DE-ORBITATION STUDIES AND OPERATIONS FOR SPIRALE GTO SATELLITES

François BONAVENTURE[(1)], **Slim LOCOCHE**[(2)], **Anne-Hélène GICQUEL**[(3)]

[(1)] *Tel. (+33) (0)5 62 19 74 27, E-mail. francois.bonaventure@astrium.eads.net*
[(2)] *Tel. (+33) (0)5 62 19 90 51, E-mail. slim.locoche@astrium.eads.net*
[(3)] *Tel. (+33) (0)5 62 19 66 99, E-mail. anne-helene.gicquel@astrium.eads.net*
[(all)] *Astrium Satellites, 31 rue des Cosmonautes, F-31402 TOULOUSE CEDEX 4*

Abstract: *Spirale mission consisted of two micro-satellites on a Geostationary Transfer Orbit, operated by Astrium Satellites for DGA, the French DoD. In accordance to the IADC recommendations and the French Space Act, de-orbitation operations were conducted once the 2-year mission was completed. Two maneuvers were performed on each satellite to lower the perigee down to an altitude of 220 km. It was sufficient to ensure an uncontrolled re-entry in less than 25 years with a probability of 90%, better than the 50% minimum required in the French Space Act. The probability is 90% and not 100% because it is quite impossible to accurately predict the re-entry time of GTO orbits: in some conditions a Sun-synchronous resonance can occur with a dramatic increase in the altitude of the perigee that could lead to a significant extension of the orbital lifetime. Furthermore the risks of collision with the International Space Station have been taken into account during operations, as well as collisions with geostationary spacecrafts. The short evolution of the orbital parameters of the satellites after passivation is also presented, showing that SPIRALE-A will reach the Sun-synchronous domain in less than one year.*

Keywords: *Geostationary Transfer Orbit, GTO, de-orbitation, orbital resonance, micro-satellites, debris*

1. Introduction

SPIRALE was a demonstrator operated by Astrium Satellites for the French DoD (DGA). Its mission was to collect infrared images of the Earth for the design of an Early Warning system. It consisted of two micro-satellites launched on February 12 2009 as secondary payload by an Ariane-5 ECA launcher on a GTO orbit, together with two GEO commercial telecommunication satellites. Their mission orbit was a GTO with a 600 km perigee altitude to reduce air drag effects. To reach this mission orbit, maneuvers have been performed with each satellite to raise the perigee altitude from 250 to 600 km, SPIRALE-A and SPIRALE-B sharing the same orbit with a time separation of 30 ±5 minutes (Fig. 1).

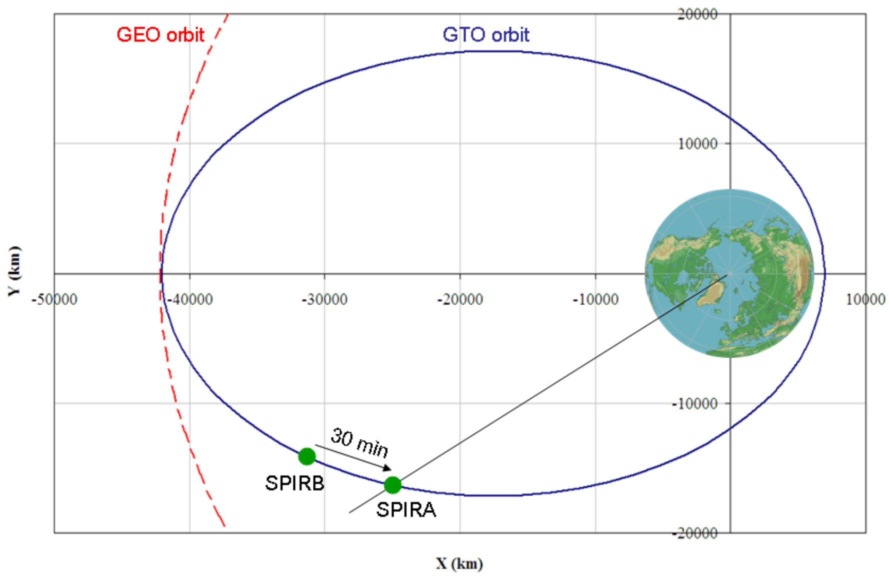

Figure 1. SPIRALE-A and SPIRALE-B spacecrafts share the same GTO orbit

After nearly two years of mission, the mission goals were achieved. De-orbitation mission analysis had been performed to determine the maneuvers to be performed to ensure a re-entry on Earth within 25 years. However it quickly appeared that the re-entry time was very sensitive to simulation hypotheses. In particular few variations of the drag coefficient could lead to huge differences, between 2 and 28 years for SPIRALE-A for example, with no obvious relationship between the drag level and the re-entry duration. This is due to a *Sun-synchronous resonance* effect caused by the Sun gravity and specific to elliptic orbits. In very particular conditions, this resonance could lead to a significant natural rising of perigee altitude over a long period of time. The conditions of the resonance are quite unpredictable but still exceptional so re-entry in less than 25 years is ensured with a probability better than 90% for SPIRALE satellites.

The initial maneuver plan was not applied due to last-minute operational constraints, and SPIRALE-A was fully de-orbited and passivated before SPIRALE-B, leading to a crossing of the spacecrafts due to the difference of their orbital periods. However separation between the two orbits was ensured up to a minimum distance of 70 km at time of closest approach.

The last maneuver for each satellite has been performed up to full propellant depletion, in order to minimize the residual pressure in the tanks. The final perigee altitudes were lower than 230 km, better than the 250 km nominally targeted. The collision avoidance aspects with the ISS and the GEO belt were also taken into account during the operations.

2. SPIRALE context

The two satellites have been launched with an Ariane-5 on a GTO orbit. On this orbit, the apogee reaches the GEO altitude whereas the perigee is around 250 km. Thus the instrument can be fully tested at GEO altitude, and observations performed on the lower parts of the orbit are corrected by a scale factor. It was however necessary to increase the perigee altitude to reduce the disturbing torques due to air drag effect at low altitude, thus allowing the use of Normal Mode (attitude controlled without the thrusters). This perigee rising from 250 km to 600 km has been achieved during the LEOP phase with very few propellant (~2 kg). Inclination of separation orbit was about 2 degrees (near-equatorial orbit) and did not require any correction for the mission.

CNES Myriade micro-satellite platform was initially designed for LEO orbits (Fig. 2). The satellite's dimensions and mass are consistent with Arianespace's specifications for secondary payloads on GTO launches. The propellant tank contains 4.7 kg of propellant, enough to achieve perigee rising, station-keeping activities and de-orbitation operations. The mission was based on two micro-satellites - SPIRALE-A and SPIRALE-B - to provide additional redundancy and allow stereo observations. Nevertheless it is worth noticing that after 2 years of crossing the Van Allen belts the spacecrafts were still fully functional.

Figure 2. SPIRALE satellites are based on CNES Myriade platform

3. De-orbitation studies

The mission of the demonstrator has been completed in 20 months. To comply with the French Space Act (French extension of the end-of-life IADC recommendations), the operator shall not leave the two spacecrafts unattended on their mission orbit if they cross altitudes lower than 2000 km or altitudes GEO ± 200 km. The aim of the de-orbitation analysis was to design an orbital maneuver plan in order to ensure that the two spacecrafts will perform a re-entry on Earth in less than 25 years with a probability of at least 50 %.

3.1. Orbital maneuvers

The maneuver plan consisted in deltaVs performed at the apogee in order to lower the perigee altitude. Then air drag at each perigee pass naturally lowers the apogee altitude and thus of the semi-major axis of the orbit, leading to a natural re-entry of the satellites on Earth.
With the estimate of the remaining propellant mass of 2.33 kg for SPIRALE-A and 2.30 kg for SPIRALE-B, it was possible to target 250 km for the altitude of both spacecraft perigees. For each satellite the required deltaV of 41 m/s was achieved in two burns at the apogee. The first burn was designed to reach the perigee altitude of 400 km. At this altitude, the satellite control was still possible in Normal Mode as air drag disturbing torques can be balanced with the reaction wheels only, without the need of thruster pulses. Then the final burn was intended to be performed up to full propellant depletion, immediately followed by the passivation of the spacecraft.

As the two satellites shared the same orbit, it was necessary to take into account collision issues that could appear if the de-orbitation maneuvers were not synchronized. As SPIRALE-B was 34 minutes behind SPIRALE-A at the beginning of the operations, it was decided to increase this gap by starting the first burn with SPIRALE-A and then alternate the maneuvers between the two spacecrafts, so as to obtain a 65 minutes separation after all maneuvers being performed (Fig. 3).

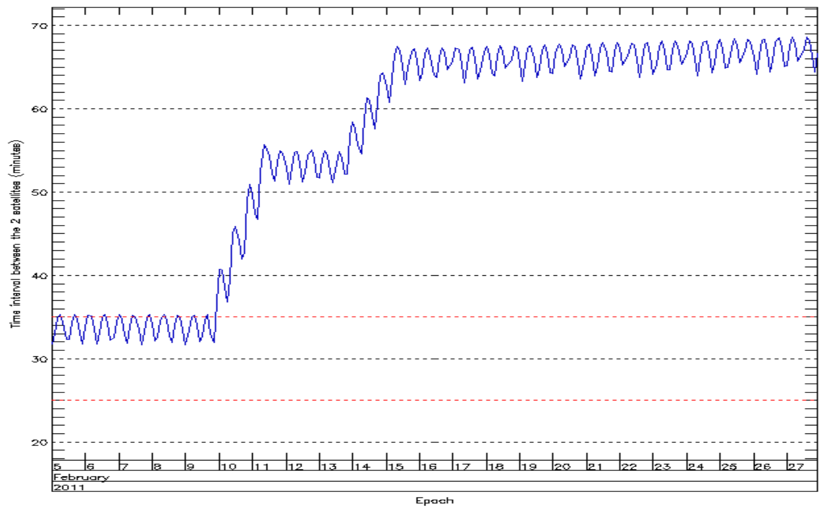

Figure 3. Time separation between the two satellites during de-orbitation operations, as planned in mission analysis

3.2. Re-entry duration

The targeted 250 km perigee altitude is low enough to ensure a noticeable air-drag braking effect at each perigee pass. As a result the apogee altitude decreases and the orbit becomes more and more circular as eccentricity tends towards zero. Simulations have been performed to estimate the de-orbitation duration, taking into account realistic hypotheses for satellite and environment modeling.

3.2.1. Hypotheses

The operations were supposed to take place between the end of 2008 and the beginning of 2009. At this time, CNES STELA tool was not available for GTO orbits. STELA is dedicated to de-orbitation analysis and is the reference tool to be used in the frame of the French Space Act to demonstrate that the spacecrafts will perform their re-entry in less than 25 years. For SPIRALE, the re-entry duration analyses have thus been performed with our internal numerical orbit propagator using the following models:

- Earth potential 36x36 (Eigen GL-04C)
- Third body perturbation of Sun and Moon
- Solar Radiation Pressure (SRP)
- Atmospheric density (NRLMSIS-00)

To estimate the solar activity in the future, the measurements of the three last solar cycles were considered (F10.7 and Ap coefficients from 1976 to 2008) and then repeated from 2009 up to 2096 (Fig. 4).

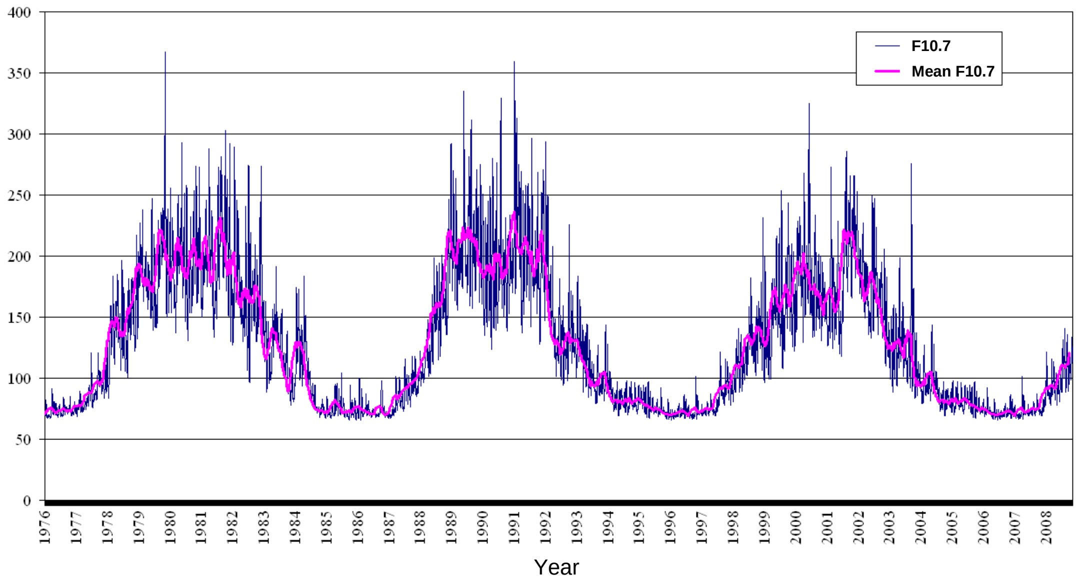

Figure 4. Evolution of the solar flux coefficient F10.7 between 1976 and 2008

A drag coefficient C_d of 2.2 was considered which is the value generally agreed for altitudes lower than 400 km. Nevertheless, dispersions on this coefficient have been taken into account in the simulations.

For the mean surface computation, the SPIRALE satellites can be considered as:

- A parallelepiped central body which surface is $S_1 \times S_2 \times S_3$
- A solar array which surface is S_{SA}

The mean geometric surface is then computed with the equation $S_{Mean} = \frac{1}{2}\left(\sum_{i=1}^{3} S_i + S_{SA}\right)$.

To take into account the uncertainties on the mean surface and the drag coefficient, simulations have been performed using ±20% variations on the drag ratio $\frac{C_d \cdot S_{Mean}}{M_{sat}}$ where M_{sat} is the spacecraft mass.

Orbits taken into account in the following chapter are the final orbits achieved after real operations and not the theoretical ones considered in the initial mission analysis. They have been updated after the passivation of the spacecrafts as the achieved perigee altitude was lower than 250 km for both satellites (respectively 216 km and 228 km).

3.2.2. Simulation results

Simulations performed to estimate the de-orbitation duration showed unexpected results. Usually when the drag ratio increases, the re-entry duration is getting shorter due to higher drag effect. We instead observed very local variations of the re-entry duration that did not seem to be directly correlated to the drag ratio (Fig. 5).

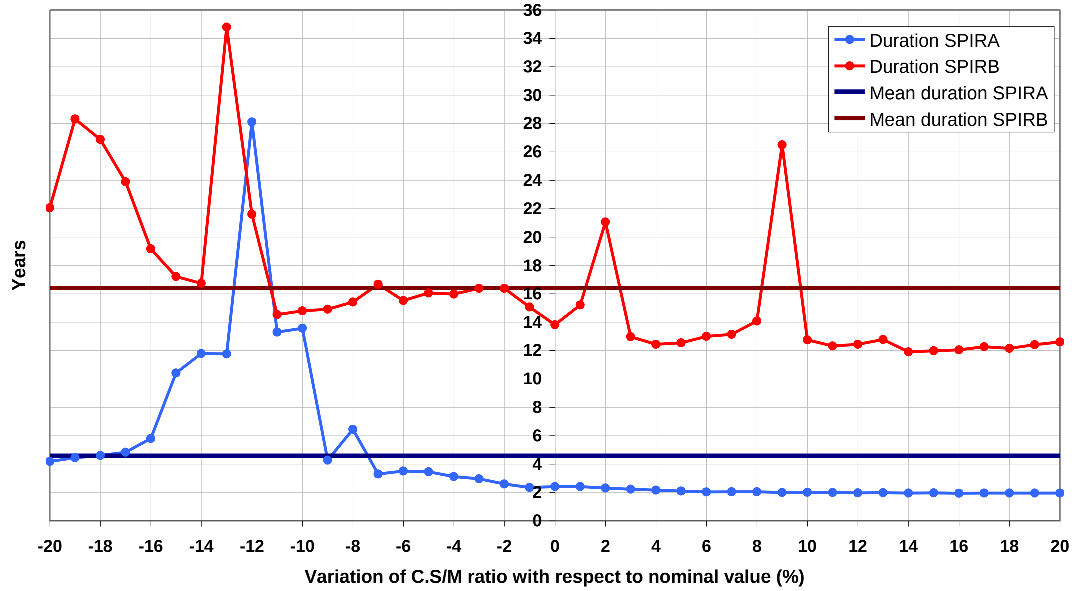

Figure 5. Estimates of re-entry durations with respect to drag ratio variations

Nominal re-entry durations (corresponding to 0% variation in Fig. 5) are 2.4 years for SPIRALE-A and 13.8 years for SPIRALE-B. However, dispersions around this value appear to be very large even for variations of drag ratio as small as ±20%:

- For SPIRALE-A: 2 < re-entry duration < 28 years (mean value = 4.6 years)
- For SPIRALE-B: 12 < re-entry duration < 35 years (mean value = 16.4 years)

3.2.3. Sun-synchronous resonance

An explanation of this behavior is described in this section. For objects deorbited from GTO as SPIRALE satellites, air drag effect is only effective near the perigee, so the variations of the drag effects are caused by the variations of the perigee altitude.

The secular drift of the line of apsides is mainly due to the J_2 term of the Earth potential (Eq. 1).

$$\left.\frac{d(\Omega+\omega)}{dt}\right|_{sec} = \frac{3}{2} J_2 \left(\frac{R_E}{a}\right)^2 \frac{n}{\left(1-e^2\right)^2} \cdot \cos i \qquad (1)$$

with R_E = Earth radius, a = semi-major axis, n = mean motion, e = eccentricity, i = inclination, Ω = RAAN, ω = argument of perigee

Inclination of SPIRALE orbit varies between 0 and 3 degrees and the cos i term can be considered as equal to 1.
Thus the drift only depends on the semi-major axis and the eccentricity, and the Sun-synchronous condition is met when $\left.\frac{d(\Omega+\omega)}{dt}\right|_{sec} \approx 0.986$ deg/day, that is:

$$a\left(1-e^2\right)^{4/7} \approx 12344\ km \tag{2}$$

Equations 1 & 2 show that at the beginning of the re-entry phase, the Sun has an apparent motion anti-clockwise around the orbit: $\dot{\alpha} > 0$ where α is the right ascension of the Sun in the orbital plane, with respect to the line of apsides. As the semi-major axis continues to decrease the Sun-synchronous condition is met and the Sun is fixed with respect to the orbit: $\dot{\alpha} = 0$. Then the apparent motion of the Sun becomes clockwise around the orbit: $\dot{\alpha} < 0$ (Fig. 6).

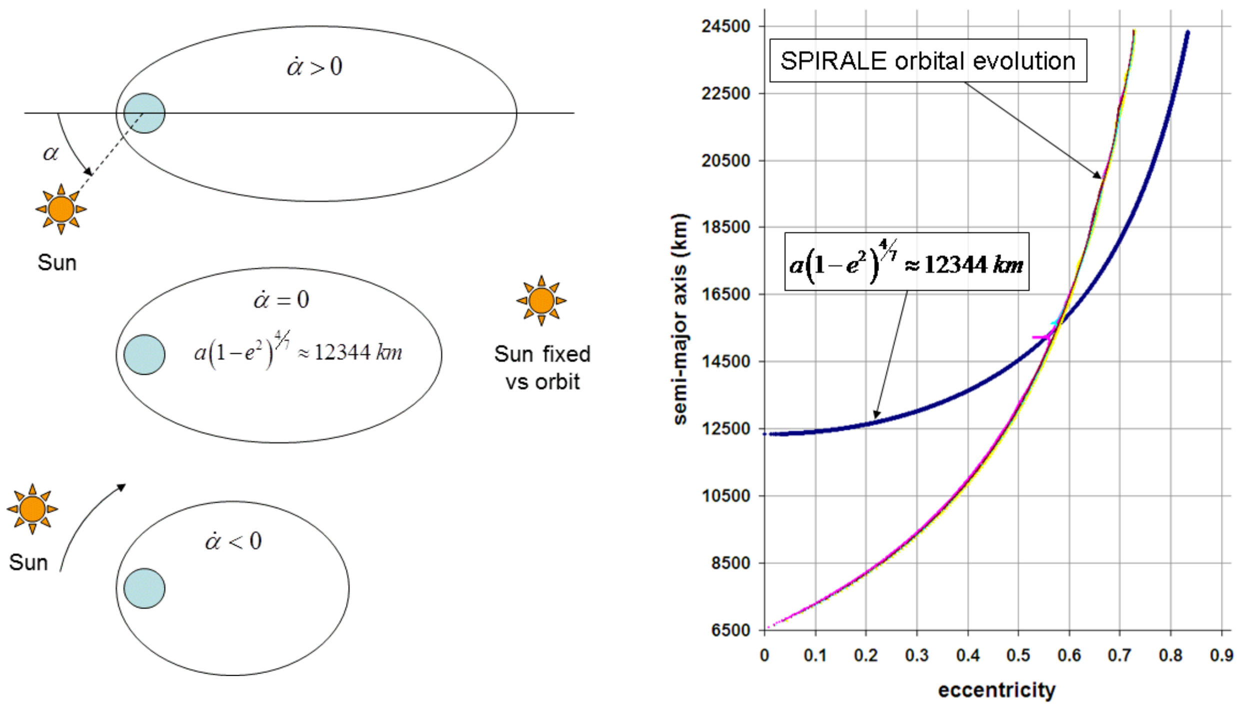

Figure 6. As the apogee altitude decreases, SPIRALE orbit meets Sun-synchronous resonance conditions

Now we can study the effect of the Sun right ascension α on the altitude of the perigee. If we consider only the Sun effect on the orbit without the drag one, the semi-major axis remains constant because gravitational attraction is a conservative force and induces no secular or long term variations.

However it has impacts on the eccentricity and the integration of the Gauss-Lagrange equations shows that eccentricity variation depends on the value of α (Fig. 7).

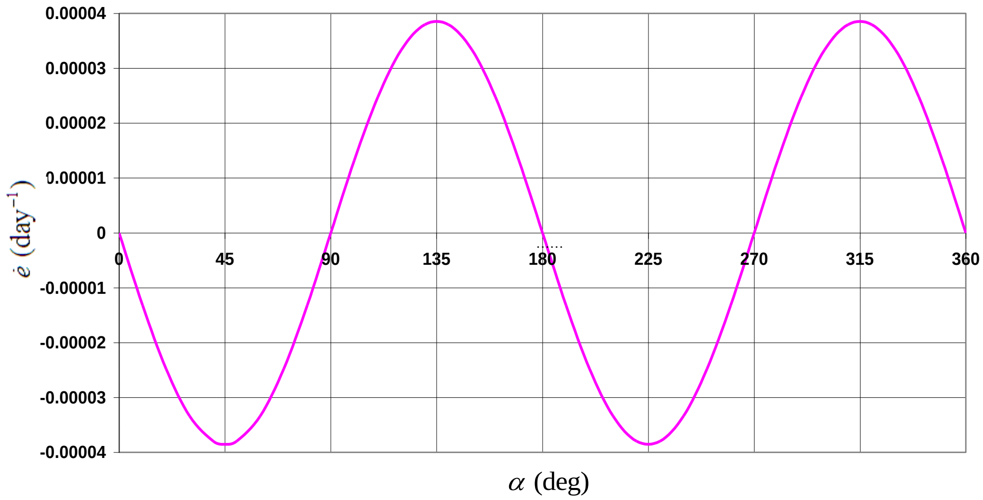

Figure 7. Eccentricity variation depends on the right ascension of the Sun

The altitude of the perigee is defined by the equation $h_p = a(1-e) - R_E$. With a constant semi-major axis, a negative variation of the eccentricity leads to an increase in the altitude of the perigee, and vice versa. Thus we can see that some positions of the Sun favour de-orbitation, namely α=135 deg or α=315 deg which produce a decrease in the altitude of the perigee, while some others lead to a longer re-entry duration (for α=45 deg or α=225 deg). Figure 8 represents the variation of the perigee altitude for different configurations of the Sun versus the orbit. Altitude of the perigee increases in red zones (quadrants 1 and 3) and decreases in blue ones (quadrants 2 and 4).

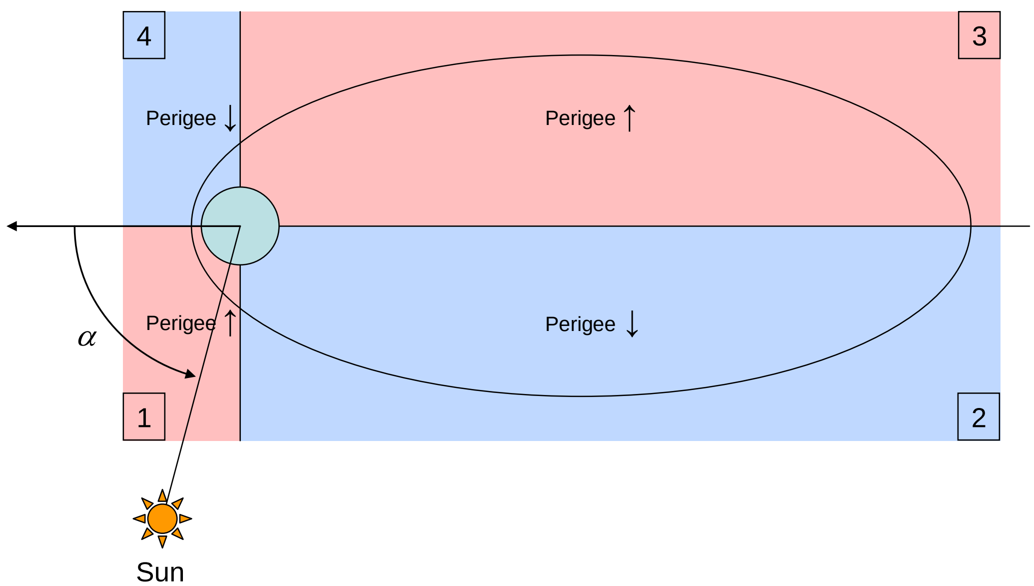

Figure 8. Variation of the perigee altitude depends on the right ascension of the Sun

This explains why, during orbit erosion, when the values of the semi-major axis and the eccentricity reach the Sun-synchronous condition (Eq. 2) and at the same time the right ascension of the Sun is in quadrants 1 or 3, *the altitude of the perigee increases*. Indeed, in these conditions, the drag effect on the orbit decreases and the semi-major axis remains constant. This is an example of what we called *Sun-synchronous resonance*: the semi-major axis is constant and eccentricity varies slowly when the altitude of the perigee increases, so the Sun-synchronous condition remains valid for a long time and the Sun stays in the same quadrant. On SPIRALE orbits, the perigee altitude may deviate up to +600 km from its nominal mean value! Figure 9 and 10 illustrate this behavior by showing the evolution of SPIRALE-A parameters with and without resonance. SPIRALE-B figures are presented in annex.

Figure 9. SPIRALE-A : Evolution of the perigee altitude for different values of drag ratio

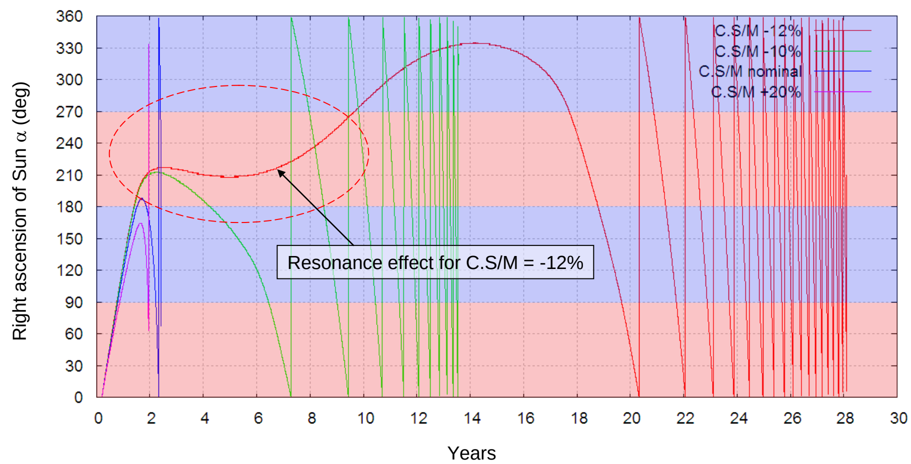

Figure 10. SPIRALE-A : Evolution of the right ascension of Sun for different values of drag ratio

In Fig. 10 the red zones correspond to right ascensions of Sun for which the altitude of the perigee increases, in the blue ones the perigee decreases. On both figures the red curves represent the resonance already observed in Fig. 5 for SPIRALE-A for a variation of -12% of the drag ratio. During the rising of the perigee from 200 to ~800 km, we can observe that the right ascension of the Sun remains between 180 and 270 degrees, in the red zone. Then as eccentricity shifts slowly the α angle reaches the blue zone (270 < α < 360 deg) and the perigee decreases.

4. Operations

The initial maneuver plan intended to alternate the maneuvers between SPIRALE-A and SPIRALE-B in order to maintain a limited separation between the two spacecrafts (see §3.1). But last minute constraints did not allow the operation team to follow the nominal schedule. First the main ground station was requested for the ATV2 operations, and second the SPIRALE-B mission has been slightly extended just before the start of the operations. SPIRALE-A has thus been fully de-orbited and passivated before SPIRALE-B.
A first set of maneuvers were performed to decrease the perigee of each satellite down to 400 km. A second set of maneuvers were performed to further decrease the perigee up to full propellant depletion, so minimizing the residual pressure in the tanks. The propellant mass available for de-orbitation maneuvers was a little bit larger than the estimation for both satellites, and the final perigee altitude was below 230 km for a targeted altitude of 250 km.
A synthesis of the maneuvers performed during the end-of-life operations is given in Tab. 1.

Table 1. Orbital maneuver synthesis

SPIRA	Orbit #	Commanded deltaV (m/s)	Observed deltaV (m/s)	Efficiency (%)	Perigee altitude (km)	Used propellant (kg)	Remaining propellant (kg)
OCM1	1637	25.09	24.83	-1.0%	401.4	1.491	0.843 (1)
OCM2	1677	12.3 (1)	17.67	43.7%	216.6	1.090	~0

SPIRB	Orbit #	Commanded deltaV (m/s)	Observed deltaV (m/s)	Efficiency (%)	Perigee altitude (km)	Used propellant (kg)	Remaining propellant (kg)
OCM1	1736	22.02	21.66	-1.6%	403.8	1.299	1.000 (1)
OCM2	1756	15.2 (1)	17.95	18.1%	228	1.067	~0

(1) nominal propellant budget

The final orbits after passivation are presented in Tab. 2. They are expressed at the end of the operations, on April 1st 2011:

Table 2. Mean orbits reached after passivation, on April 1st 2011

	SPIRALE-A	SPIRALE-B
Altitude at apogee (km)	35515	35721
Altitude at perigee (km)	185	224
Mean orbital period	10h25m10s	10h29m55s

The evolution of the perigee altitudes for both satellites is presented in Fig. 11. We can notice short term periodic variations due to the Moon potential (amplitude ~8 km), and long term periodic ones due to the Sun potential (amplitude ~100 km). SPIRALE-A perigee has reached an altitude of 130 km in June, which is very low and induces high levels of air drag.

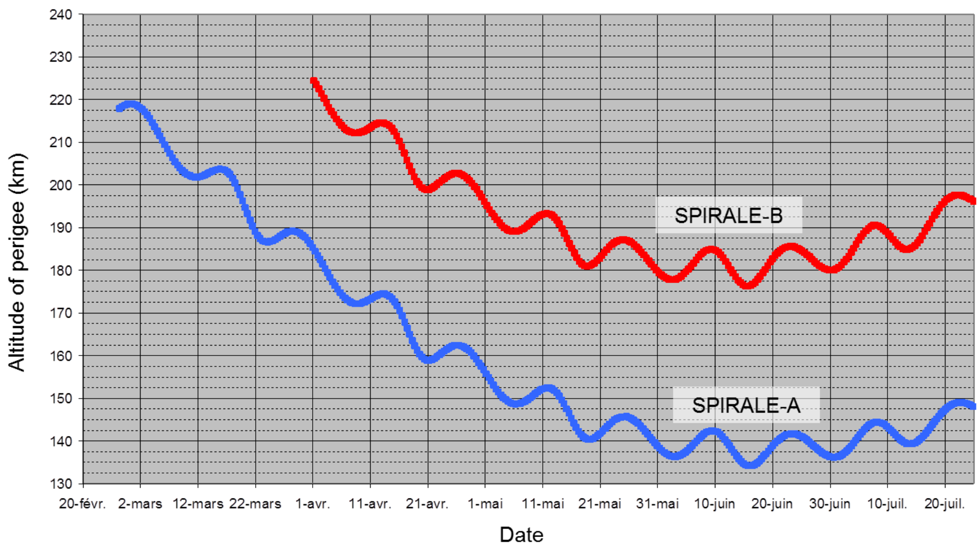

Figure 11. Evolution of SPIRALE perigee altitudes after passivation

Once the two maneuvers have been performed, SPIRALE-A period was 10 minutes smaller than SPIRALE-B one. So SPIRALE-A first drifted away from SPIRALE-B, then got closer after half an orbit and crossed SPIRALE-B position before its second maneuver.
The nominal crossing distance was 180 km (without deviation), and a minimal normal separation of 70 km was ensured thanks to the small inclination difference between the orbits of the two spacecrafts (Fig. 12). A global plot is also available in Annex (Fig. 12bis).

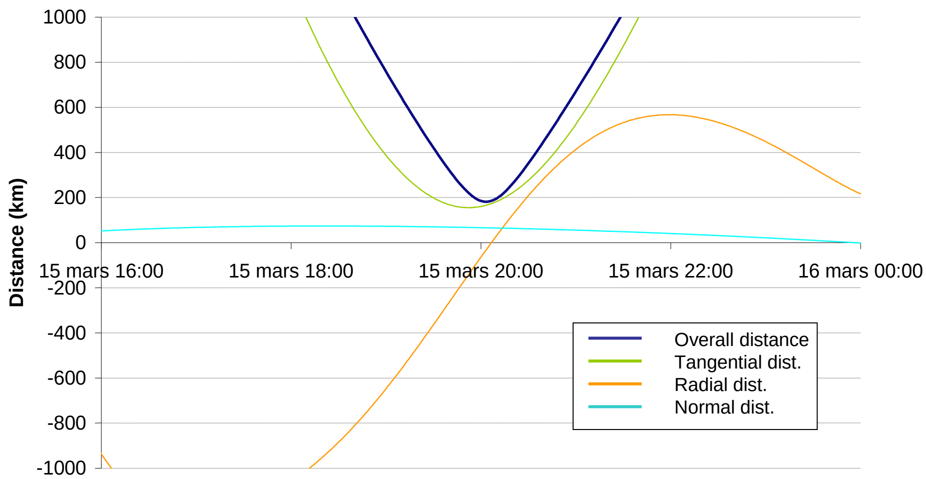

Figure 12. Minimum distance at crossing time

As the perigee of both spacecrafts was below the altitude of the International Space Station (ISS) (350 to 400 km), we had to ensure that there was no risk of collision with the ISS. SPIRALE orbits presented an inclination near to zero while the ISS one is about 51 degrees. Potential risks of collision could then only occur near the orbital nodes of the ISS. At the end of the operations the right ascension of ascending node (RAAN) of the ISS was about 93 deg. It was then sufficient to compute the altitude of the SPIRALE satellites near the nodes to predict any collision risk.

The true anomaly and the altitudes of the spacecrafts near these nodes were:

- At ISS ascending node : $\upsilon_{asc} \approx \Omega_{ISS} - (\Omega + \omega)_{SPIR} \approx 63.5 \text{ deg}$

  $h_{asc} \approx 2276 \text{ km}$
- At ISS descending node : $\upsilon_{des} \approx \Omega_{ISS} + 180 - (\Omega + \omega)_{SPIR} \approx 243.5 \text{ deg}$

  $h_{des} \approx 10592 \text{ km}$

The altitude of the two spacecrafts was then well above the ISS mean altitude, as shown also on Fig. 13.

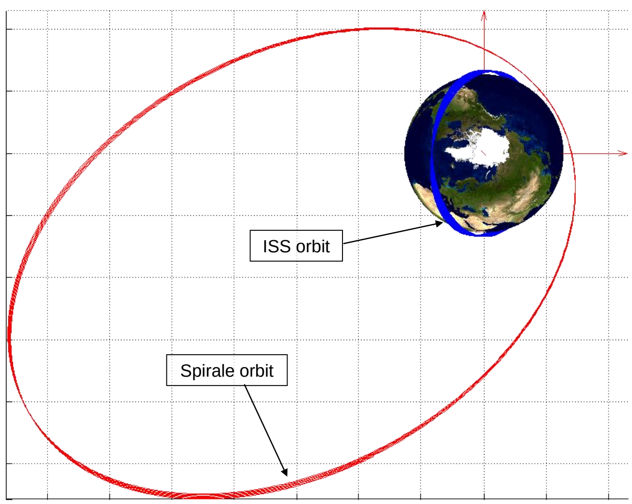

Figure 13. Orbits of the ISS and SPIRALE for 3 days after passivation, projected on the equatorial plane

Concerning the risk of collision with GEO satellites, French Space Act requires to quit the restricted GEO zone (altitude GEO ±200 km) in less than one year after passivation. At the beginning of the de-orbitation operations, the altitude of the apogees was :

- SPIRALE-A: h_{apo} = GEO – 97 km
- SPIRALE-B: h_{apo} = GEO – 66 km

Thus the initial risks of collision were already very low as operational GEO satellites are usually maintained in a GEO ±40 to 60 km radial window.

As soon as the perigee of the orbits was decreased, air drag effect started to lower the apogee at each perigee pass and SPIRALE-A went out of the restricted zone on March 23, 26 days only after its passivation, and Spirale-B on April 29, 28 days after its passivation (Fig. 14).

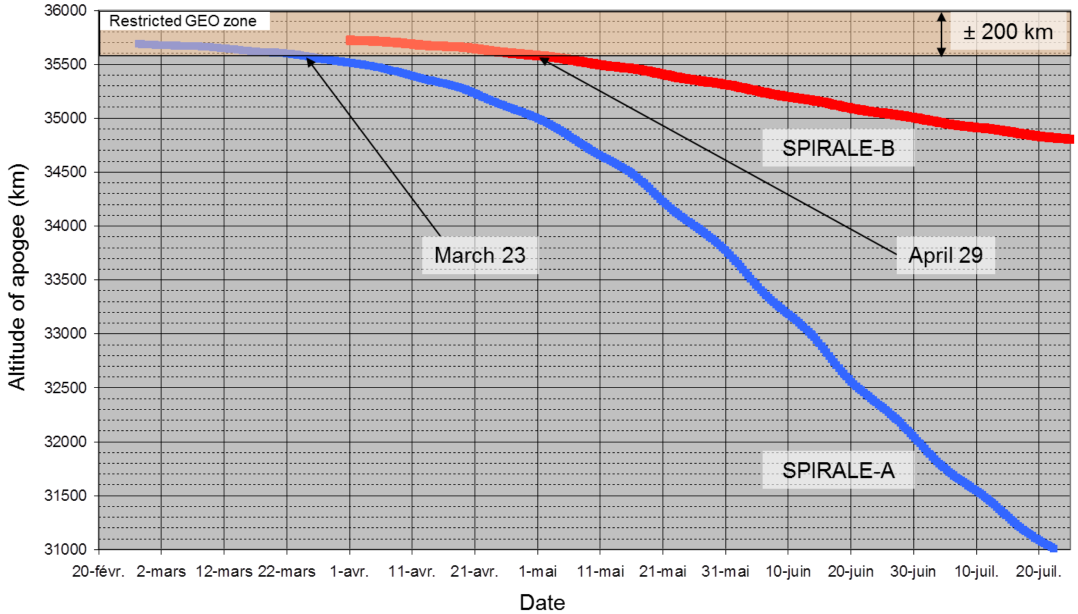

Figure 14. Evolution of SPIRALE apogees with respect to the restricted GEO zone

5. Further activities

One year and a half after the end of the operations, and thanks to the JSpOC public catalog of TLE, we have access to the cumulative orbital bulletins of both SPIRALE satellites. A snapshot of the orbital status of SPIRALE-A is presented in Fig. 15. The data cover the period from de-orbitation up to the end of September 2012.

The upper left graph represents the evolution of semi-major axis versus eccentricity, to be compared to Fig. 6. SPIRALE-A does not yet meet the Sun-synchronous resonance condition but this will occur in less than one year. However it is too early to know if the resonance will extend the lifetime or not.

The upper right plot presents the Sun right ascension. Perigee increases on red parts and decreases on blue ones (refer to Fig. 8 for explanations).

The lower left graph plots the evolution of the perigee altitude. We can notice that altitude evolution is consistent with the Sun right ascension plot. The perigee is now back to very low altitudes (160 km) and will soon start to rise again as Sun right ascension will pass 180 deg.

The lower right plot represents the evolution of the apogee altitude. We can observe that SPIRALE-A apogee has dropped by more than 10000 km in 19 months. The slope of the curve also reflects the evolution of the perigee, slowing the way down when the perigee is rising.

SPIRALE-B graph can be found in Annex. It is far from resonance criteria at present time.

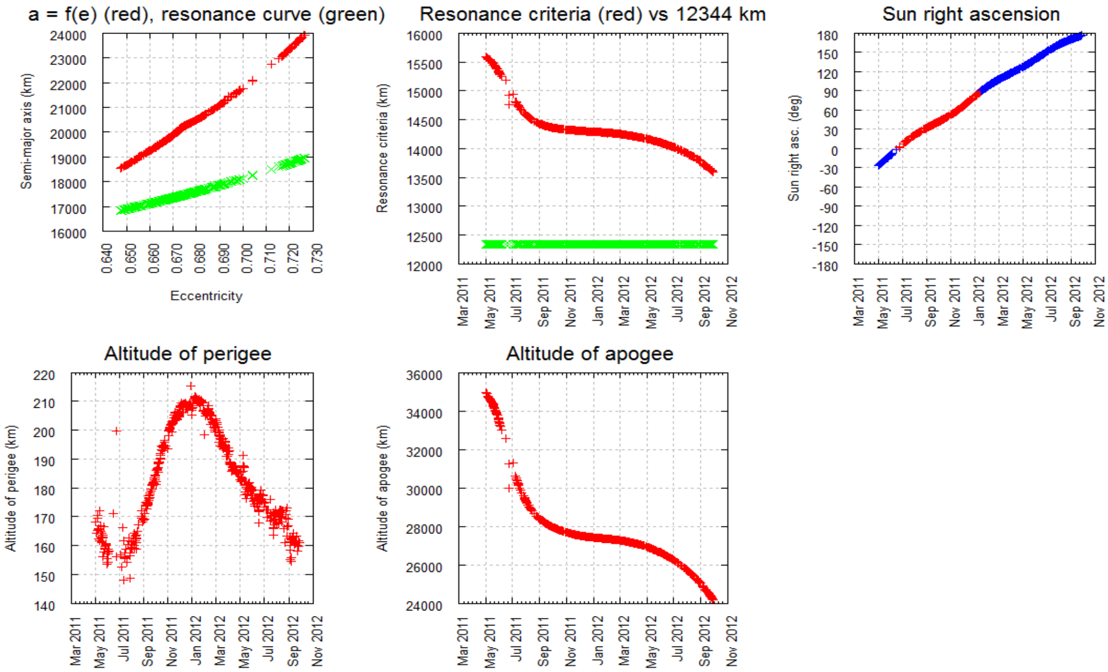

Figure 15. SPIRALE-A orbital status 19 months after passivation

6. Conclusion

The free evolution of geostationary transfer orbits with low perigee altitude (200-400 km) is difficult to predict as well as the resulting duration up to the satellite re-entry. Air drag effect at each perigee pass usually produces a decrease in the altitude of the apogee. However for some conditions between semi-major axis and eccentricity, a so-called *Sun-synchronous resonance* can be observed, when the Sun right ascension remains fixed with respect to the orbit's line of apsides. Then, the Sun gravitational effects produce a variation of the orbit's eccentricity that can lead to a dramatic increase in the perigee altitude by several hundreds of kilometers which could last for up to 20 years, then reducing the drag effects and stopping the semi-major axis evolution and the de-orbitation of the satellite.

This resonance is quite unpredictable because a variation of only one percent in the drag hypothesis can cause (or prevent from) the resonance, while predictions of solar activity are far from this accuracy.

SPIRALE satellites were the first French objects de-orbited after the implementation of the French Space Act. Risks of collision with the ISS were completely mitigated during the operations, and the GEO belt was left in less than one month after passivation.

The probability for the spacecrafts to fall on Earth in less than 25 years is greater than 90% despite the possible Sun-synchronous resonance, as shown in Tab. 3. Thus the SPIRALE de-orbitation was fully compliant with the French Space Act and the IADC recommendations.

Table 3. Re-entry durations

Re-entry duration (year)	SPIRALE-A	SPIRALE-B
Nominal C.S/M	2.4	13.8
Minimum duration	2.0	12.0
Mean duration	4.6	16.4
Maximum duration	28	35
% durations < 25 years	98%	92%

7. References

[1] F. Bonaventure, S. Locoche, “SPIRALE de-orbitation mission analysis” SPI.TCN.03065.T.ASTR (Astrium internal study), Astrium Satellites Toulouse, France, October 2010.

[2] F. Bonaventure, “De-orbitation of SPIRALE GTO satellites”, Proceedings CNES Synthesis Group on Space Debris. CNES Toulouse, France, June 2011.

[3] A. Lamy, C. Le Fevre, B. Sarli, “Analysis of geostationary transfer orbit long term evolution and lifetime”, Proceedings 22th International Symposium on Space Flight Dynamics (ISSFD), Sao Jose dos Campos, Brazil, March 2011.

8. Annex

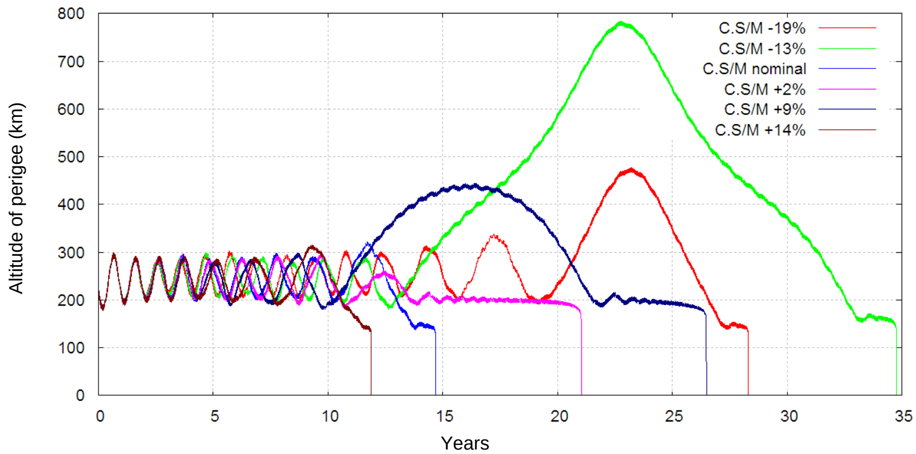

Figure 9bis. SPIRALE-B : Evolution of the perigee altitude for different values of drag ratio

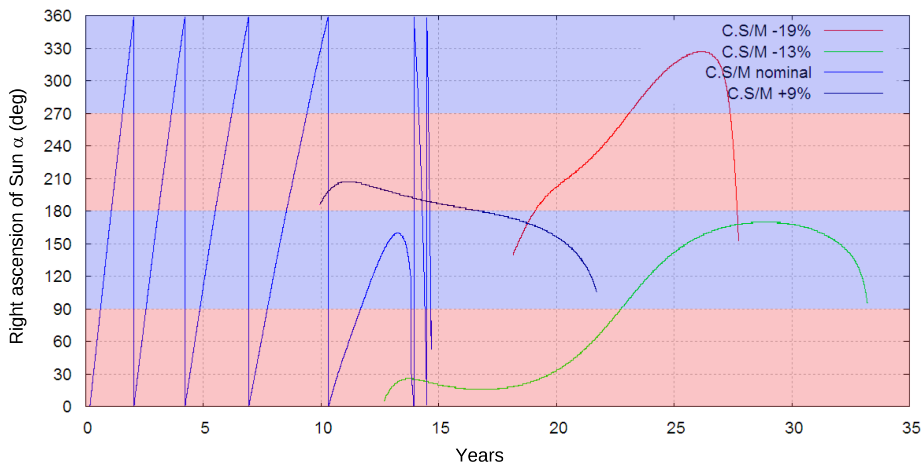

Figure 10bis. SPIRALE-B : Evolution of the right ascension of Sun for different values of drag ratio

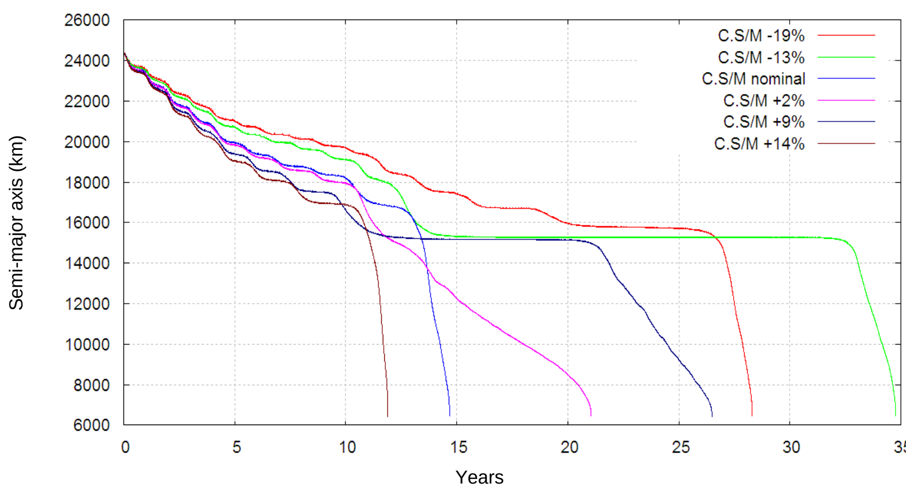

Figure 10ter. SPIRALE-B : Evolution of the semi-major axis for different values of drag ratio

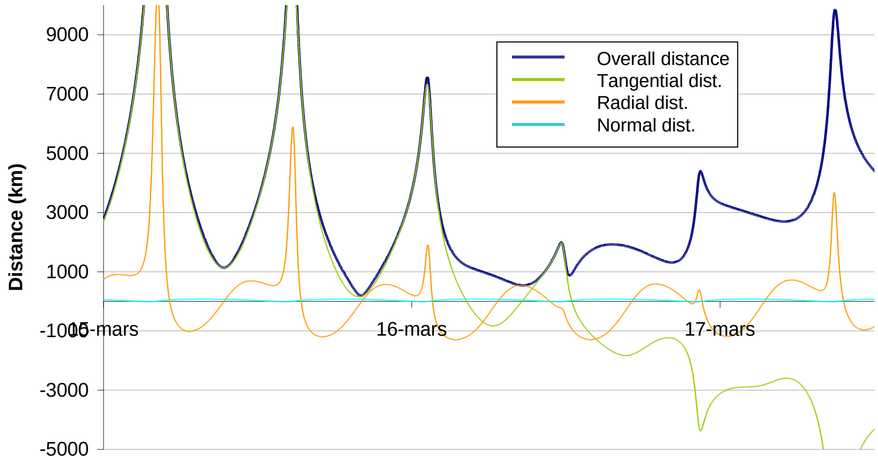

Figure 12bis. Minimum distance at crossing time SPIRALE-A - SPIRALE-B

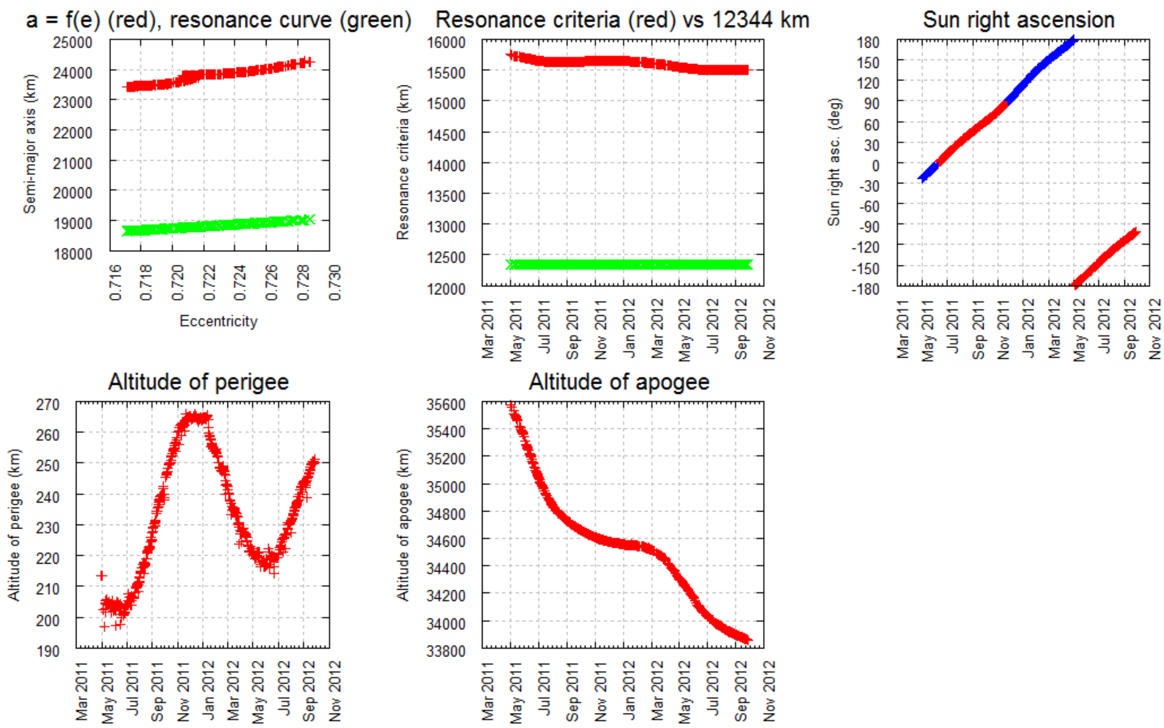

Figure 15bis. SPIRALE-B orbital status 18 months after passivation