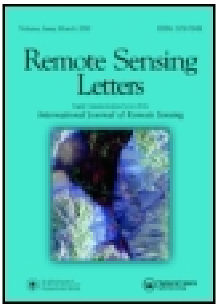

Remote Sensing Letters
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/trsl20

Absolute misalignment estimation with respect to a scanning image sensor

Hyungjoo Yoon [a], Keun-Joo Park [a], Jo Ryeong Yim [a], Doo-Chun Seo [a], Heeseob Kim [a] & Hong-Taek Choi [a]

[a] Korea Aerospace Research Institute, Daejeon, 305-806, South Korea

Published online: 31 May 2013.

Remote Sensing Letters, 2013
Vol. 4, No. 8, 754–763, http://dx.doi.org/10.1080/2150704X.2013.793462

Absolute misalignment estimation with respect to a scanning image sensor

HYUNGJOO YOON*, KEUN-JOO PARK, JO RYEONG YIM, DOO-CHUN SEO, HEESEOB KIM and HONG-TAEK CHOI
Korea Aerospace Research Institute, Daejeon 305-806, South Korea

(*Received 3 December 2012; in final form 2 April 2013*)

This letter proposes a simple but effective method for in-flight estimation of absolute misalignment, which is defined as the orientation offset error between attitude sensors and an imaging payload. The method was developed for high-resolution spaceborne/airborne imaging systems, which use a scanning image sensor in their payload. This type of image sensor operates in the pushbroom mode, so that previously existing methods are not easily applicable. The proposed method utilizes the pre-existing attitude-determination algorithms originally used to estimate the attitude of a star tracker equipped with a planar image sensor. We converted the geo-referencing relation between the GCP (Ground Control Point) directions and their image vectors into a new expression which enables the application of the attitude-determination algorithms to identify the absolute misalignment. Pointing knowledge analysis, using actual in-flight data, is presented to verify the developed method.

1. Introduction

The key performance indices of modern satellite attitude control systems include the pointing accuracy and the pointing knowledge, and they are subject to various sources of error (e.g. attitude control error and attitude/orbit determination error). Among these sources of error, the misalignment of attitude sensors directly affects the attitude control and geo-referencing performance, so the calibration of misalignment is a crucial procedure in the Launch and Early Operation Phase (LEOP). This process must also be conducted regularly to meet stringent performance requirements.

Attitude sensors, such as star trackers, gyroscopic sensors and inertial reference units (IRU), measure their own attitude and angular velocity, and this data is transformed into the spacecraft body frame using alignment information of the sensors with respect to the spacecraft body frame. The measurements are processed in the attitude-determination Kalman filter to yield the best estimates of the spacecraft attitude and angular body rate. Hence, exact alignment information of these sensors is essential for accurate control and pointing performance. Though the sensor alignments are measured as accurately as possible before launch, misalignments are inevitable because of pre-launch alignment measurement error, launch shock, thermal distortion, outgassing and other effects. Hence, in-flight alignment calibration is required.

*Corresponding author. Email: drake.yoon@gmail.com

There are two kinds of misalignments of the attitude sensors (Shuster and Pitone 1991, Shuster *et al*. 1991): one is *relative misalignment*, error in the knowledge of the relative alignments between the attitude sensors. This misalignment should be calibrated to establish consistency between the measurements of the different attitude sensors. The relative misalignment calibration needs only the attitude sensor data, so it is generally performed by attitude control system (ACS) engineers. The other type of misalignment is *absolute misalignment*, misalignment of attitude sensors with respect to a body-fixed reference frame. In particular, for high-resolution imaging satellites, the attitude of the imaging payload is of primary interest, so the absolute alignment relative to the the (body-fixed) payload frame should be calibrated. Relative calibration would be enough for some applications, but when the pointing of the payload really matters, as is the case for imaging/surveillance satellites, calibration for absolute misalignment is required. The absolute misalignment calibration requires attitude sensor data, satellite and GCP position data and payload image data; so, it is generally conducted cooperatively by ACS and the image Calibration/Validation (Cal/Val) engineers.

There are extensive published studies about relative and absolute misalignment calibrations because of their importance for satellite applications. Two major approaches have been developed from different disciplines: the ACS approach and the photogrammetry approach. Most (if not all) of the previous work from the ACS approach consider the imaging payload as an additional attitude sensor (i.e. a star tracker), from which methods for relative misalignment calibration were developed and applied, to identify absolute alignment. (For instance, see Pittelkau (2001).) These methods can be applied for a payload equipped with a planar image sensor because it would operate similar to a star tracker. However, these may not be easily applicable to modern state-of-the-art imaging satellites, which use one-dimensional scanning image payload sensors, because this type of image sensor operates differently from that of the two-dimensional planar sensors used in the star trackers, and for some low-resolution payloads.

On the other hand, in the field of photogrammetry, misalignment is estimated using a bundle-adjustment algorithm, which expresses the problem as a minimization problem; and then solves it using nonlinear least-squares algorithms (Cramer and Stallmann 2002, Hinsken *et al.* 2002). Bundle adjustment needs to be able to handle a large number of nonlinear functions and variables. For this reason, commercial or licensed software packages and libraries specialized for bundle adjustment are used in the misalignment calibration.

The present work proposes a simple method to calculate the optimal estimate of the absolute misalignment. The approach is somewhat inter-disciplinary because it is inspired by theory and algorithms from both approaches mentioned above. The derivation of this method starts with geo-referencing model relation between ground coordinates and payload images of GCPs, in which the misalignment is mixed with the time-varying satellite attitude and position. Then, the geo-referencing model is transformed into a new expression, in which the misalignment is separated from the time-varying terms. Finally, the optimal estimate of the misalignment is calculated by applying the pre-existing attitude-determination algorithms (e.g. the famous QUaternion ESTimator (QUEST) algorithm), which were originally used for attitude determination of a planar imaging sensor. Even though this letter is focused on a satellite imaging system, the proposed method is also applicable to airborne image systems, as long as it utilizes a scanning linear array image sensor.

The newly developed method was implemented for KOrean Multi-Purpose SATellite (KOMPSAT-3) with sub-metre resolution imagery and validated by pointing knowledge analysis with actual in-flight GCPs data.

2. Brief review of attitude determinations

Since the proposed algorithm is based on attitude-determination methods that are already used for star trackers, we briefly review the methods and present the key algorithm needed for this new work.

The star tracker is the most accurate attitude measuring sensor. It determines its attitude relative to the inertial reference frame using star measurements. Figure 1 shows the sketch of a star tracker. Modern high-performance star trackers acquire star images using a two-dimensional planar sensor. In order to determine its complete three-axis attitude at a certain instant, the sensor needs at least two star measurements at that instant.

The star tracker measures multiple star images at each sampling time and identifies them by comparing with a star catalogue. For each measured star, one can define the star measurement unit vector in the star tracker frame, $\hat{\boldsymbol{w}}_i = \boldsymbol{w}_i/||\boldsymbol{w}_i||$, $i = 1, \ldots, N$, where $N \geq 2$ is the number of stars imaged, and $\boldsymbol{w}_i$ is the image vector with respect to the star tracker frame, as shown in figure 1. One can also define its corresponding reference unit vector in the inertial reference frame, $\hat{\boldsymbol{v}}_i$. Since these two vectors are identical but different only in their coordinate frames, they can be related as

$$\mathbf{A}\hat{\boldsymbol{v}}_i = \hat{\boldsymbol{w}}_i, \tag{1}$$

where $\mathbf{A}$ is the 3×3 direction cosine matrix (or the rotational matrix) from the inertial reference frame to the star tracker frame. The attitude determination is to calculate the attitude matrix $\mathbf{A}$ or, equivalently, the corresponding attitude parameters, such as the Euler angles or the quaternion. In general, the solution of $\mathbf{A}$ does not exist because the measurement is corrupted by noise and sensor imperfections, among

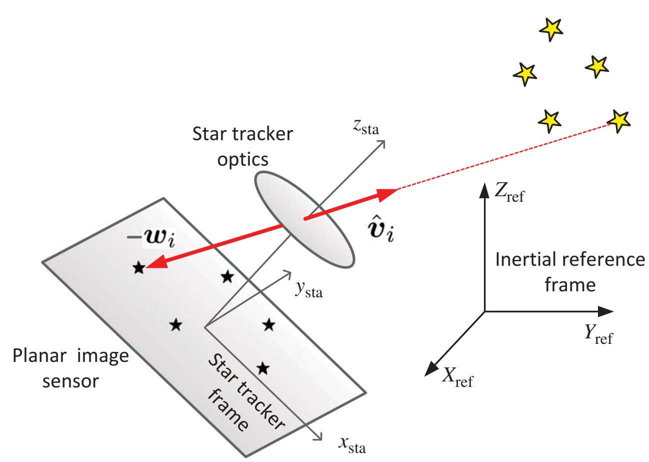

Figure 1. Sketch of a star tracker.

other things. Therefore, the attitude-determination algorithm generally calculates the optimal solution of **A** in a statistical sense, which minimizes a cost function defined as

$$J(\mathbf{A}) = \frac{1}{2}\sum_{k=1}^{N} a_k \left|\left|\hat{\boldsymbol{w}}_k - \mathbf{A}\hat{\boldsymbol{v}}_k\right|\right|^2, \tag{2}$$

where a_k is a positive weight parameter whose total sum from $k = 1$ to N is a constant. This optimization problem is called the Wahba Problem, after the name of the person who proposed it (Wahba 1965).

Numerous solutions have been proposed to solve this problem, but almost all modern solutions are based on Davenport's algorithm, which converts the Wahba Problem into an eigenvalue problem using the attitude quaternion. This algorithm is summarized in Shuster (2006) as follows.

If one defined the attitude profile matrix **B** according to

$$\mathbf{B} = \sum_{k=1}^{N} a_k \hat{\boldsymbol{w}}_k \hat{\boldsymbol{v}}_k^{\mathrm{T}} \tag{3}$$

and one defined further the quantities

$$s = \mathrm{trace}(\mathbf{B}), \quad \mathbf{S} = \mathbf{B} + \mathbf{B}\mathbf{B}^{\mathrm{T}} \quad \text{and} \quad \mathbf{Z} = \begin{bmatrix} B_{23} - B_{32} \\ B_{23} - B_{32} \\ B_{23} - B_{32} \end{bmatrix}, \tag{4}$$

where trace(·) is the matrix trace, B_{ij} is the element in the ith row and the jth column of **B**, as well as the Davenport matrix **K**

$$\mathbf{K} = \begin{bmatrix} \mathbf{S} - s\mathbf{I} & \mathbf{Z} \\ \mathbf{Z}^{\mathrm{T}} & s \end{bmatrix}, \tag{5}$$

where **I** is the identity matrix, then $\bar{\boldsymbol{q}}^*$, the attitude quaternion equivalent to the attitude matrix **A** which minimizes Wahba's cost function in equation (2) must satisfy an eigenvalue equation

$$\mathbf{K}\bar{\boldsymbol{q}}^* = \lambda_{\max}\bar{\boldsymbol{q}}^*, \tag{6}$$

where $\lambda_{\max}$ is the largest eigenvalue of the Davenport matrix. Davenport's algorithm may not be suitable for real-time implementations because of its computational burden, but is applicable to post-processing applications. It can easily be implemented using any general purpose mathematical software packages (for instance, MATLAB®; The MathWorks, Inc., Natick, MA, USA) which provide an eigenvalue problem solver.

Based on Davenport's algorithm, Shuster and Oh (1981) developed the QUEST algorithm, which is the most widely used one today. The QUEST is, in fact, a numerically efficient alternative of Davenport's algorithm (more than 1000 times faster (Shuster 2006)) and is suitable for real-time implementations.

Shuster and Oh (1981) also proposed a choice of the weights a_k to obtain the most accurate attitude estimate. When the QUEST measurement model was assumed to be

$$\hat{\boldsymbol{w}}_k = \mathbf{A}\hat{\boldsymbol{v}}_k + \Delta\hat{\boldsymbol{w}}_k, \tag{7}$$

where the measurement error, $\Delta\hat{\boldsymbol{w}}_k$, which is defined as the difference between the measured star image vector and the ideal star image vector, is assumed to be zero-mean, white and Gaussian and had the covariance matrix approximated as

$$E(\Delta\hat{\boldsymbol{w}}_k\Delta\hat{\boldsymbol{w}}_k^{\mathrm{T}}) = \sigma_k^2(\mathbf{I} - \hat{\boldsymbol{w}}_k\hat{\boldsymbol{w}}_k^{\mathrm{T}}), \tag{8}$$

where $E(\cdot)$ is the expectation operator, and σ_k^2 is the variance of a component of $\hat{\boldsymbol{w}}_k$ along any axis perpendicular to $\mathbf{A}\hat{\boldsymbol{v}}_k$, it was shown that the cost function (optimized over attitude) in equation (2) would be smallest if one chose

$$a_k = \sigma_0/\sigma_k^2, \tag{9}$$

where σ_0 is a positive constant. This choice of the weights implies that one should give larger weights to star measurements with higher accuracy. It also should be mentioned that the QUEST measurement model in equations (7) and (8) are a good approximation for a sensor with a narrow field-of-view (FOV). Details about these algorithms omitted here for brevity, can be found in Shuster and Oh (1981), Shuster (2006).

3. Linear array scanning sensor

The attitude-determination algorithm needs at least two star measurements at the same instant. Typically, the modern star trackers use 8–10 star measurements at each sampling time. This is possible because their planar sensors can detect all of the stars with sufficient brightness in the FOV nearly simultaneously.

If the payload is also equipped with a planar imaging sensor, we can easily estimate the absolute misalignment by comparing the payload attitude (determined by QUEST algorithm with the GCP images) to the attitude sensor's attitude, or the spacecraft attitude (determined using attitude sensor data and their noncalibrated alignment information).

Another approach to the estimation of misalignment is the use of alignment Kalman filter (AKF) algorithm proposed by Pittelkau (2001). This algorithm is attractive in that it can estimate not only the misalignment of star trackers and gyroscope sensors but also the alignment of the payload, all at the same time. (Simply put, the AKF algorithm estimates the absolute alignment.) Many recent space programs (for instance, MErcury Surface, Space ENvironment, GEochemistry and Ranging (MESSENGER) program) use this algorithm for relative misalignment calibration for gyroscope sensors (O'Shaughnessy *et al*. 2006).

In contrast, most modern high-resolution spaceborne and airborne imaging systems are equipped with a set of linear array scanning sensors, which generally operate in scanning or 'pushbroom' mode. Figure 2 shows a schematic illustration of a linear array image sensor and its pushbroom acquisition mode.

This type of imaging sensor operates like a 'scanner', and it stacks the acquired linear images to obtain a planar image. Therefore, even if multiple GCPs are shown in one planar image, each is taken at different instants in time. An imaging satellite is manoeuvering during acquisition of images (not to mention, in the wide-area imaging mode, yaw-steering manoeuver along the z-axis and pitch-rate manoeuver along the y-axis are needed, even in the nadir imaging mode, to compensate for the Earth's

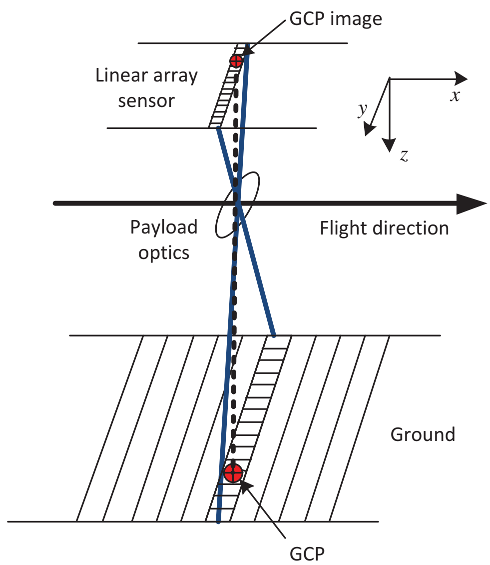

Figure 2. Linear array scanning image sensor and pushbroom image acquisition.

rotation and the orbit rate, respectively). For these reasons, each of the GCP images is generally taken with different spacecraft attitudes and positions, unless the GCPs are on an exact same scan line. Because the attitude-determination algorithm needs at least two vector measurements, one cannot use this method to calculate the payload attitude.

On the other hand, the aforementioned AKF algorithm generally requires a certain kind of attitude manoeuvering (calibration manoeuver) to make the unknown misalignment parameters observable, but a linear array sensor generally cannot obtain proper images during such manoeuvering. Moreover, the GCPs are, generally, not evenly located with a regular spatial interval, so the acquisition of GCP images occurs irregularly in time. All this makes implementation of the Kalman filter highly complex. The number of GCPs is also generally not sufficient for the Kalman estimates to converge to the real values. Therefore, neither the attitude-determination methods nor the AKF algorithms are easily applicable for misalignment calibration with a scanning image sensor.

4. MISQUEST

In the following section, we propose a simple but effective misalignment calibration algorithm referred to as the MISalignment QUaternion ESTimator (MISQUEST). We assume that the relative misalignments between the attitude sensors are already calibrated exactly enough so that the attitude measurements are consistent with each other, and, thus, that the set of multiple attitude sensors can be regarded as a single attitude sensor. The derivation of the algorithm starts with the geo-referencing model.

4.1 *Geo-referencing model*

In order to precisely calibrate the attitude sensor alignment with respect to the imaging payload, or vice versa, we use image data of GCPs whose location is known with centimetre-level accuracy. Let us assume that the imaging system acquires N GCP images for the misalignment calibration and consider the relation between ith GCP image vector and the relative position vector of the GCP with respect to the satellite. For the instant of the ith GCP image acquisition, let us assume that the satellite position is denoted by $(X_i^{\mathrm{s}}, Y_i^{\mathrm{s}}, Z_i^{\mathrm{s}})$ and the GCP's position vector by (X_i, Y_i, Z_i), both expressed in Earth-Centered Inertia (ECI) frame. In addition, denoting the image vector of the GCP as (x_i, y_i, z_i) in the payload (PL) frame, we obtain a simple relation equation from collinearity as follows.

$$\begin{bmatrix} X_i - X_i^{\mathrm{s}} \\ Y_i - Y_i^{\mathrm{s}} \\ Z_i - Z_i^{\mathrm{s}} \end{bmatrix}_{\mathrm{ECI}} = \frac{1}{\lambda_i}\mathbf{A}_i^{\mathrm{T}} \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}_{\mathrm{PL}}, \tag{10}$$

where the matrix $\mathbf{A}_i$ is the coordinate transformation matrix from the ECI frame to the PL frame, and λ_i is a normalizing scale factor, which can be removed if all the vectors are normalized. As shown in figure 2, z_i is set to the focal length of the optical system, f, and x_i is set to zero.

If we can calculate $\mathbf{A}_i$ from the GCPs' image and position vectors in equation (10), we would be able to easily calculate the absolute misalignment by comparing the payload attitude $\mathbf{A}_i$ with the spacecraft attitude at that instant in time. However, as mentioned earlier, we need at least two GCP images acquired at that instant for the attitude determination of $\mathbf{A}_i$, which is generally not the case here. Even if it is the case, the attitude determined using only few GCPs (in the exact same scan line) would not be accurate enough statistically for precise calibration.

4.2 *Misalignment estimation method*

In order to identify the misalignment using a large number of GPS images acquired at different instants, attitudes and positions, we deconstructed the matrix $\mathbf{A}_i$ apart to rewrite equation (10) as

$$\begin{bmatrix} X_i - X_i^{\mathrm{s}} \\ Y_i - Y_i^{\mathrm{s}} \\ Z_i - Z_i^{\mathrm{s}} \end{bmatrix}_{\mathrm{ECEF}} = \frac{1}{\lambda_i}\mathbf{M}_{\mathrm{ECI}}^{\mathrm{ECEF}}(t_i)\,\mathbf{M}_{\mathrm{B}}^{\mathrm{ECI}}(t_i)\,\mathbf{M}_{\mathrm{PL}}^{\mathrm{B}} \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}_{\mathrm{PL}}, \tag{11}$$

where $\mathbf{M}_{\mathrm{ECI}}^{\mathrm{ECEF}}(t_i)$ is a rotation matrix from ECI frame to Earth-Centered-Earth-Fixed (ECEF) frame, $\mathbf{M}_{\mathrm{B}}^{\mathrm{ECI}}(t_i)$ is from the satellite body frame to ECI frame, and t_i is the acquisition time instant of the ith GCP. Here the satellite body frame is a body-fixed frame determined by the attitude sensor measurement and its (noncalibrated) installed orientation matrix. The attitude of the body frame $\mathbf{M}_{\mathrm{ECI}}^{\mathrm{B}}(t_i)$ is estimated by the attitude estimation filter in the on-board flight software or in ground software. The positions are expressed in ECEF frame because they are generally measured in that frame by global positioning system (GPS). Finally, $\mathbf{M}_{\mathrm{B}}^{\mathrm{PL}}$ $(= \mathbf{M}_{\mathrm{PL}}^{\mathrm{B}\,\mathrm{T}})$ is the true alignment matrix of the payload frame with respect to the body frame, which is to be estimated.

Equation (11) was re-written so that the true alignment matrix $\mathbf{M}_{\mathrm{B}}^{\mathrm{PL}}$ appears in the form of equation (1) as follows.

$$\mathbf{M}_{\mathrm{B}}^{\mathrm{PL}}\hat{\boldsymbol{v}}_i = \hat{\boldsymbol{w}}_i, \tag{12}$$

where

$$\hat{\boldsymbol{v}}_i = \boldsymbol{v}_i/||\boldsymbol{v}_i||, \quad \boldsymbol{v}_i = \mathbf{M}_{\mathrm{ECI}}^{\mathrm{B}}(t_i)\,\mathbf{M}_{\mathrm{ECEF}}^{\mathrm{ECI}}(t_i)\begin{bmatrix} X_i - X_i^{\mathrm{s}} \\ Y_i - Y_i^{\mathrm{s}} \\ Z_i - Z_i^{\mathrm{s}} \end{bmatrix}_{\mathrm{ECEF}} \tag{13}$$

and

$$\hat{\boldsymbol{w}}_i = \boldsymbol{w}_i/||\boldsymbol{w}_i||, \quad \boldsymbol{w}_i = \begin{bmatrix} 0 \\ y_i \\ f \end{bmatrix}_{\mathrm{PL}}, \tag{14}$$

and obviously $\mathbf{M}_{\mathrm{ECI}}^{\mathrm{B}} = \mathbf{M}_{\mathrm{B}}^{\mathrm{ECI}^{\mathrm{T}}}$ and $\mathbf{M}_{\mathrm{ECEF}}^{\mathrm{ECI}} = \mathbf{M}_{\mathrm{ECI}}^{\mathrm{ECEF}^{\mathrm{T}}}$.

Now notice that equations (12) and (1) have exactly the same forms. Although the scanning camera collects data over a time interval, the attitude, orbit and image data in equation (12) are converted to spatial data now, as in equation (1). We can easily estimate the true alignment $\mathbf{M}_{\mathrm{B}}^{\mathrm{PL}}$ between the body frame (defined by the attitude sensor alignment information) and the payload frame using any of the pre-existing algorithms used to determine attitude. Though the name, MISQUEST, may imply the use of QUEST, Davenport's algorithm summarized in section 2. would also work well because the misalignment calibration is generally a post-processing procedure.

Applying the MISQUEST algorithm, one can set the weights a_k to be a constant, e.g. $a_k = 1$. This choice can be justified by equation (9) and the fact that since a high-resolution linear sensor generally has a narrow (few-degrees) FOV, accuracy of the GCP image vectors is nearly uniform across the linear array sensor. The satellite attitude and orbit informations can be assumed to have uniform accuracies as well.

One of the features of the MISQUEST algorithm is that it can obtain the optimal estimate of the alignment using hundreds of GCP images, collected from various GCP areas with various latitudes/longitudes, times and imaging modes. This is because the misalignment term is estimated after being isolated from these time-dependant factors.

Finally, we can update the installed alignment information of each attitude sensor as

$$\mathbf{M}_{\mathrm{B}}^{\mathrm{S}}\big|_{\mathrm{new}} = \mathbf{M}_{\mathrm{B}}^{\mathrm{S}}\big|_{\mathrm{old}}\,(\mathbf{M}_{\mathrm{B}}^{\mathrm{PL}})^{\mathrm{T}}, \tag{15}$$

where the superscript 'S' means each attitude sensor, and thus $\mathbf{M}_{\mathrm{B}}^{\mathrm{S}}$ is the alignment matrix of the sensor with respect to the satellite body frame. Then the body frame defined by the updated alignments information will be aligned with the actual payload frame, and the control and analysis of the body frame attitude become practically those of the payload boresight frame.

5. Pointing performance analysis

In this section, we present the pointing performance analysis of the initial calibration of the KOMPSAT-3 satellite, which was launched in May 2012. First, the relative misalignment between two star trackers was calibrated by comparing their measured attitudes. Then, the relative misalignment of the gyroscope sensor with respect to the star trackers was calibrated using the AKF filter algorithm. These processes were conducted in Bus Initial Activation and Checkout (IAC) phase because they do not need image data acquired by the payload. After the payload IAC phase was completed and thus the GCP data were available, the absolute misalignment calibration was conducted using the MISQUEST algorithm. In this process, we used about 100 GCP targets in a GCP site, set up near Ulan Bator, Mongolia.

The calibration in IAC phase was performed for two times. The preliminary estimation was conducted using GCP data acquired during one pass (about 100 measurements), and it showed that there was a considerable large initial misalignment between the payload and the attitude sensors. After the first calibration, the pointing knowledge performance was significantly improved. (The knowledge error level was reduced to less than 5% of the initial value.) The second misalignment estimation was performed after we tuned the ground-based, precision attitude and orbit-determination software parameters. The tuning of these parameters improved the attitude/position-determination performance and yielded more accurate attitude and position estimates for the satellite. More than 300 GCP data collected during three passes were used in the calibration, which resulted in further reduction of geolocation error.

Figures 3(*a*) and (*b*) show the geolocation error after the calibrations. The error analysis is conducted by using about 2000 GCP data collected after the calibrations. The geolocation error is defined as the difference between the GCP's actual location and the estimated location calculated using attitude, orbit and image data, and then is nondimensionalized by the KOMPSAT-3's geolocation error requirement, which is represented by the magenta circles, but whose value is not given for security reasons. These figures show that the Circular Error of 90% (CE90) level becomes definitely less than the requirement after the final calibration. The error distribution is elliptical because this analysis is conducted after the calibration of the external alignment offset, but before that of internal alignment (i.e. distortion of the image sensor array), which is out of the scope of this letter. We can conclude that the MISQUEST algorithm successfully estimates the absolute misalignment.

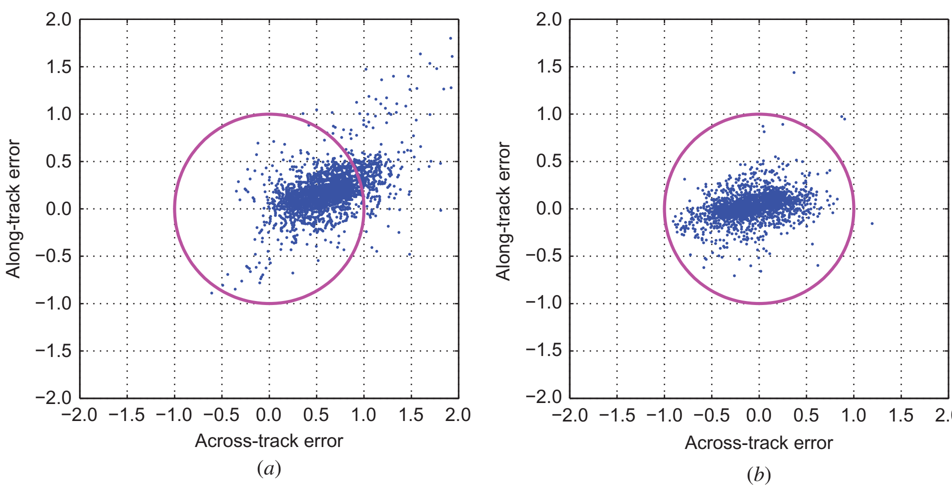

Figure 3. Geolocation error after absolute misalignment calibrations (magenta circle – KOMPSAT-3 geolocation error requirement) (*a*) after the preliminary calibration and (*b*) after the final calibration.

6. Conclusion

The proposed MISQUEST algorithm was easily implemented and applied to a real satellite programme, and showed highly effective performance in analysis of geolocation error, using actual GCP image data. The calibration was conducted as the first step in the geometric calibration of the payload system, and even more improvement in performance is expected after iteration with the internal calibration of the payload.

The contribution of this work is the introduction of the attitude-determination algorithm, which has been fully verified by successful applications to star tracker sensors, to the estimation of absolute misalignment. The authors hope this work would stimulate interdisciplinary research and applications in these two distinct, but closely-related fields.

References

Cramer, M. and Stallmann, D., 2002, System calibration for direct georeferencing. *International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences*, **34**, pp. 79–84.

Hinsken, L., Miller, S., Tempelmann, U., Uebbing, R. and Walker, S., 2002, Triangulation of LH systems ADS40 imagery using Orima GPS/IMU. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, **34**, pp. 156–162.

O'Shaughnessy, D.J., Vaughan, R.M., Haley, D.R. and Shapiro, H.S., 2006, Messenger IMU interface timing issues and in-flight calibration results. In *Proceedings of the 29th Annual AAS Guidance and Control Conference*, February, Colorado Paper No. AAS 06-086.

Pittelkau, M.E., 2001, Kalman filtering for spacecraft system alignment calibration. *Journal of Guidance, Control and Dynamics*, **24**, pp. 1187–1195.

Shuster, M.D., 2006, The quest for better attitudes. *The Journal of the Astronautical Sciences*, **54**, pp. 657–683.

Shuster, M.D. and Oh, S., 1981, Three-axis attitude determination from vector observations. *Journal of Guidance, Control and Dynamics*, **4**, pp. 70–77.

Shuster, M.D. and Pitone, D.S., 1991, Batch estimation of spacecraft sensor alignments, II. Absolute alignment estimation. *Journal of the Astronautical Sciences*, **39**, pp. 547–571.

Shuster, M.D., Pitone, D.S. and Bierman, G.J., 1991, Batch estimation of spacecraft sensor alignments, I. Relative alignment estimation. *Journal of the Astronautical Sciences*, **39**, pp. 519–546.

Wahba, G., 1965, A least squares estimate of satellite attitude. *SIAM Review*, **7**, p. 409.