A6

French current activities in the domain of Space Debris

Christophe Bonnal
CNES

CNES, the French Space Agency, has been proactive on the question of orbital debris for more than 30 years now.
The presentation will detail the status of the various actions led currently in this domain:
- Observation, both optical and radar, enable France to elaborate its own space objects catalog, fundamental for all the collision avoidance activity,
- These collision avoidance activities are an important part of the operational task of CNES, aimed at protecting not only our satellites but also several other commercial ones,
- Hyper Velocity Impact tests are performed to optimize the resilience of space objects to small debris collisions,
- Mitigation rules are a fundamental activity, both in house and in international for a, IADC, ECSS, ISO; France is the first country having a dedicated law, applicable since 2010,
- These rules are backed by significant simulation studies, testing various scenarios, propagating the orbital population in the future to check the efficiency of proposed measures and influence our work at international level,
- End of Life operations, both in LEO and in GEO, enable us to comply with the mitigation rules,
- In this frame, dedicated tools enable us to verify the compliance with mitigation rules, such as survivability at reentry, demisability with dedicated designs, passivation, optimization of deorbitation strategies…
- Preparation of future is important, with the risk of having to perform Active Debris Removal; in this domain, studies with the major French industrials have been led, driving potential solutions which will soon be tested in orbit,
- Last, the “non technical” domains are important, mainly the business plan over the ADR, but also the political aspects, legal and insurance; international cooperation is a must, for this international problem!


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Décrets, arrêtés, circulaires

TEXTES GÉNÉRAUX

MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR ET DE LA RECHERCHE

Arrêté du 31 mars 2011 relatif à la réglementation technique en application du décret n° 2009-643 du 9 juin 2009 relatif aux autorisations délivrées en application de la loi n° 2008-518 du 3 juin 2008 relative aux opérations spatiales

The front page of CNES Space Operations Law

Biography

Christophe Bonnal

Christophe Bonnal started his career in 1983 in Aerospatiale, now Airbus, working on technical topics on Ariane 4, then future studies linked to reusable launchers and servicing vehicles. He joined CNES in 1992 on the Ariane 5 program. Following the qualification of the launcher in 1998, he headed the future launchers division during 8 years before going back to Technical activities; he is now Chief Engineer in the Technical Directorate.
Christophe has been involved in space debris activities since 1987. He is French delegate to IADC. He is currently chairman of the International Astronautical Academy (IAA) Space Debris Committee, as well as the one of International Astronautical Federation (IAF). He recently published the first vulgarization book on the topic of space debris at worldwide level, soon to be translated in english.

French current activities in the domain of Space Debris

Christophe Bonnal
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7th JAXA Space Debris Workshop
Chofu, Oct. 18-20th 2016

CONTENT

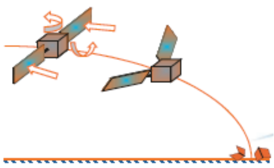
- INTRODUCTION:
  FRENCH SPACE OPERATIONS ACT – FSOA
- FSOA: REENTRY RISK
- FSOA: LIMITATION OF SPACE DEBRIS
- FSOA: COLLISION AVOIDANCE
- MODELLING
- HYPER VELOCITY IMPACTS & SHIELDING
- REMEDIATION
- INTERNATIONAL ACTIVITIES

Introduction: French Space Operations Act

- Approved in 2008 – In force since 2010
- Covers both Launch Vehicle and Spacecraft
- Art 20.1.b. and Art 44: Reentry casualty risk
  - 2.10^{-5} for each orbited and sub-orbital element
  - 10^{-7} for nominal reentry and for controlled reentry
  - If not possible, $<10^{-4}$ for random reentry, otherwise controlled reentry
  - Art 45 choice of architecture and material
- Art 21 and Art 40: Space debris limitation
  - Limitation to 1 launcher element for single launch, 2 for multiple launch
  - Pyrotechnic and solid propellant products < 1mm
  - Probability of accidental break-up $<10^{-3}$
  - Passivation
  - Protection of Regions A and B
  - Probability of successful End of Life operations > 90%
- Art 22 and 41: Prevention of collision risks
  - When practical
  - Protection of manned objects at launch

FSOA: Reentry casualty risk

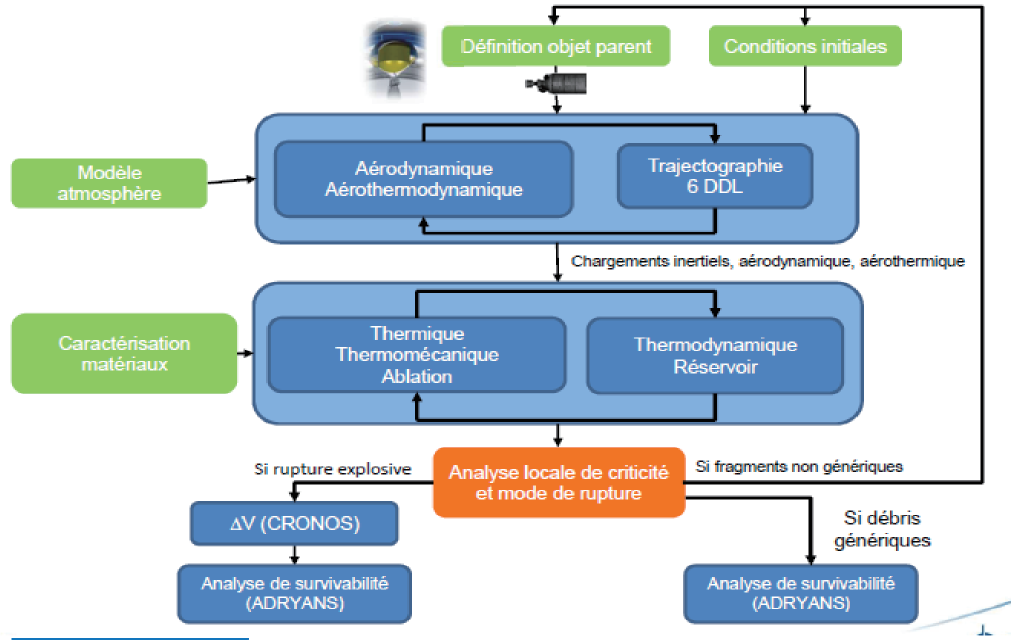
- General method called Electra
- Similar in principle to NASA, JAXA or ESA methods
- Survivability tools:
  - Object oriented: DEBRISK used operationally
    - Two versions: spacecraft and launch vehicles
  - Spacecraft oriented: PAMPERO under finalization
  - Full calculation through CFD codes not practical operationlaly
- Main hypotheses and unknowns:
  - Attitude of the objects during atmospheric reentry
  - Loss of appendages (solar panels, antennae…)
    - Based on numerous observations (EPC, ATV…)
  - Fragmentation process
  - Thermal modeling (uniform temperature)
  - Flux over specific shapes
  - Mask phenomenon due to wake of primary object
  - Oxidation and behavior of material at very high temperature in reentry plasma
  - Metallic and composite material ablation process



Resp. J. Annaloro – P. Omaly

FSOA: Reentry casualty risk

- Same approach followed by Airbus D&S under CNES contract



AIRBUS DEFENCE & SPACE

Resp. A. Espinosa – C. Thiébault

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FSOA: Reentry casualty risk

Computation time		***Precision***
5 s / object / full trajectory	**Object-oriented tool (Debrisk)**	*10-30% of the integrated convective flux*
10-60 min / object / full trajectory	**Spacecraft-oriented tool (PAMPERO)**	*5-30% of the integrated convective flux / angle of attack*
12 hours / object / determined position	**CFD (MISTRAL)**	*10-15% of the local convective flux*

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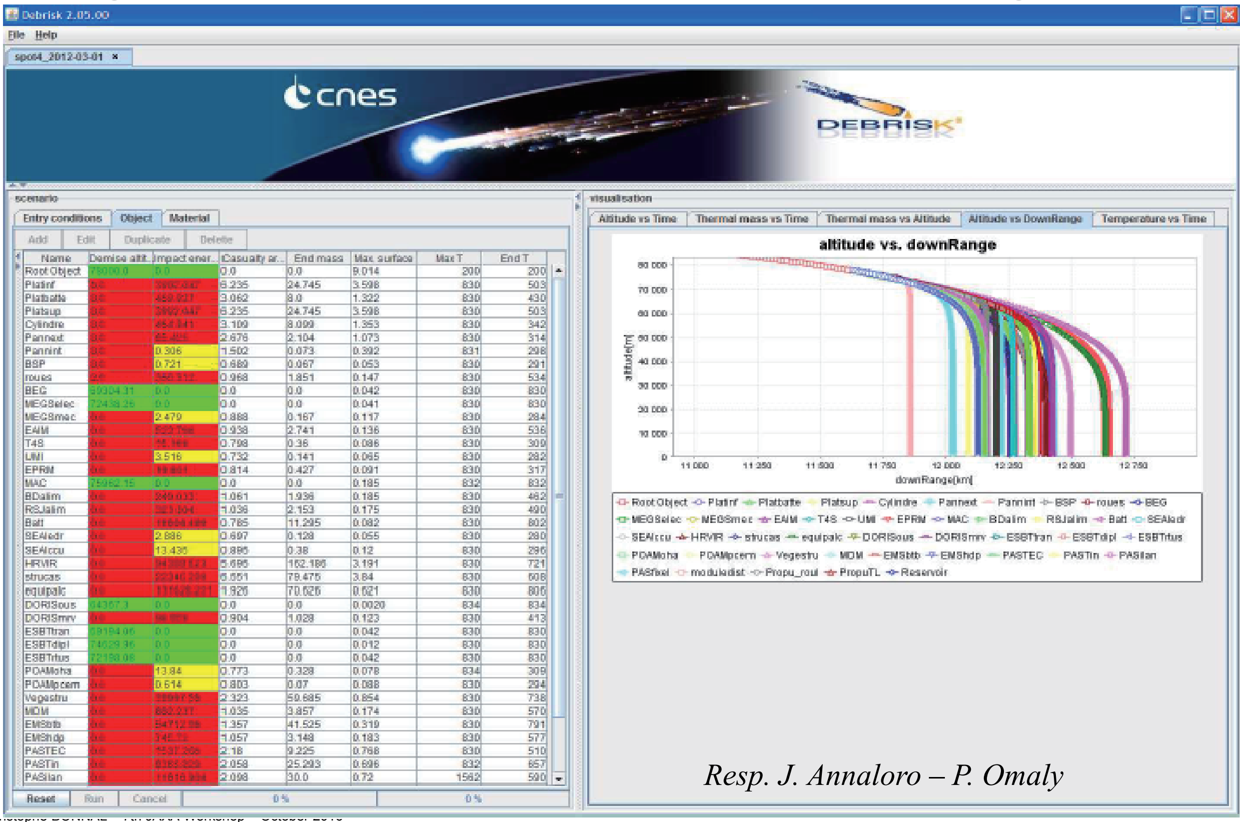
FSOA: Reentry casualty risk



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FSOA: Reentry casualty risk

- PAMPERO: CNES research code
- 6 Degrees of Freedom
  - Local computation of pressure coefficients
  - Calculation of the object attitude via a force and torque computation
  - For a given object, the computation of the complete trajectory is performed starting at the previous orbit
- Local computation of parietal thermal fluxes (convective and radiative) using analytical correlations
- Modeling of thermal transfers using a dedicated 3D thermal conduction module
- Evaluation of the ablation when a cell reaches the fusion temperature of the material

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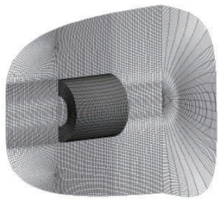
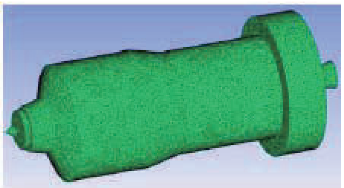
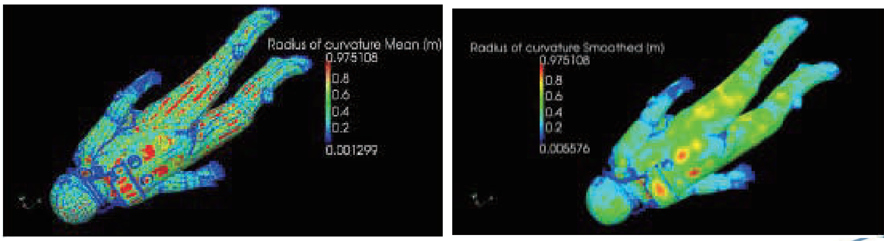
FSOA: Reentry casualty risk



- MESH tool
- Tetrahedral meshing generated
- Reading of the meshing to recognize “surface” and “volume” meshes including their connections
- Hypothesis of homogeneous material: same bulk density mass within one cell
- View factor: a cell is considered as active if facing the flow, and not masked by another one
- Local radius shall be smoothed to increase representativeness





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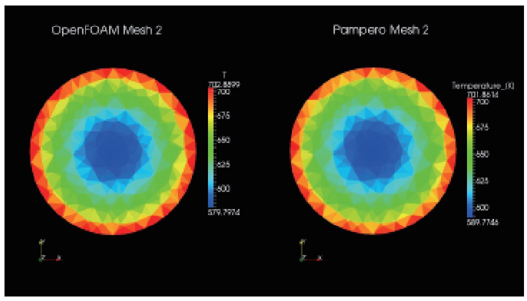
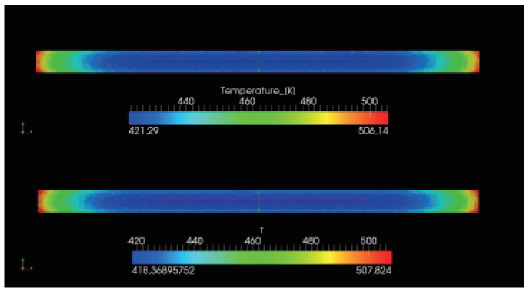
FSOA: Reentry casualty risk

- Numerous numerical test cases, comparing with full CFD codes

<u>*Sphere test-case:*</u>
- R = 0.5 m
- k = 237 W/m/K
- Cp = 903 J/kg/K
- rho = 2787 kg/m^3
- P = 400 kW (constant and uniform)
- t = 1500 s



<u>*Plate test-case:*</u>
- l = 2 m, L = 0.5 m, e = 0.1 m
- k = 237 W/m/K
- Cp = 903 J/kg/K
- rho = 2787 kg/m^3
- P = 400 kW (constant and uniform)
- t = 200 s



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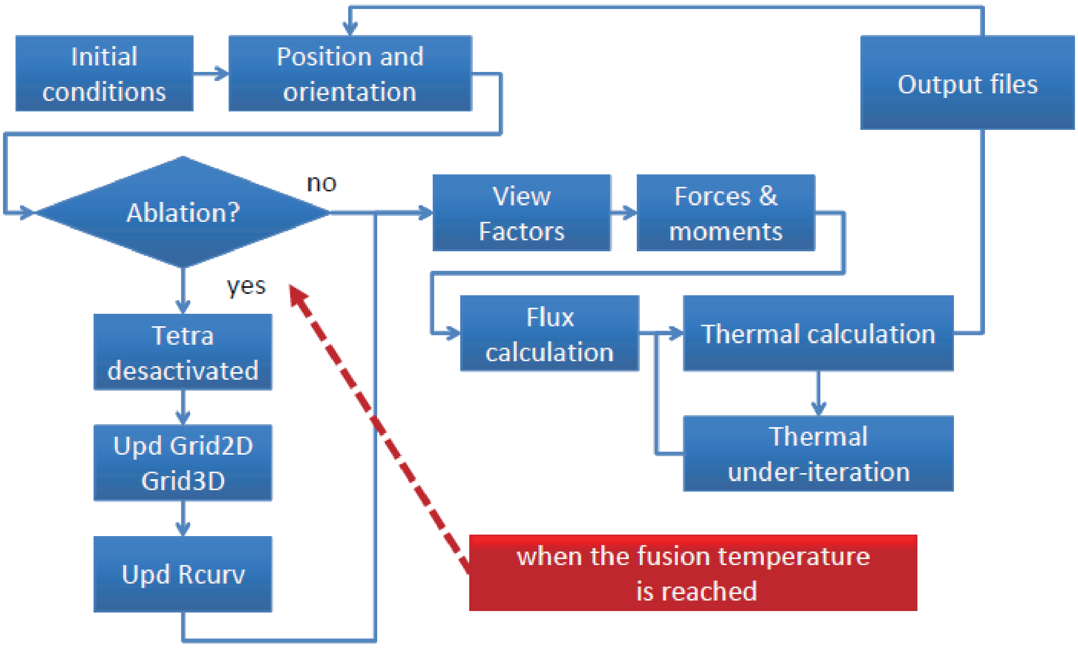
FSOA: Reentry casualty risk



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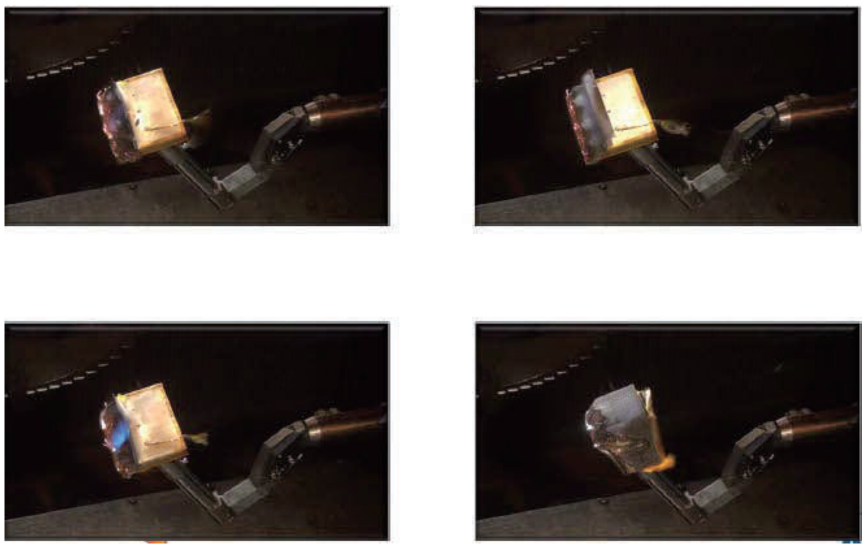
FSOA: Reentry casualty risk

- Numerous on-going R&T activities
  - Testing in Hypersonic wind-tunnel of the melting of a flat Aluminum plate



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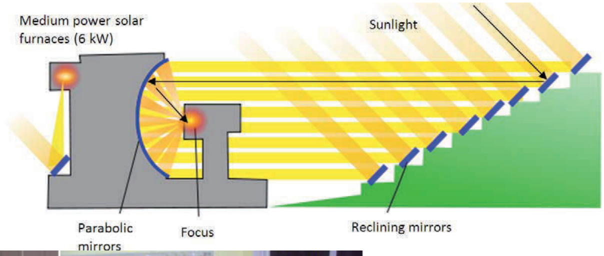
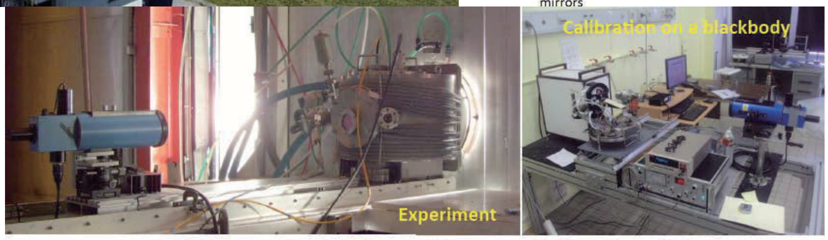
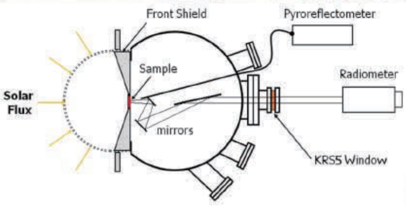
FSOA: Reentry casualty risk

- Numerous on-going R&T activities
  - Testing with the 1 MW solar furnace of Odeillo:







- High vacuum: 10^{-4} Pa or Controlled pressure
- Emissivity by a direct method =>
- Temperature from 1000 up to 2500 K, measured using a pyro-reflectometer (1.3 and 1.55 μm) => true temperature ≠ T color (particularly for metals)
- Measurement of the radiance from 0 to 80° by 10° step + 45° and 75° angles in the wavelength ranges: 0.6-40; 0.6-2.8; 7-10 and 8-14 μm or with discrete filters: 2.7 and 5 μm
- New spectroradiometer 0.25-14 μm => spectral data

Resp. J. Annaloro – P. Omaly – M. Balat (CNRS)

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Christophe BONNAL – 7th J...

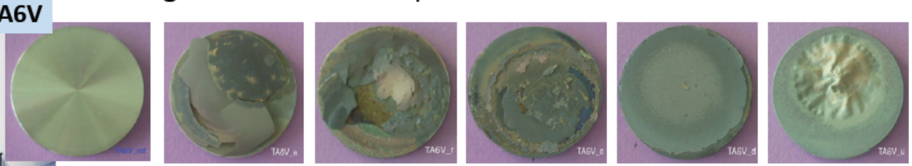
FSOA: Reentry casualty risk

- Numerous on-going R&T activities
  - Testing with the 1 MW solar furnace of Odeillo – examples:

Oxidation in air plasma - 25 mm diameter

- Images of oxidized samples TA6V and Inconel 718

TA6V



Ref. 1333 K 1558 K 1734 K 1894 K 2046 K

Inconel 718

Ref. 1320 K 1574 K 1643 K 1718 K

It appears that below the melting temperature, TA6V presents non adherent oxide layers that will contribute to decrease its mass during re-entry and on the contrary, the oxide layers are adherent on Inconel 718. Both were oxidized up to their melting point.

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FSOA: Reentry casualty risk

- Atmospheric reentries prediction: Operational activity – Tool OPERA

– Objects monitored:
  - «French» objects that could fall on foreign countries (Launching State responsibility) :
    - satellites and launcher stages registered by France,
    - launcher stages registered by ESA.
  - « foreign » objects that could fall on the national territory :
    - Potentially dangerous objects registered by other countries :

-Mass > 5T,

-dangerous materials.

– Particular cases

IADC or governmental requests.

– « Debris » objects not considered

– 11 reentries monitored in 2015

FSOA: Reentry casualty risk

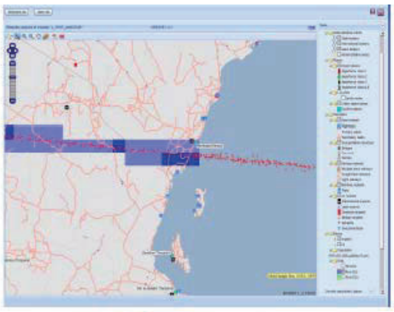
- Improvement of the Population grids

3 Objectives

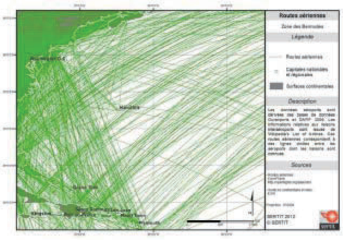
► **Calculate collective risk**
numerical distribution of population over the potential fallout zone (ELECTRA)

► **Display Critical areas**
large urban areas, communication networks, sensitive human activities, protected areas (ORESTE)

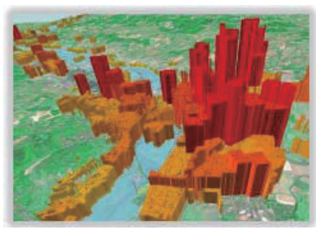
► **Provide land occupation**
for environmental studies



*Computed **ELECTRA** Impact footprint and level of risk by cell, on **ORESTE** display*



Air traffic - East coast of US



Resp. N. Fuentes

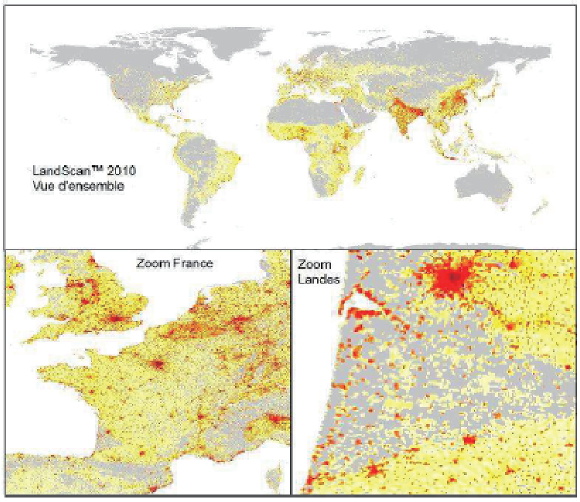
FSOA: Reentry casualty risk

- Improvement of the Population grids

Population grids:
- Landscan 2010
- GPWv3 2010

Urban areas:
- GRUMP
- Natural Earth Data
- VMAP0
- ESRI
- GLOBCOVER
- DMSP ISA

Airports:
- OpenFlights
- OurAirports
- ESRI
- VMAP0
- DAFIF



Landscan 2010 (ORNL - US)

Worldwide analysis is impossible: Selected test areas defined are on France, French Guyana, Canada, Philippines, Indonésia, Africa, …

Resp. N. Fuentes

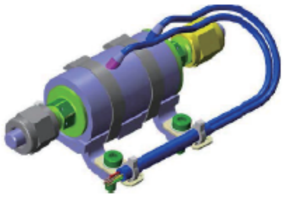
FSOA: Space debris limitation

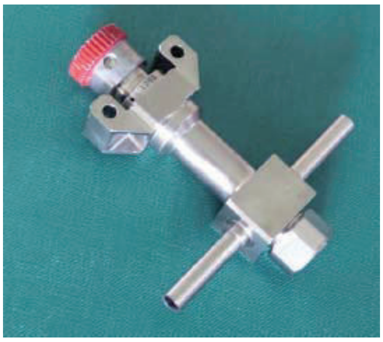
- Derives from all Standard activities at National and International level:
  - CNES first Space Debris Standard in 1999
- Several topics still require some attention:
  - Lifetime duration in orbit: STELA tool (freeware on CNES website)
    - Specific work on GTO objects, and Lagrange missions
  - Fluidic passivation
    - Some points still on discussion relative to allowable residuals
  - Electrical passivation
    - Studies relative to the proper sequencing of spacecraft electric passivation
    - Power Control & Distribution Units, Solar Arrays, Batteries
  - Limitation of solid propulsion products to less than 1 mm
  - Protection of the LEO and GEO regions
- End of Life in GEO and LEO
  - Dedicated European workshop organized by CNES every 2 years
  - Review of past experiences including anomalies
  - Preparation of the upcoming EoL

FSOA: Space debris limitation

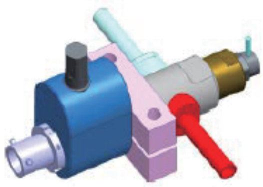
Passivation devices for complete propulsion passivation

- Devices that are potentially available, at different development stages (trade off on-going):
  - ✓ standard pyrotechnic valve
  - ✓ extended life pyrotechnic valve
  - ✓ shape memory alloy (SMA) actuator
  - ✓ positive isolation valve (PIV)
  - ✓ micro-perforator
  - ✓ evacuation valve





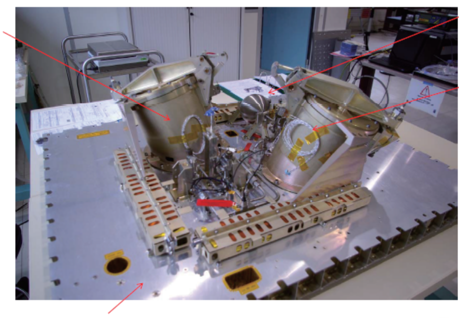
From. D. Dilhan (CNES)

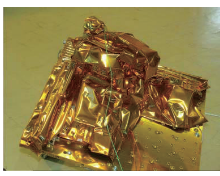



From. D. Briot (Airbus D&S)

FSOA: Space debris limitation

- Reduction of orbital lifetime to cope with the 25-year rule
- Example of the IDEAS sytem:
  - Inflatable
  - First application on the Microscope satellite (launched April 25th, 2016)
  - Increase in drag surface from 1.65 to 5.1 m²
  - Decrease in lifetime from 63 to 23.8 years

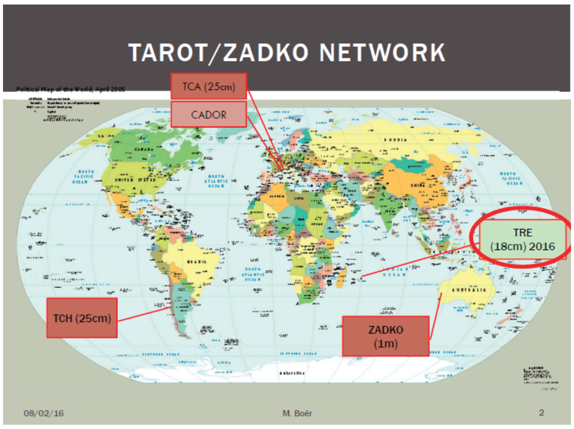


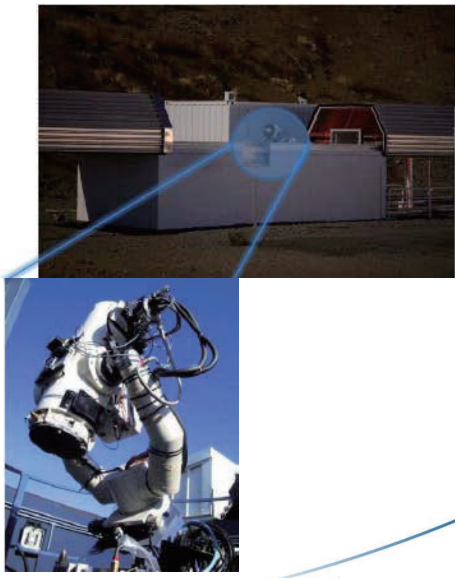



With Airbus D&S

FSOA: Collision avoidance

- Observation = Fundamental activity to help as inputs for Collision Avoidance:
  - → Optical and Radar operational observations, complementary
  - → French Space Objects catalog (French Air Force)
- Optical observation: 3 TAROT telescopes
  - TCH: Chile, TRE: Réunion, TCA: Cont. France





Resp. P. Richard cnes

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FSOA: Collision avoidance

- Optical observation with 3 Tarot telescopes

	TCA	TCH	TRE (2016)
Diamètre (mm)	250	250	180
Type	Newton hyperbol.	Idem	Idem
f/D	3.5	3.5	3.5
Champ (deg^2)	3.8	3.8	16
Détecteur	ANDOR IKON L236 BEX2 DD (2016)	ANDOR IKON L236 BI	FLI KAF 9000
Filtres	g', r', I', z', clair (2016)	BVRI clair	g', r', z', i', clair
Position	6°46'N, 43°45'E	29°15'S 70°45W	21°11'S, 55°45'E
Magnitude limite de travail (GEO)	16	16	15
Equivalent à	50cm	50cm	60cm

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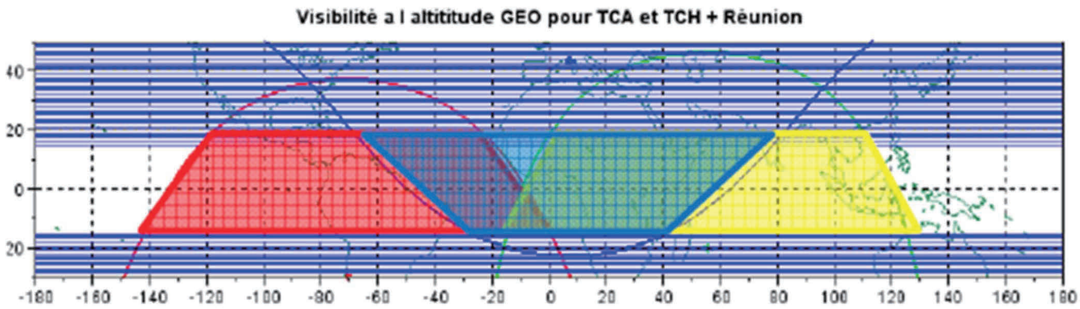
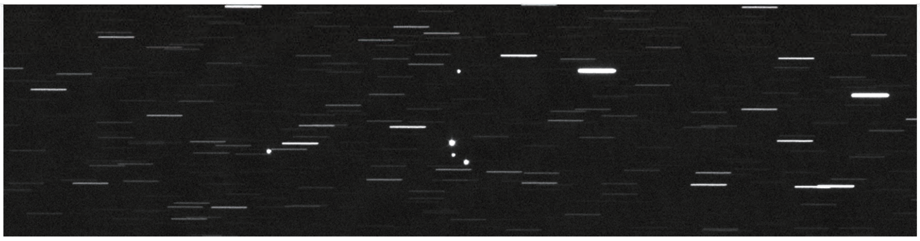
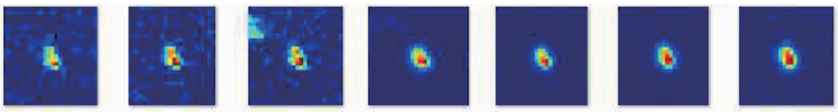
FSOA: Collision avoidance

- Optical observation with 3 Tarot telescopes
  - Good coverage of 240° of the GEO orbit region







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FSOA: Collision avoidance

- Observation
- Radar observation: Space Surveillance and Tracking Network

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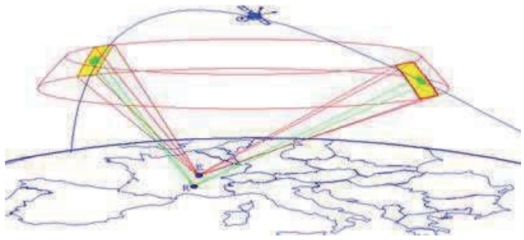
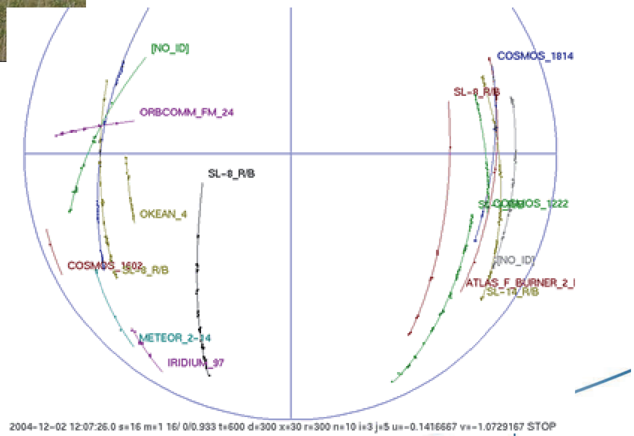
FSOA: Collision avoidance

- Radar observation: bistatic phased array radar GRAVES (French Air Force)





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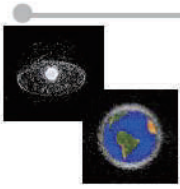
FSOA: Collision avoidance

- Operational Collision Avoidance activity: CAESAR

  (Conjunction Analysis and Evaluation Service: Alerts and Recommendations)

Middle Man Concept:
Conjunction Assessment is a two-step process



Space Surveillance Network

JSpOC Space-Track.org

Precise complete catalog

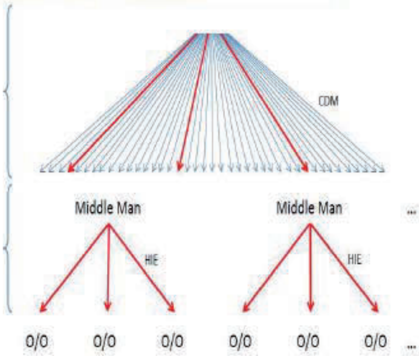
Screening – Information Messages generation

O/O must put in place an Acquisition, Evaluation, Alert and Recommendation process:

- Automatic acquisition : 24/7
- Risk Evaluation:
- Alert FD team of the Control Center
- Recommendation for avoidance

⇒*Only **very few** CMs lead to an avoidance action, but those messages (HIE) mustn't be missed.*

This process is not so easy …



Avoid… the avoidable

Resp. M. Moury
F. Laporte

caesar

REVEX CAESAR n° 2 – 1.2 – Evénements majeurs & Bilan des contrats & REX

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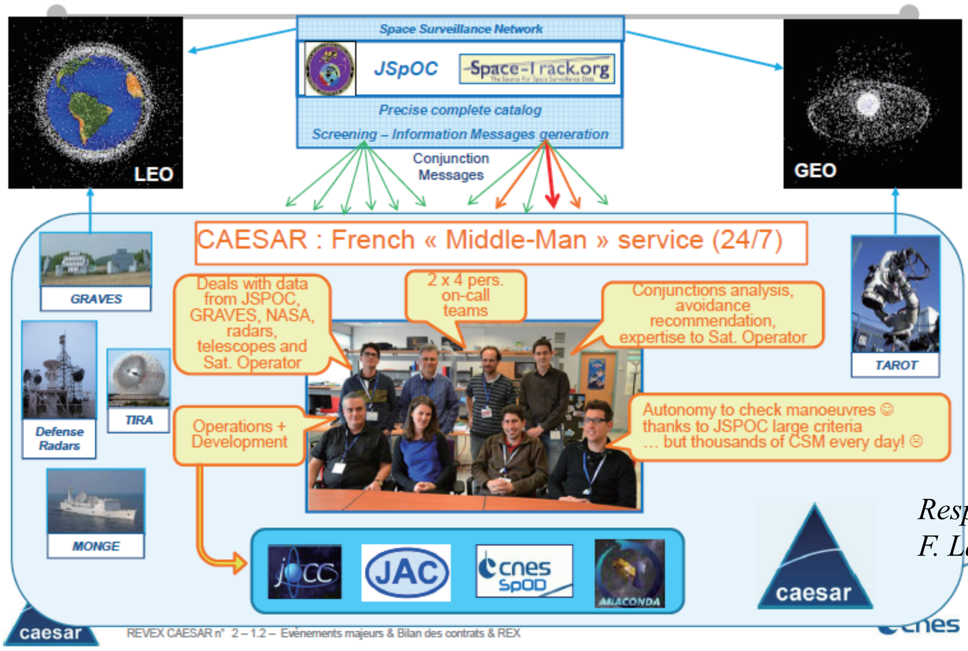
FSOA: Collision avoidance

- Operational Collision Avoidance activity: CAESAR

(Conjunction Analysis and Evaluation Service: Alerts and Recommendations)

"*Avoid the avoidable*"



Resp. M. Moury
F. Laporte

caesar REVEX CAESAR n° 2 – 1.2 – Evènements majeurs & Bilan des contrats & REX

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FSOA: Collision avoidance

- Operational Collision Avoidance activity: CAESAR

(Conjunction Analysis and Evaluation Service: Alerts and Recommendations)

CAESAR TOOLS: 4 java portable in-house tools.

	JOCC Java Orbit Computation Center	JAC Java for Assessment of Conjunctions	SpOD Space Operations Data	ANACONDA Android Application for Conjunction Data Analysis
What ?	• Orbit computation • Graves Almanac update • User data + JSpOC CDM handling • Screening • CDM generation • Automated e-mail summary • Collision risk analysis • Atmospheric re-entries • Defence dedicated functions	• Light software (laptop) • CDM/CSM management • Monitoring : automated phone calls • Collision risk analysis • Help for avoidance man. • Friendly GUI • Useful graphical displays	• Secured webserver • All shared data (on-call use) • Conjunction Messages • JAC updates • Tarot interface	• Smartphone android application • CSM/CDM download • Probability computation
Who ?	• CAESAR team • COSMOS team (French Defence Space Surveillance)	• CAESAR team • CAESAR subscribers • CARA team • **other external users (with JAC license)**	• CAESAR team • CAESAR subscribers • JAC users • Tarot users	• CAESAR team (on-call use)

caesar REVEX CAESAR n° 2 – 1.2 – Evènements majeurs & Bilan des contrats & REX

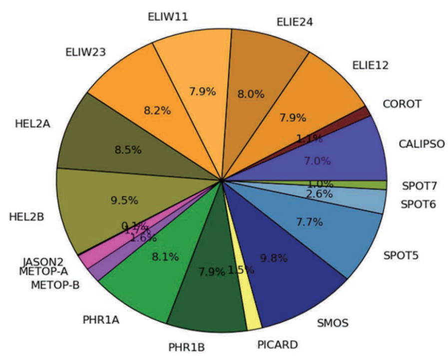
Resp. M. Moury
F. Laporte

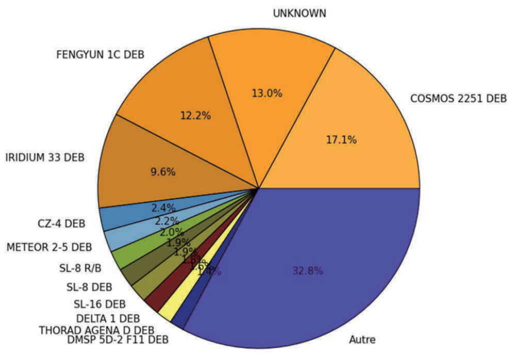
cnes

FSOA: Collision avoidance

- Statistics:
  - Currently ≅ 7,500 CDM received every day (3,000 from JSpOC, 4,500 generated)
  - From June 2015 – June 2016:
    - Protection of 21 spacecraft
    - ≅ 450,000 CDM corresponding to ≅ 50,000 conjunctions
    - Several 100s conjunctions analyzed with additional information
    - 12 Collision Avoidance manoeuvers + 5 Station Keeping modifications
- Dedicated International Workshop organized by CNES every 2 years
  - Next venue: November 2017

Resp. M. Moury
F. Laporte





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FSOA: Collision avoidance at launch

Collision risk at launch in 2015:

✦Collision risk at launch systematically evaluated wrt ISS with CORAL tool:

Launch ID	Lift-off Date	Analysis result
VS11	27.03.2015	No risk by analysis[1]
VV04	11.02.2015	No risk
VA222	26.04.2015	2 risks[2]
VA223	27.05.2015	No risk
VV05	23.06.2015	No risk
VA224	15.07.2015	1 risk[3]
VA225	20.08.2015	No risk
VS12	11.09.2015	No risk by analysis[1]
VA226	30.09.2015	No risk
VA227	10.11.2015	No risk
VV06	03.12.2015	No risk
VS13	17.12.2015	No risk by analysis[1]

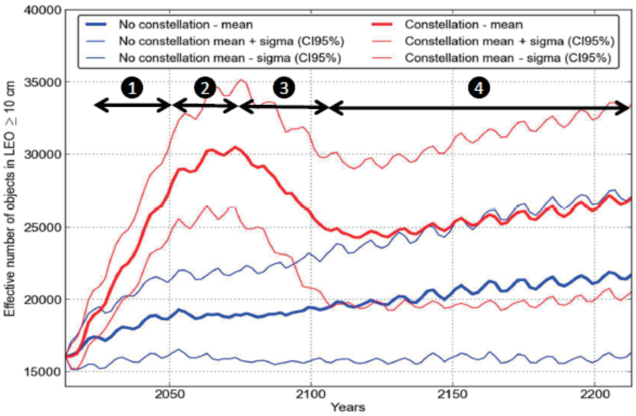
1. **VS11 - VS12 - VS13 ≡ Soyouz Galileo flights**
   High latitude at ISS's altitude
   → Safe orbital configuration
2. **VA222 ≡ GTO commercial flight**
   → 2 warnings in the middle of the window
   2 closures of 10s and 78s
3. **VA224 ≡ GTO commercial flight**
   → 1 warning in the middle of the launch window
   1 closure of 72s

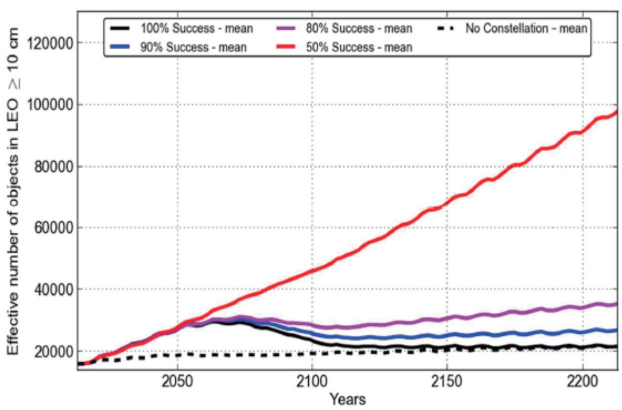
Resp. J-C. Dolado
D-A. Handschuh

Modelling

- Debris population evolution is an important activity in CNES:
  - To evaluate the efficiency of current mitigation measures
  - To prepare new ones (cubesats, mega-constellations, …)
  - Mostly in European or IADC framework
- MEDEE tool
  - Significant work to check robustness of hypotheses
  - Example of the effect of a mega-constellation

Resp. J-C. Dolado

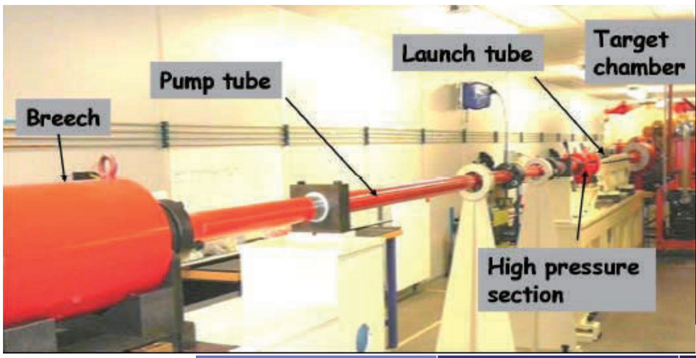


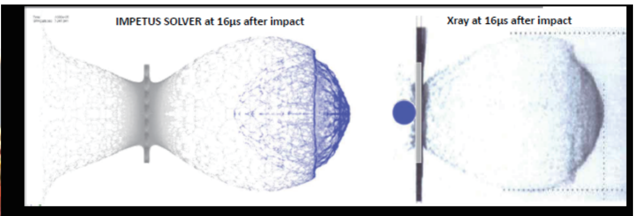


1.- Augmentation rapide de la population
2.- Quasi-Equilibre
3.- Diminution rapide de la population
4.- Phase Post-constellation

Hyper Velocity Impact and Shielding

- Test validation of impact tools:
  - R&T work with Thiot Ingenierie
  - Large Two Stage Light Gas Gun: up to 10.5 km/s for 1 mm Aluminum sphere
  - Tests on pressurized vessels





Criteria	Experiment [1]	IMPETUS SOLVER®	Error (%)
Cloud Diameter (mm)	65.6	63.2	3.6
Cloud Lenght (mm)	81.1	82.2	1.3
Crater Diameter (mm)	18.9	20.7	10
Cloud velocity (m/s)	5300	5500	3.7

Resp. CNES Toulouse and Launchers

Remediation

- Active Debris Removal:
  - No ADR exclusive dedicated activities anymore since 2015
    - No need for “system work” on ADR anymore
  - Key priority today at CNES level: Space Tug
  - Priority work on enabling technologies today

Missions around the Earth
- Transfer of a payload from a A orbit to a B orbit
- ISS servicing or similar
- Active debris removal
- Maintenance of a Hubble type platform or a post 2020 payload
- Assistance to future orbital stations
- In orbit inspection of a payload
- Uncrewed platform servicing (MTFF type)
- In space production plant servicing (metallurgy, heath, ...)

Missions with release in the plane of the ecliptic
- Moon exploration
- Heavy payloads towards Mars
- Satellites refuelling around Moon or Mars
- Lagrangian points stations servicing

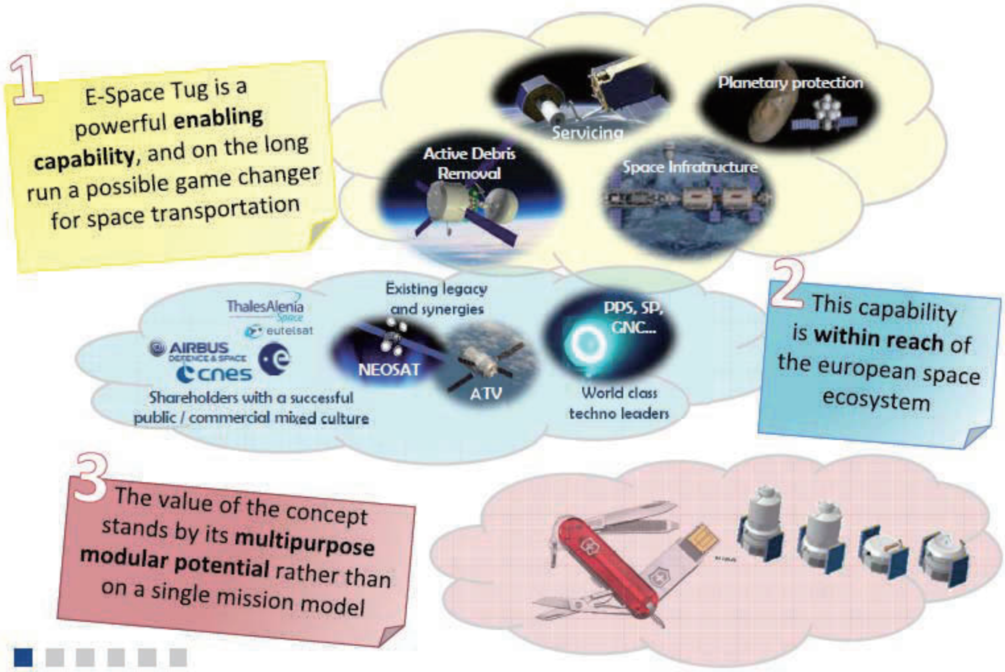
Missions with release outside the plane of the ecliptic
- Safe setting of hazardous wastes
- NEO exploration and terrestrial security

Resp. J-M. Ruault – L. Baize

cnes

Remediation

- Active Debris Removal: Space Tug



Resp. J-M. Ruault – L. Baize

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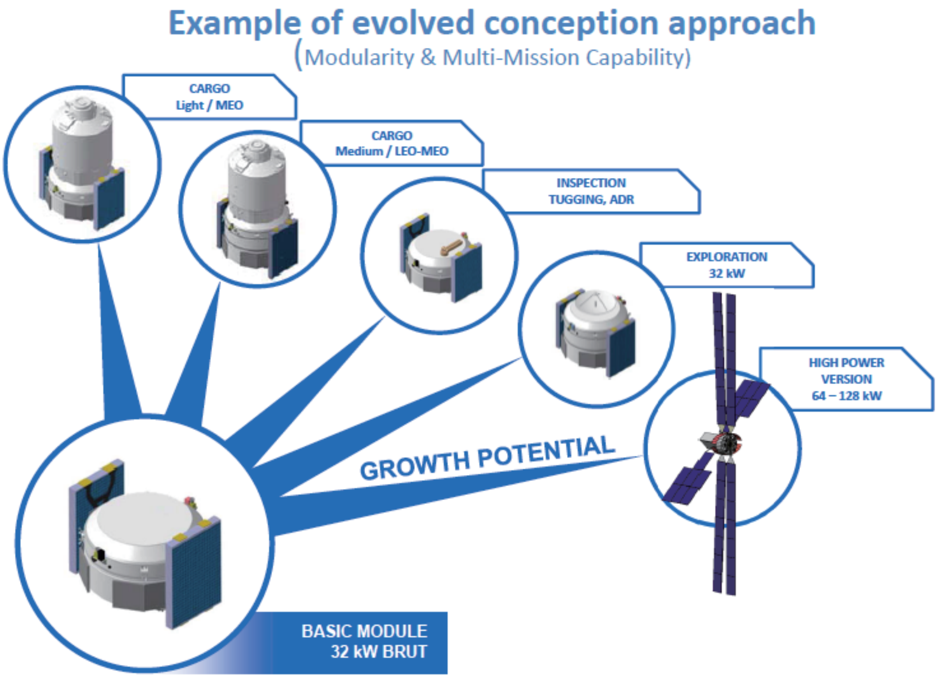
Remediation

- Active Debris Removal: Space Tug



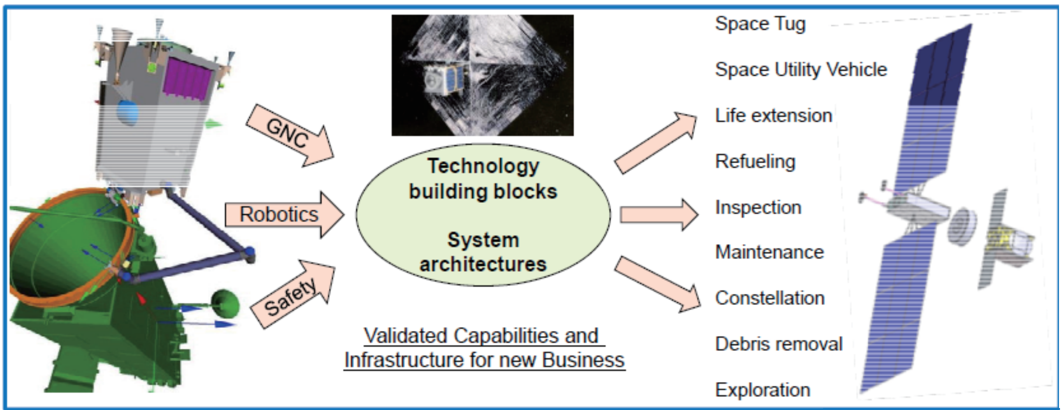
Resp. J-M. Ruault – L. Baize

Remediation

- Active Debris Removal: Space Tug – Vision totally shared by Airbus DS

Airbus DS' vision on Active Debris Removal (ADR)

- ADR missions such as e.deorbit not only address a key issue for space activities but are also a unique opportunity for maturing and qualifying key technologies (GNC, robotics) and for opening up new business opportunities such as on-orbit servicing.
- ADR could therefore be considered as a precursor for a wider range of applications based on rendezvous, capture or mating and transport.



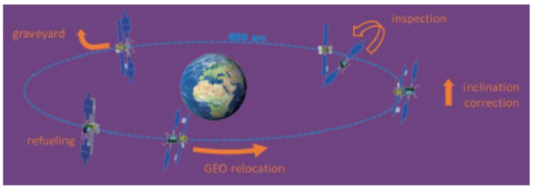
Resp. A. Pisseloup et al. Airbus DS

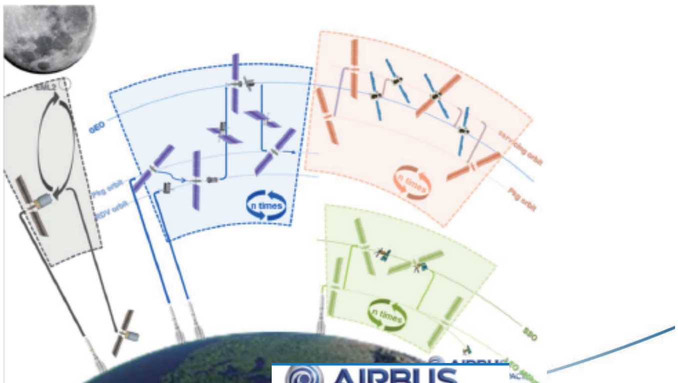
Remediation

- Active Debris Removal: Space Tug – Vision totally shared by Airbus DS
  - **Electric propulsion spacecraft** with the ability of **rendezvous** and of **docking/berthing** to and undocking fr the serviced satellite, equipped with a **robotic kit**.
  - **Resident** vehicle
  - Can **transport a satellite** from one orbit to the other and also accommodate several **On Orbit Servicing** capabilities covering inspection, life extension and refueling or removing/displacing.

4 main applications:

- Logistics for human exploration
- Tugging from low earth orbit to geostationary orbit
- Satellite servicing
- Active Debris Removal





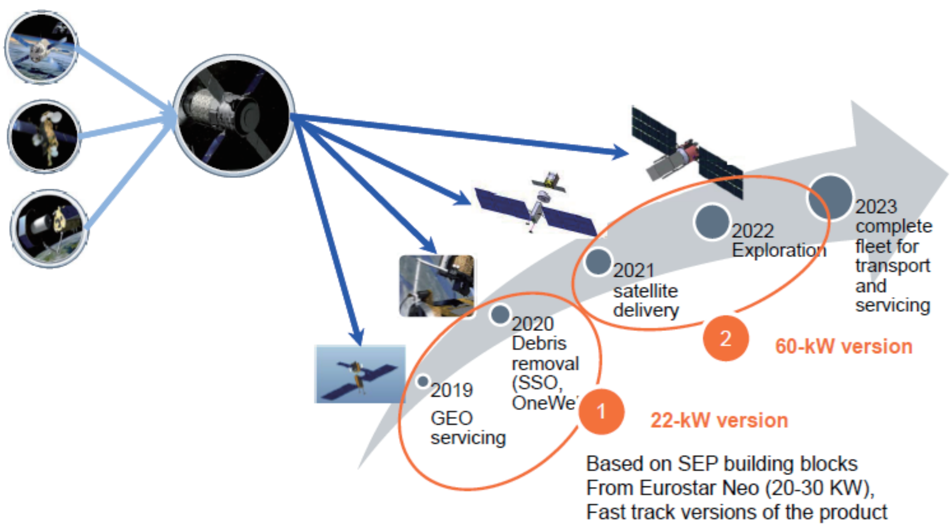
Resp. A. Pisseloup et al. Airbus DS

AIRBUS DEFENCE & SPACE cnes

Remediation

- Active Debris Removal: Space Tug – Vision totally shared by Airbus DS

Product line approach **Step-by-step market entry**

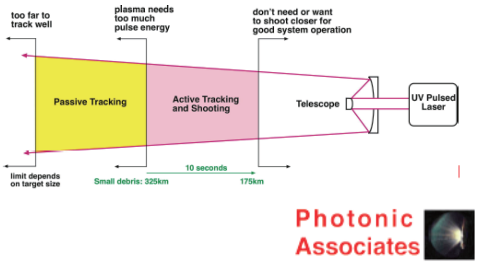


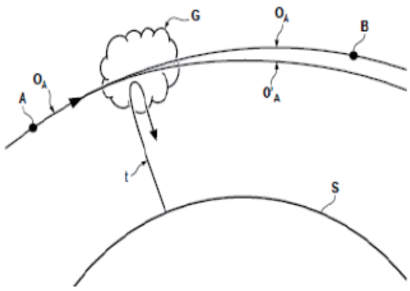
AIRBUS DEFENCE & SPACE cnes

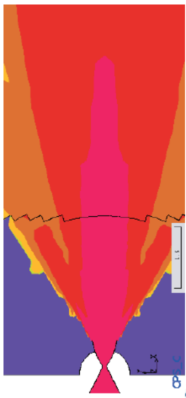
Resp. A. Pisseloup et al. Airbus DS

Remediation

- Small debris removal by lasers:
  - Significant activities with Photonics (USA)
  - On going CNES contract with ENSAM & ENSMA on characterization of laser ablation efficiency for debris removal conditions
  - Dedicated international workshop on "Lasers and Debris" co-organized by CNES
- Just in time Collision Avoidance – Large debris nudging (deviation):
  - With lasers (cooperation with Photonics – USA)
  - With gas clouds (CNES contract with Bertin Technologies)
    - Ongoing activity: promising results







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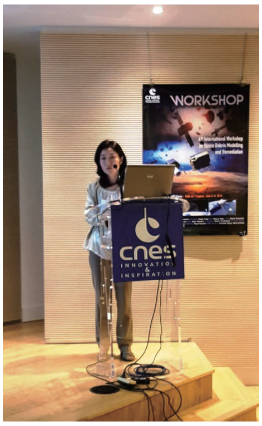
International aspects

- Strong role in the various international bodies:
  - IADC since 1996
  - UNCOPUOS, mainly LTS WG
  - ECSS (European Committee for Space Standardization)
  - ISO TC20/SC14/WG3 and WG7
- Numerous contributions at international level
  - IAC Space Debris Sessions every year
  - IAA Space Debris Committee
  - Numerous workshops every year
    - 4th Workshop on Space Debris Modeling and Remediation in June 2016
  - Numerous publications



Conclusion:

Space Debris activities are well covered in France on every topic, both at institutional, laboratory, academic and industrial level

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