THE SPACE BLOWER CONCEPT, A SOLUTION FOR JUST-IN-TIME COLLISION AVOIDANCE

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ABSTRACT

In the frame of Space Traffic Management, when surveillance detects a risk of collision between space objects, an alert is raised. But when two non-maneuverable debris are to collide, even if detected, there are currently no operational means for avoiding the collision.

One solution is the Space Blower: a sounding rocket launched from a jet plane and equipped with a device that injects a cloud of particles in the trajectory of one of the objects. These particles are small enough so that the passing object is not damaged, but shaping a cloud dense enough so that the drag experienced induces a small slowdown. This slight trajectory modification, after several drifting orbital revolutions, avoids the collision.

This paper presents (with a film viewable on YouTube: https://www.youtube.com/watch?v=7GZ3eQVjnH4) how this system - previously demonstrated feasible - could be operated with respect to the current technical and organizational limitations:

- the observation accuracy requirements for such a concept
- the need for an international organization responsible for space traffic management, including debris trajectory characterization, collision risk assessment and operational risk reduction using different solutions including the Space Blower

Eventually, the development of this Just-in-time Collision Avoidance service is envisaged.

1 CONTEXT AND ISSUE

Within the Space Traffic Management (STM), the Large Debris Traffic Management (LDTM) deals with orbiting object such as old launcher stages or defunct satellites. Indeed, a collision between orbiting objects would result in thousands of smaller but still harmful debris, which in turn could collide with another orbiting object, … increasing the probability of a chain reaction (known as Kessler syndrome).

In that context, the debris have no ability to maneuver, which represents a higher level of threat. In addition to limiting/avoiding the creation of any space debris, two philosophies are considered to address this risk of collision with existing large debris:

- A strategic approach: the Active Debris Removal (ADR), necessary to stabilise the growth of space debris thus reduce collision probability and impact
- A tactical approach: the Just-in time Collision Avoidance (JCA), to manage unavoidable proven collision risks at the last minute

Currently, all large objects in Low Earth Orbit (LEO) are tracked and their orbits predicted with a given accuracy. Surveillance and Tracking use measures and prediction methods to determine **orbits with** oblong **uncertainty bubbles**.

Prediction of all orbits are conducted on the next few days: "orbit bubbles" meeting each other means that a collision may occur, leading to a deeper surveillance and if confirmed, to an alert (as Conjunction Data Messages). Such situations lead to Just-in-time Collision Avoidance (JCA), i.e. increasing maneuvers operated by the International Space Station (ISS) and operational satellites.

But a problem arises **when neither of the two objects involved in a predicted collision has the ability to perform a collision avoidance**: even if detected, there are currently no operational means for avoiding the collision! Such non maneuverable debris represent more than 90% of tracked orbiting objects. This is the reason why, in addition to long-term actions such as debris mitigation and ADR, it is fundamental to prepare avoiding these detectable collisions between non-maneuverable objects. Several solutions are envisaged, among which the Space Blower is foreseen to act when both objects are large space debris, such as rocket bodies or defunct satellites.

2 PRINCIPLE OF THE SPACE BLOWER CONCEPT

In that case, we made the assumption that the risk assessment, related to the precision of orbits prediction,

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shall lead to an alert and the **launch of a JCA procedure 24h before** the feared collision, as shown on Fig 1. Then we imagined an ejection system to create a dense cloud on a debris path to slightly deflect it.

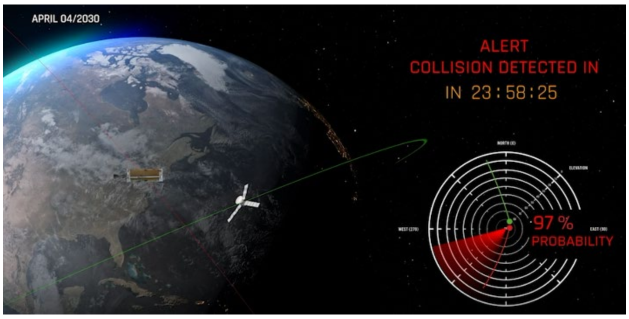

Figure 1: 24h before feared collision

The criteria for the success of a system solving such a JCA issue are its responsiveness, its accuracy, its ability to access any orbit, and, classically, its performance and cost.

Let's recall that the objective is to avoid a catastrophic collision between two non-maneuvering debris by deflecting one thanks to the **braking effect of a dense cloud** created by the **ejector called Space Blower.**

- First, a suborbital vehicle places the particles ejector up to a target altitude close to (but below) the debris'
- Once at target altitude, the ejector is switched on to generate the dense cloud
- The debris passes through the cloud and undergoes a drag force inducing a slight slowdown
- After several drifting orbits (12h allocated), the modified debris trajectory will finally result in a miss distance to the other debris avoiding the collision.

2.1 A suborbital vehicle to bring the particles ejector to the best place

The need relates to a placement system to bring the ejector to the best place, this system being unique wherever the system is launched and whatever the debris' orbit. So the system aims at **catching the orbital plane of any space junk in less than 12h** (time remaining between 24h before collision and 12h allocated to orbit drifting after deflection), from a **small number of bases** around the world, since each base shall be equipped with a ready-to-go system.

Several design were studied. In conclusion the **air-launch suborbital rocket** shows great advantages regarding these requirements:

It is responsive, with rapid deployment of the carrier, especially if an early warning phase allows rocket integration. Moreover, air-launch is far less sensitive to weather conditions than a terrestrial rocket-launch would be.

It is accurate, since a carrier can very precisely target the azimuth of the shot and the point on the orbit.

It is able to access any orbit: a carrier can target any orbit and quickly position the rocket at the best point in the orbital plane. A similar operation would require a large number of launch bases with a terrestrial launch.

An air-launch rocket also brings significant gains in performance, especially if the rocket design is adapted to airborne launch

Lowering cost is expected since many existing planes, requiring no specific carrier design, can carry the rocket (a few tons at most, this lighter rocket being itself cheaper than a ground-launched heavier rocket); operational costs would be considerably cheaper than monopolising several bases and personnel around the world.

Figure 2: Space Blower System

However, system complexity might increase with air-launch concept due to carrier-rocket association; moreover flight duration has to be included in the 12h operations timeline.

2.2 A reference preliminary design of suborbital vehicle

In order to guarantee the feasibility of the whole Space Blower system, a space vehicle has been designed thanks to CT's know-how and tools. The suborbital vehicle shall be suitable for a **last minute mission of « rendezvous »**, at culmination, with a debris (actually at a given distance below); that debris being on an orbit of any inclination and up to 1200 km altitude.

2.2.1 Design methodology and main choices

CT employed its own multidisciplinary optimal design approach, capitalizing years of space vehicles' experience in its platform HADES, for the Launch Vehicle (LV) design, which is equivalent level to a phase 0/A.

The rocket is modelled on the basis of 4 disciplines:

- Sizing of liquid propulsive stage (propulsion, structures and geometry),
- Aero-structures,
- Aerodynamics,
- Trajectory optimisation.

For each stage, the following parameters are optimised:

- mass of propellants,
- stage's diameter,
- mass flow rate,
- cross-sectional area ratio.

Regarding performance, the design has been optimised for the most energetic orbit considered, i.e. a Sun Synchronous Orbit: SSO @1200km, inclination = 100.4°.

The design has not been explicitly optimised regarding cost, but choices have been made towards economical savings: the same propulsion type with storable liquid propellants (H2O2/Kerosene as reference) is used for all stages, and an existing carrier is foreseen.

The first two stages use a storable liquid propulsion mode; different propellant pairs are possible. For practical reasons related to airborne launch, a storable propellant couple of the H2O2/Kerosene type appears to be very interesting and has been chosen as the reference propellant couple. The terminal vehicle uses a propulsion mode with storable liquid propellants to be defined more precisely (but which may be derived from the engines of the lower stages).

- *Figure 3: Visualisation of the different rocket stages*

The solution on Fig. 3 with two main propulsion stages meets the constraints of cost and simplicity in relation to the targeted performances. A solution with a single propulsion stage simplifies the rocket architecture, but this stage must, in this case, manage two different types of flight (atmospheric flight and exo-atmospheric flight) and its size will also be greater, which may pose problems of integration on an aeronautical carrier. A solution with three propulsion stages would have been far too complex in relation to the performance gains achieved.

2.2.2 Design results

The resulting launch system (see Fig. 2) includes an airborne carrier to put the 3-stages rocket (see Fig. 4) in optimal launch conditions: position, altitude, azimuth, inclination. This aircraft, which could be for example a jet class business one (a priori sufficient, more flexible and cheaper to operate than a larger aircraft), is operated to effectively meet the range requirement.

The first stage performs the resource after separation from the carrier and the atmospheric flight (incidence/gite control law).

The second stage achieves most DeltaV and allows to reach targeted altitude (heading/azimuth control law).

The final stage includes the 3-axes attitude control and re-ignitable propulsion module required to carry out the pseudo rendezvous with the debris, consisting in final approach and correct orientation of the Space Blower.

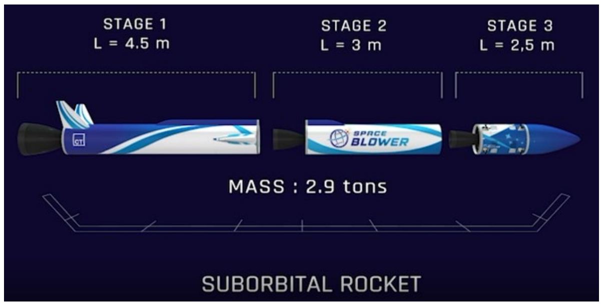

Figure 4: Dimensions of the different rocket stages

In addition to the inter-stage skirts, an additional 25% system margin was used in the performance calculation to take into account the uncertainties of the pre-design phase.

The masses of each stage including the inter-stage skirts and the system margin are given in Tab. 1.

Aerodynamic coefficients of the rocket are calculated in a simplified way and take into account the geometry of the resulting rocket. This model is valid for low incidence but has been extrapolated to higher incidence in order to model the resource phase. This is a realistic approximation for a 0 loop.

Table 1: final mass budget

FINAL MASS BUDGET	STAGE 1	STAGE 2	STAGE 3
Mass of propellants	1150. kg	650. kg	70. kg
Total mass at separation	543.9 kg	292.4 kg	55.3 kg
Total mass of stage	1693.9 kg	942.4 kg	125.3 kg
Structural index of stage	47.3%	45%	79%

The case of orbit with apogee of 1200km and inclination of 100.4° represents the reference case which allowed to dimension the rocket by considering that this orbit is the most energetic orbit reachable by our system. The corresponding trajectory is shown on Fig. 5.

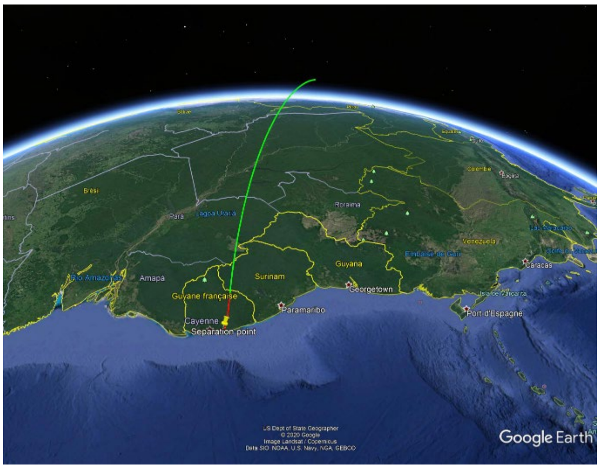

Figure 5: Rocket trajectory for a debris on orbit SSO@1200km

The reference air-launched suborbital rocket designed shows the feasibility of the launch system embedding the Space Blower ejector.

2.3 A patented mechanism for particles ejection

To find a mean for generating a dense cloud, a work group gathering multiple skills and experiences has been set up, and a proven innovation approach led by CT to foster creativity on techniques able to eject few kg/s of particles in space.

The concept chosen is the "aerospike-like" concept. The basic principle is that a specially designed aerospike nozzle is used to entrain copper particles (particles of about 50 microns). The word "aerospike" is in inverted commas because it is a concept similar to the so called nozzle but working in a different way.

The work on the ejector focused on the overall concept and feasibility. In particular, the conclusion of the study is that to brake a debris of about 1 ton, between 2.5kg/s and 11kg/s of particles are needed depending on the desired braking level and the trajectory of the debris in the plume (the density decreases with distance and radially).

Typically, one considers (with respect to the definitions in Fig. 6):

- A distance from the debris trajectory of 10m to 100m,

- An angle of 20° to 60° (90° means perpendicular to the debris),

- A transverse deviation of less than 10m (in practice, one will always manage to cross the trajectory of the debris),

- An ejection time of several seconds to ensure robustness.

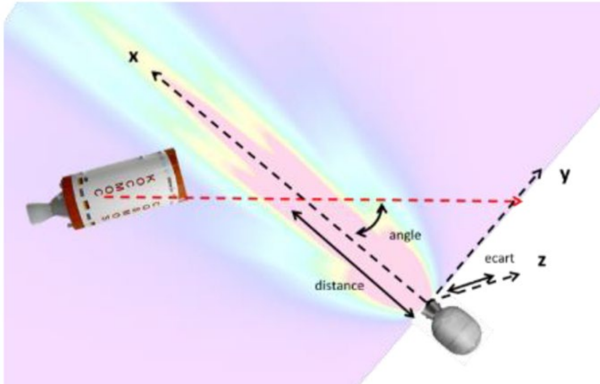

Figure 6: definition of the ejector's parameters

CT's multiphysics modeling and computing tool CPS_C® was used to calculate pressurisation, gas and particles sizing and trajectories, shapes optimisations.

All this led to an estimate of the mass of the **gas and particle ejection system** of the order of **80 kg**. This value was used for the dimensioning with the template shown in Fig. 7.

Figure 7: Representation of the particles' ejector on terminal stage

Obviously a crucial aspect is that no potential debris is created. This is achieved by keeping every part of the whole system suborbital, by preserving a safety distance of 100m under debris trajectory (estimate lately in the positioning process) and also by sizing the suborbital particles to neither be a debris nor be able to harm another object.

3 CONOPS

This chapter describes the concept of operations envisaged for the Space Blower, i.e. the sequence of events from the collision detection to its effective avoidance.

3.1 Choice of debris and launch base: blowing area

The Space Blower and the whole system are sized for a mass of debris up to 2 tons; indeed, even if some larger debris exist, the probability is very low that both debris involved in a collision course are greater than this threshold. Therefore the lighter debris would be chosen to be deflected in such case.

The Space Blower is to be deployed on launch bases located close to the equator. The **number of launch bases** needed worldwide depends on:

- The acting time, taken as reference as max 12h (time left by confirmed alert at H-24 and orbital drifting time set to 12h)
- The ability to catch up lateral offset from orbital plane (or ground track), i.e. the range of the placement system (performed by the carrier)

3.1.1 Assumptions

The rotation of the earth means that the ground track of the orbit shifts with each revolution As shown on Fig. 8, the biggest shift of the orbit track after a revolution occurs at the equator: 3060 km is the value corresponding to a circular orbit @1200 km altitude, any inclination.

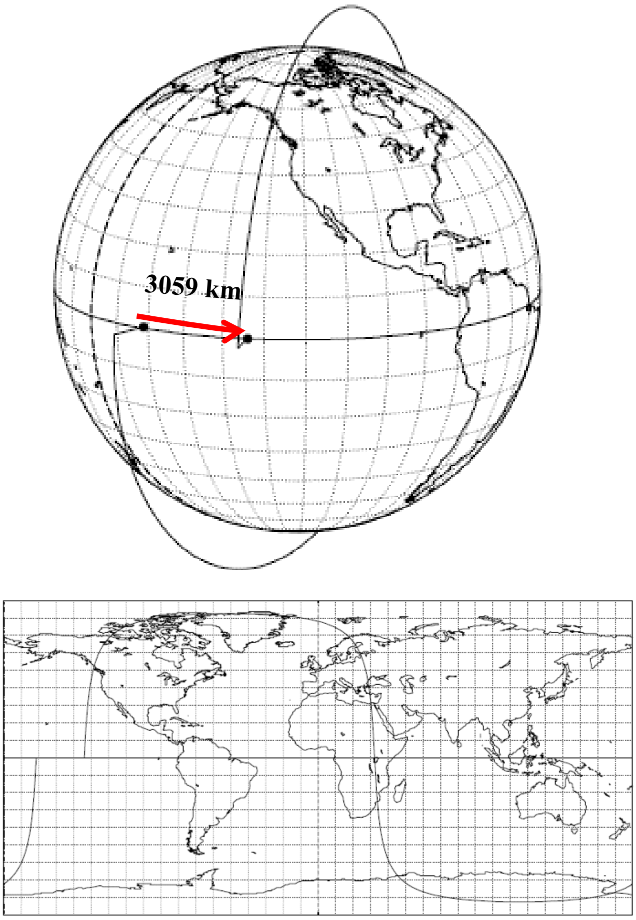

Figure 8: Ground track of satellite METEOP on an orbit (altitude 1195 km, inclination 82.6°, period 1h49', nb rev/day 13.16), shift at the equator: 3059 km

Our logic for estimating the number of required bases is based on:

- Siting of **bases close to the equator** allowing any inclination orbit to be reached,
- Seizing of **first opportunity** of track passage i.e. as soon as orbit passage can be reached at rocket culmination range.

3.1.2 Number of launch bases

Let's look at the relative positions of ground bases and debris_passage above the equator during the acting time period, choosing an inertial frame of reference, i.e. one centred on the centre of the earth but whose axes are fixed to the stars (ECI, Earth Centered Inertial) such as TEME (True_Equator Mean Equinox).

In 6h, the ground bases move by approximately ¼ of a revolution = 90°; Fig. 9 shows 2 bases needed, 90° apart:

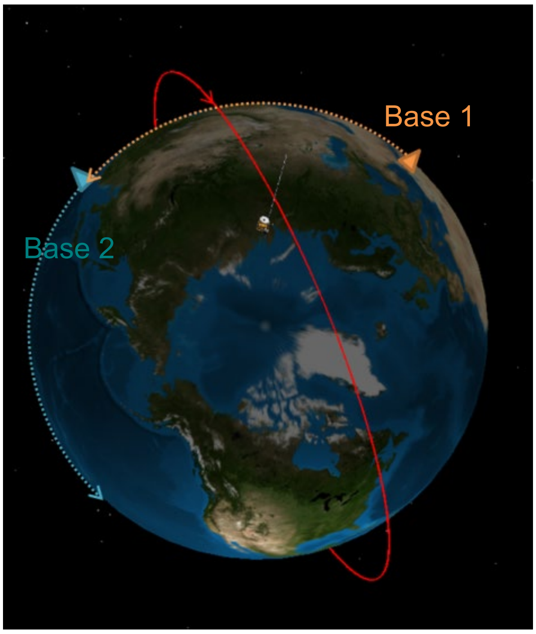

Figure 9: Movement of 2 bases in 6h (ECI frame)

In the meantime, the debris passes 4 times above the equator, with the base in 4 successive positions, see Fig. 10.

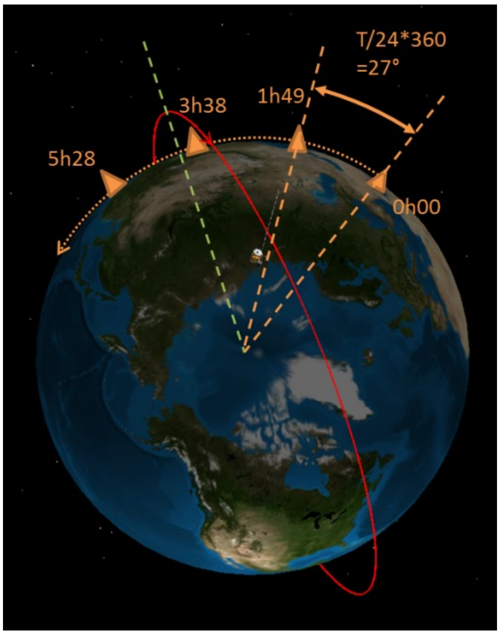

Figure 10: Base positions at different times of debris passage at its ascending node

The interception will take place at the time of the passage for which the base is closest to the node (smallest difference in longitude with the orbital plane at the time of the passage). In the previous Fig. 10, this occurs at the third revolution, after 3h38.

To find the range requirement of the base, let's take the worst case, i.e. if the node is equidistant between 2 passes, i.e. half an offset, as shown in Fig. 11.

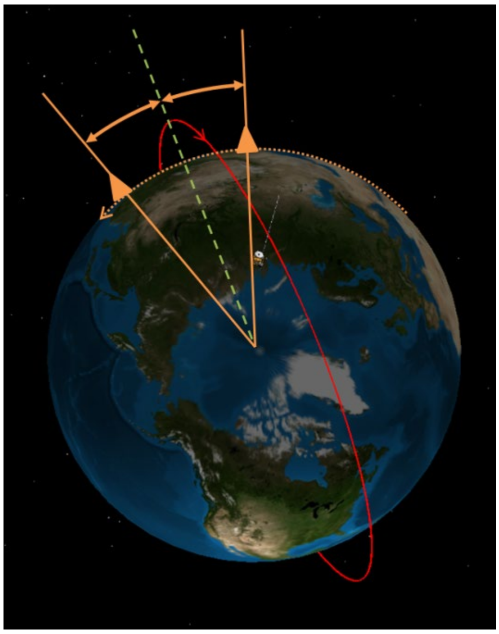

Figure 11: worst case, the orbital plane is equidistant from 2 consecutive base positions

For a target orbit at 1200km, the shift at the equator is 3060km, giving an area to cover of 3060km and a range of 1530km. It is unlikely that a sounding rocket would have such a large range. Instead of a single base to cover this area, several bases are placed equidistantly to cover a large area, as shown in Fig. 12. This wide area is centred on the position of the single base as defined above. The bases covering the same area form a base grouping. Thus, 2 groupings are needed for a 6-hour response time, as opposed to 1 for 12 hours.

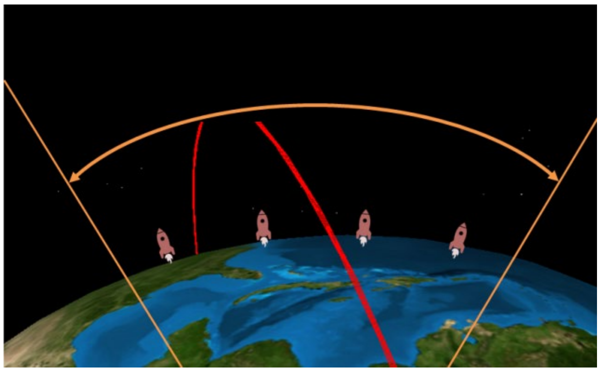

Figure 12: Base positions at different times of debris passage at its ascending node

The distance between the bases corresponds to the range of the rocket. The number of bases in the grouping therefore corresponds to the shift at the equator divided by the range of the rocket.

Table 2: estimated minimum number of launch bases required depending on acting time and range of system at culmination

ACTING TIME	***RANGE (KM)***	***TOTAL NUMBER OF BASES REQUIRED***	***NUMBER OF COVERED ZONES***
6H	3060	1 + 1	2
6H	1530	1 + 1	2
6H	765	2 + 2	2
6H	383	4 + 4	2
6H	191	8 + 8	2
6H	96	16 + 16	2
12H	3060	1	1
12H	1530	1	1
12H	***765***	***2***	***1***
12H	***383***	***4***	***1***
12H	***191***	***8***	***1***
12H	96	16	1

Tab. 2 gives the required number and grouping of bases for acting times of 6 and 12h respectively, depending on the range capability of the placement system. For limited time and range, such as 12h in the case considered in the **film, 2 to 8 bases** would be needed considering a realistic system's range of few hundreds km.

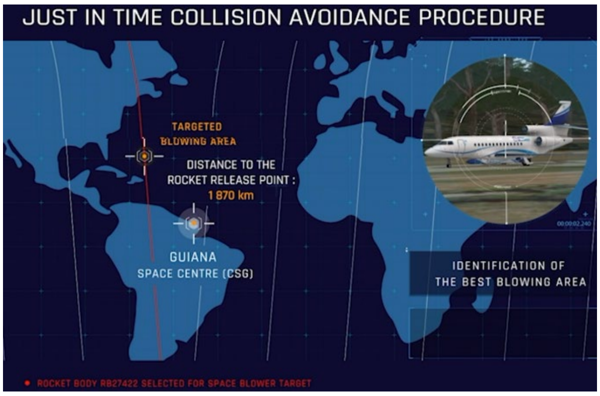

Figure 13: mission resulting of preliminary analysis

If the surveillance and tracking of debris confirms the high probability of collision once the date close and orbits measurements accurate enough, the choice of the debris, launch base and blowing area constitute the **mission assigned to the Space Blower** as on Fig. 13.

3.2 Flight sequence

Before H-24, preliminary analyses have set launch base(s) in alert, allowing Space Blower rocket to be prepared and integrated to the carrying aircraft. Once mission is confirmed and location of rendezvous is known, trajectory is computed and sent to the base managing the launch.

The system is launched, for 2 hours a half airborne flight before the flight of the rocket itself; about 8 minutes. Rocket's Global Lift-Off Mass is 2.8 tons including Space Blower's mass of 80kg.

Figure 14: rocket release

Fig. 14 illustrates the rocket release from the airplane having performed the function of catching the lateral offset from the plane (or track) of the debris orbit. Following a resource phase of few seconds, the rocket is propelled by the 1st stage engine during few tens of seconds and few tens of kilometers altitude.

Figure 15: 1st stage separation

Then on Fig. 15, the 2nd stage takes over to raise the rocket's altitude, including fairing jettisoning (Fig. 16) during this flight phase, before the 3rd stage in turn.

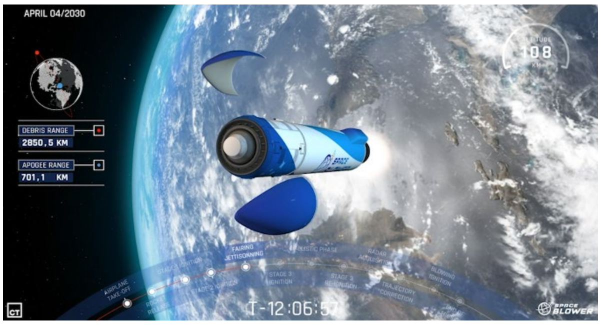

Figure 16: fairing jettisoning

Last but not least of placement system's phases, the terminal stage embedding the Space Blower ejector performs final approach. It is equipped with 3 axes-attitude control and re-ignitable engine in order to perform (see Fig. 17):

- Final approach and pseudo rendezvous
- Trajectory corrections such as time delay compensation, adaptation to changes in targeted position

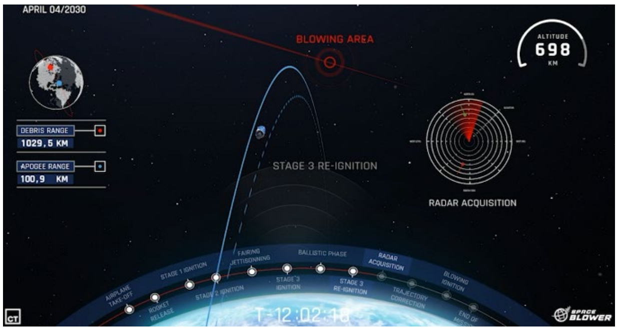

Figure 17: trajectory correction

The level of correction needs to be estimated according to the performance of the launcher, in particular on the dispersions with respect to the nominal trajectory, but also with respect to those of the observation means (ground and on board). At this phase, the accuracy of available orbital data is critical; depending on trade-off on current technologies, these data may come from:

- autonomous means of observation and trajectography (radar or on-board optical sensor)
- debris tracking system, ground-based

Once positioned on time, the patented Space Blower is ready to eject gas and particles, according to parameters that have been chosen by modelling and analysis:

CT's multiphysics modeling and computing tool CPS_C® has been used to perform sensitivity analysis on braking effect with regards to:

- Particles sizes distribution
- Distance to debris trajectory
- Angle between ejection direction and debris trajectory
- Transverse deviation from the orbital plane

Ejection duration of several seconds (typically 10s) has been set according to precision on debris trajectory measurement (date and place) to ensure that the debris crosses a dense enough cloud: The cloud sizing has been studied in the same way.

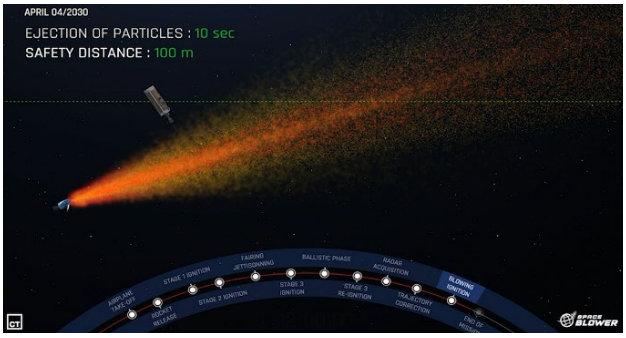

Figure 18: particles ejection

Fig. 18 shows the cloud shaped by ejected particles with the debris just passed through, the impact of particles inducing a slight reduction of the debris' velocity. Twelve hours later, the propagation of this slight braking appears to be sufficient to increase the miss distance by 13km thus to avoid the collision, see Fig. 19.

Figure 19: miss distance after 12 hours

4 CURRENT LIMITATIONS AND NEXT STEPS FOR DEVELOPMENT

This paper describes the Space Blower concept, imagined between CNES & CT Paris with a patented innovative ejection mechanism. The whole system has been designed and sized through several studies and the use of modelling and optimisation tools, thus demonstrating its technical feasibility.

However JCA implementation through Space Blower solution is foremost based on the broader need for Space Traffic Management organisational structure, to answer in particular the need for

- A legal frame with the authority to launch a mission in case of such emergency between large junks
- A policy on Large Debris Traffic Management,

foreseeing the use of different systems fitted to various action for space sustainability

One postulate of this set of studies is that observation resources will have a much higher accuracy than today's, in order to predict the position of the debris 12 hours in advance with sufficient precision. This could imply the need to embed on-board observation resources, depending if the ground-based resources provide the necessary precision. Indeed the performance of orbital debris observation and tracking systems limits the accuracy of ephemerides, and therefore the reliability of collision prediction to a level compatible with the commitment of a braking mission, to a time TE (difference between the dates of notification and the feared collision); this time limit, linked to the ephemerides, largely conditions the acting time of solutions such as the Space Blower. As the existing systems are not efficient enough to identify and predict trajectories accurately and early on, it is necessary to improve these means of observation

Next system development of the Space Blower, in relation with improvements in accuracy of orbits prediction, include:

- Increasing Readiness level of particles ejection
- Refining the design of the sounding rocket, especially in:
    - Optimizing costs through engine design (common engines architecture, COTS), consider reusability at least for the first two stages (estimated cost of the solution is on the order of magnitude of 2 to 3 million euros, 10 times less than other active removal solutions)
    - Decreasing dry mass thanks to recent technologies (3D printing, miniaturisation, etc.)
    - Choosing an airborne carrier and working on the rocket integration

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