OPERATIONAL IMPLEMENTATION OF MARS EXPRESS ORBIT AND ATTITUDE CONTROL

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ABSTRACT

On June 2nd 2003 the Mars Express spacecraft was put onto Earth escape orbit by a Soyuz rocket. Following ascend trajectory and separation from the rocket ESOC took control of the S/C. Initial attitude acquisition and solar array deployment performed nominally, leading to convergence in Sun pointing mode. The S/C established 3-axis stabilisation based on star tracker measurements and performed successfully a series of autonomous slews to direct the high gain antenna towards the Earth, thus reaching the default attitude guidance for cruise. However star tracker measurements, which had been nominally interrupted during the slews, were not recovered. Soon after, a surveillance on the inertial measurement package triggered a transition to safe mode. A challenging trip towards Mars had started.

During the cruise of Mars Express the ground segment and in particular the Flight Dynamics team had to master several problems. Some of those were originated by S/C anomalies. In other occasions, as for the October solar flare event, the problem was of natural cause.

Payload commissioning activities (e.g. MELACOM antenna beam characterisation, instrument calibration) involving highly tailored attitude profiles were supported during cruise. Also platform characterisation (e.g. High Gain Antenna pointing calibration, Main Engine calibration) and S/C troubleshooting (e.g. star tracker sky scans) required attitude control strategies of high complexity.

Several orbit manoeuvres were executed during cruise. The spacecraft was put in collision course 50 days prior to arrival to Mars. On December 16th an accurate manoeuvre was performed to fine tune the trajectory for the release of the landing probe Beagle-2, which took place on Dec 19th. The day after lander ejection, a deflection manoeuvre put the S/C onto its final Mars arrival hyperbola.

On December 25th Mars Express performed a perfect insertion manoeuvre with the 400N main engine that led to capture into Mars orbit. Eleven further orbit manoeuvres were executed to change the orbital plane and reduce the apocentre height. Operational orbit was reached on January 28th. Since then, intensive science operations are being conducted.

The Mars Express Flight Dynamics command generation team has been in charge of providing command support for the Attitude and Orbit Control and Measurement Subsystem (AOCMS) of the spacecraft. This paper deals with the operational implementation of this support. Activities related to operations that required special support are highlighted. Innovative methods for the implementation of attitude control are described. The approach for delta-V manoeuvre implementation is shown.

1. THE EARLY OPERATIONS

Table 1 gives a summary of the main Mars Express (MEX) events which took place during the Launch and Early Orbit Phase (LEOP).

Table 1:LEOP main events

T (Jun03)	Event
02T17.45	Lift-off
02T19.17	S/C separation
02T19.44	AOS New Norcia
02T19.51	SA deployment
02T22.15	Star Tracker (STR) on
02T23:22	Transition to Safe Hold Mode (SHM) STR does not recover measurements
03T02:47	HGA switch-on to verify pointing
03T06:30	Safe mode (SAFE) triggered by gyro surveillance
03T20:00	Reaction wheels (RW) switched on
03T21:21	S/C in Normal Mode (NM) (without STR)

04T03:30	Slew around +Y to bring Sun away from STRs. STR recovers measurements.
04T05:45	Slew back. STR measurements lost again.
04T08:30	Series of slews at steps of 5 deg to characterise STR straylight
04T13:45	Test RW off-loading (WOL)
04T15:15	S/C inertia tensor calibration
04T20:31	Test Orbit Control Mode (1m/s)
05T02:35	STR patched. Series of slews to test.
05T20:10	Launcher dispersion correction (5.84 m/s)

The main challenge of the early operations of MEX was the problem generated by the unavailability of STR measurements. The S/C had gone through Sun Acquisition Mode SAM, for which the STR provided good measurements. After this the S/C performed an autonomous slew based on gyros to the default Earth pointing. STR measurements were not recovered.

One immediate concern of this situation was that since the attitude measurement on-board was restricted to gyros, the S/C could be significantly drifting away from the default guidance, and attitude constraints might be violated. The second concern was that the S/C was still being controlled by thrusters, meaning fuel penalty and orbital disturbances.

The STRs had been able to provide measurements in the acquisition phase. Now an obvious difference for the Earth pointing attitude was that the angular distance from the Sun direction to the STR FoV was much smaller than for the acquisition attitude (although within the assumed operational range of the STR). Soon it was understood that the problem was due to straylight.

Different methods were analysed to perform attitude slews to bring the STR away from the Sun. The basic problem was that the S/C was in a mode (under thruster control) which does not allow commanded attitude slews. It was proposed to command to the S/C a fake Earth direction, such that when pointing to it the STR would go away from the Sun.

Finally the approach taken was to switch on the RW wheels and to force the S/C to go to Normal mode and from that point to command attitude slews to recover STR measurements. The transition to NM would normally not be authorised with a failed STR, but this was overwritten by the ground.

Once in normal mode a slew was performed to bring the sun away from the STR FoV. STR measurements were recovered. At the slew back to Earth pointing measurements were lost again.

A large number of experiments was performed, to characterise the problem, involving many attitude slews. Based on the results of these experiments the STR manufacturer developed a S/W patch that managed to resolve the acquisition problem of the STR.

Apart from the STR problems and initial triggering of a SAFE by a gyro surveillance, the performance of the S/C was outstanding. The delta-V manoeuvres were executed with high accuracy and all functionalities of the Attitude and Orbit Control and Measurement System of the S/C performed as expected.

2. S/C CRUISE

The MEX cruise was expected to be a quiet period, concentrated on the preparation for the Mars approach. Indeed, a large number of activities had to be conducted and FD support was required to troubleshoot several S/C anomalies. Table 2 shows an overview of the S/C activities and events during cruise.

Table 2: S/C activities and events during cruise

Time	Activities
03-06-09	4-RW operation commissioning
03-06-09	WOL in 4-RW mode commissioning
03-06-10	STR alignment calibration
03-06-10	Solar Radiation Pressure torques calibration
03-06-12	Fine Pointing Accuracy Mode commissioning Fine Pointing Stability Mode commissioning
03-06-12	Solar Array SA offset test
03-06-13	High gain antenna (HGA) pattern calibration
03-06-14	Reaction Control System (RCS) branch B commissioning
03-07-08	STR-B straylight test
03-07-09	SA canting experiment
03-07-13	Star scan (optical instruments calibration). RTU failure triggers SAFE#2 and SAFE#3
03-07-30	SAFE#4 triggered during RTU reconfiguration
03-07-30	STR lost track during off-loading
03-08-05	SAFE#5 (STR-AIU link error)
03-08-11	STR alarm during a CCD health check
03-08-19	Attitude inversion prior to solar opposition
03-09-02	SAFE#6-#7 Solid State Mass Memory, SSMM
03-09-05	STR sky scan for Mars approach
03-09-09	TCM#2 dry -run (outgassing effects analysed)
03-09-10	TCM#2 (0,49 m/s)
03-09-11	Re-run of attitude slews of TCM#2
09-09-18	MELACOM commissioning
09-09-18	RW#3 shows friction spikes. Troubleshooting
09-09-22	STR sky scan for Mars approach
09-10-10	STR sky scan for Mars approach
09-10-21	S/W reboot to include new AOCMS (SAFE#8)
03-10-23	STRB scan for skewed attitude SAFE#9-#10 trigger (wrong timeout)
03-10-27	ME calibration (SAFE#11)
03-10-28	Solar flare, attitude determination by processing of signal strength at station

2.1 Platform and Payload Commissioning

One of the key activities of FD for commissioning was to establish a RW momentum management strategy. Already in LEOP it had been seen that the levels of the solar radiation pressure (SRP) disturbance torques were significantly different and higher than the predicted based on analytical models.

FD proposed to perform a characterisation of the actual levels of disturbance torques. The S/C was put at a series of relative orientations from the Sun as it would be during the complete cruise and was maintained there for 1 hour for each attitude. The evolution of the RW levels was recorded and the SRP torque was derived. An empiric model was constructed based on these observations, which allowed making accurate predictions for RW evolution during cruise. Figure 1 shows a comparison between the disturbance torque derived from the analytical model based on optical properties of the S/C surfaces (grey) and the calibration result (black).

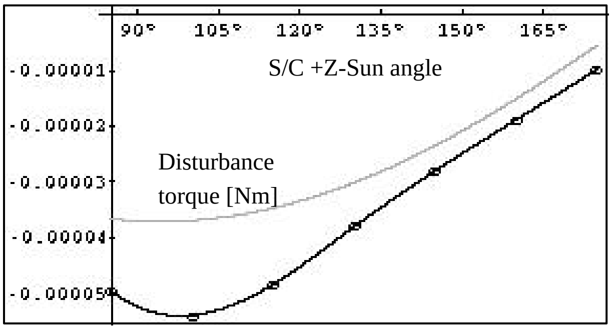

Figure 1: Disturbance torque around S/C Y axis.

WOLs on MEX are done with thrusters. Because the reaction control system (RCS) of MEX is not balanced (i.e. it is not possible to produce pure torques) WOLs result in disturbances to the orbit, which have negative impact for navigation. The large disturbance torques raised concerns on the number of WOLs and size of the associated delta-V disturbances.

FD proposed several strategies to reduce the number of WOLs and mitigate their effects, in particular for the approach phase to Mars. For instance a test was done to demonstrate that by regularly performing attitude slews and canting one SA wing, WOLs could be completely avoided. Unfortunately this strategy had to be abandoned due to a major contingency in the MEX power sub-system, which prohibited off-setting the SA.

On ESOC-FD proposal the use of four reaction wheels was introduced. Originally the fourth RW was assumed to provide cold backup. The use of four RWs reduced at least the frequency of the RW off-loadings to half and augmented the attitude manoeuvre capability of the S/C.

FD supported several activities for the commissioning of the MEX platform and instruments. The main achievement during this phase was to respond to the needs with tailored solutions. Examples of highly demanding pointing activities are the star calibration exercise, the HGA pattern characterisation and the MELACOM antenna pattern characterisation.

For instance, for the MELACOM commissioning, it was requested to generate an attitude raster pointing with 5x5 points and covering a domain of the sky equivalent to 60 deg x 60 deg to characterise the beam of the antenna. Unfortunately this attitude raster would result in long Sun light exposure of the High Resolution Stereo Camera (HRSC), which was unacceptable. FD proposed an attitude profile that would pass close to the points of the original raster, but without stopping. The duration of the exercise could be drastically reduced, as to respect the HRSC constraints. Technically the attitude profile was computed by describing a spline interpolation function for the MELACOM pointing direction, such that at given times it would evaluate at points close to the original raster.

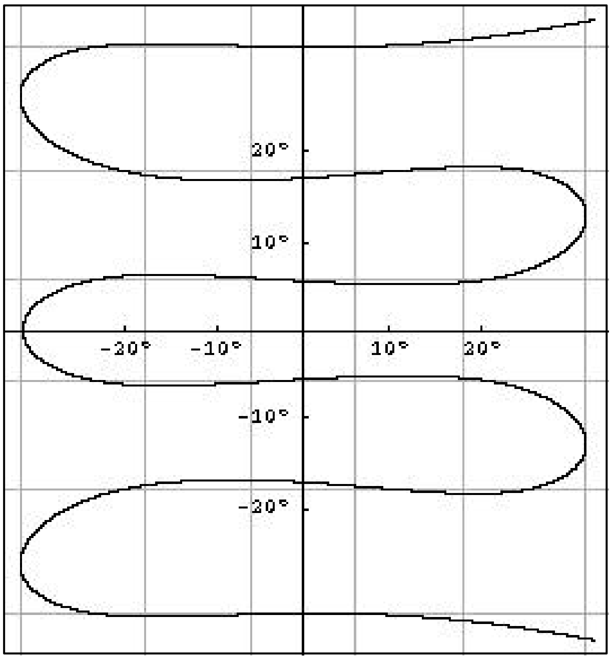

Figure 2: MELACOM characterisation: The plot shows the path of the Earth direction with respect to the MELACOM antenna axis.

2.2 S/C anomalies

MEX suffered from several anomalies during cruise originating from different sources (e.g. STR, SSMM, OBDH bus). In several occasions these anomalies resulted in S/C SAFEs. One consequence of a SAFE is that the S/C is controlled with thrusters and introduces significant disturbances to the orbit. FD provided support in troubleshooting S/C anomalies. Specially, FD supported calibration and analysis exercises of the STR.

Despite the fact that the STR had been patched during LEOP it presented again weaknesses during cruise. For instance on 2003-07-30 the STR lost track during a WOL and failed to acquire track after WOL. The loss of track during the WOL was traced to the large angular accelerations and was considered to be not ab-normal. However, the unavailability to recover track afterwards generated big concerns.

Such situation in a critical phase, e.g. lander delivery, or short before Mars orbit insertion could become catastrophic. For this reason ESOC-FD proposed to perform a scan over the regions of the sky which had to be tracked during approach to assess the risk of loosing track in that period. Several scans where performed, both for STR-A for STR-B. For each scan a number of acquisition attempts were commanded (see Figure 3).

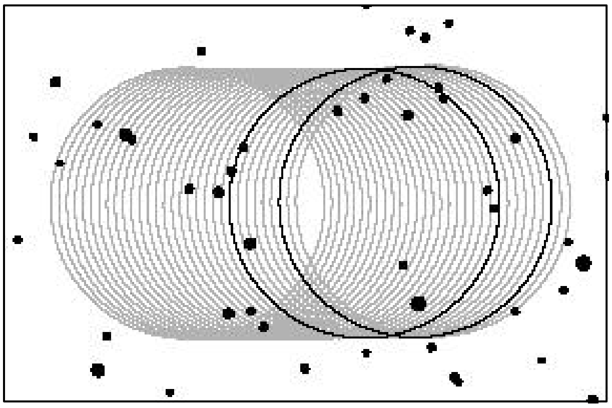

Figure 3: STR-A sky scan for last 30 days of approach. Grey circles show the region covered by the STR FoV at steps of 1 day. Black circles correspond to dates for which acquisition failed.

The result of this exercise was worrying. It was found that STR-B would be unable to perform acquisition from end November onwards, due to Mars presence in the FoV. For STR-A two periods were identified at which attitude acquisition was not possible, one around the 15/16 December and one around 22 December.

While these investigations were on going, a solar flare hit MEX. Most equipment survived the solar flare but from October 28th the STR stopped measurements for 32 hours. During these 32 hours the S/C maintained its attitude with gyro data only. As the S/C was drifting away from its nominal attitude it was feared that link could be lost. FD developed a procedure to assess the off-pointing of the HGA, by performing oscillation motions of the S/C along axes perpendicular to the HGA. By measuring the signal strength at the ground station over these oscillations, it was possible to determine the current deviation of the antenna. Further, a method was developed to correct this deviation by resetting the on-board gyro estimated drift, which would force the S/C to drift back. This activity was conducted 24 hours after loss of STR measurements and it turned out that luckily the gyro drift that the on-board system was assuming was very close to the actual drift, and hence the S/C had only de-pointed by about 0.2 deg.

Upon these events, analysis was made, to improve the robustness of MEX against STR measurements loss for the Mars approach phase. This was manifold:

For a potential case of a solar flare in the approach phase, the procedures applied during the October solar flare were improved. For instance, instead of performing attitude determination by measuring the signal strength at the ground station during an oscillation motion it was proposed to take pictures of selected windows of the STR and perform star identification and accurate attitude determination by ground processing. This approach had the advantage that it was much less intrusive and required only very few activities by the S/C.

To avoid unnecessary loss of track during WOL activities, the on-board parameters were tuned as to produce much smaller thruster pulses, thus resulting in smaller attitude disturbances.

For the basic acquisition problem of STR-B due to Mars presence and to the inability of tracking acquisition of STR-A for given periods it was decided to modify the baseline attitude strategy. The baseline attitude strategy of MEX is such that the HGA is pointing to the Earth, and the SA axis, which is perpendicular to the HGA is as close as possible to the ecliptic pole. This ensures communications, while maintaining maximum power on the SA. It was proposed to patch the on-board value for the ecliptic pole as to cause a rotation of about 15 deg around the HGA axis. The solar arrays would not be perfectly perpendicular to the Sun, but with a slight off-pointing, which was acceptable in terms of power. Mars would not be anymore in the FoV of STR-B and STR-A would as well point to different regions of the sky. It was foreseen to validate this strategy by sky scans as it had been done for the baseline pointing strategy.

Due to schedule pressure, the checking of the new attitude strategy could not be done and it had to be abandoned. Instead an emergency approach was developed. In case STR measurements would be lost on STR-A, while STR-B was unable to acquire track, the S/C would be periodically slewed (twice per day) to an attitude for which it was known that both STRs had coverage. The STR would acquire measurements in this attitude and would refresh the on-board attitude estimation.

STR-A managed to maintain track throughout the approach phase, even during the periods for which if track had been lost, attitude acquisition would have not worked. Thus, the emergency slews for recovering STR measurements were never operationally needed.

2.3 Main Engine Calibration

MEX provides two modes for performing orbit control manoeuvres, the Orbit Control Mode (OCM) and the Main Engine Boost Mode (MEBM). The OCM is intended for small delta-Vs. It is implemented by four 10N-thrusters.

The MEBM is conceived for the large capture manoeuvre (807 m/s) and the subsequent inclination and apocentre lowering manoeuvres. It is based on the use of a 400N main engine, plus RCS 10N-thrusters for attitude control. The ground can select a steering law for the attitude (i.e. such that the thrust direction is turning during the manoeuvre).

During S/C integration the alignment campaigns of the Main Engine resulted in high uncertainty of the alignment of the Main Engine. The uncertainty was so big that the torques produced by the mis alignment of the Main engine from the centre of mass (CoM) could be higher than the control authority of the RCS thrusters (which are used in MEBM for attitude control).

At the Flight Acceptance Review (FAR) it had been agreed to upgrade the on-board S/W to allow the use of the nominal and the redundant thruster branches simultaneously for attitude control in MEBM, thus doubling the control authority. An in-flight test of the MEBM had to be performed to assess the torques produced by the main engine and decide if the new S/W functionality was required.

The upgraded S/W was loaded in-flight on October 21st. The functionality to operate the RCS system using both nominal and redundant configuration was checked during a WOL.

The MEBM test manoeuvre was performed on October 27th. It consisted of a 3 seconds ME burn (the duration was sufficient to assess the torques, but short enough as to not cause any overrate in case the torques would indeed be too high).

The MEBM includes a 200s initialisation phase and a 150s liquid settling phase in which thrusters are used for attitude control and stabilisation of the propellants on the bottom of the tanks. When accounting for these phases, the total delta-V imparted to the S/C was about 3 m/s. In addition, after completion of the MEBM phase the S/C starts a full attitude acquisition (as for a SAFE), which produces unpredictable delta-V disturbances.

During the test, recording of relevant telemetry (TM) was performed at high rate, including e.g. gyro and accelerometer data, thruster pulses. The TM was analysed to assess that indeed the Main Engine was very well aligned to the Centre of Masses (CoM). Hence, the new RCS mode (by using backup and redundant thrusters simultaneously) was not necessary.

The knowledge gained during the test manoeuvre in terms of ME torque was fed into the actual operation of the ME during Mars capture (by commanding a-priori torques to be pre-compensated by the RCS). No TM was recorded during capture but the orbit achieved was so close to the target that it is sure that the MEBM at capture performed highly accurate.

3. APPROACH AND INSERIO N TO MARS OPERATIONAL ORBIT

Table 3 summarises the main events of the approach and insertion phase.

Table 3: Main events during approach and insertion

Time	Activity
03-11-10	TCM#3: S/C in collision course (0.96 m/s)
03-11-25	Attitude control test by forcing gyro drift
03-12-01	Mars picture
03-12-02	SAFE#12 triggers during SSMM maintenance
03-12-15	Last WOL before lander ejection
03-12-16	TCM#4: Lander fine targeting (0.34 m/s)
03-12-19	Lander delivery
03-12-20	TCM#5: Retargeting (6.35 m/s)
03-12-25	Mars Orbit Insertion (807 m/s)
03-12-30	Inclination change manoeuvre (117 m/s)
04-01-03	First apocentre lowering (150 m/s)
04-01-06	Second apocentre lowering (160 m/s)
04-01-11	Third apocentre lowering (54 m/s)

The driving element for the approach phase was the navigation accuracy required to deliver safely the lander into its entry corridor and to bring the S/C to the nominal arrival hyperbola.

The approach phase started with TCM#3. As from this point it was assumed that the S/C operations would be as quiet as possible, as to minimise the probability of a SAFE, which would disturb the navigation activities. Exceptions were made and for instance on December 1st the S/C was manoeuvred to point to Mars with the optical instruments. On December 2nd during a maintenance activity of the SSMM, which was pending since the solar flare event in October, a SAFE was triggered.

On Dec 15th the last off-loading prior to lander ejection took place. The delta-V effects of this off-loading were assessed from S/C TM data and were considered for the preparation of a delta-V on the next day. The delta-V on the 16th had a size of 34 cm/s, much larger than what was originally planned, because it had to compensate the effects of the SAFE on Dec 2nd. Between this delta-V and lander separation no thruster actuation took place.

Lander separation took place as planned on Dec 19th. The separation mechanism is of spring/helicoidal type, which imparts a relative delta-V between S/C and lander (~30 cm/s) and a rotational motion of the lander along its axis (15 rpm). The separation had to be performed in a special attitude, as to fulfil the lander requirements on angle of attack at entry. For this reason the HGA could not be pointed to the Earth and TM would not be available in near real time.

The angular momentum exchange between the S/C and the lander was expected to be 7 Nms, however there was large uncertainty in this value. This momentum exchange had to be absorbed on the S/C by the RWs. The WOL on Dec 15th was targeted such that when accounting for the disturbance torques until lander delivery, the S/C would have very low total angular momentum at delivery. Prior to the slew for lander ejection the angular momentum of the four RW was re-distributed, as to ensure as well low angular momentum in each of the wheels. Then the slew to the target attitude was done, the lander was ejected and immediately after and before slewing back to Earth pointing a WOL was executed. In this way, despite the uncertainties, it was ensured that the RW would be able to absorb the angular momentum imparted by the ejection. The actual impact of the ejection on the RW momentum was much smaller than anticipated (~4.7 Nms).

On Dec 20th a TCM of 6.35 m/s took place to bring the S/C out of collision course. The manoeuvre performed nominally and no further corrections were required until capture.

On December 25th the S/C was inserted into Mars orbit by a ME manoeuvre of nominally 807 m/s. Recording of TM to the SSMM was disabled, because it was considered non-essential for the success of the manoeuvre but it could originate a contingency itself.

For the case of a main engine failure, the MEBM provides a backup mode, which completes the manoeuvre by firing simultaneously 8 10N-thruster. To take advantage of this backup, FD had to command an attitude profile, which for the nominal duration of the MEBM would be optimum for ME operation, and beyond this point would be optimum for 8 thrusters operation.

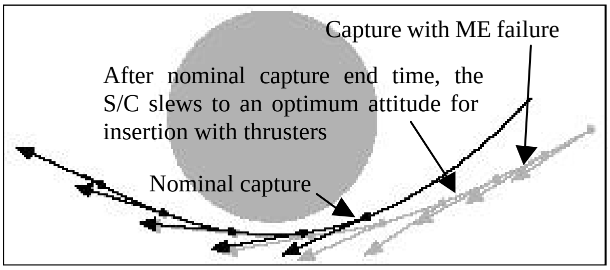

Figure 4: Thrust steering law during capture. Upon a ME failure the manoeuvre is completed by 8 10N-thrusters. The attitude law is optimised for ME for the nominal duration and slews afterwards to an attitude profile optimised for thrusters use.

On Dec 30th the inclination of the orbit around Mars was changed by an apocentre manoeuvre with the ME. During pericentre passages on Jan 3rd, 6th and 11th manoeuvres were executed to reduce the apocentre radius.

As discussed before, the MEBM makes a transition to SAM, which introduces orbit disturbances. Since the apocentre lowering manoeuvres had the same geometry, the approach was taken to assess the delta-V performance of the SAM after the first apocentre lowering by processing high rate accelerometer and gyro TM data, and assume the same disturbance (scaled by the S/C mass) for the following manoeuvres (see Figure 5). This disturbance was then considered for the overall trajectory optimisation.

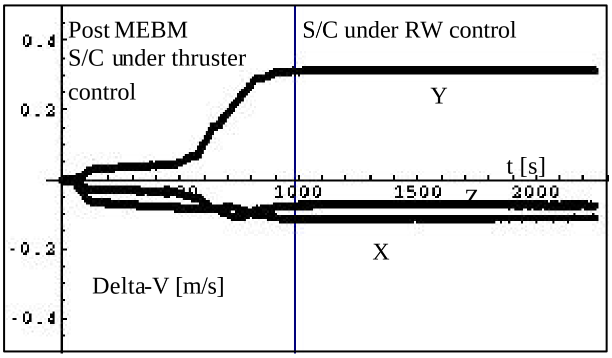

Figure 5: Delta-V of the post-MEBM for apocentre lowering #1, derived from accelerometer and gyro data

The apocentre reduction could not be completed with the ME due to constraints from the propellant management device. Seven further apocentre reduction manoeuvres were executed with 10N-thrusters, to bring the S/C to its operational orbit on Jan 28th.

The S/C is since then in Mars orbit and fulfils its scientific objectives.