GUIDANCE, NAVIGATION & CONTROL OF THE N3SS MISSION

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ABSTRACT

N3SS is a triple Cubesat planned for a launch in December 2022. This in-orbit demonstrator will embed a miniaturized Software Developed Radio-Frequency payload that will measure signals received in L and S bands. CNES, the French space agency, has been developing this satellite with the support of U-Space, a French company provider of next-generation nanosatellites.

To fulfil its mission, several GNC functions are needed. They include an active attitude determination and control system, an onboard autonomous guidance function and an adapted orbit computation that will be explained, described and illustrated in this paper.

The attitude control is based on an original and robust strategy allowing 3-axis pointing with respect to all kinds of guidance profiles, only based on magnetometer measurement. The description of this control strategy is given in this paper to emphasize its advantages compared to standard coarse pointing concepts based on the hybridization of solar, magnetic and gyro measurements.

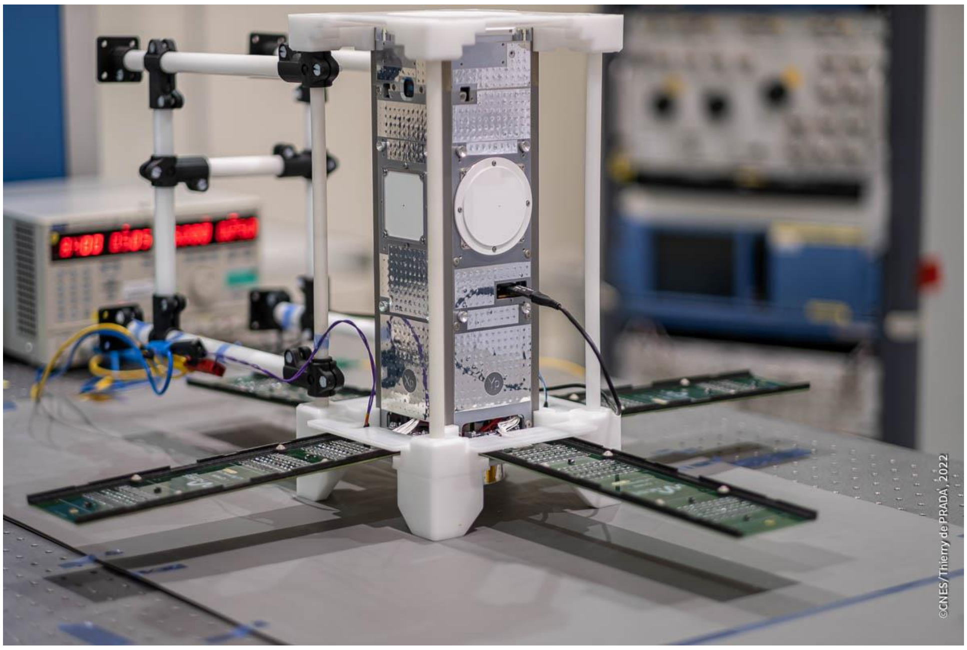

Figure 1. N3SS

1 MISSION PRESENTATION

1.1 Satellite description

N3SS is a 3U-CubeSat, technological demonstrator managed by CNES (French Space Agency). Figure 1 and Figure 2 show the satellite, which is notably composed of four deployable solar panels, two S-band patch antennae for platform telemetry and telecommand, one X-band patch-antenna for the download of the Radio-Frequency payload telemetry and a GNSS antenna for localization purposes. For attitude control purposes, the satellite is equipped with two magnetometers and three sun sensors as sensors and with three magnetorquers and four reaction wheels for actuation.

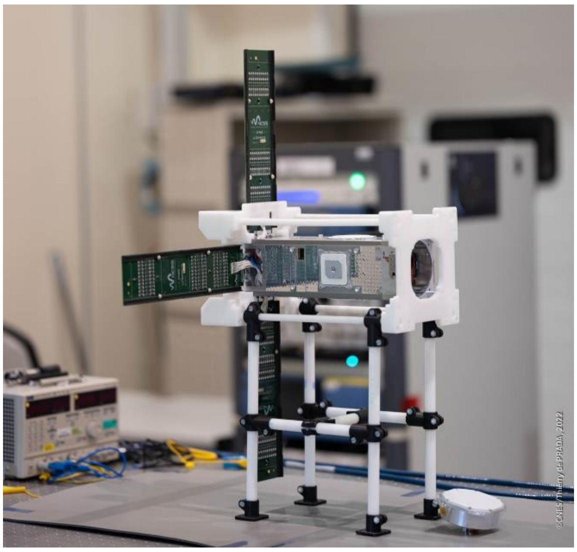

Figure 2: N3SS

1.2 Satellite modes

N3SS' mission will feature the following phases, also called satellite modes:

- Safe: this phase is used after separating from the launcher or in case of on-board anomaly detection. Its aim is to stabilize the satellite so that the solar panels face the Sun in order to ensure batteries charging. The satellite body is spun to produce a gyroscopic stabilisation and to offer a thermal balance, often called "barbecue mode". As few sensors and actuators as possible are used to minimize failure possibilities, and the pointing error can be large, but the convergence must be achieved in less than 8000 seconds to avoid a too deep discharge of the batteries.

- Standby: the satellite charges its batteries and is ready to switch to the following phases of shooting or downloading. Contrarily to the Safe phase, the satellite is 3-axis stabilized.

- Mission (Payload Measurement): the satellite is 3-axis stabilized ensuring that the payload is oriented towards the Earth.

- Downloading: during this mode, the satellite is 3-axis stabilized. The omnidirectional S-band antennae send TM to the S-band receiver on ground and receive TC. The directional X-band antenna points towards the X-band receiver on ground and sends payload data.

- Manoeuvre: Switching from a mode to another one requires an attitude manoeuvre ensuring that there is no discontinuity in the guidance profile. This manoeuvre is achieved autonomously.

2 ATTITUDE DETERMINATION AND CONTROL SYSTEM

2.1 Mission requirements

Pointing accuracy, stability and agility requirements of each satellite mode are detailed in Table 1.

Satellite Mode	Safe	Standby	Downloading	Mission	Manoeuver
Objective *Secondary objective*	**Solar panels facing the Sun** *Barbecue mode*	**Solar panels facing the Sun** *GNSS antenna oriented at best opposite to the Earth*	**X-band pointing the ground station** *Solar Panels oriented at best towards the Sun*	**Payload pointing the Earth** *Attitude around Earth direction is chosen to minimize rallying time to standby mode*	**Profile following**
Maximal Pointing error	**40°** Between normal to solar panels and the sun direction	**15°** Between normal to solar panels and the sun direction	**10°** Between the on-board antenna and the ground antenna	**10°** Between the payload and the Earth direction	**15°** *(3 axes)*
Stability	-	-	-	-	-
Temporal requirement	$t_{conv} < 8000\ sec$	-	-	-	$t_{man\_90°} < 450\ sec$
Agility			**Up to 1°/sec**	-	Up to 0,3°/sec

Table 1: N3SS mission requirements

2.2 ADCS architecture

The ADCS (Attitude Determination and Control System) architecture is inherited from the CNES EyeSat mission ([1], [2]) and is composed of two different operative modes. Figure 3 shows the different modes and their transition logic, where Launch mode (MLT) and End-Of-Life mode (MFV) are non-operative modes.

The first mode, called MAS (Acquisition and Survival Mode) is used to cover the needs of the Safe Mode of the satellite architecture. It is based on few components and a simple conception to prevent failures. Its purpose is to secure electrical supply by pointing the solar arrays towards the Sun. The flight software is of simple design and manages a minimum of equipment in order to limit possible cases of breakdowns and therefore to maximize robustness. Three sun sensors and a magnetometer are used as sensors, while the only actuators are magnetorquers. In case of anomaly in MNO, the satellite automatically falls back to MAS. There is no on-board time dependence, guidance or navigation function in MAS.

The second ADCS mode, called MNO (Nominal Mode), is used during all other satellite modes quoted in 1.1. This is the routine mode of the satellite: in this mode, it is able to charge its batteries, make payload measurements and download them to the ground.

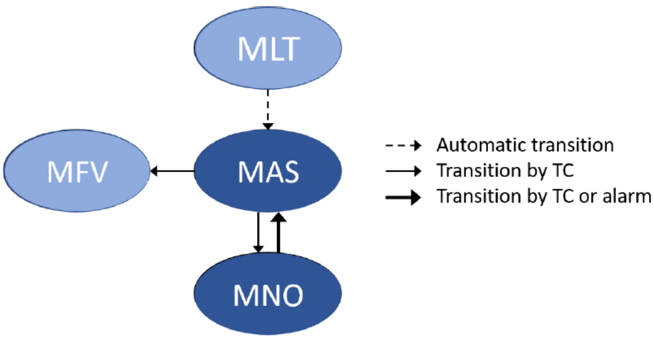

Figure 3: N3SS ADCS Architecture

3 MAS DESCRIPTION

3.1 Control philosophy

The MAS must be as robust as possible. In addition to using the minimum amount of equipment, this also means being as independent as possible. Thus, the strategy applied here does not require any information on the date or on the position of the satellite. This mode only needs the measurements of a magnetometer and the sun sensors to establish the commands to send to the magnetorquers in order to ensure a coarse solar pointing, with a pointing precision better than 30 degrees.

In opposition to more standard approaches, in which Survival modes are organised in different phases (like the CNES micro-satellite line, called Myriade and which ADCS architecture is described in [3]), the MAS mode of the N3SS mission is composed of only one phase that ensures these different roles:

- Detumbling (reduction of angular rates)
- Spin control of the axis aiming to point the Sun
- Orientation of the spin axis towards the Sun

The control depends on different laws that can be antagonist, but prioritization is managed with the controller synthesis. For example, without disabling the sun pointing law, spin control is dominant when angular rates of the satellite are high.

Although the fact of having only one phase does not make it possible to optimize the performance of pointing towards the sun in converged regime, this choice was made because it greatly simplifies the validation of the software compared to cases where there are several different phases. In those cases, it may be necessary, in the event of a reboot of the OBC, to restart in a certain configuration, and therefore to manage software context. This is not the case here

From a software point of view, the MAS application code runs at 1Hz and can be activated from 3 situations:

- Automatically following the first ignition of the satellite, after having waited for the deployment of the solar generators,
- Automatically, following a survival fall-back due to a restart of the on-board computer or following the triggering of an FDIR while the satellite was in GNC MNO mode.
- Manually, following a GNC mode change TC.

3.2 Control description

Two control laws are simultaneously applied in MAS.

The first one ensures that the satellite rotational speed is controlled to the target spin angular rate $\overrightarrow{\boldsymbol{\Omega}_{spin}}$, which the direction in the satellite frame is noted $\overrightarrow{\boldsymbol{\omega}_{spin}}$.

The second makes it possible to orient the axis of rotation of the satellite towards the direction of the sun. To do this, a torque is applied in the direction of the sun measured by the sun sensor (noted $\overrightarrow{s_{mes}}$), considering only the part of this torque which is neither in the direction of the magnetic field (uncontrollable direction) , nor along the rotation axis of the satellite (component which only impacts the amplitude of the angular momentum and not its tilting).

When the measurement of the solar direction is not available, as is the case in an eclipse for example, only the spin law is used. The control laws are presented in (Eq.1), (Eq.2) and (Eq.3).

$$\overrightarrow{\boldsymbol{M}_{com}} = \overrightarrow{\boldsymbol{M}_{spin}} + \overrightarrow{\boldsymbol{M}_{sun\_acq}} \tag{Eq.1}$$

$$\overrightarrow{\boldsymbol{M}_{spin}} = \overrightarrow{\boldsymbol{b}_{mes}} \times \left(\frac{-\overline{\overline{\boldsymbol{K}_{spin}}}}{\left\| \overrightarrow{\boldsymbol{B}_{mes}} \right\|} \left(\left(\overrightarrow{\dot{\boldsymbol{b}}_{mes}} + \overrightarrow{\boldsymbol{\Omega}_{spin}} \times \overrightarrow{\boldsymbol{b}_{mes}} \right) \times \overrightarrow{\boldsymbol{b}_{mes}} \right) \right) \tag{Eq.2}$$

$$\overrightarrow{\boldsymbol{M}_{sun\_acq}} = \overrightarrow{\boldsymbol{b}_{mes}} \times \left(\frac{\overline{\overline{\boldsymbol{K}_{sun}}}}{\left\| \overrightarrow{\boldsymbol{B}_{mes}} \right\|} \left(\overrightarrow{\boldsymbol{s}_{mes}} \bullet \left(\overrightarrow{\boldsymbol{b}_{mes}} \times \overrightarrow{\boldsymbol{\omega}_{spin}} \right) \right) . \left(\overrightarrow{\boldsymbol{b}_{mes}} \times \overrightarrow{\boldsymbol{\omega}_{spin}} \right) \right) \tag{Eq.3}$$

3.3 Results of a standard simulation

Figure 4, Figure 5 and Figure 6 illustrate the behaviour of N3SS just after solar panels deployment following the launcher separation. In this case, initial rates are rather high, (about +/-5 deg/s per axis). Convergence time to the sun is lower than the specification expressed in Table 1, even if initial conditions (norm of rates, sign of rate around the spin axis) are not favourable.

The red horizontal line illustrates the angle for which the power generated by the solar panels is equal to the power consumed by the satellite. At the beginning, the spin control is naturally prior because of high values of $\boldsymbol{M}_{spin}$: the angular rates are reduced and then converge to the target spin. Then, once the spin is established, we can see that the satellite orients its solar panels towards the sun out of eclipses when the measurement of the sun direction is possible. During eclipses, the sun pointing law is disabled, and the consequences of the magnetic control spin is to reorient slowly the spin axis towards the normal to the Earth magnetic field (which is approximatively the normal to the orbit for the polar orbit of N3SS).

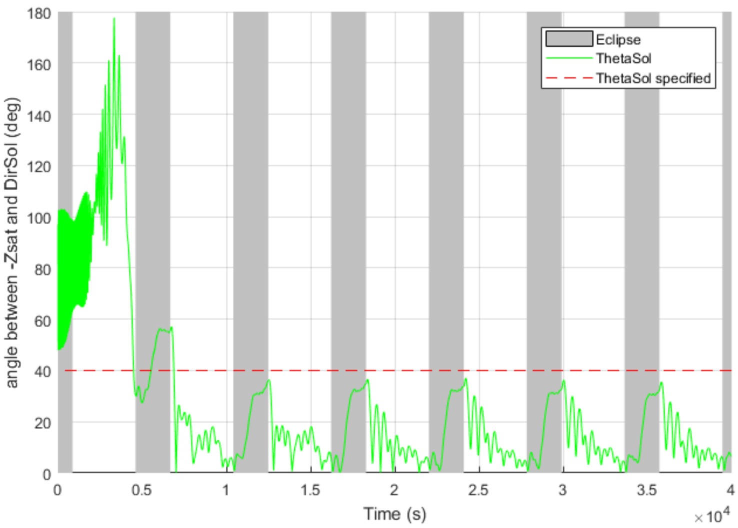

Figure 4: Evolution of Sun pointing error during MAS

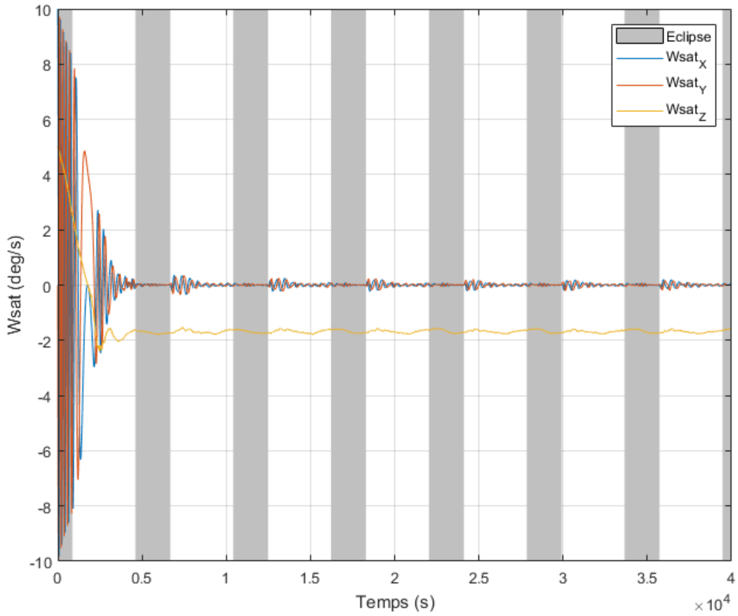

Figure 5: Evolution of rotational rates during MAS

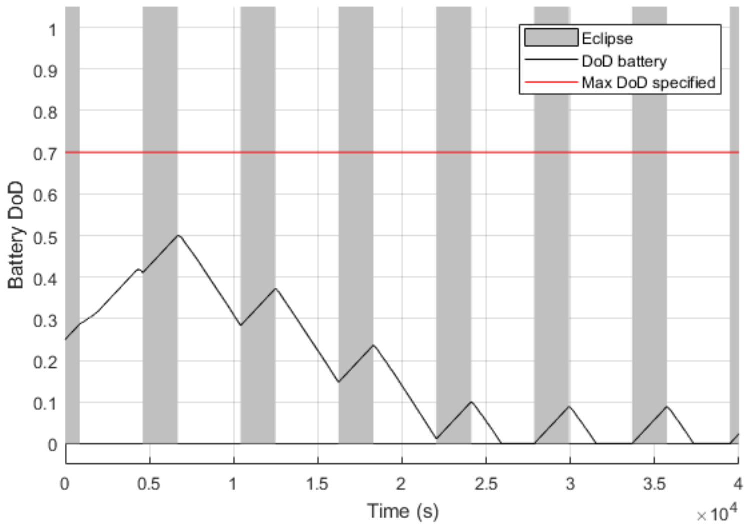

Figure 6: Evolution of battery depth of discharge during MAS

4 MNO DESCRIPTION

4.1 Orbit on-board computation

N3SS' navigation functions consist of a processing of GNSS measurements, an orbit propagator, a Sun ephemeris calculator, and a function deriving the position of the satellite in the terrestrial frame.

Such navigation functions are needed for two purposes:

- the on-board guidance, which requires the knowledge of the orbital characteristics to model the target magnetic field;
- the autonomous download, which requires knowing the relative position of the spacecraft and the X-band antenna, and the Sun direction to correctly point the solar panels during some phases.

The on-board propagator is RK4+J6, meaning Earth's gravity potential is modelled up to the sixth zonal harmonic, and integration is performed using Runge-Kutta's fourth order method. Since the on-board propagator drifts, it must be re-initialised. On the N3SS mission, it can be achieved by two means: by GNSS measurement or by TC based on ground computations using Doppler measurement and accurate ground orbit propagator.

Nominally, during a transition from MAS mode to MNO mode, the orbit propagator is initialized by an orbit bulletin from the ground, and is then only readjusted by the measurements of the GNSS receiver. This avoids having to switch on the GNSS in MAS mode, during which GNSS signal acquisition is more challenging than in MNO due to the spin of the satellite.

Once in orbit, it may happen that the antenna associated with the GNSS receiver is hidden by the Earth during manoeuvres, or that the receiver is voluntarily cut off by the operators for power constraints for example, causing unavailability of GNSS measurement. The orbit propagator also has the role of filling these measurement holes, and can do so for a duration equivalent to one or two orbits.

4.2 Autonomous guidance function

4.2.1 Guidance philosophy

The guidance profile is computed on board, with the ground only providing the timeline of the transitions between sub-modes. At each time step of the flight software, the on-board guidance function issues:

- the target quaternion describing the target attitude of the spacecraft with respect to the inertial frame of reference;
- the target angular rate with respect to the inertial frame.

4.2.2 Standby

The satellite follows a heliocentric pointing profile, with its -Z-face (bearing the solar cells), pointing towards the direction of the Sun based on the Sun ephemeris calculated by the on-board navigation function, and its -X-axis pointing as close as possible on the opposite direction of the centre of the Earth, to clear the GNSS antenna field of view.

4.2.3 Mission

The satellite follows a geocentric pointing, in which the Z-face, that bears the payload, points towards the Earth and Y-face at best along the velocity vector of the satellite, to ensure minimum rallying duration towards standby mode.

4.2.4 Downloading

The X-face, which bears the X-band antenna, points towards the X-band ground receiver and the -Z-axis is oriented as close as possible normal to the orbit, in the direction of the Sun. Defining –Z-axis at best towards the sun could lead to very high angular rates and therefore was not chosen for this guidance profile.

4.2.5 Manoeuvre

The manoeuvre sub-mode consists in rallying a target attitude from the current attitude. The gap is bridged with a bang-bang sequence, composed of an acceleration phase at constant torque, a steady rate phase, and a deceleration phase at constant torque. The rallying profile is computed on-board, based on momentum and torque allocations. Transitions between acceleration phase, constant rate phase and deceleration phase are based on angular rate thresholds and angle thresholds. Figure 7 shows the principle of a bang-bang profile for a manoeuvre between two inertial pointings, in one-dimension.

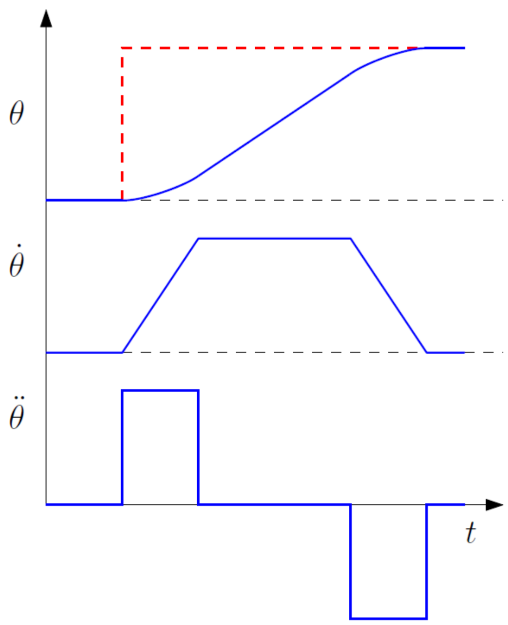

Figure 7: Bang-bang guidance profile during manoeuvre sub-mode

4.3 Attitude control

4.3.1 Control description

Because pointing performances are not very constringent for the N3SS mission, the objective for the MNO was to find the most robust solution, using as less components as possible. Naturally, a magnetic control has been chosen.

Reposing on "compass" effect, one know that when satellite applies a magnetic moment, the direction of this moment tends to align with the environing Earth magnetic field direction. This is physically due to the torque $\boldsymbol{T_{MTQ}}$ generated when a magnetic moment $\boldsymbol{M_{MTQ}}$ is present in an environing magnetic field B, which the expression is given in (Eq.4). The notation MTQ is chosen because in our satellite, the desired magnetic moment is the one realized by magnetorquers. The undesired magnetic moment also generate a torque by the same phenomenon but it is a disturbing torque small compared to $\boldsymbol{M_{MTQ}}$.

$$\boldsymbol{T_{MTQ}} = \boldsymbol{M_{MTQ}} \wedge \boldsymbol{B} \qquad \text{(Eq.4)}$$

Therefore, when it is possible to compute the magnetic field that the satellite would measure if it were perfectly pointed, it could be sufficient to order a magnetic moment with magnetorquers in this direction to orient the satellite as wanted. This target magnetic field $\boldsymbol{B_{targ}}$ is obtained from an embedded Earth magnetic field (IGRF, [4]) and computed in the target reference frame thanks to outputs of the guidance module.

Actually, in order to obtain a stable system, it is necessary to add a damping term, using derivative of the target magnetic field $\dot{\boldsymbol{B}}_{\boldsymbol{targ}}$ but also the derivative of the measurement magnetic field $\dot{\boldsymbol{B}}_{\boldsymbol{meas}}$. At the end, the magnetic control loop can be assimilated to a Proportional-Derivative controller, comparing the magnetometer measurement $\boldsymbol{B_{meas}}$ to the target magnetic measurement $\boldsymbol{B_{targ}}$.

The control law applied to magnetorquers is given in (Eq.5), where K_p and K_d are scalar gains. It is worth noting that $\boldsymbol{B_{meas}}$ is not used in the proportional term. If measurements were perfect, it would disappear because of the cross product giving the resulting torque. At the end of the day, only the derivative of the magnetometer measurement is used, which means that this control is insensitive to bias on this measurement. On this kind of platform, this is very useful, because any residual magnetic moment near the magnetometer could provoke bias on its measurement.

$$\boldsymbol{M_{MTQ}} = \frac{1}{\left\|\boldsymbol{B_{targ}}\right\|^2}\left(K_p.\boldsymbol{B_{targ}} + K_d.\left(\dot{\boldsymbol{B}}_{\boldsymbol{targ}} - \dot{\boldsymbol{B}}_{\boldsymbol{meas}}\right)\right) \qquad \text{(Eq.5)}$$

Magnetorquers only allow controlling two axes instantaneously, as they cannot generate a torque around the direction of the magnetic field. In order to perform a 3-axis attitude control, one has to use the reaction wheels to perform gyroscopic stabilization, generating a gyroscopic stiffness along the non-magnetically controllable axis. This is achieved by commanding the wheels with an angular momentum of constant norm in a direction orthogonal to the magnetic field, further referred to as the embarked angular momentum. The embarked angular momentum has to be rotated in satellite frame

during manoeuvres so that it always points in the same inertial direction, in order to avoid generating parasitic gyroscopic torques that would dramatically impact the agility of the satellite.
The magnetic control torque is too soft an action to allow performing agile manoeuvres. In addition to the magnetic closed-loop and the embarked angular momentum, one has to command the reaction wheels in open-loop to follow the guidance profile, following a kind of feed-forward strategy.

In a nutshell, the ingredients to the magnetic-based MNO are given below and the control philosophy sub-mode is summarized in Figure 8.

- A magnetic closed-loop to correct residual pointing errors about the guidance profile;
- An embarked angular momentum to provide passive third-axis stabilisation;
- An open-loop reaction wheel command to follow the guidance profile.

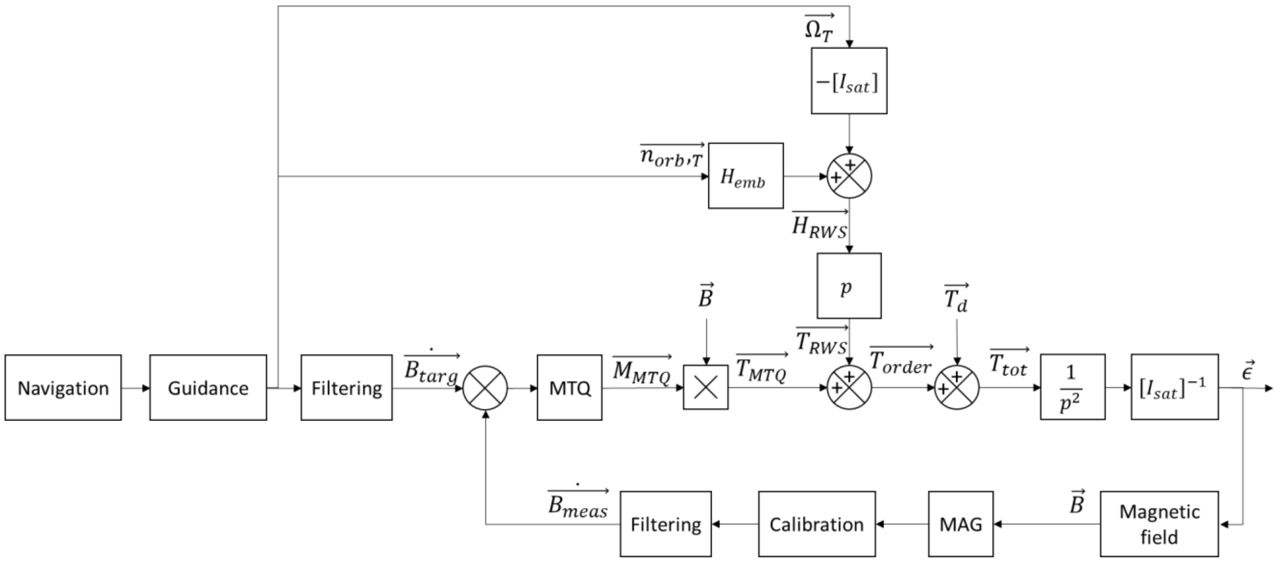

Figure 8: Schematic of the MNO control loop

4.3.2 Wheel cluster use

N3SS is equipped with four reaction wheels for enhanced performance. Indeed, the fourth wheel provides a degree of freedom when computing the command to send to each wheel and increases the actuation capacity. Thus, zero crossing is avoided for each wheel, which improves the accuracy of the wheel response. The possibility to use only three reaction wheels has been studied in [5], but the wheels are arranged in a pyramidal pattern. This configuration was chosen to be symmetric, in order not to discriminate any satellite axis.

The wheel direction matrix $\boldsymbol{M_{RWS}}$ can be seen as the transfer matrix from the 4D-wheel frame to the 3D-satellite frame. Since $\boldsymbol{M_{RWS}}$ is a matrix of rank 3, this problem has one degree of freedom, which corresponds to the kernel of $\boldsymbol{M_{RWS}}$. By definition, all commands sent to the wheels in the direction of $\mathbf{ker}(\boldsymbol{M_{RWS}})$ does not generate any torque or kinetic momentum in the satellite frame.

The actuation envelope materializes the maximum actuation available in all directions. More details about this concept and the way to build this envelop are given in [6]. In 3D, it is thus a polyhedron. All actuation vectors contained within this polyhedron are achievable, and all vectors out of its envelope are out of reach. For N3SS' 4-wheel configuration, it is chosen to constrain the wheels to one sign domain [hmin; hmax] or [-hmax; -hmin] to avoid zero-crossings. The signs attributed to wheels correspond to the sign of the components of $\mathbf{ker}(\boldsymbol{M_{RWS}})$: wheels 1 and 3 are within [hmin; hmax], wheels 2 and 4 are within [-hmax; -hmin].

The actuation envelope of N3SS' wheel array for the angular momentum is shown in Figure 9. Blue crosses indicate vertices, and centres of edges and faces. The weakest directions of actuation are towards the centres of the faces; the strongest ones are towards the vertices. It is called a symmetric envelope because it presents the same extension on all its vertices. The smallest actuation capacity is the radius of the sphere inscribed in the envelope. This value is the allocation used in the guidance algorithm covering manoeuvre phases presented in the following section.

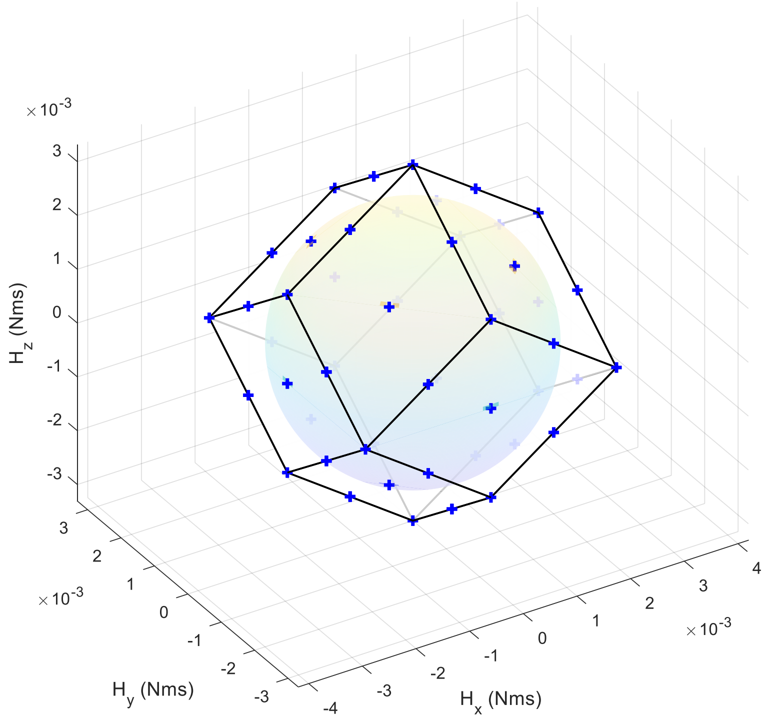

Figure 9: Angular momentum envelope of the N3SS wheel cluster

During MNO, the wheels are commanded in speed, and a null-space action along $\mathbf{ker}(\boldsymbol{M_{RWS}})$ results in all the wheel speeds increasing or decreasing by the same amount, in absolute value. It is chosen to use the degree of freedom to set the angular momentum of the slowest wheel in absolute value to hmin. The sign is determined by the sign domain assigned to the corresponding wheel. The speed of all the wheels is minimized in this process. Furthermore, the higher the speed, the higher the friction torques: minimizing the wheel speed also protects it from degradation.

The commanded wheel angular momenta are computed as follows, from a commanded kinetic momentum expressed in satellite frame in three dimensions:

- Step 1: the solution from the pseudo-inverse is computed.

- Step 2: the wheel destined to be the slowest among the cluster is identified, and the difference between the value of its angular momentum, obtained in step 1, and its target value of angular momentum is computed.

- Step 3: this difference is subtracted to the four values of angular momentum obtained in step 1. In particular, the angular momentum commanded to the wheel identified at step 2 is equal to +/-hmin.

4.4 Results of a standard simulation

Figure 10 and Figure 11 illustrate the behaviour of N3SS during some standard operations in MNO, in the worst considered case of external disturbances and sensors performance. A succession of standby, manoeuvre, mission and downloading phases is shown. In each sub mode (Standby, Download, and Mission), the angle between the reference axis and the achieved pointing axis is plotted: the pointing performance is always below 15 degrees in any mode. The frequency of the error signature is half the orbital period and peaks corresponds to the flyby of the poles, where the magnetic field varies rapidly. The only sensor used being a magnetometer, its calibration is key to achieve good pointing performances notably around the poles.

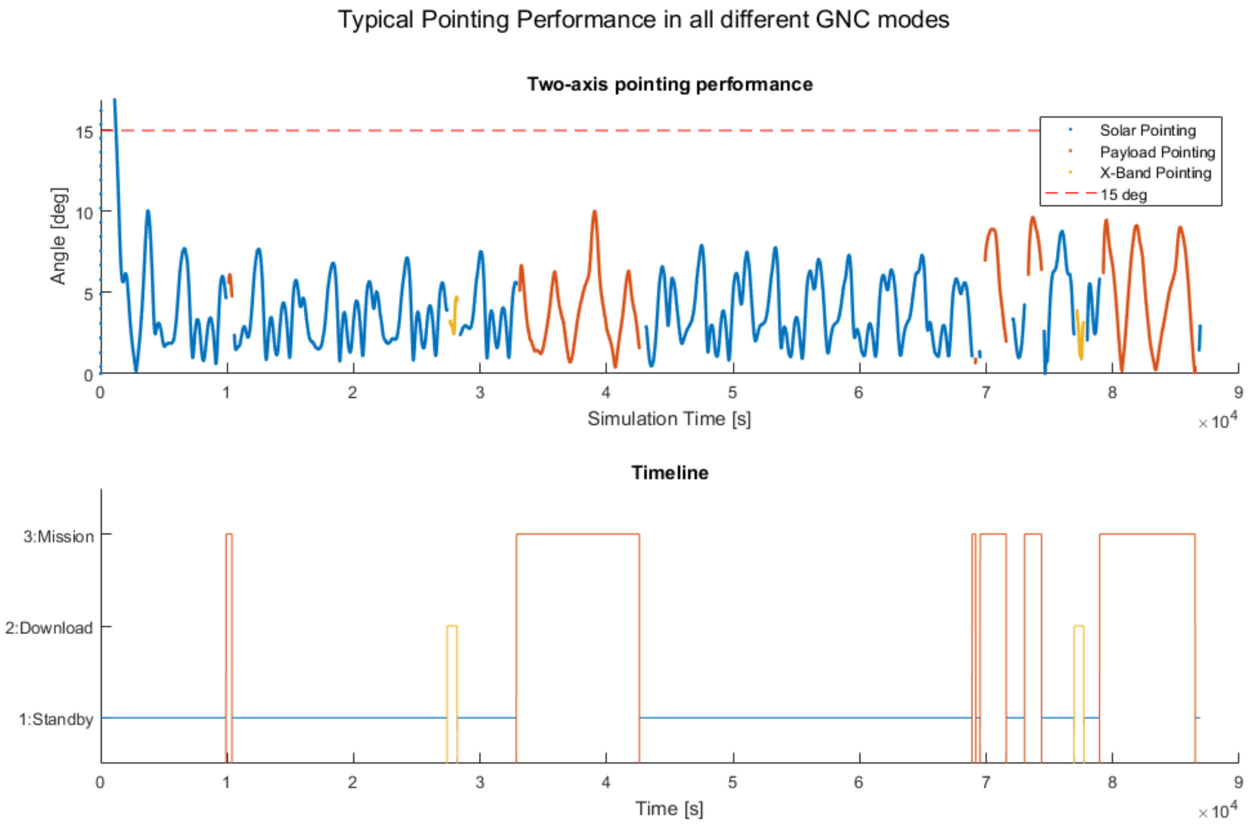

Figure 10: Pointing error in MNO

In Figure 11, satellite rotation rate are shown. Slews are performed autonomously during Standby to follow the guidance profile, and the attitude manoeuvre can be seen at a mode switch. Finally, highest rates are achieved during download mode, to point as accurately as possible the X-band antenna towards the ground station.

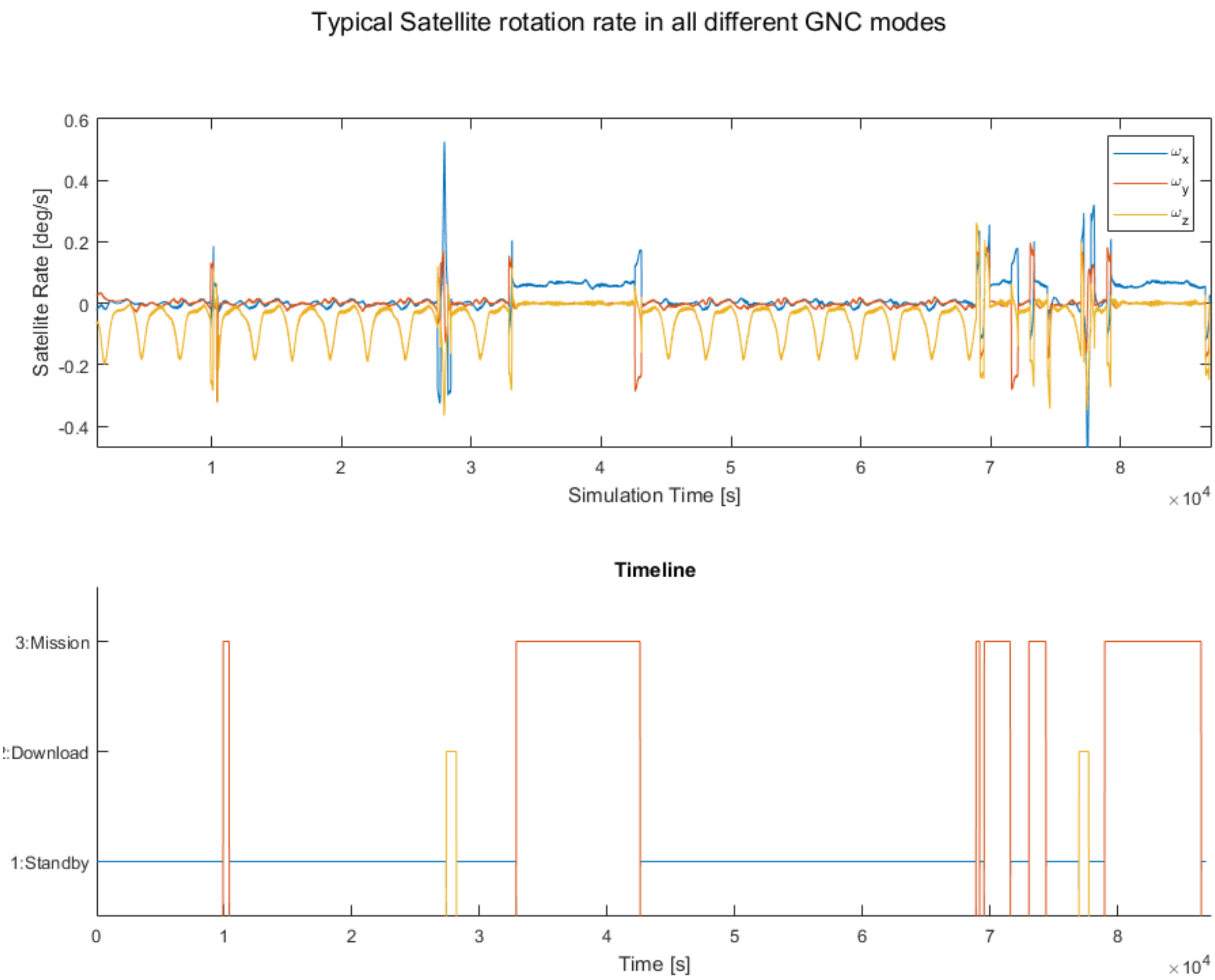

Figure 11: Evolution of rotational rates during MNO

5 CONCLUSION

This paper presented various aspects of the flight dynamics needed by the N3SS mission to fulfil its challenging mission. The innovative aspect of the concepts presented in this paper do not rely on pointing accuracy, but on autonomy and robustness with a minimal number of sensors.

The astute strategy applied in MNO is very well suited for 3-axis coarse pointing, because contrary to standard coarse pointing using magnetometer, sun sensors and gyro for estimation, only a magnetometer is needed, and the control is perfectly robust to steps on magnetic measurement due to the use of the different components of the platform (RF transceiver, heaters…).

6 REFERENCES

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