ISO: IN-ORBIT CALIBRATION OF THE AOCS SENSORS AND MAXIMISATION OF POINTING PERFORMANCE

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ABSTRACT

ISO is a three-axis stabilised satellite, which utilises a Star Tracker and Fine Sun Sensor to provide three-axis control during pointings. The relative alignment of the payload with respect to the Star Tracker is achieved using a Quadrant Star Sensor. The algorithms used to calibrate the AOCS instruments and the relative alignments between them and ISO's scientific instruments in-orbit are described.

A model for the effect of any residual alignment calibration errors on the pointing accuracy is presented as an explanation of observed pointing error. This is employed to estimate the value of alignment error and other errors, which contribute to the absolute pointing error, using a least-squares fit. One interesting result is the discovery of an unexpected error in the focal length of the Star Tracker optics. This analysis effectively bounds the accuracy of the original calibration algorithms. An enhanced algorithm for alignment estimate is given and results compared with those derived using the least squares estimation.

Both minimisation of the pointing error and in-orbit performance and degradation of the Star Tracker CCD impinge on the strategy for selection of guide stars, which is also discussed.

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 1/2 week spacecraft commissioning was performed. During this phase the alignments between AOCS and scientific instruments were calibrated. Following a 3 month performance evaluation phase full scientific operation of the satellite was commenced.

2 THE ISO SPACECRAFT

The principal structural components of the ISO spacecraft are shown in Figure 1, which also shows the spacecraft axes.

Quadrant Star Sensor (QSS)

The QSS is aligned with the ISO instruments' optical-axis. The boresight of the QSS *defines* the x-axis of the ISO body coordinate system. The QSS meets the following specification:

Field of view	4 x 4 arcminutes
Sensitivity:	Visual magnitude from +2 to +7

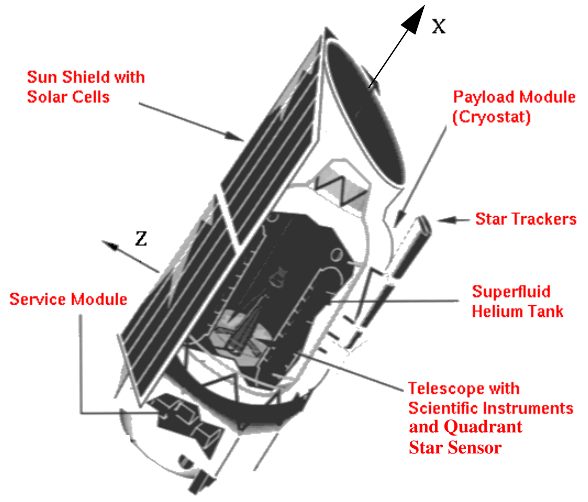

Figure 1 The ISO spacecraft

Star Tracker (STR):

ISO uses a CCD Star Tracker (STR) to provide two axis control (about the y and z axes) during scientific pointings by the tracking of a single guide star.

The STR meets the following specification:

Field of view	4 x 3 degrees
Sensitivity:	Visual magnitude from +2 to +8
Bias error:	2 arcsecs (0.5 arcsecs in field of view centre)
Tracking speed:	5arcsec/s

Fine Sun Sensor (FSS)

The FSS is used to provide control about the x-axis during pointings and about the x and y axes during slews. The FSS alignment *defines* the z-axis of the ISO body coordinate system. The FSS meets the following specification:

Active field of view per slit: ±31° about x and y axes

Accuracy:	1 arcmin about the x-axis 3 arcmin about the y-axis

Noise equivalent angle: 2 arcsecs

Gyroscopes

The gyroscopes are primarily used for control during slews and meet the following specification:

Random drift	3arcsec/hr
Gyro noise:	0.2 arcsecs at 2 Hz
Maximum rate:	1deg/s

Attitude Constraints

The ISO attitude is constrained by the Earth and Sun aspect angles to limit heat input to the cryostat and stray light into the telescope.

The sun constraint is that the line of sight of the +x-axis must be within $90° \pm 30°$ 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 satellite x-z plane. In practice tighter constraints are applied.

The Earth Constraint constrains the aspect angle between the x-axis and the Earth in a non-linear manner. An on-board Earth-limb sensor monitors this constraint.

3 INITIAL CALIBRATION STRATEGY

The calibration of AOCS instruments requiring Flight Dynamics support, were implemented based on recommendations from the AOCS manufacturer (RD1.)

An additional calibration was required to determine the precise alignment of those scientific instruments with narrow apertures with respect to the ISO spacecraft reference system, the so-called Focal Plane Geometry calibration.

STR misalignment about the y and z axes

To measure the alignment of the STR about the spacecraft y and z axes a guide star is placed in the centre of the QSS field of view using a special AOCS control mode, the “calibration mode”. The guide star is specially selected so that there it has no polluting near-neighbours within the field of view of the QSS. The alignment of the STR about the spacecraft y and z axes is determined by measuring the offset of the guide star from the STR boresight in the STR field of view and is referred to as the QSS/STR misalignment.

Note that this calibration can provide no information about any STR misalignment about the x axis (i.e. about the QSS boresight).

FSS alignment about the x and y axes

Since the FSS defines the spacecraft z axis the calibration of FSS about the x-axis is effectively a z-axis definition. The choice was made to define the z-axis as being between the boresights of the prime and redundant FSS. At an attitude chosen to place the sun on the z-axis the measured sun rotations about the x-axis by both prime and redundant sensors were used to set coefficients in the transfer functions of both sensors to achieve symmetry.

To measure the FSS misalignment about the y axis an attitude was selected which placed a guide star close to the STR boresight in the spacecraft x-z plane, and the sun on the FSS boresight. The actual distance between the star and sun is determined from ephemeris. The measured distance between them is calculated from FSS and STR output and the known STR alignment about the y and z axes. Any difference between the results is attributed to FSS misalignment about y.

Rotation of the FSS and STR with respect to their boresights (STR about x-axis, FSS about z-axis)

These remaining FSS/STR alignment errors both cause an apparent rotation error of the STR. This apparent rotation error of the STR is calculated by the following algorithm:

- perform a star map
- use pattern matching and estimation techniques to estimate the attitude during the map (RD2)
- derive the expected star positions in the STR using the estimated attitude
- for each pair of STR detections matched with a catalogue star, derive the vector joining the stars in the STR frame first using the STR measurements directly and secondly using the expected star positions and calculate the rotation angle error between these vectors.
- average the rotation angle error over all detected star pairs

Defining

$$\Phi = \text{solar aspect angle to x-axis}$$
$$\delta\theta_{sx} = \text{STR alignment about x error}$$
$$\delta\theta_{fz} = \text{FSS alignment about z error}$$

the total rotation error is given by

$$error = (\delta\theta_{sx} + \delta\theta_{fz} \cdot \cos\Phi) \qquad (1)$$

In principle two estimates of rotation error at different solar aspect angles allow us to solve for both rotation errors. However performing a map at 90 degree solar aspect angle puts the contribution of the $\delta\theta_{fz}$ term to zero enabling a direct calibration of $\delta\theta_{sx}$.

By re-estimating the STR rotation error at an extreme of the attitude sun constraint ($\Phi = 90 \pm 30°$), $\delta\theta_{fz}$ can be estimated. In fact the algorithm used both extreme solar aspect angles, taking an average result.

Gyro Drift Calibration

Stable three axis control is achieved using the STR and FSS. Thus by integrating gyro outputs during a stable pointing it is straightforward to estimate gyro drift.

Gyro scalefactor and alignment calibration

To estimate the gyro scalefactor and alignment errors at least three independent slews are required. It has been shown (RD3) that the optimum sequence of manoeuvres within the ISO pointing constraints are

1. Rotation of 60° about the sun vector from an attitude where the sun aspect angles are:
   - 0° about the spacecraft x-axis
   - ±30° about the spacecraft y-axis (i.e. at a sun constraint limit)
2. Rotation of 60° about the spacecraft y-axis to bring the sun vector to the other extreme of the sun constraint
3. Rotation of 60° about the sun vector.

Analysing the gyro measurements during these three slews provides a set of independent equations which can be solved to derive the gyro alignments and scalefactors.

In principle additional slews could be considered to provide an over-specified set of equations from which an optimal solution could be derived. This was not attempted on ISO.

STR and CCD calibrations

CCD dark current can be made available in telemetry and from this the threshold values for 99% probability of detection are calculated over a range of magnitudes.

The CCD may also degrade due to the appearance of blemish pixels which may be either "lit" due to the appearance of extra charge on the pixel or "dark", whereby no charge is ever present on the pixel.

No systematic tests were planned to detect blemish pixels, however the presence of a bright image in a star map that cannot be matched to a star catalogue is an indication of a possible "lit" blemish. Failure to detect a guide star, which can be detected successfully at many attitudes, is an indication of a possible "dark" blemish at the expected guide star position.

Focal Plane Geometry Calibration

As part of the Performance Verification phase of ISO it was required to calibrate the focal plane geometry of two of the ISO instruments. This was achieved by performing a series of raster scans whilst tracking the maximum number of 5 stars allowed by the STR. Flight dynamics was required to

- Determine the attitude at each raster point based on the measured positions of the 5 stars and the sun;
- Derive the offset of the instrument from the QSS at each raster point
- Determine the time at which point was achieved at each raster point.

The instrument teams used this data together with the measured flux in the instruments during the raster to calibrate the instrument focal plane geometry.

One result of the focal plane calibration was a refinement of the instrument boresight alignments with respect to the QSS boresight, which are taken into account in preparing the attitude commands to point at scientific targets.

4 POINTING PERFORMANCE

During a scientific measurement, the following telescope optical-axis pointing accuracy is required:

Absolute pointing error: 11.7 arcsecs
Absolute pointing drift: 2.8 arcsecs/hr
Relative pointing error: 2.8 arcsecs

The absolute pointing accuracy of ISO's observations can only be estimated a postiori, when the science teams analyse the scientific data returned from the spacecraft. After 6 months of operation the science teams reported an absolute pointing error of approximately 4 arcseconds, well within the specification. However they also observed that the absolute pointing error appeared to increase the further the guide star was from the centre of the Star Tracker field of view.

A further indication of a possible source of pointing errors was provided by the "confirmation star". During the first pointing after each perigee passage the position of a second guide star, the "confirmation star", is verified in the STR field of view to confirm that the guide star is correct and that no serious attitude deviations have occurred during the non-coverage period of perigee passage. It was observed that although the presence of the confirmation star was verified each revolution, there was am apparently non-systematic yet significant error between the expected and observed position of this star in the STR field of view.

5 ANALYSIS OF POINTING ERRORS

Three factors that introduce errors in guide star position during tracking, each of which increase with increasing star position from the STR centre, are considered:

- residual error in STR alignment about the x-axis
- residual error in FSS alignment about the z-axis
- Focal length error

Both alignment errors introduce an apparent rotation of the STR. The FSS alignment error contributes as a function of solar aspect angle. Writing

Y = expected Y CCD coordinate
Z = expected Z CCD coordinate
Y' = actual Y CCD coordinate after slew
Z' = actual Z CCD coordinate after slew
Y'' = actual Y CCD coordinate during pointing
Z'' = actual Z CCD coordinate during pointing
f = STR focal length
δf = STR focal length error
Y_{err} = residual Yslew error
Z_{err} = residual Z slew error

and using small angle approximations considering first order terms only, we have, after the slew to a target:

$$Y' = Y\left(1 + \frac{\delta f}{f}\right) - Z(\delta\theta_{sx} + \delta\theta_{fz}\cos\Phi) + Y_{err}$$
(ii)
$$Z' = Z\left(1 + \frac{\delta f}{f}\right) + Y(\delta\theta_{sx} + \delta\theta_{fz}\cos\Phi) + Z_{err}$$

If (Y_G, Z_G) and (Y_C, Z_C) are the expected positions of the guide and confirmation stars respectively then during a pointing the AOCS places the guide star on its expected position, i.e.

$$Y_G'' = Y_G \qquad \text{(iii)}$$
$$= Y_G' - Y_G\frac{\delta f}{f} + Z_G(\delta\theta_{sx} + \delta\theta_{fz}\cdot\cos\Phi) - Y_{err}$$

the confirmation star will similarly move so that

$$Y_C'' = Y_C' + (Y_G'' - Y_G')$$
$$= Y_C' - Y_G\frac{\delta f}{f} + Z_G(\delta\theta_{sx} + \delta\theta_{fz}\cdot\cos\Phi) - Y_{err}$$
$$= Y_C\left(1 + \frac{\delta f}{f}\right) - Y_G\frac{\delta f}{f}$$
$$-(Z_C - Z_G)(\delta\theta_{sx} + \delta\theta_{fz}\cdot\cos\Phi)$$

with a similar expression for the Z coordinate

The on-board FSS transfer function uses the term X_{10} rather than θ_{fz}, where $X_{10} = -\theta_{fz}\cdot\sin\Phi$.

We define the error in confirmation star position as

$$\Delta Y = Y_C'' - Y_C$$
$$= (Y_C - Y_G)\left(\frac{\delta f}{f}\right) - (Z_C - Z_G)(\delta\theta_{sx} - \delta X_{10}\cot\Phi)$$
(iv)
$$\Delta Z_C = Z_C'' - Z_C$$
$$= (Z_C - Z_G)\left(\frac{\delta f}{f}\right) + (Y_C - Y_G)(\delta\theta_{sx} - \delta X_{10}\cot\Phi)$$

Therefore by using the measured confirmation star errors over many orbits and applying a least squares fit, estimates for the alignment errors and focal length errors are obtained.

The first results were interesting in that the estimates when fitted to the data gave different variances for the ΔY and ΔZ terms. Moreover if the fit was applied to the Y and Z terms independently the estimates for the alignment errors did not agree. A possible explanation was that the focal length error was not consistent over the two axes, a hypothesis confirmed as plausible by the STR manufacturer. Considering two independent focal length errors, δf_y and δf_z gave a more consistent set of results.

The estimates obtained from considering 49 orbits were:

$$\delta f_y/f = -0.208\times10^{-3} \;;\; \delta f_y = -25\mu\text{m}$$
$$\delta f_z/f = -0.356\times10^{-3} \;;\; \delta f_z = -43\mu\text{m}$$
$$\delta\theta_{sx} = 0.370\times10^{-5} \equiv 1 \text{ arcsecond}$$
$$\delta X_{10} = 0.104\times10^{-2} \equiv 215 \text{ arcseconds}$$

A repeat of the STR/FSS calibration at the same time gave the following results:

$$\delta\theta_{sx} = -0.122\times10^{-4} \equiv -25 \text{ arcseconds}$$
$$\delta X_{10} = 0.795\times10^{-4} \equiv 164 \text{ arcseconds}$$

6 REVISED CALIBRATION ALGORITHMS

The calibration results show a divergence of 26 arcseconds in the STR x from the statistical results. If we consider this as an error in measuring the total *error* as defined in (i) then we might expect an error of double this in the FSS z estimation due to the cos Φ term in the equation. This is consistent with the difference on the FSS z estimates.

It should be noted that a rotation error of 25 arcsecs in $\delta\theta_{sx}$ and 50 arcsecs in θ_{fz} lead to a maximum pointing error of less than 2 arcseconds for a guide star 2 degrees from the centre of the STR field of view at an extreme solar aspect angle. Nevertheless we investigate to what extent we can improve the calibration.

A potential weaknesses of the algorithm is that we use an attitude estimated using both STR and FSS in calculating the relative rotation between the FSS and STR.

An alternative algorithm which addresses this by decoupling the FSS and the STR data is:

- estimate the attitude based only on the STR observations
- Assuming this attitude to be the spacecraft attitude determine the expected sun position in the FSS
- Take the difference between the expected and observed sun positions in the FSS as the rotation error.

Unfortunately this algorithm gave very similar results to the original.

The analysis of the confirmation star errors suggests a new approach by considering pairs of stars identified in the star maps. The equations (ii) also apply after slewing to an attitude for a star map. However during a star map the AOCS locks on to the first star detected and maintains its position in the STR field of view. Thus equation (iii) does not apply. Instead if we consider the difference between any star pair we have

$$Y_j' - Y_i' = (Y_j - Y_i)\left(1 + \frac{\delta f_y}{f}\right)$$
$$-(Z_j - Z_i)(\delta\theta_{sx} - \delta X_{10}\cot\Phi)$$

which we can rearrange to a similar form as (iv) and repeat in z to give

$$(Y_j' - Y'_i) - (Y_j - Y_i) = (Y_j - Y_i)\left(\frac{\delta f_y}{f}\right)$$
$$-(Z_j - Z_i)(\delta\theta_{sx} - \delta X_{10}\cot\Phi)$$

$$(Z_j' - Z'_i) - (Z_j - Z_i) = (Z_j - Z_i)\left(\frac{\delta f_z}{f}\right) + (Y_j - Y_i)(\delta\theta_{sx} - \delta X_{10}\cot\Phi)$$

Solving over maps at more than one solar aspect angle not only provides an estimate of the misalignments but also focal length errors. Reprocessing the three maps obtained from the STR x and FSS z calibrations we get:

$$\delta f_y / f = -0.288 \times 10^{-3} \;\; ; \; \delta f_y = -35\mu\text{m}$$
$$\delta f_z / f = -0.581 \times 10^{-3} \;\; ; \; \delta f_z = -70\mu\text{m}$$
$$\delta\theta_{sx} = 0.102 \times 10^{-3} \equiv 21 \text{ arcseconds}$$
$$\delta X_{10} = 0.859 \times 10^{-3} \equiv 177 \text{ arcseconds}$$

The estimation of focal lengths gives rough agreement with the statistical analysis over 49 revolutions; though the rotation error estimates are only marginally better than from the original estimates. A likely cause of errors in the rotation estimates is errors in the spacecraft attitude after the slew. The errors about other axes are the Yerr and Zerr terms is equation (ii), which disappear in the final formulation. However errors about the x-axis are not considered and these could be caused by the following:

- a simple linear formula is employed to propagate the on-board model of the sun vector. At the time of the calibration the on-board sun model was updated once per orbit from the ground leading to errors of up to 50 arcseconds in the on- board sun model. Now more frequent updates of the on-board sun model are performed throughout the scientific part of the orbit reducing significantly the sun model inaccuracies.
- For the commanding of star maps an operational mode of the spacecraft is used whereby no update of the on-board sun model is applied. This period without inertial sun reference correction was not consistent between the three maps considered. In future this error could be reduced by procedural changes in performing the maps.

By comparing the expected sun positions in the FSS with the measured position we can estimate the attitude roll error during each map:

Map 1 : $\Phi = 90$ degs	29 arcsecs
Map 2: $\Phi = 60$ degs	33 arcsecs
Map 3: $\Phi = 120$ degs	17 arcsecs

We can compensate for these errors when processing each map and then get the following results:

$$\delta f_y / f = -0.287 \times 10^{-3} \;\; ; \; \delta f_y = -35\mu\text{m}$$
$$\delta f_z / f = -0.584 \times 10^{-3} \;\; ; \; \delta f_z = -70\mu\text{m}$$
$$\delta\theta_{sx} = -0.188 \times 10^{-4} \equiv -4 \text{ arcseconds}$$
$$\delta X_{10} = 0.947 \times 10^{-3} \equiv 195 \text{ arcseconds}$$

Agreement with the statistical analysis is now very good

The results obtained are still limited by FSS accuracy. RD4 demonstrates errors due to limitations of the FSS transfer function. The ISO mission control team have found a systematic variation of FSS error about the y-axis as a function of solar aspect angle.

7 OTHER CALIBRATION RESULTS

QSS/STR misalignment

The QSS/STR misalignment must not vary by more than 1 arcsecond during the apogee part of the orbit, however was anticipated to vary during perigee passage due to thermoelastic distortion. In fact changes between consecutive orbits have remained less than one arcsecond and there has been little change during the operational period as shown in the following table:

orbit	total misalignment (arcsecs)	misalignment direction wrt. y-axes (degrees)
28	209.6	-155.3
250	213.6	-154.9
500	215.6	-155.9

Gyros

Gyro drifts in arcseconds/second are shown below

orbit	gyro 1	gyro 2	gyro 3	gyro 4
0	0.990	-0.125	0.208	-0.269
250	0.990	-0.135	0.186	-0.271
500	1.028	-0.141	0.171	-0.240

Gyro scalefactor errors are very small as seen below:

orbit	gyro 1	gyro 2	gyro 3	gyro 4
7	0.026%	0.064%	0.022%	0.046%
475	-0.136%	-0.041%	-0.013%	-0.029%

CCD degradation

The presence of lit blemishes were first discovered during the calibration maps 11 months into operations. As of April 1997, 8 lit blemishes had been detected, one of which is brighter than the limiting STR magnitude of 8.0. Also there are several suspect dark blemishes.

Problems with guide star detection were observed when the bright star ARCTURUS, was in the STR field of view. Further investigation revealed that the problems occurred when the guide star was close to the same column as Arcturus with a more positive z-coordinate than Arcturus. The STR manufacturers have confirmed that such a blooming effect from bright objects could be expected, though they predict the blooming to occur in both directions along the CCD column. No blooming along the minus z-direction has been observed with ISO.

No significant change in the CCD dark current has been observed.

8 GUIDE STAR SELECTION STRATEGIES

A number of factors contribute to pointing error due to guide star selection:

Neighbouring stars

Stars in the ISO star catalogue are classified according to the level of pollution from neighbouring stars.

Class 3: no disturbing stars as faint as mV+2.6 within a radius of 150 arcsecs

Class 2: no disturbing stars as faint as mV+3.6 within a radius of 150 arcsecs

Class 1: no disturbing stars as faint as mV+4.6 within a radius of 150 arcsecs

Class R = class 1 + no star brighter than Mv+0.3 in a search radius of 40 arcmins

Class C = class R + no star brighter than Mv + 6.2 within a radius of 120 arcsecs

Class D = class C + no star brighter than Mv=12.5 within a radius of 240 arcsecs

The bias induced by the proximity of a parasitic star is maximum for a distance of 60 arcseconds from the star being tracked, therefore the biases which can be expected from the different classes are, depending on the relative magnitude and distance of the parasitic star:

Class D & C:	from 0 up to maximum 0.17 arcsecs
Class R & 1:	from 0 up to maximum 0.73 arcsecs
Class 2:	from 0 up to maximum 1.78 arcsecs
Class 3:	from 0 up to maximum 4.26 arcsecs

Position in Star Tracker Field of View

The distance of the guide star from the centre of the field of view affects the error due to residual focal length and alignment calibration errors.

Star Magnitude

Stars detected near the dimmer limit of the Star Tracker range can be expected to be tracked less accurately. Dimmer stars are also more susceptible to transient position errors due to single event upsets.

Initial Guide Star selection algorithm

Essentially the initial guide star selection algorithm was to determine those guide stars which could be detected uniquely in the STR search window. Determine the highest guide star class amongst these and out of the set of stars of that highest class choose the brightest in a central region of the Star Tracker. If none of the set of stars of the highest class is in the central region the brightest of them in the complete field of view was selected.

Bright Stars

At all times it is now necessary to check that there are no very bright objects in the same CCD column as a guide star.

Blemishes

The following strategy is adopted to minimise the effect of CCD blemishes

1. Ensure that there are no blemishes brighter than the dimmest STR limit within an area slightly larger than the search window. Such blemishes could cause a problem, as if the guide star was acquired close to a pixel flagged in the on-board table it would be considered a blemish. (This problem could occur even for blemishes dimmer than the star tracker threshold which would not by themselves be 'seen' if they were in the on-board table).
2. Ensure that there are no blemishes within the 7 x 7 pixel tracking window. This will ensure that once an acquired guide star has been brought to its expected position, its magnitude and barycenter position are accurate (unaffected by a blemish).
3. Minimize the no. of raster points for which a blemish will fall within the 7 x 7 pixel tracking window. Assuming that during the 'tracking end procedure', the barycenter of the guide star remains within 1/2 pixel of its nominal position it will then be unaffected by blemishes.

9 CONCLUSIONS

The calibrations of the ISO ACOS have proved successful and the instruments themselves are so far stable. The calibration of relative STR-FSS rotation has proved particularly challenging but an improved algorithm has been developed which also calibrates STR focal length errors. A target absolute pointing error of 1 arcsecond set by the ISO science team now appears to be achievable and is an order of magnitude better than the specification.

In-orbit degradation of the STR has been observed, which has lead to a more rigorous guide star selection.

10 ACKNOWLEDGEMENTS

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