THE ISO POINTING PERFORMANCE

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ABSTRACT

The standard ISO observing mode was a 3–axis stabilised pointing at a selected astronomical target, allowing observations for a period up to several hours. The ISO pointing performance was found to be better than expected at the time of satellite commissioning. It appeared during the first months of the mission that further improvement was possible, which would benefit those scientific instruments using smaller apertures, in particular the SWS. Thanks to the good collaboration of motivated spacecraft and operation teams, co-located at the Ground Station, a new method for minimisation of residual errors was developed and successfully applied after a year of operations. Subsequent improvements in the pointing system were achieved also after the mission and applied in the Offline Processing Pipeline, reaching an absolute pointing error of $\approx$1.4″, which is almost an order of magnitude better than the specifications.

Key words: ISO – Pointing

1. INTRODUCTION

ESA's Infrared Space Observatory, ISO, was launched on November 17th, 1995. After three days of Launch and Early Orbit Phase operations, control of the satellite was moved to Villafranca in Spain, where a 2.5 week spacecraft commissioning was performed. During this phase, the alignments between the Attitude and Orbit Control System (AOCS) and the scientific instruments were calibrated and found to be better than expectations (see Table 2). Following a 3 months performance evaluation phase, full scientific operation of the satellite was commenced. Still, one scientific instrument (SWS) sought possibilities for improvements in the pointing accuracy. The in-orbit calibration of the SWS had shown very steep beam profiles (Beintema et al., 2003), and a better pointing would certainly improve the photometric accuracy of the instrument and other related calibrations. A series of calibration experiments by the SWS Instrument Dedicated Team (SIDT) showed that residual systematic errors were present in the pointing. This triggered a dedicated analysis by the Spacecraft Control Centre Team, leading to an enhanced algorithm for alignment estimate and other actions. The pointing was improved after about a year of operations, and the algorithm was used in the Offline Processing (OLP) pipeline to reconstruct the pointing of all ISO observations, together with other refinements after the mission. This paper gives an overview of the ISO AOCS (Section 2) and its initial calibration strategy (Section 3), the experiments unveiling the residual pointing errors, and the measures adopted to improve the pointing (Section 4). Finally, the final pointing accuracy as given by the OLP is discussed in Section 5. For a more detailed description of the AOCS, its in-orbit calibration and the enhanced algorithm for alignment estimate, see Batten and Stephenson, 1998.

2. THE AOCS SYSTEM

The main elements of the AOCS are shown in Figure 1, which also shows the ISO Spacecraft axes.

The Quadrant Star Sensor (QSS) was aligned with the ISO telescope optical axis. The boresight of the QSS defined the x–axis of the ISO body coordinate system. The z–axis was defined by the Fine Sun Sensor (FSS), which provided control about the x–axis during pointings and about the x and y axis during slews. The Star Tracker (STR), located outside the cryostat, provided two axis control about the y and z axis during pointings by the tracking of a single guide star. Slews were controlled by gyroscopes.

The ISO attitude was constrained to limit heat input to the cryostat and straylight into the telescope. The Sun constraint was that the line of sight of the +x–axis must be within $90^\circ \pm 30^\circ$ of the Sun direction and the Sun vector must not be rotated by more than 5° around the x–axis from the +z half–plane of the satellite x–z plane. This was monitored by the FSS. The Earth constraint constrained the aspect angle between the x-axis and the Earth in a non-linear manner. This was monitored by the Earth Limb Sensor (ELS). Other pointing restrictions were related to the Moon and Jupiter.

The AOCS elements were found to meet the specifications, summarised in Table 1.

3. THE INITIAL AOCS CALIBRATION STRATEGY

The initial alignment calibration strategy adopted can be summarised as follows:

The FSS alignment about the x-axis was checked by pointing the z-axis to the Sun and using the measured rotation with the two FSS sensors. The alignment about the y-axis was measured by placing a guide star on the STR centre and comparing its distance to the Sun to what was expected, given the Sun

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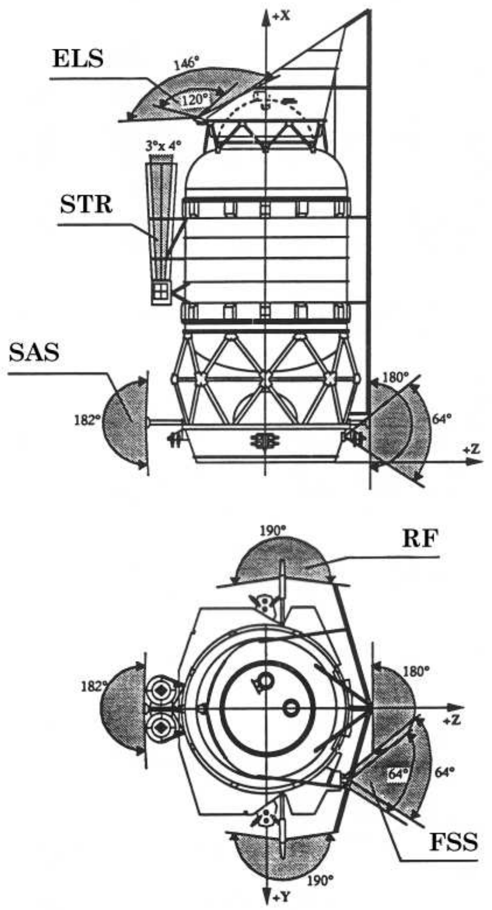

Figure 1. Schematic representation of the ISO spacecraft, locating the AOCS elements.

Table 1. AOCS elements main specifications.

Quadrant Star Sensor (QSS)	
Field of View	$4' \times 4'$
Sensitivity	$+7 < V_{mag} < +2$
Fine Sun Sensor (FSS)	
Field of View	$\pm 31°$ about x and y axis
Accuracy about x-axis	$1'$
Accuracy about y-axis	$3'$
Noise Equivalent Angle	$2''$
Star Tracker (STR)	
Field of View	$4° \times 3°$
Sensitivity	$+8 < V_{mag} < +2$
Bias error	$2''$($0.5''$at f.o.v centre)
Tracking speed	$5''$/s

ephemeris. The STR rotation about the x-axis and the FSS rotation about z-axis were calibrated by performing a star map and comparing pairs of guide stars measured versus expected positions.

The STR alignment about the y and z axis was checked by placing a guide star on the QSS centre and comparing its position on the STR. This calibration was performed at the start of each ISO orbit, as it was anticipated that it could vary due to thermo-elastic distortions. Figure 2 shows that the misalignment between the warm STR and the cold QSS has been relatively small during the mission, with an orbit-to-orbit variation of less than one arcsecond.

The alignments between the ISO scientific instrument apertures and the QSS were calibrated through a dedicated activity during the Satellite Commissioning Phase, known as the Focal Plane Calibration. This was achieved by performing a series of raster scans on selected bright stars whilst tracking the maximum number of five stars allowed by the STR, via a manual procedure. The centroids of the profiles measured by the Instrument Dedicated Teams (IDTs) were fed-back for update of the attitude in the subsequent revolution. The exercise lasted 4 revolutions for the instruments having smaller apertures, namely ISOPHOT and SWS, and involved a very close cooperation of the IDTs, the central Software Maintenance Team (with the fast provision of the pipeline products ("fast-ERDs")) and the Spacecraft Control Centre, whereby Flight Dynamics was pro-

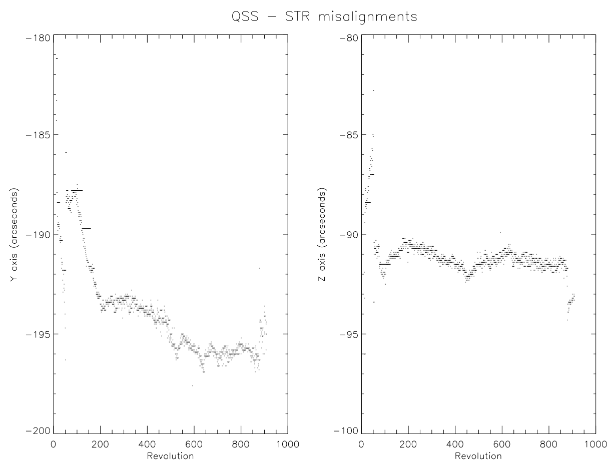

Figure 2. The measured misalignments between the cold QSS and the warm STR. At the start of the mission, the strategy for thermal control was modified, so that the "bang–bang" feedback loop was performed not directly on the operational STR, but on the close-by redundant, switched-off, STR unit, resulting in a smoother control. The measured misalignments, more representative of the whole orbit with the new strategy, were fed-back to the attitudes for that orbit. The scatter at the end of the mission is after Helium depletion.

viding the attitudes and times for each raster point. Although the centroids were determined making use of estimated models of the beam profiles (these were not known before launch). Initial misalignments were of the order of several arcseconds. The accuracy of this calibration was declared to be of the order of one arcsecond, deemed to be enough by the SIDT.

Finally, the gyros alignments and scale factors were calibrated using a defined set of three slews from the extreme limit given by the Sun constraint.

4. THE ISO POINTING PERFORMANCE

The pointing accuracy is defined according to three terms:

1. The Relative Pointing Error (RPE): the angular separation between the instantaneous absolute orientation of the satellite fixed axis at some time and a reference axis defined over 30 sec around that time. This is a measure of the jitter of the satellite and is expressed as 2–sigma, half–cone.
2. The Absolute Pointing Drift (APD): the angular separation between the short time average (barycentre of the actual pointing during some time interval) and a similar pointing at a later time.
3. The Absolute Pointing Error (APE): the angular separation between the commanded direction and the actual direction, effectively blind pointing accuracy. Expressed as 2–sigma, half–cone.

As can be seen in Table 2, the ISO pointing performance was already better than expectations at the end of the Satellite Commissioning Phase.

Table 2. The ISO Pointing performance after in-orbit calibration in the Satellite Commissioning Phase, compared with the Specifications and the pre-launch predictions.

	Specs	Predicted	After SCP
RPE ($''$)	< 2.7	< 1.2	< 0.7
APD ($''$/h)	< 2.8	< 0.78	< 0.1
APE ($''$)	< 11.7	< 8.1	< 4

In the course of the first months of the mission, the SIDT, of which I was a member, suspected that some residual errors could still be present. Correction of those residuals would improve the photometric accuracy of the instrument, due to the steep beam profiles and the internal misalignments between detectors (Beintema et al., 2003). For example, a star offset $4''$ from the centre of the aperture looses about 40% of its throughput (at 17 μm). Pointing errors of this order are also the larger contributors of uncertainty in the wavelength scale, and change the internal instrumental fringes phase. The spacecraft jitter is also seen as additional noise in the data if a source is observed on the steep side of the beam profile.

A specific calibration programme was designed and executed in revolution 137, by which a number of point-like sources were observed with ISOCAM. A simple configuration was chosen in order to fit as many as possible stars in a time deemed reasonable for such an exercise. Four hours were allocated by the Project Scientist for this experiment, as additional ISO calibration time. 79 stars, selected by the CIDT from their list of calibration stars, were observed in the ISOCAM LW9 filter (at 15 μm). Guide stars were manually selected by the Spacecraft Control Team to sample the whole field of view of the Star Tracker. The centroids of the CAM images were derived by the CIDT. 54 stars gave good centroid determination. These were correlated by the author with:

- the position of the guide star in the STR field of view,
- star ecliptic and galactic coordinates,
- the Solar Aspect Angle, and
- guide star magnitudes.

It appeared that some correlation was present with the position of the guide star in the STR field of view. The S/N ratio was not very convincing, but still indicative of a possible improvement in the ISO pointing. A second attempt was made later in revolution 264, with a more accurate star selection procedure taken by the author, based on the Hipparcos Input star Catalogue (HIC) and an ad-hoc empirical colour-colour relation between visual magnitude (quoted in the HIC) and the expected flux in CAM LW9 filter (see Figure 3).

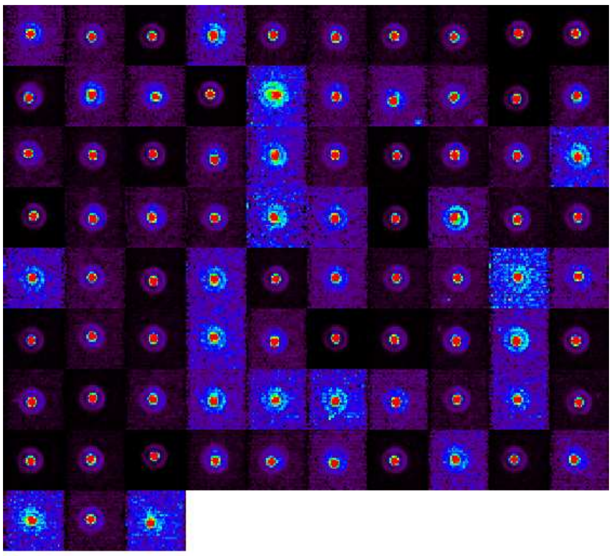

Figure 3. The 83 stars used in the revolution 264 experiment, as seen by the ISOCAM LW9 filter.

This second experiment was also confined to last 4 hours. 83 of the 84 stars gave good centroid determination. This time a convincing relation was found between pointing offset and the position of the guide star in the STR field of view, as illustrated in Figure 4.

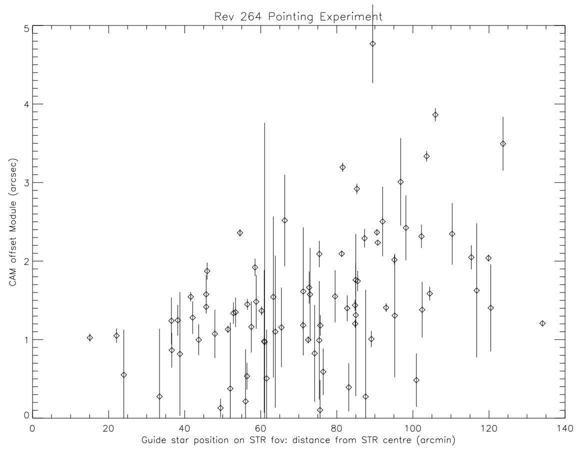

Figure 4. The analysis of the revolution 264 experiment shows a dependence of the measured offset from the centre of the CAM camera for each star with the distance of the guide star from the centre of the Star Tracker field-of-view.

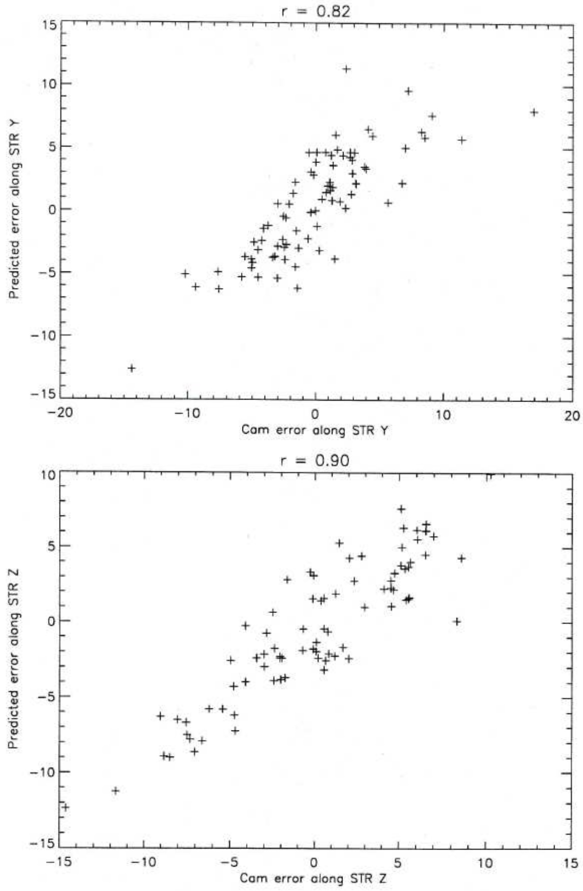

Figure 5. The model based on the confirmation star predicts the offset measured on the ISOCAM detector for the 84 stars used in the revolution 264 experiment. Units in STR CCD pixels (1 CCD pixel = 0.245″).

The Spacecraft Control Centre initiated then an independent investigation based on the absolute pointing reconstruction as given by the “confirmation star”, a second guide star used at the start of every revolution to check the correctness of the guide star and that no serious attitude deviations had occurred during the non-coverage period of perigee passage. This second star, not conditioned by the attitude controller, showed slight, but systematic errors in a sample of 120 revolutions.

A model was developed based on these data, correlating the observed error on the “confirmation-star” with the STR-FSS rotation errors and a new source of error, a focal length dependence on the angle of incidence of the visible radiation coming from the guide star. The fit was even better if two values of the focal length error were introduced, for each of the two STR axes, a proposition deemed plausible by the STR manufacturer. The model was applied to predict the offsets as measured in the REV264 experiment done with ISOCAM and the agreement with the measured offsets was excellent (see Figure 5).

Later in the mission, the new model was used in the Uplink. A verification exercise was performed in revolution 368. It consisted in a series of SWS AOT2s on and around the star HR 6705 at 3 and 17 μm (aperture 2). With the old calibration, the offsets from HR 6705 measured with the SWS were of 3.3 and -3.3 arcseconds along the Y and Z axis respectively. With the new calibration, these amounted to 2.4 and -1.0 arcseconds respectively. Further to this, the go ahead was given for the uplink implementation of the STR recalibration which became operative as of revolution 369.

Having a pointing much better than specifications means that the whole system needs to be re-inspected for factors neglected in the design phase. The first considered was the update of the Sun ephemeris on-board (the spacecraft z-axis has always to point toward the Sun). As of revolution 452, a new so-called Sun-model was introduced, by which AOCS on-board Sun ephemeris–related parameters were updated 4 times per revolution, instead of once per revolution. (see Figure 6).

The Guide Star Catalogue also needed improvement. More stringent selection criteria were adopted to make it more robust against improved performance of the AOCS. Positions were recomputed for epochs closer to the observation times. In addition, if a guide star was on the same columns of the CCD as a bright star, problems could occur due to CCD blooming (as found when the SIDT tried to observe the bright star HR 5340 in revolution 412 and got almost null signal!). All guide stars could be affected if they happened to fall on one of the blemishes of the CCD. These were mostly known, and guide stars weren’t used if it was predicted they would fall near one.

5. THE ISO ABSOLUTE POINTING ERROR

The improved pointing algorithm was first introduced in the Offline Processing Pipeline, in version 6.1, in July 1997. A further refinement of the ISO pointing was introduced in OLP version 8.6, in November 1999, by which the guide stars’ proper motions and differential aberration are taken into account, to-

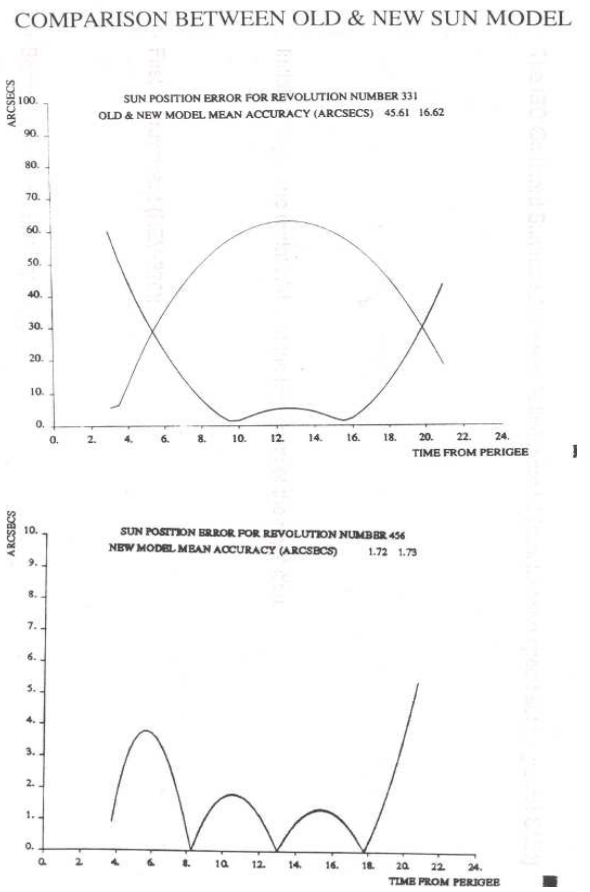

Figure 6. Comparison between the old and new Sun model, along the Z–axis.

gether with a refinement of the ISO Guide Star coordinates via the Hipparcos output catalogue. More improvements (but of a lesser extent) and bug-fixes have been introduced in OLP V9 and V10, the Legacy Archive version. For an in-depth discussion on the treatment of pointing data in the Pipeline, see Pollock, 2003.

In order to get a quantitative assessment of the ISO Pointing accuracy, the revolution 264 experiment data have been used, comparing the best known coordinates of the stars (proper-motion corrected and precessed coordinates derived from the Hipparcos output catalogue) with the CAM images centroids as determined by the CAM OLP. This is shown in Figure 7.

The fit standard deviation gives an upper limit of the ISO pointing accuracy, as it also contains the uncertainty in the determination of the CAM images centroids and of the star coordinates. The APE (Absolute Pointing Error) is then:

$$APE = 2 \times \sqrt{{\sigma_y}^2 + \sigma_z^2} = 1.4''$$

Without the fit, the APE is 3.4″, consistent with the measurements done during the Satellite Commissioning Phase (see Table 2).

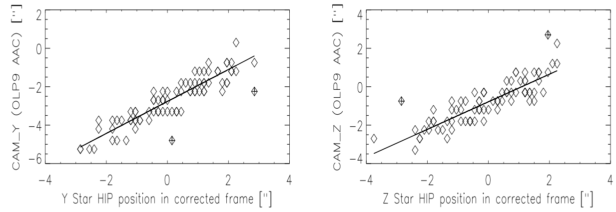

Figure 7. Comparison of the revolution 264 (prior to Uplink pointing improvements) stars positions as-expected vs. as-seen on CAM. The best known coordinates of the stars in spacecraft coordinates are compared with the CAM images centroids as determined in OLP AAC. A 3–σ clipping has been performed prior to the fit. Outliers are indicated by a cross. The large offset along the Y axis can be explained by the well-known poor reproducibility of the CAM wheel position when selecting different filters (the "CAM wheel jitter"). The effect was overcome in the REV264 experiment by not changing the instrument configuration (and thus the filter wheel position) for different pointings and therefore appears as an overall offset.

The distribution of pointing improvements during the ISO mission given by the pointing reconstruction is shown in Figure 8. The main improvement comes from the STR recalibration (upper plots) with a slight improvement given by the on-board update of the Sun ephemerides (centre plots). The lower panels show the effect of the further improvement after the mission, mainly the guide star proper motion and aberration. This later improvement was requested by the SIDT to follow-up their discovery of a modulation in the signal from a calibration star, HR 6705, regularly observed on a biweekly basis (see Shipman et al., 2003). A plausible explanation for this modulation was a residual pointing offset of about 2″. The last improvements in the pointing reconstruction do not explain this systematic

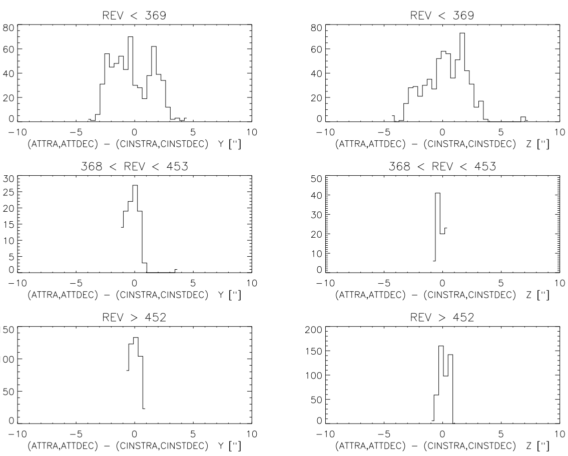

Figure 8. Distribution of pointing corrections for the three phases of the ISO mission associated with uplink pointing improvements. Only a few representative observations were considered, in the framework of the OLPV9 validation.
(For explanation please see the text, Section 5.)

offset, which I believe may be caused by a combination of a residual Focal Plane Geometry offset (I recall it was calibrated to a level of about 1″at the start of the mission without knowing the SWS beam profiles), residual error in the determination of the internal detector misalignment and a possible subarsecond residual systematic error buried within the 1.4″APE.

6. CONCLUSIONS

The ISO pointing performance has been seen to be much better than specifications after the Satellite Commissioning Phase. Further improvements were achieved one year after launch. The calibration strategy as foreseen before launch was heavily changed during the mission. Fine Star Sensor and the gyros needed less calibrations than expected. When pushing the pointing performance to the limit, some original calibration methods turned out to be inefficient and new methods and procedures were introduced. Calibrations not anticipated before launch were: Star Tracker focal length calibration, blemish pixels search and identification and overall absolute pointing accuracy calibration. The key to success for this has been the close collaboration between motivated spacecraft and scientific instrument teams, co-located at the Ground Station. Further improvements were introduced even after the mission, in the pipeline processing. The resulting Absolute Pointing Error is estimated to be 1.4″(2-sigma, half cone).

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