Appendix 2

Synthesis of the

4th International Workshop on Space Debris Modeling and Remediation

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IAA Space Debris Committee
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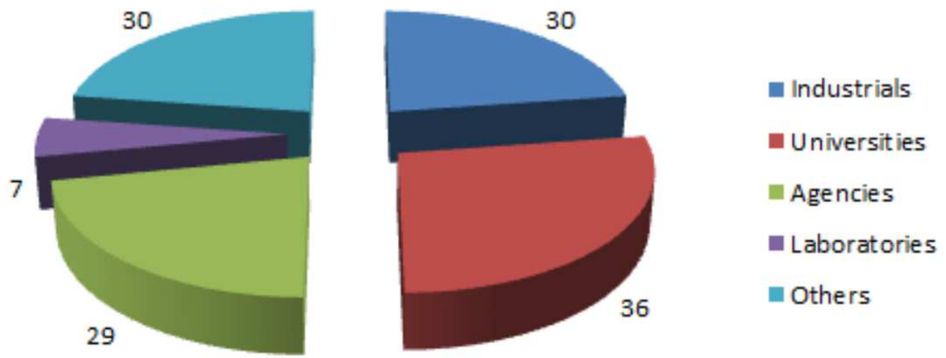
Introduction

- Regular workshop held every two years:
  - → Complementary to "End of Life" and "Collision Avoidance"
  - → 4th edition

- Participants:
  - → 132 participants coming from 15 countries (room size limitation)
    (including US, Canada, Japan, China, Singapore + 10 europeans)
  - → Good repartition among industrials, agencies, universities



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Keynote Lecture: Don Kessler

- 1st Senior Scientist NASA Orbital Debris Program Office (1979)
- 1st NASA activities : 1968-1972 following impacts on Gemini windows
- 1st program in 1976, aimed at detection of debris smaller than 10 cm
  ⇨ 1st Mitigation Directives
- IADC in 1987 following Ariane V16 upper stage H8 explosion
- Publications in 1977 and 1978 on exponential increase of orbital debris population
- Publication of the "Kessler syndrome" in 1991

Opinion:

- Problem of debris in the 1 - 10 mm range insufficiently considered currently
- Identifies a tax of 5 to 10% on launches to finance ADR
- Priority to Models and to in-situ impact analyses
- Long term strategy to be establish at international level

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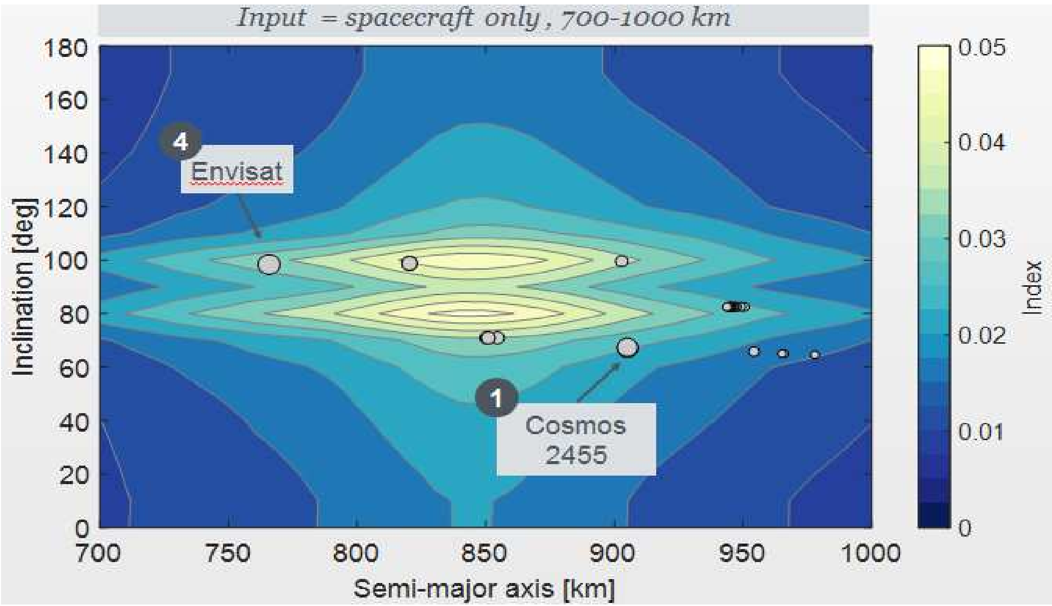
Sessions 1 & 2: Modeling

- 1.1 & 1.2: Effect of Mega-Constellations (Bastidi-Virgili, Dolado-Perez, ESA-CNES)
- 1.3: Selection criteria for ADR (Zemoura, Kyushu University)
  - Key ideas
    → Ranking position has main impact at SHORT term
    → Number of removed objects has main impact at LONG term
    → Optimal efficiency = combination of strategies from different terms
- 1.4: Evolution of a debris cloud post collision (Kebe, Obs. Paris)
- 1.5: MEO stability (Rossi, IFAC CNR)
- 1.6: Environmental index (Letizia, Uni. Southampton)



$$\Xi = \frac{m}{m_0}\frac{D(h)}{D(h_0)_c}\frac{\Delta t(h)}{\Delta t(h_0)}\frac{1+k\Gamma(i)}{1+k}$$

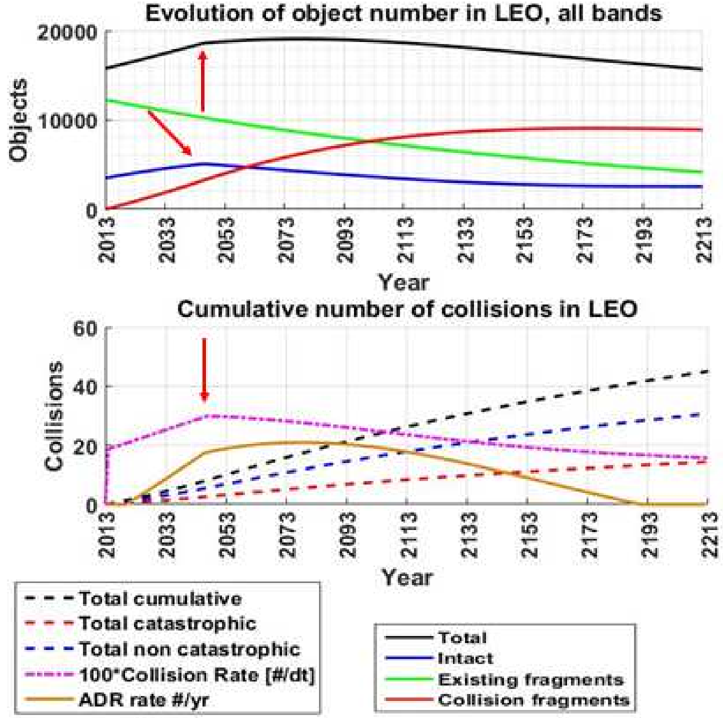
Mass | Life time | Environment | Inclination

Sessions 1 & 2: Modeling

- 2.1: Continuous approach of spatial density (Colombo, Uni. Southampton)
    - Analytical propagation of debris clouds
    - Analogy with gas kinetic theory

  The modelling of the contribution of **small debris fragments** to the collision risk requires methods that do not rely on the propagation of single objects. **Density-based models** offer an interesting alternative.

- 2.2: Stochastic modelling of HVI effects (Sagnières, Mc Gill Uni.)
- 2.4: Simplified model of evolution control – PID controller (Somma, Uni. Southampton)
- 2.5: Aerothermodynamic model reentering tank (Dupont, Bertin)



Optimistic scenario

- 90% compliance with PMD 25-yr rule
- No explosions
- PMD starts in 2013, but acts from 2046 (2013+8+25)

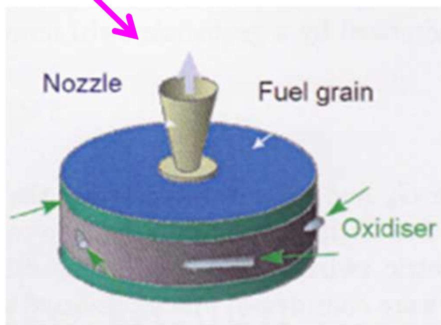
ADR

- Starts in 2020
- Max 25 removals per year

Synergy of PMD and ADR

Session 3: De-orbiting

- 3.1: D-SAT proposal:
  - 1st demonstration of controlled reentry using an autonomous deorbiting kit
  - Launch 2016 (Antonetti, D-Orbit)
- 3.2: End of Life of XW-2 (Huang, DFH Sat Co, China)
- 3.3: New hybrid propulsion concept for deorbitation system (Paravan, Poli Milan)
- 3.4: Teser – Technology for deorbitation (Voigt, Airbus D&S)
  - H2020 until 2019
  - Principle of a family of deorbitation kits



- 3.5: Use of residual propellants for deorbitation
  (Galfetti, Poli Milan & Trushlyakov, Omsk Uni, Russia)

- 3.6: Holistic approach of collision risks (Mc Knight, IA, USA)

"Preliminary analysis with JSpOC monitoring the conjunction of the 16 SL-16 (Zenit second stage) rocket bodies located 815-865km. Mass 8.3 tons. A collision of two such objects would likely double debris population in low Earth orbit (LEO) in an instant.
Data showed that over one year time there were ten encounters of less than a 1 km separation distance and three within 500m with an average relative velocity of encounter over 10km/s. Up there for still some 200years."

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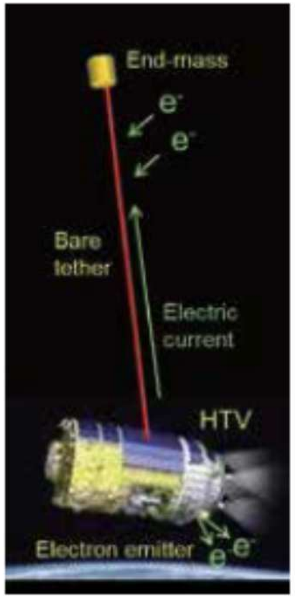
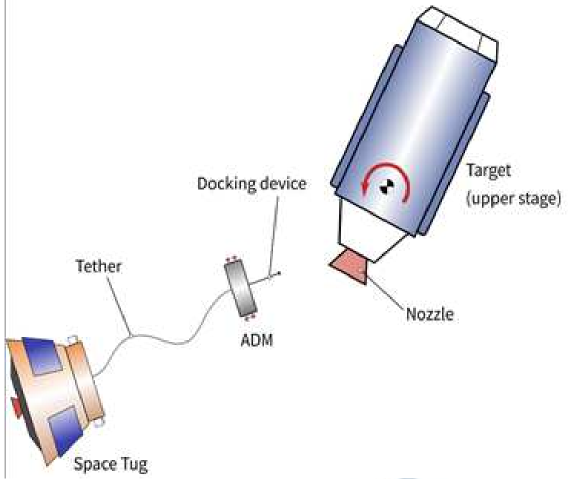
Session 4: ADR System

- 4.1: Airbus D&S vision on ADR (Pisseloup, Estable, ADS)
  - Technologies for e-Deorbit
  - RemoveDebris demonstration mission
  - Global approach: Space Tug, SUV, OOS
- 4.2: JAXA vision JAXA on ADR (Kawamoto, JAXA, Japan)
  - “Cost” analysis of ADR
  - Preparation of an EDT demonstrator
- 4.3: ADR technologies – The “CADET” project (Chiesa, Aviospace)
- 4.4: Technologies for ADR (Yamamoto, JAXA, Japan)
  - Very wide range of technologies
  - KITE demonstrator expected in 2016
- 4.5: System approach to Cosmos 3M upper stages deorbitation (Trushlyakov, Omsk Uni., Russia)
- 4.6: Mission De-Orbit (Wolahan, ESA)
  - Proposal for a maturation phase → Q2-2019

	2017	2018	2019	2020	Total
Phase B2	2	4	5	4	15
Robotics	2	3	5	2.5	12.5
GNC	1	3	3	3	10
Flexible	1	1	4	2.5	8.5
ESA Internal	1	2	3	3	9
Total	7	13	20	15	55



KITE: EDT technology demonstration (2016)



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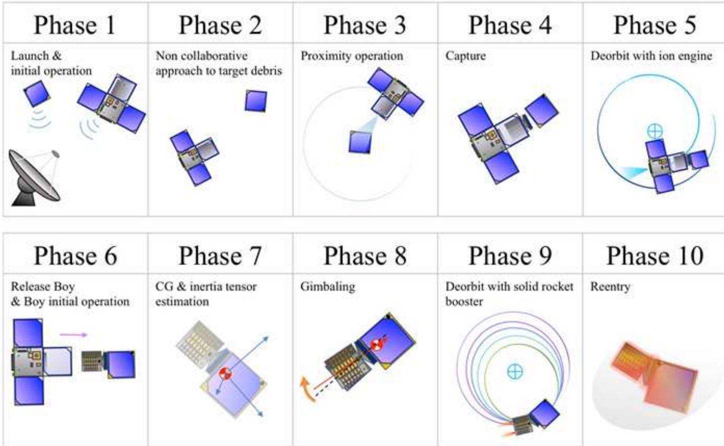
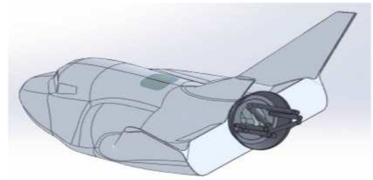
Session 5: ADR Demos & Propulsion

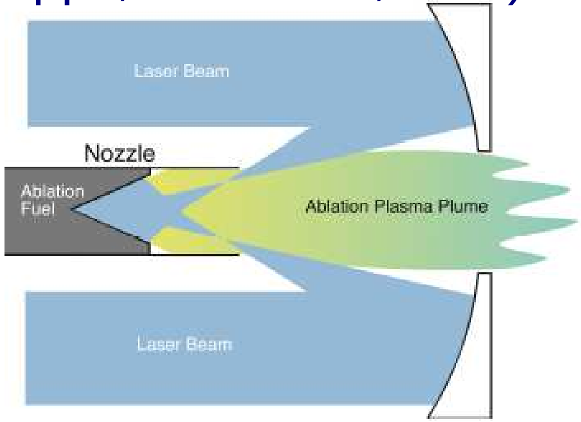
- 5.1: Remove Debris demonstrator
  (Forshaw, Surrey Space Center)
  - Flight demonstration: 13 objectives
  - Flight via ISS Nanoracks 2017



- 5.2: ADRAS demonstration
  (Okada, Astroscale, Singapour)
  - Flight demonstration: 10 objectives
  - Flight in 2018
- 5.3: Use of hybrid propulsion for ADR (Tonetti, Elecnor Deimos)
- 5.4: Use of Dream-Chaser to deorbit Envisat
  (Binet, GMV & Olson, Sierra Nevada, USA)



- 5.5: Comparison of electric and laser propulsion for ADR
  (Phipps, Photonics, USA)



Important features of electric and laser thrusters

Thruster Type	MPD	HET	Ion	Pulsed Laser	VASIMR
Thrust/Mass	Very Low	High	High	Medium	Very Low
Thrust/Area	Very High	Medium	Medium	Very High	Very High
Operating Lifetime	Medium	High	Very High	Very High	Seconds
Max Power Demonstrated (kW)	500	22.4	39	0.5	200
Max Thrust Demonstrated (N)	3.5	0.81	0.67	0.01	5.8
Device TRL	5	9	9	7	4

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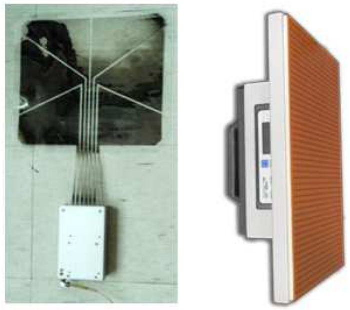
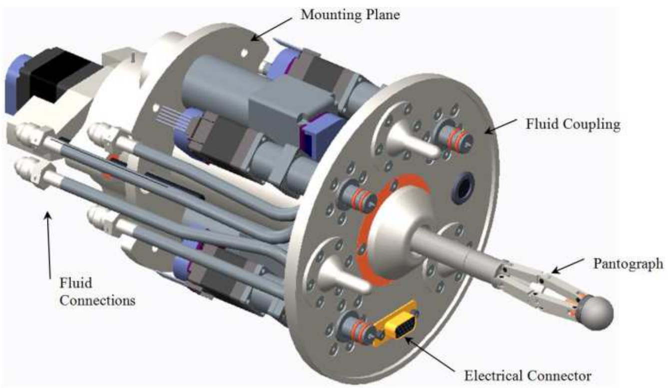
Session 6: ADR Capture

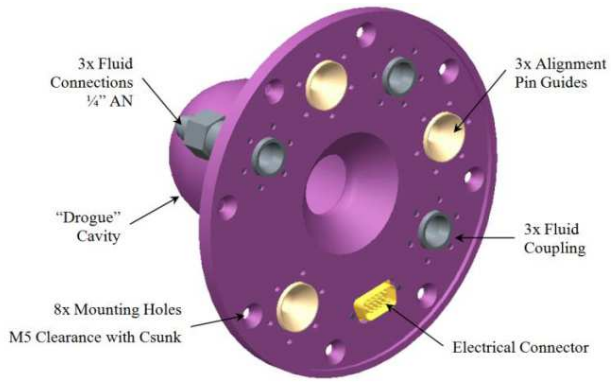
- 6.1: Deployment and capture by net (Botta, Mc Gill Uni., Canada)
- 6.2: Electrostatic adhesion (Gagliano, NASA-MSFC, USA)
  - Development of capture technologies
  - On ground demonstrations on-going
- 6.3: CleanSpace One demonstrator (Richard, EPFL)
  - Flight demonstration end of 2021
  - “Pacman like” capture, with hardware presented during WS
- 6.4: De-tumbling by electrostatic forces
  (Shaub, Uni. Colorado, USA)
- 6.5: On-orbit servicing – ASSIST (Medina-Andres, GMV)
- 6.6: Approach and capture of a tumbling debris
  (Zhu, Beijing Institute of Control Engineering, China)

The I-Lock 75

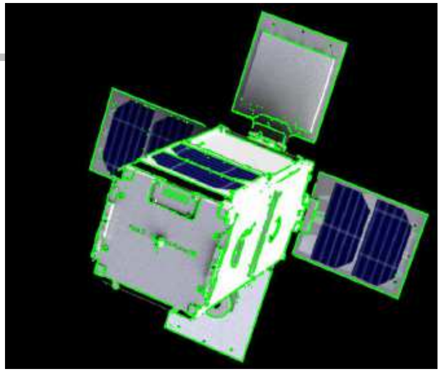


ES\EA grippers by ElectroGrip, Co. and GrabIt, Inc

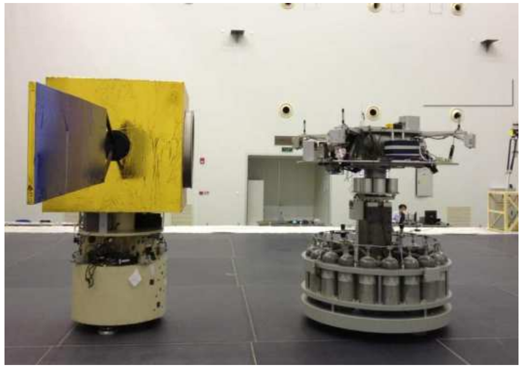




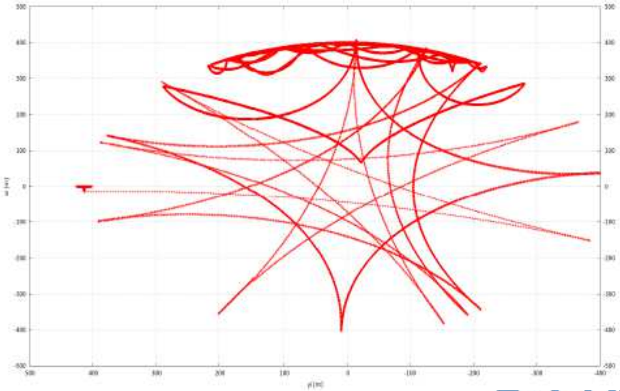
Session 7: Rendez-vous & GNC



- 7.1: Vision Based Navigation (Kanani, Airbus D&S)
  - Flight experiment LIRIS on ATV 5
  - Numerous key progresses in technologies and simulations
- 7.2: Robotic capture – STARDUST FP7 (Jankovic, German Research Center for Artificial Intelligence)



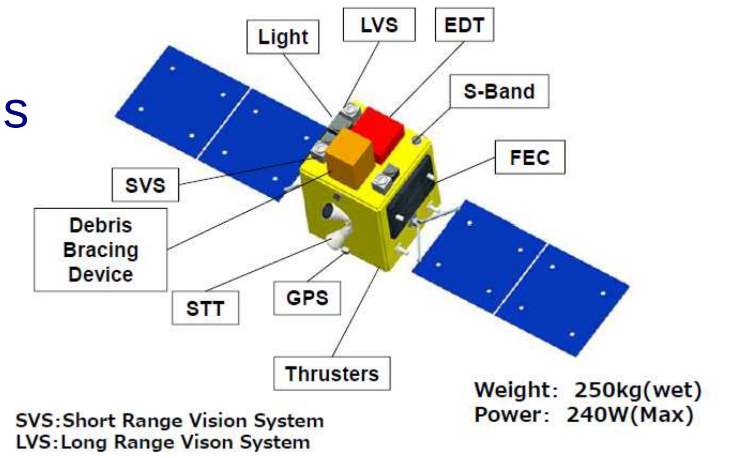
- 7.3: Vision Based Navigation for capture (Wei, Beijing Institute of Control Engineering, Chine)
  - Numerous on-ground demonstrations
  - Numerous videos presented during WS
- 7.4: Control of a tethered deorbitation (Falcoz, Airbus D&S)
  - AGADIR project – Study of various GNC modes
  - Simulation [Chaser-tether-target]
  - Closed loop control with Lidar sensors



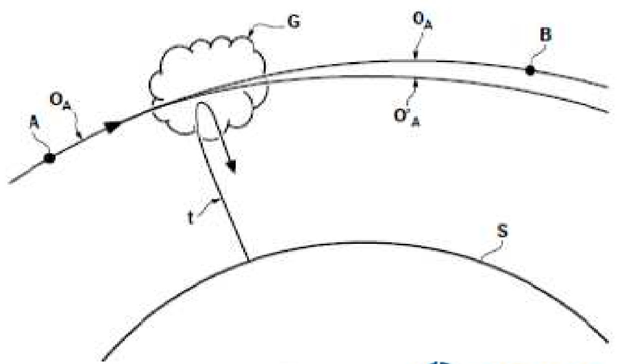
- 7.5: Tether dynamics (Beck, Belstead Research)
  - General trade-off: length, stiffness, …
  - Numerous simulations but no clear conclusion yet

Session 8 : Debris detection & Collision avoidance

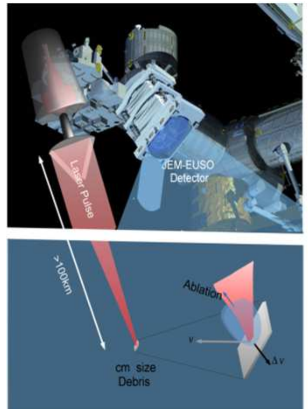
- 8.1: Development of a small stereo camera to detect small debris (Gagliano, NASA-MSFC, USA)
  - Flight validation on ISS
- 8.2: Detection of meteoroids and debris: flight experiment SODAD-ISS (Mandeville, Mandespace)
  - Flight experimentation on ISS
- 8.3: Determination of relative parameters for a rendez-vous (Trushlyakov, Omsk Uni. Russie)
- 8.4: System concept for ADR (Otsuka, NEC, Japon)
  - Flight demonstration in 2020: capture of a stage then deorbit with EDT
  - On ground experimental validation



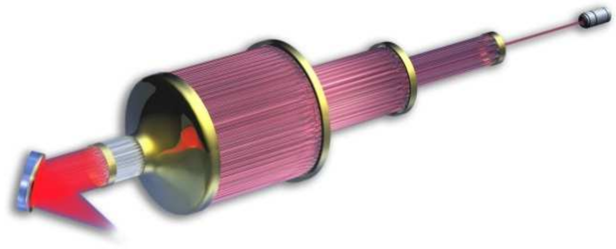
- 8.5: Cloud generation for Just in Time Collision Avoidance (Mc Knight, IA, USA & Bonnal, CNES)
  - Braking of a debris by drag to avoid a collision between two large non maneuvering objects
- 8.6: Operational Collision Avoidance (Duncan, SpaceNav, USA)



Session 9: Laser applications



- 9.1: Collision avoidance techniques (Ebisuzaki, RIKEN, Japan)
  - Proposal of a flight experiment on board ISS coupled with JEM-EUSO
  - On-ground calibration with helicopter, then balloon
- 9.2: Laser ICAN (Mourou, Ecole Polytechnique, France)
  - Very large number of fiber lasers phased together
  - So far, demonstration with 64 lasers
  - Goal of 10 000 fibers or more is challenging…



- 9.3: Orbital laser (Yang, CASC, China)
- 9.4: Laser ablation performances (Sasoh, Nagoya Uni., Japon)
  - Impulse transmittal to change orbit of a debris
  - De-tumbling
  - Numerous on-ground experiments
- 9.5: Experimental measures to determine coupling coefficients between laser and matter (Yang, CASC, Chine)
  - Description of an orbital system
  - Presentation of on-ground experimental results
- 9.6: Comments on fiber laser in space (Phipps, Photonics, USA)
  - Nice explanation between key experts, very technical and advanced… :o)

Conclusion

- Proceedings are available: christophe.bonnal@cnes.fr