MEETING MICROSCOPE'S SPECIFIC ATTITUDE-GUIDANCE REQUIREMENTS BUILDING UPON MYRIADE SATELLITE-FAMILY'S INHERITANCE

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This paper presents some of the specific and major attitude guidance characteristics of MICROSCOPE, a fundamental physics mission whose main objective is testing the Equivalence Principle by measuring the differential acceleration induced by pure gravity on two test bodies of different mass and composition. Both ground and space segments are based on MYRIADE, CNES's microsatellite product family. However MICROSCOPE exhibits several specificities with respect to MYRIADE in terms of satellite hardware, operational concept and attitude guidance requirement, which make the whole mission a real challenge. This paper will present the design choices that were made by CNES to meet the attitude guidance requirements with the existing MYRIADE's flight and ground software capabilities.

Keywords: *TC generator, Attitude-guidance, Slew,*

1. Introduction

MICROSCOPE is to be launched by mid-2016. To this date the attitude guidance TC generator software is fully developed and validated. The interest of this paper is hence twofold:

- To present some of the specific and major attitude-guidance characteristics of MICROSCOPE.
- To present the design choices that were made by CNES to meet the original attitude guidance requirements of MICROSCOPE, on the basis of MYRIADE's recurring flight-dynamics software family product.

To this aim, the paper will go through:

- An introduction to the classical MYRIADE attitude-guidance design and TC generator software.
- A brief description of the MICROSCOPE mission and the basics of the operational concept to prepare the discussions on the specific MICROSCOPE attitude-guidance requirements and challenges.
- The major challenges addressed:
  - The creation of a new quasi-inertial attitude-guidance reference frame specifically designed for the mission and its associated attitude laws.
  - The design of the slew strategies between attitude-laws, including reference frame "switch" in the case of transitions between "Mission and Servitude" attitude-laws.

2. MYRIADE Attitude Guidance Principles

2.1. Guidance Laws

MYRIADE's attitude-guidance principle is based on angular velocity laws along with an initial quaternion, which are uploaded to the spacecraft via dedicated TCs. The attitude law is then computed on-board at 4Hz by first calculating the angular velocity vector and then propagating the attitude quaternion based on the classical kinematics equation:

$$\dot{Q}_{cons}(t) = \frac{1}{2} Q_{cons}(t) * \vec{\Omega}_{cons}(t) \tag{1}$$

There are two possible forms for the angular velocity law: harmonic and polynomial:
The harmonic form is given by the following equation:

$$\vec{\Omega}_{\mathrm{cons}}(\mathrm{t}) = \left| \begin{array}{l} \Omega_{\mathrm{X}}(t) = \sum_{\mathrm{i}=0}^{\mathrm{N}} \left(\mathrm{a}_{\mathrm{xi}}.\cos(\mathrm{i}.\alpha) + \mathrm{b}_{\mathrm{xi}}.\sin(\mathrm{i}.\alpha) \right) \\ \Omega_{\mathrm{Y}}(t) = \sum_{\mathrm{i}=0}^{\mathrm{N}} \left(\mathrm{a}_{\mathrm{yi}}.\cos(\mathrm{i}.\alpha) + \mathrm{b}_{\mathrm{yi}}.\sin(\mathrm{i}.\alpha) \right) \\ \Omega_{\mathrm{Z}}(t) = \sum_{\mathrm{i}=0}^{\mathrm{N}} \left(\mathrm{a}_{\mathrm{zi}}.\cos(\mathrm{i}.\alpha) + \mathrm{b}_{\mathrm{zi}}.\sin(\mathrm{i}.\alpha) \right) \end{array} \right. \tag{2}$$

With :

$$\alpha(t) = \alpha_0 + \omega_{orb} \cdot (t - t_{pso}) \tag{3}$$

The fundamental frequency for the harmonic law is the mean orbital frequency calculated over one day. It allows computing the mean satellite PSO (Position On Orbit) as per Eq. 3 which is required in turn to compute the harmonic law.
The order considered for Fourier's decomposition of the attitude- guidance signal is either 2 or 3.

The polynomial form is given by the following equation:

$$\vec{\Omega}_{\mathrm{cons}}(\mathrm{t}) = \left| \begin{array}{l} \Omega_{\mathrm{X}}(t) = \sum_{\mathrm{i}=0}^{\mathrm{N}} \mathrm{a}_{\mathrm{xi}} \cdot \left(\frac{t - t_0}{\Delta t} \right)^i \\ \Omega_{\mathrm{Y}}(t) = \sum_{\mathrm{i}=0}^{\mathrm{N}} \mathrm{a}_{\mathrm{yi}} \cdot \left(\frac{t - t_0}{\Delta t} \right)^i \\ \Omega_{\mathrm{Z}}(t) = \sum_{\mathrm{i}=0}^{\mathrm{N}} \mathrm{a}_{\mathrm{zi}} \cdot \left(\frac{t - t_0}{\Delta t} \right)^i \end{array} \right. \tag{4}$$

All the parameters in the above equations are computed by the TC generator software on the ground. The polynomial form is used for slew, while the harmonic form is typically used for geocentric, heliocentric, or inertial guidance laws.

2.2. Reference Frames

The reference frame in which is expressed the attitude-guidance law is either J2000 or the ROL (Local Orbital Reference Frame).
The ROL is defined as follow, from the satellite Position and Velocity vectors:

$$\vec{Y}_{ol} = -\frac{\vec{P} \wedge \vec{V}}{\left\| \vec{P} \wedge \vec{V} \right\|}, \quad \vec{Z}_{ol} = -\frac{\vec{P}}{\left\| \vec{P} \right\|}, \quad \vec{X}_{ol} = \vec{Y}_{ol} \wedge \vec{Z}_{ol} \tag{5}$$

The ROL is also modelled according to a harmonic law similar to Eq. 1.

2.3. Classical Operational Concept & Guidance TC plan

The typical horizon for the TC plan is one week, split into seven one-day-long harmonic laws' TC. In addition, this plan is recomputed twice per week based on the latest orbit restitution in order to refresh the attitude-guidance law on-board.

3. Microscope Mission

3.1. Overview of the Mission

The scientific objective of MICROSCOPE is to test the equivalence principle with an accuracy of 10e-15. This will be done by measuring the differential acceleration induced by gravity solely on two cylindrical and quasi concentric test bodies of different mass and composition. In order for the test masses to be perfectly in "fee-fall", the satellite must be controlled very accurately in order to maintain the masses perfectly centered, which amounts to compensate all non-gravitational surface forces. As a matter of fact, the accelerometer is at the same time the instrument of the mission and the key 6 degree-of-freedom inertial sensor for the control loop. More over cold gas micro-propulsion system ensures the continuous and accurate actuation required for the task.

The selected orbit is a dusk sun-synchronous orbit (local time at ascending node 6pm) with an altitude of around 700km

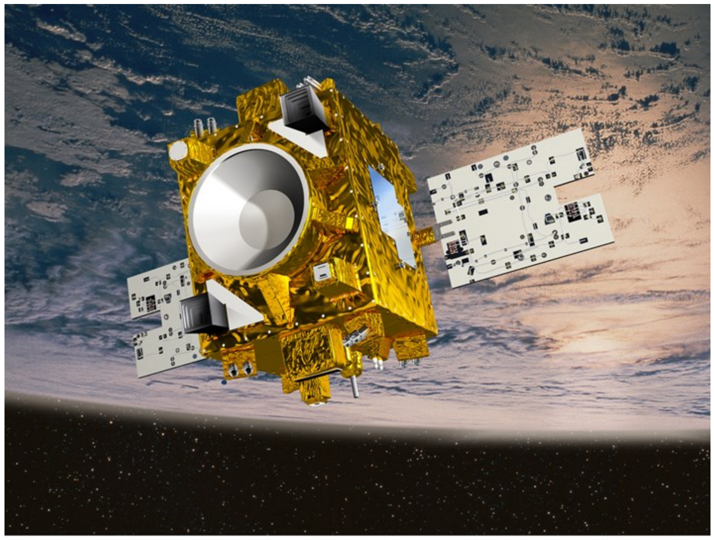
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Figure 1. MICROSCOPE satellite

3.2. MICROSCOPE's Operational Concept

The mission operational concept is completely different from the classical MYRIADE's one which has been introduced in **§2.3**.
Mission programming relies on a key file called "work-scenario", which circulates between the CMS-M (MICROSCOPE's Science Mission Center), the CECT (Expertise Center for Drag Compensation), and the CCC (Command & Control Center). This file identifies and accurately plans the different sequences (sessions ant transitions) in progress, to be programmed and to come.
The science mission is achieved strictly speaking through the succession of the scientific sessions, each of which is characterized by:

- A specific attitude guidance law
- Several parameters for the configuration of the instrument
- Several parameters for the configuration of the AOCS controller

From the attitude guidance point of view, all the TCs must be executed solely during the transition sequence preceding a scientific session. Within the scientific session, the attitude law cannot be refreshed and no slew is allowed.

Once per week, the automatic TC generator needs to program the set of sessions flagged "C" (i.e. confirmed). The design approach which has been adopted is the following:

- The TC generator receives the set of sessions to be programed for the coming 2 weeks via a dedicated file, itself created automatically from processing the "work scenario"
- For each sequences couple (transition / session), the TC generator analyses the type of guidance law.
- Then it detects in its own guidance history files the last guidance law programmed, in order to determine the appropriate slew when needed.
- Finally it generates a dedicated TC file for each couple to be programmed

3.3. Attitude Guidance Fundamental Requirement and the RNI frame

A fundamental need of the mission is to maintain the sensitive axis of the instrument in the "mean" orbital plane of the sun-synchronous orbit. Thus the classical ROL is not suited for the task as its calculation is based on the osculating orbital plane rather than a mean plane.

This made necessary to define a new mission reference frame called **RNI (Inertial Nodal Reference frame)** as follow:

- X axis is orthogonal to the mean orbital plane, oriented towards the Sun side
- Z axis is the mean ascending node direction,
- Y is the cross product of Z by X

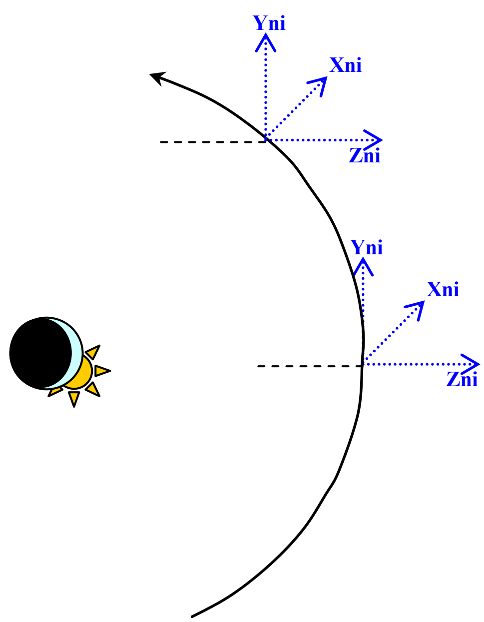

Figure 2. RNI (Inertial Nodal Reference Frame)

3.4. Calculation Method for the RNI

The calculation of the RNI is based on the following steps:

1) Generation of Position/Velocities ephemerides in CNES's Veis (G50) Reference Frame on a specific time interval equal to the duration of the scientific session to program.

2) Calculation of the normal to the orbital plane:

$$\vec{N}_{omega}(t_n) = \frac{\vec{P}(t_n) \wedge \vec{V}(t_n)}{\left\| \vec{P}(t_n) \wedge \vec{V}(t_n) \right\|} \tag{6}$$

3) Parameterization of the normal in terms of "longitude" and "co-latitude" angles:

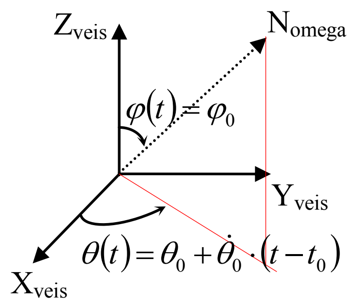

Figure 3. Parameterization of Nomega

$$\varphi(t_n) = \cos^{-1}\left(\vec{N}_{omega}(t_n) \cdot \vec{Z}_{Veis}\right) \tag{7}$$

$$\theta(t_n) = \arctan 2\left(\frac{\vec{N}_{omega}(t_n) \cdot \vec{Y}_{Veis}}{\vec{N}_{omega}(t_n) \cdot \vec{X}_{Veis}}\right) \tag{8}$$

4) Least-square fit on $\{\theta_n\}_n$ to derive the linear model of the sun-synchronous precession of the orbital plane:

$$\theta(t_n) = \hat{\theta}_0 + \hat{\dot{\theta}}_0 \cdot (t_n - t_0) \tag{9}$$

5) Calculation of $\hat{\varphi}_0$ as the arithmetic mean of $\{\varphi_n\}$

6) Computation of the RNI axes as follow :

$$\begin{array}{lll} X^{RNI}_{X\_Veis}(t) = \sin[\hat{\varphi}(t)] \cdot \cos\left[\hat{\theta}(t)\right] & Z^{RNI}_{X\_Veis}(t) = -\sin\left[\hat{\theta}(t)\right] & \\ X^{RNI}_{Y\_Veis}(t) = \sin[\hat{\varphi}(t)] \cdot \sin\left[\hat{\theta}(t)\right] & Z^{RNI}_{Y\_Veis}(t) = \cos\left[\hat{\theta}(t)\right] & \vec{Y}_{RNI} = \vec{Z}_{RNI} \wedge \vec{X}_{RNI} \\ X^{RNI}_{Z\_Veis}(t) = \cos[\hat{\varphi}(t)] & Z^{RNI}_{Z\_Veis}(t) = 0 & \end{array} \tag{10}$$

The corresponding quaternion can be calculated from the RNI axes. However we are only interested by the value at t0, thus:

$$Q_{RNI\_Init} = Q_{veis \to RNI}(t_0) \tag{11}$$

7) Calculation of the angular velocity law. We have:

$$\vec{\Omega}_{RNI/J2000} = \vec{\Omega}_{RNI/Veis} + \vec{\Omega}_{Veis/J2000} \tag{12}$$

But we can consider that on the adjustment interval the angular velocity of Veis reference frame is nearly null (the real value is related to the precession and nutation of the Earth's rotation axis) and therefore:

$$\vec{\Omega}_{RNI/J2000} \approx \vec{\Omega}_{RNI/Veis} \tag{13}$$

From the parameterization of the RNI in Veis reference frame, we have:

$$\vec{\Omega}_{RNI/Veis} = \dot{\hat{\theta}}_0 \ \vec{Z}_{Veis} \tag{14}$$

Since the Veis reference frame is considered constant over the adjustment interval, it is relevant to choose the mid adjustment date for calculating $\vec{Z}_{Veis}$ in J2000:

$$\left(\vec{\Omega}_{RNI/Veis}\right)_{J2000} = \dot{\hat{\theta}}_0.\left(\vec{Z}_{Veis}\left(t_{med}\right)\right)_{J2000} = cs\vec{t} \tag{15}$$

8) Finally, it is necessary to express the angular velocity vector with respect to the RNI axes:

$$\left(\vec{\Omega}_{RNI/J2000}\right)_{RNI} = \overline{Q}_{RNI\_init} * \left[0,\ \left(\vec{\Omega}_{RNI/Veis}\right)_{J2000}\right] * Q_{RNI\_init} \tag{16}$$

Since the RNI kinematics correspond to a slow precession of the orbital plane at the mean sun-synchronous period, the harmonic law can perfectly be used, and thus new TC have been defined for the RNI with the exact same structure as the ROL TC. This design choice helped to keep the flight software upgrade to a low complexity.

3.5. MICROSCOPE's Specific Guidance Law.

Three types of guidance laws have been defined for the science mission:

- The so called Inertial guidance, which is in reality a fixed attitude law with respect to the RNI.
- The Spin guidance, where the satellite is spun at constant speeds around its x axis, with respect to the RNI

- The Sinusoidal guidance, which corresponds to small oscillations of the satellite's attitude around its X, Y or Z axis with respect to an inertial reference attitude in the RNI.

The first two types are used for the measurement of the equivalent principle signal, while the sinusoidal guidance law is required for the calibration of the instrument.

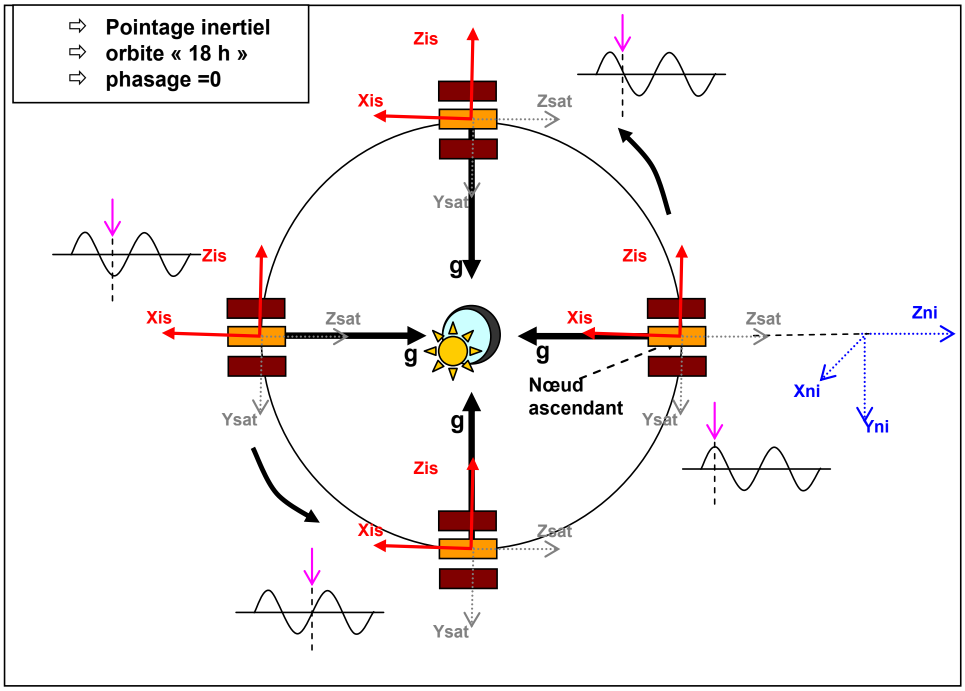

Figure 4. Inertial attitude-guidance law in the RNI

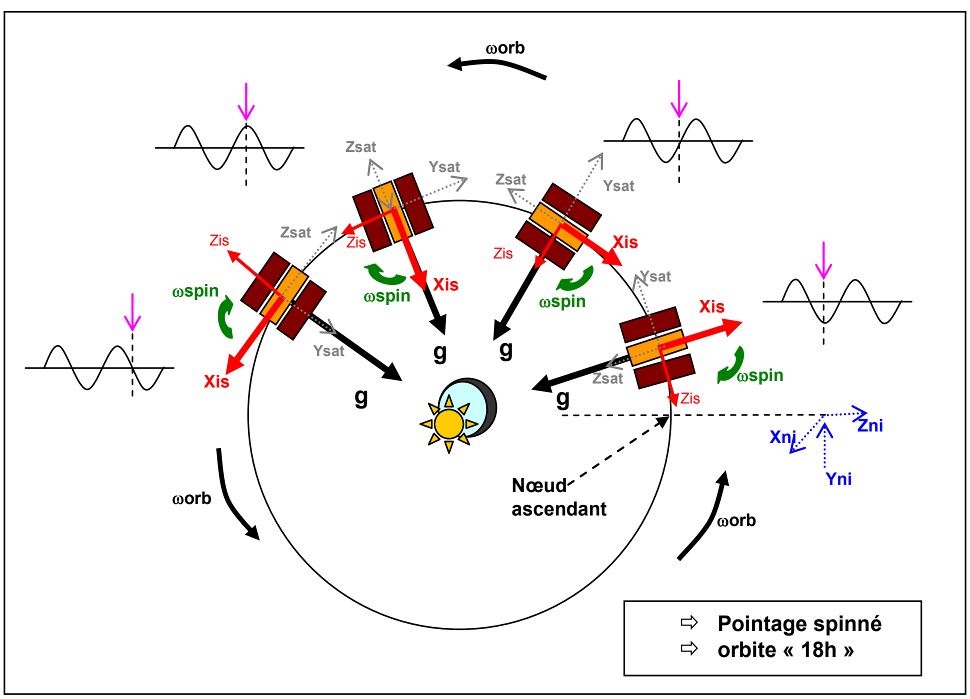

Figure 5. Spun attitude-guidance law in the RNI

The inertial and spin attitude-guidance laws are loaded through the classical harmonic guidance TC without any difficulty.
However, it has been necessary to define a new TC type for the sinusoidal guidance, which did not exist for previous missions. The usage of this TC is given below:

$$\vec{\Omega}_{cons} = \begin{pmatrix} a_x.\sin\left[\omega_x.(t-t_0)+\varphi_x\right] \\ a_y.\sin\left[\omega_y.(t-t_0)+\varphi_y\right] \\ a_z.\sin\left[\omega_z.(t-t_0)+\varphi_z\right] \end{pmatrix} \tag{17}$$

Apart from the 3 science mission guidance laws which have just been presented, MICROSCOPE also possesses two servitude guidance laws which are used during periods of mission unavailability.
Such periods occur typically for two different reasons:

- A bit less that once per month when the moon crosses the field of view of the Star-Tracker. This type of unavailability lasts a few days.
- During the eclipse season which lasts a couple of month, and which breaks the thermal stability necessary to reach the required measurement accuracy.

During these periods, it is necessary to preserve gas and therefore the satellite is switched to a magnetically controlled AOCS mode (based on magnetometers and magnetotorquers). The pointing performance in this mode is quite low, and therefore a specific guidance law with respect to the ROL called "conical-spun is applied in this mode.
Basically, the satellite x-axis which is otherwise always orthogonal to the orbital plane is tilted by 10° towards the Earth, so that when the satellite completes a full orbit the tilted x-axes generates a cone in space (hence "conical"). A the same time, the satellite is spun at 3 times the orbital pulsation (or 2 times with respect to the ROL) around the same x axis in order to acquire some gyroscopic stiffness.

To rally the conical-spun attitude law from the mission inertial attitude law, it is necessary to transit through an intermediary geocentric attitude with respect to the ROL.
The following figure illustrates the geocentric attitude, and the "conical" part only of the "conical-spun" attitude.

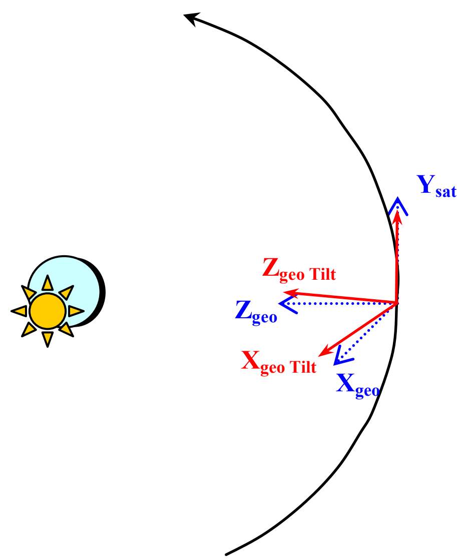

Figure 6. Geocentric Attitude in blue, and Conical-(Spun) Attitude in red

3.6. MICROSCOPE's Slew Strategies

In this paragraph, the slew strategies designed to transit between the different attitude-laws which have been previously introduced (mission or servitude) will be presented.

MYRIADE has a specific slew library to compute 3 axis slews based on reaction wheels actuation. It is possible to specify the kinematics constraints at the extremities of the slew, and several calculation modes exist. In some cases, it is required to proceed iteratively for a solution to be found.
However for MICROSCOPE, the decision was made to implement dedicated slew methods which allow:

- To express analytically the maximum acceleration in function of the slew duration very easily
- To perfectly control the slew profile given some initial and final kinematics constraints, and hence to minimize the energy of the slew, or in other words the gas consumption which is the key resource of the scientific mission.
- To control the attitude path analytically in case of transitions between mission and servitude guidance laws, which avoid the dependency on numerical iterative calculations.

The next figure represents the slew combinatory between the different servitude and mission attitude-laws .

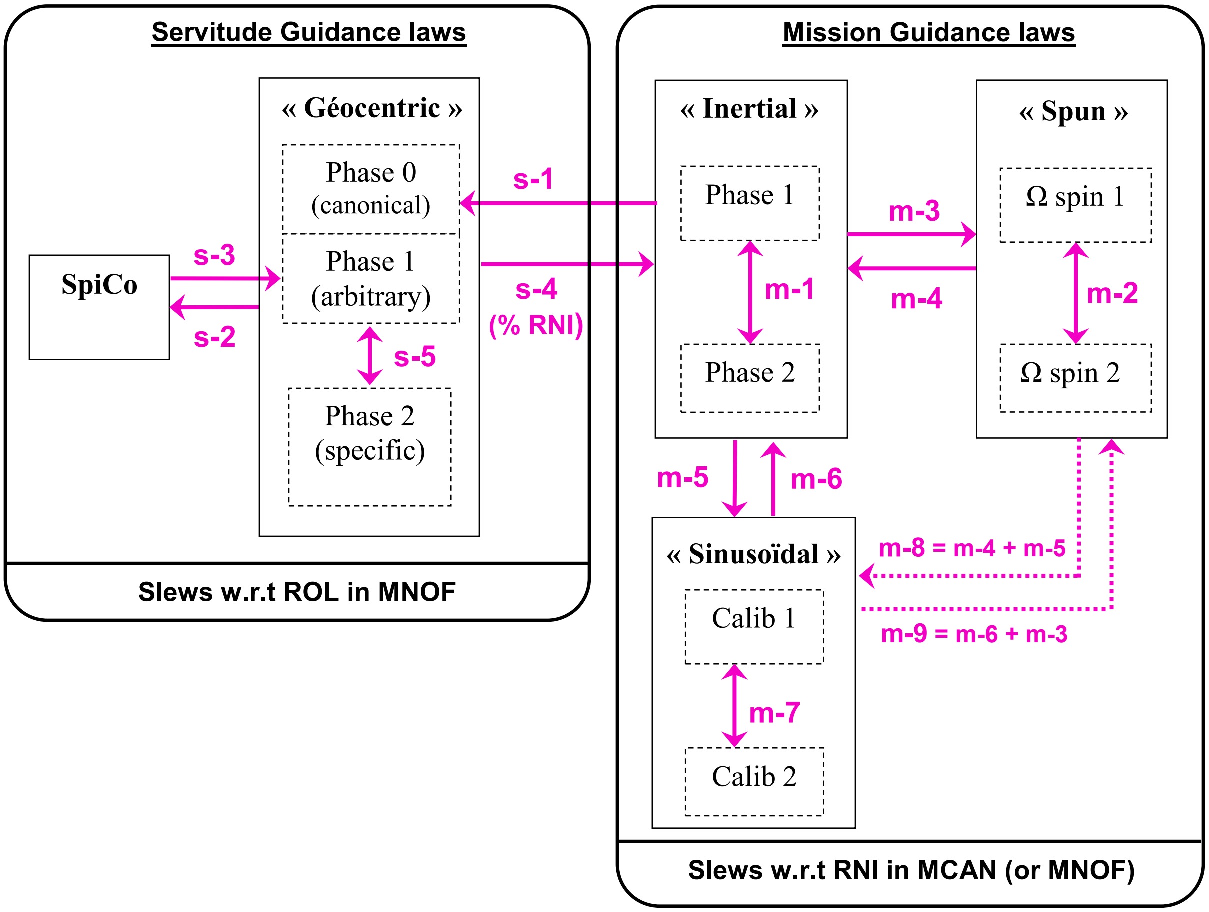

Figure 7. Slew combinatory between servitude and mission attitude laws

The diagram shows that the slew can functionally be classified into 3 categories:

- Slew between mission attitude-guidance laws
- Slew between mission and servitude attitude-guidance laws
- Slew between servitude attitude-guidance laws

However, from a practical point of view, all these possible slew can be reduced to two and and half forms:

- **A)** A change of angular phase around a single axis: this type of slew is characterized by a null initial and final velocity and a null and final acceleration, with continuity in acceleration.
- **B)** A change of spin velocity: this type of slew is characterized by a null initial and final acceleration, and a different initial and final spin velocity, one of which can be null thus corresponding to the set-up or the cancellation of a spin attitude law, with continuity in acceleration.
- **C)** A spin cancellation (i.e. technically a subcase of above) but with a specified final angular phase.

A) The polynomial for a pure change of angular phase around a single axis, with *x* being the normed variable of the slew in the range [0 ; 1], is given below. It is straightforward to check that both angular velocity and acceleration are null at the extremities of the slew:

$$\vec{\Omega}(x) = \frac{30\overline{\theta}}{T}\left(x^4 - 2x^3 + x^2\right)\vec{u} \tag{18}$$

The maximum angular velocity and acceleration during the slew are given below

$$\omega_{\max} = \frac{15}{8}\frac{\left|\overline{\theta}\right|}{T} \tag{19}$$

$$\dot{\omega}_{\max} = \frac{10}{\sqrt{3}}\frac{\left|\overline{\theta}\right|}{T^2} \tag{20}$$

B) The polynomial for a pure change of angular velocity (spin) around a single axis, with *x* the normed variable of the slew in the range [0 ; 1], is given below. It is straightforward to check that the angular acceleration is null at the extremities of the slew, and that *w_i* and *w_f* are the initial and final velocities respectively.

$$\vec{\Omega}(x) = \left[\overline{\omega}_i + \left(\overline{\omega}_i - \overline{\omega}_f\right)\left(2x^3 - 3x^2\right)\right]\vec{u} \tag{21}$$

The maximum angular velocity and acceleration during the slew are given below

$$\omega_{\max} = \max\left(\left|\overline{\omega}_i\right|, \left|\overline{\omega}_f\right|\right) \tag{22}$$

$$\dot{\omega}_{\max} = \frac{3}{2}\cdot\frac{\left|\overline{\omega}_f - \overline{\omega}_i\right|}{T} \tag{23}$$

C) The polynomial for a cancellation of spin with a specific final phase is the same as the previous case. However the slew algorithm calculates a synchronization delay, whose maximum possible duration is the spin period. The calculation is based on the relation between the initial and final velocity and the associated angular excursion given by the following equation:

$$\overline{\theta} = \frac{T}{2}(\overline{\omega}_i + \overline{\omega}_f) \tag{24}$$

Thus, the slew starts at the right initial angular phase so that at the end of the minimum energy de-spin slew, the final phase is equal to the specified one.

Note that if a general polynomial had been used, the slew would not be minimal in energy (as is the case for other CNES missions) and it may not even be achievable in all cases.

Finally the angular velocity guidance-law is then computed as follow from all the above polynomials:

$$\vec{\omega}(t) = \vec{\Omega}\left(\frac{t - t_0}{T}\right) \tag{5}$$

In the context of the transition between science mission attitude-guidance laws, it is to be noted that these slews are driven in the RNI, not in J2000.
But during every transition between mission attitude laws, even in the case of a mere “refresh”, the RNI is systematically recalculated to fit the scientific measurement session to come. This creates a very small attitude step with respect to J2000, which is easily absorbed by the controller. This design choice made the slew strategy simpler to manage and to implement than the solution of calculating the slew directly into J2000.

In the context of the transition between mission and servitude attitude-guidance laws, the previous idea was taken one step further.
Indeed, the particularity of these transitions is that they require a “switch” from the RNI to the ROL and conversely. To simplify this process, a first order approximation has been made, namely that such a switch is equivalent to consider that the initial fix attitude-law in the first reference frame can be seen as a relative constant spin at the mean orbital pulsation in the second reference frame. Moreover, it amounts to consider that the osculating and the mean orbital planes are close enough.
It turns out that these approximations leads in the worst case to an attitude step of around 1°, however this is easily damped by the AOCS controller in this robust mode, and this design strategy has made the transition between the two reference frames natural and straightforward.

4. Conclusion

MICROSOPE is a microsatellite mission with big ambition. Based on MYRIADE, CNES’s microsatellite product family, the design of all the subsystems has been a real challenge.
In this paper, we have shown some of the aspects of the attitude guidance requirements and constraints, as well as the approach that was taken to address them.
Although some significant upgrades of the TC generator were required in terms of new guidance capabilities, they were made taking into account the existing software’s architecture and philosophy in order to minimize cost and complexity.
To this date, the TC generator has been fully validated and is operational for the future launch of the satellite expected by mid-2016.

5. References

[1] Walker-Deemin, A. « Spécification de la génération des TC par G2 pour MICROSCOPE », MIC-SME-TH_GTC-5075-CN - v4.3

[2] CNES, « Spécification de la génération des TC par G2 pour MYRIADE »,
μST-SP-S-4-1036-CNS - v3.5

[3] CNES, « Spécifications de besoins du package GTC », GTC-SB-CM-3357-CN - v2.3