TANK PASSIVATION OF GEOSTATIONARY SATELLITES

Raffier Bertrand (1)

(1) *C.N.E.S., 10 avenue Edouard Belin, 31055 Toulouse, Email : bertrand.raffier@cnes.fr*

ABSTRACT

CNES has adopted in October 2004 the European Code of Conduct on space debris, which is applicable to all new space projects of the French Space Agency. Concerning old satellites launched before any recommendation for space protection was established, CNES tries to adapt their end of life strategy in order to respect the mitigation guidelines as well as possible, like for example, when de-orbiting Spot1 or re-orbiting TDF2. Both major key points are then to dispose the satellite into a post-mission dedicated orbit zone and to minimize the potential for post-mission break-up. This paper deals with the specific question of depleting the residual propellant and other fluids in the case of geostationary satellites. Due to old designs not taking into account the need for emptying the tanks at end of life, a specific strategy has to be developed, in order to fulfill this objective and respect the other mitigation guidelines. But it is necessary to persuade the operator to authorise the emptying and the industrials to design an adapted strategy. In this context, CNES has decided to facilitate the depletion guideline respect by conducting activities of Research and Technology with industrials.

1. DEBRIS MITIGATION GUIDELINES

1.1. IADC guidelines

One of the subjects studied by the Inter-Agency Space Debris Coordination Committee, I.A.D.C., concerns the space debris mitigation at the end of a satellite mission (IADC, 2002). A notion of disposal phase has been introduced between the end of mission and the definitive state of an uncontrolled space object. During this post mission phase, it is recommended to the operator to free the orbit used during the mission and to minimise the potential for post-mission break up resulting from stored energy. For this last point, all on-board sources of stored energy, such as residual propellants, batteries, high pressure vessels, self-destructive devices, flywheels and momentum wheels, should be depleted or safe.

1.2. Application to old GEO satellites end-of-life

This paper deals with the case of GEO satellites designed before the mitigation guidelines have been defined. The objective is then to realise the three following phases, as shown in Fig.1 :

- Re-orbiting the satellite above the GEO house-keeping zone (the guidelines recommend a minimum increase in perigee altitude taking into account the orbital perturbations according to the formula "235 km + 1000.Cr.A/m" where Cr represents the solar radiation pressure coefficient, A/m represents the aspect ratio to the dry mass ratio and 235 km represents the sum of the upper altitude of the GEO protected region and the maximum descent of a re-orbited space object due to luni-solar and geopotential perturbations),

- Passivating the propellant tanks,

- Passivating the electrical equipments by switching off the payload and the telemetry/telecommand receivers and emitters, by stopping all equipments in rotation (like flywheels and momentum wheels, gyroscopes, earth sensors, solar panels ....), by discharging the batteries and disconnecting their charge network.

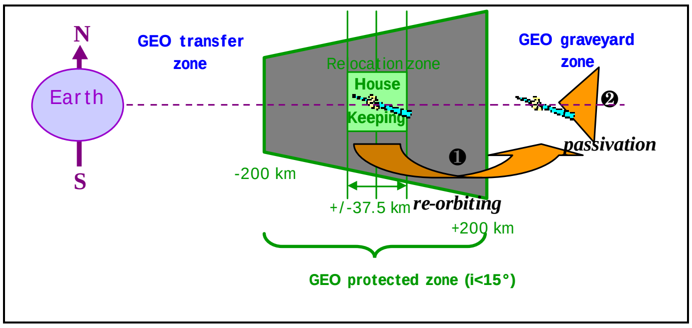

Figure 1. Activities of a GEO disposal phase respecting the mitigation guidelines.

The paper will now focus on the second phase, that is to say the passivation of the tanks.

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2. PROPULSION SUBSYSTEM

2.1. Components

The propulsion subsystem of the geostationary satellites concerned by this study and used in house keeping can be split into three main components, as shown in Fig.2 :

- A storage of the propellants in tanks pressurised by a fluid like helium. A classical propulsion subsystem uses monomethyl hydrazine as the fuel and mixed oxides of nitrogen as the oxidiser. The number of tanks varies from 1 pair to 2 pairs.

- A set of thrusters delivering the control force thanks to a reaction in a chamber between the fuel and the oxidiser. The thrusters are activated by the attitude control subsystem via a dedicated electronics commanding the opening and closing of its valves.

- A complete feed system conducting both propellants from the tanks to the thrusters.

In order to follow the behaviour of the propulsion subsystem, a given number of telemetry data are generally available:

- Pressure and temperature of the tanks,

- Temperature at the thrusters level,

- Number and duration of actuations commanded to the thrusters.

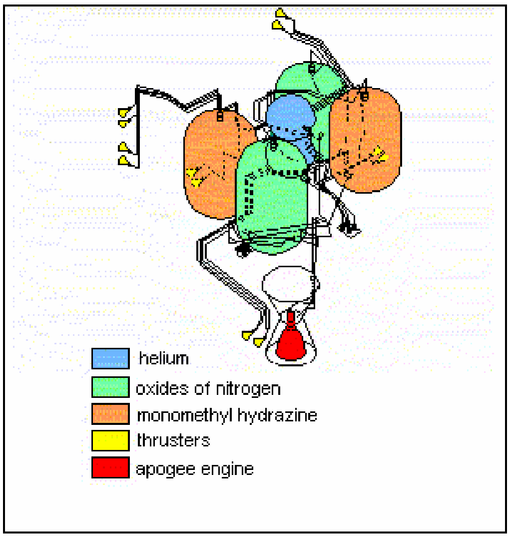

Figure 2. Example of a classical bi-propellant propulsion subsystem

2.2. Date of the end of life

The life duration of a geostationary satellite depends on several parameters:

- quantity of propellants before the launch and consumption when putting the satellite into its orbit,

- consumption of propellants during the house-keeping in order to control the orbit of the satellite,

- quantity of propellants reserved for the re-orbiting phase, generally defined in the contract between the customer and the operator,

- quantity of propellants considered as unusable residuals, like for example vapours or liquids above membranes.

All these quantities are evaluated with uncertainties thanks to direct or indirect methods. When the estimated remaining masses come near to zero, the mission has to be stopped in order to process the disposal phase.

2.3. Tank passivation

For old design of satellite, there is no way to empty the tanks without using the thrusters. Furthermore, the mitigation guideline recommends to empty the tanks from the propellants and to depressurise too the gas present in the tanks.

Then it is necessary to find or define control modes allowing the opening of thrusters.

According to the tanks contents, different phases will follow one another:

- a bi-propellant phase with bubbles for one propellant at given thrusters,

- a gas phase when liquids are run out at all thrusters,

- an intermediate phase between these two phases, wich is difficult to define.

The transition between these phases and in the same way their characteristics are difficult to predict: the generated forces and the associated flows have generally not been evaluated in these specific conditions.

One way to estimate the achieved level of passivation consists in following the evolution of the tank pressures, which decrease during the depressurisation phase.

3. DEPLETION PRINCIPLES

3.1. Earth Pointed mode

The first and simplest mode for the tank passivation is to use an Earth Pointed mode, comparable to the used mode for the station-keeping manoeuvres.

The great advantage of such a mode consists in delivering a predicted force, which can be used in order to increase the altitude and continue the re-orbiting phase. This mode offers a comfortable telemetry and control access to the satellite.

But the major problem comes from the robustness of the attitude control to the presence of bubbles inside the thrusters: if the performance of one thruster is degraded, the control capacity can be largely affected, which leads to large attitude depointing. In case of using Earth sensors with reduced field of view, the observability can be lost and the satellite control becomes impossible.

3.2. Sun Pointed mode

One way to reinforce the robustness of the attitude control to the apparition of bubbles in thrusters consists in using a Recovery mode, such as a Sun Pointed mode.

This second type offers usually more robust control laws thanks to Sun sensors with large field of view. This mode increases the probability to keep the control even when depointing due to thruster's dysfunction. And the chance to achieve a complete passivation is increased.

But several points have to be considered too:

- First it is necessary to go from the station keeping mode to this recovery mode. This transition has to be done with thrusters actuations and can be difficult in case of bubbles in the thrusters. One idea to reduce this risk is to reserve some quantity of propellant in order to guarantee this passage.

- Then we have to open the thrusters for emptying the tanks. This possibility depends on the mode definition: if necessary, the existing mode has to be modified, in order to authorise the actuation of interesting thrusters. But these modifications have to be compatible with the control law stability.

- At last, if it is not possible to actuate two opposite thrusters, the generated force is inertial, due to the constant pointing of the platform towards the Sun. The effect on the orbit is then more difficult to control than for an Earth pointed emptying. It is all the more difficult to convert the generated force into a gain in altitude since only one thrust direction is allowed.

3.3. Uncontrolled mode

The third way to empty the tanks is to open a given number of thrusters in open loop without any action by the attitude control subsystem.

This approach does not depend on the robustness of control laws, which guarantees the completion of the emptying.

But the generated force is difficult to predict, due to an unknown attitude of the platform, which has no chance to keep stable in the course of time. It is just possible to choose interesting sets of thrusters, allowing a general configuration with reduced forces and torques.

4. RISK ANALYSIS

4.1. Principles of the analysis

The objective of the risk analysis is to prevent from new risks generated by the passivation strategy.

It is in particular important to avoid risks which could be more dangerous than keeping the satellite with partially empty tanks. For example, the use of an adapted duty cycle at the thruster's level has to be studied, in order to reduce the risks of explosion. From another point of view, if new specific modes have been developed, the validation and the operational qualification of the teams are very important.

As illustration, two major impacts caused by an emptying process are presented in the following paragraphs: the effect on the altitude and the risk of control lost.

4.2. Impacts on the altitude

The satellite TDF2 was re-orbited in May 1999 with a propulsion system passivation (Pillet, 2000). The complete depressurisation of the propellant tanks was achieved by opening opposite thrusters in a Sun pointed attitude. But the altitude of the perigee after the depressurization phase has decreased of several kilometres with regard to the achieved altitude after the re-orbiting phase. Several explanations were proposed and simulations were conducted (Frémeaux, 2004) in order to model thrusts impact for such a platform and the used attitude control mode : they prove that small residual forces generated during the propellant and gas run-out are able to have a significant impact on the final graveyard orbit.

In order to consider this experience return, other studies have been recently led at CNES by P. Legendre and C. Frémeaux, specialists of space mechanics at theoretical level and operational level. They work on both sun pointed and uncontrolled modes. For both cases, the impact on the perigee altitude can be very important, if the emptying strategy is not optimised.

Fig. 3 shows an example of simulation result for an uncontrolled emptying processed in a single burst. The used criterion is the effect on the altitude of the perigee determined over one complete year and the generated force directions are modelled randomly. The worst case, which is totally uncertain, is roughly several hundred of kilometres by considering a mass to empty corresponding to several meters per second.

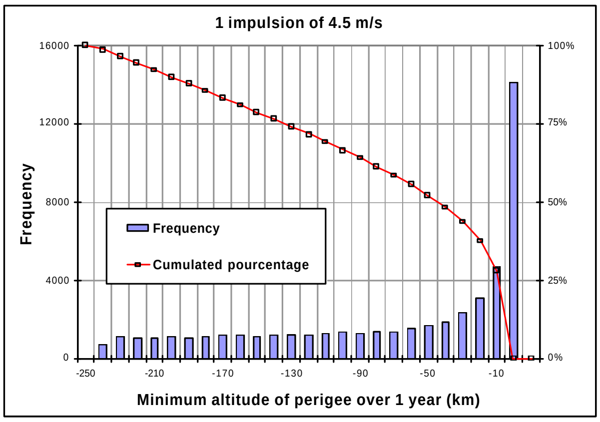

Figure 3. Example of altitude impact of an uncontrolled emptying

We can notice that such a result corresponds to a strategy without any optimisation: a given number of ways have to be explored to improve the worst cases, like for example splitting the emptying phases or searching favourable hours.

But such analysis has in all cases to be used carefully due to the great uncertainty of the thrust modeling: intensity, direction and flows have a great influence on the results.

4.3. Impacts on the control

When bubbles are coming at the thruster's level, the thrusters are not supplied with both propellants: as a consequence, the reaction is not possible and the generated force decreases a lot. Thus the attitude control subsystem is perturbed due to a bad correction delivered by the affected thrusters. According to the current attitude mode and the thrusters concerned by the bubbles, the attitude can diverge or not. In the case of divergence, it is possible to lose the telemetry and telecommand access to the satellite. This phenomenon can occur either during a re-orbiting manoeuvre or at the beginning of the emptying phase.

This is a major risk which has to be taken into account in the strategy in case of high probability. This probability depends on the used attitude mode, as seen previously in the comparison between an Earth pointed and Sun pointed mode. One way to reduce the risk of satellite lost consists in using S-band antennas with omni-direction field of view allowing a large access to the satellite. This ground capacity has to be coupled with a great reactivity of the operational teams, which have to be able to stop the current propulsion process as soon as the attitude begins to diverge. It is necessary to keep a control, in particular in order to process the electric passivation.

5. SYSTEM APPROACH

5.1. Trade-off between mitigation guidelines

As seen previously, the tank passivation can have some negative effect on the perigee altitude. In this case, passivating the tanks is processed to the detriment of the first mitigation guideline recommending a final altitude above the geostationary graveyard. It is therefore necessary to take into account this major question in the system strategy definition.

The proposed approach is to consider the worst case found during the mission analysis in terms of altitude decrease with a complete passivation. It is then necessary to define an altitude threshold we want to guarantee after the passivation phase. If we want to preserve a disposal in the graveyard zone, this threshold has to be above the graveyard limit. At the end of the re-orbiting phase, it is possible to calculate the altitude margin defined as the difference between the achieved altitude and the authorised threshold.

Two cases can be then identified:

- The altitude margin is greater than the altitude worst case associated to a complete passivation, as shown in Fig4. : it is then possible to realise the complete duration of emptying.
- The altitude margin is smaller than the altitude worst case associated to a complete passivation as shown

in Fig5. : the emptying duration has to be reduced to the proportion corresponding to the margin.

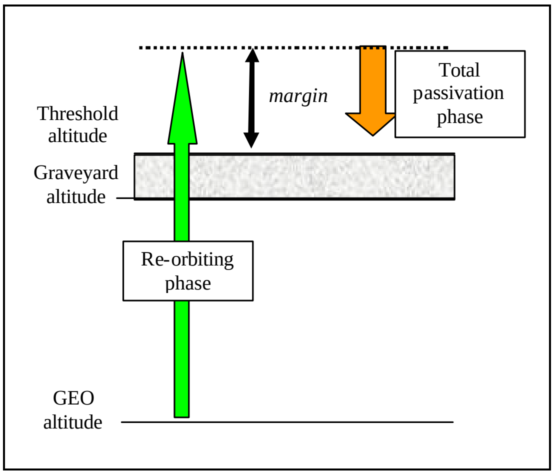

Figure 4. Case of a complete tank passivation

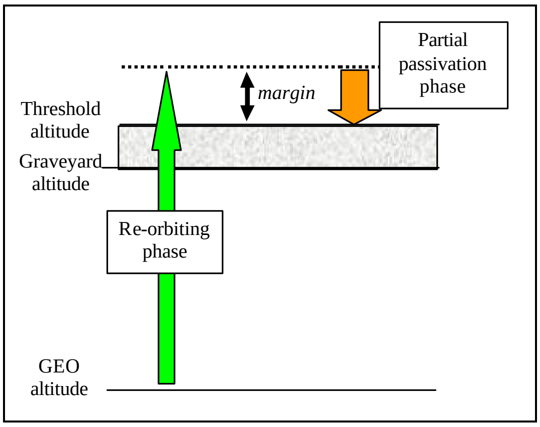

Figure 5. Case of a partial tank passivation

5.2. Proposed approach

In order to deal with the problem as a complete system approach, the definition of the passivation strategy has to be considered when constructing the re-orbiting strategy.

The first step consists in searching among the existing attitude control modes the most adapted modes taking into account several criteria: generated forces and torques, impacts of thruster's dysfunction on the control capacity, duration of the emptying phase. In case of no available mode, it is necessary to analyse the feasibility to develop a new mode offering interesting performances.

The second step is dedicated to characterize the selected modes in terms of impact on the orbit and on the operations. A preliminary mission analysis has to be led in order to determine the best hours for emptying and the effect on the eccentricity and semi-major axis. In parallel, a preliminary mission plan has to be defined by constructing the operational procedures allowing the realization at the satellite level.

The third and last step consists in defining the operational strategy by using the results of the second step. The final objective is to determine the different choices in function of the achieved altitude and of the trade-off between mitigation guidelines. It is important to write a specific document before the operations, in order to keep a good reactivity at the end of the re-orbiting phase. Each go/no-go has to be precisely defined by its position in the chronology and by its entries, criteria and outputs.

5.3. Example of general strategy

Fig 6. gives as illustration an example of strategy with multiple go/no-go.

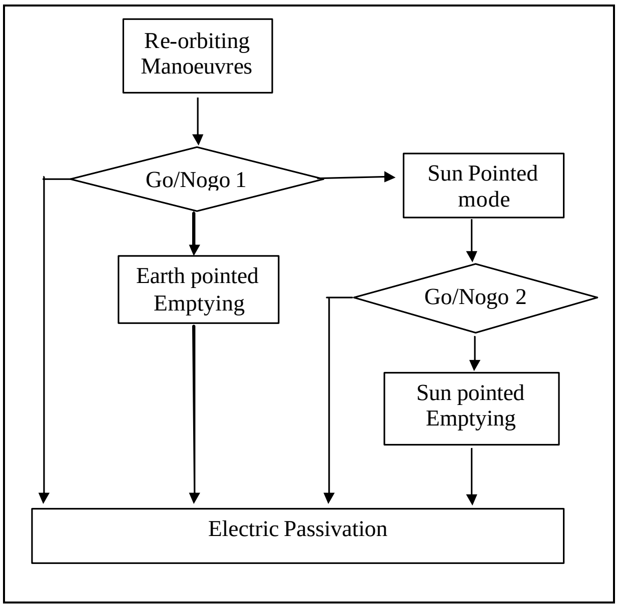

Figure 6. Example of tank passivation strategy with multiple choices

The first go/no-go comes at the end of the re-orbiting phase either due to a lack of one propellant, or by an operational decision, for example if an interesting altitude is already achieved. The objective of this go/no-go is to decide to conduct or not a tank passivation and to determine the type of passivation: either Earth pointed or Sun pointed.

If a Sun pointed passivation is chosen, the first step consists in going to the dedicated mode. Here comes the second go/no-go of the strategy: if the control of the satellite is satisfying and if the impact on the orbit during the transition is evaluated as correct, a Sun pointed emptying can be processed. In other case, it is possible to go directly to the electric passivation.

6. CONCLUSION

The generation of satellites which are coming soon to be re-orbited are not designed for an easely tank passivation. Some past examples prove that this passivation is feasible with given platforms but not always without impacts. For other cases, when no simple solution is available, it is necessary to persuade the operator to authorise the emptying and the industrials to develop a specific and adapted strategy.

This paper has presented a given number of aspects in relation with the implementation of the tank passivation on geostationary satellites. It has shown that the problem is complex, if we want to control all the effects of a passivation phase following a re-orbiting phase. The behaviour of the satellite is difficult to predict, which necessitates to be careful and to protect from potential risks.

The main objective of the proposed approach consists in establishing a predicted and validated emptying process for given platform families. This process has to be considered inside a system approach in order to respect all the mitigation guidelines.

7. REFERENCES

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