SWOT: AN AOCS ANSWERING TO HIGH PAYLOAD CONSTRAINTS AND A CONTROLLED REENTRY OF A LARGE SATELLITE

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ABSTRACT

The CNES-NASA SWOT (Surface Water and Ocean Topography) satellite was launched on December 2022. SWOT will provide the first global survey of Earth's surface water and measurements of the circulation patterns of oceans.

The platform, developed by Thales Alenia Space, is dimensioned for a large satellite on a drifting low Earth orbit with local nadir and track compensation guidance.

The first challenge of AOCS (Attitude and Orbit Control System) design was the deployment of KaRin payload, done in multiple steps. The satellite successfully achieved a converged Sun pointing attitude with large variations of inertia during the early operational phase using magneto-torque bars as actuators.

The second challenge are the requirements of dynamical stability and attitude knowledge to achieve the foreseen precision during the mission. The AOCS is based on a multi-head star tracker with data fusion and 4 reaction wheels.

The last dimensioning point is the end-of-life strategy. The French Space Operation Act is applicable to SWOT satellite, requiring a controlled re-entry. The propulsion system dimensioned for this last phase demanded adapted control laws for the orbit correction manoeuvers during the mission.

In overall, SWOT is functioning nominally and it is already providing successful results.

1 INTRODUCTION

The objective of this paper is to explain how the SWOT payload has impacted the AOCS architecture of the satellite. SWOT AOCS design is driven by the payload constraints before starting the mission (deployment phases), during the mission (large payload with strong demands on dynamical stability) and after the mission (controlled re-entry). As a result the AOCS has to manage a large satellite similar to a geostationary satellite, with a variable geometry during the payload deployment and a variable orbital domain due to the controlled re-entry after the mission.

The paper describes the mission context in the first part. Then it focuses on the different phases, starting by the payload deployment strategy and flight data. Next section covers the mission phase with the two most sizing criteria (the dynamical stability and the attitude restitution) and correlation with flight data. The last part of the paper is dedicated to the controlled re-entry description.

2 SWOT OVERVIEW

2.1 SWOT mission

Following the successful series of the Jason satellites family, the French-US SWOT (Surface Water and Ocean Topography) satellite has been launched on December 2022. The mission will provide the first global survey of Earth’s surface water measuring the height and temporal variations of lakes, rivers and flood zones, which is expected to revolutionize hydrology studies. It will also provide valuable oceanography data as it will significantly improve both offshore and coastal ocean observations and it be able to see mesoscale and sub-mesoscale circulation patterns of oceans.

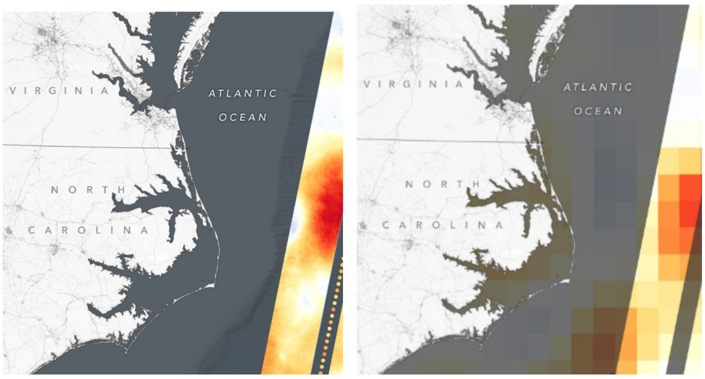


Figure 1. In the left, sea level data gathered on January 2023 by SWOT, which has 10 times the spatial resolution of the available data over the same area taken by altimeters on seven other satellites (right). Credit: NASA, swot.jpl.nasa.gov

2.2 SWOT Satellite

The satellite is classically split into a payload, with its main instrument KaRin developed by NASA-JPL, and a platform developed by Thales Alenia Space for CNES.

KaRin instrument is a wide-swath Ka-band radar interferometer constituted of two radar antennas perched at the end of two 5-meter booms. The platform is dimensioned for a satellite mass near 2 tons and a large power supply near 6.6 kWs in order to satisfy the mission needs on a drifting low earth orbit (altitude near 900 km, inclination of 78 degrees) with a local nadir and track compensation guidance. This orbit enables a global coverage every 21 days. Before reaching the operational orbit, the payload calibration is performed in a 1-day repeat orbit. The amount of power needed results in a satellite design with two large solar panels, with a surface over 15.5 m^2 each.

Figure 2. SWOT satellite during solar panels deployment tests at the Thales Alenia Space facility in Cannes, France. Credit: Thales Alenia Space.

2.3 SWOT AOCS Design

The platform uses the generic Step2 avionics developed by Thales Alenia Space. Its AOCS in mission mode is based on a gyroless estimation using a multi-head star tracker (MHSTR) with data fusion and 4 Reaction Wheels (RWs) for control. The survival mode uses a combined magnetometer and coarse Sun sensor (CSS) estimation and a 3 magneto-torque bars (MTB) for control with 2 RWs at constant rate for gyroscopic stiffness.

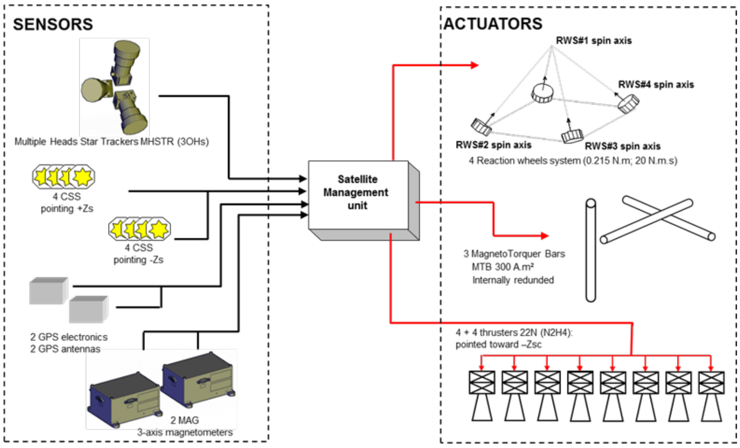


Figure 3. AOCS units architecture

The AOCS modes are:

- ESAM (Emergency and Safe Attitude Mode) is used just after launch or after an anomaly with to aim to point Zs axis towards the Sun with a spin.
- TRM (Transition Mode) is an automatic mode allowing the transition from ESAM to NOM (see [1] for more details).
- NOM (Nominal Operating mode) is dedicated to the mission phase with Zs axis pointed towards the Earth according to the local nadir and track compensation guidance law autonomously processed thanks to the GNSS orbit estimation.
- OCM (Orbit Control Mode) allows to manage the orbit configuration for initial orbit acquisition, station keeping, debris avoidance and end of life.

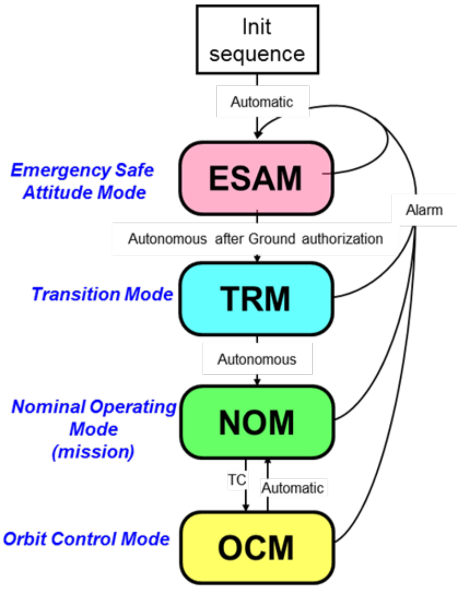


Figure 4. AOCS modes sequence

Considering the system needs, the SWOT AOCS is highly constrained all along the lifetime of the satellite, with the payload at the origin of the main key drivers for AOCS design.

- Before the beginning of the mission: KaRin instrument is deployed in 4 different stages, each one followed by a Sun convergence, which means that the mode ESAM has to be compatible with a varying geometry and with major variations in the spacecraft inertia.
- During the mission: to fulfil the quality of the products it is necessary to ensure a very high dynamical stability and a very good knowledge of the attitude. This is particularly challenging due to the large payload and large solar panels, which lead to large inertias.
- At the end of the mission: The French Space Operation Act is applicable for SWOT, and due to the payload constitution a controlled re-entry of the satellite at the end of life is required.

Each of these key points implies either a dedicated AOCS design, either an optimized operational strategy, either the development of processing tools or a specific validation process.
The four following parts of the paper will focus on each subject, presenting the problem, the adopted solution and the corresponding performance.

3 PAYLOAD DEPLOYMENT

3.1 Deployment strategy

The deployment of the KaRin instrument is realized in separated steps. Each steps begins with a spring release generating a very short but high perturbation torque, followed by the motion of the hinge and ends by the hinge latching. Each intermediary configuration has a very different geometry with a great variation of the inertia, as shown in Figure 5. The flexible modes also change with each configuration and with the latching status.

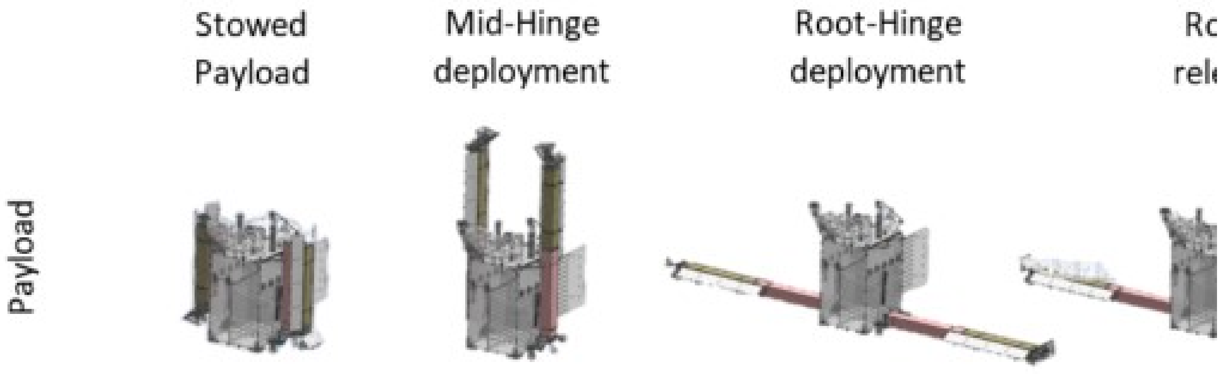


Figure 5. Payload deployment steps

Due to these characteristics, the deployment was not possible in AOCS NOM mode and it was planned in ESAM mode, where the control is done by the high capacity MTBs. Each step in the payload deployment is commanded by a ground TC sequence after having verified that the satellite is in converged ESAM conditions.
In order to prevent from any impact of the MTBs torques to the deployment mechanisms, it was decided to inhibit the control during the deployment duration. In order to be robust to any impact of the deployment on the dynamics, the strategy consisted on triggering a new ESAM convergence sequence following each change in geometry.

This imposes an AOCS design capable of Sun convergence towards the with very different inertias, including a scenario of instable nature after mid-hinge deployment where the axis to be pointed at the Sun corresponds to the axis of medium inertia.

3.2 In orbit behaviour

The effects of the payload deployment and specially the pyros can be observed in the spacecraft dynamics during the deployment.

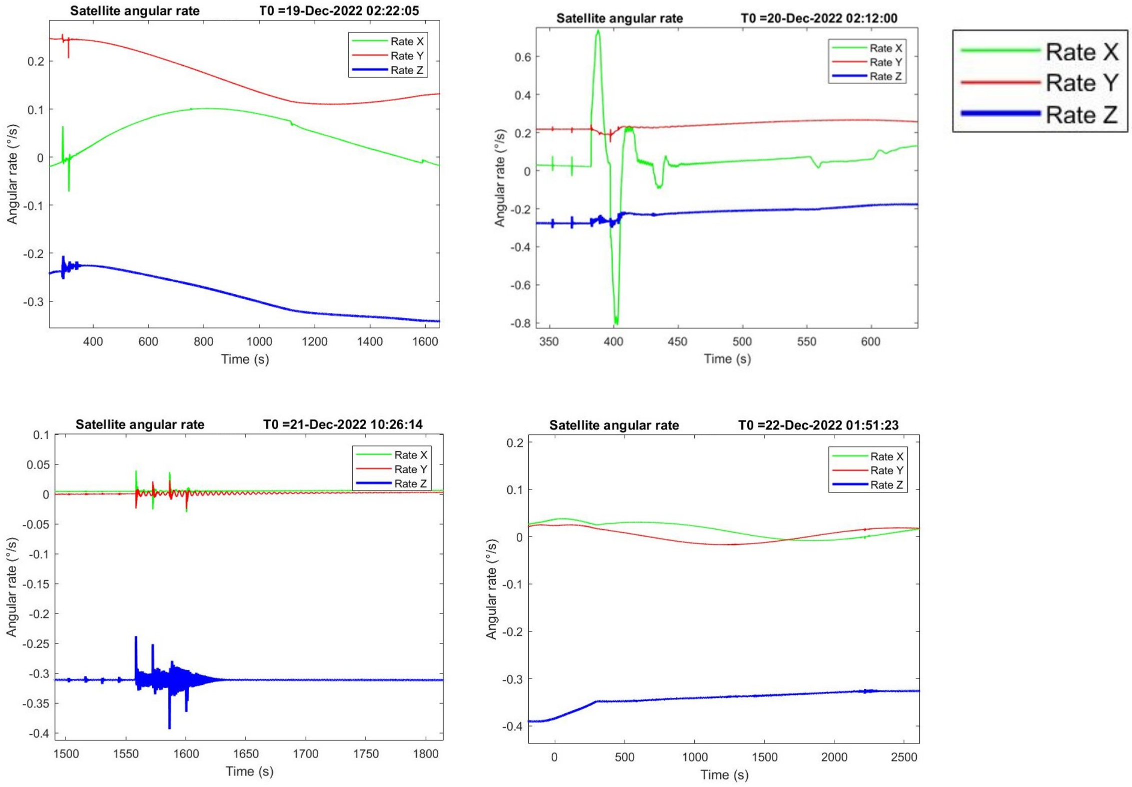


Figure 6. Satellite angular rate during mid-hinge deployment (top left), root-hinge deployment (top right), rotor release (bottom left) and rotor deployment (bottom right).

Figure 7 and Figure 8 show orbit telemetry corresponding to the first step of payload deployment, mid-hinge deployment, which leads to the most critical geometric configuration as the AOCS must point the axis of medium inertia towards the Sun.

It can be seen that each deployment is commanded in ESAM converged conditions in BBQP phase. The MTB command is inhibited for a duration that covers with margin the payload deployment (Figure 7). During the deployment, with no AOCS command, the Sun pointing error increases (Figure 8). Once the deployment timer is achieved, a PM reset is commanded to start a new ESAM convergence going through all its phases. Once the final phase is reached, it can be seen that the Sun pointing error stabilizes to values below 25 degrees.

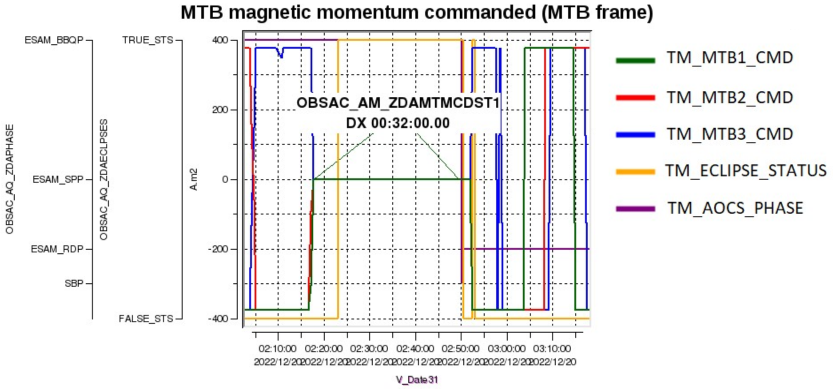


Figure 7. There is no MTB command during PL deployment.

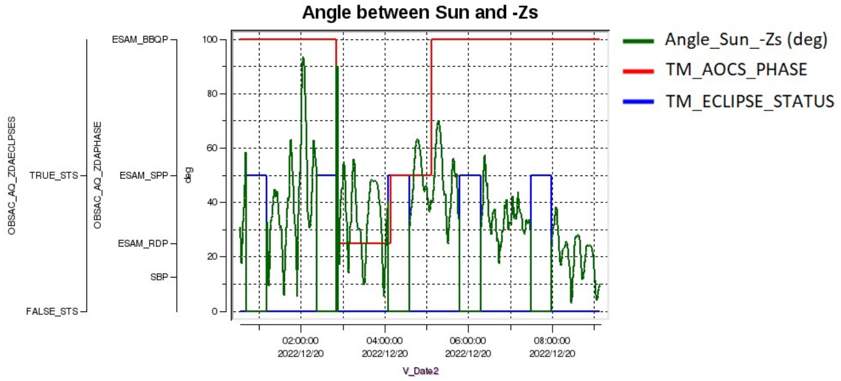


Figure 8. PL deployment occurs in BBQP phase (ESAM converged conditions). After the deployment, a PM reset is commanded to restart ESAM convergence going through all its phases.

Time to converge to spin Sun pointing attitude was within the expected range for all geometric configurations. As shown in Figure 9, the Sun pointing error with deployed payload was better than 25 degrees at all times, compared to a need of 70 degrees. The requirement on Sun pointing error is not very strict as the PL is switched off in safe mode and the power demands are low.

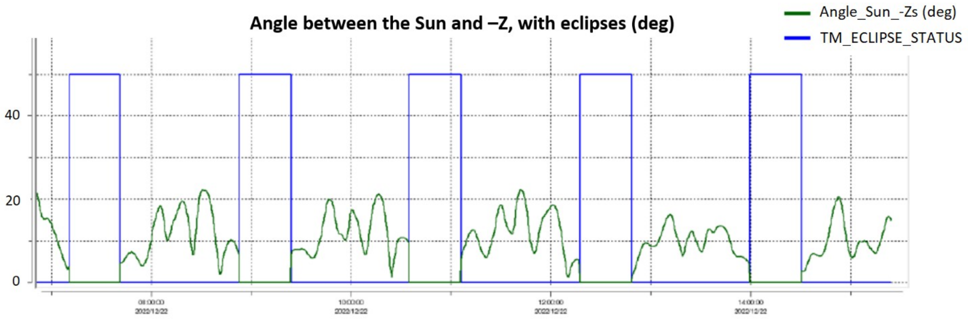


Figure 9. Angle between the Solar Panels and the Sun during converged ESAM phase. There is no Sun measurement data during eclipses (blue).

4 MISSION PHASE

The Satellite reached AOCS NOM mode at the end of 2022, after the payload deployment, initial heath checks and transition mode. The first semester of 2023 has been dedicated to payload health-checks and calibration, which is done at a dedicated orbit. The good quality of the data obtained during this calibration phase confirms that the AOCS design responds to the payload needs.

4.1 Mission guidance

In mission mode, the guidance of the satellite is based on nadir pointing with yaw steering for track compensation (LNTC).

In addition, a yaw flip of 180°deg is programmed at each a change on the sign of the angle between the Sun and the Orbit. This is done to ensure that the cold side of the spacecraft (-Ys) where the MHSTR is mounted is always in the shadow.

SWOT AOCS also offers the capabilities to perform polynomial guidance. This type of guidance has been used for the calibration of the payload instruments, as well as for the yaw flips to command the satellite to follow a given trajectory.

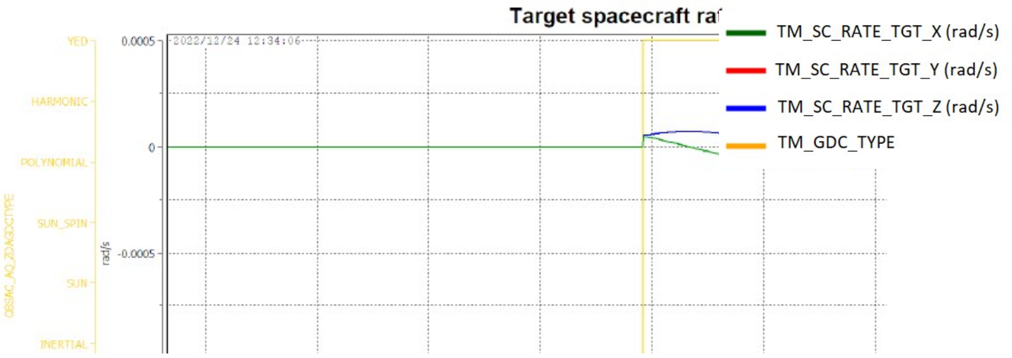


Figure 10. Flight spacecraft target transition from geocentrical guidance to local nadir with track compensation guidance (YED).

4.2 Dynamical stability

When the mission with KaRin instrument begins, the quality of the measurements depends on the stability of the large payload. To assess the payload stability, 3 geometrical components were defined (characterizing the length of the baseline, the roll and the phase), each of them based on the motion of points located on different part of the payload, as presented in Figure 11. The stability criterion is a combination of these 3 components. Two requirements applicable to the platform were defined: a PSD limit (applicable to frequencies until 6.5Hz) and a RMS limit (integration of frequencies above 6.5Hz).

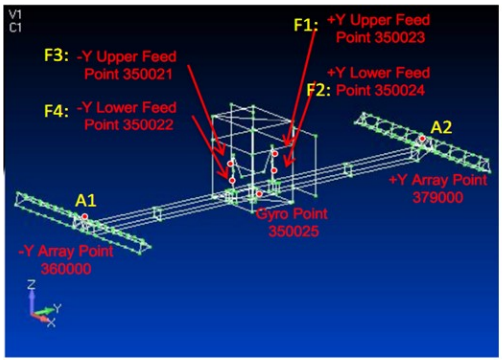


Figure 11. Payload points taken into account in the stability criterion

The possible perturbations for this dynamical stability were analysed according to their frequency.

Medium - high frequency assessment

The medium-high frequency domain corresponds to the micro vibrations due to the RWs. Different actions were implemented to reduce their impact on the PL performance.

First, Thales Alenia Space chose a RWs layout that minimized the perturbations on the payload.

Secondly, Thales Alenia Space defined the optimal RWs speed during the mission in order to keep the harmonics of the perturbation outside the most sensible frequency zones. The objective was to operate the reaction wheels within a range of frequencies, to avoid coupling with PL flexible modes (at low and high frequencies) and to remain compliant with the PSD criteria. This is easily managed with the 4 RWs configuration (which offers a degree of freedom) but a specific unloading strategy had to be implemented for the 3 RWs configuration (in case of 1 RW failure). When a modification of the attitude is requested outside the mission period (yaw flip to keep the –Y face in the shadow or slew before doing an OCM), it is necessary to modify the initial RWs rates, in order to restore a sufficient wheels capacity for doing the attitude slews, as shown in Figure 12.

Finally, Thales Alenia Space performed simulations with a dedicated micro-vibrations tool to verify the compliance to the stability criterion and to generate data for the precise verifications done by the payload team.

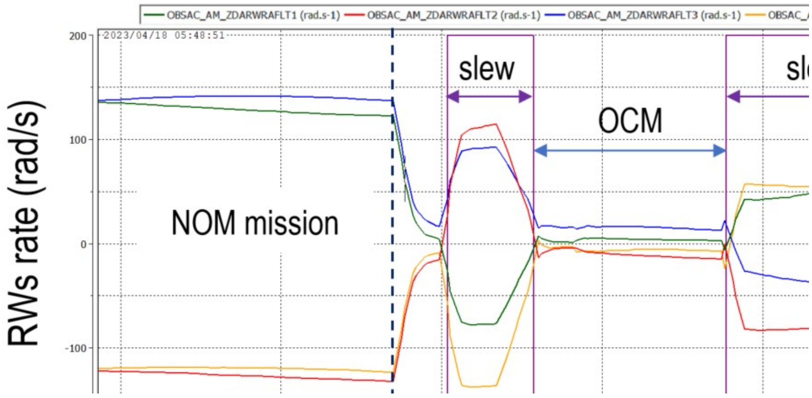


Figure 12. RWs rate management during mission and manoeuvres.

Low – medium frequency assessment

The low-medium frequency domain corresponds to the other disturbances: AOCS actuators (except RWs micro vibrations), AOCS control loop noise, solar arrays commanded rotations or solar arrays thermal snaps at eclipse transitions.

The estimation of the criterion stability was done thanks to the AOCS high fidelity simulator, where the flexible modes of the payload and the solar panels are modelled, with an estimation of the motion of the payload points involved in the criterion.

The first step consisted in estimating the criterion in routine phase (no solar array rotation, no eclipse): Figure 13 shows there is a large margin with regards to the requirement.

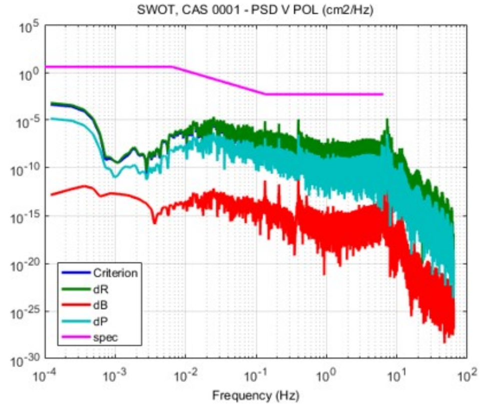


Figure 13. Dynamical stability in routine nominal phase

In a second step, the transient situations were analysed case by case.

Scenarios with thermal snap at eclipse entry and exit were within the dynamical stability requirement in less than 120s (as required for mission availability).

Scenarios with solar arrays rotation showed that the dynamical stability requirement was not fulfilled, thus it was necessary to estimate the delay to recover compliance to the requirement and take it into account in the mission unavailability budget.

Simulation results showed that after 700s the damping was sufficient for all scenarios to be compliant the PSD requirement. The corresponding mission unavailability is acceptable due to the fact that the number of solar arrays rotations is very weak. Figure 14 shows the temporal evolution of the stability criterion: it is possible to observe the damping of the initial perturbation. Figure 15 shows that after 700s the dynamical stability is compliant to the requirement.

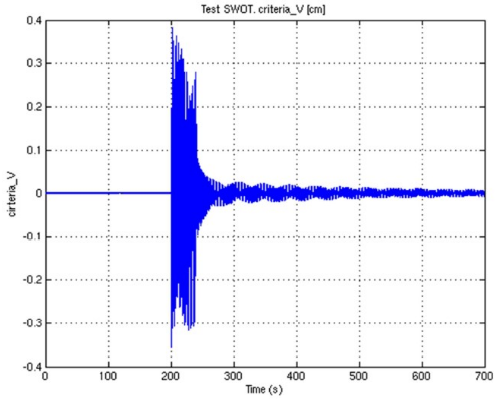
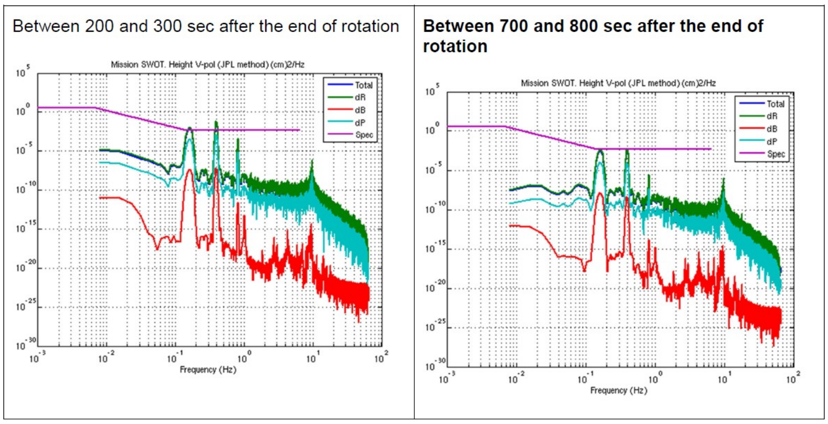


Figure 14. Temporal evolution of the stability criterion when solar arrays are rotating


Between 200 and 300 sec after the end of rotation

Between 700 and 800 sec after the end of rotation

Figure 15. Identification of the unavailability period after a solar arrays rotation

Flight observations

It is not possible to compute the dynamical stability criterion with flight telemetry. However, two indicators are used to confirm the AOCS performance:

- Payload science data: strong perturbations become visible when processing the science data. High quality data has been collected during the calibration phase outside the zones of mission unavailability, proving that the dynamical stability needs are covered.
- Disturbances of solar array rotations and thermal snap: even if AOCS is gyroless, a gyroscope is installed in the payload for ground attitude restitution. This enables the ground to the spacecraft attitude at high frequency and analyse the impact of the disturbances on different scenarios (solar array rotation and thermal snaps).

Ground computed attitude from flight telemetry shows that there are frequently perturbations during solar array rotation, which are damped after 700s.

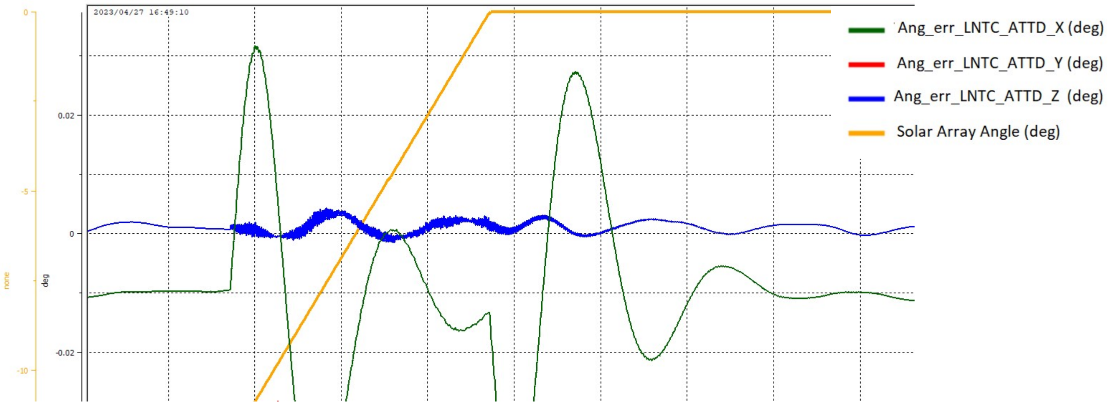


Figure 16. Angular error between target and ground computed attitude during solar arrays rotation.

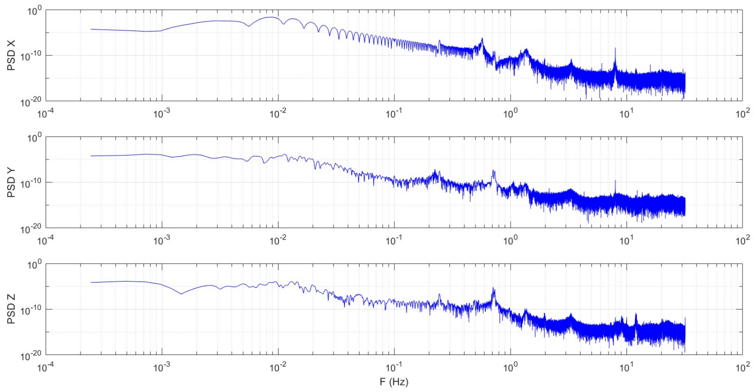


Figure 17. PSD of ground computed attitude during solar arrays rotation.

At the beginning and end of an eclipse, there is a transient pointing error due to the solar panels thermal snap. Data during the 120s following an eclipse transition is not used, hence these transients do not affect the quality of the images. Figure 18 shows that the estimated perturbation is very weak for both eclipse entry and exit, even for the worst case (Sun in the orbital plane).

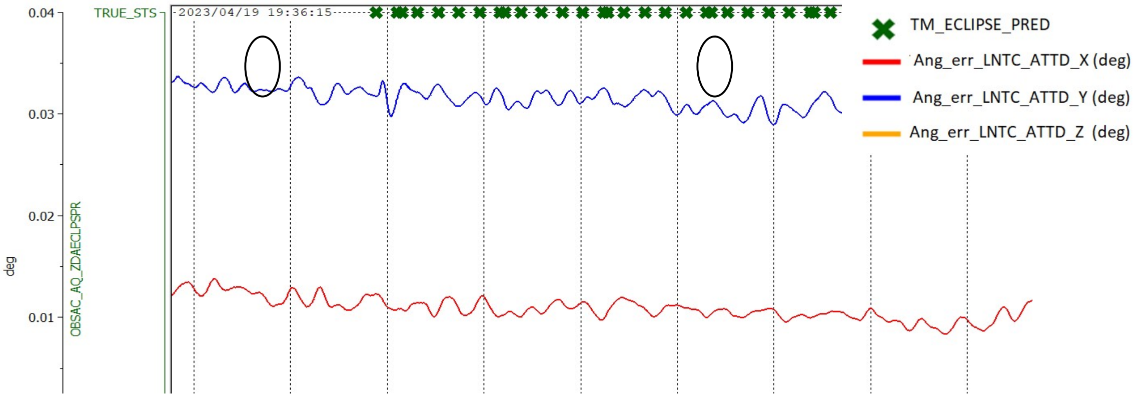


Figure 18. Angular error between target and ground computed attitude correlated with eclipses.

4.3 Attitude estimation

Another major contribution to the mission performance is the knowledge of the attitude. CNES is in charge of delivering to the scientific community a precise attitude product computed on ground, which is used then for processing the mission product chains.

For attitude estimation on-board, the AOCS uses a MHSTR with two optical heads (OH) tracking up to 10 stars each, plus an additional OH for cold redundancy. The measurements of the two OHs are combined to provide a merged measurement with reduced noise in spacecraft axis. The performance of the merged measurement improves if the angular separation between optical heads boresights is close 90 degrees. The layout of the optical heads was the compromise of performance optimisation and visibility constraints.

Telemetry data confirms that the noise level is significantly reduced when comparing the measurements provided directly by the MHSTR (Noise Equivalent Angle up to 90 arcsec in the OH boresight direction) with the attitude estimation after merging plus filtering (Noise Equivalent Angle below 4 arcsec in all axis).

Figure 19 shows the angular evolution of the on-board estimated attitude (after merging MHSTR data and filtering) on the right, and the same data for one OH measurement on the left. The angular evolution is composed of two terms: actual movement of the spacecraft (long term evolution) and noise (which is visible by the widths of the curve). It can be seen that the on board estimated attitude has significantly lower noise than the measurement of one OH.

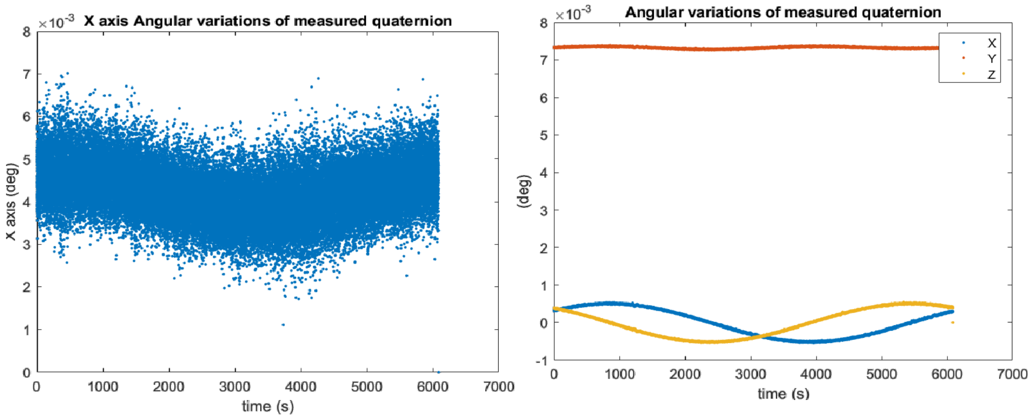


Figure 19. Left: angular variations of the attitude measurement of one optical head. Right: on-board estimated attitude using merged measurements and filter, showing significantly less noise

In order to answer to the ground requirements on attitude knowledge (a PSD limit applicable to frequencies above 5.2e-4 Hz and a RMS limit corresponding to the integration of the whole frequencies domain and equal to a few arcsec at 1-sigma), the data (8Hz) of the two OHs is combined with the measurements (64Hz) of a gyroscope installed in the payload with a dedicated filtering. The tuning of the ground tools is being adjusted with the flight data during the calibration phase taking into account the bias estimation between the KaRin frame and the OH1 frame. We observe in flight a very stable of the bias between OH1 and OH2, allowing a simple management.

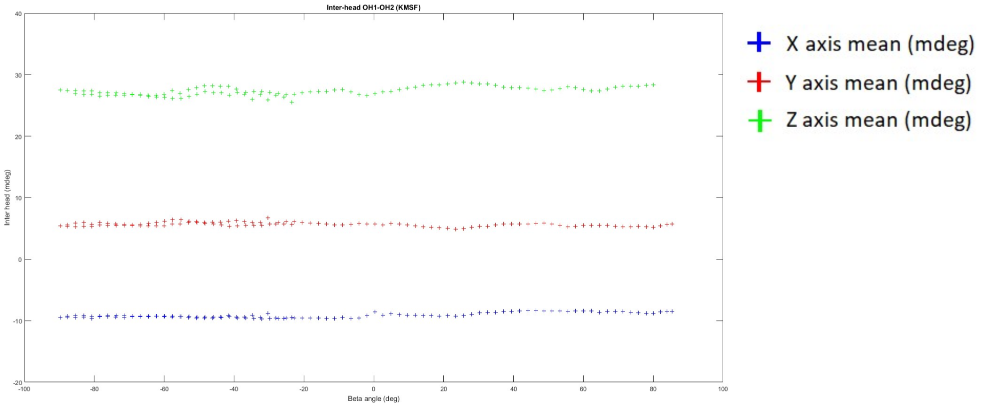


Figure 20. Inter-head between OH1-OH2 as a function of beta angle (between the Sun and the orbit).

5 CONTROLLED RE-ENTRY

5.1 French Space Operation Act

The French Space Operation Act was adopted by the French Senate in 2008. The purpose of this document is to set up a national regime to authorize and control Space operations following French government's international commitments. So the French authorities mainly voted for this act in order to assure the protection of people, good and the environment against space activities.
As SWOT launch was scheduled after the year 2020 and the control operations are done at CNES in France, the satellite shall respect the requirements existing in the FSOA in terms of end of life.
Due to SWOT payload constitution, the only possible solution for the end of life disposal is a controlled re-entry.

5.2 Adopted strategy

The strategy adopted in order to be compliant to the FSOA consists in aiming an impact of the satellite debris inside the South Pacific Ocean Uninhabited Area (SPOUA), as shown in Figure 21.
The first phase consists in creating an elliptic orbit from the mission circular orbit, with multiple manoeuvres to lower the perigee altitude, and the second phase aims at realizing a last single thrust at the apogee in order to have the perigee in the SPOUA, as described in Figure 22 (see [2]).

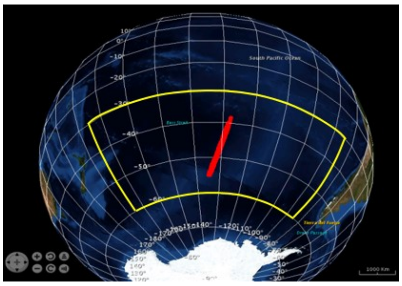


Figure 21. Example of satellite debris impacts in the SPOUA

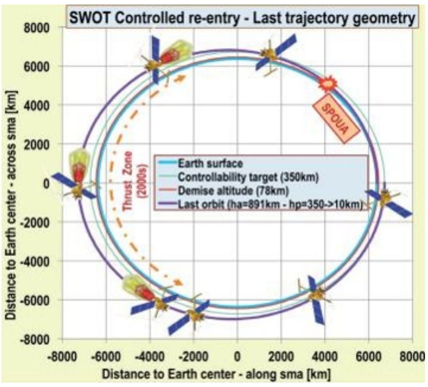


Figure 22. Orbital strategy for re-entry

5.3 Impacts on the AOCS design

This strategy has one degree of freedom: the altitude of the perigee before the last burn. If this altitude is high, it is easier to control the attitude of the satellite but the amplitude of the last burn is greater with an impact on the propulsion subsystem.
The compromise adopted for SWOT is to evaluate the lowest achievable altitude with the AOCS architecture defined for controlling the attitude during the mission phase and to design the propulsion subsystem necessary for this altitude.
This strategy results in a perigee of 250 km before the last burn. To achieve the last boost, the

satellite has 2 sets of 4 22N-thrusters (mean force over the range of pressures), a large tank (628 L). The first set of thrusters is commanded in closed loop with off-modulation to perform the control of the spacecraft attitude, the second set is commanded in open-loop with the duty cycles set by ground based on previous calibration manoeuvers.

5.4 Impacts on the mission manoeuvers

The thrusters selected to fulfil the needs of the last burn are over dimensioned in terms of force level with respect to the need for orbit correction manoeuvers during the mission, which demanded the adaptation of the control laws. In order to limit the dynamical perturbations created by the powerful thrusters, the attitude control is done by the thrusters, which have a modulated command with the following profile:

- DVs with a cumulated duration below 20s: pseudo-ON modulation.
- DV with longer cumulated duration: The command profile starts with a ramp at the beginning of the thrust and a "on-modulation" phase with a low actuation level at the end of the thrust, as shown in Figure 23.

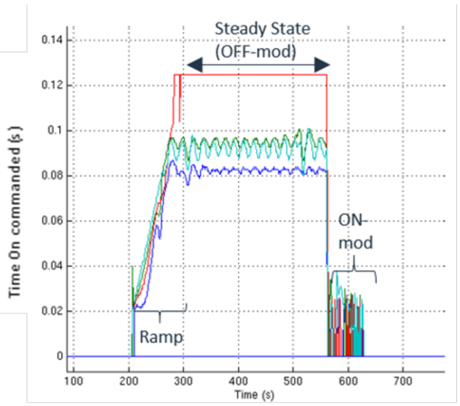


Figure 23. Thrusters actuations during a thrust long enough to have all modulation phases: initial ramp, steady state and ON modulation.

5.5 Controllability performances

In order to determine the AOCS control capacity at the altitude of the last perigee, a Monte Carlo simulation campaign has been conducted, with the scattering of multiple parameters such as the orbital configuration, the atmospheric density and wind, the variations on the geometry, the satellite and solar arrays pointing accuracy.

The payload will be switched off during this phase, hence the power demands are significantly reduced and there is a new degree of freedom: the capacity to rotate the solar arrays to optimize the geometry and reduce the aerodynamic perturbation near the perigee. Figure 24 shows the optimal configuration called "glider mode", with the solar arrays aligned along the satellite speed. This configuration is different from the mission but it is compatible with the power need during this end-of-life phase. With this configuration, the minimum controllable altitude was set to 250km.

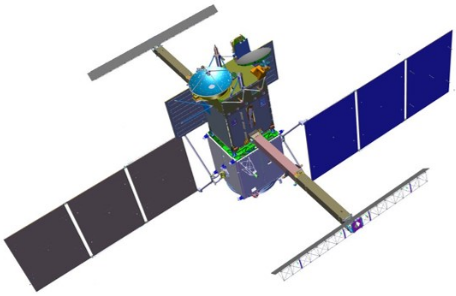


Figure 24. Solar arrays position for low altitude

With this configuration, the RWs can keep the control of the satellite even with the disturbances at low perigee. Figure 25 shows the evolution of the RWs rate for one hundred simulated scenarios, showing that even in the worst case the wheels have a good margin with respect to their maximum rate (282 rad/s).

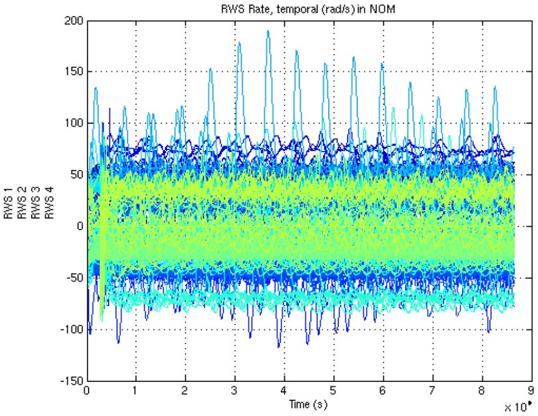


Figure 25. RW speed temporal evolution at low altitude

The last verification to confirm controllability at low perigee concerns the MHSTR: firstly, the fields of view shall not be affected by the solar arrays orientation and secondly they have to be not blinded by the Earth (especially at low altitude) or by the Sun. Figure 26 shows that there is always at least one OH available, whatever the period (and the sun position with regards to the orbit plane).

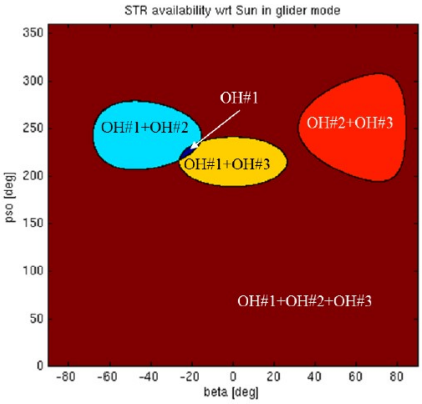


Figure 26. STR availability at low altitude

5.6 Operational implementation

The operational implementation for the controlled re-entry has been done before the launch: it consisted in the development of the adapted tools in the Flight Dynamics System (in order to compute the strategy and produce the commands to be sent to the satellite) and of the operational procedures in the Satellite Control Center (in order to orientate the satellite in the correct attitude and perform the OCM with 8 thrusters).

A specific AOCS system test has been implemented with the Satellite Simulator. The first step consisted in performing an OCM with the second set of thrusters, in order to calibrate it. The second step has allowed to validate the good behaviour of the last OCM with 8 thrusters (set1 + set2), by using the off-modulation coefficients computed with the set2 calibration. An operational qualification of the complete process is currently organized at CNES (from the decisional key point deciding the re-entry until the last boost).

6 CONCLUSION

This paper shows how the SWOT payload has sized the AOCS of the satellite and how flight performance observed during early operations and orbit commissioning confirms that the design responds well to all the key drivers.

Starting with payload deployment, the satellite has successfully converged to the Sun with a large range of inertias, proving the robustness of the safe mode controlled with MTB.

The first images acquired during calibration phase confirm that the AOCS mission strategy ensures the required dynamical stability. The ground attitude restitution, which is under calibration, also shows a successful performance and good stability of the flight sensors.

Next operational milestone is the change of orbit altitude to transfer from the 1-day repeat calibration orbit to the final orbit. The payload and platform commissioning will be then completed and the mission will start for a nominal duration of three years.

In overall, even if the satellite is in its commissioning phase, SWOT is functioning nominally and it is already providing successful results.

7 REFERENCES

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