# ASSESSMENT OF AOCS IN-ORBIT PERFORMANCE FOR MARS EXPRESS AND ROSETTA


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## ABSTRACT

ESA's interplanetary spacecraft (S/C) Mars Express and Rosetta were launched in June 2003 and March 2004, respectively. Mars Express was injected into Mars orbit end of 2003 with routine operations starting in spring this year. Rosetta is since launch in cruise towards the first Earth swingby in 2005, with spacecraft and payload commissioning activities being performed. Both spacecraft are three axes stabilised with a similar attitude and orbit control system (AOCS). The attitude is estimated on board using star and rate sensors and controlled using four reaction wheels. A bipropellant reaction control system with 10N thrusters serves for wheel off loadings and attitude control in safe mode. Mars Express has an additional 400N engine for the Mars orbit insertion. Nominal Earth communication is accomplished through a high gain antenna (HGA). The paper addresses several aspects of the AOCS performance relevant for successful spacecraft operations:

- Star tracker performance

Inertial attitude reference information to the AOCS is provided by a fully autonomous star tracker (STR). Up to 9 stars are identified and tracked. On ground the performance of the star tracker is assessed in terms of quality of the on board star catalogue, noise on star position measurements, measurement degradation due to Sun incidence, tracking probability of stars, ability of first attitude acquisition without a priori estimate.

- Delta-V measurement accuracy

Accumulated delta-v is estimated on board from accelerometer measurements to terminate orbit control manoeuvres. The bias of these sensors are regularly calibrated on ground. For Mars Express, this bias shows a strong dependency on the number of units that are switched on with a time constant of several hours. The finally measured delta-v's are consistent with radiometric data between some mm/s and some cm/s depending on the size of the manoeuvre.

- Attitude estimation during solar flares

During a solar flare in 2003, both Mars Express star trackers completely lost the stars. In this period, the AOCS estimated the attitude only by propagating gyro measurements which are known to have a residual bias of up to some tenths of a degree per hour. Small commanded offpointings of the high gain antenna form the Earth direction allowed to verify the accumulated gyro bias over several hours from ground station signal strength data.

- Main engine calibration

The Mars Express Mars orbit insertion manoeuvre was performed on Christmas 2003 with the 400N main engine. Two months before, telemetry from a special calibration manoeuvre was evaluated to verify the performance of the main engine and the ability of the attitude control system to cope with the increased disturbance torques induced by main engine thrust direction misalignments.


## 1. STAR TRACKER PERFORMANCE

Mars Express and Rosetta are both equipped with a redundant set of STRs which are based on the same hardware. The optical system is most sensitive in the optical range of wavelengths from 500 nm to 850 nm with a field of view of 16.47 degree and a focal length of 46 mm. The charge-coupled device (CCD) has an array size of 1024x1024 pixels and a capacity of 70,000 Mel in a pixel. The signal rate of a G0 star with visual magnitude 0 is about 3.7 Mel/s. The STR operates essentially (i.e. apart from test and standby modes and software initialisation) in acquisition mode or in tracking mode. In acquisition mode the STR is designed to perform an autonomous attitude determination without any a priori knowledge based on an image of the full CCD. After successful completion of the acquisition, the STR switches autonomously into tracking mode. In this mode, CCD windows around up to 9 predicted star positions are readout and processed. The resulting position measurements are provided in periodic telemetry (TM) with a frequency of 2 Hz to the

AOCS for subsequent processing together with rate sensor data in the attitude estimation filter.

### 1.1 Attitude acquisition capability from lost in space

The STR attitude acquisition capability without a priori estimate in acquisition mode depends on the following main factors.

Stars in the field of view have to be detected with sufficient accuracy. From the full CCD readout, a list of objects is derived which are considered as candidate stars. These objects are built from pixels which have an electron content higher than a specific threshold over the average background. This detection threshold has to be low enough to detect faint stars but also high enough to avoid inclusion of artificial objects, generated by random noise in the signal, into the list of candidate stars.

The stars detected on the CCD have to be identified by a suitable pattern recognition. Star patterns on the CCD are compared with a list of reference patterns stored onboard and generated from the Hipparcos catalogue. After a successful match, the attitude is determined and tested against the complete list of objects in the field of view. For Mars Express, the reference patterns are triads, whereas for Rosetta the patterns consist of 5 neighbour stars around a central star. The Rosetta algorithm has been implemented based on an algorithm proposed by ESOC (see [1]) to cope with the presence of false stars which are expected to be seen during operations around the comet.

During Mars Express launch phase, when the S/C was changing attitude to point the HGA towards the Earth, the STR could not acquire an attitude. The reason could be traced back to a Sun straylight level that was about 800 times higher than expected with a Sun aspect angle of about 45 deg. This caused the software to detect too many objects in the field of view with a subsequent failure of the pattern recognition. To avoid generation of artificial objects by the increased background level, the detection threshold was set to a higher value. With the new setting, the acquisition capability was improved again at the cost of a reduction in the number of useful stars from the onboard catalogue and a degradation in the position measurement of stars. The onboard catalogue contains 3227 stars with instrumental magnitudes between 1.7 and 5.4. Nominally, stars with magnitudes up to 6.1 are detected in acquisition mode and up to 6.6 in tracking mode (due to lower readout noise from the reduced window size). The increased detection threshold was expected to reduce the average limiting magnitude to 5.1 (the actual limiting magnitude depends on the position of the star with respect to the pixel grid). This corresponds to a reduction of the useful stars from the on board catalogue by about 30%. Moreover, all triads from the reference pattern catalogue containing a star with magnitude fainter than 5.1 could not be used for reliable pattern recognition anymore. It was therefore decided to foresee special measures during critical operations like the Mars orbit insertion in December 2003. The region of the sky which was predicted to be seen by the STR's during the operation was scanned in advance with a dedicated S/C slew and the attitude acquisition probability tested by periodically commanding the STR to autonomous acquisition. On top, regular time slots were foreseen to perform S/C slews which would point the STR to a favourable star field for attitude acquisition that allows to update the AOCS attitude estimate with a valid inertial reference.

### 1.2 Star tracking performance

Input to the Mars Express and Rosetta AOCS attitude estimator are the inertial directions and the measured directions of up to nine stars in the STR frame updated every 0.5 seconds. The performance of the attitude estimate is therefore largely influenced by the quality of these data.

**Expected performance from design specification**

Inertial directions of 3227 stars are stored on board. They have been derived from the Hipparcos catalogue. Stars have been included with instrumental magnitudes below 5.4. The conversion from visual magnitude was based on a quadratic fit of the difference in magnitude between visual and instrumental depending on the Johnson B-V colour index. The theoretical difference, according to this fit, reaches up to 4.9. Due to the finite resolution of the CCD (1 pixel ~ 16 mdeg), 2 or even 3 Hipparcos stars were combined into a single star in the onboard catalogue when their angular separation was below 250 arcsec (~ 4.3 pixels). Due to the spread of the signals across several pixels on the CCD from the defocusing optics, the total signal was predicted to be measured as only one combined object with a direction pointing to the photometric barycentre of the set of stars.

The accuracy of the measured star directions is dominated by the following effects:

The temporal noise error in the measured star direction (=noise equivalent angle, NEA), induced by CCD dark current, readout and photon noise, was expected to be between 0.1 mdeg and 1.2 mdeg for stars with magnitudes between 2 and 5.4 and for stable pointing (i.e. no apparent star motion on the CCD).

The random bias error in the measured star direction, induced mostly by the residual distortion errors (i.e. after correction with an on ground calibrated distortion model of order 5) and the centroiding error, was expected to be about 0.9 mdeg.

### Actual performance from in-flight experience

During S/C commissioning of Mars Express, the actual tracking performance was evaluated from in-flight TM. At two occasions, where the field of view of the STR's were covering a considerable region in the sky during slews, the high rate STR TM was dumped to ground and analysed. During the first sky scan, STR 1 tracked 76% of all possible stars all the time, and 84% with a probability higher than 95%. With three exceptions, all stars brighter than 5.19 have been tracked all the time. STR 2 tracked 64% of all possible stars all the time, and 88% with a probability higher than 95%. With three exceptions, all stars brighter than 4.96 have been tracked all the time. The second sky scan gave similar results. The result is consistent with the predicted reduction in the average limiting magnitude to 5.1 and to the reduction of useful stars to 70% due to the increased detection threshold.

The magnitude of stars has been measured with an standard deviation of about 0.07. The mean value was for all tracked stars in the average fainter by slightly more than 0.1.

The star direction measurement accuracy was estimated based on the variation in the angular separation of star pairs derived from the measurement in TM. If the star directions were measured perfectly, the derived angular separation would remain constant. Following measurements of star positions during tracking over time (and moving across the CCD), the variation in the derived angular separation provides a measure for the star direction measurement accuracy. As the stars appear in several pairs and assuming that the measurement errors of the stars are not correlated, a direction measurement error was derived for each tracked star. The result, depending on the star magnitude, is shown in figure 1. The solid line is the root sum square of the random bias and the NEA according to the design specification. The points (circles, crosses and triangles) are the accuracies as derived from TM. For the circles, only star pairs which have been tracked more than 100 times have been taken into account. The results for star pairs with more than 20 and 5 trackings are shown as crosses and triangles. The result confirms the degraded performance for stars fainter than about 4.75 due to the increased detection threshold.

Another effect degrading the attitude estimation performance has been observed in-flight. An entry in the on board star catalogue was the result of a merge of three Hipparcos stars which are separated by less than 250 arcsec. But actually, only the brightest star was detected by the STR. This mismatch caused an offpointing of the S/C by about 7 mdeg. The on board catalogue is now under investigation, to identify and remove similar catalogue entries corresponding to merged stars which are actually not detected as a combined object.

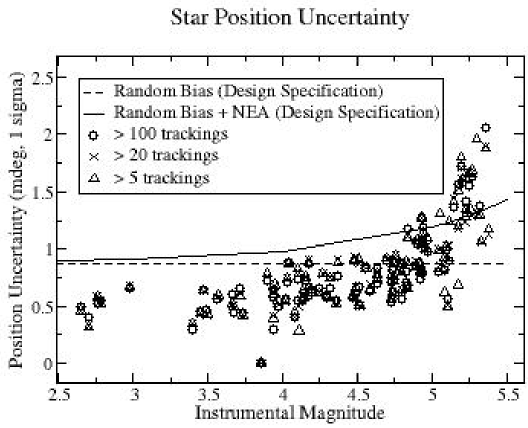


Figure 1: Star Direction Measurement Accuracy

## 2. DELTA-V MEASUREMENT ACCURACY

On Mars Express orbit correction manoeuvres are terminated autonomously by the AOCS when the estimated delta-v reaches the commanded value. The estimation is based on accelerometer data which provide accumulated delta-v measurements along three independent sensor axes. The raw data include a drift bias that has to be calibrated on ground and commanded to the AOCS in order to compensate for it. On ground calibrations are performed regularly. Especially before the manoeuvres, the bias is determined with a period of some hours to monitor its variation. Several hours before the actual manoeuvre, the latest calibration result is commanded to the S/C to be used during the burn. After that, the actual bias is still monitored to verify that the commanded value ensures a sufficiently accurate performance of the manoeuvre, or to command a correction if necessary.

Table 1 contains a list of Mars Express manoeuvres. The first 3 entries are correction manoeuvres after launch and during cruise. No. 4 , 5 and 6 are the touch-up and retargeting manoeuvre before and after lander ejection and the Mars orbit insertion. All other entries in December 2003 and January 2004 are orbit inclination change and apocentre lowering manoeuvres. In May, the final operational orbit was reached with 3 orbit change manoeuvres. The last column indicates whether the manoeuvre was performed with the main engine (ME) or with the four 10N thrusters (OCM). The third column contains the commanded delta-V, the fourth the on-board estimate after the burn. A comparison in performance with the respect to results from orbit determination based on radiometric data are given in the fifth column. The table shows, that an accuracy of better than 0.5% is usually achieved.

| No | Date | Cmd. Δv (m/s) | Estim. Δv (m/s) | Calibration (%) | Type |
|---|---|---|---|---|---|
| 1 | 2003/06/05 | 5.8430 | 5.8412 | +0.50 | OCM |
| 2 | 2003/09/10 | 0.5219 | 0.5216 | -1.50 | OCM |
| 3 | 2003/11/10 | 0.9647 | 0.9665 | -0.21 | OCM |
| 4 | 2003/12/16 | 0.3402 | 0.3402 | -0.08 | OCM |
| 5 | 2003/12/20 | 6.3552 | 6.3557 | +0.09 | OCM |
| 6 | 2003/12/25 | 806.7622 | 806.8256 | -0.014 | ME |
| 7 | 2003/12/30 | 117.1337 | 117.1844 | -0.08 | ME |
| 8 | 2004/01/04 | 149.7240 | 149.8207 | +0.11 | ME |
| 9 | 2004/01/06 | 1.6539 | 1.6558 | +0.22 | OCM |
| 10 | 2004/01/06 | 160.1370 | 160.1873 | +0.06 | ME |
| 11 | 2004/01/11 | 54.4688 | 54.5606 | +0.39 | ME |
| 12 | 2004/01/15 | 10.0000 | 9.9978 | -0.32 | OCM |
| 13 | 2004/01/18 | 17.0748 | 17.0737 | -0.32 | OCM |
| 14 | 2004/01/20 | 18.0982 | 18.0978 | -0.12 | OCM |
| 15 | 2004/01/22 | 17.4959 | 17.4951 | -0.20 | OCM |
| 16 | 2004/01/24 | 17.7179 | 17.7183 | -0.25 | OCM |
| 17 | 2004/01/26 | 12.5211 | 12.5200 | -0.11 | OCM |
| 18 | 2004/01/28 | 0.5064 | 0.5022 | -0.72 | OCM |
| 19 | 2004/05/06 | 24.0559 | 24.0572 | -0.05 | OCM |
| 20 | 2004/05/10 | 22.6927 | 22.6954 | -0.10 | OCM |
| 21 | 2004/05/13 | 0.7333 | 0.7294 | -0.34 | OCM |

Table 1: Mars Express Delta-v Manoeuvre Performance

The results of the calibrations turned out to be quite stable. Figure 2 shows results for the nominal unit (IMP-A) over several days in December 2003. For all manoeuvres, a last minute update of the bias on-board shortly before the burn was not necessary.

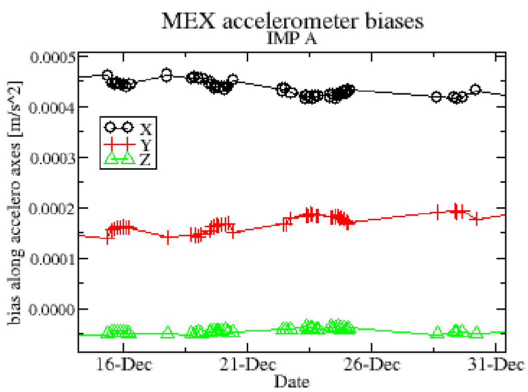


Figure 2: Variation of Accelerometer Bias over Days

Also on a monthly time scale, the variation of the bias is usually small. This is shown in fig. 3 containing the evolution of the accelerometer biases of IMP-A over several months. But there are clearly four discontinuities visible. They are due to a change in the configuration of the equipment. Around end of October 2003 and from mid December 2003 until end January 2004 both accelerometer units (nominal and redundant) were switched on, otherwise only the nominal one. After an reconfiguration, there is a distinct change in the bias, most significantly for the y-axis of the unit in the order of 0.3 mm/s^2. In each case it took about 24 hours for the bias to converge to the new stable value.

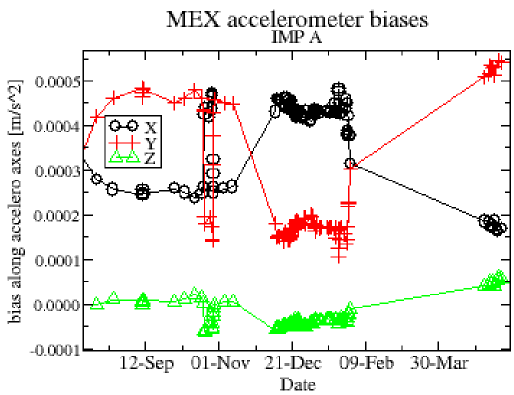


Figure 3: Variation of Accelerometer Bias over Months

## 3. ATTITUDE ESTIMATION DURING SOLAR FLARE

On the 28th of October 2003 at around 15:00, when Mars Express was in cruise to Mars at a distance of about 0.5 astronomical units (AU) from the Earth and 1.4 AU from the Sun, the nominal STR lost tracking. Several attempts to reacquire inertial reference failed. The redundant STR showed the same behaviour. All TM parameters from the star sensors indicated that the background level of the CCD's was much higher than nominal which led to a failure in the identification of stars. The disturbance could then be correlated with a strong solar flare occurring at this time.

The AOCS estimates under nominal conditions the attitude of the S/C based on STR and gyro data. The accumulated angles around three gyro axes are used to propagate the attitude quaternion estimate with a frequency of 8 Hz. The quaternion is updated by the inertial reference of the STR with a frequency of 2 Hz. Together with the attitude, the gyro drift in S/C axes is also estimated. With the loss of star tracking, the AOCS started to estimate the attitude only based on the propagation with the rates derived from the gyro measurements, taking into account the latest gyro drift estimate. Furthermore, an on-board counter was started that would trigger after a time-out of some hours an autonomous transition into safe mode, with the S/C in a rotation around the sun line without the HGA pointing to the Earth. This would mean a complete loss of contact for the whole period of the solar flare. It was therefore decided to keep the S/C in an Earth pointing attitude (by disabling the autonomous transition to safe mode) as long as possible and to compensate somehow by ground interaction for the possible off-pointing of the HGA from the Earth direction due to the degraded attitude estimation on-board.

The absolute gyro drifts were shown in TM to be in the average in the order of some tenths of a degree per hour with a variation an order of magnitude lower. The communication to the Earth was established with the HGA in X-Band with a 3dB half cone angle of about 0.5 deg. A total off-pointing by more than the 3dB half cone angle was expected to occur after about 1 day.

To measure the off-pointing of the HGA from the Earth direction, two small slews were commanded and, at the same time, the received signal strength at the ground station (G/S) recorded. The slews were commanded around axes perpendicular to the boresight of the HGA which is about 5 deg tilted from the S/C x-axis towards the z-axis. The result is shown in figure 2.

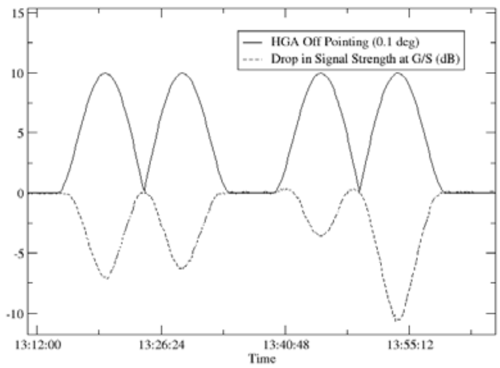


Figure 2: Signal Strength during HGA Off-Pointing Slews

The solid line shows the off-pointing of the nominal Earth direction from the HGA boresight in multiples of 0.1 deg. The first two peaks correspond to the first slew around the S/C y-axis. In this slew, the nominal Earth direction in S/C frame moved up to 1 deg towards the +z-axis, came back to the boresight of the HGA, moved 1 deg down towards the –z-axis and finally came back to the boresight of the HGA. The second pair of peaks correspond to the slew around an axis close to the S/C z-axis (5 deg tilted towards –x due to the offset of the HGA from +x). This second slew moved the nominal Earth direction back and forth along the S/C y-axis with an amplitude of 1 deg, first towards –y than towards +y.

The dashed line shows the drop in signal strength (dB) at the G/S from the mean value. The time of the measurements have been corrected for the signal delay of about four and a half minutes such that the measurements correspond exactly to the HGA off-pointing at this time.

In the first slew, the drop in signal strength corresponds quite well with the off-pointing. Only the second drop, where the nominal Earth direction is off towards –z, is smaller than the first drop, where the direction is off towards +z. This means that the actual Earth direction is biased towards –z due to the wrong on-board attitude estimate. In the second slew, the effect is considerably higher. When the nominal Earth direction is moving towards –y away from the HGA boresight, the signal strength is still slightly increasing before it drops. Also, the drop in the -y direction is much smaller than towards the +y direction. This means the actual Earth direction is biased towards –y.

A detailed analysis of the data showed that the Earth was actually off by 0.02 deg towards –z and 0.21 deg towards –y after 23 hours which is equivalent to an average gyro drift perpendicular to the HGA boresight of 0.01 deg/hour. To point the HGA boresight back towards the Earth, an additional (i.e. added to the last estimate which was used on-board) gyro drift of 0.21 deg/hour was commanded for 1 hour in the opposite direction.

At around 23:00 on the 29th of October, the STR was not disturbed anymore by the solar flare and reacquired the attitude. This made another estimate and correction of the gyro drift obsolete.

## 4. MAIN ENGINE CALIBRATION

On December 25, 2003 Mars Express was inserted into orbit around Mars by a delta-v manoeuvre of 807 m/s. The thrust for the manoeuvre was provided by the main engine (ME) with a nominal thrust level of 414 N and a thrust direction close to the S/C +z axis. Four 10 N thrusters were used for attitude control . These four thrusters are also used during the mission for orbit control manoeuvres (OCM) without main engine thrust and attitude control during thruster controlled modes and reaction wheel off-loadings (WOL). Due to this combined usage (orbit and attitude control) their mounting (on the S/C –z panel with a thrust direction tilted by about 10 deg with respect to the S/C z axis) is a compromise between maximum availability of thrust along the +z direction and maximum available torque capacity around all S/C axes. The required torques during Mars orbit insertion (MOI), on the other hand, are subject to uncertainties introduced by the position errors of the centre of mass and the position and alignment errors of the main engine thrust. These uncertainties together with the limited torque capacity during (MOI) was a matter of concern and it was decided to verify the results of on ground analyses and budgets by an in-flight calibration.

On the 27th of October, a test ME manoeuvre was commanded. The actual firing of the main engine in the burn firing phase (BFP) for 3.125 s was preceded by the liquid settling phase (LSP) of 151 s duration where only the four 10 N thrusters are activated. After the BFP, the residual rates were damped out in the rate reduction phase (RRP). During the manoeuvre, gyro and accelerometer measurements and commanded on times to the thrusters were recorded with a frequency of 8 Hz which is the frequency of the on-board AOCS controller (see figures 3 and 4).

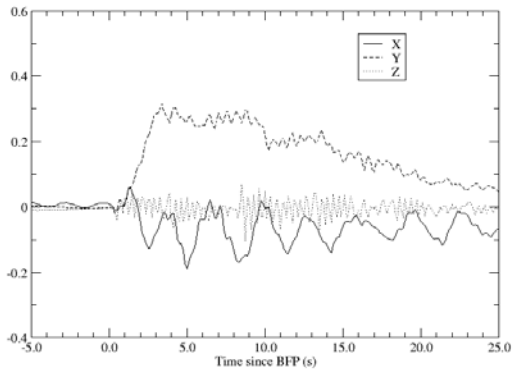


Figure 3: S/C Rates (deg/s) in LSP, BFP and RRP

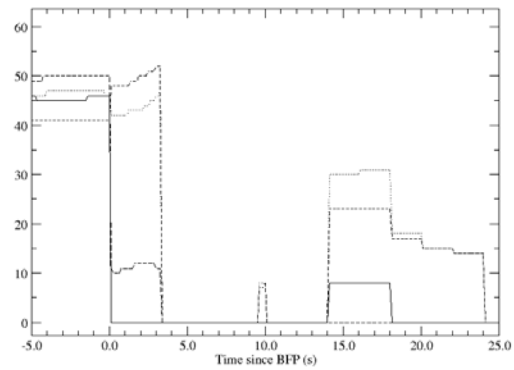


Figure 4: Thruster On-Times (ms) in LSP, BFP, RRP

On ground integration of gyro and accelerometer TM provided an estimate of the total achieved delta-v in S/C axes of (-0.031, 0.047, 2.913) m/s. As the S/C z-axis was pointing to the Earth during the manoeuvre, the delta-v along the z-axis could be derived accurately from Doppler measurements. The result was different only by 2 mm/s from the estimate derived from TM. The estimated thrust direction was off from the nominal direction by less than 0.1 deg. Taking into account the contribution of the attitude control thrusters (using on times and pressures in TM and a model for the thruster performance by the manufacturer) an average thrust of 404 N for the main engine was estimated from the total delta-v and the latest mass estimate which corresponds to 2.4% underperformance.

The maximum thruster on-time commanded in BFP was 51 ms or 41% of the control cycle. The disturbance torque induced by the ME was estimated in two ways. Both methods are based on the conservation of angular momentum:

$$T_{ME} \approx I\dot{\omega} - T_{thr} \qquad (1)$$

where *I* are the S/C inertia, $\omega$ are the S/C rates, *T* are the torques induced by the ME (subscript *ME*) and the attitude control thrusters (subscript *thr*) and where the gyroscopic torque $\omega \times (I\omega)$ was neglected. The rates as measured by the gyros and the torques as commanded by the AOCS to the control thrusters are available in TM. The inertia were previously calibrated in-flight. In the first method, the terms on the right side of equation (1) are computed for each control cycle and averaged over the BFP. The required angular accelerations are derived from finite differences in the rates at subsequent control cycles divided by the control cycle period. For the second method, equation (1) is integrated over the BFP and RRP and divided by the duration of the BFP:

$$T_{ME}^{av} \approx (I\omega_{end} - \sum_i T_{thr}^i \Delta T^i) / \Delta T_{BFP} \qquad (2)$$

In this equation, the sum is taken over all control cycles of the BFP and RRP and $\Delta T_{BFP}$ is the total duration of the BFP. The final angular momentum $I\omega_{end}$ is determined from an average of the residual rates at the end of the RRP. The results were in the order of (0.7,5.2,0.0) Nm around the S/C axes (consistent within 10% between both methods) and showed enough margin with respect to the total available torque capacity.

## 5. REFERENCES

1. Fainberg J., *RO-ESC-TN-5517*, An Algorithm For Star Pattern Recognition at Presence of False Stars, ESA/ESOC, Darmstadt, Germany, 2000.