ACTIVE REMOVAL OF LARGE DEBRIS: SYSTEM APPROACH OF DESORBITING CONCEPTS AND TECHNOLOGICAL ISSUES

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ABSTRACT

The threat induced by large space debris, dead satellites or rocket bodies, in Low Earth Orbit has been identified years ago. A first part of the Orbital Transfer Vehicle (OTV) study was dedicated to identify mission architectures that can fulfil the objective to eliminate the necessary number of critical debris. Those potential solutions and architectures have been compared taking into account cost considerations.

The present paper reports the first results of the OTV step2 study funded by CNES that addresses different solutions for large debris removal. It compares different desorbiting concepts from selected single to multiple debris complying with the Space Law, i.e. able to ensure controlled re entries.

Different capture options are presented, including sensors needs and an analysis of the problems posed by different solutions.

The overall performances of the concepts are compared, showing the adequacy, the limits of each solutions and application domains.

I. INTRODUCTION

Since more than 10 years, many studies led by the 11 agencies member of the Inter Agency Debris Committee (IADC) worked on risk identification from space debris and possible optimal solutions to reduce this risk. Several technological concepts have been identified. Nevertheless, none of those concepts has been fully validated and even compared in term of adequation to the real need, availability of technologies in the aimed schedule and in term of operational cost for the global space system.

A first OTV study, performed in 2011 by Thales Alenia Space through CNES OTV (for Orbital Transfer Vehicle) contract ([RD2]), helps to answer to the global approach. It allowed identifying most promising concepts in term of technical credibility and cost per desorbited debris. The purpose of the current study is to consolidate preliminary choices, to state on credible performances and to establish maturation logic of innovative technologies.

The distribution of the debris around the Earth is not uniform and previous studies highlight the peculiar criticality of the Low Earth Orbits. The exponential increase in the coming years predicted by the NASA LEGEND software is known as the Kessler syndrome and is due to the growing number of collisions in between large debris.

The Figure I-1 shows the targeted debris population, above 1000kg, at high inclination from 60 to 105 deg which contains various debris among satellites in end of life or large launcher upper stages.

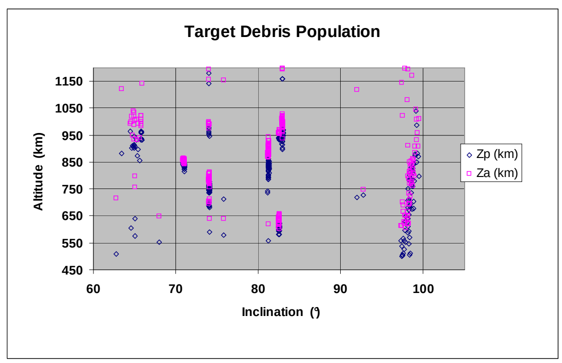

Figure I-1: Target debris population in LEO includes around 550 debris.

Among this population, two vehicles are selected as “reference debris” for the study (Figure I-2): one reference observation satellite with a mass of 1056 kg, on a 814 km altitude / 98.6° inclination SSO orbit; the second is a COSMOS 3M upper stage with 1874 kg mass and with a in orbit position distribution as shown in Figure I-3.

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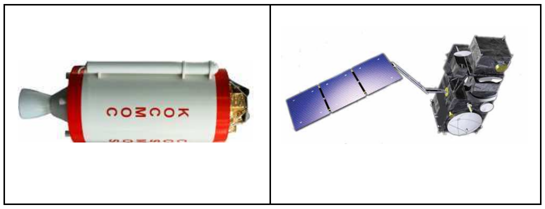

Figure I-2: “reference” debris considered in the current study

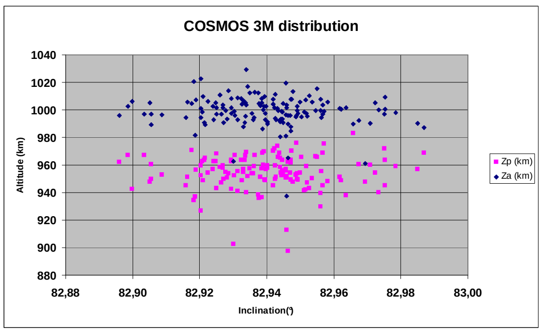

Figure I-3: COSMOS 3M in orbit distribution

Two mission concepts are assessed:

- Concept 1 consists in a large multi debris chaser, based on a single Ariane 5 launch. Due to Ariane 5 launch capacity in LEO, the spacecraft launch mass is bounded to around 15 tons. A high reliability design is needed due to mission ambition and to anticipate a high chaser recurring cost
- Concept 2 is a small mono debris chaser, based on a multiple Soyuz launch. Due to the launch concept, an architecture based on satellites Constellation heritage is chosen to target a low cost solution. This induces a tailoring of the redundancy approach to the very short mission duration.

Which strategy is more efficient for de-orbiting or re-orbiting? What is the best cost per debris ? will be the final purpose of the study whereas cost estimation for both concepts is still in progress. What are the key technical points for each concept and the associated technology issue ? This is all what the study reported in this paper is about.

II. CONCEPT 1

II.I Principles

To optimize the launch mass, the chaser mass is around 15 tons. The launcher will separate the satellite into a specific LEO orbit. This vehicle shall maintain a high reliability level as recurring cost would be consequent. This requirement will be addressed mainly for following functions:

- Final rendezvous with a dedicated redundant propulsion subsystem
- Capture and robotic aspects to guarantee fail safe operations
- Controlled final desorbitation of the OTV.

From the architecture illustrated in Figure II-4 and Figure II-5, the complete capture and desorbitation process comprises the following steps:

Step 1, 2, 3 & 4 : The kit is extracted from one of the 10 containers by the robotic arm (Figure II-1 and Figure II-2), then locked into the architecture at the centre of the chaser upper platform

Step 5 & 6 : •after fixation of the kit, the chaser performs a rendez vous preferably along the V-bar, synchronizing the chaser and debris angular rates within 1°/s. Then the same robotic arm captures the debris at the level of the payload interface and rigidifies the link (Figure II-1),

Step 7 : •the robotic arm brings the debris in contact with the kit fixation structure,

Step 8 : •after the debris is properly fixed and aligned on top of the chaser through the kit structure, the composite needs to be spinned at about 70°/s by the chaser propulsion system,

Step 9 : •after proper gyroscopic stabilization of the debris and at the correct timing in the orbit, the kit with the debris attached to it is separated,

Step 10 : after TBD seconds, the chaser is despun, and the kit is fired from the chaser at a precise time to enable a re entry at the planned location. After about 30s, the debris re enters into the atmosphere.

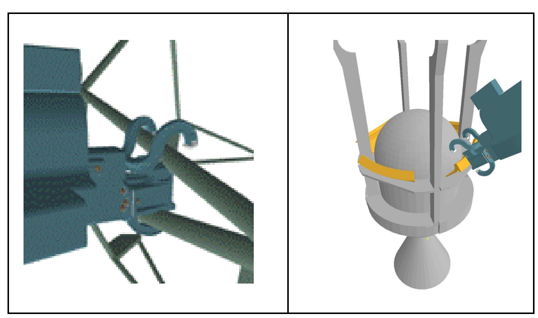

Figure II-1: robotic arm grapping strategy for debris and for solid kit

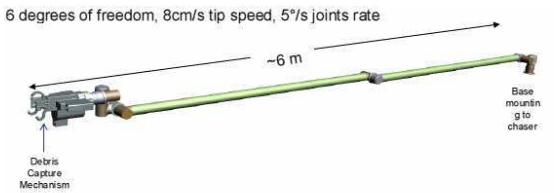

Figure II-2: robotic arm MDA concept

II.2 desorbitation kit

A solid propulsion kit is chosen for desorbitation kit for safety and cost aspects. The definition of this kit is driven by the 257 m/s DeltaV impulse necessary for safe direct re-entry of the largest debris considered as Cosmos 3M (including additional residual propellants). It has to be underlined that direct re-entry from the initial orbit is possible to guarantee a safe slope into atmosphere as figure in Figure II-3 :

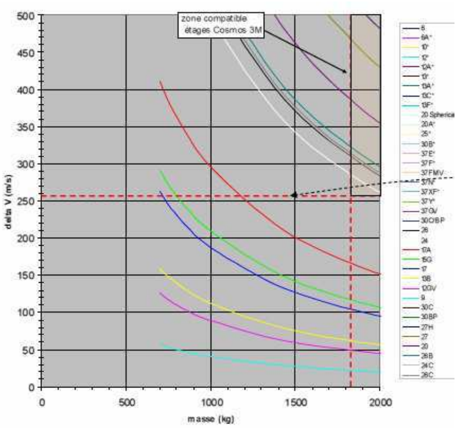

Figure II-3: deltaV for solid kits

A solid rocket derived from ATK Star 24 engine is considered, with a global mass of 220 kg including propellant mass, mounting structure (grapping system), ignition feature and electronics to allow ignition by the OTV from a certain distance.

Those propulsion kits are installed on the chaser on a central, external position to ease grapping with the robotic arm. The kits number is adapted from the chaser capacity of debris that can be treated. An elevator process moves the kit up to the surface for grapping as shown in Figure II-4 :

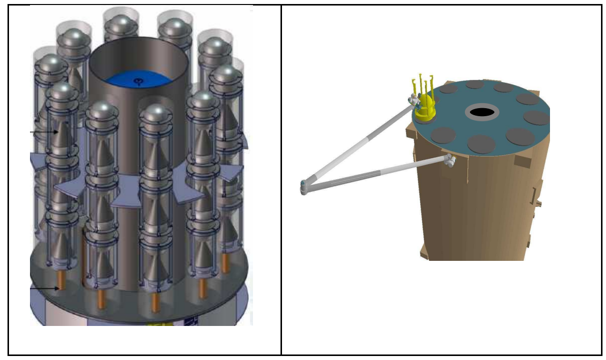

Figure II-4: propulsion kit installation on OTV

After capture by the robotic arm, the kit is installed with the help of the robotic arm on the top of the vehicle before debris capture.

II.3 OTV architecture

The mechanical architecture is based on a 3.6 m diameter and a 4.4 m high cylindrical vehicle. A 1666mm central tube houses large tank able to contain the bi-propellant mass to perform orbital manoeuvres, rendezvous and self-desorbiting deltaVs.

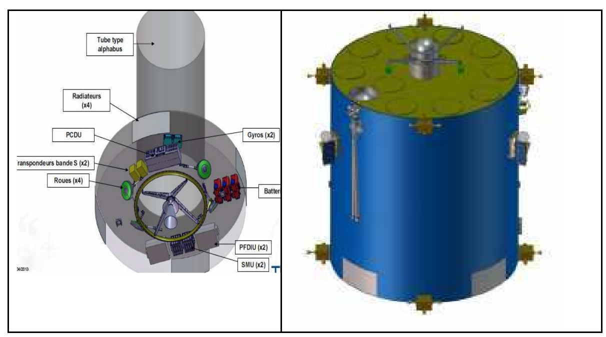

Figure II-5: concept 1 architecture

The propulsion subsystem is sized for efficient orbit changes and rendez-vous. A 445N Bi-propellant engine is chosen with additional 100N thrusters for the rendezvous phase and attitude control. Two large 3200 liters propellant tanks (1 MON, 1 MMH) are implemented.

A body mounted solar array is preferred to lower inertia and still complies with the power budget estimates. This configuration eases kit installation and global vehicle architecture with a cylindrical central tube which contains the two propellant tanks. The battery is sized in the worst case where the OTV longitudinal axis is collinear to the velocity vector and only receives limited solar energy.

II.4 AOCS analysis

Two control aspects are considered critical and are analysed further:

- control of the complete stack (OTV + debris)
- control of the debris after separation with the solid propulsion kit installed.

To minimize the effect of the misalignment between the kit thrust axis and the CoG location, the stack shall initite a spin motion before separation of the kit+debris. A sensibility to the debris spin is presented in the following Figure II-6:

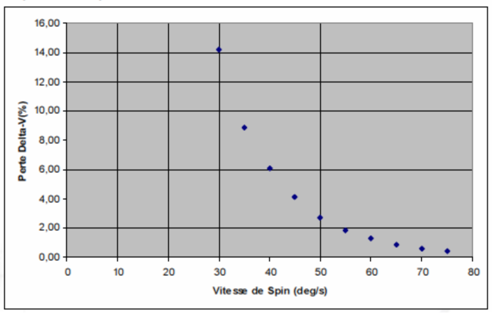

Figure II-6: concept 1, kit thrust efficiency vs spin rate

According to a realistic dispersion of debris CoG, around 70 deg/s is necessary to ensure a reliable Cosmos 3M upper stage controlled re-entry.

II.5 Applicability and debris treated

The concept 1 has been optimised wrt the desorbiting of the Cosmos 3M upper stages; it has been shown to be capable removing typically 22 COSMOS 3M-like debris from orbits:

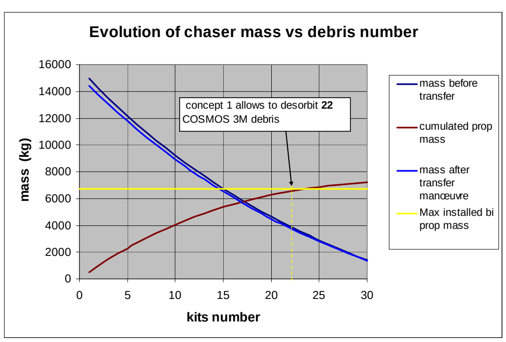

Figure II-7: Concept 1 performance for Cosmos 3M debris

It shall however be stated that this concept is NOT compatible with the typical LEO satellites debris for two main reasons:

- satellite CoG is generally far from the kit thrust axis in satellite End of Life configuration and therefore, the desorbiting is unstable
- the satellite appendices are not designed to sustain 10^{th} of kN thrust induced by solid propulsion kits.

This concept is well adapted to the desorbitation of heavy upper stages of close orbital parameters. The cost evaluation is in progress and would allow offering a cost efficient mean in term of cost per debris.

III. CONCEPT 2

III.1 Principles

This mono debris chaser implements orbital manoeuvres to reach the debris using forced RAAN drift. The capture axis is determined after in situ measurements of the debris tumbling rate and axis taking into account the planned capture area on the debris. Then, the chaser captures the debris by the mean of a harpoon and performs finally a controlled re-entry together with the debris towed with a cable.

To optimize Soyuz launch mass capacity of ~4700 kg in LEO, a multiple launch is considered with the chaser installed around a dispenser inside the fairing. This concept allows targeting a low cost solution as design and architecture is based on constellation heritage.

The overall desorbiting process comprises the following steps :

Step 1: at a proper time along the debris orbit, the chaser performs a rendez vous along the V-bar synchronizing the chaser and debris angular rates within 5°/s (TBC). It stays at a pre defined stay-out zone, 2m outside the swept volume of the debris,

Step 2: the chaser points toward the calculated and identified capture location then autonomously fires the harpoon system (see Figure III-3),

Step 3: The cable is immediately unwinded after the capture by the chaser using small thrusts to stretch it (see Figure III-3),

Step 4: after 50m to 100m of cable are unwinded and at the correct timing, 400N thrust is applied to the composite through hydrazine thruters. The controlled re entry occurs after a typically 30mn long thrust. During thrust the cable gets an oscillation motion, which depends on the cable length and initial thrust axis wrt Vbar: a long cable and good alignment with Vbar are necessary.

Figure III-1 illustrates the behaviour for a 100m cable and an ideal capture along the Vbar.

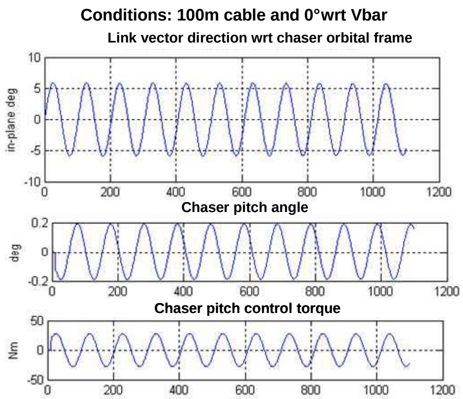

Figure III-1: robotic arm grapping strategy for debris and for solid kit

III.2 Harpoon system
Many options regarding the capture method (see Figure III-2), the anchorage technique and the OTV-debris link have been traded.

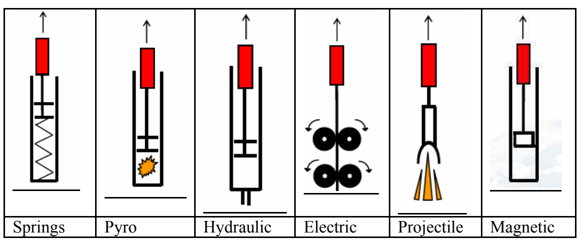

Figure III-2: harpoon propulsion capture method options

Preliminary baseline is based on a projectile ejected with a compressed spring. This allows the chaser to remain at a safety distance from the debris and potentially copes with higher debris tumbling rates.
The anchorage technique consists in a kinetic perforation of the debris (see Figure III-3). This technique is considered as the simplest solution likely to create a minimum of secondary debris. The link with the debris is a metallic cable flexible. It features suitable elasticity characteristics.
The critical issue is the energy necessary to perforate the targeted debris envelop (honeycomb panels, aluminium, …) : a minimum of 500J are typically needed for 1mm aluminium.

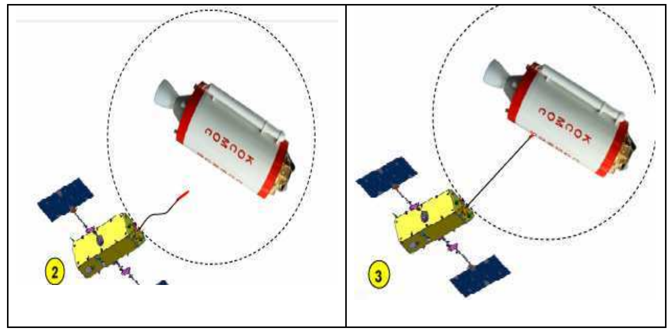

Figure III-3: harpoon technique

III.3 OTV architecture
The mechanical architecture of the vehicle is based on a 3.2m long, 2.2m wide, 930kg vehicle derived from constellation solutions. The structure consists in a simple case built around a large monopropellant tank. This architecture allows 4 chasers to be accommodated in a Soyuz launcher around a standard dispenser, for a total mass of 4400kg.

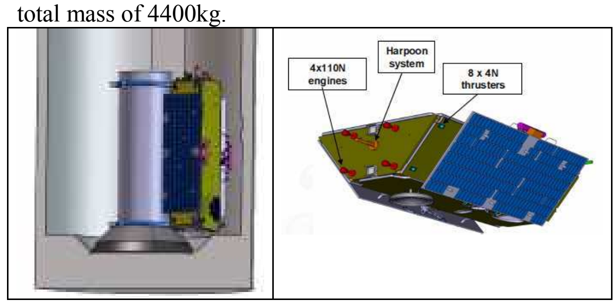

Figure III-4: concept 2 architecture

The monopropellant propulsion system uses 8x4N thrusters in pure torque for the rendez vous and 4x110N thrusters operating in blow down for the desorbiting function. A 500L tank is necessary to implement the required 250 to 300m/s desorbiting delta V. The 110N thrusters surround the harpoon mechanism at a distance which minimizes the plume thermal effect on the cable during desorbiting.

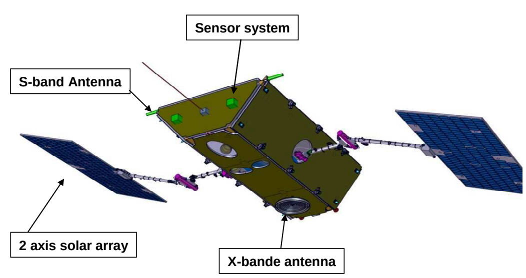

Figure III-5: concept 2 in deployed configuration

The solar array implementation consists in two 2-axis steerable, 2.5m² wings (see Figure III-5). •The design is inherited from Iridium 2 constellation. •They allow an optimum illumination during desorbiting in all orbits conditions, which authorises a very simple power regulation technique and avoids implementing reaction wheels (no roll steering necessary).

III.4 AOCS analysis

Several analyses have modelled the OTV+debris behaviour during the desorbiting; As mentioned the cable gets on an oscillating motion:

- Some absorption could be managed through thrust modulation.
- Oscillation amplitude is function of cable length and increases with :
  - cable length decrease
  - harpoon direction far form Vbar
  - thrust is low

The continuous thrust also needs to be adapted to decrease gravity loss. Thrust time duration decreases in proportion at higher orbit altitude ; for instance it represents 25% of orbital period for an initial orbit at 2500 km altitude.

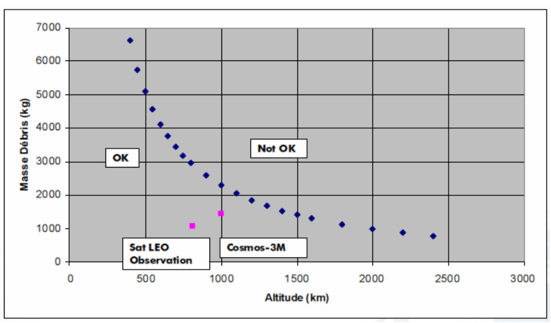

Figure III-6: deorbiting capacity of concept 2

Debris angular velocity is to be studied carefully, as it constraints:

- the cable deployment time
- the time slot for correct targeting and harpooning.

III.5 Applicability and debris treated

As illustrated in Figure III-7, Concept 2 as sized, is compatible with a majority the target debris, including upper stages and satellites, provided the capture can be performed in good conditions (thrust axis not far from Vbar).

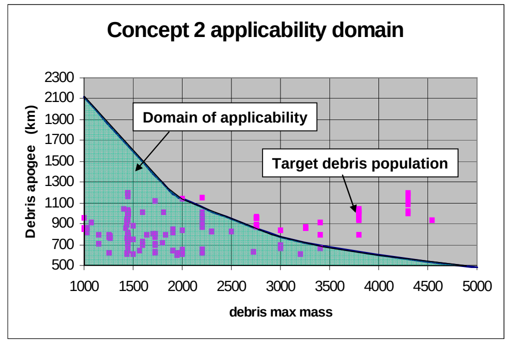

Figure III-7: concept 3 applicability domain

This lifetime of the Concept 2 spacecraft is very short, typically 30 days, and is therefore very reliable without need for a classical redundant design. A failure is indeed considered critical if it ultimately leads to an uncontrolled re entry of the debris and /or the chaser. It boils down to a failure of some critical elements of the chaser over 30 days. With only single string, i.e. no redundancy implemented in the avionics and propulsion elements, the reliability figure is 0.995, thus typically one failure every 200 chasers !

Designed with low cost as main driver, this concept would allow offering a cost efficient mean in term of cost per debris. Harpoon capabilities and associated relative motions between chaser and debris are still to be consolidated and evaluated.

IV. SOME CONCLUSIONS

The analyses performed have made clear the feasibility of the two studied concepts, both consistent with the requirement of to perform a controlled re-entry of the debris: :

- a large 15 tons able to treat more than 20 debris,
- a small chaser dedicated to mono debris desorbiting.

In the next step of this study, the two concepts will be cost evaluated. Preliminary development logic will be proposed to state on the best compromise concept and to help maturation of the technologies.

ACKNOWLEDGMENTS

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