OPTIMIZATION OF CONSTELLATION JETTISONING REGARDS TO SHORT TERM COLLISION RISKS

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1 ABSTRACT

The space debris problematic is directly linked to the in-orbit collision risk between artificial satellites. With the increase of the space constellation projects, a multiplication of multi-payload launches should occur. In the specific cases where many satellites are injected into orbit with the same launcher upper stage, all these objects will be placed on similar orbits, very close one from each other, at a specific moment where their control capabilities will be very limited. Under this hypothesis, it is up to the launcher operator to ensure that the simultaneous in-orbit injection is safe enough to guarantee the non-collision risk between all the objects under a ballistic hypothesis eventually considering appropriate uncertainties.

The purpose of the present study is to find optimized safe separation conditions to limit the in-orbit collision risk following the injection of many objects on very close orbits in a short-delay mission.

2 INTRODUCTION

The space debris problematic is nowadays no more discussed: it appears as an absolute need to limit their multiplication if we want to sustain a safe and efficient exploitation of the outer space. The first thing to do so is to prevent from any in-orbit collision between artificial satellites. In fact, in-orbit collision is the first step on the road to the Kessler Syndrome that we want absolutely to avoid.

Last few years, many private companies began to work on new orbital constellations very richly populated in satellites: OneWeb has announced a constellation of 648 satellites spread out in 18 orbital plans at an altitude of 1200km and an inclination of 87.9° [1] and SpaceX has announced another constellation of 4425 satellites disseminated on 83 orbital plans with altitudes from 1110km to 1325km and inclinations from 53° to 81° [2]. Samsung [3], LeoSat Enterprises Inc. [4] or Telesat [5], have also expressed their interest for this kind of in-orbit constellations. All these constellations are based on the exploitation of small, cheap to produce and cheap to launch satellites. With such an economic scheme, the use of multiple launchings (many satellites per launcher) seems to be a solution to focus on.

However, in this case of multiple launchings, it is essential to be sure that there is no risk of collision between all the injected bodies in a short (i.e. few minutes after the jettisoning) or a mid-term (i.e. around the orbital period duration). In fact, by definition, all injected objects will have very close orbits one to each other because the propelled phase of the launch which is the main contributor to the orbit definition is common to all of them.

It has also to be noticed that during first moments or orbits following the release from the launcher, satellites may not be operational and specifically, they could be without any capacity to control their attitude. In particular, if the attitude control of the satellite is ensured by an electric propulsive system or magnetotorquers, it is likely that this system will need a certain time delay to be turned on and configured in-orbit before being operational. Therefore, satellites have to be injected on safe orbits from their injection point to ensure that, even strictly passive, there is no risk of collision with each other. This non-collision guarantee has to be given by the launch operator and ensured by mission analysis.

In this mission analysis, launch operator has to demonstrate that it is releasing all the embedded satellites on orbits sufficiently different to ensure that there will be no overlapping of the trajectories in an time horizon defined with the satellite operator. This time horizon's definition has to take into account the delay needed by the satellite operator to manage the attitude control system. This delay should become very long (and perhaps infinite) if the satellites do not include any attitude control system as it is commonly the case for cubesats.

On the 15th of February 2017, the PSLV Indian launcher broke the world's record of the number of satellites launched on one unique rocket: 104 satellites (the Indian satellite Cartosat-2D, 2 nano-sat class demonstrators [INS-1A and INS-1B] and 101 cubesats) [6]. Such a mission is exceptional but has to be treated with a particular caution regards to the mission analysis.

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The following article is presenting classical good practices that can be used by launch operators to assess the distancing between bodies when realizing a multiple launch. Then, after introducing what could be a classical launch mission for a constellation in-orbit deployment, the article presents the different solutions that a launcher has to ensure non-collisions between all its embedded payloads. After that, an optimization of the different separations is proposed to maximize the distancing between bodies simultaneously released. At last, an optimization of the overall multiple launch missions is proposed focusing on the maneuvers of the upper stage between each jettisoning.

3 DIFFERENT WAYS TO ASSESS THE NON-COLLISION RISK

When jettisoning a satellite from a launcher, it will have to realize a set of maneuvers to join its operational orbit. These maneuvers do not necessarily begin just after the satellite jettisoning. Therefore some satellite could have operational constraints that implies to turn on progressively all the on-board systems involved in the attitude control, others can have visibility constraint or to wait availability of ground stations before acting on their orbit, others can need to calibrate their orbital control system before using it in full operational way… De facto, waiting for all these constraints to be fulfilled, the satellite will remain freely uncontrolled on its ballistic initial orbit given by the launcher. That is why it is so important that the launch operator proposes to its clients a set of maneuvers during the orbital phase of the launch mission to differentiate the orbit of each injected object. A specific analysis has to be conducted to attest the efficiency of the sequence regards to the collision risk between bodies.

Thus, the Ariane 5 user's manual [7] and the Vega user's manual [8], both edited by Arianespace, the European launch operator, include in the mission analysis the distancing evaluation between all injected bodies: "for each mission, Arianespace will verify that the distances between separated spacecraft and launch vehicle are sufficient to avoid any risk of collision and, if necessary, the separation system will be adequately tuned". To allow Arianespace to conduct this analysis, the User's Manuals are asking the satellite operator to give its flight plan description (in particular all maneuvers aiming at modifying the orbit or the attitude of the spacecraft during the firsts hours following the launch). Otherwise, Arianespace will realize its distancing evaluation considering the satellite purely ballistic.

Many techniques could be implemented to check this non-collision risk:

- One can try to inject each body on a different orbit. As an example, orbits might be differentiated through different perigee/apogee altitude, or inclination modification;
- In many cases, if orbits asked by the clients are very close one from each other, short term distancing might be implemented using the attitude control system of the upper stage between two jettisoning. Orbits will be marginally modified but distancing between bodies could be ensured. In such a case, it could be interesting to produce a statistical dedicated study to validate the lack of collision risk.
- Sometimes, it can be showed that distance between bodies is always increasing, or at last, during a certain time. In this particular case, no collision can occur.
- If the infinite increase of distance is too hard to demonstrate, it is maybe possible to show that the distance will increase monotonically till a certain safe distance and then, bodies will never come closer than this distance again.
- …

Choice of a strategy to demonstrate the safe situation should be made regards to the mission, the involved satellites, the number of satellites, the targeted orbits, etc…

In the particular case of the injection into orbit of many satellites simultaneously, as it could be the case when deploying a constellation, it suits to realize a collision risk assessment between all bodies two by two on a dedicated time horizon that could be quite long. Indeed, if there are many payloads to inject, the launcher's mission could be unusually long. The analysis will have to cover no less than all the payloads' jettisoning till the upper stage's end of life maneuver (such as potential deorbitation and, at least, passivation). It could be really recommended to proceed to this analysis during, at least, one complete orbital period following the last jettisoning. Potentially, it could be asked by the satellites operator to spread the study longer depending on its needs.

4 A TYPICAL LAUNCHER MISSION TO DEPLOY A CONSTELLATION

All the announced constellations [1] [2] [3] [4] [5] that have been presented yet evoke hundreds or even thousands satellites operating in LEO (i.e. less than 2000 km of altitude). Looking more precisely on the specific example of the OneWeb envisaged constellation [1], it appears that:

The overall network of satellite would be deployed thanks to 2 types of launchers carrying either 32 or 2 payloads. The targeted orbit is not the operating one but would be at a very lower altitude (around 450 to 475km for the injection compared to an operational altitude of

1200km). The upper stage of the launcher will be deorbited just after the end of the deployment of all its embedded clients. Thus, the upper stage will not interfere with the just injected group of satellite. At least, the upper stage has to be considered in the distancing study till its atmospheric re-entry.

It is also announced that the satellites will fly up till there operational altitude following spiral orbits using low-thrust Hall Effect ion engine. This means that the embedded attitude and orbit control systems of each satellite won't be functioning directly after the jettisoning. Indeed, these particular electrical propulsive systems need a certain time to be activated.

With such hypothesis, it is a need that every orbit where a satellite of the constellation is released is intrinsically safe enough with regards to the collision risk problematic.

Moreover, always considering these assumptions, the way up of each satellite till its operational position inside the constellation will last many weeks. Thus, it can be supposed that it won't be problematic to slightly modify the initial orbit of each satellite to guarantee the absence of collision risk. The initial added perturbation to fulfill this requirement will be easily compensated during the long ascent phase till the operational position.

It is also known that Arianespace asked to RUAG to develop a specific payload dispenser to realize the OneWeb mission [9] [10] [11]. This dispenser should be able to carry into space and to release in orbit 32 satellites in one shot. It will be organized in four tiers of eight satellites equally split all around the dispenser.

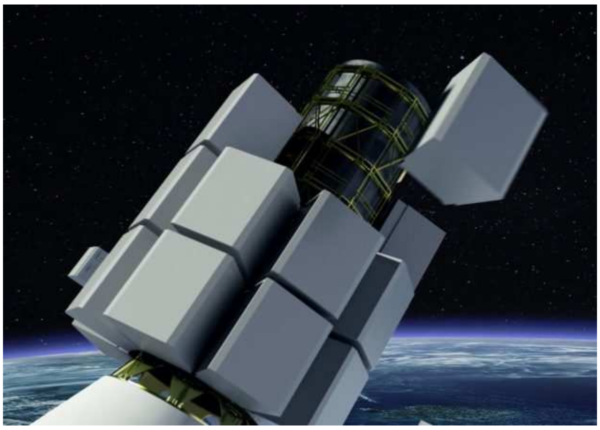

Figure 1. RUAG Dispenser for the Oneweb mission

5 AVAILABLE MEANS TO ENSURE THE NON-COLLISION

As previously said, the launch operator has the responsibility to ensure the absence of risk of collision at short or mid-term between all the injected objects via a multiple launch. To do so, the launch operator has different devices:

- The main engine of the upper stage
- The attitude and orbit control system of the upper stage
- The separation system of each satellite from the launcher
- The dispenser, if any, on which all the payloads are attached.

5.1 The main engine of the upper stage

If the main engine of the upper stage is re-ignitable, as it is on the Fregat upper stage of the Soyuz launcher or as it would be on the future upper composite of the coming Ariane 6 that would embedded the VINCI motor, it is possible to release every satellite on different orbit. These more or less important orbital modifications can be realized regards to the functional capacity of the upper stage and its engine on one hand and regards to the asked performance to the launcher on the other hand.

Thus, as an example, during the first flight of the European Vega launcher held in 2012 [12], the main payload "LARES" has been injected on a circular orbit with 1450km of altitude. Then, an AVUM main engine boost allowed reaching another orbit, elliptical (350km x 1450km), on which secondary payloads have been released among which the Almasat payload. By nature, LARES and Almasat have thus been injected on two trajectories as different as there is no risk of collision between them at short or mid-term.

Moreover, when a launcher is used to put into orbits two payloads on two really different orbits as it will be done with the Ariane 6 launcher proceeding to launch to "GTO/GTO+" orbits (meaning that the first payload is injected on a GTO [Za/Zp ≈ 250/35786 km for example] and the second one on a GTO+ [Za/Zp = 2500/35786 km for example]), the main engine of the upper stage would be used to realize the orbital modification between the two injections. The two obtained orbits are different enough to guarantee the non-collision between the two payloads.

5.2 The attitude and orbit control system of the upper stage

Usually, the launcher upper stage's attitude control system can be used to produce a longitudinal boost (inducing a translation) in addition to producing rotational movement to orient the stage. Therefore, such a boost can be used to realize a distancing between bodies. This distancing allows a short term separation between objects that ensure no interference between them (neither collision nor pollution). At mid-term, this distancing boost can also be used to differentiate orbits and obtain two trajectories different enough to ensure that the two bodies are no more evolving in the vicinity one of each other. To realize such an orbit differentiation, only a few meters per second's boost can be sufficient.

5.3 The separation system

To attach a payload on the launcher upper stage, an adapter is generally used. This adapter includes a separation system [13] that will be used during the orbital phase of the launch to jettison the satellite.

This jettisoning system, by definition, gives to the payload an additional velocity. This additional velocity (noted "ΔV") is classically included between less than an half of a meter per second and few meters per second. Integrated along the time, this ΔV should allow to generate a comfortable distance between bodies. The mere fact that a waiting time is included in the orbital sequence of the launcher will allow the two bodies to move forward along their own tracks and generate distancing between bodies. Hundreds meters distance can be achieved by this way in few minutes.

It is sometimes more simple not to do any additional maneuver and to take benefits of orbital mechanics and natural evolution of objects in space along the time to obtain a proper distancing allowing each object to evolve without interfering its launcher's co-passenger.

5.4 The dispenser

For certain multiple launches, the satellite adapter could be designed to ensure the short-term in-orbit collision risk avoidance.

As an example, ESA uses a specific dispenser to deploy the Galileo satellites (launched by pair with a Soyuz launcher or four by four with an Ariane 5 launcher) [14] [15]. This specific dispenser guarantees by construction that the satellites will not collide few minutes after their release:

Figure 2. Galileosat jettisoning from Fregat (courtesy ESA – P.Carril)

Satellites are jettisoned simultaneously two by two by opposed pairs on the dispenser. Thus, directions of separations are opposed by construction.

These directions being radial regards to the longitudinal axis of the launcher, the short-term non-collision is ensured by mechanical construction of the separation.

Concerning the mid-term analysis: considering the nominal case of the jettisoning, the two simultaneously jettisoned payloads are supposed to have the same mass, an equivalent position of their center of gravity and an equally calibrated separation system. Thus, the upper composite will not see any force or perturbing torque and both satellites put up two equals ΔV in norms and direction with opposite ways. This will place the two bodies on two trajectories that will not intersect before a complete orbit (meaning little bit more than 14h for Galileosat). Moreover, the separation ΔV induced by the release system is tuned to have a non-null projection along the orbital velocity of the stage. Thus semi-major axis will be differentiated (one satellite will have an increased semi-major axis and the second one will have a decrease of its semi-major axis while the one of the upper stage will remain unchanged) and orbital periods will be affected in the same way. Thus, even if the orbits will intersect because the separation point will belong to all trajectories, each object will come back at this common point at a different instant (till the orbits resynchronization that will occurs in many orbital periods).

Proceeding with such a dispenser will ensure that there is no risk of collision in the nominal case at short and mid-term.

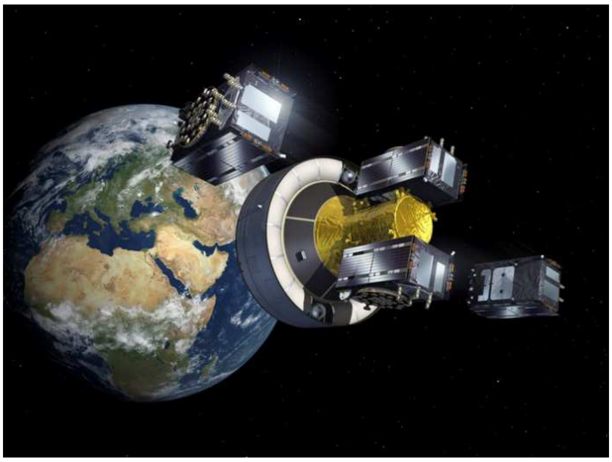

Figure 3. Galileosat jettisoning from Ariane 5/ES (courtesy ESA – P.Carril)

The other well-known dispenser that already flew all over the world is the concept of cubesat dispenser. These canons as the P-POD [16] or the ISIPOD [17] allow fixing many cubesat on the launcher and normalizing the jettisoning technics. These dispensers are directly treating the non-collision problematic between cubesats they release.

6 JETTISONING OPTIMIZATION TO MAXIMIZE DISTANCING BETWEEN SATELLITES OF A SIMULTANEOUSLY SEPARATED GROUP

6.1 Separation ΔV and orbital mechanic

When many satellites are jettisoned simultaneously from the same launcher's upper stage, as in the previously mentioned example concerning the Galileosats, one can try to take benefits of the separation system to induce orbit modifications. Thus, each body could be placed on a different orbit. Going further, this separation could be optimized to maximize the distancing between bodies in short or mid-term.

In this paragraph, three types of maneuvers are studied regards to the direction of jettisoning. These directions are expressed in the Local Orbital Frame at jettisoning defined as:

- Origin: center of mass of the satellite
- T (X axis): unit vector in the direction of satellite's velocity vector
- W (Z axis): unit vector in the same direction as the orbit's angular momentum vector, that is, perpendicular to the orbit plane
- N (Y axis): unit vector chosen so that the (X,Y,Z) trihedral is direct.

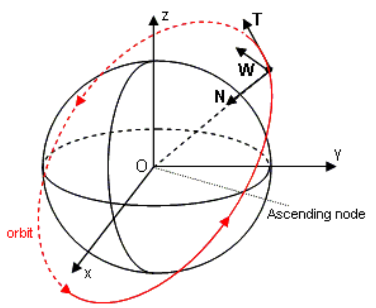

Figure 4. Local Orbital Frame Definition

The three studied separation are along T, along N and along W.

6.1.1 Separation along T

The following figure presents the effect of an additional ΔV in the direction and the way of the orbital velocity on the orbital period (in seconds) and the perigee altitude (in km). These curves are assuming an initial circular orbit with a varying initial altitude from 400 km to 1500 km (represented through different colors).

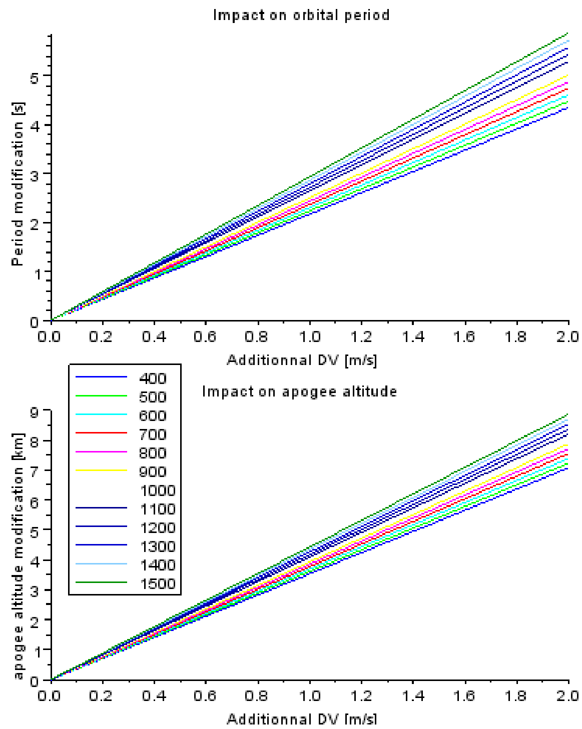

Figure 5. Impact on orbital period and apogee altitude of a ΔV realized along T

One can see that a ΔV around 1m/s induces an apogee altitude modification around 4km. In the same time, the orbital period is increased by 2.5 seconds. This means that if two payloads are jettisoned from the launcher's upper stage in the velocity direction, one in the same way and the second in the opposite way, both with a norm of 1 m/s, it allows three objects on three different orbits with apogees spread out on 4 kilometres two by two and that intersect on perigee (point of the separation). This common perigee will be joined by each object at different dates with 2.5s between two consecutives objects. As a reminder, the orbital velocity for objects on such trajectories when crossing their perigee is between 7.11 km/s and 7.68 km/s. That means that their distancing at this common perigee should be between 17.8 km and 19.2 km two by two.

Note: all the previous calculations do not take into account perturbations other than J2 (first harmonic of the terrestrial potential) what is acceptable for a time horizon as short as one orbit.

6.1.2 Separation along W

If the jettisoning ΔV is realized in a perpendicular direction regards to the orbital plane, most part of the maneuver will induce a modification of the orbital inclination of the jettisoned payloads. However, such a maneuver is known to be much less efficient to modify the orbit than the one in the plan of the track. Thus, even with a ΔV maneuver ten times more powerful than the previous one, the induced modification of the orbital period regards to the upper stage's one would be between 0.015s to 0.020s and the apogee altitude would be modified by 25m. The inclination modification would be less than 0.1°. Note that these differences would be obtained between each satellites and the launcher upper stage but both satellites would have the same modification and thus the same orbital period. Therefore, they would come back on the orbits' intersection point at the exact same date. This type of jettisoning is then not satisfying.

These results are presented in the figure below:

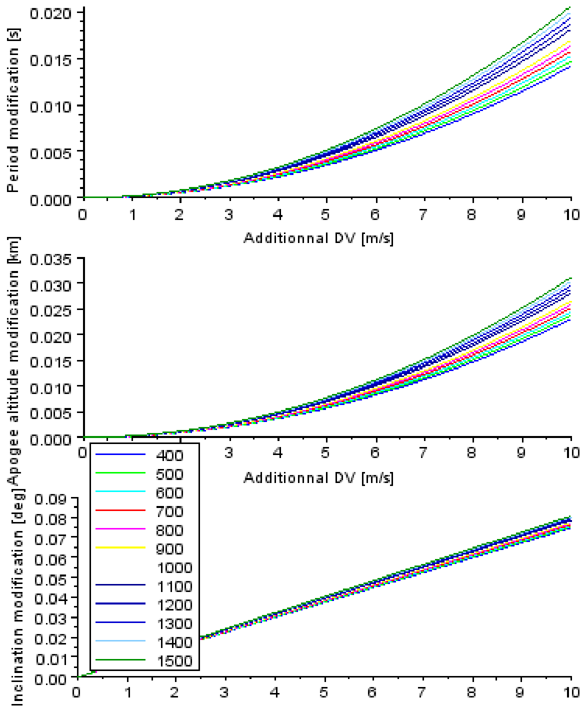

Figure 6. Impact on orbital period and apogee altitude and inclination of a ΔV along W

Note: Such a ΔV along W could also affect RAAN but without interest regards to collision risk.

6.1.3 Separation along N

If the jettisoning ΔV is produced in the orbital plane but perpendicular to the velocity, the effect on the apogee altitude seen on the Figure 8 is almost completely compensated by a modification of the perigee altitude. Thus, the orbital period is nearly unmodified regards to the launcher's one and the argument of perigee is turned to ±90°. This means that the two orbits will have two common points with one being where the jettisoning occurred. As the orbital period is not that much modified, the distancing between jettisoned bodies and upper stage will not be important when coming back at this point. Moreover, the two jettisoned bodies have the same orbital period modification and will join again each other when coming back on the jettisoning point of their orbits. Then, such a maneuver cannot be considered as acceptable.

On the two following figures are presented the previously evoked results with "alpha" known as the angle between the orbital velocity and the additional ΔV given by the jettisoning:

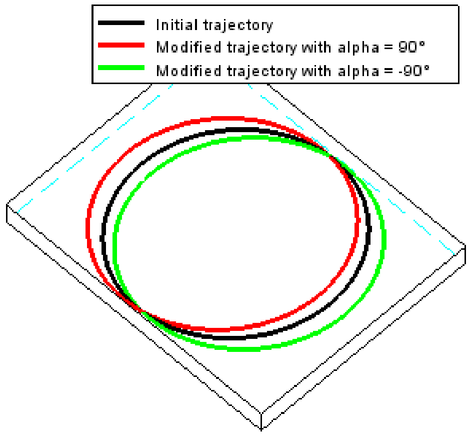

Figure 7. Obtained orbits after two jettisoning realized along ±N

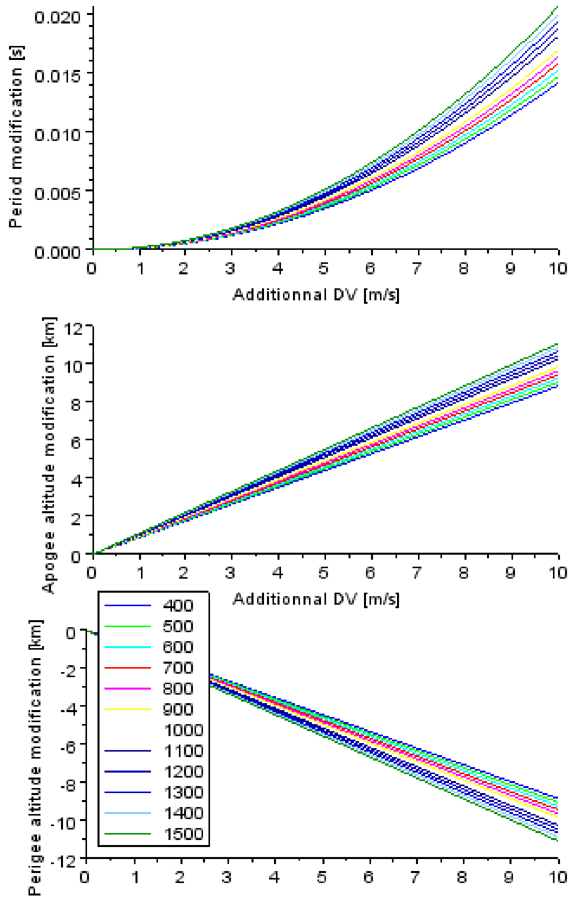

Figure 8. Impact on orbital period, apogee and perigee altitude of a ΔV realized along ±N

Note: Such a ΔV along N will mainly affect eccentricity with no modification on the orbital period and then no interest regards to collision risk.

6.1.4 Conclusion

One can conclude that to induce as efficiently as possible an orbit modification with the separation system, it is more useful to realise the separation in the orbital plane. Similarly, to maximize the ΔV effect on the orbital parameters modifications, in particular the semi-major axis and the eccentricity that will induce an orbital period shift of the bodies, projection of the jettisoning ΔV along the orbital velocity of the upper composite has to be maximized.

However, when two bodies are jettisoned in the same way relative to the velocity (both increasing either decreasing the object's velocity), if the ΔV projection along the velocity is equivalent (see Figure 9.1), orbits won't be discriminated. Indeed, such a case will induce two equal increases of apogees. Semi-major axis would remain identical. Even if short term evolutions will not be a problem (the distance between the two objects will increase because of the opposite modification of their argument of perigee), after one complete orbit, the two objects will come back to the common point of the trajectories (the jettisoning point) at the exact same time because the orbital periods will have been modified in the same way. The effect of such a separation on the orbits can be represented as follow:

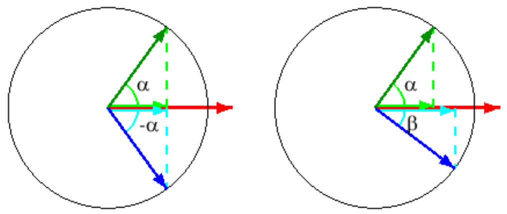

Figure 9.1 and 9.2 Projections of jettisoning ΔV (green & blue) on the orbital velocity (red)

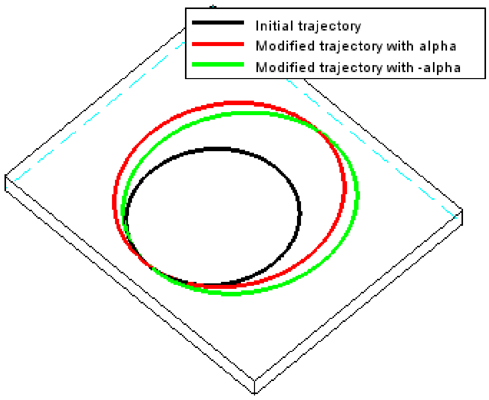

Figure 10. Orbit modification induced by a jettisoning as represented in Figure 9.1 of the composite (same semi-major axis, different argument of perigee)

6.2 Separation ΔV optimization

Under the assumptions that:

- orbits of the different injected bodies will be as much differentiated as the separation ΔV projection along the velocity is different from one payload to another,
- projection of the ΔV along the velocity shall be maximized to maximize its effect on the orbit's modification,
- magnitude of delat-v losses are comparable in the different directions of separation

thus, direction of payloads' separations regards to the orbital velocity can be optimized depending on the number of simultaneously jettisoned objects.

If it is considered that jettisoned satellites are evenly distributed around the launcher and if the angle between the orbital velocity of the composite and the first satellite's jettisoning direction is called "α", "α" can be optimized to maximize the difference of orbital modification between bodies.

In order to find this best attitude angle for separation, the velocity of each jettisoned satellite is projected along the launcher orbital velocity (as represented on Figures 9.1 and 9.2). The figures hereunder show the normalized sum of the differences between each projected satellite versus the jettisoning angle of the first satellite counted from the orbital velocity. Curves are shifted among different numbers of injected satellites to improve readability on the first graph.

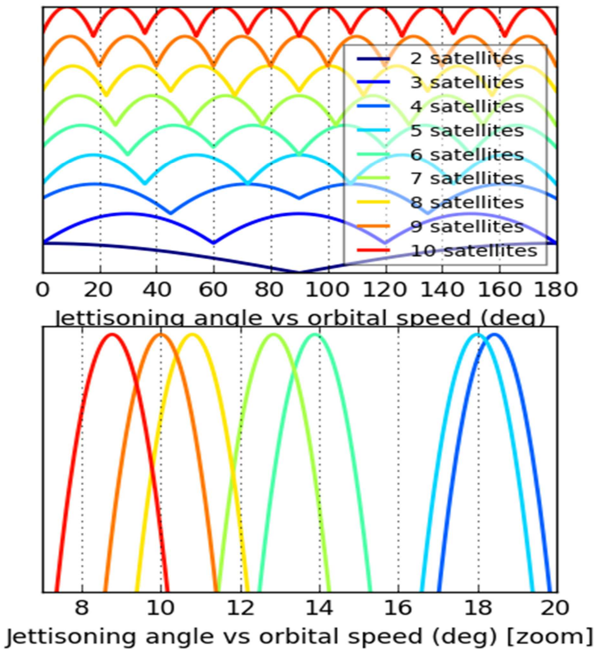

Figure 11. Optimization of the jettisoning angle (counted from the orbital velocity) and depending on number of simultaneously injected satellites

To synthetize, one can represent on the following figure the optimized jettisoning directions relative to the orbital velocity at the separation regards to the number of simultaneously jettisoned payloads:

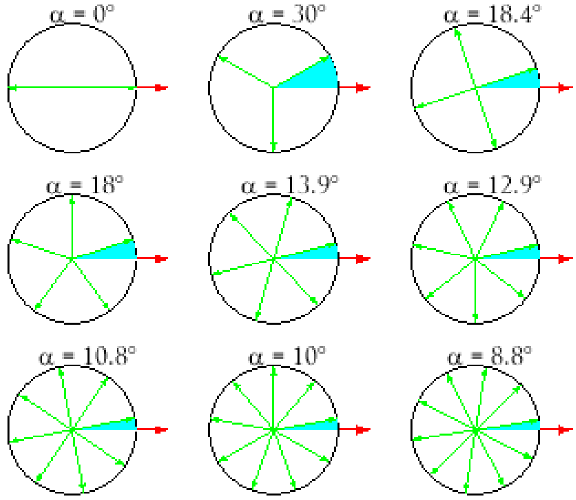

Figure 12. Optimized jettisoning direction regards to the orbital velocity (in red) and number of simultaneous ejections

Note: On the previous figure, dispenser is shown from the top and satellites are jettisoned radially.

Using the previously optimized separation angles, objects are injected on orbits that have different semi-major-axis (inducing different orbital periods and so, re-phasing is avoided when coming back on the common point of the trajectories that is the jettisoning point) and that have also different arguments of perigee (due to jettisoning ΔV not aligned with orbital velocity). As an example, when jettisoning simultaneously four bodies with ΔV that have the same amplitude and the angle α=18.4°, it generates four new orbits that can be represented as follow:

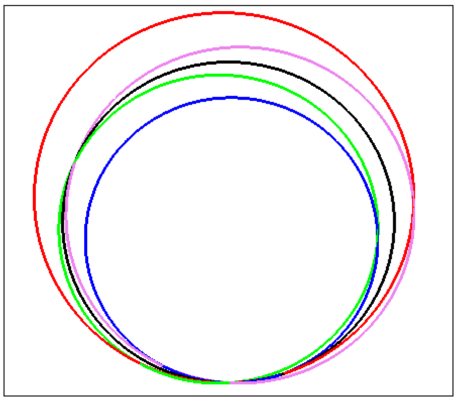

Figure 13. Amplified effect of the different orientations of the separations on the achieved orbits (black is the circular original one)

6.3 Separation ΔV optimization's limit

The previous results show that the more important the number of simultaneously jettisoned payloads is the more important the jettisoning's precision is. Indeed, as dispersions will be added to the system, it has to be controlled that differences between projections of ΔV along the orbital velocity are not nullified. Dispersions can come from:

- roll angle of the upper stage (i.e. ability of the attitude control system of the launcher to maintain a certain "α" angle with a certain precision)
- amplitude of each separation ΔV
- pointing of each separation system (as an example, if the payload is pushed by many springs, if every springs are not perfectly settled, a dispersion could occurs in direction or in amplitude of ΔV or even in attitude of payload)
- guidance, navigation and control systems and associated algorithms that could generate attitude depointing

Looking at the example of an octo-jettisoning, an error of ±5% on the amplitude of the realized separation ΔV can induce a reduction of the difference of the projection of the ΔV along the velocity of almost 58% between the two bodies separated with α = ±10.8°.

An other example is coupling an error of roll pointing of 1° with an error of the jettisoning direction of 1° and this error of 5% on the amplitude could reduce the difference of projected ΔV along the velocity of almost 75%.

It can be concluded that even if optimized angles have been determined to maximize distancing between simultaneously jettisoned bodies, it would be better not to separate more than four or five bodies in a row to ensure keeping enough distancing including dispersions.

7 SEQUENCE OPTIMIZATION BETWEEN TWO JETTISONING

If one launcher is injecting about thirty payloads in orbit on one flight, previous recommendation not to jettison more than four or five payloads simultaneously induces the need to design an orbital sequence to separate successively all the satellites. This sequence can also participate to the global distancing between bodies.

First of all, applying the previous logic, the angle between separation direction and orbital velocity can be optimized. As an example, considering 32 satellites to jettison (this example is studied all over the present paragraph), it would be optimized to fix α = 2.8°. Thus, there could be eight successive separations of four payloads with the following angles: [2.8° - 92.8° -

182.8° - 272.8°] then [14.05° - 104.05° - 194.05° - 284.05°] then [25.3° - 115.3° - 205.3° - 295.3°]… This would be manageable with a roll maneuver between each jettisoning. This technique will lead to the same problem of precision as presented previously and so, is not recommended.

It is preferably envisaged to separate satellites always with the same “α” angle adding a delay between separations allowing the composite and the remaining satellites to travel along the orbit. Thus, the true anomaly won’t be the same at instants of separations and orbits would be well differentiated being distributed along the initial circular orbit. “α” angles of separation would thus be: [18.4° - 108.4° - 198.4° - 288.4°] then [18.4° - 108.4° - 198.4° - 288.4°],… If these separations are evenly distributed along one complete orbit, the figure 12 represents the eight orbits obtained for the payloads jettisoned with α = 18.4°.

Proceeding like that, on each separation, distancing is maximized for simultaneously jettisoned satellites and the added delay allows generating difference of argument of perigee between groups of satellites to minimize the risk of resynchronization.

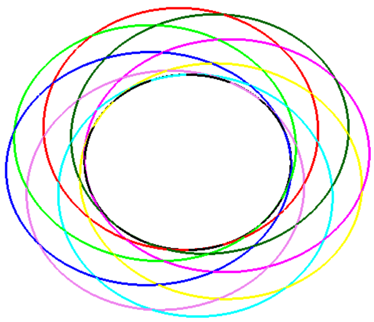

Figure 14. Different orbits organization playing on anomaly and keeping the same orientation vs. velocity

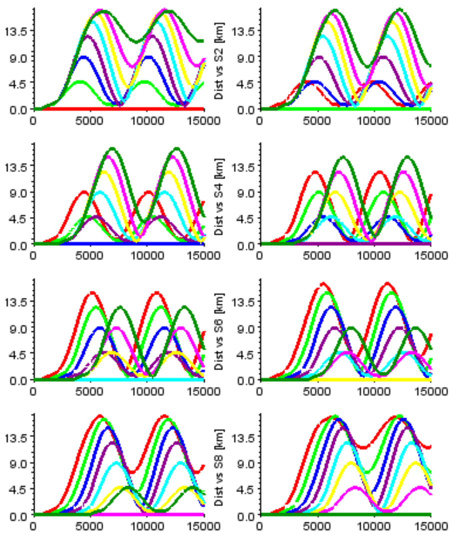

Figure 15. Distancing evaluation [km] vs. time [s]

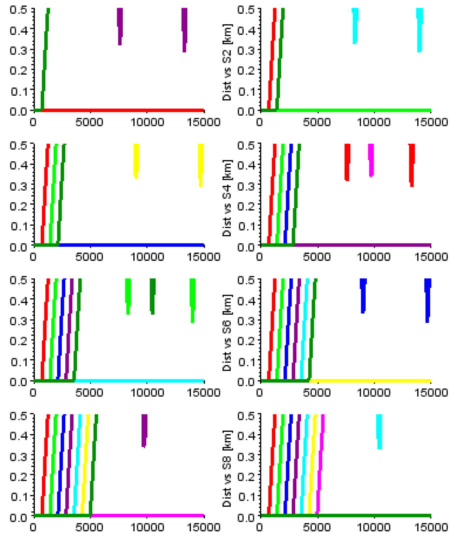

Figure 16. Zoom of Figure 13 for close approach verification

Figures 13 and 14 above are presenting the distance between each body injected as described on Figure 12 with a separation ΔV of 1m/s starting on a circular orbit 500km height. Time (in seconds) is on abscissa and distancing (in km) between bodies two by two is on ordinate. The first curve (up-left corner) is showing the distance between the “red” payload of Figure 12 and the seven others (one per color); the second curve (up-right corner) is showing the distance between the “green” payload of Figure 12 and the seven others (one per color); etc. It can be seen that during the two orbital periods following the last jettisoning the minimal distance between two injected bodies is around 275m.

It can also be noticed that, choosing to add delay between jettisoning to separate satellites on different true anomalies has another benefit: each separated body will move away from the upper composite and, at the same time, from other satellites to be injected. Thus, benefit is taken in a passive manner from elapsed time to generate “freely” distancing between bodies.

However, attention may be paid to constraints coming from the launcher or from the satellite operator: the complete jettisoning mission of the constellation could be limited in time (constraint coming from the available onboard electrical energy for example) or constrained by visibility from ground stations (if the constellation operator wants to see each separation with a direct telemetry link for example). These constraints can strongly limit the possibilities to establish the orbital jettisoning sequence.

Another interesting solution allowing ensuring a good distancing between all injected bodies could be to generate an orbit modification of the upper composite between each separation. Thus, as an example, if the main engine of the launcher’s upper stage is re-ignitable, or if the attitude control system of the stage is strong enough, they could be used to modify the orbit. This boost could be realized out of plan to generate an inclination modification of the orbit (even though this type of maneuver is not really efficient, as previously mentioned) or in plane to induce a modification of semi-major axis, eccentricity or argument of the perigee. It could be envisaged to realize a Hohman transfer-type maneuver between two successive separations of four satellites. Proceeding like that will allow injecting all bodies on circular concentric orbits of various altitudes. Such a maneuver complexity is that it is necessary to realize two boosts to join a new circular concentric orbit between each separation. The second boost will have to be realized at the apogee of the intermediate orbit meaning that it would be necessary to wait the duration of a semi-orbital period between each separation. Adding the necessary time delay to stabilize the upper stage before each separation and before each re-ignition and the needed potential time to prepare any re-ignition (propellant settling, tank pressurization, temperature management, etc.) the complete mission aiming at realizing eight successive jettisoning will last easily more than 10 hours for LEO injection around 500km. Such a time of mission is particularly long for launcher's mission and seems to be quite complicated to realize. Moreover, generally, the number of re-ignition of a launcher main engine is limited and 16 re-ignitions sounds very improbable. The utilization of a kick-stage overhead the launcher's upper stage could be a solving solution to achieve such a long and complicated mission.

8 DEPLOYMENT STRATEGY ANALYSIS

All the previously presented principles have been applied to set a strategy of in-orbit deployment of 32 satellites in one multiple launch. Different strategies have been tried:

- Satellites jettisoning by groups of two, four or eight
- Addition of waiting time between each jettisoning
- Addition of boosts to modify the orbit between each separation

For each studied case, the only way to evaluate the efficiency of the sequence is to extrapolate the orbits of all the implied objects and to study the distancing between all the bodies two by two. This study will allow checking the sufficient distancing.

It can be checked that all the distances between bodies are increasing since the injection but also that bodies are not coming closer from the others when orbits are resynchronizing. To do so, it is strongly recommended to check distancing at short term as well as at mid-term.

Curves like the one showed on the following figure allow evaluating the acceptability of the sequence regards to the distancing problematic:

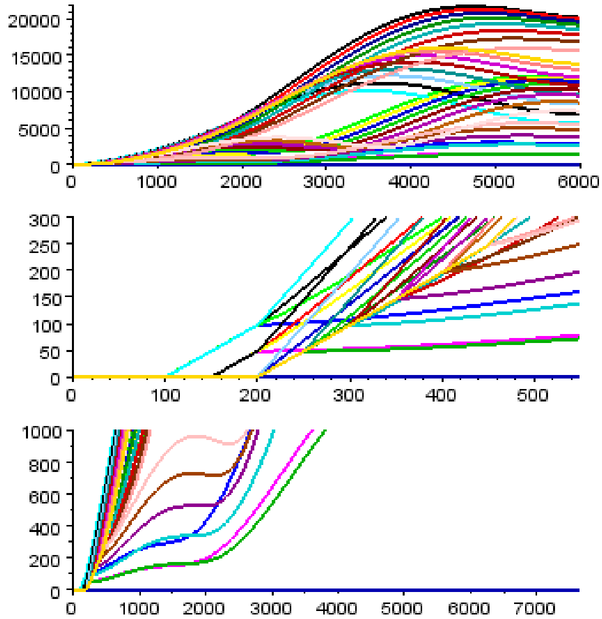

Figure 17. Proposition of sensible parameters monitoring (distancing vs. time)

On this figure, it appears first the distance evolution between all injected objects and one reference object of the constellation through more than one orbit. Then, it has been figured the very short term distancing around the reference object's jettisoning. Finally, the long term and short distance evolution has been tracked to check the potential resynchronisation of bodies.

This type of representation has to be prepared and analysed for each injected body.

Moreover, as seen earlier, dispersions have to be taken into account in the calculation. That means that statistical approach has to be envisaged to ensure a global treatment of the distancing problematic. So it is recommended to proceed a Monte-Carlo study taking into account dispersion on the angle of separation of every satellite and amplitude of the jettisoning ΔV. The results of such a Monte-Carlo analysis has to highlight the closest approach to be feared of and it would help to adjust the tuning of the orbital sequence leading to the deployment of the constellation (increase a distancing boost, adjust a waiting time, modify an orientation, …).

9 CONCLUSION

The multiplication of the in-orbit constellation projects induces a specific reflection on associated launchers' missions. Indeed, the simultaneously injection of numerous satellites questions the security of the constellation regards to the in-orbit collision risk at short or mid-term. It has been shown that the direction of separation of simultaneously object can be optimized with respect to the collision risk problematic. We also introduced the different devices the launch operator could use to minimize this risk of collision between the simultaneously injected payloads.

In any case, it seems necessary for the launch operator to produce an in-depth study of the in-orbit collision risk at short or mid-term after the jettisoning of all the payloads. Indeed, beyond the optimization of the jettisoning direction and the in-between maneuvers that the launcher could produce during the orbital phase of its mission, it seems essential to check via orbits extrapolations that all injected bodies do not come to close one from each other. As it seems impossible to develop a theoretical orbital sequence that covers all the aspects that have been presented in this paper (in-plan distancing, out of plan distancing, eccentricity distortion, desynchronization of orbital periods, etc…), in particular taking into account all the dispersions associated to the mission (pointing precision of the launcher, precision of the separation's direction or the separation's amplitude), the best way is to realize a specific study extrapolating all implied orbits and checking distancing of bodies two by two. After a first study performed on nominal case, a statistical analysis has to be completed to adjust the tuning of the sequence parameters regards to the ΔV amplitudes, jettisoning directions, waiting times between separations, distancing boost to perform with the upper stage, etc. with the objective to ensure a closest approach as big as possible on a time horizon as long as possible.

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