SPACE DEBRIS MANAGEMENT OF LAUNCH OPERATIONS

Alexis MACAIRE(1)

(1) Arianespace Bd de l'Europe, 91006 Evry-Courcouronnes - France, Email: a.macaire@arianespace.com

ABSTRACT

Orbital debris is becoming a serious challenge for space applications. This paper deals with the ways to limit the creation of debris during the launch phase. Arianespace is operating several launchers and complies as much as possible with the rules of the LOS (Loi sur les Opérations Spatiales, French Operation Act).

Two aspects are treated: the risk during the launch and the means to mitigate the outcome of each launch in terms of number and characteristics of the debris left in space at the end of the mission.

The mission analyses performed by Arianespace and specified to our industrial Prime contractors have been progressively adapted in the past years to limit more extensively the creation of new debris in compliance with the applicable rules.

The development of the Ariane 6 launcher takes into account the debris limitation constraints from the beginning and the upper stage should be deorbited systematically.

1 INTRODUCTION

The spacecraft are brought to space by launchers. This operation may leave some orbited debris produced by the launcher, from small ones and potentially large ones such as an entire stage or a carrying structure. Experience from past events showed that a collision between such uncontrolled "objects" in space can create a large number of debris: several thousands of trackable pieces. These occurrences also generate tiny pieces that become part of the numerous non-trackable debris, which constitute the greatest risk to space missions. One important article of the Technical Rules of the LOS ("RT") concerns the limitation of debris left in the two protected zones A and B (respectively close to Earth and around the GEO). Even today, large stages are put into a stable orbit during the launch, for a few days or more. For the launchers operated by Arianespace, the mission analysis takes into account as much as possible the constraint to deorbit all stages in an Ocean or in the sea, with a best effort to achieve the set target.

2 PROTECTED REGIONS

2.1 IADC guidelines

The IADC (Inter-Agency Space Debris Coordination Committee) guidelines requires to avoid leaving objects in two regions A and B, respectively the LEO (Low Earth Orbit) defined by an altitude below 2 000 km around Earth and a torus around the GEO (Geostationary Earth Orbit), see Figure 1. The proposed shape for the region B is defined by an altitude extending 200 km below and above the GEO one (about 36 000 km) as well as ± 15 deg in latitude.

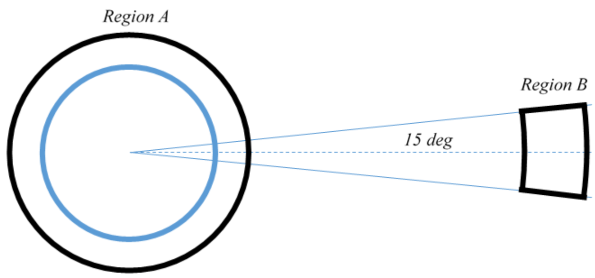

Figure 1 – Protected regions

In case it is not possible to avoid these forbidden regions at the end of the launcher mission, the minimal guideline consists in a limitation of the lifetime of the remaining objects within the protected zones; the targeted specified duration is a maximum of 25 years.

2.2 Launcher missions guidelines

Ideally, at the end of a launcher mission, the upper stage should be placed out of these regions. In addition, lower stages should also avoid these regions. It must be mentioned here that, generally speaking, the respect of this requirement, i.e. change efficiently the orbit parameters, has a performance cost which could be high.

<u>SSO missions</u>

For LEO missions, the most common mission is a SSO (Sun Synchronous Orbit) one of which the range of targeted altitude is usually between 400 km and 800 km, in quasi-circular orbit, more often close to 800 km which is almost the centre of the region A. Starting from

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a LEO, the necessary ΔV to be reached to go above 2 000 km is given in the Figure 2, as a function of the initial altitude (assuming a circular orbit). This ΔV is compared to the one that has to be applied to the upper stage to guarantee a re-entry into the atmosphere; the deorbiting ΔV is here sized to obtain a perigee altitude of 0 km. In fact, as discussed below, the targeted perigee altitude may vary in function of the mission's constraints, such as visibility of the maneuver or the conditions at re-entry in order to assure a controlled capture of the stage and a precise fall-down area.

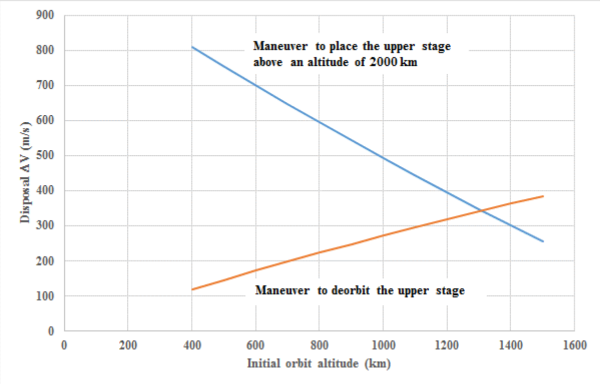

Figure 2 – Sizing of LEO disposal maneuvers

Looking at these curves, it seems obvious to opt for deorbiting maneuvers. Anyhow, realizing a re-entry of the upper stage at the end of the mission implies some difficulties of different sorts:

- The re-entry has to be performed in an Ocean or in the sea. The maneuver may have to be delayed in order to reach a proper position that leads to an acceptable fall-down zone,

- The conditions at re-entry (relative velocity and slope of velocity at 120 km) have to be kept within some ranges that have been analysed. A "qualified" domain has been determined and has to be respected,

- The flight software has to be adapted in order to manage safely the contingencies in case of anomaly; the chances of a fall-down of the stage in an inhabited area have to be minimized,

- Moreover, the RT ask reasonably for a direct visibility of the maneuver, which requires the use of a network of ground stations geographically properly located. This constraint might leads to some extra costs for the operator.

The resulting osculating perigee at the end of the deorbiting maneuver may be much lower than the strict minimum to assure the capture by the atmosphere, taking into account all uncertainties and constraints. For example, for a recent Vega flight (VV09 – 2017), the sizing of the deorbiting boost lead to a ΔV of about 300 m/s, starting from a SSO orbit at 800 km, where an order of magnitude of 220 m/s would seem to be sufficient.

GTO missions

The second important case is the GTO (Geostationary Transfer Orbit) mission, which usually leaves the upper stage in an orbit that crosses both A and B regions. Reducing the apogee will improve the situation but the orbit will still cross the regions A and B for some time. Similarly, increasing the perigee will also leave the upper stage in an orbit that might interfere with region B. Other options such as performing out-of-plane maneuvers will not efficiently solve the problem. Starting from the GTO, guaranteeing that the upper stage is placed out of regions A and B requires a large ΔV that has to be delivered in several boosts, which means a loss of performance for the launcher.

The simplest and most widely used option for GTO missions is to reduce the perigee, accepting that the upper stage will go through the two regions A and B for a certain delay, or to perform a direct re-entry (during the first orbit completion).

Reducing the perigee is chosen in case of lack of upper stage re-ignition possibilities or of performance margin for the mission to be completed; the goal is to respect a lifetime limit of 25 years. The difficulties linked to the direct re-entry listed above for LEO mission are applicable for the GTO mission type, with some extra difficulties such as the control of the upper stage re-entry zone which is more sensitive to dispersions of the delivered ΔV (ideally given at the apogee). The applied ΔV has to be large enough and as accurate as needed to target acceptable impacts locations on Earth (in an Ocean or in the sea in any case).

The controlled direct re-entry has some specificities for GTO missions. First, the upper stage is often left in an inappropriate position on the orbit at the end of the mission to perform a perigee reduction. The injection is performed low in altitude, close to the perigee. The efficiency of the re-entry ΔV is increasing as the true anomaly is approaching 180 deg. The ΔV depicted in the Figure 3 is sized to reach an osculating perigee altitude of 0 km. Applying the maneuver right after the injection is very costly in terms of performance; when it is completed at the apogee, the ΔV can be divided by more than 10 but implies a ballistic phase of several hours.

The main drawback is the management of the launcher during this delay. The main implications are the following:

- The necessity to maintain the required power for the stage management, actuators if needed, telemetry, thermal management. Some extra batteries might be necessary,

- The loss of propellant during the ballistic phases depends on the type used to perform the boost. Cryogenic ones will evaporate more rapidly than storable propellants.

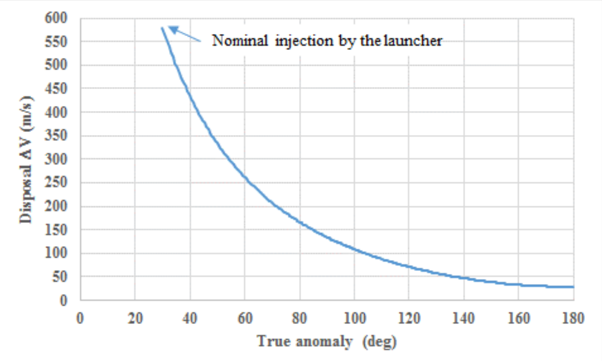

Figure 3 – Sizing of GTO disposal maneuvers to perform a re-entry

A trade-off is generally made to determine the best compromise, taking into account all aspects. In the Figure 4, a comparison of the ΔV to be reached in order to attain an osculating perigee of 200 km, starting from 250 km, with the case of de-orbitation given in Figure 3.

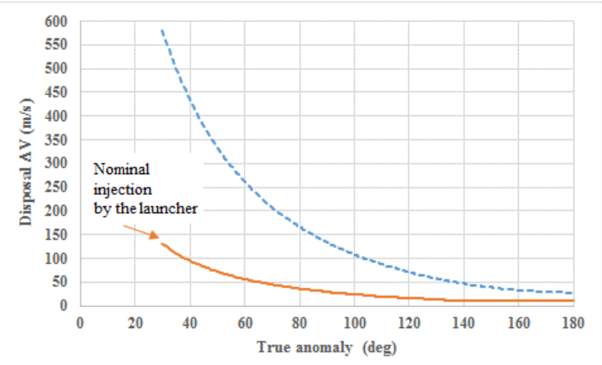

Figure 4 – Sizing of GTO disposal maneuvers to perform a perigee reduction to 200 km (compared to the re-entry case)

Reducing the perigee, without direct re-entry, is easier and more straightforward but of course an assessment of the casualty risk is necessary.

MEO missions

The MEO (Medium Earth Orbit) mission that had to be managed by Arianespace was the Galileo one, designed to complete navigation services. This orbit is located between the two regions A and B, at an altitude of about 22 900 km. No action would be required with respect to debris mitigation applicable rules. The ΔV to guarantee a re-entry of the upper stage in the atmosphere is out of reach (close to 1 500 m/s). Anyhow, for this type of mission, the debris issue is managed locally by avoiding a collision in orbit involving upper stages and operational or dead spacecraft. This means that these objects will stay forever in the vicinity of the chosen operational orbit for this mission.

L2 missions

The L2 mission corresponds to a transfer orbit with very high apogee (close to 10^6 km in altitude) and a low perigee (about 300 km for Ariane 5 and Soyuz).

Two options are possible: either staying in the gravitational sphere of influence of the Earth and Moon, or escaping this region. For the latter, the ΔV to be completed is between 15 and 35 m/s, to be delivered not too late after the separation phase.

At least, performing an escape maneuver avoids to create a debris that will evolve in the Earth-Moon system, with a trajectory difficult to assess. Even so, the stage will stay in an orbit close to the one of the Earth with respect to the Sun and may re-enter the Earth atmosphere several years later or tens of years later.

3 SOURCES OF POLLUTION

The sources of pollution linked to the launch phase [2] are discussed here for launchers operated by Arianespace: Ariane 5, Vega and Soyuz. In the future, Ariane 6 will complete the possibilities. Each one has its own background and proper characteristics.

3.1 Solid propulsion

Solid propulsion can generate bits of alumina, ejected with a limited relative velocity with respect to the launcher. Alumina dust can also be released at higher velocities (opposite to the launcher thrust direction). In addition, erosion may cause small bits of the nozzle to be released.

For Ariane 5, whatever the mission, the largest parts of the alumina and other gases coming out of the EAP (Etage d'Accélération à Poudre –solid rocket boosters) will be released in the atmosphere and thus will not pollute the protected region A. At the very end of the EAP flight phase, the instantaneous altitude is about 70 km and the osculating apogee is less than 110 km. Any projected particles will reenter the atmosphere within half an orbit at the latest.

For Vega, the first three stages are SRM (Solid Rocket Motors) (P80, Z23 and Z9). These stages are deorbited in an Ocean or in the sea at the end of their boosts. Whatever the targeted orbit, the first two SRM are deorbited in the Atlantic Ocean, close to French Guiana. The third one (Z9) has a higher orbit energy and can reach large downrange distances. The altitude of separation can be up to 180 km and the apogee up to 280 km. The reentry delay of the projected objects can be higher than the ones of Ariane 5, but will be deorbited within a few orbits anyhow.

Soyuz is not concerned by solid propulsion.

3.2 Liquid propulsion

As for the solid propulsion, the largest part of the produced gases (H_2O, etc.) will be ejected low in altitude and rapidly captured by the atmosphere. Nevertheless, the circularization boost of the upper stage for SSO missions is a source of pollution. These boosts are short enough to assess that the pollution by the exhausted gases is limited.

The most significant problems caused by liquid propulsion are linked to the residual mass left in the tanks at the end of the mission that could provoke an explosion due to uncontrolled pressures. The tanks should be emptied after the completion of the last maneuvers of the upper stage, as the explosion of such structures would create a large number of debris.

3.3 Carrying structures

The carrying (or secondary) structures are used in case of multi-payloads missions. Between two separations, this type of structure is separated, most commonly on the same orbit as the one of the upper or the lower payload. Placing this structure on another orbit requires a two-boost transfer.

3.4 Upper stage

For any flight operated by Arianespace, the lower stages are deorbited in an Ocean or in the sea. The upper stage is the only one that is potentially left in a stable orbit at the end of the mission.

4 APPLICATION FOR ARIANESPACE LAUNCHES

4.1 Ascent phase

The debris mitigation is not limited to the objects left in orbit at the end of the mission. During the ascent phase, some verifications are completed in order to assess the probability of having a "foreign" body in the vicinity of the launch trajectory, with a potential limitation of the launch window if the risk of collision is considered too high. A failure of a launcher due to a collision with debris would not only be a loss of one of several operational satellites but would also potentially create new debris.

The ascent phase may present some risk of collision for high energy missions (GTO, MEO, L2), as the launcher crosses the range of altitude where a high density of debris is present. For any flight from CSG (Centre Spatial Guyanais – Guiana Space Center), a risk assessment is performed for the cases of collision with the ISS (International Space Station), as it is a manned Spacecraft. The Chinese space station is also taken into account, when inhabited and when current orbit parameters are known. This might lead to a NOGO slot.

It would be useful to assess the risk of hitting a debris, as even a very small one could create enough damage to stop the launcher. As stated above, it is unrealistic to track all debris of any size. In LEO, the trackable minimum size, and officially catalogued by the DoD (Department of Defence), is about 5 centimeters. One can imagine that a piece of debris of 1 or 2 centimeters could be sufficient to create a hole in a tank, leading to the loss of the mission.

For GTO, MEO or L2 missions, the launcher crosses the region A and leaves it after a period of several hundreds of seconds, see Figure 5. This figure may seem large but it has to be compared to the density of debris in function of the altitude, see Figure 6 for one example published by the UNOOSA (United Nations Office for Outer Space Affairs) in 2011.

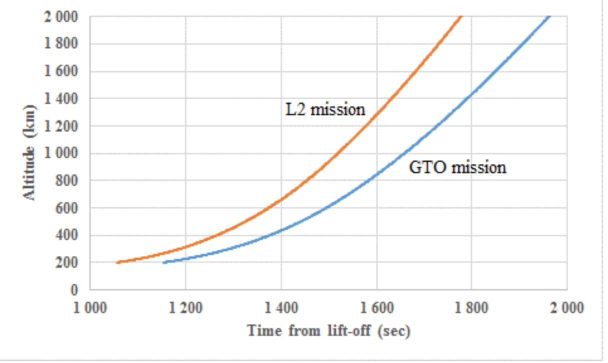

Figure 5 – Time spent in region A for Ariane 5 standard L2 and GTO missions, during the launch phase

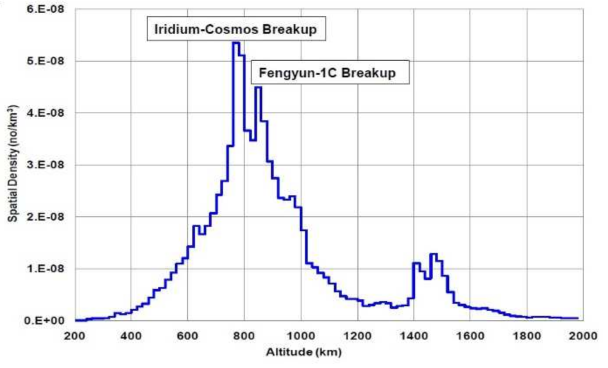

Figure 6 – Spatial density of LEO space debris by altitude, 2011 NASA report – UNOOSA [1]

The shut-off of the ESC-A is triggered at an altitude close to 650 km for GTO standard missions, before the peak of debris density which is located at about 800 km (the density is at least 2 times less at 650 km). The end of the Spacecraft separation phase occurs above 3 000 km (out of the region A), where the debris density is low, see Figure 6.

The highest density range of altitude is not achieved by the launcher during the upper stage propelled phase; the ballistic phase (separation phase) should be less sensitive to a collision with a debris. Nevertheless, it will be crossed by the satellites which are exposed anyway (separated or still on the launcher). For L2 missions, the end of ESC-A flight phase occurs at an altitude of about 880 km, after the high peak of debris density.

One cannot deny that there are some risks of collision during the flight. The time spent in the range of altitude presenting a high density of debris is short enough to limit the probability of collision. So far, no failure or anomaly caused by a collision during the ascent has been identified.

4.2 Debris disposal

LEO / SSO missions

The SSO missions performed with Soyuz launched from CSG were designed to force all the lower stages to be deorbited in an Ocean or in the sea. The fall-down area of the third stage (Block-I) has been placed in the Labrador Sea or in the Baffin Bay, respecting the limit of the territorial waters of 12 nautical miles (22.2 km) off the coast, as defined by the 1982 United Nations Convention on the Law of the Sea. The fall-down zone has to be placed out of this limit with a probability of at least $1\text{-}10^{-5}$; this rule is applicable for any mission performed from the CSG.

Usually, the upper stage ends the SSO missions at an altitude of 800 km or less. A re-entry has been performed for most SSO flights, in the Pacific, Atlantic or Indian Ocean. For a recent Vega flight (VV05 – 2015), the performance capability was not sufficient to deorbit the upper stage and a perigee reduction was made in order to respect the 25 years lifetime in orbit. The upper stage (the AVUM – Attitude Vernier Upper Module) is still orbiting today (April 2017), with a perigee of about 400 km.

For the particular case of the Vega maiden flight (VV01 – 2012), the targeted orbit was a circular LEO one, with the main payload released in an orbit at an altitude of 1 450 km. A perigee decrease maneuver was performed to reach 300 km, before the separation of several auxiliary payloads. Finally, the upper stage of this Vega flight re-entered the Earth atmosphere in November 2016, 4 years after the launch.

For LEO missions, the best effort is made concerning the upper stage, for which at least a reduction of perigee is mandatory. Recently, a dedicated procedure has been implemented to treat the case of the carrying structures used for a dual launch in SSO. As of today, the applicable rules authorizes to leave such structure orbited, and there is no obvious solution to reduce the lifetime in orbit when the structure is separated between two payloads separations.

Two similar SSO dual launch missions were performed with Soyuz. For the first one (VS02 – 2010), the ASAP-S (Arianespace System for Auxiliary Payloads on Soyuz) carrying structure was left almost on the same orbit as the one of the second released payload, see Figure 7. As a result, the ASAP-S was on a quasi-circular orbit above the altitude of 600 km after separation, unable to respect the delay of 25 years before re-entry.

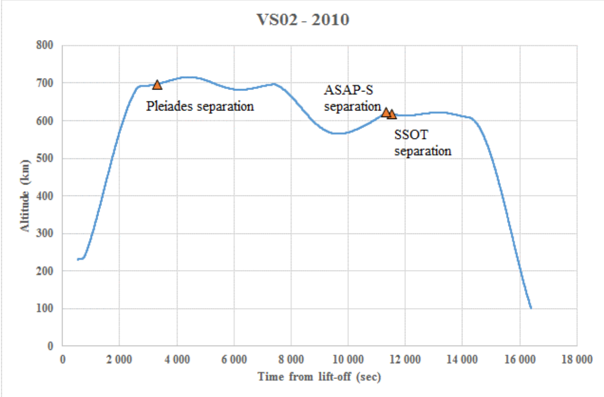

Figure 7 – Altitude profile of VS02 mission (2010)

For a more recent flight (VS14 – 2016), some ways have been searched for to treat more properly the case of these carrying structures that may constitute large debris, with the help of appropriate maneuvers completed with the upper stage during the flight. In order to reduce the lifetime in orbit of the ASAP-S, a perigee reduction maneuver was completed during the flight, before the second separation; the obtained osculating perigee was close to 450 km, see Figure 8 giving the altitude profile of this mission. By doing this, the delay before re-entry was efficiently shortened; it has been assessed that the re-entry occurs before 3 years.

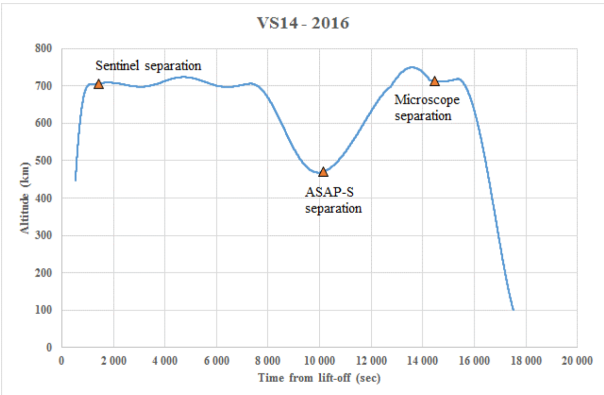

Figure 8 – Altitude profile of VS14 mission (2016)

Both missions have required 5 boosts of the upper stage, but the 2016 mission profile was more complex to design, taking into account all constraints, in particular the visibility of all active phases. The main drawback of this second case was the fact that the separation of the ASAP-S had to be made out of visibility from a ground station. This might be risky for the future flights, as no information from this phase could be made available in the event of significant anomaly.

GTO missions

For the Ariane 5 GTO missions performed by Arianespace, the upper stage (ESC-A, Etage Supérieur Cryotechnique – Cryotechnic Upper Stage) is left at the end of the mission in an orbit presenting an osculating perigee of about 250 km, which gives a sufficient level of confidence to respect the re-entry before the 25 years criteria. Nevertheless, some orbital perturbations (Sun and Moon effects in particular) may be such that the lifetime in orbit is increased beyond 25 years.

For a recent flight of Soyuz (VS16 – January 2017), the upper stage performed a perigee reduction maneuver to reach an osculating value of 200 km, for which it has been demonstrated that the lifetime in orbit was below 25 years with a good confidence level. The main drawback was linked to the delay between the separation of the Spacecraft and the end of this maneuver, which was about 5 500 sec, to increase the efficiency of the ΔV to reduce the energy of the orbit, during which the launcher had to be maintained operational.

To implement similar capability with Ariane 5, it is necessary to keep the upper stage alive during an extra 1.5 hours which has finally an impact on the performance capability. In any case, the upper stage engine (Hm7b) inherited from Ariane 4 cannot be reignited. To generate thrust, the engine can be utilized with the residual LH2; some demonstration flights have showed that this option is feasible. In the near future, it can be envisioned to decrease the perigee from 250 to 200 km. It can be mentioned that the ESC-A upper stage has already brought a major improvement compared to the EPS (Etage à Propergols Stockables – Storable propellant stage) of the initial Ariane 5 version, for which the perigee altitude was close to 600 km for GTO missions, rendering a perigee reduction difficult to implement, even if this upper stage is re-ignitable.

This impact has been taken into account in the development of Ariane 6, for which it is foreseen to keep the launcher operational up to the apogee of the GTO and to realize a deorbiting ΔV leading to the re-entry of the stage. Unlike Ariane 5, the Vinci can ignite several times during the flight, with full capability of the main engine. This capability will be used to deorbit the upper stage when the apogee of the GTO is reached. One of the main difficulties of the maneuver is linked to the accuracy of the re-entry trajectory in order to target a safe zone on Earth (in an Ocean or in the sea in any case).

MEO missions

Most of MEO missions managed by Arianespace concern the Galileo one, performed by Ariane 5 and Soyuz. Even if the operational orbit is not intersecting the two protected regions A and B, all is done to minimize the risk of collision and the creation of debris.

The dispenser, which carries 4 satellites for Ariane 5 and 2 satellites for Soyuz, stays attached to the upper stage, hence limiting the number of objects left around the operational orbit.

The disposal of the upper stage consists in placing it in a graveyard orbit, after the separation of the satellites, with a difference of several hundreds of km in altitude. Initially, the goal is to obtain a non-interference between the two orbits for a delay of 100 years [3].

For Ariane 5 flights, the launcher targets directly this graveyard orbit and the satellites complete the transfer to the operational one.

For the first two Galileo missions performed by Soyuz, the target orbit was the operational one and the upper stage performed a Hohmann transfer to reach the graveyard orbit, which lengthened the mission by about 5 hours.

The post-flight analyses showed that the stability of the resulting graveyard orbits was better and satisfactory with the first option (targeting the graveyard orbit with the launcher) even if there was not absolute confidence in the 100 years requirement.

From now on, the Galileo missions performed by Soyuz and Ariane 5 are using the same strategy based on a transfer to the operational orbit completed by the satellites. This procedure is also safer than the initial Soyuz one because in case of failure of the launcher, when realizing the transfer to the graveyard orbit, a debris would have been left in the operational one.

L2 missions

Two L2 missions have been completed up to now by Ariane 5 and Soyuz. For the first L2 flight realized with Ariane 5 (V188 – 2009), nothing was done specifically for the disposal of the upper stage at the end of the mission. For this mission, some intervals of the daily launch windows have been discarded from the flight opportunities in order to guarantee no impact with the Moon and no short-term direct re-entry on Earth. Nevertheless, the ESC-A eventually did escape the sphere of influence of the Earth and Moon system. For the flight realized with Soyuz (VS06 – 2013), the upper stage completed an escape maneuver, applying a complementary ΔV of about 33 m/s shortly after the separation, that allowed it to get away from Earth and Moon.

For a L2 mission to come with Ariane 5, it is foreseen to implement an escape maneuver after the separation of the Spacecraft, using the residual pressure inside the LH2 and LOX tanks. Exiting the Earth and Moon sphere of influence will not prevent the upper stage from potentially coming back to Earth, after some years or tens of years. Even so, the escape option is preferred because it avoids the presence of the upper stage inside the Earth and Moon system, for which it is difficult to predict the long-term evolution.

Upper stage passivation

For any flight operated by Arianespace, the upper stage is passivated by emptying the tanks; this procedure is justified by several events that occurred in space and showed that many debris can be suddenly generated. It should be done even if the missions includes a re-entry maneuver, to cover the failure cases of the final re-entry boost.

5 CONCLUSION

Considering the debris mitigation aspect, the ideal way of realizing a mission with a launcher would be to place the payload(s) in the required orbit(s) and proceed with the disposal of all remaining parts by re-entering them in the Earth's atmosphere. It is not always feasible to deorbit the upper stage and even more difficult to deorbit the carrying structures, taking into account the re-ignition and the performance capabilities of the launcher.

Thanks to the ESA code of conduct on debris mitigation and the French space law to which Arianespace has to conform with, debris mitigation aspect is playing an increasing role in flight mission analysis and has significantly modified the approach of mission analyst in designing launcher injection schemes. It is now part of the constraints that are taken into account for designing the mission with the required performance and economical costs. But also with a visible reduction of launcher debris left by Arianespace launchers in outer space for most SSO and GTO missions. Remaining limitations in debris mitigation come from limitations of the launcher definition itself – definition frozen at a time when debris reduction was not a critical issue for space community (for Soyuz and Ariane 5). For future improvement of launchers debris mitigation, the French Space law imposes as well that future launchers under development to be exploited by Arianespace be design to conform with debris mitigation regulation. This applies to Ariane 6 and Vega-C and will enable to continue minimizing the number of debris left by launchers in outer space.

In both cases (exploitation of existing launchers and development of future launchers), the regulation imposed by European and French authority has created favorable circumstances for Arianespace to be an actor of this debris mitigation policy by adapting mission analysis design and future launcher design.

It is obvious that a regulation decided by the whole international space community would have even more impact on launcher debris mitigations and would lead to more virtuous injection schemes from mitigation aspects all over the world.

6 REFERENCES

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