CLOSE SATELLITES DISPOSAL OPERATIONS : IMPROVING SAFETY AND OPERATIONAL EFFICIENCY

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ABSTRACT

The ESSAIM family was a cluster of four microsatellites flying together in a close geometric formation. They were decommissioned at the end of 2010. CNES already had a strong experience with disposal operations for GEO and LEO satellites, but it was the first time that four close satellites had to be deorbited at the same time.

Indeed, large manoeuvres performed on close satellites after many years in orbit can be risky. In addition, as a microsatellites program with limited budget, operation costs also had to be minimized.

A specific and efficient manoeuvre strategy was set up, with few manoeuvres for simplicity and a particular attention to eccentricity management for safety that allowed to avoid collision risks between the ESSAIM satellite during disposal operations and over a long term, even in manoeuvre degraded case.

Collision risks with other operational satellites on the way were also considered and handled during operations.

1 ESSAIM CLUSTER STATION-KEEPING

MYRIADE satellites are a family of microsatellites designed by CNES with a low-cost approach. Their main characteristics are ~ 120 kg, ~ 1 m^2, ~ 150 W and only a few redundancies. CNES has operated ten MYRIADE satellites, retired five of them, and other ones are currently under study.

1.1 Station-keeping main characteristics

The ESSAIM satellites were launched in December 2004 for 3 years, extended to 6 years thanks to their good health. They were controlled together in a geometric formation in two orbital plane (East and West plane) on a near-polar orbit, as shown on Figure 1. The satellites formed two quasi-isocel triangles thus passing four in a line at the two orbital planes crossings (North and South), with about 20 seconds between each satellite.

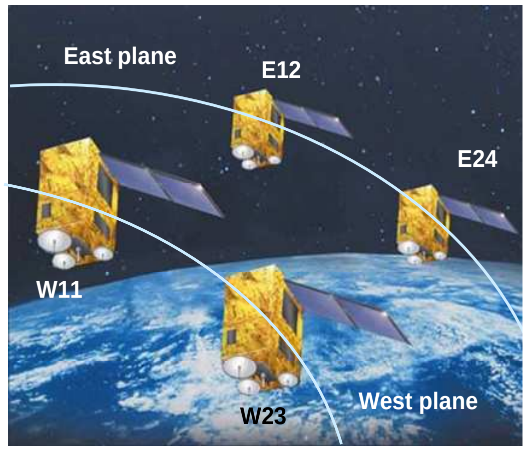

Figure 1: ESSAIM swarm geometry.

ESSAIM mean altitude was controlled and stable, but since their mission was not optical observation, there was no need for them to have a frozen orbit : the local altitude above a point on the earth changed with a period of ~100 days, according to the variation of the eccentricity vector, which was different and not phased for each satellite. For example : W11 eccentricty varied from 0 to 2. 10-3 and the apogee and perigee altitude had a 14 km variation.

Erreur ! Source du renvoi introuvable. shows W11 eccentricity vector evolution, and Figure 3 illustrate the corresponding altitude variation, compared to the altitude stability obtained with a frozen orbit.

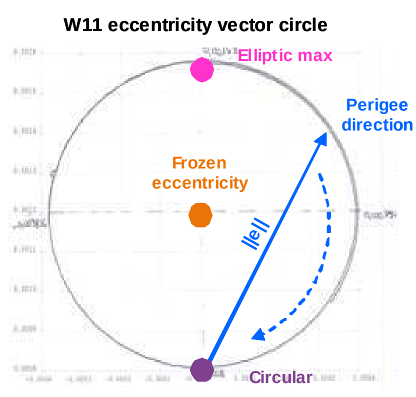

Figure 2: Non frozen eccentricity vector evolution.

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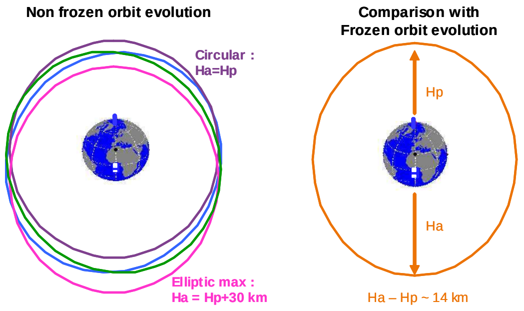

Figure 3: Frozen and not frozen orbit evolution.

1.2 Frozen eccentricity and collision risks

In the past, CNES has experienced periodic close approach situations for satellites with close orbital plane and altitude. This can occur especially for satellites which do not have frozen eccentricity because in such cases, perigee and apogee of the objects are not synchronous one with the other.
For a frozen eccentric orbit, the eccentricity is stable : $\sim 10^{-3}$, which means an apogee / perigee altitude gap of ~ 15 km, and the perigee orientation is also stable : ~ +90°, which means that the altitude profile along the orbit is always the same with the lowest point at maximum North latitude and highest point at maximum South latitude.
For non frozen orbits, the altitude profile varies. Satellites on such orbits with same or very close orbital plane and altitude separation lower than 15 km are likely to experience periodic close approach situations on the long term.
On the other hand, satellites on very close orbits : same plane and close mean altitudes will keep a good security distance over a large number of years, provided that they are given an initial frozen eccentricity : frozen orbits give a higher safety level.

2 DEORBITATION STRATEGY

Although ESSAIM disposal operations took place in October 2010, before the French Space Act comes into force (December 2010), every effort was made to assure a maximum compliance with international recommendations. Altitude was not an issue since the satellites on their operational orbit were already expected to decay within 25 years. Tank emptying could be done respecting the limit of guaranteed hydrazine quantity : studies that would allow to go on with vapour expel for further Myriade satellites disposal (applied for DEMETER) were not completed yet. Electrical passivation could also be achieved thanks to a dedicated on-board application to prevent automatic battery charge.

The specificity of ESSAIM satellites decommissioning was their proximity before, during and after deorbiting maneuvers. Therefore analysis have been made concerning collision risk issue, and have lead to put in place a specific deorbitation strategy.

2.1 Objectives

The main objectives of deorbitation strategy were the following :

- Lower the 4 x Essaim altitude in order to reduce their remaining lifetime and to deplete their tanks, without taking the risk of a full depletion. 1 kg has been considered as an acceptable quantity of remaining hydrazine.
- Freeze the orbit eccentricity and thus be able to provide a sustainable altitude gap between each Essaim : a minimum value of 3 km at the end of deorbitation has been considered as a sufficient separation value
- Avoid any collision risk between the Essaim satellites during the maneuvers, even in degraded cases : maneuver failure and delay, or +/- 10% maneuver efficiency.
- Avoid any collision risk between the Essaim satellites and a set of other operational satellites with similar altitude, during the maneuver phase and afterwards during 3 months.

2.2 Constraints

The main constraint was to minimize the cost of deorbiting operations, which implied :

- Limit the total duration of deorbitation phase
- Minimize the number of maneuvers
- Minimize the ground station extra support
- Avoid operations outside working hours

Other constraints were directly linked to maneuvers :

- only in-plane tangential maneuvers,
- thrust duration < 20 mn (13 m/s or 48 km)
- three full orbits between 2 thrusts (in order to charge battery in heliocentric mode).

2.3 Strategy definition

Reaching the frozen eccentricity ($e_x = 0$; $e_y = + 10^{-3}$) is feasible with one tangential maneuver, with a correctly chosen in-orbit position for the thrust and an amplitude depending on the eccentricity circle radius of each satellite (Tab. 1) :

Table 1. : Maneuver amplitude to freeze eccentricity

	W11	E12	W23	E24
Δe	$3.9\ 10^{-4}$	$12.1\ 10^{-4}$	$2.9\ 10^{-4}$	$8.9\ 10^{-4}$
ΔV_{min}	0.73 m/s	2.27 m/s	0.55 m/s	1.68 m/s
Δa_{min}	1.4 km	4.2 km	1.0 km	3.1 km

Lowering the mean altitude can be made by one or several tangential negative maneuvers, at any in-orbit position.
Il was decided to target a given altitude and frozen eccentricity with one set of two maneuvers per satellite (step 1), and then, if necessary, to correct the obtained result with one more maneuver per satellite (step 2). Step 2 would allow to take into account over or under performance of step 1 maneuvers if this lead to an altitude separation lower than 3 km.

Targeted mean altitudes were chosen for each satellite according to their respective propellant capacity (leaving however a step 2 maneuver reserve), with 5 km separation between each satellite, and 10 km between two satellites in the same plane.

Table 2. Mean targeted altitude decrease

	W11	E12	W23	E24
Δa_{moy}	-25 km	-20 km	-15 km	-30 km

These values however do not guarantee 3 km separation in all cases with +/- 10% maneuver dispersion, as shown in Figure 4:

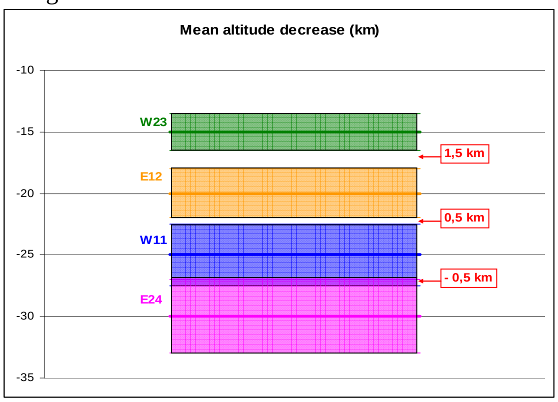

Figure 4 :Manoeuvre efficiency maximum impact

1.5 km separation (worst case between W23 and E12) was judged enough for security and would be corrected afterwards during step 2. But 500m or less (worst case W23 - E12 or W11 - E24) was considered too small. To avoid satellites being too close after step 1 maneuvers, it was decided to begin with E24 maneuvers (the largest ones), then adjust W11 target altitude 5 km higher than the obtained one for E24, realize W11 maneuvers, adjust E12 and W23 altitudes and finally perform their maneuvers together.

In order to avoid collision risk between Essaim satellites during the maneuver phase, a strategy was set up.

For safety towards the other satellite in the same plane, the first maneuver amplitude is adapted to obtain a good radial separation when the satellites will have close in-orbit positions, as shown Figure 5.

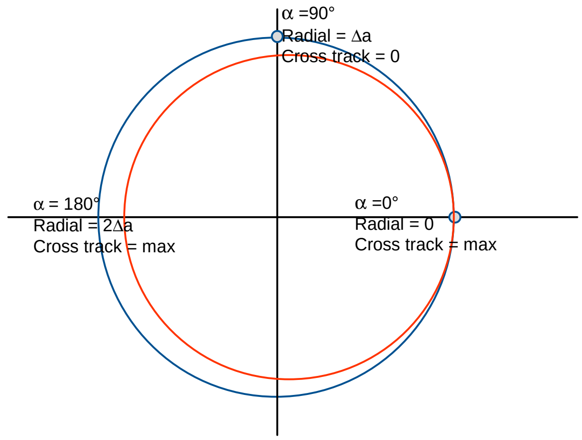

Figure 5 : Satellites on different plane separation

For safety towards the other plane satellites, in orbit position of first thrust is chosen near an orbital node, which provides a good radial separation at the orbital planes crossings which are at high latitudes (Figure 6).

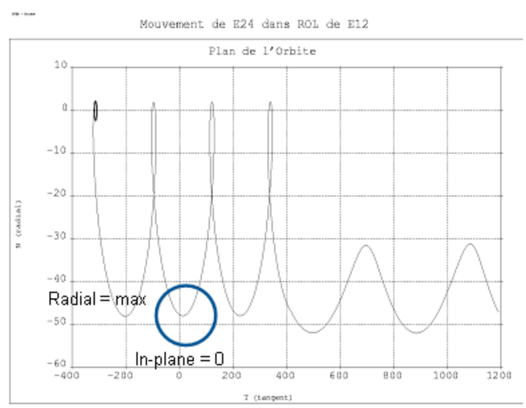

Figure 6 : Satellites on same plane separation

In fact, this simple approach is only applicable to satellites with same eccentricity and argument of perigee, which is not the case… The total separation at high latitude is the contribution of two terms : Δa and $a\Delta e_y$. The separation is thus effective only when $a|\Delta e_y|$ << $|\Delta a|$. According to the eccentricity vector evolution, it is not always possible to fulfill this condition.

For E24, maximum Δe_y (towards W11/W23) is 6.10^{-4} which gives a $\Delta e_y \sim 4$ km, small compared to E24 $\Delta a/2$. For W11 there is no problem since this satellite is before the others and increases its in-track separation after the first thrust.

For W23 and E12 on the other hand, maximum Δe_y is 9 10^{-4} , a Δe_y ~ 6 km for a relative Δa of only 5 km, which is not safe. Considering the eccentricity vector evolution, favorable periods were determined that minimized a Δe_y, (see Figure 7) and one of them was suitable for the operations to take place. If it had not been the case, maneuvers on the two satellites would have been done separately instead of together.

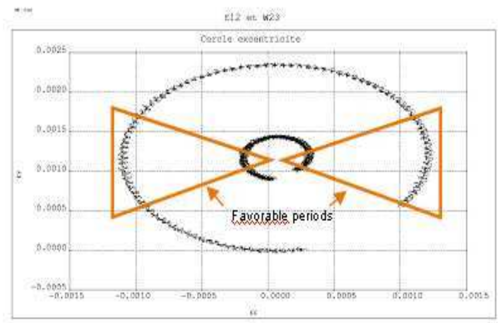

Figure 7 :Radial separation at high latitude = close e_y

This whole strategy is robust to a maneuver delay of several days : this concerns especially the second maneuver, since between first and second thrust, the satellite begins to move rapidly with respect to its nominal position and does not have yet a permanent radial separation with the other ones.

3 COLLISION RISK ASSESSMENT

Two activities concerning the collision risks assessment were performed during the operations. The first one was the daily screening of dangerous conjunctions between the ESSAIM satellites and all the catalogued objects. The second one was the mid-term analysis to guarantee that the final orbit of each satellite could not cause any close approach with a given list of operational satellites called "partner" satellites.

3.1 Screening with the catalogued objects

The routine CNES collision avoidance process[1] was used during the deorbitation. The screening process based on the CNES French catalogue of GRAVES system was executed daily and the Joint Space Operations Centre was responsible of sending e-mail alerts when a close approach with one of the Special Publication catalogue objects was detected.

Given that the uncertainty related to the performance of the maneuvers was around 10%, it was decided to not take into account the collision risks detected after a maneuver when using pre-maneuver predicted ephemeris for the computations. Dispersions associated to the orbit predictions were too large to obtain reliable results. For a quick detection of close approaches after a maneuver, predicted ephemeris calculated just after the maneuvers were sent to JSpOC in order to improve their knowledge of the satellite orbit.

A dangerous conjunction between W23 and a pièce of PSLV was detected by JSpOC on October 7th for a close approach on October 9th. The miss distance was 108 meters with a radial distance of 26 meters and a probability of collision (PoC) of 2.710^{-3}. According to the CNES collision avoidance process, which indicates that a risk mitigation action is needed if the PoC is higher than 10^{-3}, a maneuver of -50 meters in semi-major axis was executed on October 8th to reduce the risk.

Although this dangerous conjunction was detected during the deorbitation operations of the satellite W11, the nominal operations timeline was not modified. CNES teams were able to manage this contingency in parallel of the scheduled operations.

3.2 Midterm analysis with "partner" satellites

CNES board requested the ESSAIM deorbitation team to set the satellites in a final orbit that could guarantee to not produce any close approach with a given list of "partner" operational satellites during at least 3 months after passivation.

Figure 8 shows the satellites disposal, the semi-major axis of each "partner" satellite (dotted lines) and the final altitude of each ESSAIM satellite. The semi-major axis of these satellites are known but their eccentricity is not well frozen which produces altitude to raise and fall. This variation is represented by the coloured boxes. As we can see in this chart, it was not possible to find an altitude that could guarantee that no close approach would be detected during the next three months after the passivation.

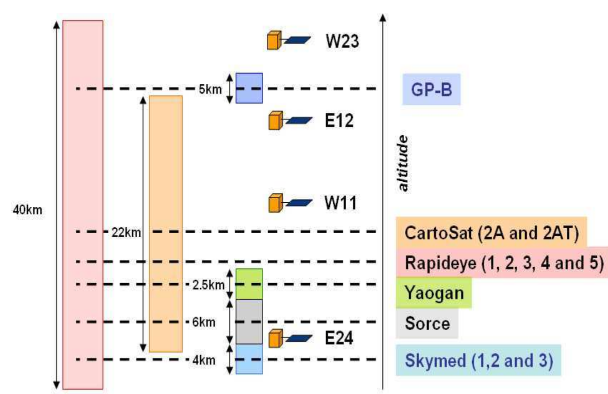

Figure 8 : ESSAIM disposal and partner satellites

To find a solution CNES flight dynamics team decided to perform midterm analyses based on the evolution of the radial separation and differences on passing time at orbit node crossing point. The idea was to be able to assure that when the orbit node crossing time difference equals 0 (both satellites are in the orbit crossing node at the same time), the radial separation at orbit crossing node was enough to guarantee that it was no collision risk. This principle is detailed in Ref. 2. An example of the results is shown in Figure 9.

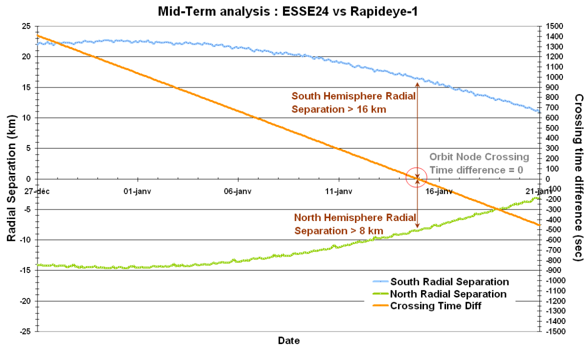

Figure 9 : Mid-Term collision analysis example

The station keeping strategy of the satellites has a direct influence on the evolution of the crossing time difference. As CNES does not known this strategy it was not pertinent to perform the study over 3 months. An horizon of 15 days was finally considered sufficient to guarantee the midterm safety of the spacecrafts.

From an operational point of view the organization was the following : for each ESSAIM satellite, flight dynamics experts in charge of the disposal maneuvers chose the final orbit using this midterm analysis technique. Then, when the final orbit was reached, the CNES collision avoidance team performed the same analysis with another software (in order to cross-validate the pre and post maneuver computations) and then, if no risk was detected, the passivation was permitted. No collision risk with the ESSAIM satellites was detected neither by JSpOC nor CNES during the next 15 days after the passivation.

4 OPERATIONS

Operations were planed in working hours and working days in the following way :

- Monday : maneuver 1 preparation and upload
- Tuesday : maneuver 1 execution, first diagnostic
- Wednesday : orbit determination, maneuver 1 calibration, maneuver 2 preparation and upload
- Thursday : maneuver 2 execution, first diagnostic
- Friday : orbit determination, maneuver 2 calibration

Satellites were maneuvered in the following sequence : E24 first, then W11, and last E12 and W23 together. So step 1 lasted three weeks. Another week was devoted to step 2 adjustment maneuvers if needed. Those maneuvers would be performed on all satellites together since there would then be no more risk of collision, and finally electrical passivation would take place.

During operations, a collision risk occurred for one of the satellites, and an avoidance maneuver had to be done. This was taken into account for the following maneuvers. It was also decided to perform a step 2 maneuver for E24 sooner than initially planned, since there was no risk for other satellites. Since no other step 2 maneuver were necessary (thanks to thrust 2 adjustement after thrust 1 calibration), this allowed to save one week operation.

Table 3. shows all the maneuvers performed and the corresponding altitude decrease.

Table 3. Essaim deorbitation manoeuvres

(km)		W11	E12	W23	E24
W 39	Tue				-13.1
	Thu				-18.2
W 40	Tue	-13.6			Step 2
	Wed				-3.5
	Thu	-12.2		Avoid.	
	Fri			-0.05	
W 41	Tue		-14.3	-6.9	
	Thu		-6.1	-8.8	
Total		**-25.8**	**-20.4**	**-15.7**	**-34.8**

Target altitude and frozen eccentricity could be reached rather precisely thanks to 2nd thrust adjustment : observed efficiency for 1st maneuver was near 106%.

The following charts show the mean semi-major axis evolution during deorbiting maneuvers (Figure 10) and the perigee and apogee altitudes (Figure 11).

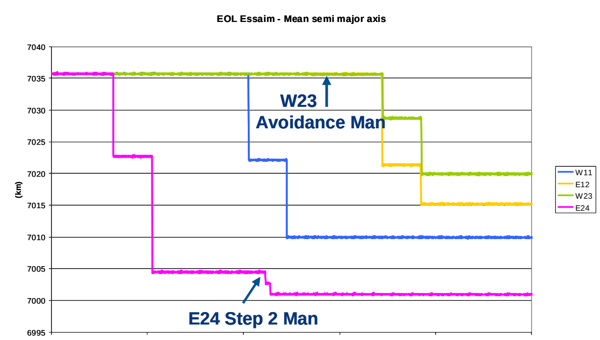

Figure 10 : Semi-major axis evolution

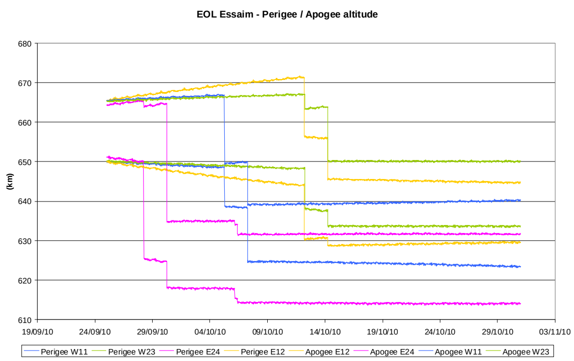

Figure 11 : Perigee and apogee altitude evolution

It is clearly seen here that 5 km mean altitude separation does not guarantee radial separation and that close approach situations are likely to occur before natural reentry, except if eccentricity is frozen.
Hereafter are shown the eccentricity vectors evolution during deorbiting (Figure 12), which provides a sustainable radial separation during decades (Figure 13).

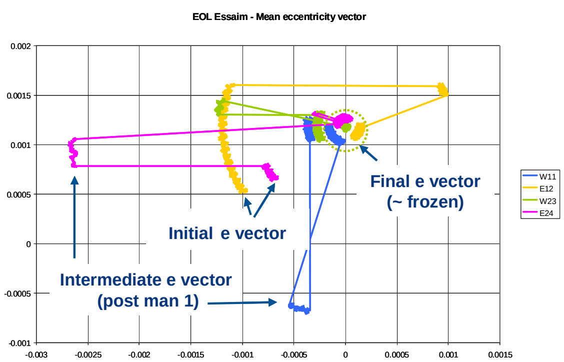

Figure 12 : Eccentricity vectors evolution

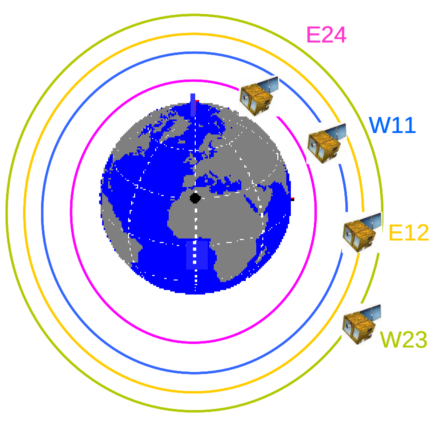

Figure 13 : Sustainable radial separation

5 COMPLIANCE WITH REGULATION

An estimation of the mean remaining in-orbit lifetime has been made using the software STELA [3], a tool developed by CNES (available on : http://logiciels.cnes.fr/STELA), which provides a simple mean to check the compliance to the international and French Space Act 25 year rule
Table 4 gives the final altitude and STELA mean remaining lifetime esimtation for the ESSAIM satellites:

Table 4. ESSAIM estimated lifetime (STELA)

	Mean altitude	STELA lifetime
W11	632 km	17.0 year
E12	637 km	18.3 year
W23	642 km	19.2 year
E24	623 km	14.9 year

It is generally admitted that the most efficient way to reduce remaining lifetime is to decrease the perigee. A perigee orientation of 270° may also be favorable. A frozen eccentricity does not meet these conditions. In order to comfort our choice, STELA simulations have been run for the ESSAIM satellites with different initial conditions (post disposal maneuvers) regarding eccentricity value and perigee orientation :

- Minimum perigee altitude, which corresponds to maximum eccentricity
- Argument of perigee = 270°
- Frozen eccentricity (= reality)

These initial conditions were realistic : they could be reached with the same amount of propellant (same semi-major axis, inclination, and right ascension of ascending node). Figure 14 shows the STELA lifetime result for these different cases :

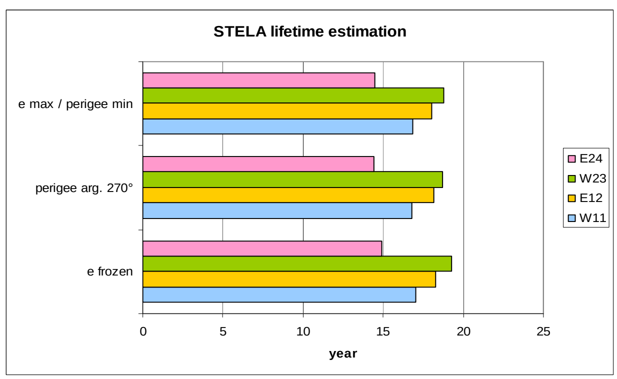

Figure 14. Remaining lifetime for different initial eccentricity vector with same EOL ΔV

At ESSAIM altitudes and with a limited delta-V capacity, lowering the perigee does not significantly

reduce the remaining lifetime : 1% to 3% only (a small number of months) in all cases.
The perigee orientation of 270° does not seem to be of particular interest in our case.

6 CONCLUSION AND LESSONS LEARNED

Disposal phase, including fluidic and electric passivation, represent important and complex operations for a satellite. ESSAIM disposal operations were managed, prepared, qualified and conducted in a similar manner as early operations phase. It needed studies and software adaptations as well as significant human resources during operations : no only nominal operational teams but experts in different domains able to deal rapidly with contingency cases, and CNES multimission teams dealing with the CNES 2 GHz Ground Stations Network.

With the recently adopted French Space Act, dealing with four close satellites and having to perform important altitude changes (10 to 15 km for each thrust) made us pay a great attention to collision risk issue.
A specific strategy was thus defined, which provided the following advantages :

- Depleting the remaining liquid propellant with no risk of "complete depleting" that was thought to be dangerous for the thrusters at that time
- Assuring a reentry within 25 years (15 to 19 years achieved), as requested by international recommendations and the French Space Act
- Preventing any collision risk between the ESSAIM satellites until decay
- Preventing any collision risks between ESSAIM satellites and a set of operational "partner" satellites during operations and for 2 weeks after their completion
- Limiting the global operational workload for the 4 satellites, including passivation and extinction, to four weeks in working days and hours.

The frozen eccentricity choice seems relevant in this case :

- it does not significantly degrade the lifetime duration
- it guarantees no collision risk between ESSAIM satellites
- it gives better altitude predictability for other satellites
- it allows to cross other operational orbits (with frozen eccentricity) during a few weeks or months only instead of during all the descent duration

Of course this choice cannot be applied to any mission : in particular, with higher initial altitude, lowering the perigee can be the only mean to meet the 25 year rule.

Concerning the maneuvers, it would have been useful to calibrate the thrusts with a smaller maneuver first : we had to face an rather important over realization of 106%. It was necessary to estimate this rapidly and give updated tracking elements to the ground stations in order not to lose passes.

Usual collision risk avoidance process was maintained during this phase, but collision risks post-maneuver were not assessed before maneuvers (except for partner satellites) : it seems useless to check collision risks with any object, knowing that a large maneuver is to be done and that it will not be realized exactly as expected. For this reason also, orbit determination after thrust was done as fast as possible (within a few hours). The standard process has proved its utility by detecting a risk and being able to mitigate it while disposal maneuvers were ongoing on other satellites.
Collision risk avoidance could not be done over 3 months for partner satellites, as initially asked, mainly because those satellites did not have a frozen eccentricity (especially Cartosat and Rapideye). More generally, when propellant must be totally depleted, one cannot know when the maneuvers will stop. It is thus impossible to try to guarantee no collision risk for all other operational satellites : they will have to deal with avoidance maneuver if necessary

And last : dealing with several satellites simultaneously is operationally tricky and needs special attention !

7 REFERENCES

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