QUANTITATIVE GEOMETRIC CALIBRATION & VALIDATION OF THE RAPIDEYE CONSTELLATION

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1. INTRODUCTION

The RapidEye system is a new generation of operational small-satellite constellations designed to meet the growing requirements for remotely sensed satellite imagery. Based on a constellation of five satellites, each carrying a 5-band 6.5 metre multi-spectral (MS) imager, the RapidEye system is capable of daily collection of over $4Mkm^2$ with access to any point on the surface of the earth every day. This high-repeat, moderate-resolution capability makes RapidEye imagery ideally suited to satisfying multi-spectral and multi-temporal applications, for which geometric accuracy (including absolute accuracy, relative accuracy, multi-temporal registration, and band-to-band registration) is critical. To satisfy these requirements, the RapidEye constellation underwent a quantitative post-launch geometric calibration & validation campaign designed to accurately commission the cameras and to characterize the quality of imagery products. This paper describes the post-launch calibration techniques developed and used to characterize the payloads on all 5 RapidEye satellites. It both highlights the advances in calibration tools and techniques made over previous calibration campaigns and summarizes the results observed in the initial post-launch activities.

2. BACKGROUND

Accurate characterization and calibration of any imaging system is critical to the overall geometric quality of the system's image products [1]. The unique characteristics of each satellite system require specific calibration programs to commission the systems [2,3]. For RapidEye, geometric calibration was comprised of two related components – internal camera calibration (or interior orientation) and external calibration (or exterior orientation).

Internal calibration includes developing a physical model for parameterizing all factors which impact the line-of-sight vector of each pixel (in the camera frame). These factors include the RapidEye focal plane design, focal length, optical distortions in the camera, and any thermal variations. While internal calibration was measured in the lab pre-flight, post launch refinements were required to quantify changes in the final in-orbit state.

External calibration includes determining the position and orientation of the imaging system, and is composed of static alignment components (e.g. the alignment between star trackers and the camera bore sight), and image-dependent components (primarily the satellite position and attitude time states). For the RapidEye satellites, these latter two time states are estimated using ancillary sensors on the satellite – GPS (for position) and a star-tracker (for absolute orientation). Unlike the internal calibration, static alignments were not measured pre-flight. Rather, our approach relied entirely on the post-launch calibration campaign to characterize the in-orbit alignments between the nominal bore sight and star tracker orientations. On the other hand, the satellite position and attitude uncertainties vary from image to image, and must be characterized with ground control points identified in the imagery.

3. RAPIDEYE IN-ORBIT CALIBRATION CAMPAIGN

The RapidEye post-launch geometric calibration campaign was designed to accurately measure the internal camera calibration parameters and the static alignments, thus enabling generation of geometrically accurate image products with relatively few ground control points. Calibration of the RapidEye constellation presented a number of challenges. First and foremost was the number of payloads. The RapidEye constellation consists of five satellites requiring independent calibration of 5 instruments in the brief post-launch calibration period. This demanded a set of tools and procedures be developed that could be efficiently applied to multiple datasets in a timely manner. Second was the focal plane design. Each RapidEye focal plane consists of five separate CCD arrays, one for each spectral band, displaced in the along-track direction. This configuration introduces significant differences in the imaging time when each band sees the same point on the Earth. This complicates the internal calibration due to the coupling between band alignment and temporal variations in attitude, requiring techniques be developed which can separate between the two phenomena.

To address these challenges, the RapidEye calibration campaign was divided into two parts – a camera alignment calibration and an optical distortion calibration. An independent set of tools was developed to measure each part.

3.1. Camera Alignment Calibration

The objective of the camera alignment calibration was to characterize the relative alignment between the camera bore sight and the star tracker on each satellite, thus allowing the attitude time state for any scene to be translated to the camera frame of reference. To determine the camera alignment, we relied on external ground control across multiple images. For any given scene, the external orientation of the imaging system can be determined with ground control. The star tracker orientation is output directly from the star tracker. While both measurements contain unknown noise for a given scene, the noise is uncorrelated between scenes. By observing the alignment over an ensemble of images, we were able to average down the error and accurately estimate the static camera alignment on all satellites.

3.2. Optical Distortion Calibration

The objective of the camera optical distortion calibration was to precisely calculate the line-of-sight vector (in the camera frame of reference) for each pixel in each band, thus improving the relative geometric accuracy of image products and the band-to-band registration accuracy. To characterize the optical distortion, we extend a technique we originally developed to assist DigitalGlobe in the calibration of the QuickBird and WorldView sensors. In summary, this technique uses reference ortho-photos (from higher quality reference sensors) and corresponding DEMs as the primary source of control. For RapidEye, 1-meter DOQQs were used. For each satellite, one or more images over available calibration sites were selected. The red band of each image was correlated with the reference ortho to automatically provide a rich set of dense candidate control which, when filtered for blunders and averaged, provided an accurate source of detailed control on both the spacecraft dynamics (e.g. attitude) and optical distortion. To reconstruct the optical distortion, we developed a rigorous sensor model parameterized by focal length, attitude states, and high order optical distortions (extending previous WorldView models), and directly solved for the high order optical distortion with a fully weighted least-squares adjustment. The remaining four bands derived the optical distortion using the corrected red band as an absolute reference (further reducing correlations noise and improving band-to-band registration). This rigorous approach enabled us to reliably separate the error contributions of the spacecraft dynamics from the camera optics, and allowed direct output of updated focal lengths and optical distortion coefficients.

4. RESULTS

The above tools and techniques were successfully used to complete the geometric calibration of all five RapidEye spacecraft, allowing the constellation to complete the post-launch testing and calibration activities needed to start commercial operations in January 2009 (5 months after launch - a similar timeframe to single satellite missions). Results, which will be presented in the full paper, shows that after sensor calibration, the mission was able to meet all its geometric accuracy requirements.

4. REFERENCES

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