Just-in-time Collision Avoidance (JCA) using a cloud of particles

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ABSTRACT

Collisions among large cataloged objects statistically happen every 5 to 10 years.

When an operational satellite, maneuverable, is implied in such a potential collision, its trajectory can be modified in what is called a Collision Avoidance Maneuver.

But when both objects are debris, dead, or operational but non maneuverable, avoiding a collision is obviously more complex.

Several potential solutions are nevertheless under study and progress reports have been published; for instance, the use of lasers, either on ground or in orbit, can potentially nudge one debris with a magnitude large enough to prevent the collision.

Other solutions have also been presented, considering the insertion of an artificial atmosphere in front of one of the two debris with the goal to induce a drag, hence a modification of its orbital parameters, enabling after several orbits to induce a margin between the two objects preventing the collision.

Trajectory modification using a cloud of particles has been studied since several years, aiming at optimizing such a system, considering three topics leading to a proof of feasibility.

- The first topic consists in evaluating the quantity of gas and particles necessary to achieve an efficient deviation, and the corresponding optimization of the braking cloud,
- The second is linked to the mission itself, identifying the requirements for the vector carrying the cloud generation mechanism at the requested altitude, including the required precision and the number of launch bases
- The third topic is the cloud generation mechanism itself; it was found that the most efficient braking cloud should consist in very small solid particles with very low velocity. A brainstorming effort led to the identification of several promising solutions, and a definite proof of feasibility

The paper deals with the tradeoffs associated to the three aspects of the question, and proposes a potential solution, hoping to raise interest and lead to an international effort to develop such a collision avoidance solution.

1 CONTEXT

The ever-increasing number of space debris raises numerous concerns, casualty risk on ground following uncontrolled reentry, damage of operational satellites, or generation of large number of new debris following massive collisions.

This risk of major catastrophic collisions in orbit between two large non-maneuverable objects is the most critical for long term sustainability of space operations as it leads to a cascading effect, potentially uncontrollable, known as the Kessler syndrome [1]. The problem comes from the fact that among the 20,000 large objects currently in the public catalog, 2,000 only are operational, among which 1,500 are maneuverable, 7.5% of the population, capable if necessary to perform an active collision avoidance maneuver. Such maneuvers are very efficient to protect our most important space assets, but by definition they can be performed only when one at least of the two objects is maneuverable; it means that 86% of the collisions among cataloged objects cannot be avoided today.

Among these potential collisions, more than half of them imply one very large non-maneuverable object as more than one third of the cataloged objects are old spacecraft and rocket bodies; one can recall that according ot our collision models, it takes a debris of half a kilogram to shatter completely a 1-ton object, generating thousands of new debris.

The most critical debris have been identified, and a formalized approach is ongoing worldwide to quantify exhaustively the criticality of each large debris. Some zones are particularly well known, housing large clusters of large debris, mainly SL-8, SL-16 and associated payloads. Darren Mc Knight has extensively studied these clusters, mainly C775, C850 and C975, the figure giving the mean altitude [2] [3]. Mc Knight has shown that the situation in these clusters is not sustainable: for instance, there is a passage in C850 of two SL-16 stages (9 tons) within 200 m distance every month; there is also an average collision rate of SL-8 (1.4 tons) in C975 of 1/90 per year. Such a collision would generate a very large number of new debris and trigger a situation which may turn out to be non-sustainable at medium to long term.

To counter these collisions among large objects, two approaches can be considered, as part of the Large Debris Traffic Management (LDTM):

- The "strategic" one consists in retrieving a certain number of large debris each year, typically among these large clusters, thus reducing the probabilities of major collisions. This Active Debris Removal (ADR) strategy [4] has been intensively studied throughout the world for more than 10 years. It appears to be technically feasible, but hard to finance, and raises numerous non-technical problems such as legal or political ones. In addition, it would be quite useless as long as the mitigation rules, internationally agreed-upon, are not complied to in a much higher way; there is no use in going to deorbit a couple of large debris as long as we generate more of them continuously,
- The "tactical" one [5] [6] is aimed at lowering the probability of a detected potential collision by acting on one of the two debris some time prior to the predicted collision date. This strategy is called Just-in-time Collision Avoidance (JCA). The first ideas were presented some 10 years ago, and among the solutions which have been proposed, slightly slowing one of the debris via an impulsive drag force appears promising. For the tactical approach, flexibility and reactivity are, with the perennial cost criterion, the main challenges.

2 JUST-IN-TIME COLLISION AVOIDANCE (JCA)

The principle of JCA is to impart a small ΔV to one of the two objects, aiming at slightly changing its orbit, semi-major axis and period; when this slight orbital change is propagated in time, it results in a progressive increase of the miss distance at the location of the conjunction. The higher the ΔV, and the higher the propagation time, the larger the miss distance becomes.

For instance, according to Clohessy-Wiltshire Equations of Relative Motion, imparting a ΔV = 3.5 mm/s along the velocity vector, positive or negative, induces a miss distance increase of 1 km over 24 hours. Such effect is globally linear, so ΔV = 1 cm/s 12 hours before conjunction generates a miss distance of 1.5 km.

Concerning the dimensioning of the system, it can be noted that 80% of the collisions imply an object lighter than 100 kg and 95% lighter than 1 ton, as was shown by Holger Krag [7]; this gives the possibility in most of the cases to choose the smallest debris as the target.

One fundamental hypothesis has to be made here, without which no JCA system could work: it is assumed that the accuracy of the ephemerids of the objects is much better than observed today, typically by one or two orders of magnitude. There is a lot of work ongoing on the topic, such as [8], but it clearly is not the case yet.

Various solutions have been proposed and are currently under study; to quote only a few in a non-exhaustive way:

- Laser-based momentum transfer, from laser ground stations, coupled to laser ranging, would impart the ΔV thanks to light pressure [1],

- A laser station in orbit could slightly nudge the orbit of a debris, considering lasers with very short pulses, very high fluence, vaporizing locally the surface of the debris, generating a recoil effect [8],
- An orbital cloud of tungsten dust was proposed by Sarver, quoted by Levit [9], with the global aim of "cleaning" a complete orbital region from small debris,
- A vapor cloud, kind of "space airbag", launched on a suborbital trajectory thanks to a sounding rocket, has been studied by Darren Mc Knight [10],

The authors have been studying a solution considering the launch on a suborbital trajectory of a cloud of small particles, generating some drag on the debris when it crosses it. Following the first evaluations, 3 feasibility points were raised and treated during a dedicated study performed by CT-Ingénierie-France and CNES since mid-2018, relative to efficiency of the system, phasing of the operations, and design of the particles ejector.

3 EFFICIENCY OF THE SYSTEM

Considering the 3 well known clusters of large derelict objects mentioned previously, we considered that the debris could be in any orbit between 600 and 1200 km, any inclination; we did not consider the slight eccentricity of the real orbits, as this is easily computable and does not represent any hurdle. We considered a maximal debris mass of 2000 kg; it means that when an SL-16 is associated to a collision, we would nudge the other debris, statistically much lighter than 1 ton. The 2 tons' requirement covers any collision implying an SL-8 stage.

Typical operations would be based on the initial identification of a potential collision above the admissible thresholds, 36 to 72 hours before the computed near conjunction. This would leave some time to refine the trajectory of the two objects, reducing the dispersions on ephemerids, and consolidating the probability of the collision risk. The time between the beginning of the launch operations and the application of the braking ΔV is considered to be less than 24-48 hours; it includes the time to prepare the rocket and the phasing delay linked to be at the nominal conditions for the launch. The requirement is to launch 12 hours latest before the foreseen conjunction.

The specification for the relative positioning of the particle generator and the debris is that the distance d when expelling the particles shall be less than 1 km, and the safety margin, difference between the culmination altitude of the braking system and debris orbital altitude precision shall be larger than 500 m (value which can be refined once realistic accuracy of the system is determined). The efficiency of the system as a function of the angle of the jet with respect to the orbital path has been established, and is not strongly modified between 30 and 90°. The out-of-plane trajectory of the JCA system (z on the Fig.1) can be compensated by the proper tilting of the ejector to make sure it aims at the trajectory of the debris.

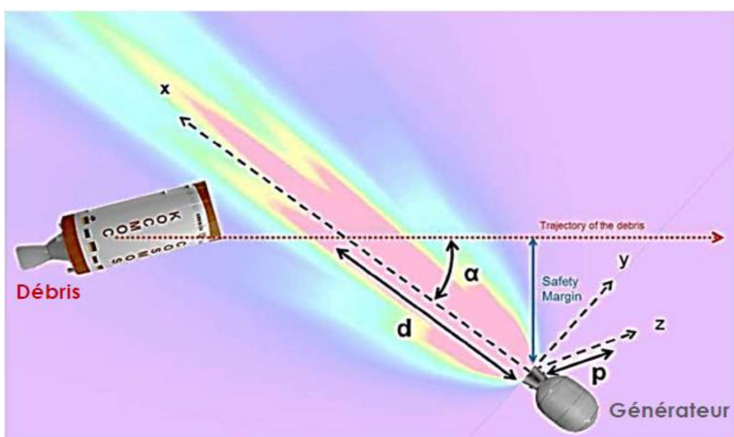


Fig. 1. Relative positioning of the debris track and the JCA system.

An example of the effect of the braking on the debris is shown in Fig. 2. This simulation shows the result of a braking of δV = 7.7 mm/s propagated during 12h on a 1200km circular orbit debris. The Fig.2 shows the new debris trajectory in a reference frame fixed to the initial debris trajectory. The reference frame is the LVLH (Local Vertical Local Horizontal) relative to the initial debris trajectory, i. e. without braking, with the axis shown as Vbar for the velocity direction (i.e. local horizontal) and Rbar for the direction from earth to the debris (i.e. local vertical). It allows seeing the effect of the braking on the debris, compared to a fictive debris which has not been decelerated.

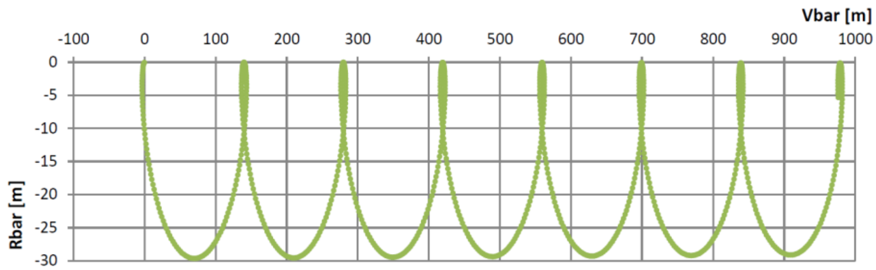


Fig. 2. Debris trajectory after braking in the LVLH frame fixed to the trajectory before braking
Braking of 7,7mm/s, simulation duration 12h

After n = 7 revolutions, i.e. almost 12h, the new debris trajectory is almost 1000m away from its initial trajectory. The avoidance distance thus depends on n, the number of revolutions the braking effect can be propagated on but also on ΔV, the deceleration transmitted to the debris. The Clohessy-Wiltshire Equations give the following formula for period difference ΔT induced by a deceleration of ΔV:

$$\Delta \mathrm{T} = -3.\, T.\, \Delta V / \mathrm{V} \qquad \text{(Eq.1)}$$

Leading to the avoidance distance δL:

$$\Delta L = -3.\, \mathrm{n}.\, T.\, \Delta V \qquad \text{(Eq.2)}$$

This calculation can be coupled with the debris mass and friction coefficient (included in ΔV calculation) to compute the required mass of particles hitting the debris, called effective mass. This is shown in Fig. 3 for a 1500kg, 800km altitude debris with a friction coefficient of 1.7. The graph shows the required effective mass depending on the avoidance distance, for 6 and 12 hours of propagation of the braking effect.

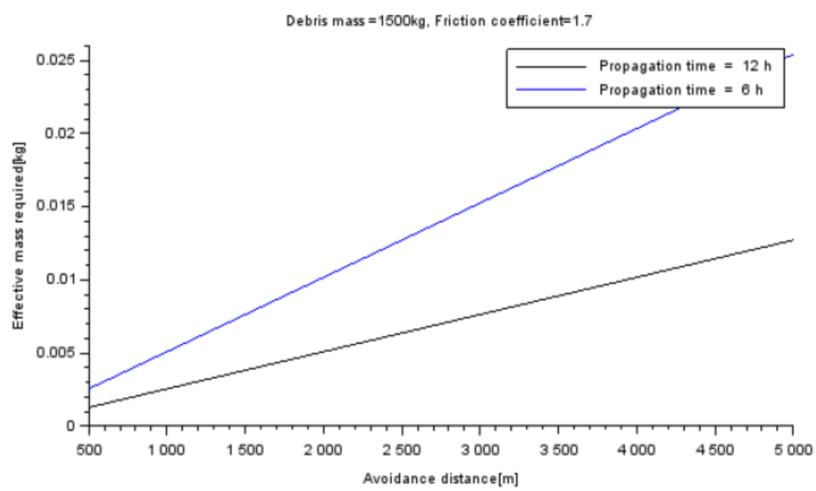


Fig. 3. Effective mass required for avoidance distance and propagation duration

As a result, the necessary effective mass required to perform the mission is surprisingly small. As a typical example, providing a ΔV = 7.7 mm/s to a 1.4 tons debris requires only 3 grams particles; applied 12 hours before the closest conjunction, it would increase the miss distance by 1 km. The main difficulty is to locate the particles cloud close enough to the target to guarantee that at least 3 grams of particles impact it!

4 PHASING OF THE OPERATIONS

One fundamental challenge of the operation is to guarantee the proper phasing of the suborbital rocket trajectory and the passage of the debris to be deflected. If, for instance, you would have only one launch base and a purely vertical launch capability only, the probability to have the debris passing precisely at the proper time and proper location would be very small. The first studies led to disregard solutions based on sounding rockets launched from ground bases, too limited in performance in general, with limited lateral deport in particular, and not optimally located. The reference solution here considers airborne suborbital rocket, enabling some cruise and adjustment to the optimal geographical location prior to the launch.

In order to reach any orbit, a certain number of ground bases from which the carrying planes can takeoff are required. This number depends on:

- The capability of lateral “out-plane” shift by the system, both the plane and the rocket,
- The delay between the decision to engage the procedure and the expected collision. Fig. 4 shows the timeline of the process: the acting time TA is the time between the decision to engage DE and the moment when it is too late to act on the debris DF. One of the requirements is that the acting time shall be small enough to cope with the precision of the debris positions prediction (TP=24h) and the braking propagation time required (TB=12h).
- The time TA is used to wait for a suitable debris pass and to launch, catch-up with the lateral deport and reach the apogee where the systems acts on the debris. Its maximum value is 12 hours but the baseline for the study is 6h

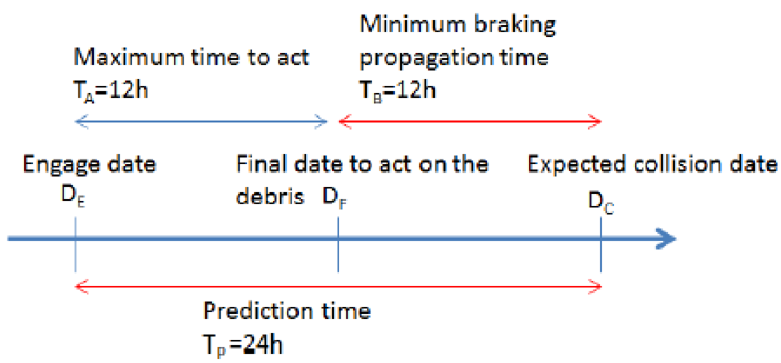


Fig. 4. Timeline

We considered bases located near the equator in order to be able to reach any orbit inclination; obviously, solutions with slightly higher latitudes would work as fine, considering the cruise range of the carrying plane. Moreover, one of the drivers of this analysis is the orbital drift, and due to the equatorial constraint, the equatorial drift. Figure 5 shows the worst case in the range of orbit studied for this analysis (maximal altitude 1200km and polar inclination 90°): up to 3060km can separate two orbits at the equator. This number was used as requirement for the plane.

Fig. 5. Maximal orbital drift

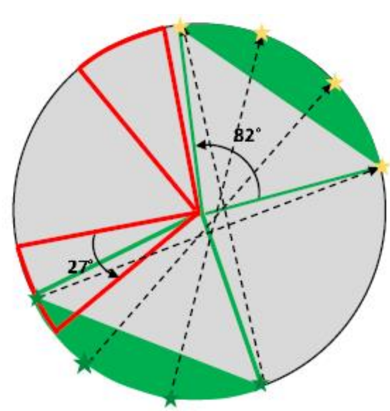


Fig. 6. Ground bases locations

A geometrical approach can be used to compute the number and locations of the ground bases. Figure 6 shows in dashed line the orbit of the debris during 6 hours in a fixed Earth reference: the ascending and descending nodes will be shifted by 82° in longitude in 3 periods (5h30), the equivalent of 3 x 3060km around the equator. The green zone shows the equatorial footprint for both nodes. One possible solution of coverage by the ground station is shown by the two red triangles. They represent the necessary coverage zone (at the equator): if both coverage zones are 27.3° large in longitude and 90° one from the other, at least one dashed line will always fall into one of the triangle. This shows that at least one opportunity for reaching the orbit occurs in 6h. If the triangles are smaller or with a different angular separation, this is not ensured anymore.

The number of bases required in this coverage zones can be computed using the apogee range of the system. Indeed, the 27.3° longitude represents 3060km on the equator. The number of bases per triangle is 3060km divided by the range of the carrying plane and launcher. The Table 1 shows the number of coverage zones and the number of bases required for a given acting time and a given launcher range.

Table 1. Number of bases required

Acting time	Range (km)	Total number of bases required	Number of coverage zones required
6h	3060	1+1	2
	1530	1+1	2
	765	2+2	2
	383	4+4	2
	191	8+8	2
	96	16+16	2
12h	3060	1	1
	1530	1	1
	765	2	1
	383	4	1
	191	8	1
	96	16	1

This table shows a worst case of 32 bases, for a worst case of a range lower than 100 km and an acting time limited to 6 hours; this would simply be too expensive and complex to manage and keep operational 24/7. On the opposite, considering an acting time of 12 hours with a 1000 km range for the plane would necessitate 2 departing bases at the most. This explains the need for a large range or a large acting time in order to reduce the number of bases. With the air launched system considered as reference here, the range will be done by the carrying plane. Improvement of the Space Situation Awareness and the accuracy of the observations and ephemerides of the space debris will also tend to increase the acting time.

It is also important to mention the redundancy of the bases. Indeed, if for a meteorological reason, one of the bases is unable to perform the required launch, another base shall be able to replace it and perform the launch. This particular problem is very global and has not been addressed in this study but will impose extra bases to the system.

5 PARTICLE EJECTION

The initial simulations performed on the system [11] were based on a cloud of combustion gases coming from a Solid Rocket engine. The conclusion of that study was that solid particles impact would be much more efficient, and that the ejection velocity should be as low as possible in order to avoid too much dispersion.

The current study therefore considered as baseline small solid particles. These particles should be of high-density to keep the jet direction and avoid diffusion with gas expansion; they shall have a maximal size of 50 to 100 µm in order to avoid significant ejecta at collision on the debris, but have a size of 5 to 10 µm at least to be efficient. We wanted particles to be commercially available off-the-shelf, cheap, with a constant diameter. As an arbitrary choice, we considered an action of the ejector during 10 seconds, in order to have some built-in robustness. The total mass of particles resulted to be in the range of 10 kg. We selected 50 µm copper marbles, but similar highly dense material could work as well.

A very wide trade-off was performed to find the best concept for the ejector. More than 12 potential solutions and variants were identified, and the selection was done following a Model-Based System Engineering (MBSE) approach, considering as major criteria the global mass, the reliability of the complete function, the dispersion of the particles cloud both in time and in space, and the availability of the solution, TRL and Cost.

The preferred solution turned out to be a classical bladder tank, such as widely used for propellant tanks on satellites and launcher stages. The principle is described in Fig. 7, from [12]: the tank is composed of an external metallic shell and houses an internal polymer bladder which crushes around a stand-pipe with holes. The volume between the external shell and the bladder is pressurized using a neutral nontoxic gas, and the volume inside the bladder contains the fluid which has to be ejected. The stand-pipe enables the expulsion of the fluid through the tank liquid discharge orifice which include a pressure regulator (if necessary) and a nozzle (not shown on the sketch).

We selected one well-known tank, used on Ariane 5 but also on the ARD reentry demonstrator flown in 1998, pictured in Fig. 8 from [13]; it is manufactured by ArianeGroup and is an off-the-shelf product.

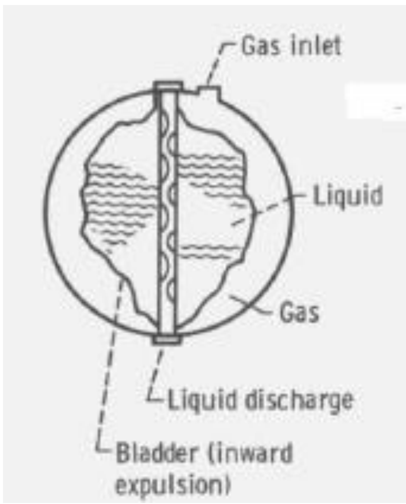


Fig. 7. Schematic of a spherical bladder tank [12]

Fig. 8. Ariane 5 58 litre hydrazine bladder tank [13]

This tank, 48 cm in external diameter, has a total volume of 58 liters and an internal volume of 39 liters. The external shell is made of Titanium Ti6AlV and the bladder is made of Ethylene-Propylene-Dyene monomer. The Maximal Expected Operational Pressure MEOP is 26 bars, and the Burst Pressure is 52 bars. We would use dry air or Nitrogen for pressurization.

The fluid shall have a high viscosity in order to guarantee the dispersion of the particles in the fluid stable in time with no sedimentation during storage or under the acceleration forces of the flight. Calculations were performed for a variety of fluids to determine what the maximal migration velocity U_{tc} would be following Eq. 3, for a particle of diameter d and density ρ_s, under an acceleration g, migrating in fluid with density ρ_L and dynamic viscosity µ.

$$U_{tc} = \frac{d^2.g}{18.\mu}.(\rho_s - \rho_L) \quad \text{(Eq.3)}$$

This principle was evaluated for d = 50µm copper particles with an acceleration of g = 50 m/s², which is by far the worst condition that would occur in the life of the system, as if the maximal trajectory acceleration was applied constantly. Application of this principle to water, oil SAE10W and glycerin, shows migration velocities respectively of 5.6 cm/s, 0.56 mm/s and 36 µm/s; in this last case, with glycerin, the particles would not migrate at all and remain well dispersed within the fluid.

The tank itself, bladder and stand-pipe included, has a total mass of 8.5 kg. We consider an additional dry mass of 6.5 kg to take into account regulator, valves, throat, nozzle… We would load the tank with 17 kg particles, 33 kg glycerin, 700 g pressurized Nitrogen, leading to a total mass for the ejector system equal to 65 kg.

6 SYSTEM ARCHITECTURE

Numerous air-borne launcher have been studied since decades, so the performances of such systems are well known. A bibliographic study was performed considering a 2.8 tons' sub-orbital rocket, 7 meters long and 90 cm in diameter (values are justified later in the paper). Considering business jet, fighter aircraft, commercial aircraft and dedicated planes, the final choice was to baseline business jets such as Dassault Aviation Falcon 7X or Gulfstream IV. The Falcon 7X for instance would have a published range of 8800 km with the rocket defined above, carried under its fuselage. Performances are very similar for the Gulfstream, as presented for instance in the GOLauncher-2 from Generation Orbit, Fig. 9.

The preliminary concept for the sub-orbital rocket is a three stages vehicle:

- The first stage performs the atmospheric phase, from the separation with the plane to the edge of atmosphere, with a guidance law based on incidence; its propulsion is based on storable non-toxic liquid propellants such as H_2O_2-Kerosene,
- The second stage provides most of the ΔV and enables to reach the target point for the separation with the 3rd stage performing a dog-leg if necessary to reach the proper azimuth. It uses the same kind of propulsion as the 1st stage and includes the performance reserve required to compensate the scattering in hardware definition, as well as atmospheric dispersions,
- The 3rd stage aims at performing the final approach and rendezvous, and the proper orientation of the particles ejector; it is 3-axis controlled and potentially uses a monopropellant system.

Fig. 9. GOLauncher-2 [Generation Orbit]

Fig. 10. General layout of the suborbital rocket

The general dimensions of the rocket have been chosen in a reverse way to fit exactly the maximal performance allowable for the Falcon 7X: 7 m overall length, 86 cm in diameter (under fuselage) and a maximal mass at plane take-off of 2.8 tons. The table 2 presents more details on the general architecture.

Table 2. Typical dimensioning of the suborbital rocket

Stage	Inert mass kg	Propellant mass kg	Combustion time s	Vacuum Isp s	Nozzle exit area m²
1st	241	1615	27	300	1
2nd	80	538	13	300	0.6
RDV (inc generator)	241				
Fairing	50				

The corresponding flight sequence is described in Table 3.

Table 3. Flight scenario sequence

Time (s)	Event	Altitude (km)	Flight Path angle (°)
0	Rocket drop	12	20
5	1st stage ignition	12.181	4.1
32	1st stage end of burn	33.2	76.6
	28.4s coasting phase , 1st stage separation		
60.4	2nd stage ignition	86.9	74.9
71.1	Fairing jettisoning	113.8	84.1
73.4	2nd stage end of burn	122.4	85.0
	540.6s nominal ballistic phase to apogee, terminal stage guidance		
614.1	Nominal apogee	1199.5	0

An important point which acted as a driver for the sizing of the launcher is the general robustness to all the dispersions which can be encountered. Some parameters can reasonably be considered as known with a very high accuracy, such as the position of the orbital plane of the debris; the position of the debris on that trajectory should be well known also: a typical uncertainty of 1 km on the position corresponds to +/- 130 ms in time, and the preliminary requirement for the system was to have an ejection of particles lasting 10 seconds, so there should be plenty of margin.

But the initial position of the airplane may be non-optimal, in case of meteorological problem in the launch zone, inducing some variations in position and in time of launch. The system shall be capable to perform a time correction such as schematized in Fig. 11; a bi-boost strategy has been defined and detailed for the case where the launch from point A was not at the optimal time, for which debris B would have been in point Rn nominally, reaching the Ra real case slightly later. In a similar way, the system shall be capable to modify the flight trajectory and mission duration to reach any point in 3D in the vicinity of the planned target; Figure 12 schematizes this king of Lambert optimal trajectory to modify the target during flight. Significant ΔV margins have been considered to take into account this requirement for robustness.

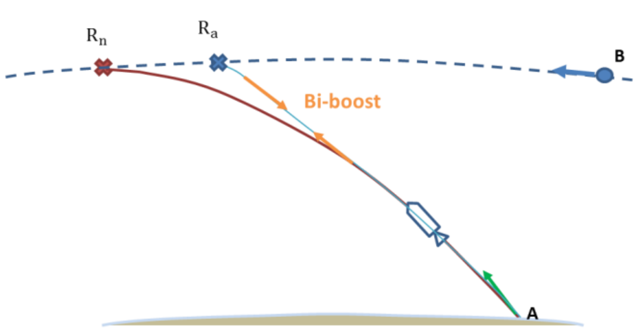


Fig. 11. Typical maneuver to compensate a delay in launch time

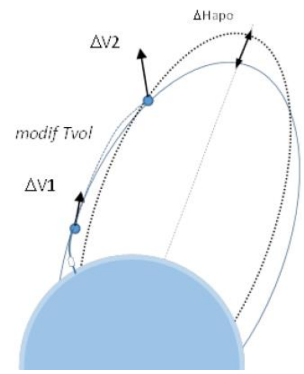


Fig. 12. Typical maneuver to take into account a modification in the target location

7 CONCLUSION

The initial study performed on the idea of using a cloud of particles to slightly nudge the trajectory of a large debris pointed out 3 feasibility points which had to be studies further.

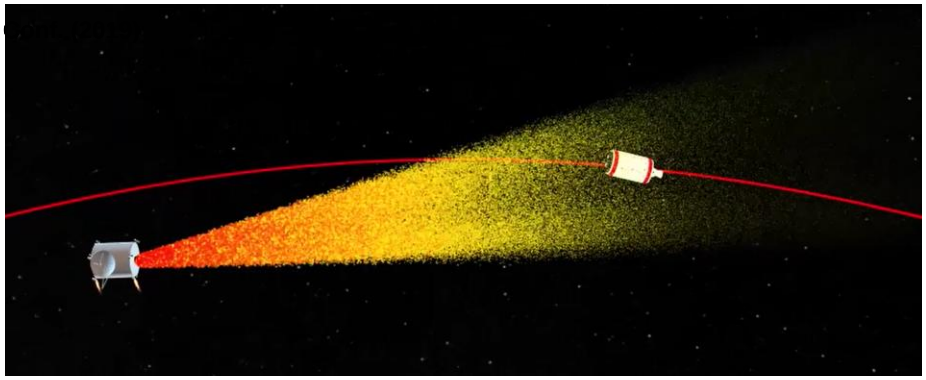
First, the global efficiency of the particle cloud has been consolidated, showing that indeed only a tiny fraction of the particles have to impact the debris to impart the required braking ΔV: the system was dimensioned considering 17 kg particles, when 3 g would normally be enough, if correctly located! The ejector spreads the cloud of particles with a relative velocity of 100 m/s during 10 seconds, starting 5 seconds before the theoretical passage of the debris; this way, the cloud spreads over 1 km centered on the nominal targeted point.

Second, the phasing between the ascent trajectory of the rocket, precisely its culmination point, and the debris is tricky. The solution selected here considering a modern business jet offers enough payload capacity and a very large range of more than 8000 km, enabling a couple of planes to reach any point for any orbit up to 1200 km altitude within a couple of hours.

Third, the ejector system was defined, based on a very well-known bladder tank used on Ariane 5 to expel Hydrazine; the adaptation to a much more viscous fluid with particles dispersed in its bulk has to be verified, but no blocking point is identified so far.

The overall dimensioning of the system, although preliminary, was performed considering robustness at mission and architecture levels to cope with trajectory dispersions, coming from the debris, the plane or the rocket.

The next step consists now in imagining an international cooperative scheme to deploy such system, with 3 or 4 launch bases spread around the world, striving together to avoid THE collision between two very large derelict objects which would strongly question the sustainability of our space operations. Even before that, as said in the introduction, we shall aim at improving drastically the accuracy of the ephemerids of our space objects, otherwise such JCA ideas are not realistic.



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