

Figure 15. STELA result for W23

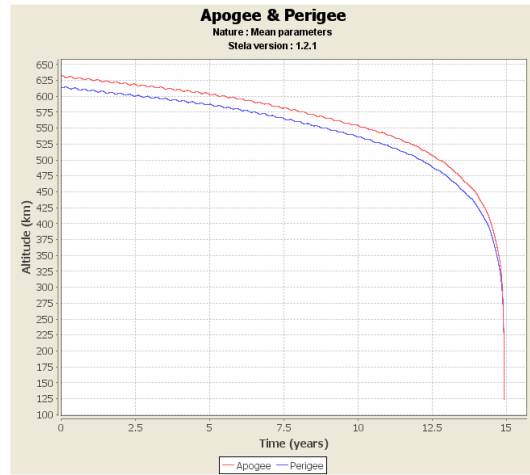


Figure 16. STELA result for E24

It is generally admitted that the most efficient way to reduce remaining lifetime is to decrease the perigee. A perigee orientation of  $270^\circ$  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 =  $270^\circ$
- 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). Fig. 17 shows the STELA lifetime result for these different cases :

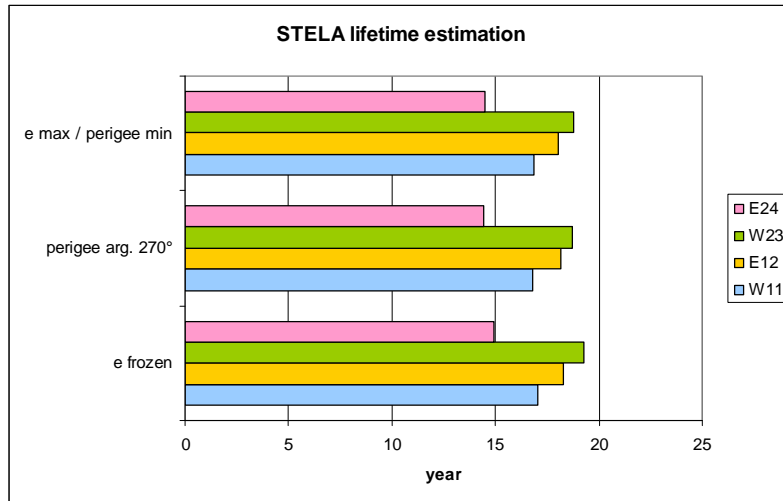


Figure 17. Remaining lifetime for different initial eccentricity vector with same EOL  $\Delta V$

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  $270^\circ$  does not seem to be of particular interest in our case.

## VIII. Main results 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 can be tricky and needs special attention !

## **Appendix A**

### **Acronym List**

<b>EOL</b>	End-of-Life
<b>GRAVES</b>	Grand Réseau Adapté à la VEille Spatiale (Large Network Adapted to Space Surveillance)
<b>JSpOC</b>	Joint Space Operation Center
<b>GEO</b>	Geostationary Orbit
<b>LEO</b>	Low Earth Orbit (mean altitude below 2000 km)
<b>MYRIADE</b>	Microsatellite family
<b>PoC</b>	Probability of Collision
<b>PSLV</b>	Polar Satellite Launch Vehicle
<b>STELA</b>	Semi-analytic Tool for End of Life Analysis

### **Acknowledgments**

Many acknowledgments to all CNES teams that have taken part in this adventure and allowed to conduct the first Myriade satellites disposal operations in an efficient way and in perfect compliance with the French Space Act and international regulations.

### **References**

<sup>1</sup>Laporte, F., Moury, M., “Adaptation to changes in Collisions Avoidance operations at CNES for in-orbit satellites,” *European Space Surveillance Conference*, Madrid, Spain, 2011

<sup>2</sup>Pena, X., and Brown, C.W., “Operational Collision Risk Assessment of Calipso and Landsat 5 Crossings,” *12<sup>th</sup> International Conference on Space Operation*, Stockholm, Sweden, 2012

<sup>3</sup>Fraysses, H., et al, “Long term Orbit Propagation techniques developed in the frame of the French Space Act,” *22<sup>th</sup> International Symposium on Space Flight Dynamics*, São José dos Campos, Brazil, 2011