Lessons Learnt from N3SS GNC Operations

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ABSTRACT

N3SS is a triple Cubesat launched the 9th of October 2023. This in-orbit demonstrator embeds a miniaturized Software Developed Radio-Frequency payload that measures 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. After about two weeks of commissioning, the spacecraft started its mission, which has been ongoing for six months now.

This article is focusing on the lessons learnt from the design, validation and commissioning of N3SS Guidance, Navigation and Control (GNC) system.

The GNC of N3SS includes attitude and orbit determination, on-board autonomous attitude guidance and a three axis stabilized control system that were described in a previous paper presented in 4S conference in 2022. This new paper now focuses on the robustness of the control design, especially against space environment (solar activity mainly). In particular, it is shown that the spacecraft attitude control is able to cope with a much higher level of solar activity than the satellite was expected to encounter during its mission at the time of design.

Second, this paper describes the impact of magnetic perturbation on N3SS GNC, and actions taken to mitigate it. In fact, a major lesson learnt from the previous cubesat launched by CNES (Eyesat) is that magnetization could be a major perturbation to satellite pointing and stability.

Several steps, from ground to commissioning, were performed to ensure the best pointing performance for the satellite, such as:

- Measurement of the residual magnetic moment of the complete satellite (on-ground, CNES facility)
- Demagnetization of the satellite (on-ground, CNES facility)
- Magnetometers calibration (on-ground, CNES facility)
- Magnetometers calibration (commissioning, in orbit)

The calibration algorithm, based on a non-linear least square algorithm (Gauss-Newton) is described in this article, as well as the in-orbit pointing performance gain from the calibration.

This article will also focus on a method to manage a cluster of reaction wheel during satellite lifetime to increase the reaction wheels lifetime in orbit, using the degree of freedom given by a cluster of four reaction wheels.

Finally, this document highlights how the design, validation and commissioning of the GNC N3SS were made possible with few human resources, making maximum use of CNES's assets and experience.

MISSION AND SATELLITE DESCRIPTION

N3SS is a 3U cubesat demonstrator, launched in October 2023, managed by CNES (French Space Agency). It is 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.

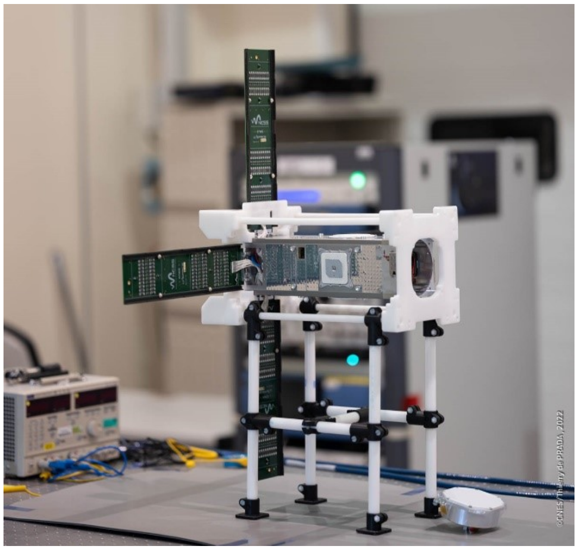
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Figure 1: N3SS Satellite

N3SS is orbiting at about 560 km altitude, with an original 22h30 LTAN, which is derivating (N3SS does not embark propulsion and therefore no orbit control is done for the mission). Its mission lasts nominally one year.

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A GNC DIMMED TO THE RIGHT LEVEL

The N3SS GNC is inherited from EyeSat mission ([1], [2]) and is detailed extensively in [3]. The mission requirements dedicated to GNC are presented below:

Table 1: Mission requirements for GNC

Satellite Mode	Objective Secondary Objective	Maximal Pointing error	Agility
Safe	Solar panels facing the Sun *Barbecue mode*	40° Between normal to solar panels and the sun direction	N/A
Standby	Solar panels facing the Sun *GNSS antenna oriented at best opposite to the Earth*	15° Between normal to solar panels and the sun direction	N/A
Downloading	-X-band pointing the ground station *Solar Panels oriented at best towards the Sun*	-10° Between the on-board antenna and the ground antenna	Up to 1°/sec -
Mission	Payload pointing the Earth *Attitude around Earth direction is chosen to minimize rallying time to standby mode*	-10° Between the payload and the Earth direction	-N/A
Manoeuvre	Profile following	15° (3 axes)	- Up to 0,3°/sec

The pointing requirements of N3SS are low, and thus, the minimum amount of GNC equipment to fulfill those requirements were selected: Two magnetometers and three sun sensors for the sensors, and three magnetorquers and four reaction wheels for actuation.

Moreover, the emphasis was put on the robustness of the design for N3SS GNC: reuse of robust and well-known equipments, re-use of flight-proven algorithms, minimization of mode and sub-mode transition, controllability margins regarding the environment…

One good example of robustness is the ability of N3SS to cope with the very high solar activity happening in 2024. As shown in the figure below ([5]), the solar activity in 2023 and 2024 is largely exceeding the forecasted values (and are even above the Marshall-95 percentile). The major impact is the increase of the atmospheric density, and thus the increase of atmospheric torque on the satellite. It could have had dramatic effect on the satellite as it was initially designed to be launched and operated in 2021-2022.

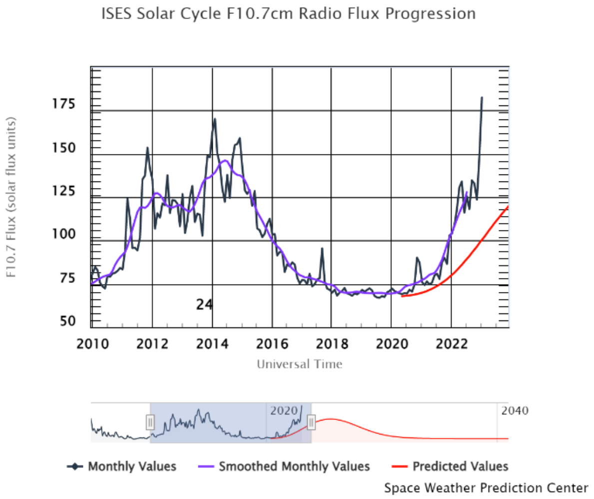

Figure 2: Solar Radio flux with observed and predicted values

As a robust approach, the sizing of the magnetorquers (which are the main equipment to counter environmental torques) was done using the worst case predicted value at the time (125 sfu) on which a significant margin was taken. With the level of solar activity seen in 2024, it is certain that without this robust approach, a controllability loss would have happened during the operation of N3SS.

The design of the GNC is detailed with great precision in [3], but a reminder is given below, focusing on the key points of the design:

The GNC is divided in two modes, MAS (Survival mode) and MNO (Normal mode).

In MAS, the objective is to stabilize the satellite and orient the solar arrays towards the sun to ensure the survivability of the satellite, with maximum robustness. To ensure this, the sensors used are the sun sensors and the magnetometers, and the only actuators used are the magnetorquers.

The sequence for the MAS is the following:

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

To minimize the complexity of the sequence, the three control laws are executed as the same time, but each are tuned to be prioritized at the right timing. For example, the Detumbling control law is dominant over the others when the satellite angular rates are high. This design simplifies greatly the validation of the GNC software, since only one sequence is to be tested.

In MNO, the satellite shall be able to fullfill its mission:

- Ensure the charging of the battery
- Point the payload towards the earth to take measurements
- Point the X-Band antenna towards ground antenna to downlink payload data to earth

Those three functions correspond to the three guidance modes of N3SS, which are fully autonomous and the guidance laws are computed onboard:

- Standby
- Mission
- Download

To ensure smooth transition between the guidance laws, an autonomous slew guidance is computed onboard, using a bang-stop-bang profile.

The control strategy is driven by a robust approach, using as less components as possible. Therefore, a magnetic control has been chosen, using the magnetorquers. In addition, and to enhance performance when slewing and in Download guidance mode, four reaction wheels are commanded in open loop to follow agile guidance profile. A command in the kernel of the reaction wheels is added to avoid zero-crossings.

3 MANAGEMENT OF MAGNETIC CONCERNS

As mentioned before, reaction wheels are only used in open loop and their main purpose is to give agility to the satellite so it can follow the guidance profile, especially during the download phase. Thus, the entire pointing strategy repose on using the magnetic field of the Earth:

- Magnetometers for the measurement part
- Magnetorquers for the actuation part.

This means that N3SS is very sensitive to everything related to magnetism: magnetometer calibration, on board Earth magnetic field, satellite residual moment…

Feedback from the EyeSat project shows that magnetic testing is essential to the success of a mission of this type. The N3SS satellite is very similar in this respect, with the same satellite template (3U cubesat), the same magnetometer models and the same magnetorquer models.

On EyeSat, it was observed that the satellite's residual magnetic moment was too high in relation to the capacity of the GNC actuators, which would have led to the loss of the mission if nothing were done. It is very likely that the mechanical tests carried out on the satellite using a vibrating pot resulted in the satellite becoming magnetized. Indeed, measurements taken before and after these vibration tests clearly illustrate this phenomenon.

Facility for magnetic testing

In CNES, it exists a dedicated facility to magnetic testing and demagnetization, named “BIOT”. The facility is composed of 12 wooden coils, that allow to cancel out the Earth's magnetic field by generating a second, artificial magnetic field, in order to get a very clean magnetic environment. This lab is usually used to measure the magnetic moment (the intensity of a magnetic source) of space equipment (e.g. batteries, jet wheels, etc.), satellite parts and entire small satellites, such as nanosats. It can also be used to demagnetize these same objects or simulate a magnetic field of the desired strength. The picture below shows the wooden structure used for magnetic measurement and demagnetization.

Figure 3: The BIOT Facility

Residual Magnetic Moment

After vibration tests, N3SS went to BIOT to evaluate its residual magnetic moment, which is a key contributor to perturbation torque acting on the satellite. The test sequence was as it follows:

1. Measure the satellite's residual magnetic moment,
2. Demagnetize the satellite if the measured value exceeds a certain threshold (decision taken by the GNC Architect),
3. Re-measure the satellite's residual magnetic moment. The measured value is then taken into account in the GNC software, ensuring greater robustness to magnetic disturbances and improved performance.

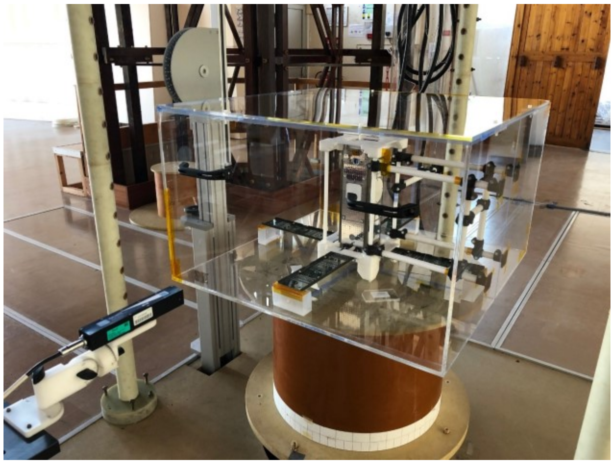

Figure 4: Test setup for residual magnetic moment measurement

The results of the test is summarized in the table below:

Table 1: Residual magnetic moment before demagnetization

Axial Magnetic moment (mA.m²)		Magnetic moment Norm (mA.m²)
Mx	-6.3	**187.56**
My	-21.28	
Mz	186.24	

For N3SS, the requirement states that this value should be below 30 mAm². If the satellite was launched in that state, it would be impossible to control and stabilize, since the magnetic torque induced by the residual magnetic moment would exceed the actuator capabilities.

A demagnetization was then realized, according to the process described in the ECSS-E-ST-20-07C with a peak amplitude of 5mT.

After demagnetization, the residual magnetic moment is measured once again, and the results are summarized in the table below:

Table 2: Residual magnetic moment after demagnetization

Axial Magnetic moment (mA.m²)		Magnetic moment Norm (mA.m²)
Mx	4.86	**4.99**
My	-1.05	
Mz	-0.36	

It shows that the demagnetization was very effective, and the value of the residual magnetic moment is now below the requirement, which ensure controllability of the satellite.

On Ground Magnetometer Calibration

The poor performance of non-calibrated magnetometers observed during the EyeSat project lead to the decision of doing a calibration of both magnetometers flight model on-ground before the launch. The calibration was realized in the same facility six months after the demagnetization, in September 2022. Only the results of the main magnetometer are presented in this paper, the back-up magnetometer being an opportunistic equipment (on the same board of the magnetorquers) and is never used in practice.

Two parameters are used to model the magnetometer:

P_{mag} the compensation matrix, which models the scale factor, the misalignments and the orthogonality faults.

b_{mag} a bias vector

The following equation describes the relationship between the real magnetic field and the measured magnetic field

$$B_{sat_{mes}} = P_{mag} * B_{sat} + b_{mag}$$

With the following notations:

$$Y = B_{SATmes}$$

$P = P_{mag}$

B=B_{sat}

$b = b_{mag}$

The measurement equation can be written as:

$$Y = P.B + b$$

Avec: $P = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix};$

$B = \left[B_x\ B_y\ B_z\right]^T; b = [b_1\ b_2\ b_3]^T$

This can be reformulated as:

$$Y = A.X$$

With:

$$X = \begin{bmatrix} a_{11} \\ a_{12} \\ a_{13} \\ a_{21} \\ a_{22} \\ a_{23} \\ a_{31} \\ a_{32} \\ a_{33} \\ b_1 \\ b_2 \\ b_3 \end{bmatrix}, Y = \begin{bmatrix} Y_{1x} \\ Y_{2x} \\ \dots \\ Y_{nx} \\ Y_{1y} \\ \dots \\ Y_{ny} \\ Y_{1z} \\ \dots \\ Y_{nz} \end{bmatrix},$$

$$and\ A = \begin{bmatrix} \frac{\partial Y_{1x}}{\partial a_{11}} & \frac{\partial Y_{1x}}{\partial a_{12}} & \cdots & \frac{\partial Y_{1x}}{\partial b_3} \\ & \cdots & & \\ & \cdots & & \\ \frac{\partial Y_{nx}}{\partial a_{11}} & \frac{\partial Y_{nx}}{\partial a_{12}} & \cdots & \frac{\partial Y_{nx}}{\partial b_3} \end{bmatrix}$$

X is the state vector of size 12x1, Y the measurement vector of size 3nx12 where n is the number of measurements used, and A the partial derivatives matrix. Finally, the least square problem is solved and:

$$P_{mag} = \begin{bmatrix} 1.09 & -0.004 & 0.007 \\ -0.04 & 1.05 & 0.003 \\ -0.003 & -0.01 & 0.97 \end{bmatrix}$$

And

$$b_{mag} = \begin{bmatrix} 4785 \\ 281 \\ 8771 \end{bmatrix} nT$$

The calibrated matrix is then updated in the flight software before flight for improved performance.

In Flight Magnetometer Calibration

During commissioning of N3SS, a calibration of the magnetometer was performed to improve pointing performance. Indeed, the calibration realized on ground was done in an environment, which was not representative of space, and magnetometers are especially known to be sensible to temperature. Therefore, as the on-ground calibration was not performed in a temperature-controlled room, it is expected to see differences in the measurements on ground and in flight.

The method used for in-flight calibration is the Gauss-Newton algorithm which is based on a nonlinear least square algorithm. The principle is the same as the on ground calibration, except for the fact that only the norm of the measurement is used and not the three components. As the satellite true attitude is not known, it is not possible to compare the expected magnetic field with the measured one. However, as the position of the satellite is well known thanks to GNSS measurements, it is possible to use the norm of the magnetic field as reference. In addition, as the norm of the magnetic field and the satellite attitude are varying along the orbit, it is possible to get enough observability on the estimated parameters, if enough measurements are available.

From the measurement equation defined previously, the following must apply in any point of the orbit:

$$\left\|B_{SAT_{MES}}\right\|^2 = \|M_{MAG}.\mathrm{B_{sat}} + b_{MAG}\|^2$$

We define the state vector X as:

$$X = \begin{pmatrix} M_{11} \\ M_{12} \\ \cdots \\ M_{33} \\ b_x \\ b_y \\ b_z \end{pmatrix}$$

And the state function f(X, t_i) :

$$f(X, t_i) = \|M_{MAG}.\mathrm{B_{sat}} + b_{MAG}\|^2$$

The measurement function Y(t_i) is defined by :

$$Y(t_i) = \left\|B_{SAT_{MES}}\right\|^2$$

The Gauss-Newton algorithm aims at minimizing the residuals, which are defined as:

$$\epsilon_i = Y(t_i) - f(\boldsymbol{X}, t_i)$$

At each iteration of the algorithm, the state vector increment is calculated as:

$$\Delta\boldsymbol{X} = -(\boldsymbol{J^T} * \boldsymbol{J})^{-1} * (\boldsymbol{J^T} * \boldsymbol{\epsilon})$$

Where $\boldsymbol{J}$ is the jacobian of $\boldsymbol{f}(\boldsymbol{X}, \boldsymbol{t})$

Once the state vector increment is below a threshold, the algorithm has converged and the optimal M_{mag} and b_{mag} were found.

The measurements from the nominal magnetometer were used for $B_{sat_{mes}}$ computations, and the magnetic field computed onboard from IGRF model was used as reference (named as B_{sat} here)

The sample duration is 18 hours, from October 11th, 14:30 to October 12th, 7:30, and the frequency of the measurements used during this period is 1/20Hz.

The figure below shows the norm of the magnetic field, computed from different sources. The blue dot is the norm of the reference magnetic field, computed using IGRF 2020 model. The red dot is the norm o the magnetic field computed directly from the magnetometer. Finally, the yellow dots is the norm of the magnetic field computed in the flight software, which takes into account the ground calibration detailed in the previous section.

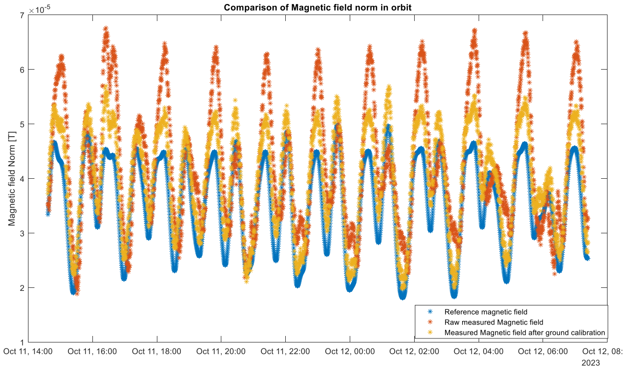

Figure 5: Norm of the magnetic field, computed with different measurements

An improvement can already be seen just with the ground calibration, but the norm given by this is still far from the reference norm. This is because the measurement technology in the magnetometer is sensitive to temperature, about 0.3% per degree. In flight, the magnetometer temperature is about 0°C, whereas the calibration took place in September in Toulouse, where the temperature was about 25°C. This gives an expected difference of 7.5% between the results obtained on ground and in flight.

The results given by the Gauss-Newton algorithm are detailed in the table below:

Table 3: Results of Calibration on ground and in flight

	M_mag (-)	**b_mag (µT)**
Ground Calibration	$\begin{bmatrix} 1.0916 & -0.004 & 0.0073 \\ -0.0403 & 1.0454 & 0.0032 \\ -0.003 & -0.0132 & 0.971 \end{bmatrix}$	$\begin{pmatrix} 4.785 \\ 2.81 \\ 8.771 \end{pmatrix}$
Flight Calibration	$\begin{bmatrix} 1.1772 & 0 & 0.0279 \\ -0.04 & 1.2084 & 0.0178 \\ 0 & -0.0665 & 1.0984 \end{bmatrix}$	$\begin{pmatrix} 5.6489 \\ -2.9079 \\ 10.320 \end{pmatrix}$

The non-diagonal terms of the matrix are small, indicating good alignment of the magnetometer axes with respect to its expected position in the satellite. On the other hand, the scaling factors are relatively high (+20%), which is consistent with a measured norm that is higher than the reference norm.

The figure below is the same as **Figure 5**, with the flight calibration added in purple. This curve corresponds best to the reference norm and thus improves magnetometer measurements.

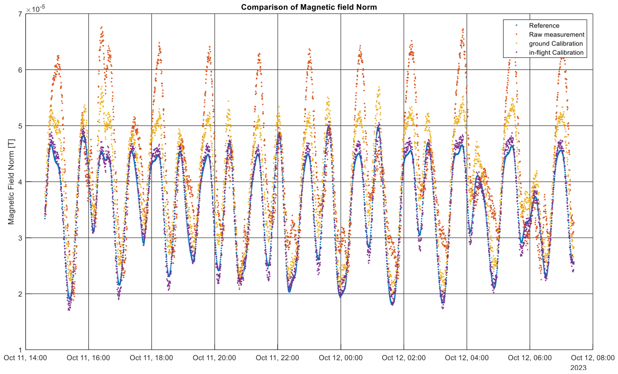

Figure 6: Comparison of magnetic field norm

Before uploading the new parameters on board the flight computer, five calibrations were performed from October 24th to November 14th to study the stability of the solution given by the Gauss-newton algorithm. The results are shown in the table below:

Table 4: Sensibility to time of the Magnetometer calibration

Parameter	Mean	Deviation from the mean, max (%)
bias_X	**5.86061.10-6**	3.50%
biais_Y	**-3.3628.10-6**	20%
biais_Z	**9.9465.10-6**	3%
Mcomp_LV_X	**0.8489**	0.30%
Mcomp_LV_XY	0.0284	150%
Mcomp_LV_XZ	-0.0158	70%
Mcomp_LV_YX	0.0075	500%
Mcomp_LV_YY	**0.8226**	1.38%
Mcomp_LV_YZ	0.00016	87%
Mcomp_LV_ZX	-0.0021	140%
Mcomp_LV_ZY	0.0253	60%
Mcomp_LV_ZZ	**0.9105**	0.30%

The scaling factor matrix evolves slowly over time: we observe a drift of less than 1.4% on the diagonal terms of the matrix. Non-diagonal terms evolve very little around zero, which explains the high percentages.

On November 21th, 12 parameters (the compensation matrix and bias vector) were uploaded via PUS140 to update the GNC flight software. The observability of the pointing error being low on N3SS satellite, it was decided to put the mission on hold for 6 orbits, (3 before the upload, and 3 after) and to stay in “Standby” guidance mode. Indeed, in this mode, Sun sensors can be used to have a better estimate on the pointing error. Even though these sensors are not used in Nominal Mode, they were turned on and telemetry was treated on ground to estimate the performance gain. The figure below shows how the magnetic field and the estimated point error improved after the upload of the magnetometer parameters: The pointing error decreased by a factor 2 with the new calibration. This is consistent with simulation that were performed before the upload of the parameters, which showed a performance improvement of the same order of magnitude.

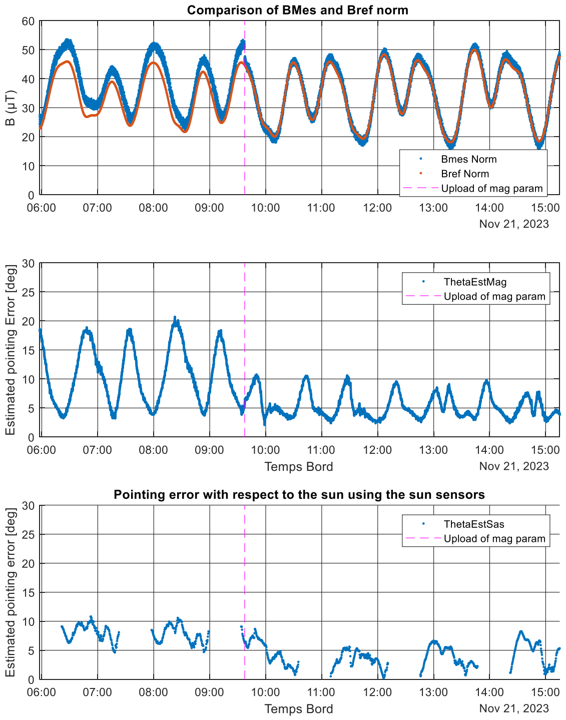

Figure 7: N3SS pointing performance before and after the upload of magnetometer parameters

MANAGEMENT OF A FOUR REACTION WHEELS CLUSTER

N3SS is using a cluster of four reaction wheels, commanded in open loop. As mentioned in section 2, the wheels are only used to follow guidance profile which can be challenging, as a flip every orbit in standby, or in downloading mode, where the X-band antenna shall remain pointed towards the ground antenna. Therefore, this equipment is essential for the mission and was monitored carefully during commissioning.

A suspicious behavior appeared on the consumption of one wheel, at the very end of LEOP. One wheel (n°3) showed an unexpected and progressive increase in consumption, as illustrated below (the blue curve is the suspicious one).

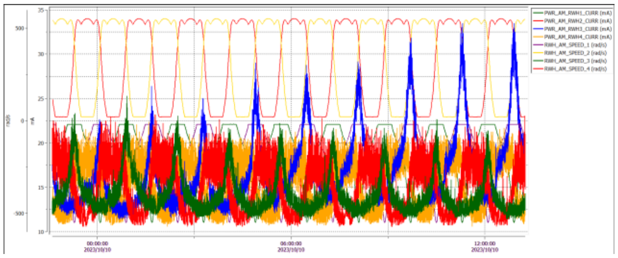

Figure 8: Speed and Reaction Wheel Consumption

In a few hours, the current consumption of the reaction wheel went from below 25 mA to almost 35 mA. Since consumption is highest at maximum rotation speed, a friction problem may be suspected. The cause might be the accumulation of grease (or lubricant) in one area of the bearing, or the appearance of deposits after the wheel has been used for some time.

N3SS reaction wheels are operated to limit the zero-crossings during lifetime. This is achieved by commanding into the kernel of the 4-wheel cluster: since there are four reaction wheels, and only three axis to command, it exists a kernel of dimension 1, generated by the eigenvector [-1 +1 -1 +1] in the N3SS layout, which does not affect the satellite pointing. The on-board algorithm is detailed in [3], but this allows the wheel speed to keep their sign of rotation constant and avoid zero-crossings. One drawback though, is that it can cause the problem seen on reaction wheel 3, with an accumulation of grease in one area of the bearing.

To mitigate this issue, one can change the sign of the reaction wheels speed. This would help re-distribute evenly the grease in the bearing and avoid accumulation at one area in particular. Since the eigenvector of the kernel is a tunable parameter in the GNC flight software, its value was changed to the opposite ([+1 -1 +1 -1]. This value still being in the kernel, it is expected to see no perturbation on the spacecraft pointing during this update.

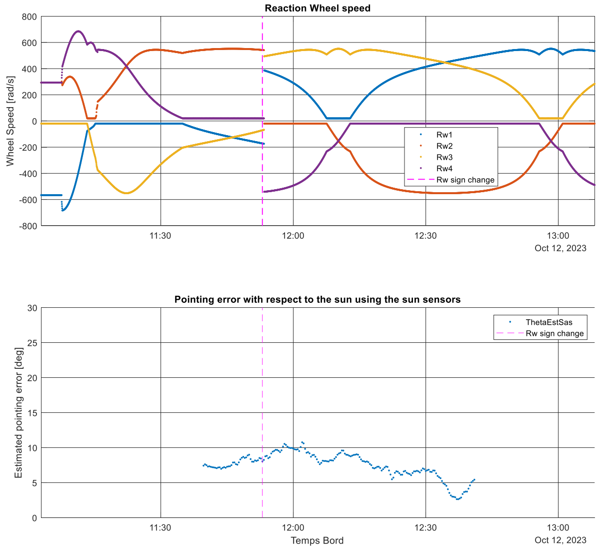

Figure 9: Rw Speed and pointing error during Reaction wheel speed sign change

To see the impact of this change, we can have a look at the wheel consumption over a longer period. The figure below shows the wheel consumptions over a period of 4 days before and after the sign change:

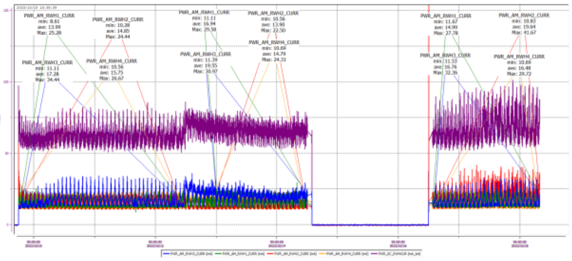

Figure 10: Wheel Consumption before and after the speed sign change

The blue curve represents reaction wheel #3's consumption. After the speed sign change, one can observe a change in the consumption profile, and a reduction after some time of the peak consumption. Same can be observed on the purple curve, which shows the total consumption of the four wheels. A few days later, survival mode was entered (no wheel are used in that mode), but when the nominal mode was entered again the consumption increased again, on both wheel 3 (blue curve) and wheel 2 (red curve). This is partly explained by the reset of the speed sign parameter after the reboot of the spacecraft onboard computer. However, this does not explain the increased consumption on wheel 2.

It was decided to change the sign of the wheel speed every two weeks for the rest of the mission, to prevent accumulation of grease in the bearing of the wheels. It is not expected to reduce instantly the consumption of the wheel, but it is a long term mitigation method to avoid the increase of the wheel consumption, which could lead to a wheel loss.

CONCLUSION

This article focused on the lessons learned during the design, validation and commissioning of N3SS satellite.

The GNC developed for the N3SS mission with very low resource (1fte) in CNES shows very good results in terms of performance and robustness. The robust approach chosen during the actuator's sizing phase allowed N3SS to cope with much higher aerodynamic and solar perturbations than expected at the time of design. In addition, the flexibility of the flight software allowed for code evolution during commissioning (calibration of magnetometer, reaction wheels spin direction) which enabled N3SS to achieve higher performance during its mission.

We explained how the magnetic concerns where managed, regarding the residual magnetic moment issue, or the calibration of the magnetometers. A simple method, based on the magnetic field norm measured in orbit, was proposed to calibrate in-flight the magnetometers and improve the performance of the satellite pointing.

Finally, the management of the reaction wheels cluster was detailed since unexpected behavior in one wheel consumption was seen during commissioning. This method was set to mitigate the risk of failure of the wheels during the mission.

N3SS mission was lately extended by one more year, proving the GNC's good performance in space and validating the design and the commissioning operations.

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