GEOMETRIC EVALUATION AND CALIBRATION OF X-SAT SATELLITE IMAGERY

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ABSTRACT: X-SAT, Singapore's first locally-built micro-satellite was successfully launched on 20 April 2011. This satellite carries a multispectral camera IRIS with three spectral bands (NIR/Red/Green) at 10m resolution. The data acquired were transmitted to CRISP ground station for post processing. CRISP was also involved in the development of the ground processing system as well as post flight geometric and radiometric calibration of the sensor. This paper presents the satellite camera model developed and the processes for geometric calibration and validation of the imagery. By design, the three lines of CCDS (NIR, Red and Green) are physically separated in the focal plane and their first pixels not absolutely aligned. In this exercise, we computed the band to band separations as well as alignment of the CCDs relative to each other. In addition, we also computed the focal length of camera. The results of the band to band along-track separation agree well with the pre-flight values provided by the vendor (0.093° and 0.046° for the NIR vs red and green vs red CCDs). The band cross-track alignments were 0.05 pixel and 5.9 pixel for the NIR vs red and green vs red CCDs. The focal length was found to be shorter by about 0.8%. This was attributed to the lower operating temperature which XSAT is currently operating.

1. Introduction

XSAT, a Singapore built Earth Observation microsatellite, weighing about 110kg, was placed in polar orbit on 20th April 2011, on PSLV-C16 into an 822km polar sun synchronous orbit (SSO). XSAT has completed its LEOP phase and has now begun its primary mission of earth observation. The main EO payload is the IRIS, a multispectral camera with green (520 nm – 600 nm), red (630 nm – 690 nm), and near-infrared (760 nm – 890 nm) wavelength range and designed as a push-broom scanner with three individual scan lines. The 3 individual scan lines are geometrically separated in the focal plane as shown in figure 1.

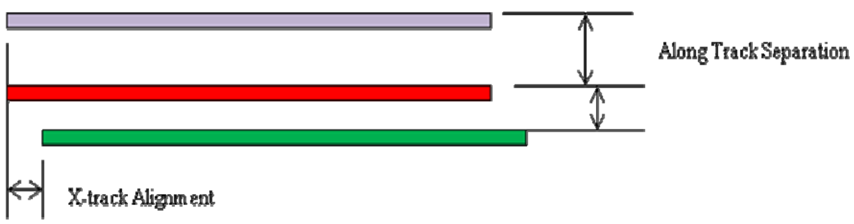

Figure 1 – Separation and Alignment of the CCDs on the Focal Plane

This paper presents the satellite camera model developed and the processes for calibration and validation of the imaging geometry.

2. IRIS Camera Model

Before geometric calibration can be carried, the IRIS camera model has to be developed. The camera model relates a line and pixel coordinates in the imagery to the corresponding latitude and longitude on the Earth's surface. The model currently implemented is a rigorous model similar to that implemented for SPOT satellites, which is described in the SPOT Satellite Geometric Handbook (SPOT Image, 2002). The XSAT is designed to provide GPS timing and locations of the satellite and star tracker attitudes quaternion as ancillary data. Unfortunately, due to a design error, the star tracker is not operable after launch, thus there is no a-priori attitude information for its imagery. The available pointing information is for slewing and pointing the satellite body and is not accurate enough for geometric computation. As a workaround, we use GCPs to compute the attitude knowledge of roll, pitch and yaw.

The IRIS being a push-broom scanner system has only one row of CCD per spectral band. The line number (j) of any band in the image is thus related to the CCD sampling time t_j as follows:

$$t_j = t_0 + (samp\_rate) \times j \tag{1}$$

The sampling rate of IRIS is (3.001/2040) s^{-1}. t_0 is the UTC time at line 0, or the start time of the image.

Assuming the separation of each pixel are linear and CCDs are parallel, the look vector for each pixel (i) for band (k) is given below:

$$\vec{u}_{ik} = \begin{bmatrix} -\tan\left(\dfrac{FOV}{2}(1+\Delta F)\right) \times (i + \Delta x_k - \dfrac{N}{2}) \\ \tan(\Delta\psi_k) \\ 1 \end{bmatrix} \tag{2}$$

Where $\Delta\psi_k$ is the along track separation of band k CCD from the red band CCD,
Δx_k is the cross-track alignment of band k CCD from the red band CCD and
ΔF is the scale change in FOV from the nominal FOV (pre-flight FOV is 4.21°).
N is the number of pixel elements in one image line (5066).

$\Delta\psi_k$, Δx_k and ΔF are the parameters we will determine.

From Vector $\vec{u}_{ik}$ is then normalized to give the unit vector:

$$\hat{u}_{ik} = \frac{\vec{u}_{ik}}{|\vec{u}_{ik}|} \tag{3}$$

The vector is then subjected to the satellite's roll, pitch and yaw. Its rotational matrix is denoted by $\mathbf{M}_{rpy}$ where r,p,y are the roll, pitch and yaw angles at time t_j corresponding to image line j, of any band. As the satellite platform travels in space, and due to some instability issue, the roll, pitch and yaw angles are not constant throughout the image. We choose to use polynomials to model these angles as follows:

$$\begin{aligned} r &= r_0 + \dot{r} \times t_j + \ddot{r} \times t_j^{\,2} + \dddot{r} \times t_j^{\,3} + \overline{r} \times t_j^{\,4} + \ldots \\ p &= p_0 + \dot{p} \times t_j + \ddot{p} \times t_j^{\,2} + \dddot{p} \times t_j^{\,3} + \overline{p} \times t_j^{\,4} + \ldots \\ y &= y_0 + \dot{y} \times t_j + \ddot{y} \times t_j^{\,2} + \ldots \end{aligned} \tag{4}$$

The look vector is then in the orbital coordinate system. It is then transformed into the Earth Centred Initial (ECI) coordinate system, followed by transformation to the Earth Centred, Earth Fixed (ECEF) coordinates system. The whole transformation is as follow:

$$\hat{u}_{ecef} = \mathbf{M}_{eci2ecef}\mathbf{M}_{orb}\mathbf{M}_{rpy}\hat{u}_{ik} \tag{5}$$

The $\mathbf{M}_{orb}$ =(X_{orb},Y_{orb},Z_{orb})is determined by cross multiplying the position and velocity vector at time t_j as follows:

$$\begin{aligned}\vec{Z}_{orb} &= \frac{\vec{S}(t_j)}{\left|\vec{S}(t_j)\right|} \\ \vec{X}_{orb} &= \frac{\vec{V}(t_j)\times\vec{Z}_{orb}}{\left|\vec{V}(t_j)\times\vec{Z}_{orb}\right|} \\ \vec{Y}_{orb} &= \vec{Z}_{orb}\times\vec{X}_{orb}\end{aligned} \tag{6}$$

Where $\vec{S}(t_j)$ is the instantaneous position of the camera at line *j*, which is conveniently taken to be the centre of mass of the satellite and $\vec{V}(t_j)$ is the instantaneous velocity of the satellite. $\vec{S}(t_j)$ and $\vec{V}(t_j)$ may be obtained by interpolating the position coordinates and velocity provided by the on-board GPS receiver, but for the current implementation, we computed them from the TLE, as we have not fully verified the values provided by the on-board GPS receiver.

The transformation $\mathbf{M}_{eci2ecef}$ is obtained from the angular rotation speed of the earth and the instantaneous angle between the ECI and ECEF reference frame. We use the routines in the SGP4 Library (Kelso, 2000) to compute for this transformation.

The geocentric (*X*,*Y*,*Z*) coordinates of the corresponding point on earth $\vec{P}$, is obtained by projecting a vector from the instantaneous position of the satellite $\vec{S}(t_j)$, along the look vector in the ECEF frame until it intersect the earth surface, as shown in figure 2.

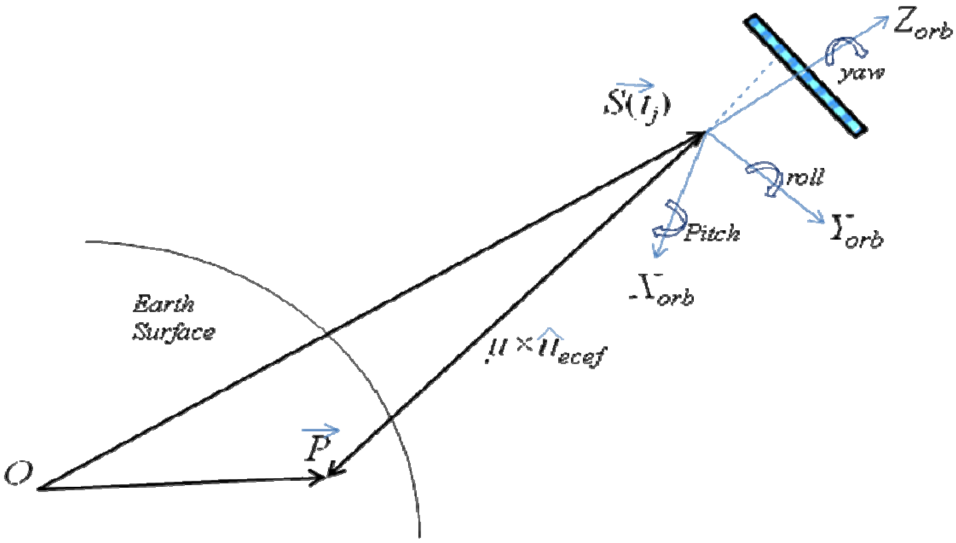

Figure 2 -- Imaging Geometry and intersection of look vector with earth surface

This is computed by solving the following vector equations:

$$\vec{P} = \vec{S}(t_j) + \mu \times \hat{u}_{ecef} \Rightarrow \begin{cases} X = X_S + \mu \times \left(\hat{u}_{ecef}\right)_X \\ Y = Y_S + \mu \times \left(\hat{u}_{ecef}\right)_Y \\ Z = Z_S + \mu \times \left(\hat{u}_{ecef}\right)_Z \end{cases} \tag{7}$$

Where $(X_S,Y_S,Z_S) = \vec{S}(t_j)$ is the instantaneous position of the camera. μ is a scalar multiplier. Since *P* is on the earth surface, its coordinates must satisfy the equations for the earth ellipsoid as follows:

$$\frac{X^2+Y^2}{A^2}+\frac{Z^2}{B^2}=1 \tag{8}$$

Where A and B are the semi-major and semi-minor axis of the earth ellipsoid. Substituting equation (7) into (8) and rearranging the equations give us a quadratic in μ.

$$\left[\frac{(\hat{u}_{ecef})_X^2+(\hat{u}_{ecef})_Y^2}{A^2}+\frac{(\hat{u}_{ecef})_Z^2}{B^2}\right]\mu^2+2\left[\frac{X_S(\hat{u}_{ecef})_X+Y_S(\hat{u}_{ecef})_Y}{A^2}+\frac{Z_S(\hat{u}_{ecef})_Z}{B^2}\right]\mu+\left[\frac{X_S^2+Y_S^2}{A^2}+\frac{Z_S^2}{B^2}\right]=1 \tag{9}$$

Solving the quadratic in (9), give us either no solution, in which case the satellite is not looking at the earth, or 2 values of μ. The smaller will be chosen and is substituted back into the equation (7) above to give the geocentric (X,Y,Z) coordinates.

The geocentric (X,Y,Z) coordinates are then converted to the geographic latitude, longitude and height (φ,λ,h) coordinates in the usual way.

3. Solution of Camera Model

In the current implementation, the red band is taken to be the reference band. The imaging parameters of the red band were solve by least squares solution from a number GCPs with pixel, line (i,j) co-ordinates from the image and latitude, longitude (φ,λ) from GoogleEarth. From experimentation, we found that 4th order polynomials for pitch and roll and 2nd order polynomials for yaw worked best so far. The ΔFOV was also solved in the process. The total number of unknown parameters to be solved were thus (5+5+3+1) = 14. For the red band, the along track separation $\Delta\psi_k$ and cross track alignment Δx_k were zero (being the reference band).

For the along-track separation $\Delta\psi_k$ and cross track alignment Δx_k for the NIR and green bands, a set of tie-points with image coordinates in NIR and red bands, and another set of tie points with image coordinates in green and red bands were measured for the image used for calibration. Since each line number, regardless of band, represents the same instant in time, the camera model computed with the red band will be applicable for the NIR and green excepts that the $\Delta\psi_k$ and Δx_k were now not zero, but to be computed from the tie-points.

4. Preliminary results

The computations were applied to 23 XSAT IRIS images acquired on 25 May, 31 May, 2 June, 3 June, 6 June and 27 June 2011. Table below shows the summary of the preliminary calibration values:

	Pre-Flight (from vendor)	In-Flight	Std Dev
NIR vs Red Along Track Sep	0.092086°	0.092773°	0.00082°
Grn vs Red Along Track Sep	0.046049°	-0.045974°	0.00033°
NIR vs Red X-track Alignment		-0.05302 pix	0.90591 pix
Grn vs Red X-track Alignment		-5.92516 pix	0.35291 pix
FOV	4.21°	4.24318°	0.00857°

From the table, the average measured FOV was 4.243° (pre-flight measurement is 4.21°), indicating a possible shortening of effective focal from 896mm to 889mm. This shortening could be due to the lower operating temperature of the camera.

The along-track angular separation of 0.092773° and 0.045974° compare well with the pre-launch figures of 0.092086° and 0.046049° given in the IRIS operational handbook.

The cross-track alignments were not given in the IRIS operational handbook, but were measured to be 0.05 pixels between the NIR and Red bands and 5.9 pixels between the Green and Red bands. The standard deviation of the cross-track alignment at 0.9 pixels and 0.35 pixels were higher than expected. This could be due to satellite attitude variations not sufficiently modeled by the polynomials for roll, pitch and yaw angles. Further investigations will be carried out.

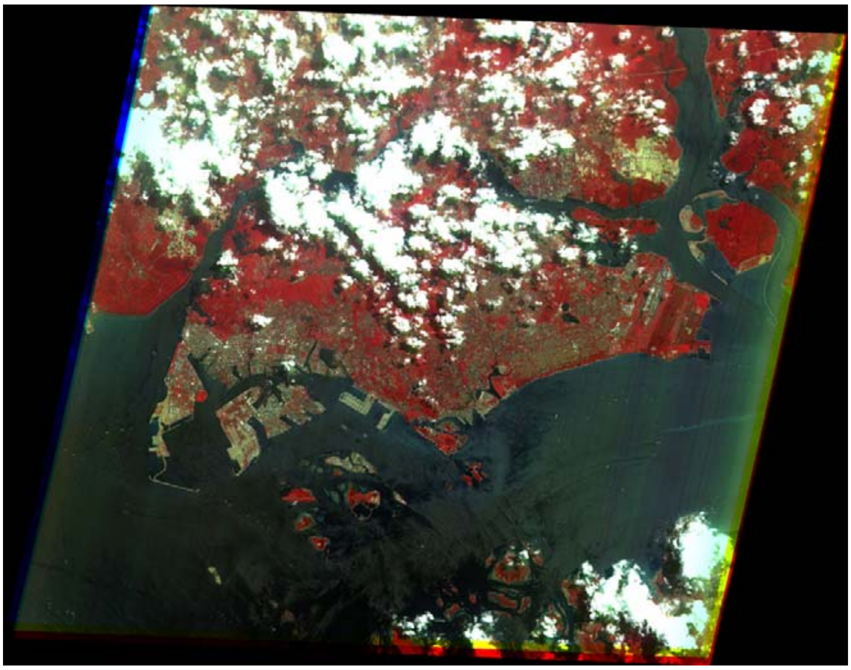

Figure 3 -- Orthorectified XSAT IRIS Imagery of Singapore, image taken on 11 May 2011

5. Conclusion and Future Work

XSAT has started its main work of earth observation and CRISP will monitor the performance of the IRIS payload over time. The current camera model will be revisited to improve the camera model and precision of the parameters. Periodic calibration and validation exercise will also be carried to study any changes over time. The current camera model had been used to generate orthorectified multispectral images for subsequent applications.

6. References

1. SPOT Image, 2002, SPOT Satellite Geometric Handbook (S-NT-73-12-SI)

2. T.S. Kelso, 2000, SGP4 Pascal Library Version 2.65 (http://celestrak.com/software/satellite/sgp4-plb26a.zip)