

IN-FLIGHT GEOMETRIC CALIBRATION - AN EXPERIENCE WITH CARTOSAT-1 AND CARTOSAT-2

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ABSTRACT:

The Cartosat-1 satellite was launched in May 2005 followed by Cartosat-2 in January 2007. Cartosat-1 is a stereo mission having twin cameras or two imaging sensors (Fore and Aft) with 2.5m resolutions while Cartosat-2 is a high-resolution satellite having single imaging sensor. The two cameras of Cartosat-1 provide systematic stereo coverage of the globe for mapping applications while Cartosat-2 has capability to provide scene specific spot imageries in paint-brush or spot or multi-view modes for city/urban application needs. Both mapping and urban applications demand accuracy of data products to be within a few meters. One of the important activities during post-launch period of mission qualification stage is to assess the mission performance in terms of geometric quality and improve further using in-flight calibration exercises. The geometric quality or accuracy of data products is determined by the knowledge of precise imaging geometry, as well as the capability of the imaging model to use this information. The precise imaging geometry in its turn is established by the precise knowledge of (i) orbit, (ii) attitude, (iii) precise camera alignments with respect to the spacecraft and (iv) camera geometry. The imaging geometry is derived from measurements carried out on the spacecraft during the qualification stage. However it was found that (by experience from IRS series) there is a need to re-establish the imaging geometry from image data itself. Cartosat Data Products team had conducted study and specific exercises related to in-flight calibration of Cartosat-1 and Cartosat-2 imaging geometry model during initial period of three months. The data used for the in-flight calibration are a few ground control points and images for different cameras/strips for relative control point identification in the overlap area. This experiment called for estimation of image coordinates for the known ground coordinates of GCPs using photogrammetric collinearity condition based imaging model to compare with observed image positions of those points. Scan differences and pixel differences were used to statistically derive platform biases, focal length, camera alignment angles etc. On the other hand, presence of multiple imaging payloads (Cartosat-1) or multi-viewing of strips (Cartosat-2) and other sensors for measuring spacecraft orientation provide additional advantages, strengthening in-flight calibration exercises to make use of only imaging sensors as attitude sensors to derive pseudo parameters without resorting to any controls. The derived alignment angles and re-estimated camera parameters were incorporated in the software used for geometric correction of data products. Significant improvements in the location accuracy and internal distortion of Cartosat data products have been achieved after incorporating various geometry parameters determined from the imagery. Similar exercises were carried out for Cartosat-2 during January 2007 to April 2007. Experience of working with Cartosat-1 has helped in quickly developing imaging model for Cartosat-2. Different formulations and multiple observations are used for unambiguous resolution of disparity between predicted and observed image positions to derive platform biases. This paper describes the methodology and experimental details of exercises carried out during the initial phase of Cartosat-1 operations by which the imaging geometry for Cartosat-1 cameras was re-established. Also, details on the development of new approach using stereo imaging sensors with minimum or no control for Cartosat-1 are addressed. Results obtained for Cartosat-2 using in-flight calibration experiments are also covered in this paper.

1. INTRODUCTION

The Cartosat-1 satellite was launched on May 05, 2005 followed by Cartosat-2 in January 10, 2007. Cartosat-1 is a stereo mission having twin cameras (Fore and Aft) with 2.5m resolutions while Cartosat-2 is a high-resolution satellite having single imaging sensor with ground resolution of around 1m. The two cameras of Cartosat-1 provide systematic stereo coverage of the globe for mapping applications while Cartosat-2 has capability to provide scene specific spot imageries in paint-brush or spot or multi-view modes using step-stare mode of imaging, for city/urban application needs. Both mapping and urban applications demand geometric accuracy of data products to be within a few meters. The geometric quality or accuracy of data products is determined by the knowledge of precise

imaging geometry, as well as the capability of the imaging model to use this information. The precise imaging geometry in turn is established by the knowledge of (i) orbit, (ii) attitude, (iii) precise camera alignments with respect to the spacecraft and (iv) camera geometry. The system level accuracy specifications for both Cartosat-1 and Cartosat-2 are around 200m. For cartographic and urban applications, the above quoted accuracy is not adequate, which needs to be improved with or without control points. One of the important activities during post-launch period of Cartosat missions' qualification stage was to assess the mission performance in terms of geometric quality and improve further by using in-flight calibration (Srivastava et al. 1997) exercises.

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The Data Products(DP) team at Space Applications Centre, Ahmedabad has established operationalisation of DP s/w and Stereo Strip Triangulation(SST) s/w at ground processing facility in India. While DP s/w caters to generation of good quality orthokit, ortho products to national/global users (Nanda Kumar et al. 2005), SST s/w is meant for generation and archival of strip Digital Elevation Model(DEM) and Triangulated Control Points(TCPs) from stereo strips of Cartosat-1 for generating highly accurate data products. Using the above two s/w along with additional utilities, Cartosat DP team had conducted study and specific exercises related to in-flight calibration of Cartosat-1 and Cartosat-2 for modelling imaging geometry during initial phase of operations to assess and qualify the mission performance. This becomes essential and important activity for any remote sensing mission before declaring it operational for normal use. Significant improvements in the location accuracy and internal distortion of Cartosat data products have been achieved after incorporating various interior and exterior orientation parameters determined from the imagery. Similar exercises were carried out for Cartosat-2 during January 2007 to April 2007.

This paper describes the methodology and experimental details of in-orbit exercises carried out during the initial phase of operations by which the imaging geometry of both Cartosat-1 and Cartosat-2 cameras was re-established. Also, details on the development of new approach using stereo imaging sensors with minimum or no control for Cartosat-1 are addressed. Results and discussions on in-flight geometric calibration experiences for Cartosat-1 and Cartosat-2 are presented in this paper.

2. IN-FLIGHT CALIBRATION

One of the important activities during post-launch period of mission qualification stage is to assess the mission performance in terms of geometric quality and improve further using in-flight calibration exercises. As mentioned earlier, the geometric accuracy of data products for Cartosat-1 and Cartosat-2 is determined by the knowledge of precise imaging geometry as well as the capability of the imaging model to use this information. Though the system level knowledge of various parameters contributing to the imaging geometry (e.g. alignment angles between spacecraft cube normal to payload, star sensor to payload, inter sensor alignment angles, orbit, attitude, rate parameters) are used in the geometric correction process with an a-priori knowledge, all in-flight parameters (both camera and platform) are well characterized and re-established with the real data from the respective sensors after the launch.

In-flight calibration is required (i) to achieve the specified system level accuracy of the data products consistently through out the mission life (ii) to obtain the precise relation between the data products of various sensors, so that data fusion/merging of these data sets becomes more easier for further applications, (iii) for better mosaicking of data between the scenes/strips, (iv) for generating precise DEMs (Cartosat-1 stereo pairs), (v) for generation of precision products and (vi) for understanding and improving the system performance and (vi) for validating various payload and mission parameters. In-flight calibration exercises is being carried out periodically for the Cartosat-1 and Cartosat-2 missions to ensure the consistency of the data product's accuracy.

2.1 Approach for in-flight calibration

The imaging geometry for both Cartosat-1 and Cartosat-2 are derived and characterised from measurements carried out during spacecraft integration, pre-launch qualification stage and on ground payload calibration. Changes happen due to environment, injection impact, temperature etc and re-establishing the imaging geometry from image data itself is resorted to using in-flight geometric calibration exercises. The approach involves development of image-to-ground and ground-to- image transformations for the sensor under consideration in the presence of known system parameters (ancillary data, alignment angles, focal length etc.) and re-estimating some or all of these parameters with the actual image data and some control points. Usually, the adjustment is carried out using photogrammetric collinearity model for image-ground or ground to image transformations for deriving a set of platform biases or more rigorously by using resection approach or bundle adjustment for estimating interior(camera) parameters and exterior(platform) parameters.

The in-flight geometrical calibration is based on measurements (observed image positions) on images from different cameras/strips and a few ground control points(GCPs) or triangulated control points(TCPs) whose ground positions are precisely known. In general, a comparison is made between observed scan, pixel positions against estimated positions for all GCPs or TCPs. The differences observed in image positions are used to statistically derive various biases and alignment parameters. A major problem is the unambiguous resolution of disparity between predicted and observed image positions. Also, the set of parameters (like alignment angles, Attitude biases, focal length etc.) which are kept floating for adjustment are highly correlated calling for judicious discretion for removing inconsistencies. The success of the adjustment method is decided by the location accuracy, the scale variation and various camera/inter camera-mounting angles and further confirmed with the help of post-adjustment techniques through multiple observations.

Here, scan against scan differences and scan against pixel differences are used for deriving pitch & roll biases while pixel against pixel differences and pixel against scan differences provide estimation of focal length and yaw component respectively.

2.2 Photogrammetric model

Cartosat-1 and Cartosat-2 imaging geometry or sensor orientation is well represented by the conventional photogrammetric model. Data products s/w uses the principle of photogrammetric collinearity condition in image to ground model and in ground to image mapping through a series of coordinate transformations.

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = s M \begin{pmatrix} X_A - X_S \\ Y_A - Y_S \\ Z_A - Z_S \end{pmatrix} \dots\dots\dots(1)$$

where (x,y,z) are image coordinates of a image point in the focal plane, s is scale factor, M is the transformation matrix between object and image space, (X_A,Y_A,Z_A) are geocentric coordinates of a ground point and (X_S,Y_S,Z_S) are geocentric coordinates of the perspective center.

$$M = (R_P) \cdot (R_M) \cdot (R_A) \cdot (R_O), \text{ ----- (2)}$$

where 'R_O' is orbit rotation matrix, 'R_A' is attitude rotation matrix, 'R_M' for spacecraft master reference to payload cube and 'R_P' payload cube to optical axis of the sensor(device).

The above relation is used by both DP s/w and SST s/w for Cartosat-1 and Cartosat-2 data products generation and this forms the major mathematical model for adjustment of interior and exterior parameters for Cartosat-1 and Cartosat-2. Details of the in-flight geometric calibration exercises carried for Cartosat-1 and Cartosat-2 are briefly discussed in the following sections.

3. EXPERIMENTS WITH CARTOSAT-1

One of the tasks taken up during post-launch scenario as part of initial phase activities is to monitor the overall system performance and assess the geometric quality of Cartosat-1 data products. Initial evaluation carried out by Data Quality Evaluation (DQE) team on Cartosat-1 data products confirmed that location accuracy of the data products was high and large systematic differences in errors between Fore and Aft cameras in both scan and pixel directions (both mean and standard deviation) were observed. Relative scale error was also found to be high apart from Fore Camera results showing yaw effect. In fact, the location accuracy was poorer for Fore data set than Aft because of large view angle (26 deg.). The outputs of Stereo Strip Triangulation(SST) s/w in the form of GCPs' residuals before and after adjustment from both cameras, for various dates on full pass basis, strengthened the analysis.

Reference for the geometric in-flight calibration is the test bed areas, where a large number of GCPs are available with high accuracy. These data points (test bed GCPs) were used to derive alignment angles and re-estimate camera parameters from the initial values. Significant improvements in the location accuracy and internal distortion of Cartosat data products have been achieved after incorporating various in-flight parameters estimated from Cartosat-1 imagery. However, the final accuracy of the re-estimated parameters using in-flight calibration procedures depend on the (i) accuracy of the reference data, (ii) the models used for the characterisation of the parameters and (iii) knowledge on the various input parameters. Major activities carried out as part of in-flight geometric calibration are described below.

3.1 Correct usage of payload parameters

DP and SSTS s/w use photogrammetric collinearity condition model to establish a precise relation between image and ground for products generation and DEM generation respectively. It was found that the values being used during initial operations required changes to meet the performance demands of mission. Analysis of location errors evaluated using a large number of GCP points for image products generated and SSTS results over test bed areas indicated that in both Fore and Aft cases pixel differences versus pixel number was very high and this was attributed to using payload cube axis as optical axis instead of optical axis as reference in the Cartosat-1 camera model. Incorporation of correction for this - a two level transformation from spacecraft master reference(MRC) to payload cube (PLC) and then PLC to camera optical axis, brought down the error

substantially leading to improvement of standard deviation at both pre(system) and post resection results of SSTS.

3.2 Estimation of platform biases

As mentioned earlier, location accuracy of data products were found to be of the order of 500m and 100m for Aft camera and 700m and 400m for Fore camera in along and across directions respectively. Analysis of outputs of SSTS s/w with optimum GCP configurations over a segment for 8 data sets confirmed the presence of large errors at model as well as check points. Residuals at each GCP and thus mean, standard deviation and root mean square(RMS) were calculated at pre-resection level for both along and across track directions. The evaluation of Hyderabad (08th June '05) and Bangalore (28th May '05) test bed data sets for which a substantial number of accurate GCPs were available, indicated that there is common bias angle in pitch and yaw directions, which if incorporated would bring down the location errors observed in the data products. The angles estimated were about 0.04 degree in pitch and -0.06 degree in yaw as platform attitude angles by using scan differences and pixel differences against time. **Figure 1.0** gives a typical example for Fore camera for bias estimation. By incorporating 0.04 degrees in pitch and -0.06 degrees in yaw as the angle between star sensor and MRC, the location errors in image products were brought down.

3.3 Estimation of Camera bias angle

Further analysis of location error data (scan line error as a function of pixel number) after incorporation of above biases indicated that for Fore camera there is a yaw angle of about -0.146 degrees. While Aft showed that the yaw estimated was within measurement errors. This yaw angle was incorporated in the payload model for Fore camera (**Figure 2.0**). Upon using -0.146 deg yaw value between payload cube normal and optical axis of Fore camera, *standard deviation at system level has improved*. A comparative results at system level with and without biases is given in **Table 1**.

3.4 Adjustment of focal length

Accuracy inconsistencies between Fore & Aft seen in individual SST segments over test bed areas at pre-resection level (system level) even after accounting for all biases, prompted further scrutiny of systematic errors. By using error values and analyzing them as *delta pixel* as a function of *pixel number* and *delta scan* as a function of *pixel number*, one could obtain the corrections in focal length and residual yaw for Fore and Aft cameras. This exercise and analysis indicated that focal length numbers used for both Fore and Aft needed correction factor of 1.0072 and 1.00024 respectively. With adjusted focal length, scale variation came down from eight to maximum three pixels for 12000-detector array of Fore camera (**Figure 3**). For Aft camera, the effect was very negligible.

3.5 Re-estimation of platform biases

Though all the above exercises resulted in meeting the Cartosat-1 overall system level accuracy, recent evaluation of products confirm that there is still some residual error of around 150m common to both Fore and Aft being observed in along track direction and relative error of 100m between Fore and Aft in across direction. Sensitivity analysis carried

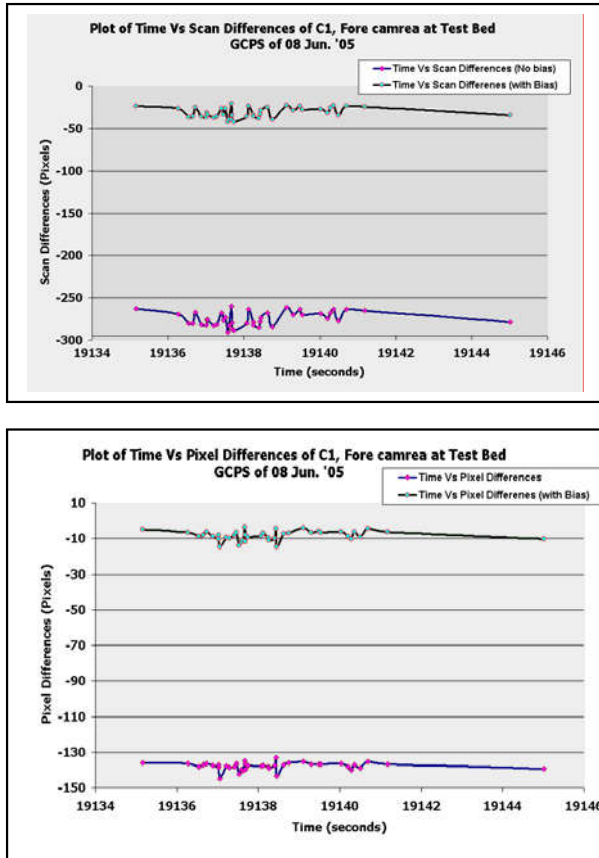


Figure 1.0 Bias estimation from FORE camera

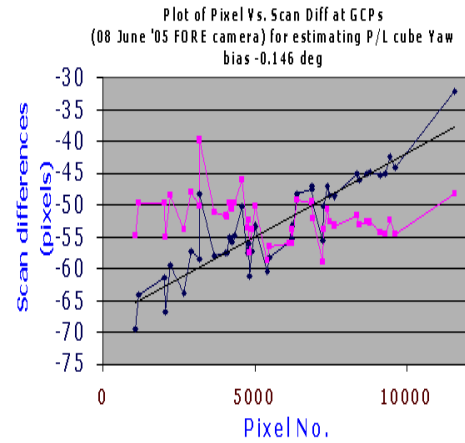


Figure 2.0 Fore camera bias estimation

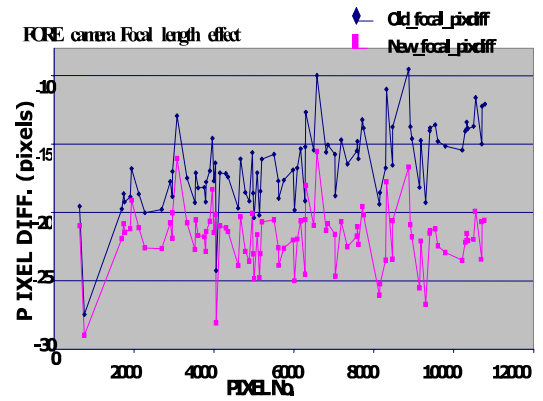


Figure 3.0 Focal length adjustment for

DATE OF PASS	AFT		FORE		No. GCPs
	SCAN RMS (pixels)	PIXEL RMS (pixels)	SCAN RMS (pixels)	PIXEL RMS (pixels)	
Below: Before using biases					
19May 05	178.41	43.27	158.82	173.02	8
28May 05	218.71	21.49	291.24	129.86	38
04 Jun 05	170.79	85.72	232.78	180.79	18
08 Jun 05	207.02	15.66	299.71	165.02	49
21 Jun 05	186.28	15.3	239.43	134.81	7
Below: After using all estimated and accounted biases					
30 Aug.05	31.28	25.12	43.45	25.36	12
05 Sep.05	25.39	18.99	43.36	19.05	10
03 Oct.05	34.45	22.69	50.66	7.92	10
14 Oct.05	37.14	26.66	50.30	13.64	17
17 Oct.05	16.57	27.76	32.31	14.47	8
01 Mar.06	38.10	18.26	53.66	21.93	21

Table 1.0 Cartosat-1 system level accuracy

out confirmed that a residual yaw of about 0.02 degrees could bring down the across track error for Fore. Further exercises and fine-tuning of residual biases are under progress.

3.6 Development of new techniques

A new development in in-flight calibration was resorted to exploit the capability of stereo sensors of Cartosat-1. Photogrammetric *coplanarity condition* (Mikhail et al. 2001) is used treating only two imaging sensors (stereo imaging in the same orbit) as attitude sensor to derive pseudo attitude parameters with minimum or no controls. This has given some promising results. Also, *line based resection* approach (Tommaselli et al. 1996) was developed and tested with Cartosat-1 to derive platform parameters making use of only image points as observations in the presence of other ancillary data. Absolute accuracy could be achieved with the help of a few controls. Preliminary results from these exercises are shown for comparison purpose in **Table 2.0**.

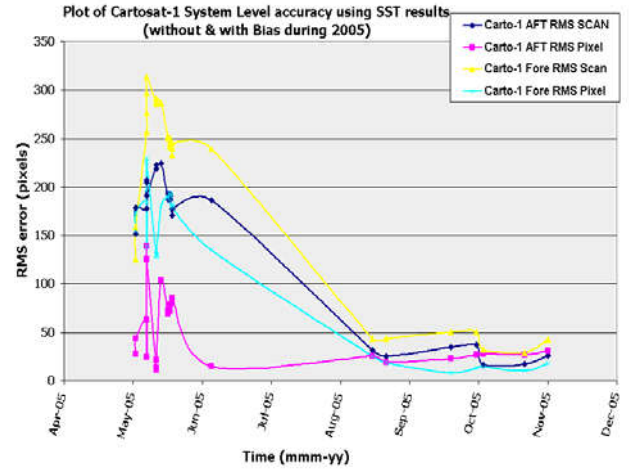


Figure 4.0 SST results showing improvement

Date Of Pass	Camera	Pre resection at system level (pixels)		Coplanarity Model (pixels)		Line Based Approach (pixels)	
		RMS Scan	RMS Pixel	No control used		Two control points used	
				RMS Scan	RMS Pixel	RMS Scan	RMS Pixel
08 Jun. '05	F	29.86	5.84	6.58	7.74	6.67	2.27
	A	12.69	3.21	2.87	4.31	2.47	1.81
04 Nov. '05	F	29.13	10.39	4.28	10.58	9.35	1.32
	A	17.2	26.77	1.08	25.43	3.46	1.02

Table 2.0 Cartosat-1 results with different imaging models

3.7 Results and discussions

As described above, in-flight geometric calibration exercises has helped in re-estimation of some of the payload and platform parameters for use in Cartosat-1 DP s/w and SST s/w. The experiments conducted with SST s/w at various test bed regions using very precise GCPs establish that pre-resection results are within system level accuracy of 200m and post-resection show model performance of SST better than 25m (Srinivasan et al. 2006). It is seen from SST results that large error occurring during earlier dates have come down considerably after accounting for various biases (**Figure 4.0**). Proper usage of payload alignment parameter, estimation of platform biases and adjustment of focal length for Cartosat-1 had resulted in improvement of system level accuracy and standard deviation of data products thus meeting the Cartosat-1 mission specifications.

4. EXPERIMENTS WITH CARTOSAT-2

As part of initial phase operations, in-flight geometric calibration exercises were taken up for Cartosat-2 to re-establish the imaging geometry especially for step-stare

viewing in order to improve the system level accuracy and deliver high-precision cartographic quality products. Various Cartosat-2 data sets along with a large number of test bed GCPs and TCPs from Cartosat-1 were used to re-estimate pseudo platform parameters. Report on the in-orbit geometric calibration exercises is given in the following subsection.

4.1 Estimation of platform biases

One of the activities identified as part of Cartosat-2 Post-launch Initial Phase Activities is the estimation of payload alignments with respect star sensor-1(SS1) & star sensor-2(SS2). This activity demands precise identification of GCPs or TCPs in Cartosat-2 images. Using DP s/w utilities and precise imaging model, which in turn uses Cartosat-2 orbit, attitude and other payload, mission alignment parameters, image coordinates are estimated for the known ground coordinates of GCPs or TCPs. Then, a comparison was made between observed scan, pixel positions against estimated positions for all GCPs or TCPs. The differences observed in image positions are used to statistically derive various bias and alignment parameters as was done for Cartosat-1.

4.2 Results and discussions

It was observed that system level accuracy of Cartosat-2 data products during initial days were of the order of **1.3 km** in along (scan) and around **1.1km** in across (pixel) directions. All calculations carried out for this exercise was based on start sensor-1 knowledge. GCPs and/or TCPs were identified over various scenes from different test bed areas to assess the system level accuracy of the Cartosat-2 mission at model and product level. The overall initial system level accuracy at model points, taken up for analysis is given in **Table 3**. The data sets used include 1m as well as 2.5m cases. Cartosat-1 in-flight experiences were used for Cartosat-2 to derive the platform biases. As seen from the **Table 3**, it is observed that there is a consistency among various data sets in terms of along track and across track errors i.e around 1600 pixels and 1300

pixel respectively. On further analysis using pixel versus scan difference comparison, it was found that there was no substantial yaw effect. This has prompted to arrive at a roll bias of 0.096 deg approximately and 0.119 deg in pitch bias in attitude angles. After incorporation of these values, estimation showed significant improvement in both directions and was put to use for product generation. **Table 4** shows the improvement in mean error after accounting for biases. Additional refinement to biases was estimated subsequently as 0.083 deg for roll and 0.110 deg for pitch. DQE evaluated a number of products and the results show significant improvement (**Figure 5.0**) in the location accuracy of products and was better than 100m in most of the cases, thus meeting the mission specifications.

Cases	Mean Scan Error (pixels)	Mean Pixel Error (pixels)	No Of GCPS / TCPs
Case 1	1791.57	1332.42	114 (1m) ^θ
Case 2	1307.47	1400.58	11 (2.5m)
Case 3	1307.08	1385.25	10 (2.5m)
Case 4	1636.05	1303.42	11 (1m)
Case 5	1637.68	1305.28	39 (1m)
Case 6	1632.26	1309.70	10 (1m)
Case 7	1630.74	1313.36	15 (1m)
Case 8	1553.87	1326.17	15 (1m)
Case 9	1569.47	1322.35	13 (1m)

^θ - values in () indicate different input imaging resolutions

Table 3.0 Cartosat-2 initial system level accuracy

Cases	Mean Scan Error (pixels)	Mean Pixel Error (pixels)
Case 1	2.91	34.58
Case 2	3.84	31.66
Case 3	34.96	12.72
Case 4	28.56	16.67
Case 5	11.62	30.50
Case 6	16.79	23.29

Table 4.0 Cartosat-2 improved system accuracy

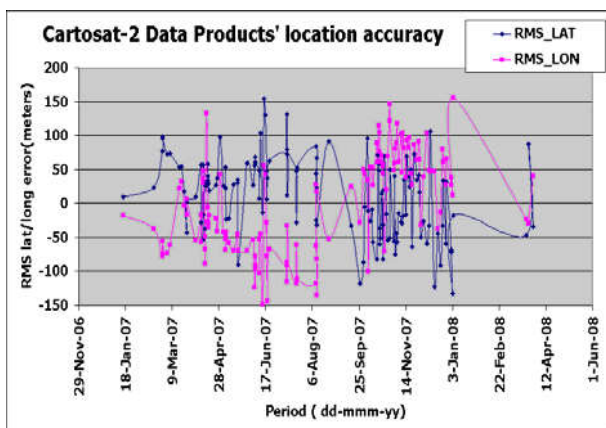


Figure 5.0 Cartosat-2 Data Products accuracy

5. CONCLUSIONS

One of the important activities undertaken during post-launch period for Cartosat-1 and Cartosat-2 was in-flight geometric calibration. Being a stereo mission, Cartosat-1 offered many an opportunity to understand various parameters and estimate them correctly through in-orbit calibration activities to improve the overall system performance. SST is one of the unique software identified for operational generation of DEM and TCPs for Indian region from Cartosat-1 stereo pair, whose abundant results strengthened the in-flight analysis work. It has been demonstrated that system level accuracy could be improved to meet the accuracy demands of various mapping applications with the help of in-flight exercises. Similar exercises were carried out for Cartosat-2 to improve the data products accuracy. This paper has briefly covered some of the in-flight geometric calibration experiences with Cartosat-1 and Cartosat-2 missions.

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