AOCS INNOVATIONS for AIRBUS ONESAT PLATFORM

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ABSTRACT

Supported by ESA and National Space Agencies in France and UK, Airbus Defence and Space is developing the OneSat software-defined telecommunications satellite product line.

Several challenges have been addressed in order to adapt the Eurostar NEO design, on which OneSat AOCS architecture is based, to meet the mission's specific needs.

OneSat relies on a stacked launch strategy to reduce launch costs. The platform design is thus highly compact, and requires a large number of deployable appendages. This paper discusses analysis tools developed to manage the high number of possible configurations, and appendage command strategies implemented to manage flexible responses.

In order to optimize the Launch and Early Operations Phase, an autonomous transition to a 3-axis Star Tracker based control mode is introduced, as part of the automatic post-launcher separation spacecraft initialisation sequence.

As Eurostar NEO, OneSat implements a combined full electric orbit and wheel momentum control strategy, using two 3-dof robotic arms on which electric thrusters are accommodated. The offloading capacity of this strategy has been improved by introducing the Twin Manoeuvre concept. As a means of simplifying interfaces and Ground SoftWare development, Airbus delivers to Customers an auto-coded library and corresponding API implementing the algorithms for wheel offloading management.

1 ONESAT PLATFORM OVERVIEW

Designed for dual stacked launch, the OneSat platform is highly compact in stowed configuration. It relies then on a large number of deployable appendages to fulfil the different stages of the mission:

- After launcher separation and rates damping, the two **S**olar **A**rrays (SA) are deployed, to provide power to the **S**pace-**C**raft (S/C).
- During the **E**lectric **O**rbit **R**aising (EOR) phase, thrust is provided by **H**all **E**ffect **T**hrusters (HET) mounted on two robotic deployable arms (so called **D**eployable **T**hruster **M**odule **A**ssembly or DTMA). They allow optimizing the overall thrust direction, and provide full 3-axis authority for wheel momentum control.
- Once the final GEO orbit is reached and the S/C is at its intended location, the two booms supporting the antenna reflectors are deployed to configure the S/C for its telecommunications mission. DTMA's positions are adjusted to orient the HET thrust vector for the needs of

Station Keeping (see §5). The two deployable radiators are as well set in their On Station configuration.

From an AOCS perspective, this specific configuration featuring many deployable flexible appendages has been the source of challenging design innovations, detailed in the following sections:

- Some appendages (Solar Arrays, DTMA's) are directly commanded by AOCS algorithms. Specific command techniques have been introduced to limit interactions between command and flexible response (see §2).
- Given the number of appendages, and all their possible configurations, a high number of possible S/C configurations need to be taken into account in AOCS analyses. A specific framework has thus been developed to consistently manage this complexity and the large amount of numerical data required to parameterize S/C dynamic models (see §3).

Figure 1. OneSat, stowed configuration.

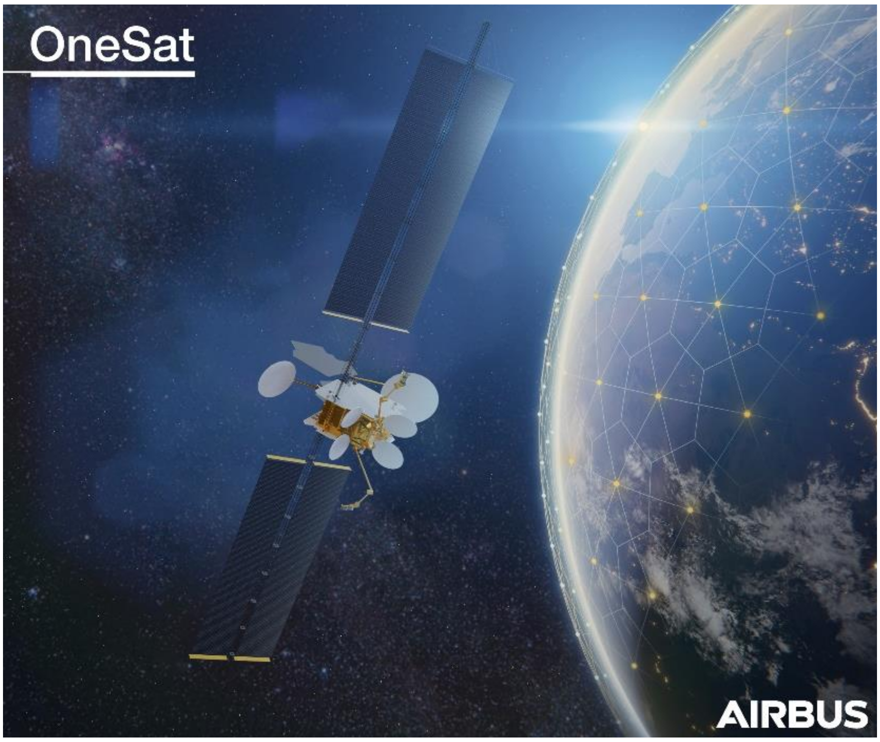


Figure 2. OneSat, deployed configuration.

2 FLEXIBLE APPENDAGES MANAGEMENT: CONTROL STRATEGIES

2.1 OneSat challenges and general principles for appendage control

The management of flexible structures is a well-known problem in space systems engineering. On OneSat, this challenge is all the more acute as the mission performance (i.e. the antenna **B**eam **P**ointing **E**rror – BPE) is directly impacted by the flexible response of the deployable antenna booms. This flexible response must thus be minimized over all phases of the On Station mission, and in particular considering that some of the flexible appendages must be continuously or periodically controlled:

- the Solar Arrays are continuously rotated through the **S**olar **A**rray **D**rive **M**echanism (SADM) to track the Sun;
- during Station Keeping manoeuvres, the DTMA is used to adapt in closed-loop the HET thrust direction, in order to compensate for thrust misalignment and generate control torques for wheel offloading.

Special care must thus be taken when driving these mobile appendages to avoid command frequency coupling with their own modes, or those of antenna booms, which would have a highly detrimental effect on mission performance. Command strategies must also be designed to be robust, since flexible characteristics (e.g. mode frequencies, damping) are only imperfectly known.

In order to control as much as possible the frequency content of the command sent to the appendage actuators, the following principles are introduced:

- **Command shaping:**
  To avoid specific harmonics, the principle of command shaping is to send step commands in pairs, with a fixed delay between steps.
  The mechanism is depicted in Figure 3, showing a 2-step equivalent command, distributed over two delayed steps.

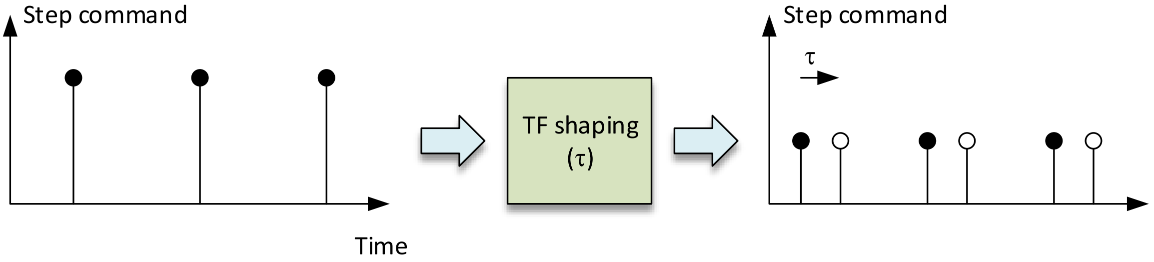


Figure 3. Command shaping principle

The resulting transfer function *TF*, and its magnitude *M*, are given by the following equations, where $s = j2\pi f$ is the Laplace variable and *f* the frequency (in Hz):

$$TF(s) = \frac{1}{2}(1 + e^{\tau s}) = \frac{1}{2}(1 + e^{\tau j 2\pi f}) \quad (1)$$

$$M(f) = |\cos(\pi.\tau.f)| \quad (2)$$

This equation shows that it is possible to cancel the frequency content at a specific frequency f_0 by selecting an appropriate delay τ as follows: $\tau = \frac{1}{2f_0}$.

- **Command spreading:**
  The aim of command spreading is to avoid regularity when multiple steps are commanded, thus avoiding flexible response build-up at specific frequencies. This is performed by introducing random delays between commanded steps. The amplitude of the command (i.e. the overall number of steps) is maintained, but the frequency content is spread, avoiding peaks at specific frequencies.

2.2 Management of regular mechanism stepping: SADM

In On Station configuration, Solar Arrays are continuously driven by SADM to track the Sun. The stepping frequency is imposed by the Sun rate (1 revolution per day) and the mechanism step size. With OneSat design, the natural command frequency is therefore close to 1.05 Hz, generating command harmonics at frequencies $f_k = k \times 1.05\ Hz$.
Unfortunately, the analysis of the transfer function between SADM command and **B**eam **P**ointing **E**rror (BPE) resulting from the flexible responses of the antenna booms reveals an increased sensitivity around 1 Hz, due to the presence of one of the boom main modes. This is illustrated in Figure 4. This figure provides the maximum gain envelope of transfer functions obtained considering all possible variations of relevant parameters (mass, inertia, mode frequencies, …) over the considered uncertainty range.
The SADM command spectrum is however known and fixed. The command shaping principle described in section §2.1 can therefore be efficiently used to suppress the fundamental harmonic at 1.05Hz. A command delay of τ = 0.5s is introduced, cancelling the frequency content at 1Hz, as illustrated in Figure 5. The side effect of this command is the generation of additional harmonics at 0.5 and 1.5 Hz, but these are now at frequencies with much lower sensitivity.

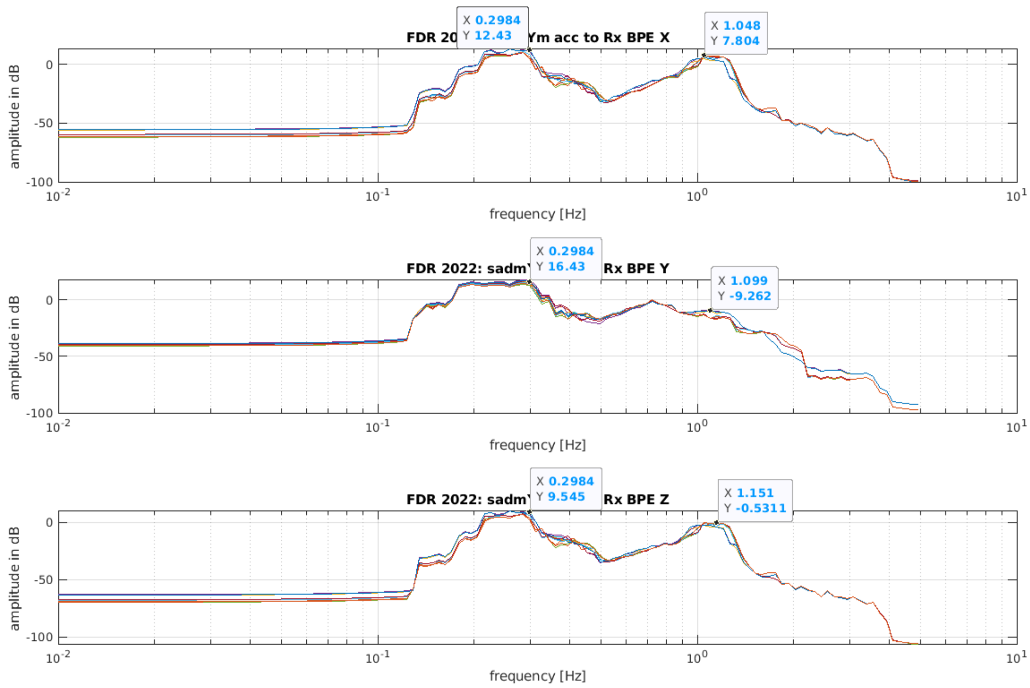


Figure 4. Maximum gain envelope for transfer functions from SADM command to Beam Pointing Error in S/C axes (X, Y, Z).

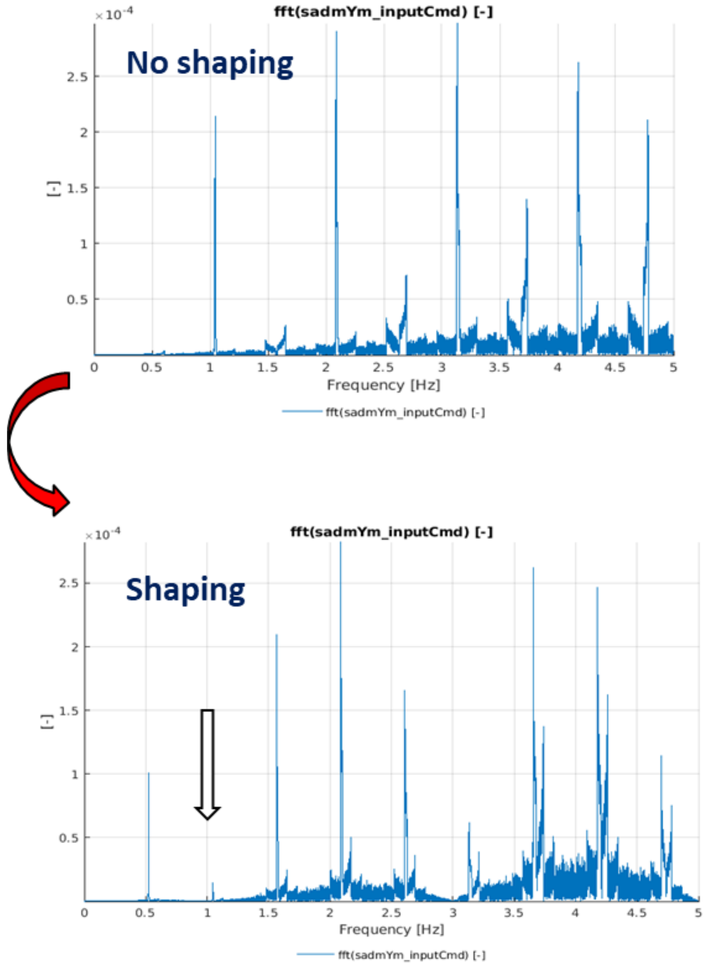


Figure 5. Effect of shaping on SADM command spectrum: 1.05 Hz harmonic is suppressed.

2.3 Mitigation solutions for closed-loop mechanism command: DTMA

The DTMA is used during Station Keeping manoeuvres to control in closed-loop the HET thrust direction, in order to:

- compensate for disturbing torques generated by the thrust (thrust direction misalignment, plume effects on Solar Array, …)
- and offset the thrust direction with respect to the S/C **C**enter **o**f **M**ass (CoM), in order to generate control torques used for wheel offloading.

Due to the large inertia of the DTMA, this motion generates a transient flexible response of the antenna booms, resulting in a corresponding Beam Pointing Error which needs to be minimized.
Unlike for the case of SADM presented in §2.2, the appendage command spectrum is wide and driven by the needs of the closed loop control.

The transfer function between DTMA command and flexible Beam Pointing Error is illustrated in Figure 7, which provides the maximum gain envelope of transfer functions between DTMA command and antenna BPE, for parameter variations over the considered uncertainty range. Maximum gain is expected in the range [0.3-0.5] Hz, corresponding to the antenna booms main modes.

The mitigation of the antenna booms flexible response relies on a combination of techniques, using the principles described in §2.1. The command strategy is summarized in Figure 6:

- DTMA commands are sent in pairs, introducing a **command shaping**, as described in §2.1. Following the transfer function envelope analysis, the command delay is selected so as to minimize frequency content in the range [0.3-0.5] Hz. Furthermore, the ability to randomly select a different delay for each command pair is introduced. This allows increasing, in average, the frequency range over which frequency content is minimized.

- In order to avoid regular stepping, and thus possible build-up of flexible response, a random **command spreading delay** is introduced between command pairs. The random value probability density is customized so that the probability to have delays in the range [2 - 3.5] seconds is null. This corresponds to the frequency range [0.28 – 0.5] Hz, over which maximum gain is expected. Exact mode frequency is not precisely known, but this technique limits the risk of consecutive steps with a repetition rate close to a mode period.

- Finally, a **command dead zone** is implemented, to avoid as much as possible unnecessary stepping. The dead-zone is of "backlash" type, rather than a linear one, thus avoiding larger stepping when the limit of the dead-zone is reached.

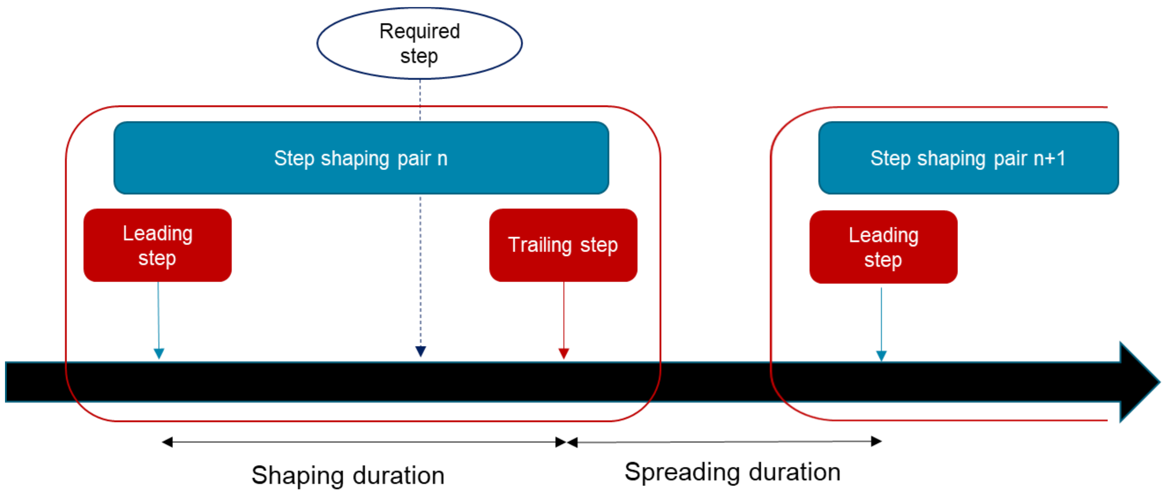


Figure 6. DTMA command strategy, including shaping and spreading principles.

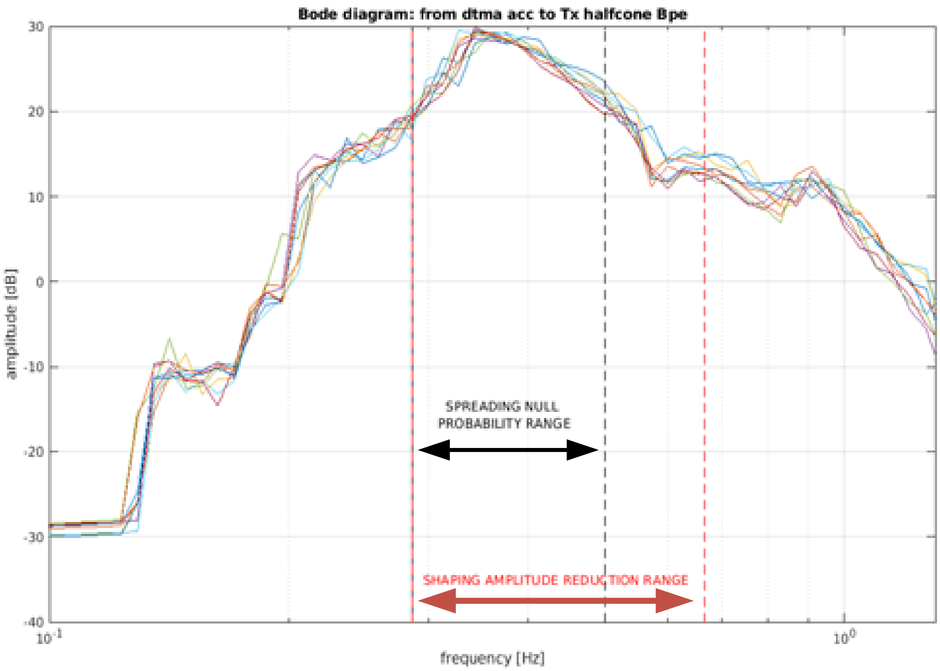


Figure 7. Maximum gain envelope of transfer functions from DTMA command to antenna boom flexible Beam Pointing Error.

2.4 Performance results

The performance improvement brought by these appendage command techniques is illustrated in the following figures.

Thanks to their introduction, it has been possible to meet the stringent antenna pointing error requirements imposed by the OneSat telecommunications mission.

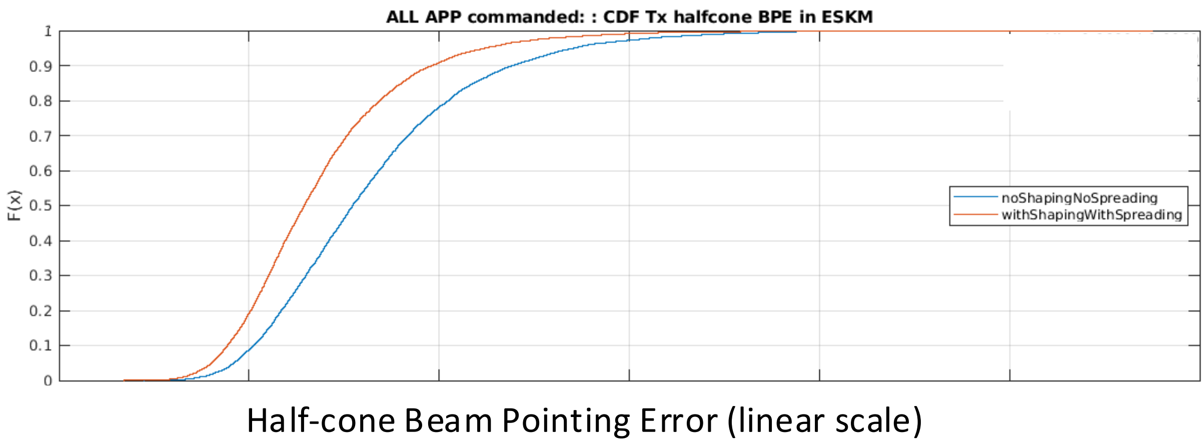


Figure 8. Cumulated Distribution Function of maximum Beam Pointing Error over a Monte-Carlo simulation campaign of Station Keeping manoeuvres.

Performance is compared without (blue curve) and with (red curve) spreading and shaping.

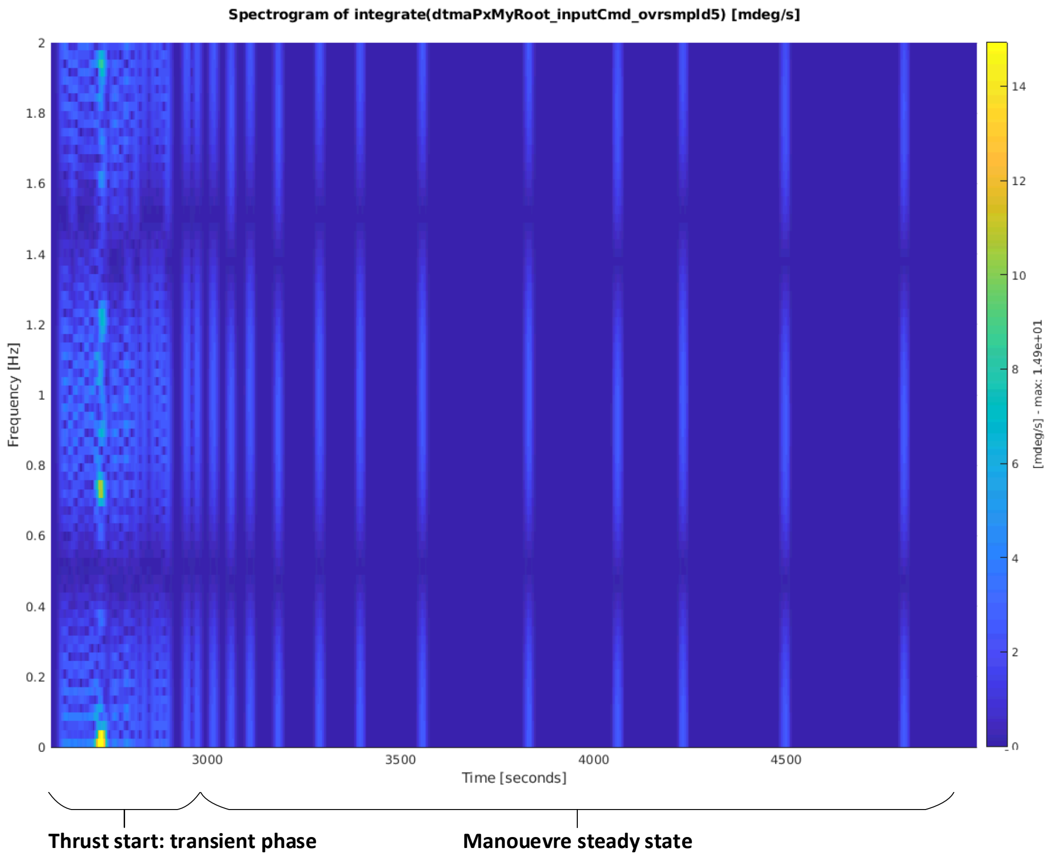


Figure 9. DTMA command spectrogram. Shaping and spreading techniques are used to minimize frequency content in the range of maximum pointing error gain [0.3-0.5] Hz.

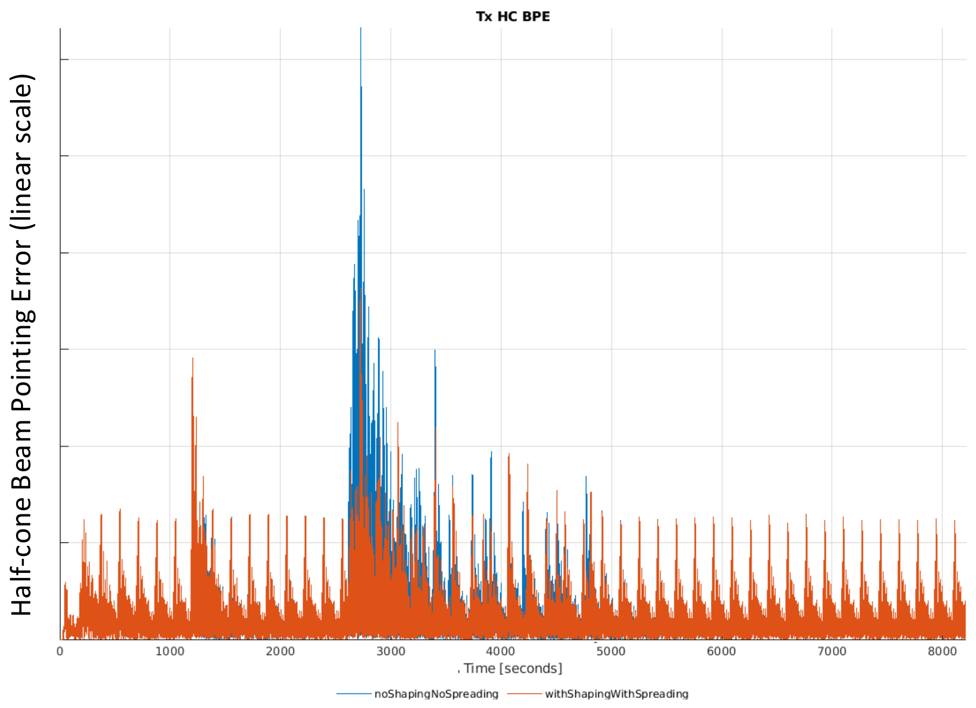


Figure 10. Flexible Beam Pointing Error over a Station Keeping manoeuvre.
Performance is compared without (blue curve) and with (red curve) spreading and shaping.

3 FLEXIBLE APPENDAGES MANAGEMENT: TOOLS FOR AOCS DESIGN

One additional challenge resulting from the high number of deployable appendages present on the OneSat platform is the correct management of the large number of possible configurations in the frame of AOCS design and performance analyses. A specific framework has been introduced, allowing to manage the large amount of data (appendage mass, inertia, flexible characteristics, uncertainty range on parameters, etc.) in a consistent way throughout all AOCS analyses (from controller tuning to performance validation on detailed simulator). The framework overview is provided in Figure 11, and detailed in the following sections.

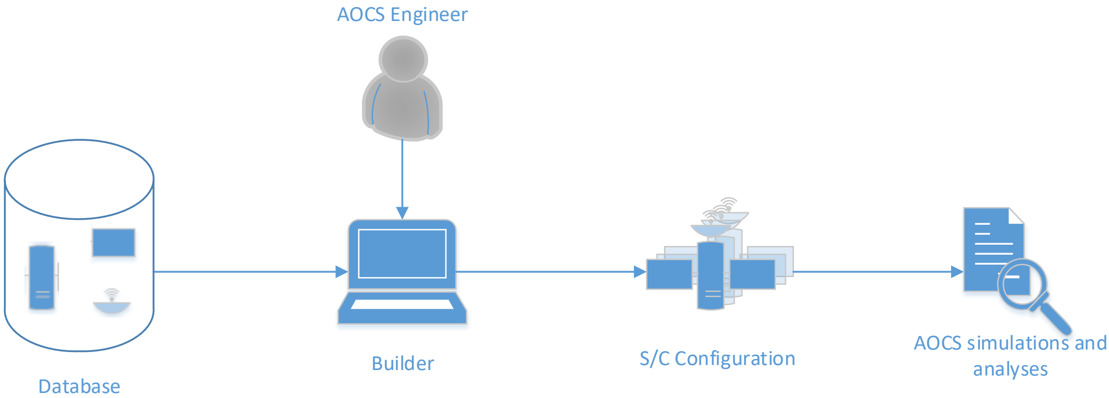


Figure 11. AOCS framework overview.

3.1 S/C elements database

The S/C configuration generation workflow relies on a database gathering the dynamic properties of all the S/C elements (central body, SADM, Solar Arrays, DTMA, antenna booms, etc.).

This database is managed in configuration as a proper library and with its own versioning so as to act as a unique reference for every AOCS analysis. In this way, the dynamic properties of the S/C are defined in a single location and once for all.

The database is organized in a 2-level structure. First, the data are organized by S/C elements, then delivered for each of their configurations, as shown on Figure 12. The database contains:

- the nominal characteristics of each appendage (mass, centre of mass, inertia, flexible characteristics if applicable),
- the link elements (e.g.: DTMA hinges, SADM linking central body to Solar Array),
- the definition of the dispersion characteristics to be considered for a predefined set of parameters (list of discrete values or range, probability law, seed for random values generation in order to manage correlation or non-correlation between parameters); particular care is taken to ensure that dispersion ranges are defined in such a way that generated dynamic configurations are always physical (e.g. mass/inertia and modal properties are defined simultaneously through a random scaling coefficient, and not defined as separate random variables).

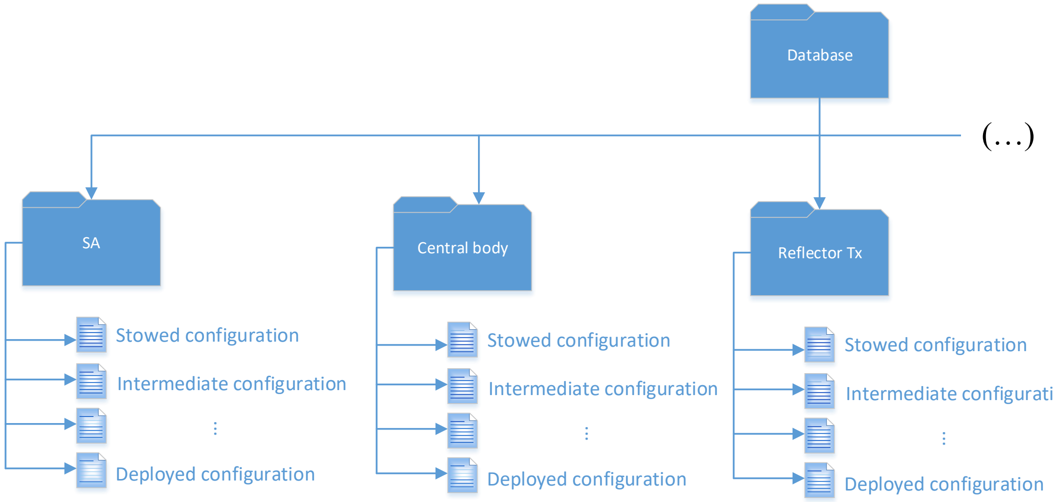


Figure 12. S/C database definition.

3.2 Global S/C builder and configuration

The global S/C builder is the interface allowing the AOCS engineer to build a complete S/C dynamic model from the S/C elements database loaded in its environment. From a simple list of human-readable metadata which are basically the appendages to consider and their respective configuration, the builder simply picks out and executes the appropriate file from the database to instantiate and group together the desired S/C elements.

Note that only the S/C elements and configuration list needs to be provided to the builder, the S/C link elements and configuration list is automatically deduced, which highly simplifies the builder API. An example of user call to the builder function is provided below:

mySc = scBuilder('centralBody','DEP', 'SA','BOTH_DEP', 'Rx','DEP_MAX', 'Tx','DEP_MAX', 'DTMA','DEP_OSM')

stands for the generation of a S/C with central body for deployed configuration, both Solar Arrays (SA) deployed, antenna booms in maximum deployed configuration, DTMA deployed in On Station Mode configuration.

The builder is also equipped with many checks performed on the user inputs so as to prevent any non-viable S/C assembly. In particular it is verified that:

- for each S/C body element, the selected configuration is among the existing ones,
- the selected configurations for all S/C body elements are consistent with one another.

There are two basic use cases for the generation of S/C dynamic models:

- Create multiple models within a set of S/C configurations, with varying random parameters. This may be the case for controller stability margins verification, or simulator initialization in the frame of a specific mode performance Monte Carlo simulation campaign (in the range of thousands of simulation runs). In this case, a cyclic call to the builder will generate a series of S/C configurations through random value generation according to the database definition.
- Create only one specific model, e.g. for dynamic simulator configuration in the frame of a specific simulation. For this case, the builder allows the user to define a specific random value generation method to consider for parameter values. The user is thus able to select

max/mean/min values of the dispersion ranges for instance. This feature is implemented to minimize any user error:

- The builder automatically checks whether the user workflow is meant to create a single S/C dynamic model or a full S/C configuration where the full random value generation is applicable.
- The user is not able to modify the database parameter values, only the random value generation method is modifiable. This prevents the risk of introducing parameterization errors.

3.3 Main benefits

The implementation of this specific framework allows a comprehensive management of the large amount of numerical data required to define the S/C dynamic models. It ensures full consistency of all AOCS analyses, simplifies the reviewing process (numerical data needs to be checked only once, in the database) and reduces the risk of parameterization error that could originate from input data duplication on different analysis scripts.

4 AUTONOMOUS TRANSITION TO STAR TRACKER BASED CONTROL

In order to optimize Launch and Early Operations Phase (LEOP), an autonomous transition to a 3-axis Star Tracker based control mode is now introduced, as part of the automatic post-launcher separation spacecraft initialisation sequence:

- After launcher injection, Star Tracker is switched ON as part of the AOCS initialization phase, and a gyro-based rate reduction phase is triggered.
- After rate reduction completion, Star Tracker tracking may not be achieved due to sensor blinding by Earth or Sun: an un-blinding manoeuvre is then performed. As soon as Star Tracker measurements are available, an automatic transition to a 3-axis Star Tracker-based cruise mode is triggered.
- Robustness is always ensured in case of unavailable Star Tracker measurements: a power safe Sun Acquisition is then performed using gyro and a Coarse Sun Sensor for attitude detection.

This evolution is an enabler to simplify and accelerate operations during LEOP:

- Compared to a sequence based on heritage Eurostar NEO design, the duration to reach a Sun pointed attitude after launcher separation has been significantly reduced (-35%).
- Moreover, the transition to a 3-axis control mode allows optimizing the attitude for the 1st perigee crossing at low altitude with Solar Arrays deployed, reducing air drag disturbances and hence propellant consumption.

The reference attitude in Star Tracker based mode has been selected to be a simple Sun pointed attitude, independent from the injection orbit. Although the knowledge on-board of the current date is necessary (for Sun ephemeris), this date need not be precise (a 1 day error would only translate to a 1 deg Sun pointing error).

5 TWIN MANOEUVRE STRATEGY

5.1 Eurostar heritage

OneSat Station Keeping concept is strongly based on the flight-proven strategy introduced in Eurostar satellites (E3000 Mk2 and Eurostar NEO, see [1] and [2]). This full-electric concept relies on a combined control of both orbit and wheel momentum, using the HET mounted on the two robotic arms (DTMA).

During Station Keeping manoeuvres, a single HET is fired, and the DTMA is used to control the thrust direction to fulfil orbit and momentum control needs:

- HET thrust is mainly directed towards the S/C CoM; thanks to the DTMA geometry, the North/South force component is improved for higher inclination control efficiency.
- The 3-axis DTMA hinge actuators are used to provide:
    - 2-axis torque capability in the plane perpendicular to the thrust direction (by slightly offsetting the thrust direction with respect to the S/C CoM)
    - and a precise control of the thrust tangential component.

Since only 2-axis momentum control is possible over one given manoeuvre, 3-axis wheel offloading needs are spread over a pair of manoeuvres (North and South). This is achieved by imposing a minimum separation between inertial thrust directions through manoeuvre Right Ascension and differential tangential force demand.

5.2 OneSat challenge and solution: Twin Manoeuvre concept

The mass of OneSat S/C is significantly lower than for equivalent Eurostar 3000 or NEO satellites. For a similar orbit control ΔV need, the required impulse is therefore lower, meaning that less control momentum (impulse x DTMA lever arm) is available for wheel system offloading.

The wheel offloading needs are however similar or even higher than for previous S/C. The capacity of the offloading scheme needs therefore to be increased.

As presented in §5.1, 3-axis controllability is obtained by imposing a minimum separation angle between the inertial thrust directions of the two manoeuvres in a North/South pair. Higher separation yields higher offloading capacity.

On OneSat, this is obtained by allowing the manoeuvre programming **G**round **S**oft**W**are (GSW) to split one or both manoeuvres into two "Twin thrusts". Both "Twin thrusts" have similar characteristics (duration, tangential force request), which streamlines the resolution of the Flight Dynamics problem. Offloading capacity is highly increased thanks to the natural separation between thrust directions so introduced, at the cost of a slight degradation of manoeuvre efficiency (overall thrust duration is slightly higher). The efficiency degradation is however lower than for the heritage Eurostar manoeuvre scheme: thanks to this Airbus patented strategy, higher controllability is obtained with lower cost.

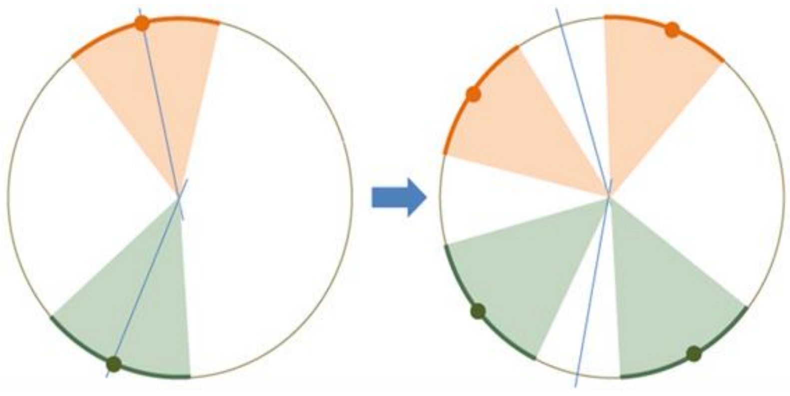


Figure 13. Eurostar heritage and Twin Manoeuvre concepts.

Additional versatility is therefore introduced for wheel momentum control, spreading the offloading need in N-uplets of manoeuvres (N=2, 3 or 4), instead of only pairs.
Figure 14 illustrates the wheel momentum evolution over a day with 4 manoeuvres, and over a full manoeuvre cycle (3 manoeuvres per day over 2 weeks):

- Outside manoeuvres, wheel momentum drifts due to inertial disturbing torques (solar pressure, gravity gradient, etc.).
- During manoeuvres, wheel momentum evolution is split between:
    - a controlled part in the plane perpendicular to the thrust direction,
    - an un-controlled part along the thrust direction (mainly due to HET axial torque and plume effects on Solar Array).

The Ground SW is in charge of optimizing the offloading setpoints for each manoeuvre, in order to minimize the overall momentum excursion and guarantee that AOCS constraints are respected:

- maximum momentum excursion vs allocated capacity,
- maximum momentum variation over a given manoeuvre consistent with maximum available offloading torque.

On-board, a closed loop corrective term is added to ensure robustness to momentum evolution prediction errors.

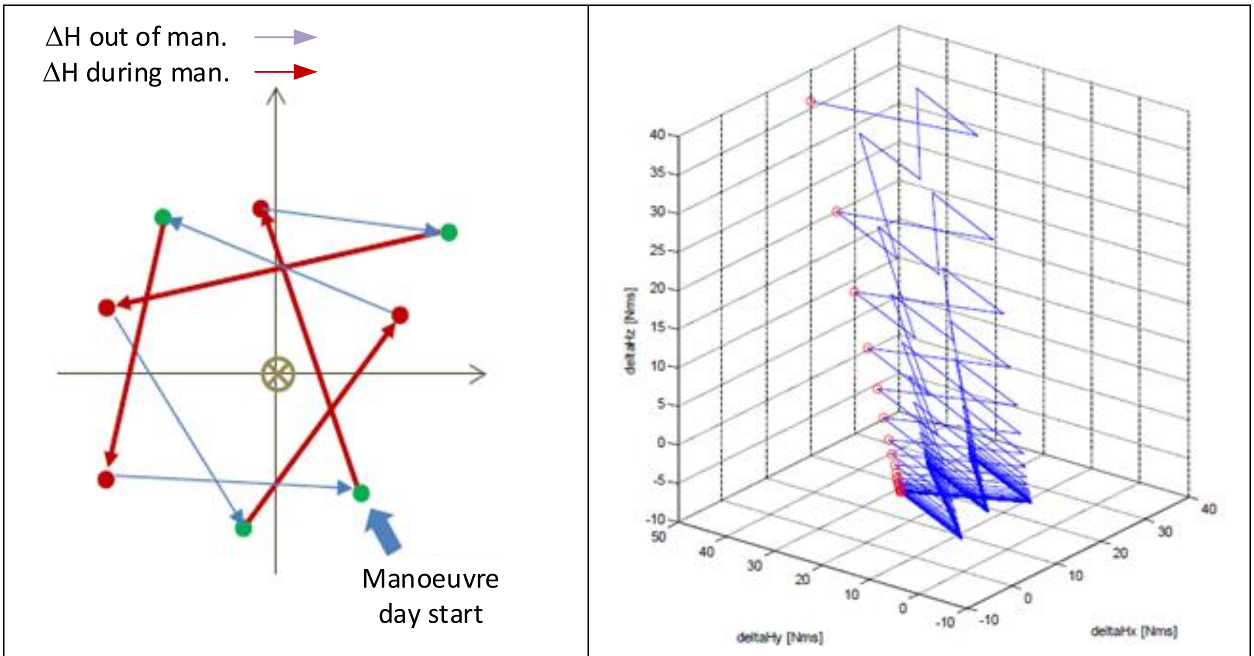
Note that the overall number of manoeuvres is nevertheless not increased with respect to previous Eurostar applications. Indeed, given the mass of the S/C, the ΔV impulse can be performed over only 3 days of manoeuvres per week. The average number of manoeuvres per HET remains therefore similar to previous Eurostar S/C, and fully consistent with HET thrusters qualification (typically 1 manoeuvre per day over 15 years in average).

The Station Keeping scenario and operational flow diagram are summarized in Figure 16 and Figure 17. Starting from the required orbital corrections required, the Ground SW will select the most efficient solution fulfilling both orbit and AOCS offloading constraints with minimum Xenon consumption.

5.3 Support to Customer Ground SoftWare development

In order to ease and streamline the development of Customer Ground SW for Station Keeping operations, Airbus Defence and Space provides an external C library, devoted to the verification of AOCS offloading constraints (momentum setpoints optimization, verification that maximum momentum excursion and maximum offloading torque constraints are fulfilled).

This library is auto-coded from the Matlab® functions used for AOCS performance analysis and simulations. The process ensures full consistency with Aibus performance analyses, and removes the need for costly implementation validation iterations.
This SW delivery process builds upon the extensive experience gained by Airbus through the development of AOCS auto-coded flight software for Eurostar NEO (see [2]) and other application programs.



(a) Wheel momentum evolution over a manœuvre day (4 manœuvres)

(b) Wheel momentum evolution over a full manoeuvre cycle (3 manoeuvres/day over 2 weeks)

Figure 14. Illustration of wheel momentum evolution.

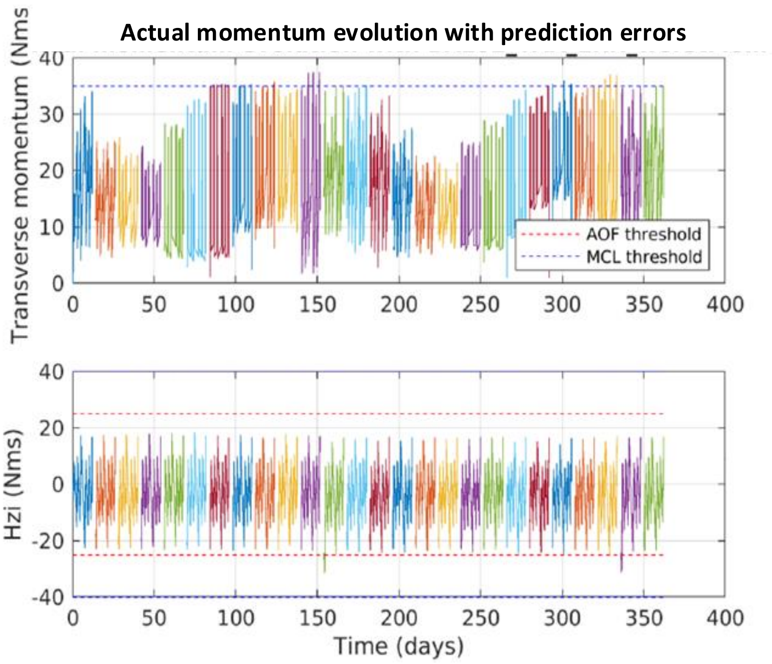


Figure 15. Simulated momentum evolution over a full year, including prediction errors.

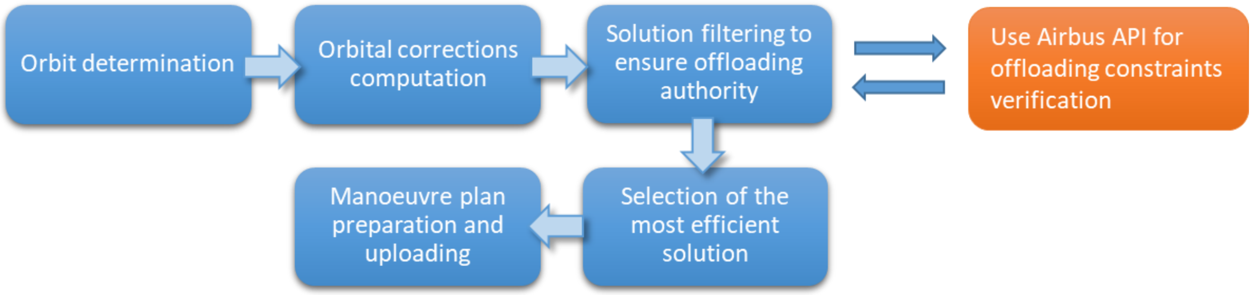


Figure 16. OneSat full-electric Station Keeping operations flow diagram.

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14
Maneuver	N/EW		N/EW		N/EW			N/EW		N/EW		N/EW		
	S/EW		S/EW		S/EW			S/EW		S/EW		S/EW		
Orbit Determination														

Figure 17. OneSat Station Keeping scenario.

6 CONCLUSION AND PERSPECTIVES

OneSat AOCS design relies on a solid heritage from flight-proven Airbus Eurostar 3000 and NEO platforms. In order to adapt to the specificities of the mission, several design topics have been successfully tackled in order to:

- manage a large diversity of appendage configurations,
- develop flexible appendage command strategies for pointing performance optimization,
- improve the efficiency of the combined orbit and wheel momentum control,
- simplify and accelerate operations during LEOP.

All these design innovations are currently undergoing qualification, paving the way for the 7 OneSat S/C already in development.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] Guyot M., Fondeville M., Lainé I., Kowaltschek S., *Eurostar E3000: ADCS evolutions for full electric satellites*, 10th ESA Conference on Guidance Navigation and Control Systems, 2017.

[2] Reuilh A., Beroud J., Roussel S., Rosso C., *AOCS innovations for Eurostar NEO full-electric platform*, 2021 ESA Conference on Guidance Navigation and Control Systems, 2021.