END OF LIFE OPERATIONS FOR LEO AND GEO SATELLITES : 30 YEARS OF CONTINUOUS IMPROVEMENT

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ABSTRACT

CNES is celebrating in 2013 its 40th year of satellites operations with nearly 40 satellites cared for from Symphony 1 (1973) to Pleiades 1B (2012). Half of them reached its end of mission.

Although they were not designed for it, CNES imagined, prepared and executed end-of life operations for geostationary and low earth orbit satellites, in accordance with its strong involvement at international level in favour of space activity sustainability and space debris mitigation.

With increasing experience, efficiency and completeness of operations have strongly improved : optimization of resources, precise orbit and eccentricity management, collision risk concern, controlled fluidic and electric passivation, concern for degraded or emergency cases…

This paper presents the evolution and improvement of end of life operations handled by CNES for 30 years, with a highlight on the last evolutions in the whole process since the French Space Act came into force.

1 GEOSTATIONARY SATELLITES

1.1 Introduction

CNES experience with satellite on-orbit operations first started nearly 40 years ago with the German and French program of experimental geostationary satellites for telecommunication : Symphonie 1 and 2, launched in 1974 and 1975. Other telecommunication programs followed : TDF, TELECOM 1 and TELECOM 2, and a total of leven geostationary satellites have been operated by CNES.

All of them have now reached their end of mission : from 1984 for Symphony 1 to end of 2012 for Telecom 2D, and CNES performed for each one some end-of-life operations. Table 1 summarizes the main disposal results:

Table 1: CNES geostationary satellite disposal results

Satellite	Launch date Disposal date	Reached Lifetime	Altitude / GEO	Tank depressur.
Symphonie 1	12/19/1974 Aug - 1983	8.7 years	+ 60 km	
Symphonie 2	08/27/1975 Dec - 1984	9.3 years	+ 60 km	
Telecom 1A	08/04/1984 Apr - 1992	7.7 years	+ 375 km	
Telecom 1B	05/08/1985 Jan - 1988	2.5 years	0 km	Failure
Telecom 1C	03/11/1998 Feb - 1996	7.25 years	+ 250 km	
TDF 1	10/28/1988 Oct - 1996	8 years	+ 280 km	Yes
TDF 2	07/25/1990 May - 1999	8.8.years	+ 270 km	Yes
Telecom 2A	12/16/1991 Oct - 2005	13.8 years	+345 km	Yes
Telecom 2B	04/15/1992 Jun - 2004	12.2 years	+ 185 km	Degraded case in EOL
Telecom 2C	12/06/1995 Oct - 2009	14.7 years	+575km	Yes
Telecom 2D	08/08/1996 Nov - 2012	16.75 years	+ 455 km	Yes

Telecom 1B suffered a major failure concerning the propulsion subsystem : thrusters could not be use anymore and the satellite had thus to be abandoned on the geostationary orbit. Except from that case, all satellites were reorbited at their end of mission.

From Symphonie 1 to Telecom 2D, disposal operations became more complex, complete, studied, prepared and qualified in advance, together with an increasing concern about leaving this unique and most valuable geostationary orbit available for the future generations.

1.2 SYMPHONIE 1 & 2 : free the GEO orbit

Symphonie 1 and 2, German - French program, were the first European geostationary satellites. They were successfully controlled on orbit during nine years, form 1974 to 1984. At the end of their mission, long before any international recommendation was issued, it was decided to remove the satellites from the geostationary orbit. The aim was to protect future satellite operating on geostationary orbit from any risk of collision with the Symphonie satellite.

Since the nominal altitude of a controlled satellite typically varies from – 40 to + 40 km around GEO altitude (mainly due to eccentricity), it was considered

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that the minimum altitude after end of life manoeuvres should not be lower than + 50 km above GEO. Taking natural eccentricity into account, this required a semi major axis increase of + 90 km.

The approach here was very similar to IADC one, with a smaller "protected region" since it only considered an operational geostationary ring and did not take into account the +/- 200 km region which can be used by operational satellites for longitude drift phases.

Two long East manoeuvres were therefore executed, and the target was successfully achieved : Figure 1 shows Symphonie 1 altitude evolution above geostationary altitude since re-orbitation manoeuvres, according to the public NORAD historic data available for this satellite.

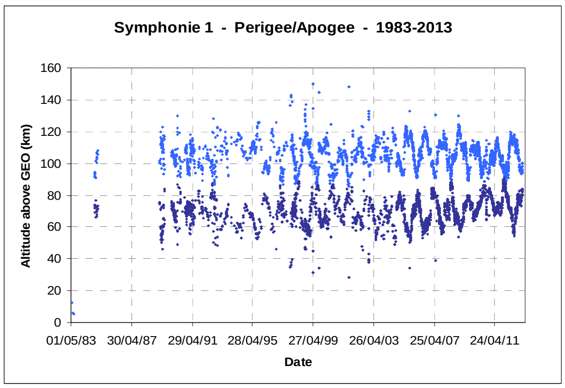

Figure 1: Symphonie 1 altitude above GEO since EOL

It can be seen that the desired protected region of +/- 40 km has been perfectly preserved for now 30 years. The result is quite similar for Symphonie 2.

Transmitters were switched off so that there would be no interference with future satellites.

At that time, although the major part of remaining propellant was used for these disposal manoeuvres, there was no tentative to empty the tank : attitude control was performed by thrusters and the satellite control had to be maintained nominally in station-keeping mode until the last telecommand was sent.

1.3 TELECOM 1 : + 200 km

Telecom 1 A, B and C were French satellites with both civilian and defence telecommunication payloads. They were operated from 1984 to 1996. TC1B had unfortunately a small lifetime and had to be left on the orbit. TC1A and TC1C were reorbited after 7 or 8 years, after the next generation of satellites (Telecom 2) had replaced them. These operations took place in 1992 and 1996, before the IADC international committee was born.

Several significant improvements were applied :

Remaining propellant mass estimation was refined using 2 methods : PVT (Pressure, Volume, Temperature) method, nominally used since launch was replaced near end-of life by book-keeping method which proved to be more precise at lower pressure. Uncertainty budget was also estimated.

Strategy included tank emptying : after a first sequence of manoeuvres executed with the guaranteed hydrazine quantity, a second set of long emptying manoeuvres were scheduled until the fist sign of tank emptying appeared : mainly attitude control perturbation. Last manoeuvre would then be interrupted by immediately sending a manual "stand-by mode" order.

The last emptying manoeuvres were long and carefully followed up by propulsion and attitude control experts. Therefore they were positioned during daytime in working hours. As a consequence, the final orbit eccentricity could increase a lot, according to the actual amount of propellant left.

End of life for TC1.A was planned in the end of 1992, but in September of this year, one of its solar array sections was damaged. The mission was not impacted immediately but this configuration did not allow to pass successfully next eclipses season which would start a few days later : the available power was no more sufficient to provide complete battery charge during daylight before next eclipse.

An exceptional meeting of the coordination board decided to proceed immediately with the end-of-life operations. Re-orbitation principles had been previously discussed but there had hardly been any preparation… Anyway, as the strategy was quite simple with manoeuvres in nominal station-keeping mode, and all the needed experts and operational teams being present, the operations could be organized and executed within the few days available before eclipses ! The result was excellent, with an altitude that has remained above H_{GEO}+300 km for more than 20 years as shown Figure 2 :

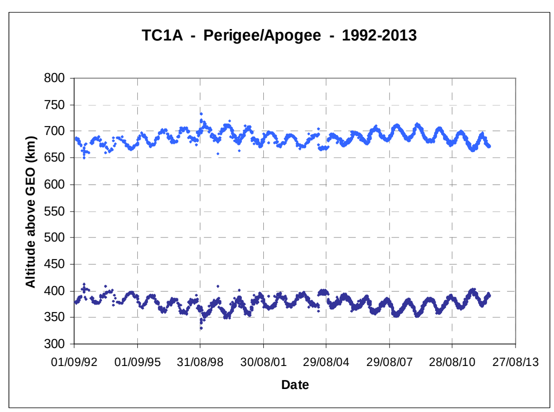

Figure 2: Telecom 1A altitude above GEO since EOL

1.4 TDF : fluidic passivation

CNES had experienced tank emptying for Telecom 1 satellites, but only liquid propellant was expelled : in station-keeping mode, the attitude control was not adapted to tolerate gas bubbles or cold gas thrust without switching to safe mode.

In order to be able to depressurize the tanks, it was necessary to activate the thrusters in a more robust mode. This was studied and executed for TDF 2 [1].

Reorbitation manoeuvres stopped when the first bubble was detected. Satellite was put in Sun Acquisition Mode, in order to improve stability and robustness, and emptying operations began, using simultaneously two thrusters on opposite walls in the roll axis direction so that there should be no torque and opposite thrusts : the aim was to minimize the need for attitude control and to avoid any degradation of the achieved disposal orbit.

The thruster activations were done in several firing phases with carefully selected on-times, (duty cyles from 10% to 100%), especially during transition phases with still liquid hydrazine mixed with gas : two hours were necessary to switch from complete liquid to complete gas phase, and nine more hours to decrease the tank pressure below 2 bar. These passivation sequences took place during working hours and lasted several days.

This first fluidic passivation was a complete success : the satellite control was never lost until final extinction, and the final pressure was lower than 2 bar.

There was however an unexpected effect on the orbit : the eccentricity increased, as shown Figure 3, causing the perigee altitude to decrease by 27 km. This could be explained by a possible freezing of the permanently shadowed thruster after the end of combustion. Fortunately, the reached altitude was sufficiently high and the perigee altitude has permanently remained higher than GEO + 235 km.

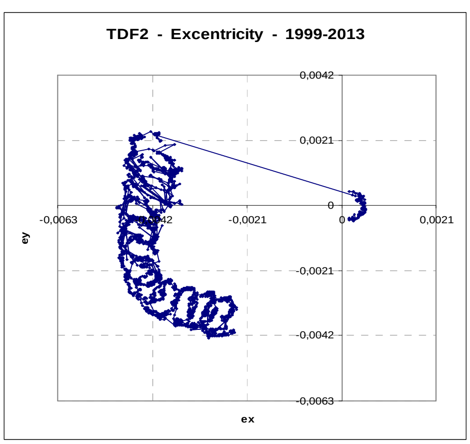

Figure 3: TDF2 eccentricity vector evolution since EOL

1.5 TELECOM 2 : degraded cases prevention

TELECOM 2 satellites were designed around 1990 for ten years of mission, but were operated during 12 to 17 years, thanks to their good health and with an inclined orbit during the last few years. For the first time, an amount of propellant was reserved for reorbitation : 6 m/s, corresponding to a semi major axis increment of 164 km.

TC2A, B and C had an anomaly that caused East manoeuvres to consume twice as much as West manoeuvres for the same delta-V. The initial reorbitation fuel budget would therefore sufficient to increase the semi-major axis by 80 km only. In order to improve the result and preserve the on-orbit mission duration, a specific strategy was imagined: a “turnover manoeuvre” would be done prior to reorbitation, around the Earth axis, causing the “North” satellite axis to be Southwards and the East one to be Westwards. In that way, the East reorbitation can be done with the “West” thrusters with a nominal fuel cost. This specific turnover manoeuvre was defined and thoroughly qualified.

TC2.B was re-orbited first, in June 2004, (several longitude changes had it ran out of fuel first) and unfortunately suffered a degraded case during the turnover manoeuvre : the solar array sun sensors, never used since LEOP, had degraded perfomance that prevented to obtain correct Earth acquisition. Several days of expertise and tests were necessary to solve and correct the problem and some fuel was wasted during this time. As a consequence, the obtained altitude was slightly below the 200 km GEO protected region as defined by IADC : 185 km.

Propellant remaining mass estimation also was a tricky issue : four tanks, two propellants, three methods, and 800 kg out of 1000 used for initial station acquisition… A new dynamic “thermal gauging” method was implemented by the manufacturer (Astrium) with interesting results, the main of which was a decreasing uncertainty when there is little fuel left. But finally the results were not stable enough to be the unique reference, especially for the oxidiser because of its volatility and the chemical energy involved. This method was combined with book-keeping one, still allowing some significant improvement for uncertainty.

Another mean of getting the maximum propellant available for reorbitation was to cool the tanks prior to reorbitation : a greater quantity of liquid oxidiser was available at 11°C instead of being in vapour form at 30°C. To do so, every non indispensable equipment and heater was switched off.

Due to a specific propellant device that must not be emptied, manoeuvre size was limited on Telecom 2 and re-orbitation meant a lot of manoeuvres. The frequence of manoeuvres has been increased in order to be able to perform all operations within two weeks : two, three, four, and up to six manoeuvres a day have been experienced for TC2.C ! And of course orbit determination and manoeuvre calibration were done between each one, thanks to a performing software able to give the current orbit and previous manoeuvre component with only four couple of distance measurements. The times of manoeuvres were chosen so as to "circle" around the targeted eccentricity vector. Figure 4 shows TC2.C manoeuvres on eccentricity circle :

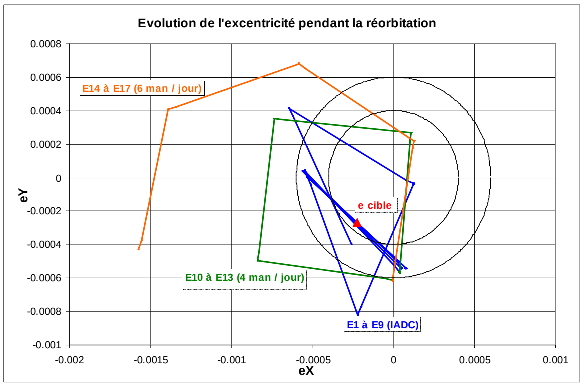

Figure 4: TELECOM 2 C reorbiting manoeuvres

A different strategy has also been set up for fluidic passivation, taking into account lessons learned from TDF : passivation thrust would be done by one thruster, oriented towards the sun in order to minimize the freezing risk, and activated at a favourable position on orbit so that the main thrust component would be a tangential positive one, increasing the semi major axis. After two hours or so, the thruster force would decrease a lot in monoergol and cold gas phase, and the position on orbit would then be of smaller importance. This is shown on Figure 5

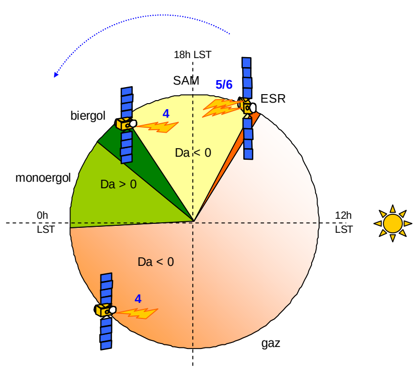

Figure 5: TELECOM 2D fluidic passivation strategy

Automatic modes have also been conceived and implemented in order to secure passivation execution even in case of satellite control loss. As soon as the guaranteed propellant has been consumed, a timer is re-set on-board several times a day and fluidic passivation would be automatically executed if this timer came to 0, showing a durable loss of telecommand acces. This automatic fluidic passivation is of course different from the nominal one since the satellite might then be in "stone mode" : three thrusters would be activated on opposite walls (in order to minimize torque and force) with a 10% duty-cycle for higher pressure and 100% duty cycle for cold gas phase, assumed when the tank pressure has reached a lower value showing that depressurization has started. Another timer, together with a surveillance of electric power level, would then trigger automatically electric passivation : battery discharge and disconnection and transmitters switch off.

TC2.A in 2005, TC2.C in 2009 and TC2.D in 2012 perfectly implemented these strategies, although in neither case the automatic process had to be activated : all operations could be executed nominally with a good TM/TC access allowing the teams to observe the effective passivation until the end and trigger manually the satellite extinction.

For TC2.D, another degraded case have been studied : the earth sensor failing. In such a case, mission cannot be continued and nominal reorbitation manoeuvres can no longer be done either. A strategy similar to fluidic passivation was studied : in Sun Acquistion Mode, activate East and West thrusters twice a day at favourable times in order to progressively increase the altitude. Of course in such a configuration, the manoeuvre efficiency is worse, attitude control does consume propellant, and the propellant tanks have not been cooled before. Nevetheless, it was shown that this strategy would ensure the satellite to get out of the operational geostationary corridor (40 km), and have good chances to reach IADC recommended altitude, depending on the effective propellant quantity. This case was studied in advance because if such a failure occurred, it would be vital to proceed quickly with operations since every day spent in sun pointing mode would consume propellant… It was then identified as an emergency case by the French Space Act board.

2 REMOTE SENSING SATELLITES

2.1 Introduction

CNES operational teams has operated a fleet of eleven remote sensing satellites : 5 civilian (SPOT) satellites, 4 military (HELIOS) satellites and 2 PLEIADES satellites with both civil and military applications.

These satellites are devoted to Earth observation purpose : they are placed on low Earth, near polar, phased and sun-synchronous orbits, in order that they re-visit the same place on the Earth surface within a determined period of time, and always with the same illumination.

Five of them have reached end of life (EOL) : their disposal result is summarized in Table 2

Table 2: CNES remote sensing satellites disposal results

Satellite	Launch date Disposal date	Reached Lifetime	Orbit altitude	Re-entry duration
SPOT 1	02/22/1986 11/28/2003	17.7 years	581 / 801 km	24 - 31 years
SPOT 2	01/22/1990 07/29/2009	19.5 years	572 / 797 km	18 - 25 years
SPOT 3	09/26/1993 11/14/1996	3.1 years	808 / 845 km	(Failure)
HELIOS 1A	07/07/1995 01/18/2012	16.8 years	640 / 650 km	< 25 years
HELIOS 1B	12/09/1999 10/21/2004	4.8 years	~ 655 km	< 30 year

SPOT3 and HELIOS1B end of lives were due to on-board major failures. In SPOT3 case, operational teams did not succeed to recover the control of the satellite and no disposal operation could be done. In HELIOS1B case, disposal operations could be performed in a very stringent way. These two experiences led a working group to define a methodology in order to anticipate and take into account some unexpected on-board events that could not only affect the mission continuation but also the disposal operations [2]

For SPOT 1, SPOT 2 and HELIOS 1A, end-of life operations could be prepared and executed in a nominal way with constant improvement in process, completeness and safety, as shown in the following sections.

2.2 SPOT 1 : first LEO de-orbitation

SPOT 1 was the first remote sensing satellite launched for CNES, in 1986. The fleet was completed by SPOT 2 and 3 launched on the same orbit in 1990 and 1993 : this allowed to reduce the revisit period. After SPOT 3 failure, 2 satellites were left during 1.5 year, until SPOT 4 launch in March 1998.

In 2001, SPOT1 solar panel was partially damaged and a new degradation could be expected at any time and be fatal for the satellite. So in 2002, CNES decided to start studies to be ready to de-orbit the satellite as soon as the next satellite would be operational.

SPOT 5 was successfully launched in 2002, and SPOT 1 commercial mission could be stopped, after more than 17.5 years in orbit. Relative position of SPOT satellites at that time are shown on Figure 6.

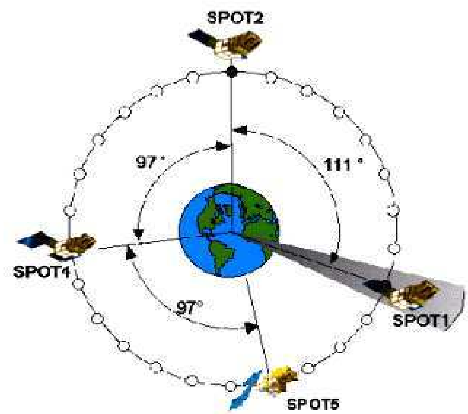

Figure 6: SPOT fleet orbital configuration

The main objective of this de-orbitation was to preserve the space environment in accordance with the Inter-Agency Space Debris Coordination Committe (IADC) recommendations : decrease the remaining in-orbit lifetime below 25 years and passivate energy sources.

Since SPOT operational altitude is 832 km, the more efficient way to decrease lifetime, taking into account the remaining propellant quantity, was to perform apogee manoeuvres and reduce perigee altitude. But is was first needed to clear the operational orbit in order to avoid collision risks with other SPOT satellites : this was done with a 1st manoeuvres in 2 thrusts which lowered the altitude by 20 km. Then eight single burn apogee manoeuvres were performed (one per day), with following characteristics : 1000 s duration, 5 kg hydrazine, - 25 km perigee altitude decrease.

A final long single burn manoeuvre (2400 s) allowed to expel the remaining propellant and observe the beginning of gas phase : valve temperature increase (no more cooling by fresh hydrazine) and pressure decay [3]. Then the batteries were disconnected and the transponder emitters were successfully both switched off, ending the passivation operations. This phase was particularly critical and was made mainly with ground-station visibility. The whole operations lasted two weeks.

The nominal station-keeping software was not adapted for such operations : orbit determination had to be made by the Orbit Computation Center (OCC), and a specific software was developed in order to compute the single-burn manoeuvres : the nominal station-keeping software could only handle double-burn manoeuvres.

Final EOL orbit was computed precisely by the flight dynamics team : it led to an estimate of natural re-entry duration between 24 and 31 years (depending on the solar activity and assumptions on the spacecraft attitude).

2.3 SPOT 2: lessons learned and improvement

SPOT 2 EOL operations took place six years later in 2009 , after nearly 20 years of mission,. The strategy was very similar to SPOT 1 because both the operational orbits and the spacecraft designs were similar : an escape manoeuvre from operational orbit, daily apogee manoeuvres to lower the perigee, and a final long passivation manoeuvre mostly in visibility. There were however a few differences :

The control mode between burns (wait mode) used for SPOT 2 was a reaction wheels control mode, whereas a thruster control mode had been used fro SPOT 1 : this allowed to save a significant amount of hydrazine.

CNES collision avoidance process had been put in place earlier was used during end-of-life operations. Post manoeuvre orbits were sent to Joint Space Operations Center (JSpOC) as soon as they were available to improve collision risk assessment for SPOT 2 and towards other satellites.

For last manoeuvre, the chosen thrust time ensured a maximum probability of visibility for the end of burn and passivation phase, taking into account the remaining propellant mass knowledge uncertainty : the manoeuvre was scheduled on an ascending night orbit with a large visibility duration successively with Kerguelen, Hartebeestoek, Aussaguel, Kiruna and North Pole ground stations so that the tank unpriming had the best chances to be observed, as shown on Figure 7.

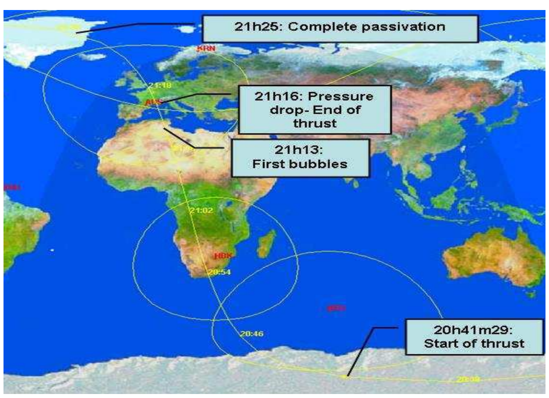

Figure 7: Positioning of SPOT 2 last thrust

Estimation of remaining lifetime was also improved, taking into account a smaller mean drag surface as it had been observed during the first years of SPOT 1 orbit evolution after its end of life.

SPOT 2 de-orbitation operations were perfectly nominal with a remaining lifetime between 18 and 25 years, observation of tank emptying and complete electrical passivation.

2.4 HELIOS 1A : a different strategy

HELIOS 1A mission was stopped after nearly 17 years. It was a different satellite, operating on a lower altitude orbit, with sufficient propellant : an eccentric orbit was not necessary to speed up the decay. It was thus chosen to perform two double-burn manoeuvres before the final endless passivation burn, as shown Figure 8.

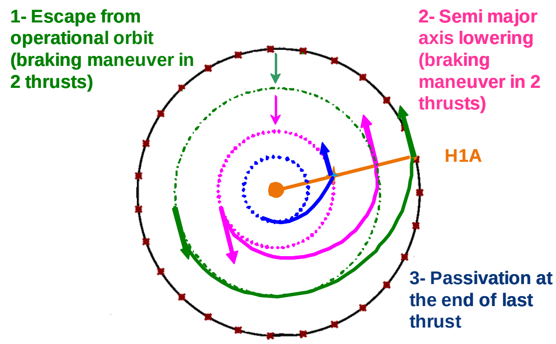

Figure 8: End-of-life strategy applied for HELIOS 1A

This strategy was simpler than SPOT 1 / 2 one : the nominal station-keeping software could be used, and shorter : operations lasted only 3 days with only 3 manoeuvres executed. Preparation and validation phase was also much simpler and shorter.

During the last manoeuvre, tank emptying was observed with pressure drop, and thrust continued during a significant duration with cold gas only, in order to depressurize the tank and achieve complete fluidic passivation.

Remaining lifetime was for the first time estimed with STELA tool [4] : final orbit gives a remaining orbital lifetime of about 15 years, as shown Figure 9

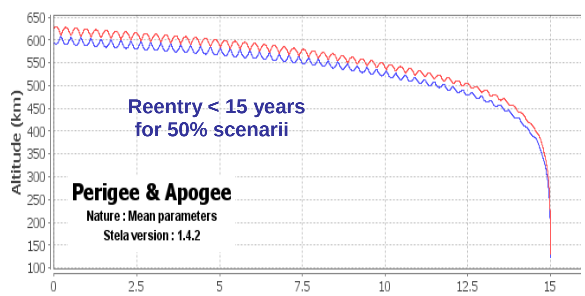

Figure 9: HELIOS 1A estimated remaining lifetime

2.5 HELIOS1B : emergency de-orbitation

Hélios 1B experienced a critical situation. An emergency coordination meeting took place in the following hours, and it was decided to prepare immediately a minimal set of contingency disposal operations that would be executed on the following day.

A two-thrust manoeuvre was scheduled to decrease the semi major axis. For this manoeuvre, no new parameters were uploaded and specific housekeeping monitoring were inhibited. The fluidic passivation was not completely achieved because all the propellant could not be consumed with only one manoeuvre, but the telemetry transmitters were switched off and the batteries disconnected half an hour after the end of the second thrust, before the satellite was definitely lost. The operational orbit was secured and the final orbit reached gave a natural reentry duration assessment of 30 years.

It was a great success to have been able to successfully perform those disposal operations in such a short delay. This was possible thanks to the availability, high competence and efficient cooperation of operational teams and experts who handled the situation.

HELIOS 1B experience showed that is was necessary to prepare in advance some degraded scenarios for end-of-life, that could be applied in certain emergency situations.

2.6 SPOT 4 : secured passivation

SPOT 4 commercial mission has been stopped after 15 years, at the beginning of this year. The satellite is currently used on a slightly different orbit to validate some concepts of ESA SENTINEL program. The de-orbitation is planned in June 2013.

A strategy similar to HELIOS 1A one will be applied for manoeuvres, essentially for operational reasons : it is much more simpler for this satellite family to perform two burns manoeuvres and keep frozen eccentricity. The impact on remaining lifetime has been estimated to less than 5 %, which is very low and quite acceptable.

The tricky period is definitely the endless thrust carried out to exhaust propellant: there is an uncertainty of 4000 s for this final thrust. Several measures have been taken to secure the whole passivation phase : time-tag execution of electrical passivation after completion of fluidic passivation, inhibition of unnecessary equipements and "safe mode" handling,

2.7 SPOT 5 / HELIOS 2 / PLEIADES : future

Some major improvements have been added to the deorbitation process.

Emergency EOL cases have been identified, and corresponding procedures prepared and validated : they are ready to be used. One difficulty is to maintain these procedures in coherence with the on-board equipments status. For instance, recent deterioration of the behavior of two gyroscopes requires us to rethink the global strategy of our emergency procedure for SPOT5 deorbitation

Electrical passivation will be automatically performed if undervoltage is detected on the power supply bus. It is expected to occur after the end of the final thrust, when the satellite attitude – due to the propellant depletion phase - will no more allow a proper refill of batteries.

For HELIOS 2, other modifications of the on-board software have been made to improve the satellite behaviour during a potentially very long final endless thrust, in case of an anticipated emergency end –of-life. The remaining propellant quantity would then be quite important and it was necessary to be able to adapt some parameters (such as the orbital period and the thusters torques) several times during the thrust, to take into account the orbit altitude and pressure evolution

For PLEIADES satellites, end-of-life was prepared as the other phases of mission : launch and early orbit phase, and operational phase. Plans and procedures are ready, nominal strategy has been tested and qualified before launch, and emergency operations have also been qualified within a few months following launch.

3 MINI & MICRO-SATELLITES

Since 2001, CNES has operated five mini-satellites based on Proteus bus and eleven micro-satellites from Myriade family, with various missions such as signal intelligence, earth sciences (altimetry, atmosphere, water…) or astronomy (Sun, exoplanets…). Five of them have been de-orbited and two others have been removed from their operational orbit and are now operated on a different orbit, because of a failure risk.

3.1 ESSAIM : constellation de-orbitation

Essaim is a swarm of four satellites flying together, launched in 2004 and arrived at end of mission in 2010.

While preparing de-orbiting strategy, a particular attention was paid to multiple manoeuvres, collision risks between the Essaim satellites themselves and towards other operational satellites. A dedicated manoeuvres strategy was put in place which ensured a minimal number of manoeuvres (to reduce the operations duration), depleting tanks, target in altitude and eccentricity, no collision risk between Essaim satellites during operations in case of a manoeuvre failure, and no collision risk either during the remaining in-orbit lifetime. This strategy is detailed in [5].

For these satellites, fluidic passivation have not been completed because at that time, an explosion risk in case of full exhaustion of the hydrazine diaphragm tank could not be excluded. Electric passivation included turning the solar panel back towards the Sun in order to discharge the battery, and activating a flight software which "does nothing" in order to avoid any satellite restart, before switch-off.

3.2 DEMETER : hydrazine fluidic passivation

Demeter was de-orbited a few months after Essaim. The tank depletion study had been completed and concluded that there was no risk of explosion in case of complete hydrazine exhaustion.

Complete hydrazine depletion was decided as a technological experiment, to prove feasibility and validate the estimation method of the remaining propellant mass.

Fifteen short one burn manoeuvres were executed (1.6 km altitude impact each), one manoeuvre per day. The depletion was seen during burn 13 with attitude perturbation and manoeuvre efficiency drop. Burns 14 and 15 were done with liquid and gas, had very poor efficiency and were ended by safe hold mode due to depointing, as expected.

The propellant estimation proved to be pessimistic : this passivation experience was source of improvements. Satellite control could be kept until successful electric passivation. Remaining lifetime is estimated to 18 years.

3.3 JASON 1, PARASOL : failure prevention

Both Jason 1 and Parasol suffered failure or arrived near propellant exhaustion. They also largely exceeded their nominal lifetime and the qualification duration of most equipments, and both of them occupy a specific operational orbit shared with many other satellites : Aqua-Train orbit for Parasol, altimetry orbit for Jason 1.

For both of them, if a failure occurred that prevented to execute manoeuvres anymore, in addition not to be able to deorbit the satellite, it would not be possible to remove it from the operational orbit either, which would represent a danger for remaining satellites on this orbit.

After nominal mission lifetime, any prolongation is submitted for approval to a committee including French Space Act representatives, and risks are examined. For Parasol and Jason 1, the risk was judged not minimal and it was decided to remove them from their nominal operational orbit : both satellites were lowered and placed on an alternative orbit where they continue their mission or an adapted mission. They will be nominally deorbited if possible, and they would not cause any problem to other satellites in case of failure. Detailed strategy is described in [6] for Parasol in the frame of A-Train coordinate station-keeping.

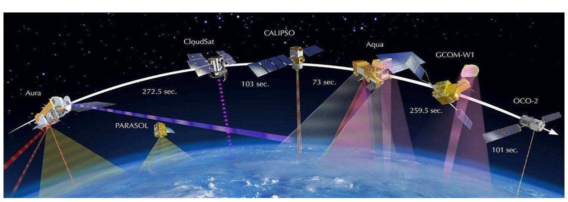

Figure 10: PARASOL exit from A-Train orbit

4 CONCLUSION

CNES has up to now executed end of life operations for 19 satellites and is currently preparing next ones. Concern for space activity sustainability has increased considerably from simply trying to get out of operational orbits to improving the efficiency and reliability of disposal operations. This came along with CNES active participation in IADC activities, especially the "space debris mitigation guidelines" definition, UN-COPUOS activity, a lead place in elaboration of the "European Code of Conduct" and more recently the "French Space Act", applicable since the end of 2010.

During the last few years, many progress were made regarding degraded cases, safety and reliability : it seems indispensable to be able to guarantee a minimal set of disposal actions even in case of failure. It is particularly important for passivation, that reduces explosion risks in the future.

CNES efforts to preserve a safe space are steady, with a continuous improving of end-of-life management and an increasing expertise and experience in collision risk avoidance.

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