IN-FLIGHT GEOMETRIC CALIBRATION OF FORE AND AFT CAMERAS OF CARTOSAT- 1

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Abstract

Cartosat-1 (IRS-P5) is the first satellite of ISRO designed to provide high resolution along-track stereo imagery for mapping applications. The platform contains two panchromatic camera payloads with +26º and –5º tilted with respect to nadir. A method for in-flight geometric calibration of Cartosat-1 images is presented in this paper. In-flight calibration includes alignment calibration of both payloads and calibration between the payloads. The objective of this study is to ensure the best absolute 3D pointing accuracy and relative location accuracy of the cameras. Taking advantage of the same orbit acquisition, calibration of different cameras is done with rigorous geometric reconstruction of the sensor orientations. Boresight misalignment computation methodology is explained in the paper. Accuracy of the direct orientation observation could be brought down to better than100m with the inclusion of in-flight calibrated parameters in to the adjustment model. Correction of the orientation parameters with a single GCP further improved it to 5m.

Keywords: In-flight calibration, sensor model, payload alignment, inter-camera alignment, staggered array.

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1. Introduction

In-flight calibration is important for satellite sensors because during the launch, the environmental conditions change rapidly and drastically and this usually causes changes in the internal sensor geometry that is determined in a pre-launch calibration. Therefore, in-flight calibration of the cameras in the initial phase is very essential to ensure the system performance. It also makes the daily data processing operations cost-effective. In-flight calibration of the sensor is a pre-requisite for direct geo-referencing. This idea is explained by Honkavaara [2004]. Pre-flight and in-flight geometric calibration of SPOT-5 HRG & HRS images is studied by Breton et al [2002]. Mulawa [2004] explains a method for the on-orbit geometric calibration of the orbview-3 high resolution sensors. There are different approaches for performing in-flight calibration. The most common approach is to extend the collinerity equations with additional parameters which take care of the distortions and represents the imaging process more accurately corresponding to the actual imaging condition (Ebner (1976), Fraser (1997), Cramer et al. (2002), Cramer (2005), Jacobsen (2004)). Image co-ordinates are updated for compensating the radial and tangential deformations along with shearing. We are following an approach in which the identification and quantification of systematic ground residual patterns followed by their application to sensor model and re-computation of the bundle adjustment. In our approach, boresight alignment parameters are part of the rotation matrix of the collinearity equations used in the sensor model. Similarly, focal plane geometry parameters are also part of the condition equations. Therefore, computation of corrections over these parameters during in-flight calibration is straightforward without including additional parameters. It can be applied to multiple cameras and payloads with little or no change to the bundle adjustment pattern. It only requires some post-processing software to analyse the residuals. Another advantage of this approach over the approach based on additional parameters during the adjustment is that it can consider systematic effects on image co-ordinates from any sources and not those just dependent on modelling optical geometry.

A description of Cartosat-1 mission is available in Krishnaswami (2002). Here, we recall some of the parameters, which are directly relevant for the discussions in the paper. Cartosat-1 has two panchromatic camera payloads Fore and Aft, with a tilt in flight direction of $+26^0$ and $-5\ ^0$respectively. The base to height ratio is about 0.62. Data is quantized with 10 bits. Integration time is 0.336ms.Nominal GSD is 2-2.5 m. Each CCD has 12000 pixels, separated in to 6000 each of odd and even pixels. These odd and even pixel rows are separated by 35μm (equal to 5 pixels) .To avoid any gap in the image due to this separation, coupled with the earth rotation, the spacecraft is given a rate about Yaw axis. A roll bias allows across-track pointing. A pitch biasing about the body frame is also possible.

1.1 Scope of the Work

The objectives of this study are to ensure the best location performances of both cameras, to obtain the best height accuracies from the stereo pair, to ensure same relative location accuracy from both cameras and alignment of staggered arrays. Direct georeferencing is accomplished with position and orientation of the camera given by inertial and GPS systems. The inertial measurement system senses angular rates and linear accelerations from which the orientation parameters of the camera – positions and angular orientations – are calculated. These are converted into Euler angles with respect to the body frame. The body co-ordinate system is rigidly connected with the camera. Their coordinate systems must be mutually aligned. Angular deviations are called boresight angles. Boresight angles cause scale errors of the observed positions and orientations, which are eliminated within the scope of a least squares adjustment procedure in a sensor model.

2. Calibration parameters.

Full sets of radial and tangential distortion parameters are difficult to address because they correlate with other. Therefore, the appropriate parameters must be selected based on analysis of their correlations and quality. It is important, that the treatment of the deformation parameters and the analysis of the correlations and accuracy are efficiently implemented to the software. Important parameters of in-flight calibration are

1. Boresight misalignment parameters
   The boresight parameters, $d\kappa$, $d\varphi$, $d\omega$, are the central parameters in the in-flight calibration.
2. Camera interior orientation parameters
   Focal length and principal point co-ordinates are the main interior orientation parameters. Stagger parameters between the odd and even detector arrays are also computed for both the cameras.
3. Flying direction dependent corrections
   These arise from position shifts in the given ephemeris and errors in time tagging.
4. Height parameter
5. Datum/Co-ordinate transformation

When we correct the orientations with the help of GCPs and then do the transformations between image space and ground space, datum/co-ordinate transformation effects will get nullified. But, these are very important in the case of direct geo-referencing. Co-ordinate system definitions for image, payload, body and orbit should be precisely known. Bursa Wolfe model (7 parameter) is used for datum transformation, which includes 3 rotations, 3 translations and 1 scale.

Correlation between the physical parameters of the camera and the boresight parameters is very significant. For example, focal length and $d\kappa$ are correlated. In the present approach, the principal distance correction is modelled as a yaw bias correction. Similarly, roll and pitch angles of the middle detector in the focal plane with respect to the payload cube normal are related to $d\varphi$ and $d\omega$. Effects of certain parameters cannot be measured explicitly. Instead, a resulting total effect will be measured and assigned only to the selected parameters. The significance of a certain parameter was evaluated by comparing the parameter value to its standard deviation and RMS; if the RMS value was larger, the parameter was considered as significant. Otherwise, that parameter is not considered and its effect is accounted through another significant parameter with which it has a correlation. So, the in-flight calibrated parameters may not facilitate the best characterization of the individual parameters of the camera, but it will provide the most accurate total pointing error. An important aspect of this assessment is to help decide which parameters of the geometry of the camera most probably needed adjustment.

3. Calibration methodology

At first, individual camera alignment calibration is done which is followed with inter-camera alignment calibration. Individual camera alignment calibration includes the determination of the attitude relation and shifts between the coordinate system of star sensors, body and the camera along with the interior orientation. The primary challenge in alignment calibration is the need to estimate the underlying alignment trend for each camera from a series of precision correction solutions, which measure a combination of orbit, attitude and alignment errors. Modelling error, that is the inability of the model to reconstruct the viewing geometry, also will reflect as an error at the checkpoints after precision correction. Therefore, using a correct mathematical model is very important for in-flight calibration. Including a DEM while handling errors from individual cameras is also important to eliminate terrain induced errors, especially in Fore camera. Few distributed GCPs and checkpoints are identified in the images. Initially, we assigned zero value to the payload alignment biases in the rotation matrix of the sensor model. Then, ground co-ordinates are computed for the checkpoints using the sensor model and the given GPS/INS (Inertial Navigation System) orientation parameters. Difference between the derived ground co-ordinates and the actual co-ordinates are analysed. The error vectors from many images showed the same trend. Now, the sensor orientation parameters are updated with the rigorous sensor model and GCPs. The difference in exterior orientation parameters before and after correction are computed for many data sets and compared. These biases will account for offsets between body frame and payload, small variations in the interior orientation of the sensor and focal plane geometry, alignment offsets between inertial frame and body frame and uncertainty in the given orbit and attitude parameters. We cannot really apportion each of them. But, the common bias (trend) from the images (of a sensor) should be taken out as the offset of the payload.

After obtaining the possible range of residual biases of each camera, errors from both cameras over the same area are compared. Fore camera alignment offsets are fine tuned in such way that errors are comparable with errors from Aft camera. Inter-camera alignment is done to ensure same relative location accuracy from both the cameras. The height correction is probably the most problematic unknown. Several causes result in need for the height correction; these include changes in the principal distance, yaw bias of the detector arrays in the focal plane and datum errors. To analyze and separate the camera dependent height corrections from the other mentioned sources, inaccuracy of images from Fore and Aft cameras should be evaluated independently with a DEM. The parallax errors will be in the along-track direction. Now, height errors are computed through intersection from stereo pair. The height errors are influenced with a change in effective focal length or yaw residual in the boresight misalignment of either one camera or both the cameras. Fixing of this will ensure the 3D pointing accuracy from the along-track stereo. Once the relative calibration is considered as reliable, remaining location errors are shared by both cameras and are due to the uncertainty in the given attitude.

3.1 Sensor Model

A generic sensor model for georeferencing of linear CCD array images has been developed at ADRIN. This model is very flexible and has been successfully used for the orientation of SPOT-1, IRS-1C/1D, TES, IRS-P6 IRS-P5 and Cartsat-2 (Radhadevi et al., 1994, Radhadevi et al.1998, Radhadevi, 1999, Radhadevi et al, 2008) The algorithm is purely based on the viewing geometry of the satellite, combining the principles of photogrammetric collinearity equations, originally developed for SPOT-1 and further adapted and tested for different sensor geometries.

Collinearity equations express the fundamental relationship that the perspective centre, image point and object point lies on a straight line i.e.

$$\begin{pmatrix} f \\ -x_s \\ -y_s \end{pmatrix} = d.\ \boldsymbol{M} \begin{pmatrix} X - X_p \\ Y - Y_p \\ Z - Z_p \end{pmatrix} \qquad (1)$$

where $(f, -x_s, -y_s)$ are the image coordinates, (X, Y, Z) are the coordinates of the object point and (X_p, Y_p, Z_p) are the co-ordinates of the perspective centre, d is the scale factor and M is the orthogonal rotation matrix to transform the geocentric to sensor co-ordinate system.

The rotation matrix $\boldsymbol{M} = \boldsymbol{Q}_{GI} * \boldsymbol{Q}_{IO} * \boldsymbol{Q}_{OB} * \boldsymbol{Q}_{BP} * \boldsymbol{Q}_{PC},$ where

$\boldsymbol{Q}_{PC}$ is CCD to payload transformation matrix that is a function of the roll and pitch bias angles of the middle detector with respect to the payload cube normal. This transformation will relate the individual detectors to the payload. Odd and even arrays are considered as two detectors and the stagger parameter is computed from the image Y-coordinate shift due to the separation of these arrays in the focal plane. The roll and pitch angles of the middle detector of each CCD are available in the payload geometry of the camera calibration data generated during the pre-launch calibration. Small changes in these parameters will reflect as tangential distortions, which are static in nature and can be attributed to the boresight alignment angles during in-flight calibration.

$\boldsymbol{Q}_{BP}$ is Payload to body transformation matrix. The basic scan model is a line-of-sight vector from the detector in the focal plane, through the payload, body and orbit to the ground point. This vector is orthogonal to the platform axes. Slight deviation from this orthogonality is the boresight misalignment angles, which are the main parameters in the in-flight calibration.

$\boldsymbol{Q_{OB}}$ is Body to Orbit matrix, which is a function of roll, pitch and yaw angles .The Euler angles with respect to body frame are not given explicitly. They are computed from the given quaternions. Over a long pass, the variation in the attitude angles will not be a bias and therefore, time-dependent coefficients are also computed. After keeping the boresight alignment angles as zeros, refinements to the coefficients of the computed attitude angles are done as corrections to the constant term and 1st order term using a few GCPs. The difference between the refined and original attitude angle gives the boresight alignment in that direction.

$\boldsymbol{Q_{IO}}$ is Orbit to Inertial transformation matrix. This rotation will convert the position of the pixel in the orbit co-ordinate system to ground co-ordinates. This matrix is a function of position and velocity of the satellite.

$\boldsymbol{Q_{GI}}$ is ECI to ECEF matrix, which is a function of the sidereal angle.

Through the rotation matrix, any pixel in any array of any camera can be projected on to ground and through inverse rotation matrix, this ground location can be re-projected on to any other array /camera by using the corresponding parameters in $\boldsymbol{Q_{PC}}$ and $\boldsymbol{Q_{BP}}$. The relative positions of individual arrays in the focal plane can be fixed through these transformations.

4. Results and Analysis

An extensive analysis with different datasets reveals the behaviour of each sensor. Many datasets, imaged over a period of two years, covering different types of terrain with different imaging configurations are studied. The limitation of this approach was especially with the identification of distributed GCPs. To analyse the trend, the boresight misalignment angles are incremented in a loop and substituted in the rotation matrix. The accuracy was evaluated in each iteration. This is done in the object space by calculating the ground coordinates of the checkpoints using the calibration parameters and direct orientation observations and comparing the calculated values to the measured values. GCPs were used as checkpoints. Figure 1 shows such patterns. This clearly shows the underlying trend of boresight alignment parameters. Each line represents a dataset. Errors are decreasing and then increasing at a particular value. It was observed that Roll bias of the Fore camera is within the range -0.08° to -0.06°. Similarly, the Roll bias of Aft camera was observed within the range +0.06° to +0.08°. Pitch bias of the Fore camera fall within 0.02° to 0.24° and Aft camera is within 0.185° to 0.21°. Yaw bias range observed for the Fore camera was within -0.15° to -0.12° and Aft camera was within -0.05° to +0.05°. Aft camera yaw bias shows a wider range for different datasets. As the magnitude of angles are small, this can be due to the uncertainties in body yaw steering within 52 sec time gap between imaging. The reason that Fore camera yaw bias does not show that big range also justifies that. Average of the minimum values shown by different datasets was calculated as boresight alignment angles. Relative latitude and longitude RMS errors (for various data sets) from Fore and Aft cameras are evaluated and they were also minimum with these alignment offsets. Incidentally, it was noticed that even though RMS errors from different datasets are within the limit, there is a small trend in height error in the across-track direction, the source of which was not clear initially. This behaviour was seen in almost all datasets. This can be either due a change in the effective focal length or due to a yaw bias left out. Finally it could be traced that it was arising from a wrong yaw bias given for Aft camera. As the range of yaw bias for Aft camera was within –0.05° to 0.005°, zero bias had given. The trend was computed from positional errors alone. When it was recomputed again with height errors, it was clear that the nominal Yaw bias of the Aft camera was around –0.04°. Figure 2 shows this behaviour over a data set before and after correction of yaw bias.

After incorporating the boresight alignment angles in the rotation matrices, bundle adjustment is performed once again. Refinement is done for constant and first order terms of attitude angles. Solving of six unknowns ($d\kappa_0$, $d\varphi_0$, $d\omega_0$ $d\kappa_1$,$d\varphi_1$, $d\omega_1$) is done with weight matrices included in the adjustment model. The general trend of the attitude variation is captured from the given INS data. Time dependency of these parameters also can be analysed. We include a co-factor matrix for observations and a weight matrix for parameter estimates into the system. The values of the co-factor matrix for the observations represent the uncertainty in the control point measurements. Similarly, the apriori weights of the parameters represent the uncertainty in the attitude information. Appropriate weights for the parameters define threshold limits (defined by the uncertainty of the attitude data) within which each individual parameter can vary. These weights impose constraints to the parameters. The solution is now iterated. Using the updated satellite parameters, the ground coordinates of the used GCPs are calculated in each iteration. If the differences between the calculated and original values are negligible, the iterations are terminated. The Yaw biases are given more weightage in the adjustment model to account for yaw steering uncertainties in the combined adjustment of Fore and Aft cameras. Figure 3 shows the residual uncertainties computed for different datasets over and above the biases incorporated in the sensor model. They are within +/- 0.02° for all the datasets and do not show any systematic behaviour. After the initial phase operations of the mission, which were completed within six months after the launch, the attitude pattern is very stable. Therefore, the residuals due to the attitude uncertainties of imaging conditions of different passes will be corrected only during the data products generation.

Figure 4 shows the system level RMS errors for different datasets after correcting the boresight alignment biases in the model. System level accuracy specifications of the mission was 250m. But, accuracy of the direct orientation observation could be brought down to 100m.with the inclusion of in-flight calibrated parameters in to the adjustment model. After the stabilization phase of the satellite, the errors are less than 60m in almost all the datasets. Correction of the orientation parameters with a single GCP (conjugate point) further improved it to 5m. We have accounted the effects of most of the in-flight calibration parameters of interior orientation through boresight misalignment angles. Computation of stagger parameter is one of the pre-processing requirements for video alignment. A study was done to analyse the behaviour of stagger with different imaging conditions. Figure 5 shows the stagger parameter computed from the geometry of imaging. The difference between odd and even detectors computed for Fore camera is around 5.5 pixels (vertical) and that of Aft camera is around 4.7 pixels (vertical). With a roll bias for the body, these values change up to 5.8 and 4.5 pixels respectively with extreme negative angles. These values are in good agreement with what is observed in the image data.

Conclusion

In this article, results of analysis of 32 strips of data taken over a period of two years are given. The most significant calibration parameters are boresight misalignment angles. The treatment of the deformation parameters and the analysis of the correlations and accuracy are efficiently implemented to the software. Absolute in-flight calibration of individual cameras as well as relative calibration between the cameras is performed to ensure the best possible relative and absolute location accuracies. The in-flight calibrated parameters may not facilitate the best characterization of the individual parameters of the camera, but it will provide the most accurate total pointing error. System level accuracy specifications of the mission was 250m. But, accuracy of the direct orientation observation could be brought down to 100m.with the inclusion of in-flight calibrated parameters in to the adjustment model. The imagery was collected over a period of two years and this demonstrates the stability of the calibration parameters. The calibration results are included in the Value Added Product generation System (VAPS) of Cartosat-1 for operational use with which the geo-rectification during standard processing is significantly simplified.

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