Disposal Operation Strategies for Remote Sensing Satellite Fleets In Nominal and Emergency Situations

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Since December 2010, a new French Law on Space Operations (LSO) must be complied with by any entity related to space activities. It imposes, for instance, that any satellite operator shall demonstrate his capability to control the space vehicle, whatever the mission phase from the launch up to its End Of Life (EOL). The French Space Agency (CNES) is currently operating several remote sensing satellites (the last one called PLEIADES 1A), among a larger fleet of satellites. In that context, CNES has decided to perform several specific studies in order to define satellite disposal operation plans in any situation. The typical scenario of EOL operations consists in implementing five phases : disposal orbital manoeuvres, fluidic passivation, electrical passivation, transmitter disconnection and EOL orbit computation. One shall point out that these satellites (except PLEIADES 1A and 1B) were not originally designed to conform with the constraints imposed by the LSO. Thus, detailed analysis were conducted to identify the on-board and the on-ground improvements, as well as the operations chronology, without compromising in any way the security in the conduct of the operations. Depending on the context (nominal, contingency or emergency case) and the satellite subsystems status, different scenarios have been defined and compared in terms of strategy of disposal orbital manoeuvres, on-board and on-ground software upgrades, cumbersome operations, complexity, feedback… This paper addresses this trade-off, and moreover, it focuses on two main points : 1) the on-board software upgrades (monitoring parameters, Failure Detection Isolation Recovery strategy, chronology and constraints of modifications upload) and the equipment that must be switched off or for which configuration parameters must be tuned, 2) the different disposal orbit manoeuvre strategies : several Orbit Control Manoeuvres (OCM), one or two OCMs followed by an infinite-duration thrust, or an unique infinite-duration thrust. In conclusion, the generic principles applied in these studies could be considered as guidelines for any other satellite platform EOL operations.

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I. Introduction

The CNES is currently operating nearly twenty satellites among which five remote sensing satellites. This fleet is composed of two civilian (SPOT) and two military (HELIOS) satellites, the first PLEIADES satellite (PHR for Pleiades Haute Resolution in French) which is devoted to both civil and military purposes and is about to be complemented by the second PLEIADES satellite by the end of this year or at the beginning of 2013. The French government published the Law on Space Operations (LSO) in December 2010. This law states that any satellite operator must demonstrate its capability to control the space vehicle whatever the mission phase from the launch up to the EOL (End Of Life) [32]. In that context, the CNES operation board decided to set up a Working Group (WG) [1] in order to anticipate and to tackle issues related to the emergency End Of Life (EOL) operations due to unexpected on-board events affecting the satellite. The work done by this WG allowed to initiate a complete process (steering committee meetings, validation tests, feasibility studies…) dedicated to EOL disposal operations, especially for contingency cases. For several years, the CNES has prepared and has been involved into several EOL operations. The paper focuses on the process used to prepare and to conduct EOL operations for remote sensing satellites. Firstly, it briefly presents the different remote sensing satellites. Secondly, it describes the analytical process developed to provide the necessary inputs to lead a trade-off between the different strategies and to define the best fitted EOL strategy. Then, it focuses on all the activities required to lead such an operation by giving concrete elements especially from an on-board point of view. In addition, it gives some spaceflight dynamics experience feedback. Finally, it concludes by showing that a generic approach can be highlighted and its main principles can be applied to other satellite EOL operation.

II. CNES Remote Sensing Satellites

The CNES ensures the station keeping of all these remote sensing satellites on its usual customers' behalf which are the DGA (Direction Générale de l'Armement in French) depending on the Ministry of Defence for the military satellites and the private owned company ASTRIUM Geoinformation Service Toulouse for the SPOT family. They are maintained on Low Earth Orbits (LEO), characterised by an altitude between 700 and 830 km and an inclination close to 98.5 degrees with respect to the equatorial plan. Periodic station keeping manoeuvres are defined and executed to maintain such operational orbits. Spacecraft operation teams are in charge of the platform and the payload monitoring based on the analysis of the housekeeping telemetry and of conducting all the required operations to ensure the satellite safety as well as the mission. The payload programming is also in charge of CNES operations team with regards to customers' needs. All these tasks are supported by CNES teams with respect to the exploitation agreements between the CNES and its customers.

The table 1 gives for each CNES remote sensing satellite the key dates (launch and disposal), the reached lifetime and the type of platforms. It recalls all the remote sensing satellites operated by CNES since its beginnings.

The satellite design (architecture, on-board redundancies, on-board software) was well robust to face failures as Table 1 illustrates it by looking at the reached lifetime that is two or three times the specified lifetime.

Table 1: Key dates (launch and disposal) and reached lifetime of CNES remote sensing satellites and platform types.

Satellite	Launch Date	**Disposal Date**	Reached Lifetime	Platform Type
SPOT 1	02/22/1986	**11/28/2003**	17.7 years	MK1
SPOT 2	01/22/1990	**07/29/2009**	19.5 years	MK1
SPOT 3	09/26/1993	**11/14/1996**	3.1 years	MK2
SPOT 4	03/24/1998	TBD	14 years	MK2
SPOT 5	05/04/2002	TBD	10,1 years	MK3
HELIOS 1A	07/07/1995	**01/18/2012**	16,5 years	MK2
HELIOS 1B	12/09/1999	**10/21/2004**	4.8 years	MK2
HELIOS 2A	12/18/2004	TBD	7,5 years	MK3
HELIOS 2B	12/18/2009	TBD	2,4 years	MK3
PLEIADES 1A	12/16/2011	TBD	0,4 year	
PLEIADES 1B	Late 2012	TBD	-	

One may notice that two satellites SPOT 3 and HELIOS 1B almost reached their lifetime due to fatal anomalies which lead to their loss even with such a high level of on-board redundancy. These cases are consequences of serious on-board anomalies which directly act on the capabilities of the satellites to continue their mission and to perform the entire EOL operations. For these two satellites, the EOL operations have been realised in a complex emergency way which would not have been foreseen and tested properly.

This is one of the reasons why the CNES decided to prepare EOL operations before the exploitation phase for the next satellites, and as soon as possible, for the in-flight ones by giving priorities according to the status of the satellites. In the last case, emergency EOL procedures shall be defined before the nominal ones. This process uses the work done by the Working Group on Emergency EOL Operations as a reference.

The CNES shall demonstrate its capabilities to conduct successfully EOL operations whatever platform modes.

The main AOCS equipments used by these satellites are gyroscopes, Digital Earth Sensor (STD), Digital Sun Sensor (SSD), Magnetorquers (MAC), reaction wheels, Star TRackers (STR), Control Moment Gyroscope (CMG) and DORIS navigator. In addition, SPOT/Helios satellites have four batteries while PLEIADES satellite has only one battery.

III. Analytical Process To Define EOL Strategies

Based on the results obtained by the Working Group (WG) on emergency EOL operations due to unexpected on-board events affecting the satellite, it was identified that feasibility studies, technical and operational qualification of EOL procedures for nominal, emergency and some degraded contexts shall be done before the satellite launch. In that way, this critical task could be done by all the experts in charge of the satellite design. Furthermore, they could define the on-board strategy and the software patches needed for the different contexts (emergency, contingency, nominal). The contingency cases correspond to particular situations (consequences of on-board failures affecting the satellite integrity) for which the typical EOL scenario cannot be fully realised.

This WG elaborated the definition of the “minimal Withdrawal From Service (WFS) configuration” which is applicable to every CNES LEO satellites. It may be formulated as follows: the minimal WFS configuration corresponds to a particular spacecraft status presenting at least one Single Point Failure on the functional chains or equipments needed for the implementation of the nominal disposal operations. The remaining propellant mass as well as the power capability are included in this specific configuration. In addition, three different emergency levels were defined :

a/. The failure is considered as isolated. In this case, the satellite can continue its mission.

b/. The failure is serious but non urgent. Here, the EOL operations have to be planned within a reasonable delay, i.e. longer than several weeks.

c/. The failure is fatal and could affect the satellite integrity within a short-term period. In such a case, EOL operations have to be done in an emergency way by the operational teams.

According to the emergency situations, it was identified that :

- for all a/. type situation happens, feasibility studies have to be done in order to analyse the part of EOL operations which could be implemented without the remaining equipment or function. This supposes that an additional anomaly may affect the redundant equipment or function.
- For all the b/. type and c/. type identified situations, the WG recommends to develop and to test operational procedures even if on-board software modifications are required.

For all SPOT/HELIOS/PLEIADES satellites, this WFS configuration was elaborated and is part of the satellite configuration status document. For in-flight satellites, some feasibility analyses have already been engaged according to the emergency situations. In addition, the validation process of the emergency flight control procedures is on-going for each satellite as a first priority, and after that, the nominal ones and some identified degraded ones will be processed. For PLEIADES satellites, the EOL flight control procedures were defined and validated for both nominal and emergency cases before launch.

A. Feasibility, mission analysis and system studies

To define the EOL flight control procedures and the associated operation chronology, a certain number of inputs is mandatory. These data are obtained thanks to different major studies that are presented hereafter in terms of goals. Some examples of these studies will be given in the following sub-section.

1) AOCS studies

To begin with, one shall first define the AOCS platform modes of interest for EOL operations. For MK1, MK2 and MK3 satellites, these AOCS platform modes are : Safe mode, CAM (Coarse Acquisition Mode), RRM (Reduced Rate Mode), FAM1 (Fine Acquisition Mode), FAM 2, FPM (Fine Pointing Mode) or OPM (Operational Pointing Mode) /FMP or SOPM (Stellar Operational Pointing Mode) for Helios satellites, OCM (Orbit Control Mode). For PLEIADES satellites, the main modes useful here are : safe mode, normal mode, OCM, biased Geocentric Accurate Pointing .

An AOCS feasibility study combined with an AOCS performances study shall be done by the satellite contractor. It consists in demonstrating that the EOL operations are feasible. Such studies take into account the initial, intermediate and final orbit altitudes, the orbit orientation, the AOCS sensors used in the different modes with their field of view limitations, the AOCS actuators with their maximum capabilities, the atmospheric density, the satellite residual propellant mass, the different spaceflight dynamics strategies to lower the orbit altitude, the status of the propulsion subsystem, the different epoch times of EOL operations and so on. Moreover, it also considered the platform wait mode which is the intermediate mode which the platform returns back between two Orbit Control Manoeuvres (OCM).

Thanks to either theoretical analysis and numerical simulations, the important outputs of such studies are :

- Identification of the main AOCS on-board software patches to upload in order to fit the AOCS equipments as for instance the mean Earth diameter used by STD Earth sensors, the STD equipment masking values according to the EOL phases (beginning, intermediate and final).
- Identification of the main AOCS constraints in terms of orbit orientation and in particular the position of perigee in order to avoid the divergence of reaction wheel rates due to increased air drag, Sun and Moon STD masking, the sensors to switch off, and so on. For instance, it was decided in order to secure and to facilitate the operations to execute OCMs in a predefined period such that no Moon masking has to be applied. Another example concerns the STD sensor which allows the reconstruction thanks to an on-board software of the roll and pitch attitude angles of the satellite thanks to the observation of the Earth position in its field of view. Its field of view is composed of two half-cones which allow to locate the Earth thanks to four transitions “Earth/Space or Space/Earth” that are linked into two traces. In our case, the STD must be used by masking the two traces in order to reduce the attitude degradation and the fuel consumption in FAM 2 mode.
- Identification of the on-board memory telecommands (TCH) to be uploaded after each OCM as the thrusters’ parameters, the satellite position on the orbit called PSO (Position On Orbit) and the delay to do it.
- Evaluation of AOCS performances in terms of gyroscope drifts, pointing or depointing, hydrazine consumption profile, kinetic momentum and MAC actuation rate, reaction wheels rate,
- Identification of the on-board surveillances to be inhibited or for which the threshold values shall be adjusted with respect to the operations.
- Evaluation of the robustness of the performances according to key parameters (solar activity, no update of PSO parameter,..).

2) Propulsion study

Another key study concerns the feasibility of the emptying of the tanks close to the unusable propellant mass and the de-pressurization of the tanks. In addition, it identifies the potential sources of perturbations that may impact the propulsion and AOCS sub-systems during the two phases of emptying (Hydrazine and Helium). A rough duration estimation of the two phases of tanks emptying and the associated thrusts for each phase is given as a result of this study. These information are helpful to build the whole chronology.

Furthermore, the evolution of the fuel residual masses that were estimated by the two pressure tanks sensors was assessed over several years and compared with the estimation obtained thanks to the pulse count method to check if no drift between the two sensors is present.

3) Mission analysis

The mission analysis goal is to show the compliance with the 25-year criteria, which is the specified natural re-entry duration after the de-orbitation manoeuvres, according to the de-orbitation strategies in terms of OCMs. There are two classes of de-orbitation strategies : a circular or quasi-circular de-orbitation or an eccentric one.

For the “circular or quasi-circular” de-orbitation strategy, three different approaches may be considered :

- Strategy 1 : several OCMs with two thrusts each using a pre-defined wait mode between OCMs,
- Strategy 2 : an unique infinite-duration thrust,
- Strategy 3 : one or a few OCMs with two thrusts each at opposite orbital positions, to release the operational orbit and then followed by an infinite-duration thrust.

For the “eccentric” de-orbitation strategy, one approach may be considered :

- Strategy 4 : one or a few OCMs with two thrusts each to release the operational orbit and then followed by successive OCMs of one thrust positioned at the apogee to decrease the perigee altitude and thus getting an elliptical orbit at the end.

One shall mention that these fourth disposal manoeuvre strategies can be linked to different de-orbitation contexts.

- The strategy 1, based on several OCMs keeping the orbit circular or quasi-circular, can be used for nominal situation. Furthermore, it can also be useful in the case of an "important" remaining propellant mass and an altitude of re-entry easily reachable or also when AOCS equipment in-flight limits can be reached (e.g. STD can be used for altitude greater than a given threshold).
- The strategy 2 is used in the frame of emergency contexts (emergency level c) whatever satellite altitude.
- The strategy 3 can be applicable either in nominal or contingency contexts (emergency levels a and b). This means that the satellite altitude may not be too high in order to reach the re-entry duration specified by the LSO.
- The strategy 4 can be used for nominal de-orbitations. This one may be useful for satellite whose altitude is relatively high and fuel reserves not very important. The goal of its strategy is to use the atmospheric drag to lower the apogee and the perigee in a passive way.

All these strategies are evaluated with regards to the reached orbit at the end of the operation including the exhausting tank phase. Moreover, the conflicts between the satellite "constellation" in terms of orbit crossover and frequency, and the jamming between in-flight satellites are also assessed for each strategy during all the operations to compare them. The duration needed for a natural re-entry is also assessed and compared to the LSO criterion of 25 years for each strategy.

4) Risk analysis

Another major study is the risk analysis. In the first place, one defines the different phases of the de-orbitation operations from its study phase up to the natural re-entry phase. In the second place, the goals are declined for each phase. This analysis is based on several parameters :

- Feared events. It means that the consequences of such event impact directly the goals of the phase.
- Probability. The occurrence of such feared events are categorized into 3 sets : P1 is the highest probability (the risk is almost certain), P2 is the mean one (the risk may occur) and P3 corresponds to a weak probability (the risk might occur but it is quite improbable).
- Gravity . The impact of such events are set into three classes :
    - G1 : the consequences are very serious and may endanger human lives or lead to the loss of the satellite for instance.
    - G2 : the consequences are important which may lead not to qualify the overall de-orbitation operation, not to ensure the well conduct of the operations, not to respect the 25-year natural re-entry criterion.
    - G3 : all cases not covered by levels 1 and 2.
- Criticality. This parameter is characterized by the couple (gravity, probability). It is composed of 3 levels.
    - C1. it is the highest and the risk is considered as inacceptable.
    - C2, the risk is accepted only under specific conditions.
    - C3, the risk can be accepted without any condition.

Table 2: Criticality levels versus (probability,gravity) parameters

Criticality		Probability		
		P1	P2	P3
Gravity	G1	C1	C1	C2
	G2	C1	C2	C3
	G3	C2	C3	C3

Finally, the risk analysis identifies the feared events and gives them a certain level of criticality. Depending on the criticality level, one shall define one or more actions to apply in order to decrease the criticality level.

In such analysis, only single failure cases are taken into account except for double failure cases with a non-negligible probability (the major ones).

5) Monitoring and control analysis

The monitoring and control analysis of the spacecraft deals with all the operations that shall be performed on the spacecraft to set it into configuration before starting the EOL operation and to passivate it in nominal and emergency contexts, and if necessary, in contingency one also. It gives all the software patches to load (modification of threshold monitoring, modification of FDIR – Failure Detection Isolation Recovery, ..), the AOCS constraints to be compliant with, and in particular, when generating the spaceflight dynamics telecommands, the equipments to switch off or to modify their operational mode and so on.

6) Trade-off

Finally, thanks to all these previous inputs, a trade-off is led in order to determine which strategy is the most convenient according to the system, operation, mission, spacecraft, spaceflight dynamics points of view and the context of the EOL (nominal, contingency or urgent). A Key Point is then organised to define officially the strategy to apply with the experts, the operational teams, the management and the LSO representatives. In addition, at this stage, we are able to identify also the ground software modifications required to conduct this operation. For instance, SPOT 2 and 4 spaceflight dynamics system (former generation) was not adapted to de-orbitation and emergency mode in FAM2 or to OCMs with a single thrust so some tools were developed to cope with it and they needed to be validated.

B. Illustration of these studies

This subsection aims at giving some concrete examples or short extracts of all the studies that were previously presented in order to understand the necessity to perform these analyses.

1) AOCS feasibility and performances studies example

For SPOT2 satellite, the study showed that the main limiting factors/constraints were the magnetorquers sizing and reaction wheels maximum kinetic momentum with regards to increased air drag in the lower altitudes around perigee.

For SPOT2, it was decided to maximize the fuel efficiency, and thus, the wait mode between two OCMs was FPM instead of FAM2 for SPOT1. So, it was necessary to carry out AOCS analyses to ensure wheels de-saturation feasibility. The analysis outcome was a feasibility statement, but it highlighted a constraint consisting in fixing the orbit large axis orientation (perigee PSO) in such a way that the air drag is minimized around the perigee, i.e. having the solar array in canonical or anti-canonical position (i.e of minimum air drag) around 0° of PSO (variable with the season) in the end of the operation. This constraint was much less stringent in case of low solar activity period. Similar analyses were performed for SPOT4 and SPOT5 EOL operations and they concluded that, in spite of their larger MACs and wheels capabilities, the constraint on orbit perigee location still applied for high solar activity periods.

It is interesting to compare the results obtained for both SPOT4 and SPOT5 satellites (two different platforms).

The main conclusions of the AOCS study for SPOT4 are given below.

- The feasibility of EOL operation in the FPM mode is settled under strong constraints relative to the orbit orientation. The perigee argument shall be set on the eclipse side and may evolve in an 80-degree interval taking into account the perigee argument drift of around 3 degrees per day. Depending on the season, the perigee argument extrema changes.
- It is also recommended to set the SSD gains of the FMP estimator to zero as the impact on the AOCS performances is negligible if the SSD corrections are not taken into account.
- Both STD traces shall be masked simultaneously to guaranty the correct execution of the OCM thrust when it is performed during an one-trace period and to limit the attitude degradation and hydrazine consumption in FAM2. In FPM, two solutions of STD masking are possible : masking of one trace or masking of the two traces. But, the second solution allows also to avoid a too rough roll depointing computations in this mode.
- The value of the Earth mean diameter (which is used by internal algorithms and estimators) shall be modified for one-trace use in CAM Earth re-acquisition mode.
- In order to ensure the CAM convergence, it is recommended to reduce the STD physical mask values around +/-14 degrees on both sides of traces 1 and 2 transitions areas. But this point needs to be confirmed through a dedicated test by using the redundant STD on-board in order to check if no side effect appears.

In comparison, the major conclusions for SPOT5 are now discussed.

- The feasibility of EOL operation in the FPM mode is settled for any orbit orientation. However, during a strong solar activity, it is preferred to set the perigee argument on the eclipse side and far from poles to prevent from a wheels saturation event.

- It is also highly recommended to mask simultaneously both STD traces in order to allow for accurate roll measurements and hydrazine consumption in FAM2 as for SPOT4.
- The value of the Earth mean diameter shall be modified.
- The recommendation concerning the CAM convergence is likewise for SPOT5.

The SPOT4 performances study leads to the main following conclusions on the AOCS subsystem.
At the beginning of the EOL operations,

- the necessary software patches are the ones identified on the SSD and on the Mean Earth diameter by specifying the values.
- The on-board memory telecommands (TCH) giving the STD software masks are uploaded once and are identical on both traces and some STD correction parameters (Earth's infra-red model) are not updated during the operation.

After each thrust, one must upload :

- A new PSO TCH within a 24-hour delay maximum as well as the TCH giving PSO information for the monitoring and the control of the solar array driving motor.
- Updated values of the thrusters torques and the parameters used in FAM2 control are computed by taking into account the tank pressure and sent to the satellite.

The on-board monitoring to be modified are related to the STD attitude deviations in FAM2 and non converged FPM, the estimated attitudes in the FAM2 and FPM modes, the acquisition duration, the Earth diameter (factor 2) and the canonical position of the solar array driving motor.
The on-board monitoring that must be inhibited are the FAM2 propulsion, the STD transition status, the SSD monitoring.
This analysis also shows that the AOCS is robust

- if the PSO is not updated during up to 24 hours in terms of satellite depointing performances, solar array pointing and wheels saturation.
- To errors between the maximum thrusters torques and the true thrusters capabilities in the range of -20% to +5% .

Besides, it also demonstrates that the physical STD masks have an impact on the AOCS in terms of monitoring thresholds and re-acquisition duration. And finally, the feasibility of the safe mode on an elliptical orbit is also confirmed.
The SPOT5 performances study leads to the following main conclusions on the AOCS subsystem.
At the beginning of the EOL operations, the same principles of software patches have to be applied except for SSD as the ones defined for SPOT4 (as SPOT5 does not have SSD).
After each thrust, the same kind of TCHs than SPOT4 should be updated.
The on-board monitoring to be modified are the same as for SPOT4. The on-board monitoring that must be inhibited are the FAM2 propulsion, the STD transition status, the OCM duration.
The same conclusions concerning the AOCS robustness as SPOT4 can be applied to SPOT5, except for the feasibility of the safe mode for an elliptical orbit. Depending on the level of the atmospheric density, for instance, for a robustness case (worst case multiplied by a factor 2), it is recommended to proceed to the de-orbitation by aiming at a value of the perigee argument at the end of the operation between a range of +/-40 degrees around given values according to the seasons (+30° for winter solstice, 0° for equinox, -50° for summer solstice) to avoid large Sun depointing values.

2) De-orbitation operation principles examples

<u>SPOT4 and SPOT5 illustrations</u>

For SPOT4 and SPOT5, the goal is to maximise the decrease of the perigee altitude according to the hydrazine amount and the operational satellite altitude.
One possible strategy is composed of some OCMs respecting a circular orbit decrease in order to clear the operational orbit, and then, some separated thrusts whose aimed at decreasing the perigee only. The emergency strategy is based on a single infinite-duration thrust. But, other strategies exist as it was previously mentioned. The process of selecting the strategy is still on-going for SPOT4 and shall be defined in June of this year.
The wait mode between two OCMs is the FPM for both satellites as feedback from SPOT1 and SPOT2. But in addition for SPOT4, the FAM2 mode is also considered in case of an anomaly on the reaction wheels, magnetorquer electronics and command subsystem as such an anomaly already occurred, and thus, the only available redundancy is already used.

The preparation of the EOL operation consists in, firstly, configuring the satellite. To do it, the following steps are performed for SPOT4 and/or SPOT5 :

- The calibration tank pressure sensor measurement gain is set to its end of life value and the tanks are in communication to optimize the emptying.
- The payload is set to a safe mode in order not to deal with payload anomalies during the EOL operations, and in a lesser extent; to reduce the power consumption.
- To switch off the SSD for SPOT4 satellite only, as it is not useful and also to avoid a failure propagation towards the equipment in charge of AOCS monitoring and safe mode sensors.
- To inhibit the wheel desuspension during OCM for all satellite. It is highly recommended for SPOT4 satellite due to such a previous anomaly.
- To load the specific STD masking configuration telecommand to reduce the physical masking values.
- To define an intermediate Earth diameter which fits with the different altitudes for CAM.
- To disable some functional monitoring, as for instance, solar array driving motor rotation direction monitoring for SPOT5 only, the cumulated number of thrusts in FAM2 monitoring (as there is an increase of the number of thrusts around the perigee due to the altitude decrease in case of an anomaly that sets the satellite into this mode), the STD Earth transition status for the end of the operation if the reduction of the masks values are not sufficient, and so on.
- To modify the standard monitoring threshold values of the STD differences in FAM2 and FPM, the estimated differences and the MEGS position differences.
- To increase the range of the PSO MEGS monitoring values.
- For SPOT4, additional patches and actions shall be done in the case of FAM2 mode as wait mode between two OCMs for instance.

Secondly, the daily de-orbitation operations are executed by updating the spaceflight dynamics parameters and all relevant AOCS parameters.

Once the criteria of the "last extended thrust" is reached, then, the final operations can start and two cases are identified : the first one based on several "possibly final" thrusts of a finite duration corresponding to the ground station visibilities coverage (around 2000 seconds) and the second one based on an infinite time duration thrust using time-tagged telecommands, to passivate the satellite.

<u>First case : several final thrusts</u>

Let's focus on the first case based on several thrusts. The last operations consists in :

- Disabling some functional monitoring of OCM time-out, AOCS global monitoring, STD Earth diameter, battery current sensors.
- Inhibiting the safe mode order in the RSJD (Regulator Shunt Junction Distribution). Indeed, one of the passivation actions when setting the satellite into the safe mode due to an anomaly consists in switching ON automatically both transmitters.
- Disabling the STD safe mode alarm (Earth presence loss).
- Increasing the acquisition frequency of one of the tanks pressure sensors to get a better observability.
- Uploading the passivation telecommands on both bus couplers (to secure the execution of the telecommands) during the visibility where the tank exhausting is detected or the next visibility (a few minutes later). The passivation can also be done by time-tagged telecommands dated at the possible maximum thrust time with regards to the residual hydrazine mass incertitude. In this last case, we can not ensure the full depressurization of the tanks. The orders of the telecommands are : to disconnect the batteries 1 to 3, then to switch off both transmitters (depending on the satellite, it may be necessary to switch ON the servitudes board B to switch off the B transmitter) and finally to disconnect the last battery. If the last battery is disconnected in the day, then, it may induce some RSJD dysfunctions which may not allow a right functional behaviour of the satellite. If the disconnection is done during the eclipse, then the satellite is no more supplied. So, this command shall be sent just after the hydrazine exhaustion.

At any time, the satellite operations team is able to passivate the satellite if an anomaly occurs and sets the satellite into the safe mode. One needs to partially exit the satellite from the safe mode, to switch ON very few equipments (Computer and data handling subsystem) in order to get the telemetry back and to passivate electrically the satellite leaving fuel in that degraded case.

Second case : one infinite duration thrust

Now, let's consider the one infinite time duration thrust case. The M&C operations are described below by mentioning the actions that must have been done before :

- The calibration tank pressure sensor measurement gain is set to its end of life value.
- The payload is set into a safe mode
- To disable all the AOCS global functional monitoring (attitude estimate, gyroscope rate...), all the STD except the optical head, wheels/wheel electronics and MAC monitoring, the SSD monitoring for SPOT4 only, solar array driving motor position monitoring, the BNR (unregulated Power bus) supply functional monitoring
- To switch off the SSD equipment for SPOT4 only as already explained.
- To upload the patch of inhibition of the end of the thrust, the new monitoring calibration value during the thrust mode.
- To switch ON the propulsion heating.
- Just prior the last thrust, the Ground must load specific AOCS parameters as mean values suited for the whole thrust duration : mean values of thrusters torques which drive the control loop gain and the mean value of position on orbit, mean Earth orbital rate which drives the pitch attitude keeping. In addition, the on-board software is patched to take into account the permanent STD masking in either FPM or OCM modes as well as the updating of some STD algorithm parameters (inhibition of some computations) for SPOT4 only.
- To upload several software patches:
    - A patch to prevent the abandon of time-tagged telecommands in the frame of an anomaly, and thus it ensures the propulsion heating switch off , as well as the AOCS alarm and safe mode order inhibition in a first time, and then allows to passivate the satellite.
    - Another one to transform the RRM mode transition into a safe mode transition following a gyroscope failure.
    - A patch to maintain the OCM in case of a propulsion anomaly for SPOT5 only.
    - A patch to enable automatically the electrical passivation commands (switching OFF both transmitters and the four batteries) sequence instead of the FDIR process following the triggering of the unregulated bus minimum voltage monitoring for SPOT5 only.
- To load the updating OCM telecommands
- To load the time-tagged telecommands for :
    - The propulsion heating switch off to limit the batteries discharge, the STD Earth presence alarm inhibition, the safe mode order (controlled by RSJD) inhibition, the batteries disconnection authorization for SPOT5 only, at the earliest theoretical end thrust time.
    - The switching OFF of the batteries (1 to 3) , than both transmitters and finally the battery 4 at a given date that is later than the tank exhausting estimated time in the worst case for SPOT4 only. For SPOT5, it is done thanks to the unregulated bus minimum voltage criteria patch uploaded before.

In sunlit phase with actually disconnected batteries, the bus voltage may no longer be steadily controlled due to RSJD shunt with very quick ON/OFF actions; so, the satellite behaviour is unknown and considered as unable to ensure the nominal units working. This is why the last battery disconnection is applied after the transmitter switching OFF.

Pleiades example

Another example concerns the Pleiades 1A nominal EOL scenario. The satellite configuration at the beginning of the operation is the operational standard state. To begin with, the payload is set into a safe mode for the same reasons as previously mentioned. And then, several OCMs are planned to be performed in order to lower the altitude of perigee around 450-500 km (initial altitude of 700 km). It is not recommended to lower the perigee altitude less than 450 km due to an AOCS unpredicted behaviour. If the decrease of the perigee is insufficient to empty the tanks, then, the mission analysis recommends to either lower the apogee altitude or to perform inclination OCMs. The next step consists in deleting the transmitter programming before the end of the set of OCMs in order to let the transmitter on.

The standard OCMs are executed until the tank propellant mass is around 2 kg in order to avoid a transition to the safe mode due to AOCS depointing. When only 2 kg of propellant remains (tanks pressure less than 5.8 bars), OCMs are performed in the normal mode (biased Geocentric Attitude Pointing mode) by using only 2 thrusters (X or Y) without any off-modulation and by limiting the duration of the thrust to approximately 50 seconds. This threshold of 2 kg comes from the fact that the tank pressure measurement in an “empty state” accuracy is of 1 kg, and at 1 kg, the risk of cooling Hydrazine and Helium alternatively is real. This induces some perturbing torques rather important on the AOCS monitoring which are then compensated for by the CMG.

Then again, several surveillances are inhibited to prevent from any reconfiguration and the on-board software is modified by patches to avoid any switch ON of the transmitters further to a reboot of the processor.

- On-board software patch on Processor Module (PM) A to avoid switching ON the TM transmitter following a satellite reboot
- On-board software patch to automatically discharge the battery.
- To change to Processor Module B.
- To wait for boot on PM B and then, transition to a given mode that allows the Ground to know the satellite attitude.
- On-board software patch on Processor Module PM B to avoid switching on the TM transmitter following a satellite reboot.
- On-board software patch to discharge the battery on PM B
- To disable monitoring relative to OBMU (On-Board Management Unit)
- To switch OFF the TM transmitters by executing a reboot on PMA.

Finally, the battery is passivated by not commuting the solar array sections thanks to software patches : the opening of all the solar array sections and the closing of the Over Voltage Charge (for battery charge regulation). Only the section number 12 can recharge the battery. The battery is discharging quite quickly, and then, the satellite is set into a safe mode, and is passivated due to the lack of energy. Once the satellite is switched OFF, it might restart (to be confirmed) (due to the section 12 which is still ON) but the modified on-board software will command the discharge of the battery again. In fact, the section 12 alone does not provide enough energy for a normal behaviour of the satellite even in a safe mode.

3) Mission analysis

The analysis on-going for SPOT4 in the frame of the preparation of nominal EOL operations shows that the satellite will re-enter in nearly 60 years with strategy 4 compared to 67 years with strategy 3. These results are obtained thanks to a CNES tool (called STELA) which is based on a statistic study of the different sun cycles already observed and computes an equivalent mean solar effect. The nominal re-entry duration is then given in 50% of sun cycles cases. This tool uses a MSISE model and a given set of parameters defined by agreement with our LSO group (solar activity, atmospheric model, drag coefficient,..).

For SPOT2 satellite for which strategy 4 was applied, the expected re-entry is October 2034 in 50% of sun cycles cases that is to say a re-entry duration of about 25 years as illustrated by Figure 1.

For Helios 1A EOL, the chosen strategy was constituted of two OCMs with a higher amplitude than the ones programmed in exploitation phase and an infinite-duration thrust : one OCM to release the operational orbit, the second one to be compliant with the 25 years of natural re-entry criteria, and then, followed by an infinite-duration thrust to passivate fluidically the satellite. The expected computed re-entry date is April 2027 in 50% of sun cycles cases that gives a re-entry duration of about 15 years.

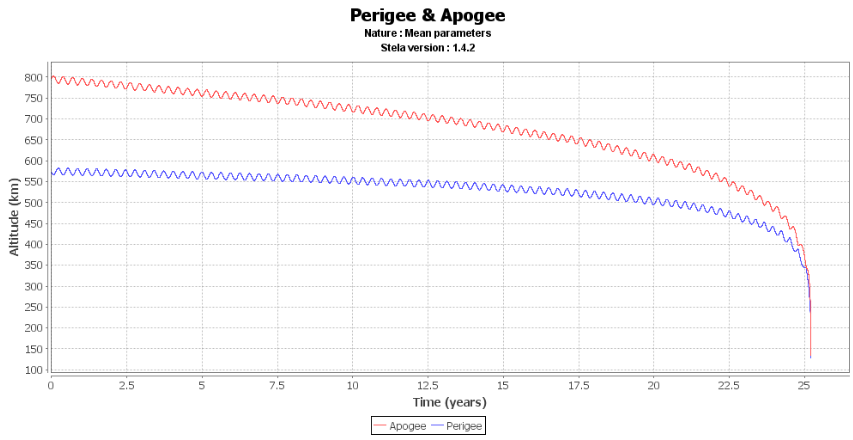

Figure 1. SPOT2 Apogee/Perigee Evolution

4) Risk analysis example

Here is an extract of the SPOT2 risk analysis.

First, the synthesis of all the goals by EOL phases are recalled through table 3.

Table 3: EOL phases and associated goals

N°	De-orbitation Phase	De-orbitation Goals
P1	Qualification	To qualify the operation : to prepare and to validate the operation
P2	Extended business exploitation without inclination correction	To operate the satellite two additional years without excessive consumption of hydrazine.
P3	Operational orbit clearing	To eliminate the collision risk with the other SPOT satellites
P4	Satellite configuration	To adapt the satellite configuration to the new orbital conditions (elliptical orbit)
P5	De-orbitation	Set of braking manoeuvres according to the available hydrazine, to lower as much as possible the perigee altitude to respect the natural re-entry in less than 25 years
P6	Fluidic passivation	Execution of the last manoeuvre until tank exhaustion, to empty the hydrazine tanks to avoid potential explosion in case of a collision.
P7	Electrical passivation	To disconnect the batteries to avoid explosion risks and to switch off the transmitters to avoid inopportune telemetry transmission
P8	Natural re-entry	Re-entry through the lower coats (layers) of the atmosphere in less than 25 years. Satellite disintegration thanks to atmospheric drag without any human life impacted.

One may have added to this table the following separated phase that has been identified on other satellites (for SPOT2, it is included in phase P2) : "Mission stop and particular technical operations planned to get some feedback for the future ." The goal is to maintain the satellite on its operational orbit after the end of the mission (or on a disposal orbit) and to lead some particular technological experience.

An identified generic goal is to keep the satellite integrity over the whole phases from P2 up to P7 (and in particular to avoid any collision risk).

Table 4 gives some examples of feared events over each phase.

In addition, one can also identify some generic risks from phase 2 up to phase 7 :

- Collision with another satellite,
- Collision with a space debris
- Loss of the satellite command (including TM/TC loss due to an on-board failure)
- Transition to the safe mode
- Failure of one operational mean (station, network, satellite control centre, ..)
- Transition to the FAM2 mode due to an anomaly with or without abandon of the non-vital memory)

These first five generic feared events can also be selected for other satellite de-orbitations while the sixth is a SPOT2 specific one.

For SPOT2, this analysis identified 64 risks and 19 actions were defined to reduce them. There wasn't any risk of level 1criticality. There remained 28 risks of level 2 for which 17 of them are identical risks as the ones that could be encountered in the routine exploitation phase.

Table 4: Some examples of identified feared events and the associated actions to reduce their criticality

Phase	Some examples of Feared Events (except generic risks)	Examples of Actions to reduce the criticality of the risks.
P1	-Satellite simulator failure as it is an old hardware test simulator -Change of teams as the delay between the operation qualification phase and the Rehearsal test may be of 2 years -Evolution of ground software and hardware means due to this 2-year delay	-All the operational data shall be validated during the technical qualification phase. The management shall state on different solutions to lead the operational qualification and rehearsal test with or without simulator connected or not with the command control centre or use the simulator located in the satellite contractor to improve the level of qualification of the operation. - For each member who decides to change of job, it will be discussed that he keeps his EOL functions. If not possible, the new team member shall be trained to the SPOT2 EOL operations as part of his training plan. -The risk is accepted as it.
P2	-Risks induced by the technological operations	To validate the technological operations on simulator to reduce the risks and to write/to validate the procedures
P3	-Erroneous TCH -Abandon of TCHs between 2 thrusts of the disposal manoeuvre	-To update the flight control plan to validate the binary profile of the critical TCH by two different experts. -To update the spaceflight dynamics control plan by adding a collision risk analysis after the first thrust, and to include the procedure that defines the complementary thrust to lower the apogee altitude, and to update the General Operation document.
P4	-erroneous TCH	-The TC are validated during the technical qualification phase. But, a download of the on-board software will be done after the configuration setup of the satellite to check if it is compliant with the modifications. If not, to upload again the patches.
P5	-transition to FAM2 due to an off-limit of the wheel rate -interruption of the thrust -Sun constraints not respected	-Modification of the set of values of the wheels kinetic momentum to be done, if needed, during the operations thanks to a flight control procedure. -To program the satellite to set it to the FPM mode, to book several additional ground station visibilities to estimate the orbit, to re-plan a new manoeuvre as soon as possible. - to generate a new TCH to take into account the new masking areas and to load it and to clarify in the spaceflight dynamics plan how to generate asynchronous TC.
P6	-Failure of satellite control centre (SCC) -erroneous computed data -interruption of the last thrust	-For instance, in the frame of the satellite control centre loss during the real time, the redundant SCC can be used as it is set into a hot redundancy. -the principles of generation of these TCH are validated during technical qualification phase, and each data is cross-checked before its uploading. -Decision to start the electrical passivation
P7	-failure of a satellite equipment - transition to FAM2 due to an off-limit of the wheel rate	-A TM/TC or a supply failure may occur, then the action consists in sending the TC on the redundant way. -To execute the EOL procedures in FAM2.
P8	-collision with another satellite or a space debris -Decay of satellite debris on habited areas	The risk is accepted because the satellite is now considered as a space debris. The Operational Orbitography Group will follow the evolution of the satellite orbit and will inform the Safeguard Group of the date and the probable decay ground area.

5) Illustration of a trade-off between different de-orbitation strategies

Several strategies exist as above-mentioned in the article. Let's briefly recall them by keeping in mind that all these strategies are completed by the fluidic and electrical passivation phases.

Table 5: Summary of the de-orbitation strategies

1st strategy	2nd strategy	3rd strategy	4th strategy
several OCMs to decrease the orbit altitude by one or more daily OCMs of two thrusts (circular orbit)	To decrease the orbit thanks to an one infinite-duration thrust (more than one orbit)	-To clear the operational orbit by performing one OCM or a few OCMs with two thrusts, - and then to decrease the orbit thanks to an one infinite-duration thrust (nearly one orbit)	- to clear the operational orbit by executing one or two OCMs of two thrusts, -to decrease the perigee altitude thanks to several OCMs of one thrust at the apogee position, inducing an elliptical orbit.
Nominal situation	Emergency situation	Nominal or contingency situations	Nominal situations

A comparison was made by the spaceflight dynamics and satellite teams according to these different items :

- The initial orbit, the duration of natural re-entry and the residual mass of propellant, the reached orbit at the end of the operation,
- The used sensors, the initial status of the satellite and the in-flight domain of qualification of equipments,
- Technical documentation in terms of feasibility of such operation,
- The feedback obtained from these different strategies,
- The planned duration of this operation,
- The on-board software to upload either by a new on-board software or by patches,
- The on-board standard and functional monitoring to be modified or disabled,
- On-ground software modifications to apply,
- The advantages and drawbacks of each strategy.

In short, the trade-off aims at defining the best strategy according to all the points of view (satellite, spaceflight dynamics, mission, operation, system). But, in addition, this trade-off also takes into account the following constraints : to secure the operation, to simplify it and to improve the observability of the operation to be able to demonstrate compliance with the LSO requirements.

As illustration, Table 6 presents an extract of some pros and cons examples comparing the different strategies.

From a mission point of view, the impact on the operability of the remaining satellites of the constellation have to be assessed in terms of conflict or jamming between the one to de-orbit and the other operational satellites especially if one satellite drifts in comparison to the others. In such a case, the second and third strategies might be preferred than the first one.

From an operation point of view, the first strategy can last up to one week or more depending of the remaining hydrazine mass. This duration is variable as the last thrust is only considered according to the remaining fuel mass. Thus, an uncertainty of roughly one day can be possible in the executing of the EOL operation, without taking into account any collision avoidance manoeuvre or satellite failure.

Now considering the second and third strategies, the duration of the operations is fixed without taking into account any collision avoidance manoeuvre or satellite failure. But, the level of uncertainty to position the actions to carry out due to the long duration of the thrust is quite tricky to handle. So, these two last strategies are easiest to implement with regards to the availability of all teams. Moreover, one shall also consider that these teams are also in charge of operating other satellites or participating to other satellite launching activities. So, the human resources topic shall not be considered as negligible.

Table 6: Pros and Cons examples comparing 3 of the four the de-orbitation strategies

	Strategy 1	Strategy 2	Strategy 3
Advantages	-After the first manoeuvre, the operational orbit is released. -The first manoeuvre allows to check and to calibrate the thrusters -Possibility to interrupt the de-orbitation operation at any time in order to take into account a collision risk or to change of strategy (long thrust) -A specific OCM can be executed in order to do the technological operations on a non operational orbit.	-Very short duration of operations -Few ground station visibilities to reserve -No orbit restitution to be done.	-After the first manoeuvre, the operational orbit is released. -The first manoeuvre allows to check and calibrate the thrusters -only one orbit restitution to be done after the disposal manoeuvre (less ground station visibilities to reserve, and less human resources) -Possibility to interrupt the de-orbitation operation only after the disposal manoeuvre in order to take into account a collision risk or to change of strategy (long thrust)
Drawbacks	-The duration of the operation and the daily associated activities induced an heavier charge. -High number of ground station visibilities requested -STD parameters updating activities -Numerous TCH to manually generate so potential source of errors -limitation of final altitude due to AOCS equipment design constraints (e.g. STD sensor) -AOCS constraints to position the manoeuvres on the orbit -....	-the operational orbit may not be fully released if the thrust is interrupted at an early stage. -Impossible to validate the right behaviour of the thrusters. -Difficulty to designate to ground station	-two different ways to generate OCMs and thus an human risk can be identified. -STD constraints with regards to the Moon -technological operations are lead on a disposal orbit implying to manage the conflict and jamming between this satellite to de-orbit and the others still in exploitation.

The strategy four can be, in some ways, compared to the first one as it lasts quite long. What may be difficult is to update and to deal with AOCS parameters in the frame of an elliptical orbit (masking values for STD, and so on).

For SPOT1 and SPOT2, the strategy 4 was used, while for Helios 1A, the strategy 3 was selected as it was the most interesting one (a moderated operational effort, an important decreasing of the orbit, ..) and represented a quite good compromise between the two others strategies as the thrusters behaviour could be calibrated, the orbit could be released, the 25-year criterion could be respected without a lot of OCMs and so on. But, what can be added is that the emergency flight control procedures of all satellites uses the strategy number 2.

IV. Preparation Of The Operation and Operation results

A. Satellite Monitoring and Control

Once all the activities (studies) previously described are completed, the technical and operational qualification phases can start. One may believe that the most difficult job has already been done through all theses studies. But, this is not really true as all the identified constraints and M&C principles shall be set together in order to build a Sequence Of Operations (SOE). During these phases, the scenarios are often improved in terms of security and observability.

Firstly, it is necessary to define different tests to validate nominal and degraded scenarios thanks to risk analysis. This point must be highlighted because a very good coverage of tests by implementing several satellite failures allows to identify new on-board risks and to prevent them by defining new actions. For instance, two anomaly tests showed that the M&C passivation principles were not robust to a propulsion or battery failures during the final thrust. It implied, for instance, that the critical telecommands shall be sent on both Bus Couplers in order to be sure that they will be well executed. Another example concerns a gyroscope anomaly which was defined between two thrusts of an OCM and it shows that the satellite PSO must be updated within a very short period, if not, the monitoring will trigger. Thus, the margins of PSO error were increased in order to be robust to several-hour delay before uploading flight dynamics TC. During these qualification phases, flight control procedures were tested and validated in nominal and degraded scenarios as the goals were to go on with passivation whatever happened, as e.g., a satellite anomaly setting the spacecraft into a safe mode during the final thrust.

Secondly, the characterization of the end of the thrust shall be clearly defined in order to have criteria to stop or to continue the operation. It consists in observing the following events :

- The FCV (Flow Control Valves) temperature are greater than the stabilized temperature during a standard OCM,
- The thrusters temperature decreases below a given threshold,
- The tanks pressure decreases below 5.5 bars on our platforms,
- The gyroscope rate increase over a given threshold,
- The estimated depointing is greater than a given threshold.

Thanks to the different EOLs that the CNES led, the following comments can be made. The last thrust showed some “spurious” (i.e. unexpected) advanced tanks very small de-primings, followed in the end by the expected sudden final de-priming. Depending on the satellite, these drops were either spread or grouped. This phenomenon is not understood yet. The thrusters temperatures dropped when only gas began to flow. The FCV soak-back start was also visible, appearing progressively when bubbles and gas were mixed. The pressure drop was also observed. During one EOL operation, a great effort was made to ensure tanks depressurization. This event was followed in real-time and the tanks Helium de-pressurization trend could be measured. The exhausting of the tanks appeared first on the tank pressure that dropped, and then on the Z attitude. The attitude, when OCM was controlled only with gas, showed a steady behaviour about X and Y, and, as expected, a more “random” behaviour about Z. It was expected that Z axis control showed some unbalances if the gas regime would not appear simultaneously on both thrusters; actually no large unbalance appeared (maybe partially due to tanks in communication). In addition, it could seem surprising, but no one thought to adapt the OCM control gains to Helium, only hydrazine was considered. Anyway, the integral control gain appeared to be not useful for this last thrust and it could be patched to zero. This is a lesson learned for the next satellite EOL operations for which the Helium depressurisation improvement is an objective.

Thirdly, the major remaining difficulty is then to define the criteria of electrical passivation and the associated process of decision. Time is going very fast during the latest minutes of such an operation, and it was obvious that a clear health status of the key satellite sub-systems (AOCS, power subsystem, propulsion, TM/TC) was needed in order to know if one let the on-board time-tagged telecommands to be executed or if immediate telecommands should be sent very quickly to passivate the satellite. It was decided according to the SOE and when the tanks exhaustion occurred, to get a status from the experts that was synthesised by a system responsible who decided to start immediately the electrical passivation or not thanks to clear criteria on AOCS, batteries charge, power budget, TM/TC. This was a really touchy activity which led to a lot of discussions.

Fourthly, one main identified feedback is to remove the alimentation constraint during the final thrust. This can be done by modifying the on-board central software such that the electrical passivation commands sequence is automatically sent at the very latest moment, that is to say, upon an unregulated bus minimum voltage criterion. This allows also to ensure the maximum possible delay before electrical passivation which means a maximum tanks depressurization duration. This last point has already been taken into account for the MK3 platforms.

Then, it will be interesting to have a power and electrical analysis that synthesises the needs and the constraints related to these equipments and which covers all phases of such EOL disposal operations. Usually, one may find some parts of needed information spread into several documents.

And finally, as it was previously illustrated, this operation needed to update some AOCS parameters by loading mean values once. One can also imagine that if several AOCS parameters updates are needed due the long duration of the thrust (large pressure drop and large orbital rate change), which was not our case, it might be done through an automatic process of the on-board software.

B. Spaceflight mechanics

CNES has already tested through its different EOL operations a few strategies[4,5] : several OCMs to decrease the perigee altitude after releasing the operational orbit, or an infinite-duration thrust after a few OCMs. Several items of interest have been highlighted.

1) Uncertainties

What can be mentioned is that the uncertainty of tanks exhausting moment is more difficult to manage when dealing with an infinite duration thrust than with regular OCMs. This implies that it is even more difficult to position correctly the start of the thrust.

In addition, another difficulty was to estimate the duration of the final thrust from a propellant mass not enough accurate in low pressure conditions. The experience shows, for instance, that for Spot 1 the mass was overestimated by 3% while for Spot 2 realistic margins were taken on the measured quantity from -4% to +1.5%. At the end, these operations allow to estimate the percentage of error attributed to the pressure sensors that is of around 2% for SPOT1 and 2 (opposite sign). Usually, the satellite contractor recommends to take into account +/- a few percent of error if no feedback on the tanks pressure sensors electronics is available from other platforms and operations.

Then, one can also mention the lack of knowledge of the hydrazine mass needed to recover the satellite from the safe mode. This data is quite important to define the time from which the AOCS convergence in safe mode will not be possible anymore.

2) Definition of criterion or update of parameters

It is necessary to define the detection criterion of the last thrust. It is based on the worst case of unusable mass and the maximum restitution error that corresponds to a certain percentage of error of the pressure sensors. The theoretical criteria of programming the last thrust is defined by checking if the residual mass is less or equal than the sum of the unusable mass taking into account the restitution error and the mass needed for a thrust of a given duration (for example 1000 sec for SPOT4) at the end of the emptying. In a practical way, one adds a margin to take into account a potential transition into FAM2 due to an anomaly, that gives a mass at the end. Thus, the manoeuvre before the last one is limited in order to program the last thrust with this unusable mass plus the error plus the FAM 2 margin.

The duration of OCMs shall also be defined in such a way that the thrust efficiency is kept the highest, to maximise the decrease of the perigee or the orbit altitude. An analysis compared short duration thrusts versus longer ones in terms of efficiency and the final orbit that is reached. On SPOT2 satellite, the results showed that thrusts of duration around 500 seconds (to be close to the impulse manoeuvre and to avoid the thrust spreading) compared to 1000 seconds led to a significantly greater number of apogee manoeuvres for a rather small gain in terms of perigee altitude decrease and thus re-entry duration.

It is also difficult to sometimes calibrate the thrusters and to define the right thrusters efficiency. These values were defined according to the historical use of the thrusters, by taking into account the last manoeuvre efficiency with these thrusters, the temperature, the tanks pressure, and some experience feedback.

To ease their work and to avoid errors, simplified STD Earth sensor masking had to be generated. Only Sun masking was defined as the most illuminated Moon interception risk was avoided by restricting the operation outside full Moon to 3/4 Moon period (3days) and by a fixed masking PSOs accommodating the Sun declination variations over the whole period.

As OCMs of two thrusts were performed to clear the operational orbit, the orbital rate (pulsation) varied with the orbit altitude decrease and thus induced a PSO drift. This drift could lead to reach the software masking boundaries in a short time period. In order to avoid that, the STD sensor margins should be updated after the OCM.

3) Collision risk assessment

During these operations, the CNES also evaluated the collision risks between the satellite to de-orbit and all the catalogued objects. The CNES applied two different processes to assess the collision risks according to the de-orbitation strategy .

When performing standard OCMs (that is to say of a standard amplitude), two dedicated screenings were performed :

- One using the determined orbit just after the manoeuvre,
- The other one using predicted post-manoeuvre ephemeris to take into account the incoming manoeuvre.

The post-manoeuvre ephemeris was also sent to JSpOC to inform them of the next manoeuvre and to perform the screening using the accurate Special Publication (SP) catalog. This process could be done as the dispersion of the orbit is small.

When performing OCM of high amplitude, to release the operational orbit for instance, the collision analysis from post-manoeuvre predicted orbits is not relevant as the uncertainty of the manoeuvre realization is more important and shall be compared to the accuracy of collision risk assessment. This is why, in that case, the screening was performed according to the following process :

- Daily collision risks analysis after each post-manoeuvre orbit determination,
- Screening from GRAVES TLEs (alert threshold: 10-4),
- Collision risks analysis with other active CNES satellites (alert threshold: 10-4),
- JspOC support by providing them with each post-manoeuvre determined orbit.

For Helios 1A, no collision risk was identified during the whole operation while for SPOT2, only one collision risk was identified but with such a low collision probability that the manoeuvre was cancelled.

C. System and operations

To build the Sequenced Of Events (SOE), it is finally not so easy as, at the first stage, one wants to observe all the satellite events. Therefore, it is necessary to define a hierarchy between the LSO observability constraints versus the ground station visibilities that is to say : do we want to follow the first thrust, or the beginning or the end of the theoretical final thrust, the latest date of the end of the theoretical thrust, the battery disconnection, the apparition of the bubbles and so on ? For example, one could say that following the first OCMs in real time may not be of the highest priority, but it is obvious that the electrical passivation may be followed in real-time for LSO purposes. Some other interesting events are the earliest or the latest theoretical time of the end of the final thrust, but also the earliest theoretical time of the first bubbles. In addition, depending on the satellite behaviour, the electrical passivation can be done either in sunlit or in eclipse, but in general, the satellite subcontractor preferred to do it in eclipse for supply/power purposes. One shall define the observation priorities between all these events to allow the elaboration of the SOE.

As it is mentioned, according to the chosen spaceflight dynamics strategy, it may be difficult to position the start of the thrust, to define the best fitted ground station visibility coverage in order to observe the on-board events related to LSO in real-time, to secure the electrical passivation, to correctly date the time-tagged telecommands, to take into account the dispersion for station designation and so on. That is why some actions were taken in order to bound in a certain way these uncertainties. For instance, it was decided to follow some events thanks to on-board record of some satellite telemetry parameters. For ground station designation purposes, three different ephemeris were provided for the final thrust in order to cover all uncertainties as it is more difficult to determine the orbit in real-time and then to give an updated information to the ground stations. During one EOL operation, due to a high uncertainty of the last thrust, the spaceflight dynamics team had to compute in real time the updated ephemeris when the end of the thrust was confirmed by the experts and to send this updated information to the next ground stations in visibility with the satellite to follow the passivation activities.

The conflict and the jamming between satellites shall also be managed and shall not be under-estimated in terms of operations.

One shall point out that the CNES is able to have a rather good whole coverage of these operations thanks to its own station network that is completed by other stations belonging to PRIORANET network. In addition, new stations as INUVIK is of great interest to follow such operations. Here is an example of the ground station coverage during the last thrust of HELIOS 1A EOL operation.

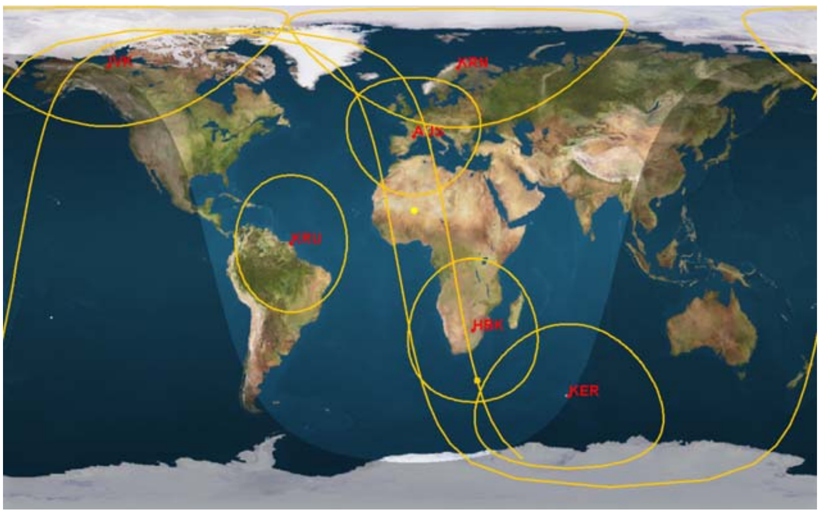

Figure 2. Ground station coverage for the last thrust

The last burn was of more than 1 hour. The orbit was chosen to maximize the TM-TC link, with 5 antennas (Kerguelen, Hartebeesthoek, Aussaguel, Kiruna and Inuvik antenna). The last burn started on Inuvik support, near the North pole, the end of burn was foreseen on Hartebeesthoek support. The last operations were performed on Inuvik support near the North Pole. So, these operations were carried out on one complete orbit, with beginning of burn in visibility, followed by a gap between Inuvik and Kerguelen support during the first part of the burn, then the second part of the beginning of the burn is monitored till its nominal end with Kerguelen and Hartebeesthoek antenna. The last support is done with Aussaguel, Kiruna and Inuvik antennas to monitor the end of the thrust in case of upper remaining propellant dispersions and the final satellite electrical passivation.

V. Generic Approach Applicable To Other Satellite De-orbitations

Through the different sections of this paper, one can highlight that a generic process can be defined and applied to prepare any other satellite EOL operations.

First of all, the identified inputs studies and the documentation mentioned in the first part of this paper are the preliminary information and results to get to go on with the process. These studies shall be done with an important support of experts. The definition of the strategy is obtained through the conclusion of a trade-off that takes into account all the constraints, the identified risks and their level of criticality. This proposal is formally accepted by a steering committee during an official Key Point. What the WG on emergency EOL shows, is that the major studies shall be performed before the launch of the satellite for the new projects as well as tests.

Next, a set of tests (operability and system) and a rehearsal test shall be planned in order to validate flight controlled procedures in nominal and contingency cases, the operational data, the software modifications and the sequence of Events by using a representative satellite simulator. These simulated tests shall be sufficient to cover different satellite anomalies during critical time periods of operations in order to highlight the weaknesses of the chosen strategy and then to identify actions and thus to reduce the risks. The presence of experts is also requested in these phases. A review is set at the end of the operational qualification phase in order to state about the level of preparation of the operation and the identified risks, and to allow the EOL operation.

Then, as it was said, the definition of the SOE depends strongly of the chosen approach. Moreover, one may define the priorities between all the LSO constraints to observe, to clearly characterise the tanks exhausting, to clarify the criteria and the decision process to start the electrical passivation. And then, according to the manoeuvres strategy, one has to deal with the difficulties to position the OCMs, to select the right thrust efficiency and the AOCS parameters needed for the generation of the OCMs.

The feedback accumulated through our different EOL operations is applicable from one operation to the next one in terms of information or results coming from the studies, from the different simulated tests and from the way to build the SOE by well identifying the constraints by topic (spacecraft, spaceflight dynamics, LSO,...). As for instance, the core and the logic of the risk analysis or the main principles of the AOCS study is of high interest from one operation to the next. Some principles to secure the operation such as the inhibition of the safe mode order, the use of time-tagged telecommands, sending telecommands on both bus couplers, and so on are some of the examples that can be re-used from one operation to the next as the main principles of the FDIR logic is similar between satellites. In addition, the approach for defining the coverage of tests versus the LSO constraints and the feared events is of high interest for the next EOL preparation.

Of course, even if this generic approach can be applied to each satellite EOL operation, such an operation still remains specific at the end as it depends on the health status of the satellite and more precisely on the health status of the equipments used during the operation and their in-flight range of use, on the initial altitude orbit and the context of constellation, on the residual mass of propellant for example. What can be said from one EOL operation to the next one is, that each time, one enhances the operations in order to make them simpler and more secure and to improve as much as possible the observability of this operation.

VI. Conclusion

Several satellite EOL operations have been performed successfully by the CNES for several years. These first operations were carried out on satellites which were not designed for such passivation actions. The best efforts were done to be as much compliant as possible with, first, the IADC recommendations[2] and later, with the French Law On Space Operations. Each EOL operation brings to the operational teams some real experience feedback that is integrated into the next EOL preparation. It allows to improve the way to deal with the preparation of such operation, to better identify the main and critical topics, to enhance the operations from a security and simplification point of view.

The process, that is currently applied on SPOT/HELIOS/Pleiades satellites to prepare and to conduct such operations, has been discussed. It highlights the different key studies that shall be led before any operation, the monitoring and control actions that must be performed. It points out the different critical moments during the operation and the need to define a characterization of the key events, several criteria and a decision process to start the passivation operation. Besides, it presents the spaceflight dynamics activities and challenges. Several concrete examples have been given to highlight the interest of these different topics.

The principles of this approach can be applied to any other satellite EOL operations. Then, this approach shall be instantiated by taking into account the particularities of each satellite and context, that is to say, health status of the satellite, the health status of the equipments used during the operation and their qualification range of use, the initial altitude orbit and the context of constellation, the residual mass of propellant, and the human resources available.

Appendix A

Acronym List

AOCS	Attitude and Orbit Control System
CAM	Coarse Acquisition Mode
CMG	Control Moment Gyroscope
CNES	Centre National d'Etudes Spatiales
EOL	End Of Life
FAM1	Fine Acquisition Mode 1
FAM2	Fine Acquisition Mode 2
FDIR	Failure Detection Isolation Recory
FPM	Fine Pointing Mode
JspOC	Joint Space Operations Center (NASA°
LEO	Low Earth Orbit
LSO	French Law on Space Operations
OCM	Orbit Control Manoeuvre
OPM	Operational Pointing Mode
MAC	Magnetorquers (Magnéto-Actuateur Coupleur in French)
M&C	Monitoring And Control
PSO	satellite Position On Orbit (Position Sur Orbit in French)
PM	Processor Module
RRM	Reduced Rate Mode
RSJD	Regulator Shunt Junction Distribution
SOE	Sequence Of Events
SOPM	Stellar Operational Pointing Mode
SSD	Digital Earth Sensor (Senseur Solaire Digital in French)
STD	Digital Earth Sensor (Senseur Terrestre Digital in French)
TCH	On-board memory Telecommand
TLE	Two-Line Element
TM/TC	TeleMetry/ TeleCommand
WFS	Withdrawal From Service Configuration
WG	Working Group

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