A4

Active Debris Removal activities in CNES

Christophe Bonnal (CNES)

A vast majority of studies led at international level, mainly in the frame of IADC, has shown that the future stabilization of the orbital density in Low Earth Orbits (LEO) imposes the active retrieval each year of some 5 to 10 large debris. This Active Debris Removal (ADR) activity, theorized since more than 30 years, appears now as a must since 2007 and the Fengyun 1C destruction, then the Iridium 33 – Cosmos 2251 collision.

CNES has published on ADR since 1998 and has been pro-active on the subject ever since, mainly through internal studies jointly led by the Toulouse Space Centre and the Launcher Directorate, through industrial studies financed since 2009 and through numerous smaller actions at laboratory or academic studies performed on the most sensitive technological hurdles.

The first part of the paper is devoted to the elaboration of the high level requirements, mainly devoted to the number, type, and frequency of objects to be retrieved, together with the influence of the date of operational availability of an ADR system. This activity is fundamentally led at international level, mainly through cooperation with JAXA, NASA and Russian entities. Some questions are of paramount importance, such as the acceptability of a random re-entry, potentially non compliant with applicable safety rules.

The second part deals with the various potential schemes at system level, trading between small chasers devoted to a single debris up to huge ones dealing with some 25 to 30 debris, with numerous variants using de-orbiting kits, or medium sized Orbital Transfer Vehicles OTV dealing each with some 4 or 5 debris.

The third part aims at identifying the criticality of the technologies required for ADR operations. Five functions are identified: long-range rendezvous; short-range rendezvous up to contact; mechanical interfacing; control of the chaser-debris assembly; de-orbiting. For each of these functions, associated sub-systems and equipment are identified together with their degree of maturity. The specificities of ADR compared to "conventional" rendezvous missions are identified, mainly the fact that rendezvous is performed with non-cooperative, un-prepared, potentially tumbling, potentially optically undetermined object. The fact that a debris may be dangerous in some cases, prone to explosion at contact, is addressed.

The fourth part of the study gives a status on some of the "smaller" studies led in the frame of ADR, such as the control of the "chaser-tether-debris" assembly required for a towing de-orbiting solution, as well as most recent results concerning the potential random movement of debris in orbit.

As a conclusion, the paper deals rapidly with the non-technical issues of ADR, and proposes potential ways to be explored.

Biography - - - - -

Christophe Bonnal is Senior Expert in charge of Systems in the Technical Directorate of the CNES Launcher Directorate in Paris.
Since 1984 he has been in charge of numerous technical and project activities dealing with all current and future European launchers.
Christophe Bonnal is in charge of Space Debris aspects since 1987, French delegate to the IADC, member of the ECSS-ISO Working Group on Space Debris Mitigation, Chairman of the Space Debris Committee of the International Academy of Astronautics, coordinator of the IAC Space Debris Symposium and Editor of the IAA Position Paper on Space Debris Mitigation.

ACTIVE DEBRIS REMOVAL:
CURRENT STATUS OF ACTIVITIES IN CNES

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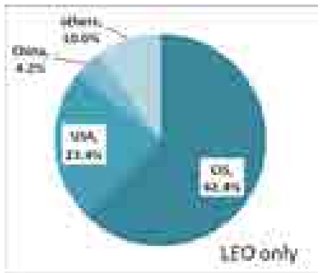
Content

Introduction

■ Kessler syndrome

- Identified theoretically by Don Kessler and Burt Cour-Palais in 1978 [1]
- Four sources of space debris:
  - Mission Related Objects, Break-up, Aging, Collisions
  - When the “collision” source becomes larger than the “atmospheric cleaning”, natural increase of orbital population
  - Critical density varies strongly with the orbit altitudes:
    ↳ Most critical zones in LEO, between 700 and 1100 km, highly inclined (including SSO)
- Potential need for Active Debris Removal (ADR)
- International problem
  - Sources of debris from every space-faring nations
  - No nation shall nor can solve the problem alone



[1] *D.J. Kessler, B.G. Cour-Palais, Collision frequency of artificial satellites: the creation of a debris belt, JGR 83 (A6) (1978) pp. 2637–2646.*

Introduction

■ Logic of the activities

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

1. High Level Requirements

- **Number of debris to remove**
  - **Studied at worldwide level since more than a decade**
  - **Reference studies from NASA Orbital Debris Office [1]**
    - **Need to remove 5 large debris per year to stabilize the environment**
    - **Numerous robustness and sensitivity studies**
  - **Cross-check led by 6 other IADC delegations**
    - **Same hypotheses, model and mitigation**
      - 100% explosion suppression
      - 90% success of end of life measures
    - **Different tools**
    - **IADC Action Item 27.1**
    - **Coherent results, and confirmation of the need to remove 5 large objects, at least, per year**

    ↳ ***"new mitigation measures, such as Active Debris Removal, should be considered".***
- **Highest level priority for CNES:**
  - **Development by Toulouse Space Center of a predictive tool, with different modeling, enabling robustness studies**

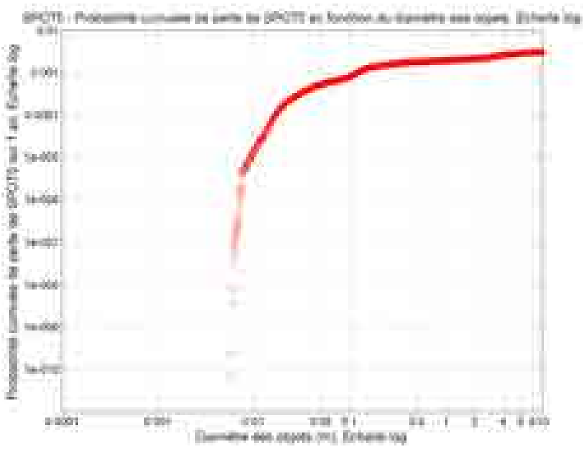
  ↳ **Tool MEDEE is now available and will be presented in Darmstadt**

[1] *J.-C. Liou, N.L.Johnson, N.M.Hill, Controlling the growth of future LEO debris populations with active debris removal, Acta Astronautica 66 (2010) pp. 648 - 653*

1. High Level Requirements

- **Size of Debris**
  - **Removing large debris enables a long term stabilization of orbital environment**
  - **Operators' main concern is short term risk induced by small debris**
  - **Examples:**
    - **Risk on Spot 5 (CNES) [1]**
    - **- Mission loss 0.3% per year**
    - **- Main influence of < 5 cm**
    - **Risk on Sentinel 1 (TAS-I draft) [2]**
    - **- Mission loss 3.2% over lifetime**

  ↳ **Large integer objects may not be the only ones to remove:**
    - **Different concerns**
    - **Very different solutions**



[1] *P. Brudieu, B. Lazare, French Policy for Space Sustainability and Perspectives, 16th ISU Symposium, Feb. 21st, 2012*
[2] *R. Destefanis, L. Grassi, Space Debris Vulnerability Assessment of the Sentinel 1LEO S/C, PROTECT Workshop, Mar. 21st, 2012*

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1. High Level Requirements

- **Stabilization of environment**
  - **Current recommendations aim at stabilizing the orbital environment**
  - **↳ But do we really want a stabilization ?**
    - Is the current risk considered acceptable by operators ?
    - Could it be increased ? To which level ?
    - Should it be decreased ?
    - When should we act ? Now ? In 20 years time ?
- **Acceptability of random reentry**
  - Can ADR operations lead to random reentry of large dangerous objects ?
    - ⇨ Casualty threshold = 10^{-4} per operation
    - ⇨ By definition, ADR shall be done on large objects ≡ Dangerous
    - Random reentry would be illegal according to French Law on Space Operations
    - However, it improves both debris situation and casualty risk
    - Action on-going at CNES Inspector General level
    - Action to be led within IADC WG4

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1. High Level Requirements

- **JAXA-NASA-CNES Coordination Working Group in the area of Orbital Debris Removal**
  - NASA, JAXA and CNES shall use reasonable efforts to carry out the following responsibilities:

1. Provide information regarding the orbital debris removal inputs and requirements;
2. Participate and contribute to the technical discussions on orbital debris removal requirements
3. Participate and contribute to the discussion of possible common approaches to orbital debris removal requirements
4. Participate and contribute to the discussion on the advantages and disadvantages of possible concepts and technologies in the area of orbital debris removal

- Priority shall be given to:
  - Need for stabilization criteria for environment
  - Size of debris
    - **↳Probability of mission loss**
  - Acceptability of random reentry
  - Date of operations

2. System architecture options

- **Debris playground**
  - **Definition of an "interesting target":**
    - **Function of size – mass – orbit density**
    - **Function of the debris population in one given zone in case of multiple debris chasing**
      - Minimization of the mission ΔV
      - Minimization of global mission duration
    - **Could be function of criticality of random reentry:**
      - Random reentry not acceptable if casualty > 10^{-4}
      - To be confirmed at national level, then at IADC level
      - Typical threshold in size: 500 to 1000 kg
      - Could be antagonist with finality of ADR
      - ⇘ Only solution with Direct Controlled Reentry are studied today
    - **Could be function of nature of debris**
      - Launcher stages pose potentially less problems than Satellites (definition of a debris, confidentiality, mechanical robusteness…)
    - **Not function of country**
      - Deliberate choice to consider for the operational phase all debris
      - ⇘ International problem, tackled at international level
  - **Identification of the most interesting zones:**
    - **Initial sorting identified 10 critical zones**
    - **Refined subdivision into coherent sub-regions [2]**

[1] *JC. Liou, The top 10 Questions for Active Debris Removal, #S1.3, 1st European Workshop on ADR, Paris, June 2010*
[2] *P. Couzin, X. Rozer, L. Stripolli, Comparison of Active Debris Removal Mission Architecture, IAC-12-A6.5.5, Naples 2012*

2. System architecture options

- **Strategy for successive debris removal**
  - **Numerous possible schemes:**
    - **Single shot: one chaser, one debris**
    - **Multiple debris: one chaser, several debris**
    - **Multiple debris: one carrier + multiple deorbiting kits, one debris per kit**
    - **Multiple debris: multiple chasers in one launch, several debris each**
  - **No obvious solution:**
    - **Cost of the launch → Dedicated or Piggy-back**
    - **Size of the launcher**
    - **Cost of the chaser "functions" → Effect of mission rate**
    - **Sizing of the multiple debris chasers → Global mission ΔV**
  - **Analyses performed by Astrium, TAS-F and Bertin under CNES contract**
    - **Results are still differing !**

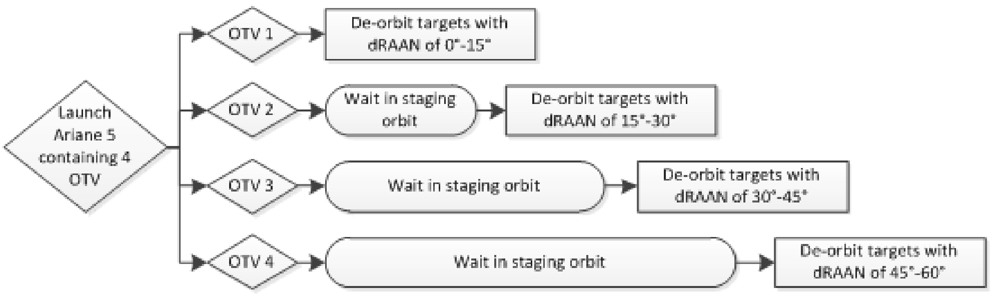
2. System architecture options

■ **Among the most promising solutions:**

- **Considered for the Operational phase**
  - First Generation may show different optimum
- **Large launcher with multiple chasers, each delivering multiple kits [1]**

◆ **Big launcher (e.g. Ariane 5) launching N different multi-debris OTV's**

- Group is divided into N RAAN regions
- Each OTV targets a certain part of the group
- Lower launch staging orbit generates a shorter wait



[1] *P. Couzin, X. Rozer, L. Stripolli, Comparison of Active Debris Removal Mission Architecture, IAC-12-A6.5.5, Naples 2012*

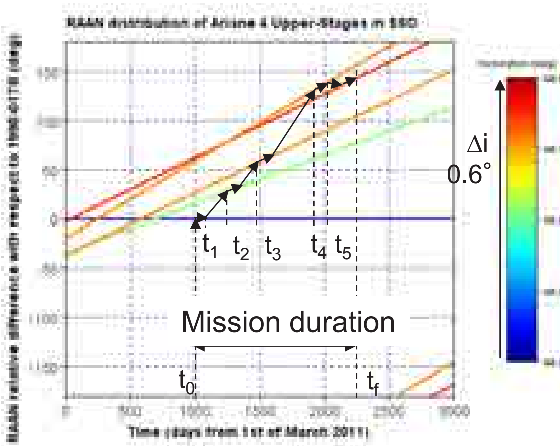
2. System architecture options

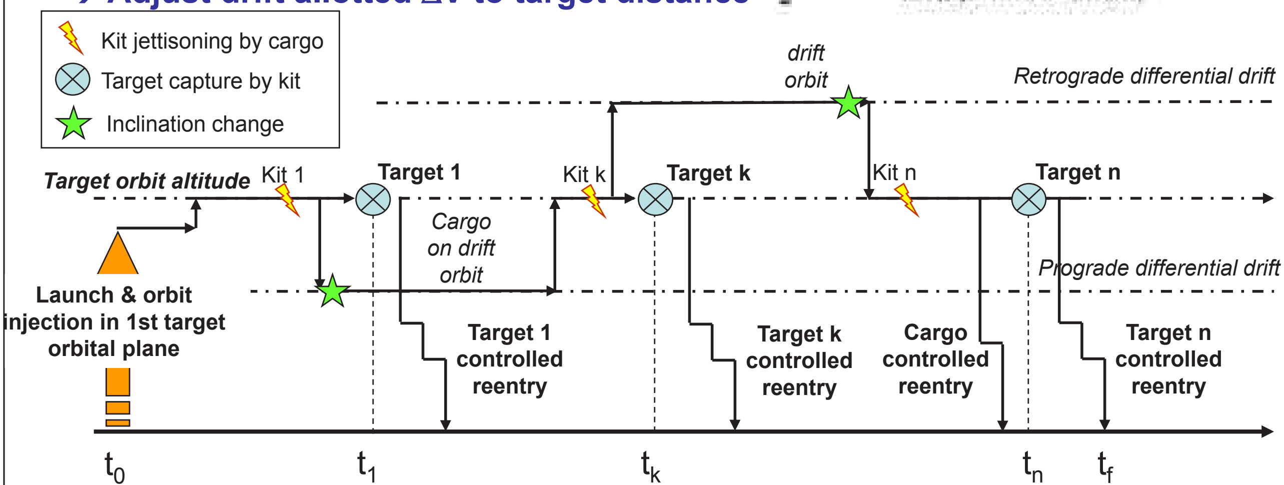
■ **From CNES Internal Study OTV [1]**

- ◆ **Removal of 5 Ariane upper stages**
- ◆ **Autonomous kit achieves capture**
- ◆ **Similar targets**
- ◆ **+/-200 km Δa → +/-36° /yr drift capacity**
- ◆ **Targets visited in increasing order of inclination → cumulated 0.6° Δi**

→ Mission duration depends on launch date

→ Adjust drift allotted ΔV to target distance





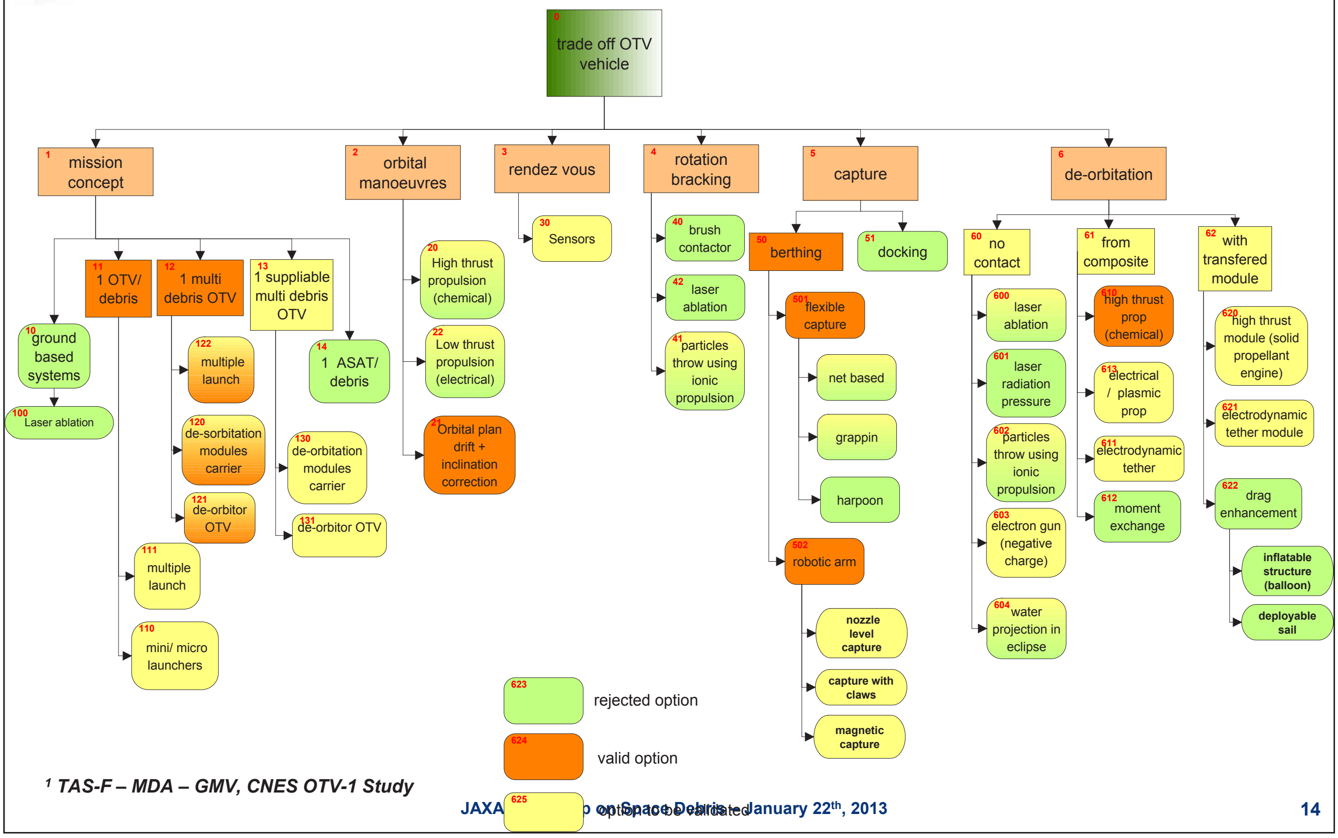
[1] *E. Pérot, Active Debris Removal Mission Design for LEO, #479, 4th EUCASS, St Petersbourg July 2011*

3. ADR High Level Functions

- **Active De-orbiting of a debris requires 5 functions:**
  - **F1: Far Range rendezvous between Chaser and Debris:**
    - **Up to 10 to 1 km from target**
    - **Can be done through absolute navigation**
    - **Already demonstrated and space qualified**
  - **F2: Short Range rendezvous, up to contact**
    - **Never demonstrated (published) yet for objects which are:**
      - Non cooperative
      - Non prepared
      - Potentially tumbling
      - Potentially physically and optically different from expected
  - **F3: Mechanical Interfacing between Chaser and Debris**
    - **Never demonstrated (published) yet for a non prepared object**
  - **F4: Control, De-tumbling and Orientation of the debris**
    - **Partially demonstrated in orbit, but Human operations**
  - **F5: De-orbitation**
    - **Low thrust or drag augmentation solutions are discarded here**
    - ↳ **Lead to uncontrolled reentry**
    - ↳ **Or too high complexity if coupled with high thrust for final boost**

3. ADR High Level Functions

- **General approach and trade-off (example from TAS-F [1]):**



[1] *TAS-F – MDA – GMV, CNES OTV-1 Study*

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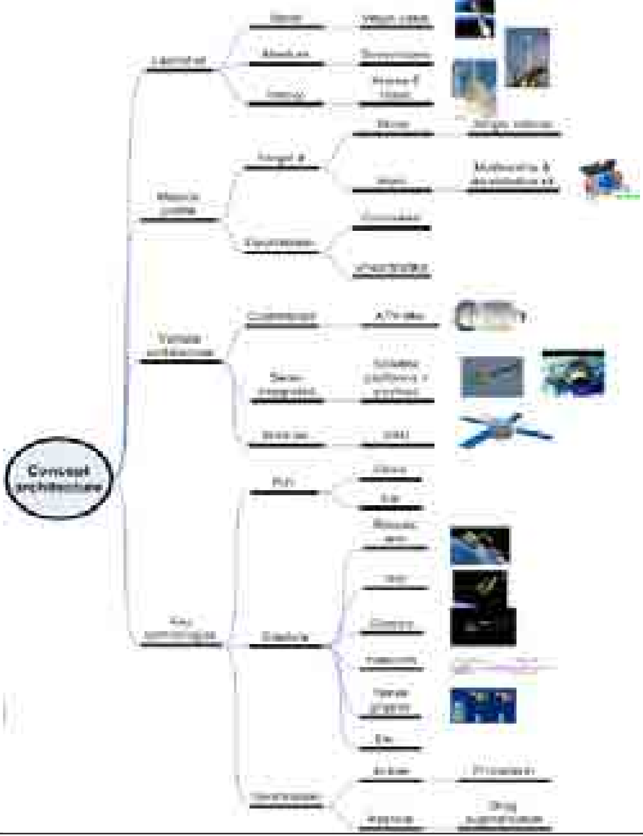
3. ADR High Level Functions

- General approach and system breakdown (example from Astrium):



[1] *Astrium, CNES OTV-1 Study*

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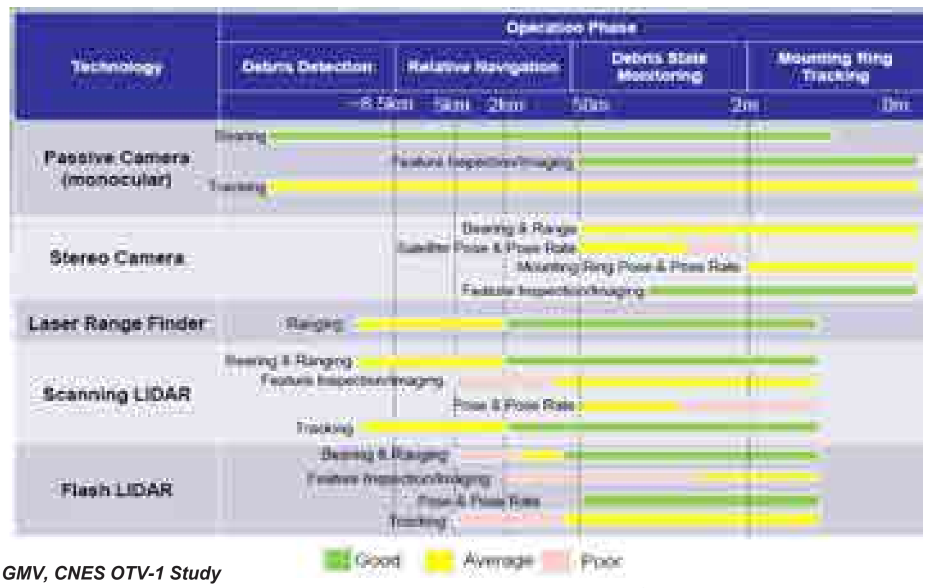
3. ADR High Level Functions

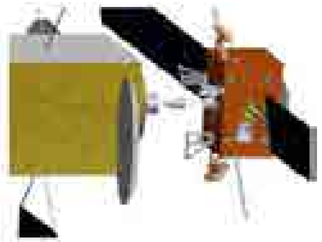
- F2: Short Range rendezvous, up to contact
  - Numerous sensors can be considered
    - Optical, Mono or Binocular, Lidar / Radar…
    - Example from MDA-TASF [1]
  - No single technology can cover the complete function

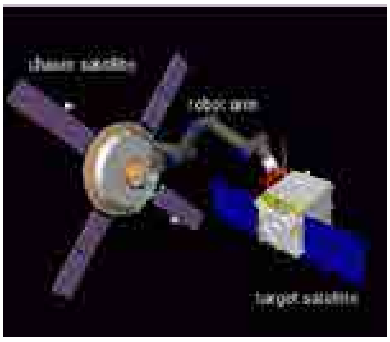


[1] *TAS-F – MDA – GMV, CNES OTV-1 Study*

3. ADR High Level Functions

■ F3: Mechanical interfacing, some examples:


OSS: clamp inside the target nozzle

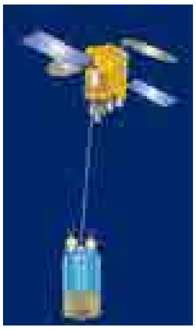


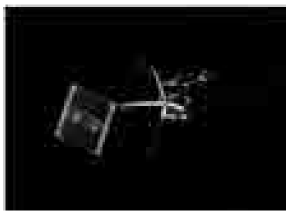
DLR: robotic arm DEOS


Astrium UK: harpoon


Uni. Roma: foam gluing


CNES: deorbiting kit with robotic operations


ESA-Astrium: hook ROGER


EPFL: claw

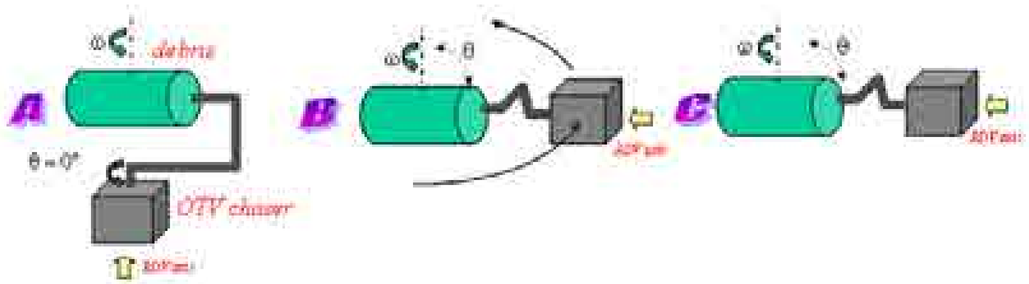

Astrium: net capture

3. ADR High Level Functions

- ■ **F3: Capture – Mechanical Interfacing**
  - ◆ **No reference solution yet**
  - ◆ **Solutions without mechanical interface are discarded here:**
    - Electrical engine beam pressure
    - Electrostatic tractor
    - ➢ **Lead to uncontrolled reentry**
  - ◆ **Solutions may impose different modes of deorbiting**
    - Net, hook… will impose “pulling” the debris
    - Some allow the control of the debris, other don’t
  - ◆ **Among the preferred:**
    - Net capture
    - Harpoon or hook
    - Robotic arms
    - ➢ Trade-off ongoing during the OTV-2 study (AST and TAS)

3. ADR High Level Functions

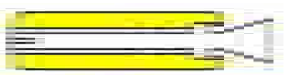
- **F4: Control-Detumbling of the debris:**
  - Example from MDA [1]
  - Rendezvous analyses demonstrate:
    - A dramatic dependency of the rendezvous sizing to the tumbling rate
    - The importance of the rendezvous axis
  - Results suggest to assess different rendezvous scenarios, associated to different robotic solutions:
    - A – RDV along the debris tumbling axis
    - B – RDV along the robotic capture axis
    - C – Approach perpendicular to the tumbling axis

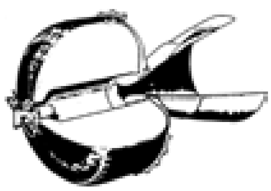


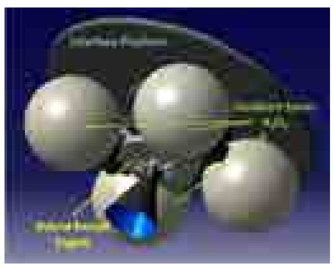
[1] *TAS-F – MDA – GMV, CNES OTV-1 Study*

3. ADR High Level Functions

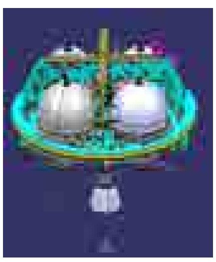
- **F5: Deorbitation:**
  - High thrust deorbitation, Controlled reentry
  - Rendezvous analyses demonstrate:
    - Conventional chemical propulsion
      - Solid, Hybrid, Monopropellant, Bi propellant
      - Each have drawbacks and advantages
    - Potentially most promising: Hybrid propulsion

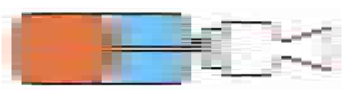






DeLuca et al. IAC-12-A6.5.8





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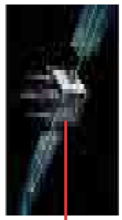
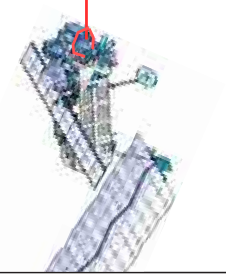
4. Support studies



Velocity vector

- **Envisat:**
  - **One of the highest priorities debris**
  - **Proposal to reorbit above 2000 km:**
    - **First generation**
      - Would allow a full scale demonstration of most of the functions
      - Need to find the cheapest solution possible
    - **Electrical propulsion**
      - Derived from Smart 1 (x 4)
      - Compatible with a Vega launch
      - Long tether (500 to 1000 m)
    - **Mechanical interfacing with hook on one of the "zenit" instruments**
    - **Global mass budget ≅ 820 kg**
  - **Presented in Ref [1]**

Earth center



[1] *C. Bonnal, C. Koppel, 2nd European workshop on ADR, Paris, June 2012*

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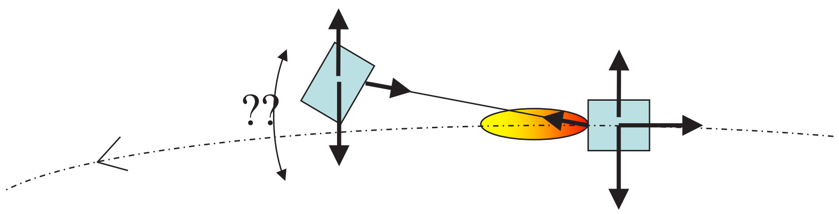
4. Support studies

- **Stability of the Chaser-Tether-Debris assembly:**
  - **Towing = Preferred solution today, but very low TRL**
  - **Control laws of the chaser during de-orbiting boost:**
    - Parameters of tether: length, elasticity, damping
    - Initial conditions of Debris: 6 DOF = orientation = angular motion
    - Parameters of Chaser: MOI, thrust and variation, initial orientation
    - Parameters of tether-debris interface: unbalance
    - Acceptance criteria: ΔV amplitude, orientation, dispersions
    - Control laws
  - **Three teams working on the topic in France**
    - Mines Paris-Tech
    - Supelec
    - Thales Alenia Space

  - **Numerous other teams worldwide (ESA, Russia, USA…)**
  - **Results not yet available**

  ↳ **Dedicated session during upcoming EUCASS in July 2013**



5. Conclusions

- First priority is to consolidate high level requirements:
  - Question today is not yet How, but What and When
  - Study of technical solutions:
    - Necessary for programmatic evaluations
    - Necessary for R&T programs for TRL increase
  - Numerous questions have very high priority:
    - Legal and insurance framework, ownership, launching state
    - Political hurdles: Parallel with military activities
    - Financing schemes
    - International cooperation framework
- Recommendation to work on a reference test case
  - Cosmos 3M upper stage could be a good example
  - Benchmarking of solutions over same hypotheses
  - Initial steps of international cooperation
    - Ad-hoc framework: JAXA-NASA-CNES Working Group