ACTIVE DEBRIS REMOVAL: CURRENT STATUS OF ACTIVITIES IN CNES

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ABSTRACT

Most of the ongoing studies led at worldwide level, mainly through IADC Actions, conclude that in order to keep a stable Low Earth Orbit environment in the coming decades, it may be necessary to retrieve some 5 to 10 large objects annually. These operations, known as Active Debris Removal (ADR), raise a huge amount of difficulties in numerous domains: political, legal, insurance, defense, financing and, last but not least, technical questions.
The current paper aims at reviewing the current status of the ADR activities led by CNES both at National and Multi-lateral level.

The first question which is raised is that of the high level requirements to be applied. What are the requirements coming from the operators; do we want to stabilize the environment, decrease it or could we accept some increase over the years; when do we have to act; can we baseline random reentry of such large objects or do we have to stick to controlled destructive reentries?… There may not yet be clear answers to these points, so efforts at international level are required.

The second part of the paper deals with the potential solutions at system level. Numerous possibilities can be identified, depending on the size of the launcher and of the strategy selected to de-orbit the debris. Large space tugs visiting some 10 debris or small dedicated chasers launched as piggyback are among the solutions which have been traded. The currently preferred solution is described in details.

The third part of the paper is devoted to the chaser-debris operations themselves, following five key functions;

- the long range rendezvous,
- the short range rendezvous up to contact,
- the mechanical interfacing of the debris,
- its control by the chaser, when required,
- the de-orbiting maneuver itself.

For each of these functions, the current status of available technologies is described, enabling the identification of the most critical ones requiring additional R&T effort and subsequent demonstrations. Among them, two are already identified as critical: the final rendezvous with an unprepared, non-cooperative, potentially tumbling target of unknown physical status has never been demonstrated yet; the physical interfacing between the chaser and the target during the do-orbiting boost is also far from obvious.

The paper is essentially based on the on-going findings of the two significant industrial studies under CNES contract, as well as several smaller actions led by Universities and internal work.

1. INTRODUCTION

Identified theoretically as early as 1978 by Don Kessler and Burt Cour-Palais [1], the so-called Kessler syndrome has been the subject of numerous studies in the world: among the various sources of orbital debris, the collision among objects is the hardest to avoid and can potentially generate thousands of objects per event. If this "collision" part alone becomes more important than the "natural atmospheric cleansing", then some kind of "chain reaction" can be triggered in the most densely populated areas of space, increasing slowly but ineluctably the overall population of debris.
This phenomenon has been studied worldwide ever since, leading to an impressive number of publications, dedicated workshops, special sessions during congresses, aso. As per today, most of these studies tend to state that the Kessler syndrome was effectively started with the couple of major

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fragmentations which occurred in 2007 and 2009. The vast majority of these studies, if not all of them, conclude that in order to keep a sustainable space activity on the long term one shall apply the internationally agreed mitigation rules as efficiently as possible, and nevertheless de-orbit actively at least 5 large objects per year from the most overpopulated orbital regions: mitigation and remediation appear to be both necessary to preserve long-term space operations.

The need for such an Active Debris Removal (ADR) has to be confirmed and stated in an unambiguous way as the corresponding space missions rapidly turn out to be nightmares! Cleaning space could require technologies which are not yet available, cost hundreds of millions of Euros per year, raise tremendous problems of legal responsibility and insurance, with no clear perspective on how to finance such operations. As the orbital pollution in Low Earth Orbits (LEO) originates from all the space faring nations, even though some have more responsibility in it than others, ADR shall be dealt with at international level! No country or organization can nor shall bear the burden of such an activity alone.

It appears therefore compulsory:

- To consolidate the need, if any, to perform ADR in addition to the proper application of mitigation rules,
- To identify the corresponding system solutions,
- To identify the required technologies and clarify the corresponding development constraints,
- To identify some reference scenarios, with solutions precise enough to evaluate the programmatic consequences,
- To propose a scheme at international level to initiate such operations if, once again, they appear compulsory.

These few priorities have guided the works led by CNES since nearly 13 years [2]. The current status of the ongoing studies is described in the following paragraphs.

2. HIGH LEVEL REQUIREMENTS

2.1 Number of debris to be removed

The intensive studies led by the Orbital Debris Office at NASA-JSC since decades have produced a vast amount of results, generally consolidated with sensitivity analyses implying sophisticated statistical approaches. The most well known conclusion has been summarized by J.C. Liou, N. Johnson and N. Hill [3] which has been used as a the reference by most of the orbital debris research teams in the world. It states that even if one assumes an almost perfect Post-Mission-Disposal, with 100% explosion suppression and 90% success rate for the disposal measures, it is necessary to actively de-orbit 5 large objects from densely populated orbital regions in order to keep the orbital environment stable.

Consolidation of these findings

This major finding has been cross-checked by teams from several of the IADC delegations within the Action Item 27-1 (Roscosmos, ISTI-CNR-ASI, JAXA, ESA, University of Southampton-UKSpace Agency, ISRO in addition to NASA); every delegation used its own model, sharing the same set of inputs, and came to very similar conclusions “new mitigation measures, such as Active Debris Removal, should be considered”.

The highest priority for CNES has therefore been to develop a simulation tool in order to cross-check these results. This predictive model, called MEDEE, is now available, developed by the Toulouse Space Centre, and starts giving results coherent with the findings from the other Space Agencies [4].

The next step is now to use this model under different assumptions to validate the number of objects to retrieve every year, if any.

Robustness of these findings

The simulations performed in the frame of the IADC AI 27-1 led globally to similar results with independent methods but were all based on the same break-up model from NASA. This model is definitely the best available today, based on experiences and observations, but it can probably be improved as it is one of the most influencing parameters of the computation.

The Monte Carlo analyses led by both NASA and University of Southampton show how sensitive the results can be on the date of the first break-up or the effective efficiency of mitigation measures. In some cases where the first collision occurs only far from now, the problem even appears critical in some 50 years only; whatever the results, it anyhow always ends up with an exponential growth of the debris population.

One of the priorities in CNES will be to assess the robustness of the ADR requirements.

2.2 Size of debris

There are two ways of dealing with the danger space debris represent to operational spacecraft:

- The long term concern, associated to the collision on large debris leading to swarms of smaller debris,
- The short term concern, much more critical for operators today, associated to the impact of small debris leading to loss of functions or of missions.

The operator’s main concern today is of course the short term risk induced by small debris.

Some analyses have been led on this subject:

- The risk on the Spot 5 satellite, orbiting in an Sun Synchronous orbit at 820 km altitude, has been analyzed by CNES in the ANRICO study [5]. It consisted in a detailed analysis of the effects of impacts on the satellite, assessing the loss of functions or loss of mission as a function of the size of the impactors. Figure 1 shows the cumulated probability of loss of the mission over 1 year, as a function of the size of the debris. It shows a global mission loss probability of 0.3% per year, equivalent to 3 to 5% over lifetime, with a main influence of debris smaller than 5cm.

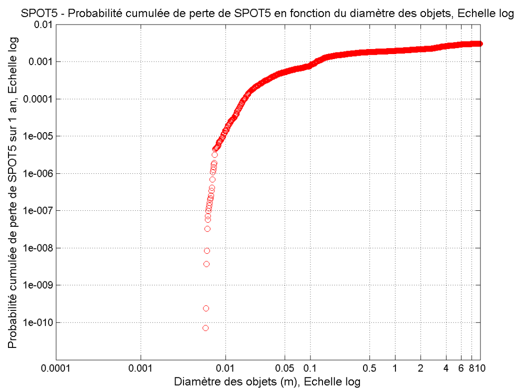

Figure 1: Cumulated probability of loss of Spot 5 function of the size of impacting debris (CNES)

- A similar analysis has been performed by TAS-I in the frame of the ONERA led P²ROTECT study within the EU FP7 [6]. The analysis was led on the satellite Sentinel-1 in a very detailed manner, subdividing all functions within a general fault tree and analyzing the effects of impacts on each critical element of the satellite through a complete physical model. It showed a cumulative probability of 3.2% loss of mission over the 7.5 year lifetime of Sentinel-1.

Both studies, performed in a completely independent frame, give very coherent results.

It can therefore be stated that the orbital debris remediation effort may not be limited to large integer debris, general topic of ADR, but may be extended to the question of smaller debris, in the range of 1 to 5cm in size, even though it corresponds to very different solutions. There are indeed two different problems, on concerning the short term operability of space assets, driven by small debris, the other one concerning the long term stability of orbital environment, driven by large debris; these two problems have very different solutions and need to be evaluated at international level.

2.3 Stabilization of environment

The high level ADR requirements mentioned in the previous paragraphs have been established aiming at stabilizing the current orbital environment, i.e. aiming at keeping on the long term a constant number of catalogued objects.

However, this assumption implicitly means that today’s situation is acceptable, which is far from assessed! The proper high level question today is “do we really want a stabilization of the orbital environment?”:

- The current risk, as quantified in the previous paragraph, may be considered as acceptable to operators in the long run; it means in such case that we must stabilize the number of debris in the 1 to 5cm range, which was not the subject of the ADR efficiency studies so far which aimed more at stabilizing the number of catalogued objects (10cm or more). A new set of analyses may be required in this case.
- A higher risk that the one currently observed could possibly be acceptable by operators; this topic is complex as it deals with the strategy of satellite replacement, or even function fractioning; big operators may accept a higher risk, whereas small operators may suffer from any significant loss in orbit,
- On the opposite, one may consider a risk in the range of 5% loss of mission over lifetime as excessive, in which case the requirement would be to lower this risk and retrieve more debris from orbit,
- Associated to these questions is the timeframe in which actions shall be taken: is ADR urgent, or can we wait for a couple of decades before “cleaning” space? Publications from J.C. Liou show the effectiveness of acting now, compared with acting in 2060 as an example [7]; starting effective ADR in 2020 would lead to 25 major collisions in the upcoming 200 years (compared to 47 if we take no action), but starting such actions in 2060 only would lead to 32 major collisions in the next 200 years.

These questions are complex and require a significant amount of work to be solved. To this extent, a significant cooperative effort at international level is compulsory, aiming at identifying the highest level requirements in the field of Remediation.

This effort should enable us to share common high level requirements, and feed them as inputs in the corresponding actions at IADC level.

3. SYSTEM ARCHITECTURE OPTIONS

3.1. Debris playground

Sorting of debris

The general ADR requirement states that we shall fetch and de-orbit 5 to 10 large integer debris every year, removed from the most crowded orbital regions. But how can we define an "interesting" Target and determine a-priori which ones we should de-orbit?

This sorting is of course based on size, mass and probability of collision with the rest of the orbital environment, equivalent to orbital density of the considered region.

A first general identification of the most critical regions has been established by J. C. Liou in [7] with the description of the 10 most interesting orbital regions.

Such a list can also be established considering debris individually and no longer by orbital regions. This sorting has for instance been proposed by C. Wiedemann in [8]. The summary of the 24 high-risk objects with the highest probabilities of catastrophic collisions and generation of high numbers of debris is given (considering only known, catalogued objects); it starts with Envisat, then includes some 20 Zenit upper stages; in that sense, this kind of sorting leads also to define promising regions, not just individual Targets.

When considering a "single-shot" ADR mission where one Chaser fetches one single Target, the selection process is quite simple: the debris shall be one of the highest ranking in the priority list, considering its accessibility (if for instance the Chaser is launched as a piggy-back, associated to a larger spacecraft which will impose initial orbit, mainly RAAN and inclination).

Situation becomes much more complex when considering a multi-Target Chaser, i.e. one for which the complete mission implies the de-orbiting of more than one debris, and the transfer from one debris to another. The optimal debris list shall then take into account criteria such as the global minimization of the mission ΔV, or the total mission duration. Such optimum may then well lead to the selection of debris ranked at a lower level in the priority list.

Selection of debris depending on their re-entry criticality

One major question associated to ADR is the acceptability or not of a random re-entry following a removal action. By definition, the debris to be removed are large integer objects, of which 10 to 20% in mass is likely to survive atmospheric re-entry, leading potentially to a risk of casualty higher than specified in the various Guidelines documents, Standards or Laws. For instance, the French Law on Space Operations specifies a maximal acceptable casualty risk of 10^{-4} per space operation. This threshold is widely shared at international level, as identified in the IADC Action Item 27.2. Applying strictly this rule would imply limiting ourselves exclusively to controlled atmospheric re-entries.

Such a conclusion is however very limiting in terms of potential solutions, and leads to reject all the "simple and cheap" solutions such as drag increase. Considering the strong impact of such a requirement, it has been decided to open a dedicated IADC Action Item on the topic in order to achieve a commonly shared approach.

This criticality threshold can be translated roughly into a mass requirement: if a debris has a mass higher than 500 to 1000 kg, it shall be de-orbited in a controlled way.

This has led CNES to study in priority solutions associated with a controlled atmospheric re-entry, but this orientation is not shared at international level yet.

Selection of debris depending on their nationality

The question of the nationality of the debris to remove was also raised; one could consider that depending on the launching state a debris could be or not a potential Target for an operation led by another launching state.

However, it was considered, as recalled in the introduction, that the ADR operations will be (and shall be) only considered in a widely international context, the "cleaning" effort being shared among all the space faring nations. The first missions, aiming mainly at demonstrating the feasibility of such operations, may be different: if CNES decides for instance to perform a 1st generation mission to remove Spot3 satellite, it may be performed at French or ESA level; the operational ADR phase, or 2nd generation will on the opposite only be led at international level, enabling to share the financial burden and to ease all proprietary and legal questions.

We therefore selected in our CNES studies not to take into account any "nationality" constraint in our debris selection.

Priority list

Following the criteria listed in the previous paragraph, we have chosen as reference an orbital region called 5E, defined by an inclination ranging from 82.83 to 82.99°, at an altitude close to 1000km, mostly filled with Upper Stages.

This region has been identified, described and justified by TAS-F (together with GMV and MDA), published in [9]. It consists in 264 debris, with an average mass of 1600kg (see Figure 2).

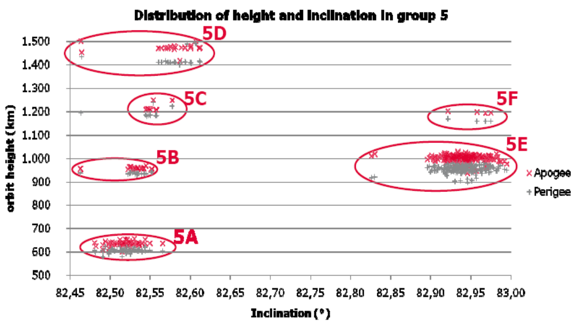

Figure 2: Selection of the reference ADR orbital zone (TAS-F, GMV)

3.2. Strategy for successive debris removal

High Level System Architecture

There is a very wide range of possible schemes at system level when considering the successive removal of several debris during one ADR mission:

- The most obvious scheme consists in a single shot Chaser aiming at a single debris. Such a mission may be interesting as a 1st generation one with the goal of demonstrating the qualification of the required technologies, but it is probably not viable on a operational basis: the Chaser would have to be piggy-back to a larger satellite, but unfortunately such missions are seldom occurring in the most crowded regions; in addition, all the necessary functions would be required on the Chaser (rendezvous chain, robotic arm, GNC, TM-TC…) which would most probably lead to an excessive mission cost for just one debris. For these reasons, such a scheme has been discarded from our studies,
- A large Chaser may aim at de-orbiting several debris in a very simple way: it performs a rendezvous with the 1st Target, then de-orbits it using the Chaser propulsion. Once the re-entry trajectory is achieved, the debris is released and the Chaser re-accelerates to reach the orbit of its 2nd Target, and so on. The major drawback of this solution is the fact that the Chaser is itself de-orbited with each of its Targets, with is far from optimal in terms of mission ΔV budget. One has to trade the simplicity of the Chaser with its inefficiency, number of Targets de-orbited for a given launch mass,
- The system may be improved considering a large Chaser delivering de-orbiting kits to the debris. The global system is more complex, mainly concerning the interface definition of such kits, but it is much more efficient as the mass devoted to the de-orbitation is always optimal,
- A variant identified mainly by Bertin Technologies consists in a large "barge" cruising at low altitude, delivering de-orbiting kits which perform the rendezvous with the Targets, then de-orbits them; unfortunately, the complexity of the kits is such that little is gained compared to the "single shot" Chaser identified previously,
- A last variant consists in delivering a limited number of Chasers, each carrying a number of de-orbiting kits. When analyzing the complexity of missions aiming at Targets with very different orbital planes, this solution turns out to be the best one.

Trade-off

The selection of a high level reference system architecture is far from obvious and depends on a large number of factors:

- The size of the launcher impacts the trade-off in several ways: the cost of the launch generally follows a rule stating that the larger the launcher is the lower the specific cost is, but on the opposite, the possibility to launch a Chaser on more than one launcher is also important in terms of operational flexibility,
- The cost of the "Chaser functions" (rendezvous, robotic arm, …) has a strong influence; if one considers a drastic reduction in these costs associated to a large production rate, autonomous kits and small Chasers may turn out to be cost effective; if on the opposite they remain expensive, then it is better to mutualise them in a larger Chaser performing all the rendezvous.

The architectures have been studied in depth both in the frame of the CNES internal studies and within the industrial studies funded by CNES (Astrium, Thales and Bertin Technologies) but there is no clear conclusion yet, the results being still very different! The ongoing second phase of studies may help solving this question. Two industrial teams are in charge of this second phase of the OTV studies:

- A consortium led by Astrium ST and SAS, from France and Germany, associated to Surrey-Sat from United Kingdom, Bertin Technologies from France, Swiss Space Center from Switzerland and Oceaneering from USA,
- A consortium led by Thales Alenia Space from France, with GMV from Spain and MDA from Canada.

Their results should be available by mid-2013.

Among the most promising solutions, the one schematized in Figure 3, proposed by TAS-F, consists in using a large launcher, Ariane 5 class, to launch 4 identical Chasers, each distributing 5 de-orbiting kits or more. Each Chaser aims at one specific orbital region defined by its RAAN. The size of such Chaser, typically in the class of 4 to 5 tons, also enables it to be launched on a wide variety of launchers. Details of the corresponding trade-off are presented in [Ref.9].

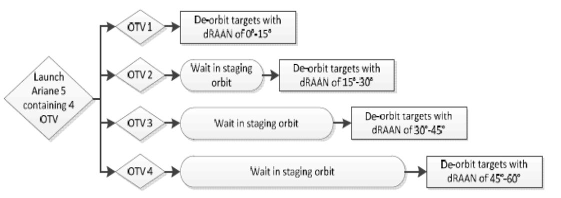

Figure 3: Typical mission architecture optimization (TAS-F, GMV)

<u>Chaser mission optimization</u>

Since all the Targets are very close from each other in terms of altitude and inclination, the major problem associated with multiple debris rendezvous is the dispersion in RAAN. As a propulsive manoeuvre aiming at changing the RAAN drastically increases with the angle to be corrected, it was chosen to use the natural RAAN drift due to J2 effect to shift from one orbit to another.

This manoeuvre has been studied in depth by CNES then by GMV. It leads to a higher complexity of the mission by adding one more degree of freedom, with the altitude of the drift orbit; if such a drift orbit is not introduced in the system scheme, the mission may turn out to be far too long to be realistic.

The following figures 4 and 5, extracted from [10], show the principle of such a global optimization of transfers, applicable to a Chaser as described in the previous paragraph.

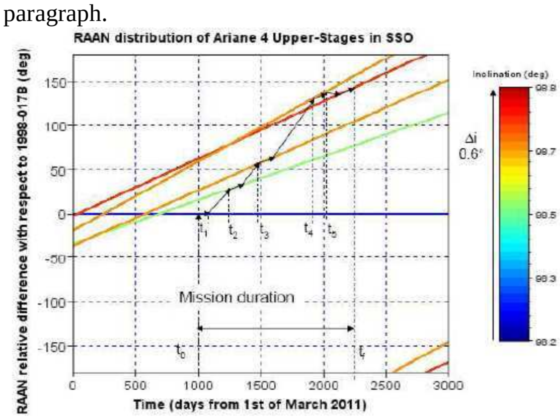

Figure 4: Typical use of RAAN drift during a multi-Target mission (CNES)

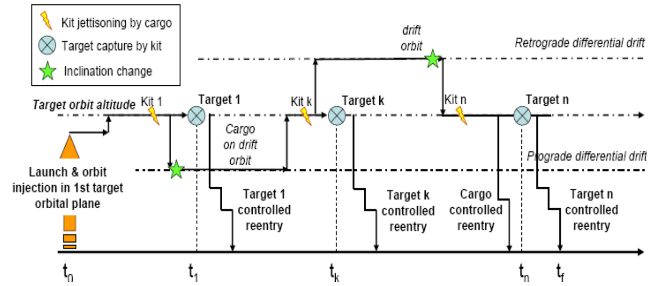

Figure 5: Schematic of a multi-Target mission using RAAN drift (CNES)

4. ADR HIGH LEVEL FUNCTIONS

Whatever the mission architecture and the size of the corresponding Chaser, a certain number of high level functions have to be implemented in order to proceed with the de-orbiting of a given debris.

The following paragraph describes the 5 high level functions which have been identified, and give a brief description of the technical solutions which may be envisaged to cover them, attempting to give a status of their availability.

4.1. Function F1: Far-range rendezvous between Chaser and Debris

The first function a Chaser has to perform, either directly after its launch or after a drifting period to be properly phased with the next Target, is to perform a far-range rendezvous, typically up to 10 to 1 km from the debris.

This can a priori be performed using absolute navigation, which seems to be very well known and demonstrated at numerous occasions in orbit.

4.2. Function F2: Short-range rendezvous between Chaser and Debris

Once in the vicinity of the debris, the Chaser has to perform a rendezvous with the debris, up to contact (or at least very short range, depending on the solution selected for the debris interface).

Such a rendezvous is complex as:

- The debris is non cooperative: it does not help the rendezvous, as it is not equipped with visual cues, radar corner reflectors or any of the equipment commonly used for missions such as the ATV, HTV, Soyuz, Progress or Dragon,

- The debris is potentially tumbling: there may remain some movement, even when the debris is gravity gradient stabilized; this movement should be limited, typically in the range of a few °/s along all axis, as one can expect to have a natural damping of the movement due to Eddy currents induced in a metallic objects moving in the Earth magnetic field [11]. Some preliminary observations tend to show that such a movement could be more important, possibly higher than 6°/s, but we are currently lacking detailed information concerning this point; a dedicated action at IADC level is ongoing and should bring a clear diagnosis on this critical point,
- The debris may potentially have a physical and optical state different from what is expected: as an example, the thermal protection covering a rocket upper stage, white before lift-off, may well be blackened once in orbit following the effect of the thermal fluxes encountered during the atmospheric phase of the launch.

Such a short-range rendezvous under these assumptions has never been published and can possibly raise strong difficulties.

A wide range of potential sensors usable during this phase has been identified, optical or radar, with numerous possible variants (Lidar, Mono or Binocular vision, …). Figure 6 prepared by MDA under CNES contract summarizes some of these potential solutions.

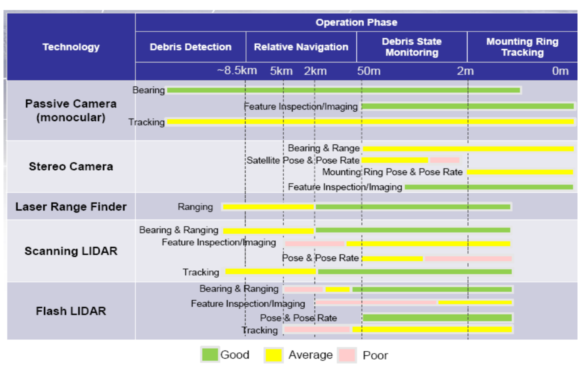

Figure 6: Typical technologies usable for short-range rendezvous between Chaser and debris (MDA)

One promising technology has been presented by Astrium, worth mentioning here: a vision-based solution using a monocular camera enables to assess the pose (attitude and position) of a Target; by comparing with the a-priori known 3D model of the Target, it enables a real-time assessment of its position and attitude [12].

It is important to note that no single technology can cover the complete function. A significant effort in terms of Research & Technology, then in demonstration, is most probably required.

4.3. Function F3: Mechanical interfacing

One of the specific features encountered for the mechanical interfacing function is the fact that the Target is unprepared: it does not have a grapple fixture, or a handle, or any kind of docking port, which makes this function much harder to realize than during a conventional rendezvous such as the ISS, Hubble Space Telescope or Prisma.

Three families of Chaser-debris interface can be identified.

- The first one corresponds to the solution where no mechanical interfacing is required: the corresponding solutions are for instance the Ion Beam irradiation [13] and [14] or the electrostatic tractor [15], but these solutions lead to uncontrolled re-entry, and therefore may not be considered for LEO ADR. On the opposite, as well described by their authors, they are perfectly adapted to the re-orbiting of large GEO satellites, and look in this case very promising,
- The second one corresponds to hard mechanical interface between the Chaser and the debris, meaning a full control of the relative 6 degrees of freedom. This can be achieved thanks to a robotic arm, as studied by DLR in the DEOS program frame [16], or as described by MDA within the CNES studies. In a similar way, solutions analogue to a robotic arm may also be considered, such as the tentacles solution described by ESTEC in the frame of the CleanSpace project [17]. Such solutions may appear complex, mainly in the case of a tumbling Target, but they have the advantage to lead to a well mastered situation for the Chaser-Target assembly, enabling to transmit torques and ΔVs in any direction. Furthermore, robotic arms are well mastered and demonstrated in orbit, so little effort only is required in the ADR frame.
- The third one corresponds to soft mechanical interface, such as the one achieved with a net, a hook, a clamp, a claw, a harpoon,… to quote only a few of the solutions which are currently under study at worldwide level! In general these solutions appear much simpler to apply than the previously mentioned, but offer also only a limited control of the Chaser-Target assembly. Among the recent progresses achieved in studying these technologies, one can mention the work done by Astrium in the field of the net capture [18], including some tests performed in a drop tower and in the Airbus 0g, or the work done by Astrium concerning capture with a harpoon [19] and

[20]. The Technology Readiness Level of such solutions remains however rather low, and significant work has to be undertaken prior to a full scale orbital mission.

As a synthesis for this function, such mechanical interfacing between a Chaser and an non-cooperative, unprepared, potentially tumbling Target has never been demonstrated (or at least published), but there are reasons to believe the required complementary development to achieve orbital operation readiness may not be excessive.

4.4. Function F4: Control, De-tumbling and Orientation of the debris

Prior to the de-orbit itself, the Chaser-Target assembly has to be properly oriented and, depending on the selected interfacing, the residual movement has to be stopped.

For solutions such as a robotic arm or tentacles, the main problem is associated to the potential difference between the rendezvous axis, the tumbling axis and the de-orbiting direction.

MDA work performed in the frame of the CNES study has identified different rendezvous and control scenarios associated to different robotic solutions. Such options are schematized in figure 7. The following 3 cases (from Left to Right) have been studied:

- A: rendezvous along the debris tumbling axis
- B: rendezvous along the robotic capture axis
- C: approach perpendicular to the tumbling axis

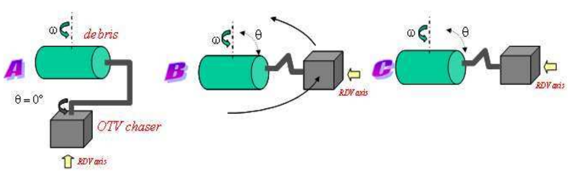

Figure 7: Options for capture and control of a debris with a robotic arm (MDA)

According to the huge experience of MDA in this domain, no technical difficulty is expected, whatever the scheme, provided the tumbling rate remains reasonable; the various cases will just correspond to different fuel consumptions. To give an example, stopping a very large debris such as Envisat with a large Chaser, even under the assumption of a 5°/s tumbling rate, requires less than 10 seconds.

For solutions with a soft interface such as a net or a harpoon, the tumbling motion of the debris cannot be stopped. Some proposals have been made considering ion beam irradiation, or even small pellets projection, to slow the movement prior to the interfacing, but the corresponding TRL is definitely low. For these solutions, the Chaser shall pull the Target using a tether of a given length. The stability of the assembly is one of the major open points, depending on the stiffness of the tether, its length and the thrust profile applied by the Chaser (on-off or modular thrust). This problem is currently under study in CNES, and has been very well assessed already in ESTEC [17]; it clearly remains one of the key unknowns of such solutions, requiring significant progress in GNC for the de-orbiting boosted phase.

4.5. Function F5: De-orbitation

A very large number of possibilities have been identified to perform the de-orbiting itself, including drag augmentation devices such as balloons, EDT, sails (solar or dynamic pressure), ion beam irradiation, electric propulsion, aso… Unfortunately, as mentioned previously, they are not considered as potential references in CNES studies as they lead to uncontrolled re-entry, with an excessive casualty risk on ground; we have nevertheless kept them in the frame of our studies in order to have a comparison point, but we will not devote significant effort on them.

As the de-orbitation boost shall lead to a controlled re-entry in the Pacific, the associated acceleration shall be high enough to guarantee an efficient orbital transfer leading to a perigee low enough to minimize the debris footprint at the surface of the globe. This limits the solutions to the conventional chemical propulsion in all its forms; unfortunately, none of them appears to be ideally fit for this function:

- Bi-liquid propulsion is efficient, enables moderate thrust, and can be commanded in order to cope exactly with the required ΔV; unfortunately, it is potentially expensive, such a system being relatively complex,
- Mono-propellant propulsion is much less efficient, but is also much simpler and cheaper; the question of the replacement of Hydrazine is open, with good options (H2O2, HAN, ADN) but it is of course a question which has to be solved in a different frame,
- Solid propulsion is promising, with relatively high performance, high compacity, simplicity of use, and relatively cheap system. It however generates high thrusts which may be detrimental to the structural integrity of the debris, and the exact matching of the provided and required ΔVs is complex to achieve, although solutions have been proposed such as described in [21],
- Hybrid propulsion may turn out to be the best adapted to this function, with potentially high Isp, relative simplicity, good compacity and controllability of the ΔV; it nevertheless still suffers from a TRL lower than other solutions, but innovative concepts such as described in [22] appear today very promising.

5. CONCLUSIONS

A lot of work is being done on the subject of Active Debris Removal at worldwide level. However, some of the high level questions do not yet have clear and un-ambiguous answers: what is really the need: to stabilize the environment? To lower the orbital density? Or on the opposite should we consider there is no real urgency and we can wait a couple of years or decades?

The key question today may well not be “How?” but rather “What for and When?”; this consolidation of high level requirements shall be the highest priority at international level, mainly through IADC actions.

The study of technical solutions is a must in order to identify the availability of the required technology, and affordable solutions. No Agency will, nor shall, give priority to such missions compared to Earth Observation ones for instance, unless it is deeply convinced of its necessity, which is not yet the case.

Numerous questions, not mentioned here, have equally high priority:

- The questions of legal and insurance framework, together with ownership problems associated with the notion of launching state shall be dealt with urgently,
- The political hurdles, keeping in mind the risk of militarization of space, must be treated in parallel,
- The financing schemes, potentially leading to a Global worldwide program, have also to be looked at,
- The international cooperation framework, associated to this previous point, has to progress.

These key open points show that it would be an error to focus only on the technical aspects of Active Debris Removal.

It is suggested here to select a test case to compare solutions, enabling us to work under a reference case. It has been proposed by T. Rhyzhova, from ISTC in Russia, to focus on the case of the Cosmos 3M upper stage, some 300 of such large debris being in orbit in some of the most crowded orbital regions. This would allow to benchmark the various solutions under the same set of hypotheses, and would pave the way to the initial steps of international cooperation. The initiative taken by ISTC (Russia), currently involving NASA, JAXA, ESA, Poli Milano, OSTU, TsSKB, ISTC and CNES, to promote an ad-hoc working group is therefore encouraged by CNES as this could lead to the premises of an internationally agreed solution [Ref.23].

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