

Detailed AOCS & FDIR Architecture of a new de-orbit mode

*Brice Dellandrea**, *Lorenzo Bitetti***, *Bruno Guerin****, *Andrea Guiotto*****, *Roger Jansson******

**Head of CCPIF/IAPP R&D Service, Thales Alenia Space-Cannes, France*

Email : Brice.Dellandrea@thalesaleniaspace.com

***AOCS, Space debris R&D engineer, Alten, Sophia Antipolis, France*

Email : Lorenzo.Bitetti@external.thalesaleniaspace.com

**** System Dependability Expert, Thales Alenia Space-Cannes, France*

Email : Bruno.Guerin@thalesaleniaspace.com

***** R&D and advanced studies Software engineer , Thales Alenia Space-Turin, Italy*

Email : Andrea.Guiotto@thalesaleniaspace.com

******Head of AOCS Division, ESA-ESTEC, Netherlands*

Email : Roger.Jansson@esa.int

Abstract

Until now satellite operators were not obliged to realize end-of-life (EOL) disposal operations and satellites were not designed to sustain such a final critical phase. They were therefore usually left in orbit or only “best effort” solutions were followed in order to free their operational orbit and to limit their presence in low Earth orbits (LEO) protected regions as much as possible.

Nowadays given the proliferation of space debris and after recent in-orbit collisions some standards and requirements have established to promote global efforts to deal with the space debris issue.

Satellite architectures and FDIR usual schemes have therefore to be updated to cope with new EOL disposal and passivation constraints. This has been the final goal of a R&D study realized by Thales Alenia Space.

1. Introduction

Currently an AOCS/FDIR heritage is often reused from missions to missions with only some add-ons or tailoring for some specific requirements and payloads constraints. The FDIR development and definition process comes late in the project and is not properly addressed in early architectural design and trades (phases A/B). This limits the AOCS/FDIR capabilities and leads sometimes to major design modifications in already advanced phases of the project which are complex and costly.

In addition, new space debris mitigation regulations [1][2][3] impose additional constraints on the AOCS design requiring robust de-orbit functions with a demanding reliability at end-of-life (EOL). ‘Best-effort’ disposal solutions adopted till now could no more be accepted and the capability to de-orbit the satellite have to be demonstrated after the occurrence of major failures in order to be authorized to continue or extend the operational mission.

Because of all these reasons, there is an emerging need to develop improved safe and de-orbit modes and to reassess the AOCS/FDIR architectures in order to be able to execute EOL disposal operations in a safer and more reliable manner even in presence of failures.

In this sense a R&D study has been performed by Thales Alenia Space for the detailed FDIR analysis of a new AOCS de-orbit mode making future satellite fully compliant to space debris mitigation requirements and allowing to limit the proliferation of space assets in already crowded low Earth orbits as satellites will be able to execute end-of-life operations even in presence of failures.

1.2 Study objectives and assumptions

The main objective of this study has been to answer to these emerging needs with the development of an improved and as far as possible generic :

- AOCS/FDIR architecture for a de-orbit mode valid for different classes of LEO missions;
- and of an improved AOCS/FDIR development process in order to take into account FDIR inputs/outputs since the early phases of a space project and avoid later modifications.

In order to define an optimal and as generic as possible AOCS/FDIR architecture it has been decided to start the analysis from the design of current TAS LEO platforms, to evaluate their EOL disposal capability and to identify the major modifications required to be compliant to international space debris mitigation requirements.

1.3 Current and future approach to EOL disposal

Up to now several LEO satellites have already been successfully disposed even if they were not specifically designed for such a phase. However the current approach to EOL has been in most of the cases only a “best effort” one: trying to be as much compliant as possible with space debris mitigation requirements depending on the satellite status and on the still available resources at the time the disposal is executed. The selection of a particular disposal strategy has been usually addressed just before the EOL and only still achievable solutions have been considered for trade-offs. In most of the cases this approach has led to a final solution which significantly varies from a satellite to another and anyway is far from to be an optimal one.

Instead, in order to define an optimal de-orbit mode which could be applicable to different mission classes, EOL constraints have to be taken into account since the early phases of the development process and the preferred disposal strategy has to be selected by comparing the benefits and drawbacks of all possible solutions. Then one can derive the satellite design and hardware redundancies guaranteeing that at least the minimal on-board resources needed for the execution of the disposal operations would be still available at EOL.

This approach, followed in the frame of this study, has allowed to find commonalities between different LEO missions and to optimize the AOCS/FDIR design of current multi-propose platforms while limiting the costs linked to the use of additional or independent hardware specifically designed for the EOL disposal.

2. Post-mission phase and requirements analysis

The goals and operations of the post-mission phase have been analysed in details in order to derive the needs and constraints at satellite and AOCS levels. Here the typical sub-phases of the EOL disposal are briefly recalled.

- Disposal manoeuvres needed to release the operational orbit and to realize controlled or uncontrolled re-entries on Earth or a re-orbit into graveyard orbits;
- Fluidic passivation where all fluid and thermal management issues aboard the spacecraft are consumed, made safe or jettisoned in order to bring the satellite to a minimum energy configuration and minimize the destructive capability of its components;
- Electrical passivation of the power system, mainly the batteries which are the most common and dangerous source of stored energy left on-board;
- Transmitter disconnection to complete the satellite passivation by switching off all means of communication and command of the satellite.

Once having analysed these sub-phases, the driving requirements for the end-of-life de-orbitation have been derived. The major specifications taken from [1] [2] [3] and influencing the most the AOCS/FDIR design are recalled here :

- A spacecraft or launch vehicle orbital stage operating in the LEO protected region, with either a permanent or periodic presence, shall limit its post-mission presence in the LEO protected region to a maximum of 25 years from the end of mission.
- In case the total casualty risk is larger than 10^{-4} , uncontrolled re-entry is not allowed. Instead, a controlled re-entry must be performed such that the impact foot-print can be ensured over an ocean area, with sufficient clearance of landmasses and traffic routes.
- The probability of successful disposal of a spacecraft shall be at least 0.9 at the time disposal is executed.

3. EOL disposal strategies selection

Before defining the baseline AOCS/FDIR architecture a trade-off analysis has been realised between several EOL disposal strategies in order to identify the ideal and preferable solution for each class of missions considered in this study : Science, Earth Observation, Telecommunication, Meteorological and HEO. The main removal means described in ISO24113 [2] have been considered :

- Controlled re-entry: targeted re-entry with a well-defined impact footprint over non inhabited areas;
- Uncontrolled re-entry: over a circular orbit re-entering into the Earth atmosphere in less than 25 years;
- Uncontrolled re-entry: over an elliptical orbit re-entering into the Earth atmosphere in less than 25 years;
- Drag augmentation devices: propellant-less solutions reducing the remaining orbital lifetime;
- Orbit change + drag device: combination of lowering manoeuvres and propellant-less solutions;
- Re-orbit: transferring the satellite into a high enough graveyard orbit beyond LEO protected region.

Different selection criteria have been evaluated in order to derive a preliminary selection of the preferable EOL disposal strategies for each mission class. Those influencing the most this choice have been the total casualty risk and the delta-velocity change.

The total casualty risk can be defined as the probability that a person is killed or seriously injured by the surviving fragments not completely burn up during the atmosphere re-entry and, as requested by international space debris mitigation requirements, it shall be lower than 10^{-4} . In case of higher values two main solutions exist:

- one can execute controlled or semi-controlled re-entries or a re-orbit if these solutions are feasible from a space mechanics point of view as described hereafter;
- or choose the Design-for-Demise solution which consists in modifying the satellite design (equipment and their accommodation) and/or the materials used in order to guarantee that less objects, ideally none, will survive the re-entry.

In both cases major modifications of the satellite design could be necessary.

For what concerns the second criterion, the delta-velocity change required for each of the disposal strategies has been computed as a function of the initial satellite orbit and then compared to the current delta-velocity budget of LEO platforms. It has been derived that the current ΔV budget is not always sufficient and more propellant mass and thus larger tanks are needed.

To serve as an example some of our current delivered LEO satellites at 800 km of altitude should use more than half of its total ΔV budget to reach the circular or the elliptical disposal orbits while the controlled re-entry is infeasible as the required propellant mass is greater than the available one. This scenario is even worse for a micro-satellite of the Myriade Evolution family, for instance, which would have to use all or more than its current propellant mass to reach a disposal orbit if placed at an altitude above approximately 750 km.

Considering the typical altitudes of different LEO missions, the delta-velocity change criterion has allowed to quantify the additional ΔV needed and to derive the preferable EOL disposal strategies for each mission class. It has been derived that controlled re-entry has to be selected only if strictly imposed by the mission or by the satellite design (total casualty risk higher than the maximum 10^{-4} value, for instance) as it is very demanding in terms of both delta-velocity change and on-board resources needed.

The uncontrolled re-entry represents the “best” solution for almost all the satellites orbiting at low altitude except for those satellites placed in higher orbits (above approximately 1400 km) for which the re-orbit should be preferred. These two solutions require lower delta-velocity changes with respect to other strategies and can be realized with only few improvements of the current AOCS design of LEO platforms.

Finally propellant-less solutions are very interesting and promising but the Technological Readiness Level (TRL) of some of them is still too low to be proposed nowadays as preferred solutions. They represent however the ideal solution for small and micro satellites placed at low altitudes, like those of the Myriade Evolution platform. In fact given their limited size and mass, propellant-less solutions are the only viable ones without a complete change of the satellite design. The use of electrical propulsion represents another promising solution for all LEO missions but a complete re-design will be needed as current platforms are not equipped with such a high specific impulse (Isp) propulsion system.

4. AOCS & FDIR Architecture definition

The following figure illustrates the final architecture (b) and the mode transitions selected after a trade-off between two main solutions : performing the de-orbitation inside current OCM or SAFE modes as additional functionality (a) or from independent modes specifically designed for the post-mission phase (c).

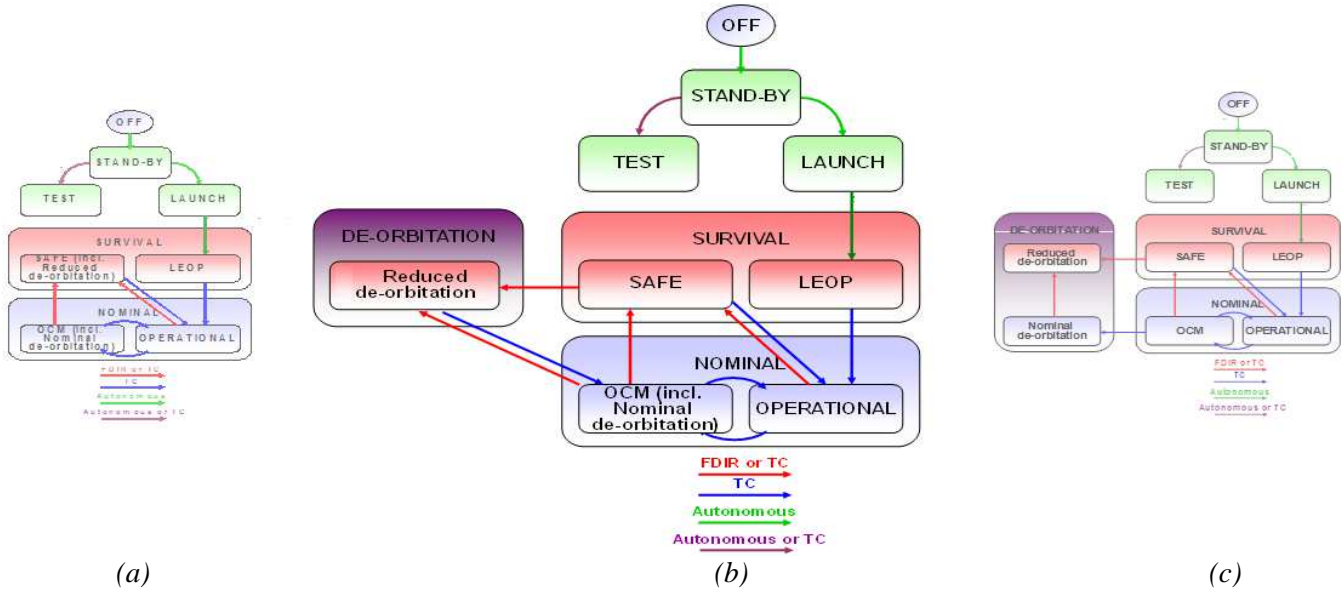


Figure 1: AOCS/FDIR architecture including the new de-orbit mode

The Reduced De-Orbitation Mode (RDOM) has been derived in the frame of this study and this particular AOCS/FDIR architecture has been selected for reliability and robustness reasons. Indeed the satellite will ideally realize the EOL disposal manoeuvres through the nominal set of hardware of the OCM but in case of a temporary or permanent unavailability an alternative solution exists : a transition to the RDOM will be triggered and the final phases of the satellite disposal could be accomplished from this mode.

This solution has the great advantage of allowing to continue or extend the mission operations even after the occurrence of one or several failures and at least until when the units used in this mode will be still available and well performing.

A functional redundancy has been preferred to the physical redundancy as the goals have been here to use as much as possible the units already available in current LEO platforms and to limit the extra costs and complexity linked to the need of additional hardware specifically designed for the EOL disposal.

An overview of the units involved in the AOCS functional chain is provided by the following figure :

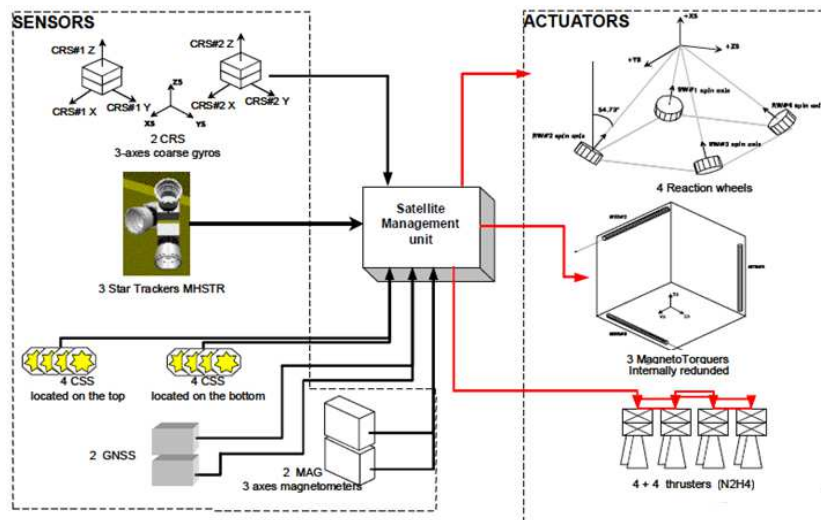


Figure 2: AOCS functional chain

The proposed AOCS design is based on TAS LEO heritage in order to benefit from flight proven functions and retour over experience . However some modifications have been realized because of the constraints imposed by post-mission disposal. In fact at least more powerful thrusters are necessary in order to reach the disposal orbit with a reasonable number of manoeuvres. Section 5.2 presents the results obtained with the current 4x1N and the proposed 4x5N thruster configurations.

The redundancy schemes and cross strapping principles of the AOCS HWs are summarized in the next table which shows the units employed in the different satellite modes including the new de-orbitation one.

The AOCS configuration selected for the RDOM is based only on the minimum set of the sensors and actuators necessary to conduct the EOL disposal operations. These units are less performing with respect to those used in the OCM but are very reliable and thus expected to be still available for the post-mission disposal as demonstrated by reliability analyses presented in the following chapter.

Table 1: AOCS hardware matrix including the RDOM

Hardware	Number	Redundancy	Mode		SAM		TRM		NOM		OCM		RDOM	
			ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF
MHSTR	2 EU + 3 OH	Cold for EU Both EUs address the 3 OHs		X (1)	X			X		X				X (1)
GPS	2 antennas 2 receivers	Cold 1 out of 2		X (1)	X			X		X				X (1)
CSS	8 solar cells	Hot	X				X (1)		X (1)		X (1)		X	
MAG	2	Cold / 1 out of 2	X				X		X		X		X	
CRS	2	Cold / 1 out of 2		X (1)	X				X	X				X (1)
RWS	4	Hot / 3 out of 4	X (2)		X			X		X			X (2)	
MTB	3	Cold / 1 out of 2	X		X			X				X	X	
THR	4	Cold / Set of 4		X			X		X	X			X	

- (1) Equipment unit switched ON but not used in AOCS closed loop.
- (2) Wheels maintained at constant speed for gyroscopic stiffness purpose

The RDOM configuration is similar to that of the SAFE mode except for the use of thrusters. It has anyway been considered as an independent mode from the already existing ones because of the specificities of the disposal and passivation phases. In fact usual FDIR principles and threshold monitoring used in other satellite modes are contrary to the whole notion of post-mission disposal as they aim at keeping the spacecraft operating or alive.

In addition particular disposal strategy and AOCS actuation logics have been developed for the RDOM as depicted in the following figure showing four main sub-phases :

- I. SAFE attitude maintaining
whose main goal is to maintain the satellite SAFE attitude (Sun or Earth pointing depending on the mission constraints) allowing to maximize the power generation and/or the communication window with the ground.
- II. Orbit change attitude acquisition
where the satellite changes its orientation in order to achieve the attitude allowing to execute the orbit change manoeuvre.
- III. Orbit change manoeuvre execution
where thrusters are activated in order to accelerate or decelerate the satellite and change its orbit. Thrusters are commanded in OFF-modulation in order to achieve the desired velocity change while creating a null disturbing torque on each satellite axis. Instead in case of failure this strategy is no more viable and MTBs are used to counteract THR's disturbance torques and to control the satellite attitude.
- IV. SAFE attitude acquisition
after having executed the orbit change manoeuvre, the satellite changes its orientation to achieve once again the SAFE attitude.

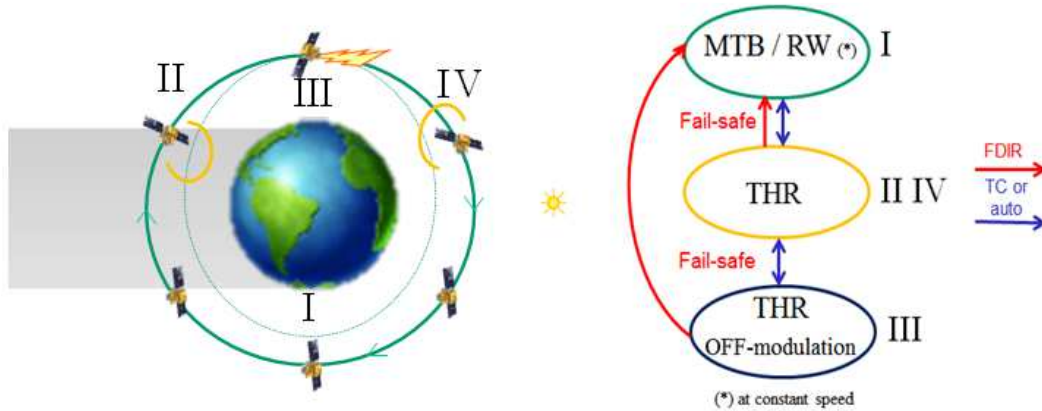


Figure 3: RDOM disposal strategy and actuation logic

A Fail-safe concept has been chosen for the RDOM in order to simplify the whole FDIR strategy. This strategy is compatible with the needs of this phase where payloads will be normally switched-off and the disposal operations could be interrupted at any time and then rescheduled in order to guarantee the satellite safety.

5. AOCS & FDIR Architecture validation

Several analyses and simulations have been conducted in order to assess the feasibility of the new de-orbit mode proposed in the frame of the R&D study and to evaluate the AOCS/FDIR performance in both nominal and failure contexts.

5.1 Reliability analyses

Reliability analyses have been conducted for the reference satellite of this study in order to evaluate the probability of successfully dispose the satellite from the RDOM and then to compare this value to that imposed by international space debris regulations. The reliability of the disposal has been computed without condition of success concerning the mission phase as suggested in [2] because this approach would have led to values better than 0.99.

$$P(D|M) = \frac{P(M \cap D)}{P(M)} \quad (1)$$

This result can be justified by the fact that if you consider that your mission is successful at the end of your operational lifetime, the probability of failure during the disposal phase is very low because the duration of this phase is very short compared to the mission phase.

A more pessimistic approach but at the same time one more representative of reality has been used : the reliability of the disposal has been computed by taking into account all the needed functions to de-orbit over the whole satellite mission. 10 years of operational mission plus 2 months for the de-orbit have been considered. The results are shown in the following table.

Table 2: Reliability budget for the Reduced De-Orbitation Mode (RDOM)

Global Phase (89060 hours)	
RELIABILITY AT 10 YEARS +2 MONTHS	
PLATFORM SUBSYSTEMS FOR UNCONTROLLED RE-ENTRY	
PROPULSION	0.998
ELECTRICAL POWER	0.978
TELEMETRY TRACKING AND COMMAND	0.991
SATELLITE MANAGEMENT AND ATTITUDE ORBIT CONTROL	0.946
STRUCTURE	0.999
PLATFORM	0.917

This analysis has allowed to verified that the satellite architecture and the redundancy schemes defined for this reference satellite are compliant to the requirement related to the success of the disposal as the reliability of the platform is higher than the required 0.9 value.

5.2 Space mechanics analyses

Several analyses have been realized in order to derive the ideal propulsion system configuration and to evaluate the impact on the complexity and duration of the disposal in terms of propellant mass and number of manoeuvres needed to dispose the satellite. Table 4 presents the results obtained for the reference satellite of this study.

Table 3: EOL disposal strategies with the current satellite configuration (THR force @ EOL of 0.4 N)

EOL disposal strategy	Controlled re-entry	Uncontrolled re-entry (circular)	Uncontrolled re-entry (elliptical)	Re-orbit
Disposal orbit (perigee / apogee) [km]	50 – 800	600 – 600	475 – 800	2030 - 2030
Δ semi-major-axis [km]	375	200	162,5	1230
ΔV disposal [m/s]	208	106	87	566
Propellant mass disposal [kg]	101	50	41	300
Mean ΔV per burn [m/s]	(*)	1.77	1.78	2.05
Number of manoeuvres	(*)	112	92	601

(*) not provided as 1N thrusters not compatible with the execution of this strategy, or at least the last burn

Note that, as said before, the uncontrolled re-entries over circular or elliptical orbits have to be preferred for this satellite as they lead to a much lower propellant consumption with respect to a controlled re-entry and the re-orbit. However a significant number of manoeuvres have to be realized with the current configuration of the reference satellite (4x1N thrusters at BOL) given the limited force provided by thrusters at EOL with the decrease of the tank pressure. These values can be considered as prohibitive and could probably not be accepted for future missions, especially in case of constellations, from both operational and reliability points of view. This means that additional and/or more powerful thrusters are needed.

A 4x5N thruster configuration has been selected in the frame of this study as it represented a good compromise between the number of manoeuvres and AOCS needs and constraints. In fact in this case approximately 22 and 18 manoeuvres are needed to reach the circular and elliptical orbits, respectively, and the impact of thrusters' disturbance torques on the attitude control is limited with respect to configurations with more powerful thrusters.

5.3 AOCS simulations

AOCS simulations have been realized in order to assess the attitude controllability at the disposal orbits and to evaluate the AOCS performance of the new de-orbit mode during the burns in both nominal and degraded contexts.

Because of the considerations made previously, a major attention has been paid on the AOCS performance of the RDOM during a burn executed with only 2 THR over 4 because of failures. This scenario has been said to be a worst case with respect to the 4 THR configuration where the OFF-modulation allows to 'easily' control the satellite attitude. The following figure shows the S/C rates evolutions in the case of a commanded 600s burn executed with THR 1&3 of the 4x5N configuration and an attitude controlled by MTBs.

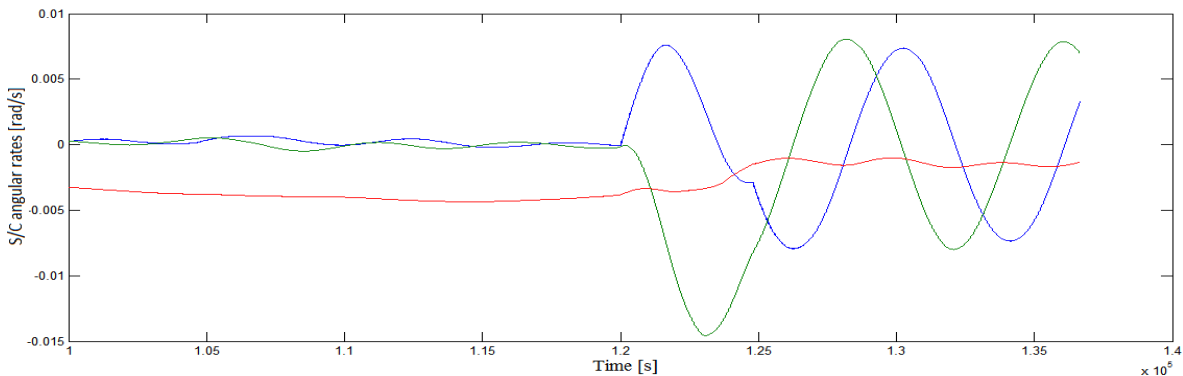


Figure 4 : Satellite angular rates in case of a 600s burn with THR 1&3

As expected, as soon as THR are activated satellite rates increase significantly as MTBs used in the RDOM cannot counteract THR disturbance torques. Also attitude pointing errors, even if not shown here, increase significantly and attain high values which are not compatible with the execution of orbit change manoeuvres. Such an extended burn duration could not be commanded by the ground in this degraded configuration but anyway FDIR level 2 monitoring should interrupt the THR activation before losing the attitude control capability.

Shorter burn durations have been then considered in order to assess the AOCS performance and the feasibility of the RDOM even in this degraded context. The following figure presents the rates evolutions in the case of two 30s burns. In this case, even if the angular rates increase during the burn, the maximum values attained remain acceptable and still compatible with the execution of EOL disposal manoeuvres from the RDOM.

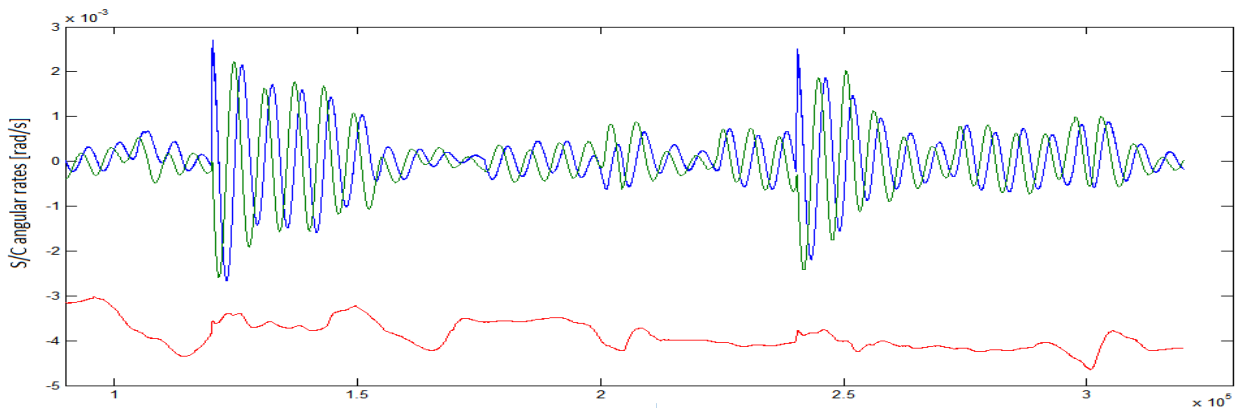


Figure 5 : Satellite angular rates in case of two 30s burns with THR 1&3

The AOCS simulations have demonstrated that the EOL disposal could be executed from the RDOM (if the OCM will be no more reachable in case of failures) and even with only two thrusters even if at the cost of a larger number of manoeuvres because of the limited burn duration acceptable in this degraded scenario.

The AOCS architecture derived in the frame of this study can be thus considered as robust and fully compliant to space debris mitigation requirements.

5.4 AOCS/FDIR simulations

Finally AOCS/FDIR simulations have been executed by means of the AOCS Design Escape Simulator where failure detection, isolation and recovery mechanisms have been added. Both mechanisms at equipment level (FDIR level 1) and AOCS level (FDIR level 2) have been implemented for those units used in the RDOM. The occurrence of both temporary and permanent failures has been simulated in order to evaluate the AOCS performance and the FDIR correct behaviour in presence of failures.

The first step to validate the choice of the monitoring and threshold values has been to verify that FDIR is not triggered if no failures occur. These simulations have guaranteed that no unwanted and unnecessary transitions to the SAFE mode will be realized in no-failure conditions. Then the capability to detect temporary or permanent failures and to correctly reconfigure the sensors and actuators have been assessed by simulating several outages between those identified by Failure Mode and Effect Analyses (FMEA).

All these simulations have shown that the architecture presented in the frame of this study is compatible with the execution of the EOL disposal operations even in failure conditions. An additional outcome has been that it is very useful to introduce FDIR mechanisms in the AOCS simulator as this allows to modify and validate FDIR concepts and threshold monitoring since the first phases of the satellite development process.

Ideally AOCS/FDIR simulations similar to those conducted in the frame of this study will allow to avoid or at least limit major modifications in already advanced phase of the project as the correct AOCS/FDIR behaviour in case of failure could be assessed well before the validation phase.

6. Conclusion and perspective

A R&D study has been performed by Thales Alenia Space for the detailed FDIR analysis of a new AOCS de-orbit mode answering to the emerging needs of disposing of improved safe and de-orbit modes and of reassessing the AOCS/FDIR architectures of current LEO multi-purpose platforms in order to be able to execute EOL disposal operations in a safer and more reliable manner even in presence of failures.

The EOL capability of current LEO platforms has been evaluated and it has been derived that at least an increased delta-velocity budget and additional or more powerful thrusters will be needed in order to reach the disposal orbits with a reasonable number of manoeuvres. A major focus has been paid on the uncontrolled re-entry in less than 25 years and on the re-orbit beyond LEO protected regions even if semi-controlled re-entry with a high specific impulse propulsion system or propellant-less solutions, like drag augmentation device and electrodynamics tethers (EDT), have been said to be promising solutions for future LEO platforms disposal.

A new AOCS de-orbit mode have been derived: the Reduced De-Orbitation Mode (RDOM) allowing to realize EOL disposal operations even if the Orbit Control Mode could not be reached anymore. This will allow to continue or extend the operational mission after the occurrence of failures of Nominal AOCS units as less performing but more reliable ones will be used in this de-orbit mode. A functional redundancy has been preferred to the physical redundancy as the goals have been here to use as much as possible the units already available in current LEO platforms and to limit the extra costs and complexity linked to the need of additional hardware specifically designed for the EOL disposal. Finally particular disposal strategies and FDIR concepts have been defined for the RDOM and the AOCS performance and feasibility have been verified through simulations.

This study has also demonstrated the benefits of considering FDIR, payloads and de-orbit requirements since the early design phases (A/B) of the AOCS development process as this allows to avoid or at least limit major modifications of the AOCS architecture in already advanced phases of the project. In this sense the Failure and Anomaly Management Engineering (FAME) process [4] has been enriched with some topics derived by NASA Fault Management process [5] in order to define a generic FDIR development process for AOCS covering all lifecycle phases and allowing the definition of an optimal and robust AOCS/FDIR design.

All the results obtained in the frame of this study provide useful recommendations allowing to make AOCS/FDIR architecture of future satellite fully compliant to space debris mitigation requirements and to limit the proliferation of space assets in already crowded low Earth orbits as satellites will be able to execute end-of-life operations even in presence of several failures.

References

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