AOCS DESIGN FOR SCIENTIFIC MISSIONS

ROSETTA/MARS EXPRESS

Pascal REGNIER, Eric ECALE, Saturnino VAL SERRA

MATRA MARCONI SPACE France, 31, rue des Cosmonautes, 31402 TOULOUSE, Cedex 4 - FRANCE
Tel: 33 5 62 19 79 09 , Fax: 33 5 62 19 77 69

Abstract

In the frame of the ESA scientific missions ROSETTA and MARS EXPRESS, MATRA MARCONI SPACE is developing AOCS solutions to cope with specific mission needs.

The purpose of the present paper is to put forward the constraints that have driven the AOCS design and to describe some of the concepts which have been chosen for both missions. Among the design drivers are worth noting:

- autonomy level : tightly adapted to the different mission needs and on-board resources,
- AOCS flexibility: the AOCS modes which are being developed have to face extremely different environment conditions which depend on mission phases (variable sun distance, variable perturbation levels, ...) and to provide numerous pointing facilities,
- specific AOCS equipment: autonomous star tracker, navigation camera, accelerometers for orbit correction,
- dynamic constraints: lander ejection, sloshing disturbances, large flexible appendages, articulated antenna.
- performance achievement: orbit correction accuracy, pointing and stability requirements during operational phases,

In addition to the general mission requirements the AOCS design and development has taken into account the stringent budget and planning constraints. This paper also shows how these latter constraints have led to the optimisation of the commonality between both satellites and of the development strategy.

ACRONIMS

BM Braking Mode
AFM Asteroid Fly-by Mode
MEBM Main Engine Boost Mode
NM Normal mode
NSH Near Sun Hibernation
OCM Orbit Control Mode
SAM Sun Acquisition Mode
SHM Safe Hold Mode (Earth acquisition mode)
SKM Sun Keeping Mode
SPM SPin up Mode
TTM Thruster Transition Mode

1. MISSION CHARACTERISTICS

ROSETTA mission consists in the observation of a comet nucleus from deep space to its perihelion with an increase of comet "activity" as it comes close to the Sun. The comet observation period will last one and a half years.

The fixed-date launch by Ariane 5 is scheduled in January 2003. The rendezvous with comet Wirtanen will take place in 2012. In the meantime ROSETTA will fly-by at two asteroids (Siwa and Otawara). During the mission one Mars and two Earth gravity assists are scheduled.

Matra Marconi Space is responsible for the ROSETTA avionics (AOCS and Data Management System).

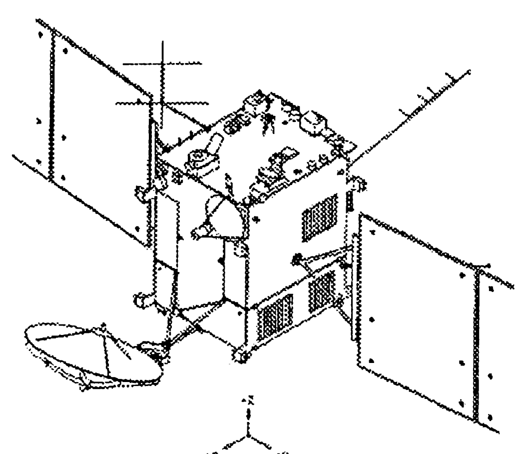

Figure 1: ROSETTA configuration

MARS EXPRESS mission is the observation of MARS: high-resolution imaging, radar sounding, atmosphere analysis, and geological, mineral and geo-chemical studies.

Proceedings 4th ESA International Conference on Spacecraft Guidance, Navigation and Control Systems, ESTEC, Noordwijk, The Netherlands, 18-21 October 1999, (ESA SP-425, February 2000)

The launch by Soyouz-Fregat is foreseen in June 2003. Mars will be reached 9 months later. Before orbiting Mars, MARS EXPRESS will eject a lander (BEAGLE2). The planet observation phase will last for 2 years. The mission may be extended 2 years in order to provide a relay to future American missions.

Matra Marconi Space is MARS EXPRESS prime contractor and is responsible for the AOCS.

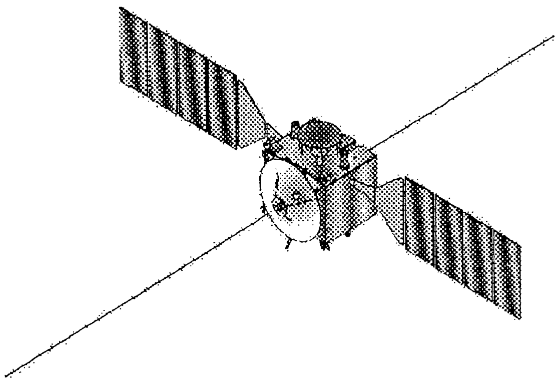

Figure 2: MARS EXPRESS configuration

2. DESIGN CONSTRAINTS

Autonomy constraints

ROSETTA and MARS EXPRESS are the first ESA interplanetary 3-axis stabilised spacecrafts. The satellite/ground link is a strong constraint: both satellites must ensure an autonomous Earth acquisition and the safe mode must support the communication link.

During nominal operations (observation phases), the autonomy level required to the satellites is similar to that required on Earth observation missions such as ERS or ENVISAT: about 2 days.

The existence of Earth/Sun/satellite conjunctions (up to 1-month duration) leads to a TM/TC interruption. The satellites must be able to survive without ground contact. This calls for a safe mode which minimises propellant consumption (see mass constraints); therefore based on the use of reaction wheels.

The definition of the reconfiguration strategy must take into account the criticality of some mission phases:

- during the Mars insertion phase of MARS EXPRESS, the manoeuvre shall not be interrupted,
- power constraints on ROSETTA are such that in case of reconfiguration the solar arrays shall be kept facing the Sun; no batteries are available in the worst case.

Dynamic constraints

Probe/lander ejection: on both missions the lander ejection must be performed in a wheel-controlled mode so as not to generate orbit disturbances through the attitude control, before and after the ejection.

Propellant mass: one of the main dynamic constraints in both missions is that the propellant mass represents about 50% of the satellite mass, thus generating non negligible sloshing effects and inducing sensitive mass and inertia variations along the mission.

Flexible appendages: presence of large solar arrays (especially on ROSETTA) in order to ensure sufficient power at a distance of several AU from the sun. On MARS EXPRESS there are two large radar antennas (25 meters long each, at a frequency of 0.05 Hz). In both cases, flexible appendages are rather low-frequency and represent a significant amount of the spacecraft inertia.

Mass constraints

The AOCS must be designed in such a way that the propellant consumption be minimised.

This is particularly a stringent constraint in the design of the back-up modes and ROSETTA hibernation modes.

Performance requirements

The main performance requirements concern three different mission aspects:

- the pointing performance during the observation phases (asteroid, comet or Mars observation) and the lander ejection; the pointing requirement is about 0.05° during these phases,
- the pointing performance concerning the antenna pointing in order to ensure the Earth/satellite link is about 0.15°,
- the accuracy of delta-V generation during orbit control manoeuvres is typically 1%.

3. AOCS DESIGN

Design overview

Figure 3 here below shows the organisation of the AOCS modes on both MARS EXPRESS and ROSETTA. The underlined modes are those which are common to both projects.

On both missions there is an initial automatic Sun acquisition phase (SAM), followed by an Earth acquisition phase (SHM). The ground can then command the transition to the operational mode (Normal Mode) which is mainly dedicated to scientific operations.

From the Normal Mode it is possible to enter on ground request the modes dedicated to orbit corrections (Orbit Control Mode, Braking Mode and Main Engine Boost Mode). In the case of ROSETTA, the ground can initialise the hibernation phases (near Sun or deep space) or the asteroid fly-by (AFM).

In case of serious anomaly, there is a back-up strategy with return to SAM (MARS EXPRESS) or SKM (ROSETTA) for Sun acquisition and further Earth acquisition with TM/TC link.

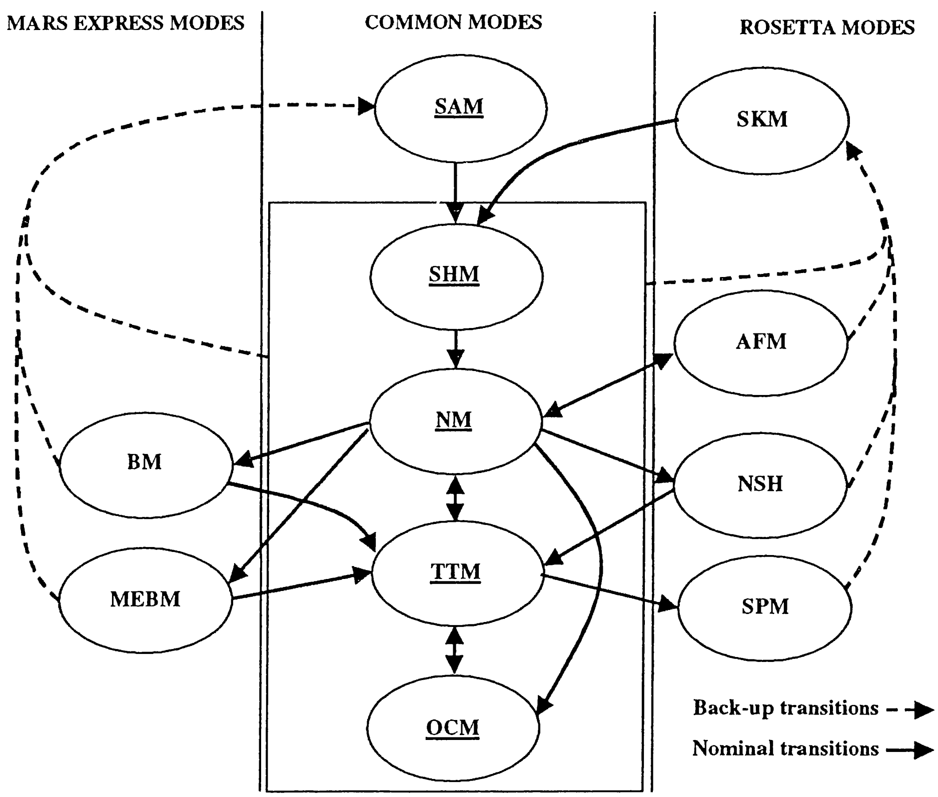

Figure 3: ROSETTA and MARS EXPRESS modes

The design characteristics of both satellites are presented here after. The first paragraph presents the common features to both projects. The specificities of each satellite are introduced afterwards.

Common features

Acquisition modes

The purpose of the acquisition modes is to ensure the Sun acquisition and the Earth acquisition.

The principle of the Sun acquisition is derived from ENVISAT: two Sun sensors determine a field of view centred about the satellite XZ plane. The Sun acquisition based on Sun sensors and gyros brings the Sun close to the +X direction. The attitude control is performed with thrusters.

During the Sun acquisition, the solar arrays normal is commanded towards the +X direction.

The Earth acquisition consists in pointing the satellite +X axis towards the Earth with a good accuracy (about 0.1° TBC) in order to support the satellite/Earth link with the high-gain articulated antenna.

Such an acquisition requires the use of an autonomous star tracker (STR) and of Earth/Sun ephemerides. The Earth and Sun ephemerides are based on polynomials that provide the spacecraft-Earth and spacecraft-Sun direction in the inertial frame J2000.

The slew manoeuvre between Sun pointing and Earth pointing is calculated on-board in such a way that the solar arrays keep facing the Sun. During the initial phase of the Sun acquisition the attitude control is based on thrusters. Once the Earth has been acquired, the control is transferred to the wheels for fine Earth pointing.

The Earth acquisition is part of the back-up mode as it is a waiting mode which restores ground communications and minimises fuel consumption.

Orbit control mode

This mode ensures the orbit manoeuvres by means of four thrusters located on the -Z face of the satellite.

The thrusters are off-modulated to generate 3-axis attitude control. The requirement on ΔV accuracy (1% error on the generated ΔV amplitude) makes it necessary to estimate the current ΔV value and to determine the end of the manoeuvre: depending on the ΔV amplitude of the correction, the estimation is performed either by means of accelerometers or by means of a thruster pulse counting algorithm.

An important feature of this mode is the estimation of the disturbing torques generated by the thrusters because of alignment errors, centre of mass variation. The torque estimator makes it possible to improve the pointing performance thanks to a reduction of the static error. The estimation principle is described here after.

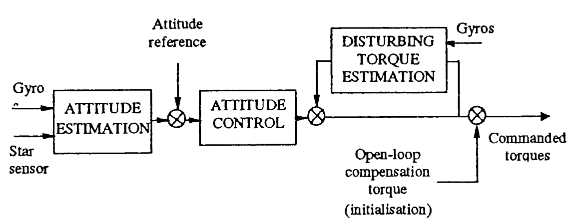

Figure 4: Principle of the disturbing torque estimator

Normal mode

This is the operational mode during which all scientific experiments and all observations will be carried out. In fact this mode covers a wide range of needs; the Normal Mode is therefore divided into several phases.

- wheel damping phase: this phase is the entry point to the Normal Mode. Its purpose is to settle down dynamic transients, which are likely to exist in the previous modes. During this phase the commanded attitude is constant (defined by the ground) and the control bandwidth is maximised so as to obtain a short response time. The lander ejection will take place in the wheel damping phase.
- slew phase: the purpose of this phase is to enable the satellite to rally as fast as possible two particular attitudes. During this phase the driver is not the pointing performance but the manoeuvre duration, mainly limited by the wheel capacity. This constraint has to be taken into account by the ground, which is responsible for the attitude guidance profile programmation,
- fine pointing phase: this is the phase actually dedicated to science operations. The attitude guidance profile during the observation phases is determined by the ground,
- ephemerides pointing phase: during this phase, the guidance quaternion of the satellite is determined by the Earth/Sun ephemerides function.

The attitude estimation in the Normal Mode is performed by means of a gyro-stellar estimator. The main characteristics of this estimator are the following:

- 6-state Kalman filter with a constant covariance matrix,
- inputs: spacecraft rates provided by the gyros and star co-ordinates provided by the star sensor,
- outputs: estimated attitude quaternion in the J2000 frame and gyro drift estimates in spacecraft axes,
- estimator initialisation with the attitude quaternion provided by the star sensor in the J2000 frame.

The interest of this attitude estimator is that it leads to a reduced computation load thanks to the constant covariance, without performance degradation. Moreover the use of quaternions (instead of Euler angles) makes it possible to operate at large angles: this is necessary given the slew manoeuvres that are envisaged during the normal mode.

The attitude control is performed by means of three reaction wheels (among four). The controllers are adapted to each phase of the Normal Mode in order to ensure an adequate response time.

Autonomous wheel off-loading

The purpose of the wheel off-loading is to prevent wheels from saturation but also from zero crossing under the effect of external disturbing torques. The off-loading is performed by means of short open-loop thruster pulses and takes place autonomously as soon as one of the wheel speeds is outside the authorised range. The off-loading will bring the wheel speed to a specified value up-linked by the ground.

The wheel off-loading function can be activated in the Normal Mode and during the Earth acquisition when the attitude control is ensured by the wheels.

In order to avoid unexpected thruster firings generated by the autonomous off-loading at some stages of the mission (critical observation phases, lander ejection), the ground can either inhibit this function or force the off-loading.

Thruster Transition Mode

This mode has been developed for the tranquillisation phase after the orbit control manoeuvres. In the case of ROSETTA this mode is also used as a transition between the Normal mode and the hibernation mode.

Thruster selection

The thruster implementation on MARS EXPRESS and ROSETTA is such that the generation of a given control torque about X, Y or Z axis requires the activation of several thrusters. Indeed, a given thruster generates torques about the three axis.

It is therefore necessary to select carefully at each time step which are the thrusters to be commanded. An optimisation of the selection is necessary in order to avoid fuel over-consumption. A one step optimisation algorithm based on a pseudo-simplex method has been developed.

Controller definition

Common methods have been developed for controller synthesis, based on H_∞ techniques. The interest of this approach is the maximisation of the control bandwidth while filtering out the flexible modes. Figure 5 here after shows a comparison between a classical PID controller and a controller synthesised with H_∞. The resulting control bandwidth is multiplied by a factor 2.

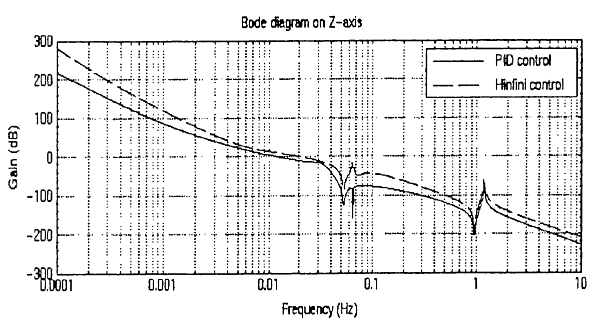

Figure 5: Comparison between PID and H∞ controllers

ROSETTA specific features

Sun Keeping Mode

This mode is a back-up mode to all the other modes (except the Sun Acquisition Mode) and is also entered after deep space hibernation. It has been introduced in order to satisfy the requirement for a safe mode, which does not need batteries.

The principle of the mode is to acquire the Sun by means of two Sun sensors located on the solar arrays. The sensors are used for solar aspect angle monitoring in nominal operations and for direct closed-loop attitude control in SKM, in case of anomaly triggering.

During this mode the solar arrays are commanded to hold their initial orientation with respect to the central body.

This mode is robust to a failure of one SADM (Solar array drive mechanism) and to a misalignment between the solar arrays of up to 30 degrees.

Asteroid Fly-by Mode

This mode uses the navigation camera (CAM) in order to track the asteroid optical centre. The information provided by the CAM at 0.4 Hz enables the generation of the attitude guidance profile through a Kalman filter.

During this mode the asteroid optical centre is tracked by rotating the satellite about the minimum inertia axis (Y axis): the maximum angular rate corresponding to the minimum satellite-asteroid distance is 0.8°/s.

The attitude estimation is provided by the gyro-stellar estimator developed for the normal Mode. The four wheels are used simultaneously in order to produce a maximum torque of 0.4 Nm about the satellite Y axis.

Figures 6 and 7 hereafter show respectively the principle of the asteroid fly-by and the mode block diagram.

The AOCMS validation includes the simulation of representative image processing algorithms based on virtual 3D surface models.

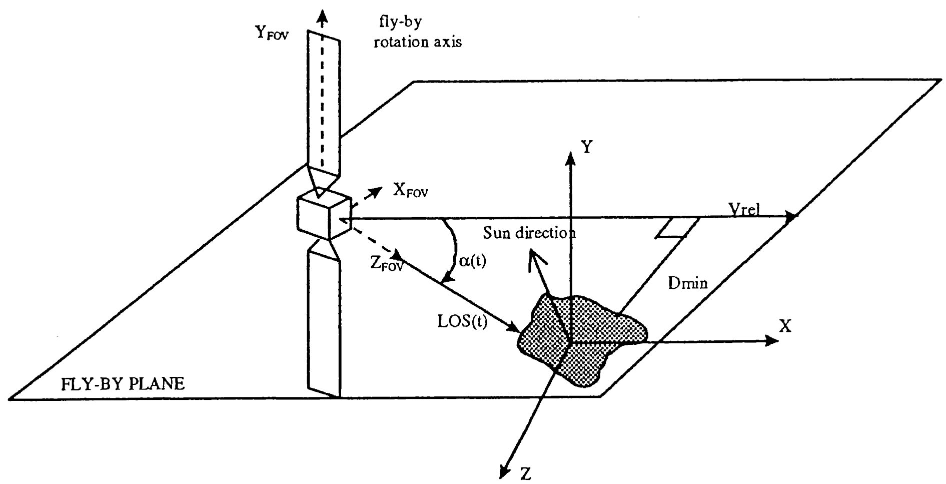

Figure 6: Principle of the asteroid fly-by

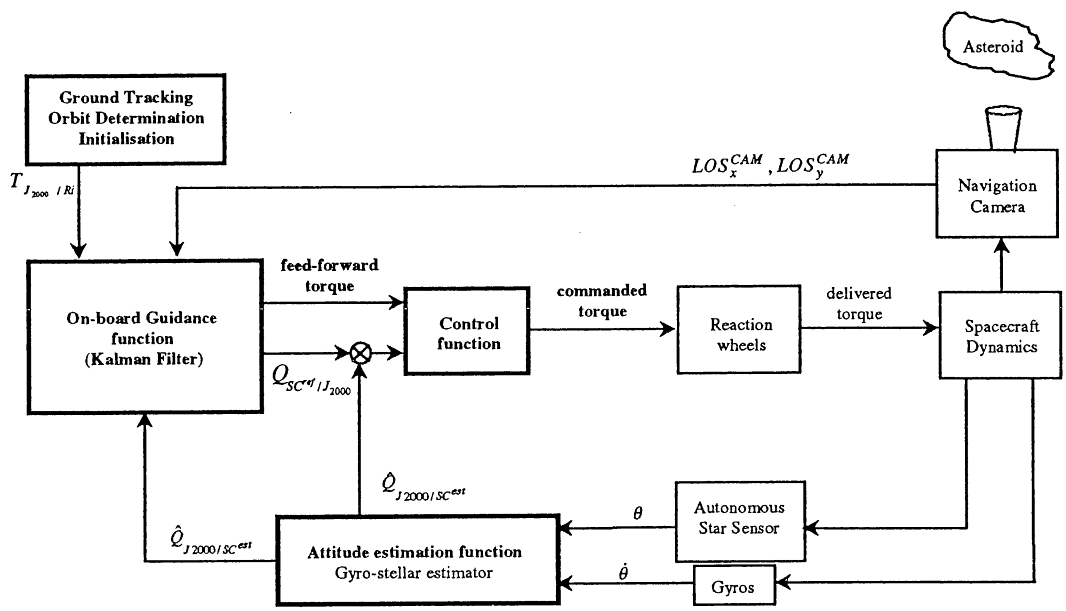

Figure 7: Block diagram of the asteroid fly-by

Near Sun Hibernation Mode

This mode is used for the hibernation phases below 4.5 AU from the Sun. The satellite will stay in NSH about 4.5 years.

The NSH is intended to minimise the number of equipments in order to maximise equipment life and increase mission reliability: the attitude estimation is determined with the STR and a gyroless estimator. The prediction stage of the estimator is based on a non-linear spacecraft dynamic model; the update stage is identical to that of the gyro-stellar estimator.

The attitude control is provided by thrusters using a 1-sided limit cycle with autonomous pulse-width adaptation in order to minimise the fuel consumption, which should not exceed 12 kg over 4.5 years in NSH.

The NSH can also be used as a back-up mode to the deep space hibernation, which is spin stabilised.

The attitude profile during the hibernation is determined by means of the Sun/Earth ephemerides function which ensures a full autonomy for at least 2 years.

During this mode the solar arrays and the high-gain antenna are fixed.

Spin-up Mode

The purpose of this mode is to spin the satellite up to 1 rpm before the AOCS switch-off for the deep space hibernation.

The spin-up requires the use of gyros and thrusters. The Spin-up mode includes three phases:

- a spin-up phase,
- a nutation damping phase,
- an on-board estimation of the principal inertia axes for final check and pointing of the high-gain antenna.

The exit from the deep space hibernation will take place after a 2-year timer has elapsed.

MARS EXPRESS specific features

Main Engine Boost Mode

The purpose of this mode is to achieve the orbit corrections that are necessary for Mars insertion and for the reduction of Mars orbit altitude during the initial phase. This manoeuvre is performed with a 400 N engine located on the -Z side of the spacecraft. The attitude estimation is performed by means of the prediction stage of the gyro-stellar estimator: the STR is not used actually because of dynamic transients. The attitude control is carried out with the four 10N-thrusters. During the manoeuvre the ground will program a non-constant guiding profile in order to optimise the orbit modification.

The main characteristics of the Mars insertion manoeuvre are the following:

- duration of the manoeuvre: about 2000s,
- ΔV amplitude: 850 m/s.

This is a critical manoeuvre for the mission. The required precision on the generated impulse must be better than 0.5%. In order to achieve such accuracy, the delta-V amplitude is measured by means of accelerometers, which will determine the end of the thrust phase, like in Orbit Control Mode.

The disturbing torque estimator is also used in the Main Engine Boost Mode in order to reduce the impact of the disturbances generated by the main engine. A preliminary manoeuvre is performed with the main engine so as to obtain a correct initialisation of the torque estimate.

Figures 8 and 9 show the impact of the initialisation of the torque estimator. In the first case, the initial torque is set to zero whereas the actual disturbing torque due to the main engine is equal to 8 Nm: the consequence is a large transient pointing error especially about the Y axis (smallest satellite inertia). In the second case, the initial torque estimate is set to the value estimated during the preliminary manoeuvre. We observe an important decrease of the pointing error.

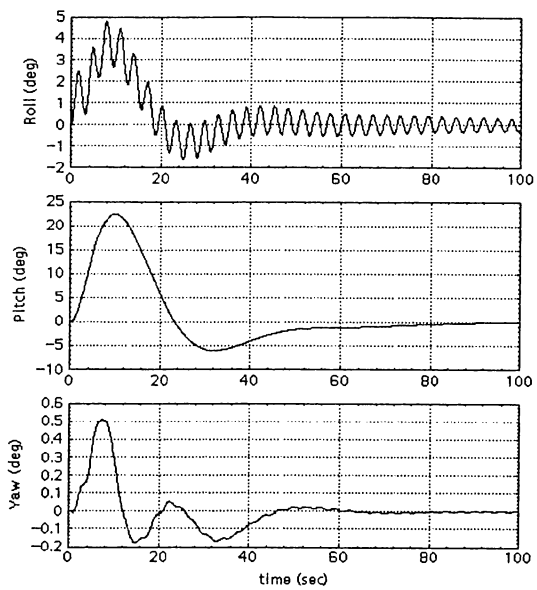

Figure 8: Attitude errors in MEBM with an 8Nm disturbing torque and a non-initialised torque estimator

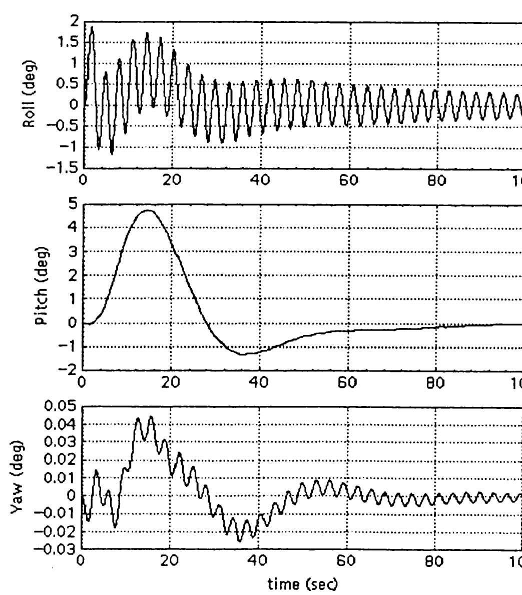

Figure 9: Attitude errors in MEBM with an 8Nm disturbing torque and a properly initialised torque estimator

It is worth noticing that the thruster implementation on MARS EXPRESS is strongly dependent on the disturbing torque amplitude determined on ground.

Braking Mode

This mode is a fuel-saving alternative to the Orbit Correction Mode for the reduction of the Mars orbit apo-centre. The principle of the mode is to brake thanks to the interaction between Mars atmosphere and the solar arrays: the proposed strategy will use a soft aerobraking, limited to a dynamic pressure between 0.2 and 0.3 N/m^2. This approach does not induce any constraints at equipment level nor specific thermal qualification, even for the solar array.

The four –Z thrusters provide the attitude control during the braking.

All operations are pre-computed by the ground for this phase. Just before the atmospheric pass which lasts less than 10 minutes, the satellite is approximately aligned with the aerodynamics frame. Solar array wings are horizontally positioned and the main engine axis is aligned with the satellite velocity. This position is selected to protect as far as possible satellite equipments and to limit the difference of pressure between the two wings (see figure 10 here after).

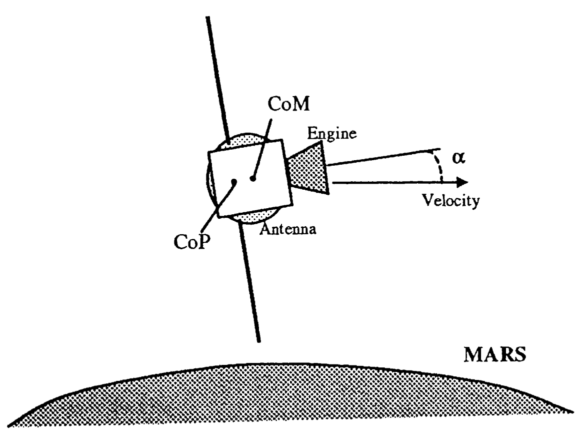

Figure 10: Aerobraking configuration

Important air drag torques are applied to the satellite during the atmospheric pass. Controlling these torques would lead to a propellant consumption that would counter-balance the mass gain brought by the atmospheric braking. It is then necessary for the satellite configuration to be aerodynamically stable. The stability is ensured if the Centre of Mass (CoM) is ahead of the Centre of Pressure (CoP) with respect to the flight direction: this condition is realised by the MARS EXPRESS layout

During a control-free atmospheric pass and since entry conditions are not perfect (initial small attitude and rate errors w.r.t. the stable attitude), the satellite oscillates about its stable position.

It is not possible to predict the exact stable reference attitude due to the limited knowledge of satellite on-orbit position and of CoM and CoP positions. Trying to control the attitude with a very high precision would lead to compensate for air drag torques beyond the wheels capacity, and as a consequence to use thrusters and to use propellant. The solution is then to relax the attitude pointing precision (15°) to limit as much as possible the thrusters use at the end of the atmospheric pass, to go to the Inertial Pointing Mode. Oscillation periods and dynamics pressure evolutions knowledge is used to precisely define the limits of this corridor. At the end of the atmospheric pass, the corridor width is slowly decreased until the satellite attitude and rate are compatible of wheels capacities. Then the transition is made to the 3-axis control using wheels.

CONCLUSION

On both programmes the launch date (January 2003 for ROSETTA and June 2003 for MARS EXPRESS) with a limited launch window is a driving factor, which leads to a very short development program.

From phase B start till satellite CDR, the durations are the following:

- 36 months on ROSETTA,
- 30 months on MARS EXPRESS.

Another important point concerning both projects is that given the costs constraints (especially on MARS EXPRESS), "re-use" is a keyword in the design and development. This means that as far as possible the same concepts have been implemented on both satellites.

As a consequence the design and technical solutions which have been proposed on ROSETTA and MARS EXPRESS correspond to the exact mission needs.