MICROSCOPE : MYRIADE AOCS ADAPTATION FOR A DRAG-FREE MISSION

Ch. Pittet (1), P. Prieur (1), A.Torres (1), A. Peus (1), C. Fallet (1)

(1) Centre National d'Etudes Spatiales, 18 av. Edouard Belin, 31401 Toulouse cedex 4, France
E-mail : christelle.pittet@cnes.fr, pascal.prieur@cnes.fr, alex.torres@cnes.fr, alain.peus@cnes.fr, christine.fallet@cnes.fr

ABSTRACT

MICROSCOPE is CNES fourth microsatellite based on the MYRIADE product line, but the AOCS differs a lot from the previous microsatellites DEMETER, PARASOL (in flight) or PICARD (expected to be launched in 2008). Indeed, the mission is dedicated to the test of the Equivalence Principle (EP) with an improved accuracy of 10^{-15}, and therefore requires the 180-kg satellite accelerations to be finely controlled. The project is in advanced preliminary design phase, and is expected to be launched on a 700km dusk dawn orbit in 2009 for a one year mission.

This papers deals with the adaptation of MYRIADE AOCS for the drag-free mission. First the mission needs are presented, and the payload is described, as it is one of the sensors used in the acceleration control loop. Then the AACS (Attitude and Acceleration Control System) general description follows, telling apart the modes and equipments which belong to MYRIADE standard avionics from those specific to the drag-free mission. The AACS modes are then detailed, with their objectives, the equipments used, the control algorithms principle and the expected performances. Finally on-going and future activities conclude the paper.

ACRONYMS

AACS	Attitude and Acceleration Control
EPSA	Electric Propulsion System Assemblies (pod of 3 FEEPs)
EP	Equivalence Principle
ESCAPE	Enhanced Simulink® Control and Analysis PackagE (Alcatel Alenia Space)
FDIR	Failure Detection Isolation and Recovery
FEEP	Field Emission Electric Propulsion thrusters
KWS	Kinetic Wheel System
MAG	Magnetometer
MAS	Acquisition and safehold mode
MCA	Accelerations Control Mode
MGT2	Coarse Transition Mode
MSP	Stellar propulsive Mode
MTB	Magnetotorquer bar
PID	Proportional Integral Derivative
SAS	Sun Acquisition Sensor
STR	Star tracker
IS	Inertial Sensor (payload 4 proof masses)

1. INTRODUCTION

1.1. Scientific objectives

The MICROSCOPE mission (MICRO Satellite with drag Control for the Observation of the Equivalence Principle) has been proposed by ONERA and CERGA Institutes. Its primary scientific objective is the test of the universality of free-fall of masses, which is one of the most famous consequences of the Equivalence Principle, with an improvement in the accuracy up to 10^{-15} (Touboul and al.,2001).

The payload designed by ONERA to test the Equivalence Principle is composed of two differential electrostatic accelerometers, each one including two proof-masses. In the first accelerometer, the masses are made of the same material to assess the accuracy of the EP experimentation and the level of systematic disturbing errors. The masses of the second one are of different materials. A violation of the Equivalence Principle will appear as a difference in the electrostatic forces necessary to maintain the latter masses on the same orbit. A double comparison with the first accelerometer will avoid systematic errors.

1.2. Drag-free requirements

To be able to measure these differential forces with the required accuracy, the satellite must compensate the non gravitational forces. The propulsion subsystem continuously overcomes theses non gravitational forces and torques (air drag, solar pressure, etc.) in such a way that the satellite follows the test masses in their pure gravitational motion. As the EP violation signal should be a sine at F_{EP} frequency (rotation frequency of the 'g' vector in satellite frame), the AACS most stringent requirements are also at F_{EP} : residual linear accelerations in mission mode must be less than 10^{-12} m/s².

To limit angular to linear coupling, additional pointing requirements at F_{EP} are stated. Three guidance strategies are required :

- inertial mode : the attitude stays quasi inertial with its +X axis normal to orbital plane and sun pointing for 120 orbits. The required acceleration stability performance is 10^{-11} rad/s², which corresponds to

Proceedings of the 6th International ESA Conference on Guidance, Navigation and Control Systems, Loutraki, Greece, 17-20 October 2005 (ESA SP-606, January 2006)

8.8 µrad at the orbital frequency Forb (which is the frequency of the gravitationnal field in satellite coordinate system F_{EP}).

- spinning mode : the satellite spins slowly opposite to orbital movement. Then F_{EP} is increased such that F_{EP} = Forb + Fspin. Several spin rates are demanded. The observation duration is 20 orbits and the angular rate stability performance is 10^{-9} rad/s, which is equivalent to 0.166 µrad at F_{EP} frequency.
- calibration mode : the problem is the characterisation of the sensibility of the accelerometers (scale factor, bias, misalignment and coupling factors) ; the on-ground reached accuracy being not sufficient, a calibration phase is directly accomplished in orbit. The considered solutions use attitude manoeuvres in order to characterise the sensibility of each accelerometer. The AACS allows to excite the accelerometers very precisely. During each manoeuvre (linear and angular oscillations) the satellite moves along one axis while the attitude is controlled on the others with a very low residual acceleration level. The angular rotations may also be compounded with linear oscillations of the proof masses to measure the Coriolis force. Calibration mode is under study to refine the calibration strategies and find the adequate control solutions. Further details about calibration needs are given in (Guiu and al., 2005).

All three MCA modes must also satisfy some pointing performances during observation phases of about 1000 µrad to minimize the combined effects of orbit eccentricity and gravity gradient. The AACS contribution to this is 100 to 200 µrad.
Finally, absolute pointing better than 4 degrees (3 sigma value) is required to avoid the star tracker illumination by the Earth. This requirement mostly applies to MSP and MGT2 to MSP transition (in MCA the pointing requirement during observation phases is more stringent).

2. AACS GENERAL DESCRIPTION

MICROSCOPE belongs to MYRIADE microsatellite product line, and the standard AOCS equipment and modes are reused as far as possible, to avoid extra development and qualification costs.

Four modes are defined for attitude and accelerations control :

- acquisition and safehold mode MAS
- coarse transition mode MGT2
- stellar propulsive mode MSP
- accelerations control mode MCA

The Acquisition and Safehold Mode (MAS) which performs sun pointing used either for the first acquisition or the safehold mode is strictly similar to the product line MAS mode (Le Du and al., 2002).

The Coarse Transition Mode (MGT2), which performs a coarse pointing by using the Earth magnetic field is similar to MYRIADE one for the equipment use and the control principle, but different because of the specific guidance profile around the pointing reference. It allows the using of the star tracker in MSP.

The next mode is partly specific to MICROSCOPE, because of the actuation systems it involves : the Stellar Propulsive Mode (MSP) uses the stellar sensor and the 3-axis stabilization control laws of MYRIADE normal mode, but the control torques are provided by twelve Field Emission Electric Propulsion thrusters (FEEPs), developed by Alta SpA for ESA and CNES, instead of reaction wheels.

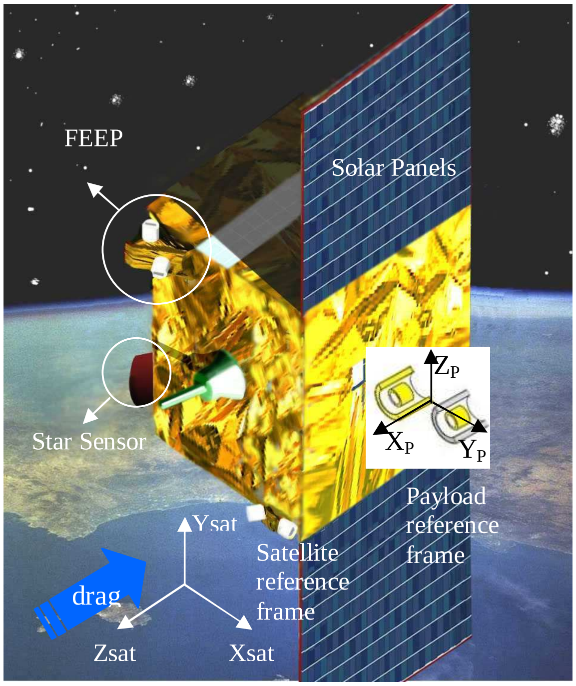

Figure 1 : Artist view of MICROSCOPE in orbit

Last, the drag-free mission mode is specific to MICROSCOPE : Accelerations Control Mode (MCA) mode, with three sub-modes for inertial (MCAi), spinning (MCAs) and calibration modes (MCAc). The control loop involves MYRIADE star tracker for attitude measurement, one of the four IS of the payload for linear and angular accelerations measurement, and FEEPs for control forces and torques.

The modes transitions are illustrated on Fig.2.

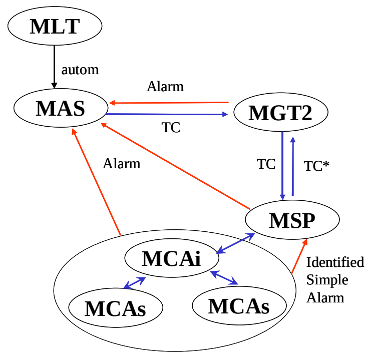

Figure 2 : MICROSCOPE AACS modes and transitions
(TC*) : after spinning up the kinetic wheel

The interesting thing to notice is that the MYRIADE FDIR strategy consisting in going to MAS when any anomaly occurs is modified for MICROSCOPE. Indeed, a new transition is added from MCA to MSP in case of payload accelerometer failure, EPSA overloading or partial failure. The reason for the new transition is that a transition to MAS (which is the default transition in any other anomaly case) will disturb the thermal control in such a way that the return to mission mode with the former thermal conditions could take several days. In MSP, the accelerometers are not used (no linear control applies), and MSP is robust to one EPSA failure.

The nominal number of equipments used in the different modes is summarized in Tab. 1.

	MAS	MGT2	MSP	MCA
MAG	1	1	0	0
MTB	3	3	0	0
SAS	3	0	0	0
KWS	1	1	0	0
STR	0	0	1	1
FEEP	0	0	12	12
IS	0	0	0	1 to 4

Table 1 : Equipments list

Compared to MYRIADE AOCS equipments, only one kinetic wheel is used in MGT2 (instead of two), and FEEPs are used as actuators for MSP and MCA instead of reaction wheels.

3. AACS MODES DESCRIPTION

3.1. Acquisition and Safehold Mode (MAS)

MAS is reused from MYRIADE acquisition and safehold mode. It is divided into three phases :

- Angular speed reduction using magnetometer and sun sensor measurements and magnetotorquers actuation.
- X-axis wheel spin-up. The satellite is slowly spinning around X axis to meet thermal requirements.
- Coarse sun pointing of X axis via magnetotorquers actuation.

No specific adaptation has been made for MICROSCOPE. The only additional studies could come from the presence of INVAR within the payload, which could disturb the magnetic measurements and increase the magnetic disturbances level.

A detailed description of the mode can be found in (Le Du and al., 2002).

3.2. Coarse Transition Mode (MGT2)

MGT2 is also reused from MYRIADE coarse transition mode, as far as the equipments and control principle are concerned. Indeed, MGT2 uses magnetometers measurements, magnetotorquer bars actuation and kinetic wheel stiffness to align the satellite reference frame to the local geomagnetic field (see Le Du and al, 2002 for details about the control). But the guidance profile is different : MYRIADE spins at the orbital frequency providing a geocentric pointing, whereas MICROSCOPE spins at twice the orbital frequency (that is what the “2” of MGT2 stands for), with a roll bias.

MICROSCOPE guidance profile must satisfy the following constraints :

- The geomagnetic control must be stable. Simulations showed a chaotic behaviour at the MAS/MGT2 transition and a bad convergence of the pointing error in some cases of inertial pointing. Thus inertial pointing is not chosen.
- The attitude reference must be as close as possible from the mission one (MCA inertial or spinning pointing). This constraint is dealt with in MSP.
- In steady state, the star tracker measurements must be continuously available. For that reason also and given the MYRIADE MGT pointing performance (10 degrees typically, see (Fallet and al., 2005)), the inertial pointing is not possible (illumination by Earth if roll error larger than 4 degrees).
- No satellite wall must be facing the Earth continuously for thermal reasons. Thus, a spin at orbital frequency is not allowed.

To meet these requirements, a conic profile spinning at twice the orbital frequency is proposed. The conic profile, corresponding to a constant roll bias, allows the star tracker use. The spin at twice the orbital frequency meets the thermal constraint. Moreover, it is equivalent to inertial pointing from a thermal point of view, because the satellite spins in both cases at orbital frequency wrt local orbital reference frame. Finally, the geomagnetic control is stable and the performances are met.

3.3. Stellar Propulsive Mode (MSP)

MICROSCOPE Stellar Propulsive Mode is close from MYRIADE normal mode, but is not the mission mode. It must meet the following requirements :

- Perform the transition from MGT2 to mission pointing in MCA (inertial or spinning). The pointing error at MSP entry should be close to 15 degrees and the steady state MSP pointing error close to 1 degree (on each axis). The pointing objective (inertial or spinning) is liable to be modified by the ground. A Moon avoiding manoeuvre can also be commanded, the star tracker being not Moon proof.
- Without any linear control, the angular and linear accelerations levels must enable the payload accelerometers switch on and their in-flight test in Full Range Mode during MSP.
- MSP must be designed to withstand with only nine out of the twelve thrusters, as it is foreseen to fold back autonomously from MCA to MSP in case of failure of a pod of three thrusters (EPSA).

The control principle is similar to MYRIADE normal mode, the main modification being the use of twelve Field Emission Electric Propulsion thrusters (FEEPs) instead of reaction wheels for 3 axes stabilisation.

When entering in this mode, the X-axis wheel is spun down and switched off, while the closed-loop control allows the convergence to target attitude. This target attitude remains the same as in the previous mode (MGT2 or MCA) for some orbits, and becomes inertial later (spin down and roll reduction) ; the pointing manoeuvres are possible without any change in MYRIADE generic methods for attitude guidance computation.

Attitude is given by the star sensor. The satellite linear accelerations are not controlled. The control laws are adapted from MYRIADE normal mode ones (see Pittet and Fallet, 2002).

The satellite inertia matrix being almost diagonal, the control laws are decoupled. The SISO control loop includes :

- an attitude and angular velocity estimation filter. The attitude measurement is provided by the star tracker. It is derived to get the angular velocity. Both signals are then filtered by a low pass filter to eliminate high frequency noise and avoid FEEP high frequency excitation.
- a FEEP control law. As for MYRIADE, the control law includes a large angle nonlinear algorithm (speed bias law) and a small angle linear algorithm. The speed bias allows the pointing error decrease by applying a speed reference in the right direction, with a zero control torque in steady state. The control torque *T* is given by the Eq.1 :

  $$T = -K_{sb} \text{ x } (\delta\omega + \text{sign}(\delta\theta) \text{ x } \omega_{sb}) \quad (1)$$

  where K_{sb} is a scalar, $\delta\omega$ is the angular speed error, $\delta\theta$ is the pointing error, and ω_{sb} is the bias speed.

  When reaching an error threshold $\delta\theta_l$, the control switches to a linear PID law. The integral term initial condition is zero at the transition. Then, the conditions given by Eq.2 allow the theoretical control torque continuity (*T=0*):

  $$\begin{aligned} K_{sb} &= K_D \\ K_D \times \omega_{sb} &= K_P \times \delta\theta_l \end{aligned} \quad (2)$$

  where K_D is the PID derivative gain, and K_P is the PID proportional gain.

  In practice, the control torque at pointing threshold is continuous when switching from large to small pointing error. It is not from small to large pointing error due to the integrator state. At this transition, the switch always generates a small discontinuity of the control torque, which is compatible with the required performance.

- a FEEPs selection logic. This algorithm is common with Acceleration Control Mode and some elements will be given in section 5.
- a sensor measurement loss management. In case of short loss of measurements, the states and outputs of the estimation filters and FEEP controllers are frozen. After a 2-second loss, the control torques are set to zero, and the FDIR strategy apply.

With this control loop, the pointing accuracy is 0.04 degree on each axis.

Preliminary simulations prove the robustness of the control to one EPSA failure.

3.4. Accelerations Control Mode (MCA)

Accelerations Control Mode is completely new in terms of objectives and equipments. Its main particularity is the need to provide linear acceleration control, with a very high accuracy (10^{-12} m/s² residual acceleration at F_{EP}), in addition to MYRIADE traditional 3 axes attitude control.

MCA control loop uses four EPSA of three FEEPs each to overcome force and torque disturbances. The FEEPs have a very low thrust noise above the control bandwidth : 0.1 µN/(Hz)$^{1/2}$. An autonomous DTU star tracker (from MYRIADE equipments list) and payload very accurate accelerometers provide respectively the attitude measurements and the linear and angular acceleration measurements.

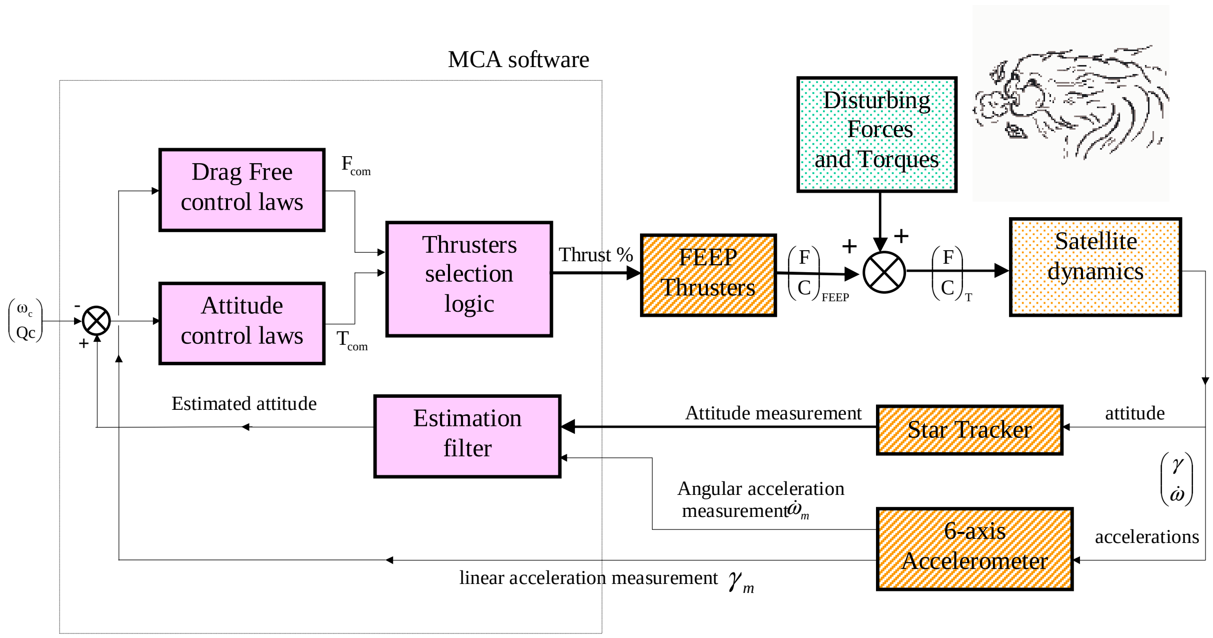

Figure 3 : MCA control loop

Limiting the perturbations on the payload is a design driver. The satellite structure and the orbit parameters have been carefully studied and chosen to achieve that goal :

- No eclipses during the 9-month-full-performance mission (no sudden solar pressure variation).
- No structural flexible mode under 4.5 Hz
- No mobile element during mission mode

With these constraints, the remaining acceleration disturbance is due to the air drag, with 25.10^{-6} / 180 = $1.4.10^{-7}$ m/s² at F_{EP} (the control objective is 10^{-12} m/s² at F_{EP}).

The MCA control loop is described on Fig. 3. It is identical for inertial, spinning and calibration modes. Only the performance requirements and the software tunings are different.

For validation and simulation purpose, a phase B Matlab®/Simulink® simulator of MCA control loop has been developed with ESCAPE software application. The MICROSCOPE specific models are related to the linear accelerations of the satellite. They apply to the following blocks :

- Satellite dynamics : the linear acceleration of the satellite centre of mass is simply derived from Newton's law. The gravity gradient between the satellite centre of mass and the accelerometer centre, the tangential and normal accelerations are then taken into account to compute the acceleration of the accelerometer centre.

- Accelerometer model : the accelerometer measurement is submitted to bias, scale factors and misalignments. Also, the measurement high frequency noise, time delay, saturation and sampling is taken into account. The accelerometer anti-aliasing filter is not included in the simulator yet, but the phase lag induced is taken into account in the controller phase margin objective.
- Drag-free controller : three linear SISO controllers compute the suitable control forces to be applied by the FEEPs to compensate for the drag. An example of the controllers robust synthesis will be presented in section 4.
- Thrusters selection logic : it is the same algorithm as in MSP, with the linear control forces in addition to the control torques for attitude control. The algorithm performance will be detailed in section 4.
- Thrusters dynamics : the FEEPs dynamics includes a first order low-pass filter. The FEEPs thrust noise and direction noise is also included.
- External perturbations : the forces (drag, including the effect of the satellite speed and the atmospheric wind, solar pressure and Earth albedo) are applied to the satellite model. Stochastic air density variations extrapolated from CHAMP in orbit data are taken into account.

Another block is specific to MICROSCOPE for performance reasons : the attitude estimation filter. It will be detailed in section 4.

4. SOME TECHNICAL POINTS

The main studies have concerned the MCA mode, with a special care to the propulsion control and actuation matrix optimisation, and the attitude and acceleration estimation.

4.1. FEEPs architecture and selection logic

The use of FEEP thrusters is a particularity of MICROSCOPE in MYRIADE product line. A lot of work has been done to make a better use of them and meet the mission stringent requirements.

The first problem is the choice of the nominal number of thrusters and their best orientations on the satellite from a AACS point of view.

- The first configurations stressed the torque capacity on X axis, because it allows the spinning down of the kinetic wheel in MSP, and the MCA or MSP spinning up. Two configurations with four pods of two or three thrusters were studied. It was shown that with eight thrusters the loss of only one reduced the minimal control capacity to zero. Thus, the configurations with four pods of three thrusters were preferred for safety reasons.
- Then the FEEPs tilt angles have been optimised to decrease the power consumption and allow the use of two FEEPs over three on the four pods simultaneously. A trade-off has been considered between the torque capacity on X and Z axis (less efficient because the EPSA are on Z walls). Mechanical constraints finally modified a little the optimum found.
- Finally the minimum control capacity with thrusters failure has been studied. It represents the minimum of the norm of forces and torques vectors applied by the thrusters in any direction, with one thruster at least at is maximal capacity. It is determined by Monte Carlo iterations. The results show that with 4 EPSA available, the minimum control capacity is 128µN and only 64 µN with 3 EPSA. This capacity is in theory just sufficient to cover the needs of the mission (estimated at 64 µN). If the simulations show a good behaviour of MSP with only three EPSA, the four EPSA configuration is preferable for safety reasons.

Then the second problem is, given the nominal configuration, to apply the suitable force on each thrusters to generate the desired forces and torques on the satellite : this software is the thrusters selection logic.

The tested logic uses an iterative algorithm. It will not be discussed here in details because a patent may be delivered about it. The time computation has been assessed to 30 ms for 20 iterations carried out on a T805 processor. It requires the presence on board of 5 tables of less than 250 parameters each (2 koctets for each table). Finally, it is quite precise, the additional error induced by the logic has been estimated less than a few micro Newton or micro Newton meters for forces and torques of several tens or hundreds micro Newton or micro Newton meters.

This algorithm is also used in the MSP mode for torque generation.

4.2. MCA FEEPs control laws

Robust control laws (for both linear and angular movement) have been designed to provide the necessary attenuation of disturbances at F_{EP}, and to guarantee large stability margins.

The performance requirements for linear accelerations at accelerometer centre (point A) are given in Tab. 2.

Residual linear acceleration at drag-free point A	**X**	**Y**	**Z**
Offset (without accelerometer bias) **$m.s^{-2}$**	$3.0\ 10^{-8}$	$3.0\ 10^{-8}$	$3.0\ 10^{-8}$
Random stability around F_{EP} **$m.s^{-2}.Hz^{-½}$**	$3.0\ 10^{-10}$	$3.0\ 10^{-10}$	$3.0\ 10^{-10}$
Sinusoidal stability at F_{EP} **$m.s^{-2}$**	$1.0\ 10^{-12}$	$1.0\ 10^{-12}$	$1.0\ 10^{-12}$
Max over the AACS bandwidth] 0-0.1 Hz] **(m/s^2)**	$1.25\ 10^{-6}$	$1.25\ 10^{-6}$	$1.25\ 10^{-7}$

Table 2 : Linear accelerations control requirements

The attitude control requirements for inertial and spinning modes are respectively given in Tab.3 and Tab.4.

Inertial Mode	**X**	**Y**	**Z**
Mean Pointing error (rad)	$2.0\ 10^{-4}$	$1.0\ 10^{-4}$	$1.0\ 10^{-4}$
Sinusoidal ang. stab. at F_{EP} (µrad)	8.8	8.8	8.8
Sinusoidal ang. stab. at 3 F_{EP} (µrad)	2	2	2
Random ang. stab. around F_{EP} ($rad.Hz^{-1/2}$)	$2.6\ 10^{-3}$	10^{-3}	10^{-3}
Max. residual ang. velocity ($rad.s^{-2}$)	$1.25\ 10^{-6}$	$1.25\ 10^{-6}$	$1.25\ 10^{-6}$

Table 3 : attitude control requirements in MCAi

Spinning Mode	**X**	**Y**	**Z**
Mean Pointing error (rad)	$2.0\ 10^{-4}$	$1.0\ 10^{-4}$	$1.0\ 10^{-4}$
Sinusoidal ang. stab. at F_{EP} (µrad)	0.166	0.166	0.166
Sinusoidal ang. stab. at 3 F_{EP} (µrad)	2	2	2
Random ang. stab. around F_{EP} ($rad.Hz^{-1/2}$)	$1.59\ 10^{-4}$	$1.59\ 10^{-4}$	$1.59\ 10^{-4}$
Max. residual ang. velocity ($rad.s^{-2}$)	$1.25\ 10^{-6}$	$1.25\ 10^{-6}$	$1.25\ 10^{-6}$

Table 4 : attitude control requirements in MCAs

The controllers are designed to ensure sufficient rejection of sinusoidal perturbation (force and torque) at F_{EP}. Maximum perturbation allowed at controller output is calculated from the general specifications:

- Linear acceleration : $1{\cdot}10^{-12}$ m/s^2 between F_{EP} -F_{orb}/2 and F_{EP} +F_{orb}/2, with F_{orb} the orbital frequency.
- Angular acceleration : $5{\cdot}10^{-12}$ rad/s^2 (MCAi) or $3{\cdot}10^{-12}$ rad/s^2 (MCAs) between F_{EP} -F_{orb}/2 and F_{EP} +F_{orb}/2

On the other hand, maximum perturbation at the input has been estimated to 25 µN and 2.5 µN.m (aerodynamic force and torque). Thus, the following gains are required on the band (F_{EP} -F_{orb}/2, F_{EP} +F_{orb}/2) :

- $\gamma_{out}/\gamma_{pert}$= -103 dB
- $\dot{\omega}_{out} / \dot{\omega}_{pert}$ = - 88 dB (MCAi) or -93 dB (MCAs)

In addition to this, a 40 degrees phase margin is demanded for the whole control loop. This requirement is especially severe for the linear acceleration controller, introduces as much as 57deg/(rad/s) of phase lag. With a reasonable bandwidth fixed at 0.3 rad/s, the phase margin required for the controller is 40+57×0.3=65 degrees, which corresponds to a delay margin of 3.8 seconds.

In order to comply with such severe requirements, an H_∞ design approach was chosen. Fig. 4 shows the linear control loop rewritten in standard 4 blocks H_∞ form :

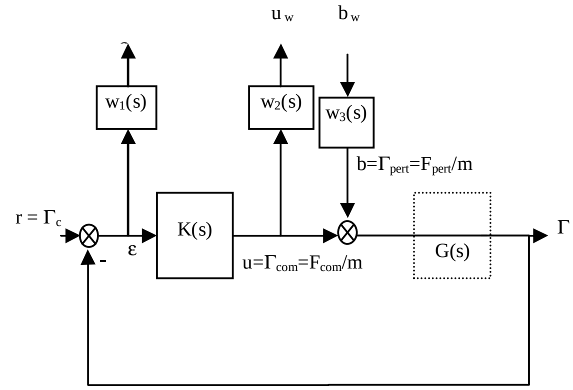

Figure 4 : AACS linear synthesis control loop

The satellite is modelled by its mass *m*, which is used to scale the control and disturbances forces.

The target transfer Γ / Γ_{pert} turns out to be equivalent to ε / b, one of the four transfers of the standard H_∞ problem. Consequently, it can be constrained by the functions $1/w_1(s)$ and $1/w_3(s)$, which are then used to impose the aforementioned requirements for the linear controller of MCAi.

The problem is solved using a Riccati solver (γ=1.37) and the controller obtained complies with the specifications (Fig. 5).

The attitude controllers design follows the same principle, except that the control loop is more complex (the satellite model is a double integrator scaled by inertia matrix diagonal coefficients, and the estimation filter must be included).

Finally, the coupling effects between axes, mainly due to the distance between the satellite centre of mass and the accelerometer measurement centre, must be evaluated (pumping has been observed on simulations). The need for MIMO controllers has to be analysed.

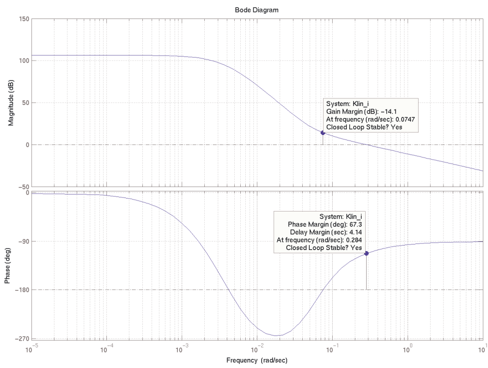

Figure 5 : linear controller Bode diagram

4.3. MCA Attitude and acceleration estimation

The attitude and angular acceleration estimation is an important issue in the performance achievement, first because of the very high stability required at F_{EP} frequency and because of the observation duration (120000 seconds (20 orbits) for spinning mode, 720000 seconds (120 orbits) for inertial mode).
The payload measurements provides the linear and angular accelerations whereas the star tracker provides the angular positions. The linear accelerations are directly used by the linear controllers. The star tracker angular measurements are mixed with the accelerometers angular accelerations in a Kalman filter to reach the angular accuracy at F_{EP}.

The main problem is linked to the star tracker measurement error at F_{EP}. The main part of this error comes from internal thermoelastic error and thermoelastic disturbance between the star tracker and the accelerometers. Some minor parts are linked to optical pollution by Earth and residue of relativistic errors. The expected values are 2.2 µrad at F_{EP} = 0.006 rad/s in spinning mode, and 10 µrad at F_{EP} = 0.001 rad/s in inertial mode. To be compliant to the specification with a contribution of 50% due to estimation errors, the estimation gain of the transfer function between the star tracker measurement and the estimated angular position must be :

- -30 dB for spinning mode to reach 0.166/2 µrad
- -8 dB for inertial mode to reach 8.8/2 µrad

This means that at F_{EP} frequency, the accelerometer must provide the measurement for the estimation :

- The first solution is to force a very low hybridisation frequency for the Kalman filter. This solution was successful in inertial mode, but was inefficient in spinning mode because of the coupling transfers.
- The second solution is to estimate the thermoelastic sine by adding a oscillator in the Kalman filter dynamics, as shown in Eq.3. This solution has been applied to both inertial and spinning modes.

$$\begin{aligned} \theta_{STR} &= \theta_{SAT} + \nu + x \\ \ddot{x} &= -(2\pi F_{EP})^2 x \end{aligned} \qquad (3)$$

with θ_{SAT} the real satellite angular position, θ_{STR} the star tracker measurement, ν the star tracker measurement noise and x the thermoelastic oscillator.

The synthesis result for spinning mode is shown in Fig. 6. At F_{EP}, the accelerometer provides the measurement, while the star tracker is attenuated under -30 dB.

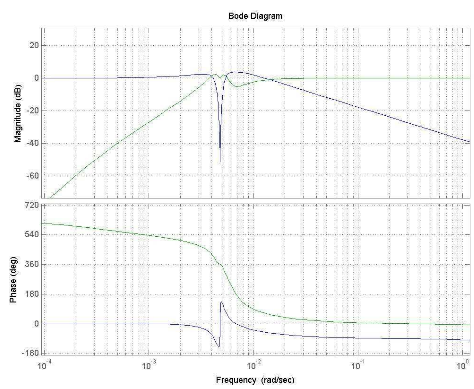

Figure 6 : Estimator transfers $\theta_{est}/\theta_{STR}$ (blue) and $\theta_{est}/\theta_{acc}$ (green)

Actually, on Fig. 6, two oscillators are used to cope with an additional requirement : the attenuation must apply to a “large” frequency interval around F_{EP} to be compatible with the post-treatment shaping function ($\pm 1.3.10^{-5}$ Hz).The Bode diagram shows that the -30dB attenuation is valid in the [F_{EP}-$1.3.10^{-5}$; F_{EP}+$1.3.10^{-5}$] Hz band.

The estimation studies are still going on, to address the problem of a larger thermoelastic error (20µrad instead of 2µrad), and the convergence transient duration problem, which may require a succession of filters with increased performance.

5. CONCLUSION

In this paper, an innovative AOCS has been described for drag-free control on a CNES MYRIADE satellite. The very high level of performances required by the scientific payload led to several adaptations of MYRIADE avionics, in particular the use of FEEPS to produce control forces and torques, and the use of the payload measurements to control linear and angular accelerations. The AACS architecture has been tested. Studies are going on to validate it , in particular on the two following points : the attitude estimation with larger star tracker disturbance at F_{EP} and the need for controllers coupling. The AACS concept will then be validated through exhaustive simulation campaigns, and the on-board algorithms will be completed with FDIR logic.

6. REFERENCES

Guiu E., Rodrigues M., Touboul P. and Pradels G., *Calibration of MICROSCOPE*, to be published in Advances in Space Research.

Fallet C., Le Du M., Pittet C., Prieur P., Torres A., *First in-orbit results from DEMETER*, in Proc. 28th annual AAS Control and Guidance Conference, February 2005.

Le Du M., Maureau J. and Prieur P., *Myriade : an adaptative concept*, in Proc. 4th GNC ESA, Frascati, 2002.

Pittet C. and Fallet C., *Gyroless attitude control of a flexible microsatellite*, in Proc. DCSSS'02, Cambridge, 2002.

Touboul P., Rodrigues M., Métris G., Tatry B., *MICROSCOPE, testing the equivalence principle in space*, CR Académie des Sciences Paris, T2, série IV, pp1271-1286, 2001.