consistency between the two datasets. The model improves the dominating RPCs and the ground coordinates of the LiDAR points, decreasing the inconsistencies between the two datasets and improving their geopositioning accuracy. Experiments were conducted using ZY-3 and Pleiades-1 imagery and the corresponding airborne LiDAR data in Hong Kong. The results verify that the geometric integration model effectively improves the geopositioning accuracies of both types of imagery and the LiDAR points. Furthermore, the model enables the full comparative and synergistic use of remote sensing imagery and laser scanning data collected from different platforms and sensors.

1. Introduction

High resolution satellite imagery (HRSI) has been widely used to derive 3D spatial information in a variety of applications such as building modeling (Baltsavias et al., 2001; Fraser et al., 2002), coastal mapping (Populus et al., 2001; Di et al., 2003a, 2003b) and disaster monitoring (Glenn et al., 2006; Kasai et al., 2009). Recently launched satellites such as GeoEye-1 and WorldView-2 from U.S. company DigitalGlobe and Pleiades-1 from the European company Airbus Defence and Space provide sub-meter geometric resolution for panchromatic imagery (Croft, 2008; Poli et al., 2013). The first Chinese civilian high-resolution mapping satellite, ZY-3, offers a 2.1-m resolution for panchromatic nadir imagery (Wang et al., 2014). HRSI is becoming more attractive in various applications due to its high quality imaging, short revisit time and lower cost. In the past decade, airborne laser scanning or light detection and ranging (LiDAR) technology has also been widely used to rapidly capture 3D surface data (point clouds) for a variety of applications (May and Toth, 2007). LiDAR has several advantages in that it offers very short delivery times that are much faster than traditional photogrammetric compilation, and provide extensive information that contains a wealth of detail due to the extraordinary number of points involved. HRSI and LiDAR are currently two major sources for obtaining 3D spatial information.

However, in circumstances where both HRSI and LiDAR data are available in a single area, it is not unusual to see inconsistencies in their derived 3D spatial information. For example, the differences between the 3D locations of objects (e.g., buildings) derived from LiDAR data in Hong Kong and those derived directly from the Pleiades-1 and ZY-3 imagery of the same objects range from several meters to over 20 m. Photogrammetric image processing

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generally provides better accuracy in the horizontal direction than in the vertical direction (Li et al., 2007). Although LiDAR data is known to produce better vertical accuracy than horizontal accuracy (May and Toth, 2007; Qiao et al., 2010), the inconsistencies between the two datasets may be reduced via their geometric integration. This may improve the geopositioning accuracy of both datasets, which cannot be achieved when only the data from a single source are used.

The geometric integration of HRSI and LiDAR data has rarely been investigated. We developed an approach for the integrated processing of lunar satellite imagery and laser altimeter data to eliminate the possible discrepancies between the two datasets (Wu et al., 2011a, 2014). However, the lunar surface is relatively smooth, and it is more complicated to geometrically integrate HRSI and LiDAR data in metropolitan areas such as Hong Kong. Metropolitan areas present significant height variations due to their dense distributions of tall buildings and skyscrapers. A sudden change in an elevation or a slope makes the surface continuity constraint non-functional, but this also introduces new clues of using boundary features with significant elevation changes to provide constraints to the integration process.

This paper aims to geometrically integrate HRSI and LiDAR data in metropolitan areas to improve the geopositioning accuracy of both datasets. After presenting a literature review on the geopositioning accuracy analysis of HRSI and LiDAR data, we investigate the influence of HRSI's individual rational polynomial coefficients (RPCs) on geopositioning accuracy, and identify RPCs dominating that accuracy. A geometric integration model is then presented in detail for the integrated processing of HRSI and LiDAR data in metropolitan areas. The results of experimental analyses involving LiDAR data, ZY-3 imagery and Pleiades-1 imagery in Hong Kong are then used for experimental analysis. Finally, concluding remarks are presented and discussed.

2. Related work

The rational function model (RFM) is typically used to derive 3D spatial information from HRSI. It involves a mathematical fitting of the rigorous sensor model using polynomials that contain RPCs. Third-order polynomials usually consist of 78 RPCs, which the image supplier provides as image metadata (Li et al., 2007; Habib et al., 2007). Establishing the geopositioning accuracy of HRSI directly from RPCs depends on the quality of the HRSI's orbital navigation and stability. For example, ground coordinates derived from the RPCs of the IKONOS (Geo Level) stereo product have exhibited a systematic horizontal shift (16–25 m) (Dial and Grodecki, 2002; Li et al., 2007, 2008). The typical QuickBird stereo (Basic Level) imagery has exhibited a similar shift of 23 m (Qiao et al., 2010). Fraser and Ravanbakhsh (2009) reported that systematic errors of about 2.5 m in horizontal and 7.6 m in height resulted from a direct space intersection when RPCs were used for a GeoEye-1 stereo image pair covering the Hobart HRSI test field in Hobart, Tasmania, Australia. This type of error is mainly caused by the possible biases within the RPCs, and can be removed or lessened by bias-correction models in either image or object space through a few good-quality ground control points (GCPs). Di et al. (2003a, 2003b) used a 3D affine transformation model to refine the RPC-derived ground coordinates of IKONOS images and achieved an accuracy of 1.5 m in planimetry and 1.6 m in height. Wang et al. (2005) tested different bias-correction models including translation, scale and translation, affine, and second-order polynomial models using IKONOS and QuickBird imagery. Their results indicated that meter lever accuracy can be obtained using an appropriate model and GCPs. Fraser and Hanley (2005), Toutin (2006), Habib et al. (2007) and Fraser and Ravanbakhsh (2009) reported similar results. Instead of adding corrections in image or object space, Tong et al. (2010) presented a method to directly modify and regenerate the RPCs based on bias-correction models for a stereo pair of QuickBird imagery in Shanghai, China. The results indicated the existence of high-order error signals in the original RPCs. Sub-meter accuracy can be achieved according to their approach with sufficient and appropriate GCPs. The direct regeneration of RPCs enables the convenient processing of HRSI through commercial photogrammetric software. However, their method requires a large number of GCPs and may arrive at unstable solutions given the large number of RPCs (78) involved.

The geopositioning accuracy of LiDAR data is related to the accuracy of the navigation solution, boresight misalignment angles, ranging and scan angle accuracy, and laser beam divergence (May and Toth, 2007). In the first few years of LiDAR mapping development, most providers quoted root mean square error (RMSE) accuracies of 15 cm. In fact, such accuracy can only be obtained in ideal situations (Hodgson et al., 2003). Bowen and Waltermire (2002) examined the errors of the LiDAR data collected in Richland County, South Carolina, and their results showed that the horizontal error of LiDAR points is typically large (a RMSE of about 120 cm). Xhardé et al. (2006) analyzed LiDAR data collected on the south coast of the Gaspé Peninsula, Canada in 2003 and 2004, and reported that the RMSEs were about 54 cm in horizontal and about 16.5 cm in vertical. Other research has demonstrated LiDAR data range accuracies for large-scale mapping applications at RMSEs from 26 to 153 cm (Adams and Chandler, 2002; Hodgson et al., 2003). The research has seldom addressed improving the accuracy of LiDAR data. Csanyi and Toth (2007) investigated the use of LiDAR-specific ground control targets to improve data accuracy. The test results they obtained from two flights showed that specifically designed LiDAR targets improved the centimeter-level accuracy of the final LiDAR product. However, the improvement mainly relied on specifically designed ground control targets. In recent years, the improving capabilities of direct geo-referencing technology (GNSS/INS) are having a positive impact on the accuracy of the LiDAR data. Habib (2008) reported an accuracy of 50 cm in horizontal and 15 cm in vertical for the LiDAR data collected using an OPTECH ALTM 2070 system from a flying altitude of 975 m, and the accuracy was further improved by applying several internal and external quality control means. Hladik and Alber (2012) presented a method to improve the LiDAR data based on high accuracy RTK observations, which reduced the overall mean error from about 100 cm to 10 cm. The ASPRS positional accuracy standards for digital geospatial data listed the expected horizontal errors (RMSE) for LiDAR data ranging from 13.1 cm at a flying altitude of 500 m to 67.6 cm at an altitude of 5 km (ASPRS, 2014).

Most research related to the integrated processing of HRSI and LiDAR data has concentrated on enhanced feature extraction, in which the elevation information provided by the LiDAR data is used to support the extraction of features from the imagery (Teo and Chen, 2004; Sohn and Dowman, 2007). St-Onge et al. (2008) and Steinmann et al. (2013) investigated the methods of assessing the accuracy of the forest height and biomass using satellite images and LiDAR data. Stal et al. (2013) presented a method of integrating aerial images and LiDAR data for 3D change detection in urban areas. A digital surface model (DSM) extracted from a stereo aerial images acquired in 2000 was compared with a DSM derived from LiDAR data collected in 2009 to obtain the information of 3D building changes. In the planetary mapping community, several endeavors have been made to geometrically integrate satellite imagery and laser altimetry data. Anderson and Parker (2002) investigated the registration between the imagery and laser altimeter data collected by the Mars orbiter camera (MOC) and Mars orbiter laser altimeter (MOLA), which were both onboard