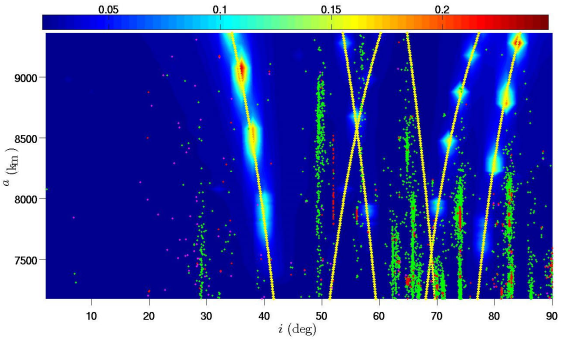
A06

A global approach to passive space debris mitigation

Alessandro Rossi (IFAC-CNR)

Since the realization of the danger represented by the space debris it became clear that an effective prevention and mitigation action was needed to control the proliferation of the Earth orbiting population of objects. Those actions were able to partly stabilize the growth of the population, but more aggressive measures should be undertaken in the future decades, including possibly Active Debris Removal (ADR), also in view of the proposed launch of the mega constellations of satellites in Low Earth Orbit (LEO) which are prone to change in radical way the traffic and operations in this region of space. The impact of orbital debris on the space activities should be reduced tackling the problem from different points of view, including prevention, mitigation, protection and, in a near future, remediation (i.e., ADR). These goals can only be achieved through a global approach that considers, from the outset of a space mission, opposing and challenging constraints for the space environment preservation, the spacecraft survivability in the harsh space environment and the safety of humans on ground. A new paradigm in the planning of space missions has to be considered, where the space debris issue is central, from different perspectives: theoretical, technological (hardware and software) and political. In the talk, first, a brief history of the past mitigation measures and of their main effects will be presented, also by means of criticality indexes able to quantify their effectiveness.
Then a summary of the most recent findings on this subject obtained in the framework of the H2020 ReDSHIFT (Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies - REA grant agreement n. [687500]) project, will be presented.



Location of the dominant resonances determining the long-term behavior in LEO (yellow lines). The color map shows the residual lifetime, as a function of the initial inclination and semi-major axis,computed in 120 years for an object with A/m = 1 m^2/kg, starting from e = 0.001, Ω = 0° and ω = 0°. The red and green dots show the location of the spacecraft and fragments, respectively, according to MASTER2009.

Biography

Alessandro Rossi

Alessandro Rossi is the head of the "Astrodynamics and Planetary Science Group" at the "Institute of Applied Physics" (IFAC) of the Italian National Research Council in Florence., Italy. He obtained his Ph.D. in "Astrophysique et tecniques spatiales" (Astrophysics and Space Tecniques) (cum laude) at the University Denis Diderot in Paris (France).
He is working on the modelling of the space debris since the early '90s.
From 2004 to 2006 he served as the Chairman of Working Group 2 of the International Advisory Debris Coordination Committee (IADC) and he is currently still a member of the IADC WG 2.

His other research interests include: orbital dynamics and orbit determination of natural and artificial objects, collision risk evaluation, terrestrial and interplanetary space missions, planetary sciences (orbital and rotational dynamics of asteroids, space geodesy, Near Earth Objects impact risk).
He is author of more than 150 papers on international journals with referee and congress proceedings.
He was the recipient of the "2016 Edoardo Kramer Prize" for his work on astrodynamics and space debris.
The asteroids 1990 RV2 was re-named (5185) Alerossi in his honor.

A global approach to passive space debris mitigation

A. ROSSI

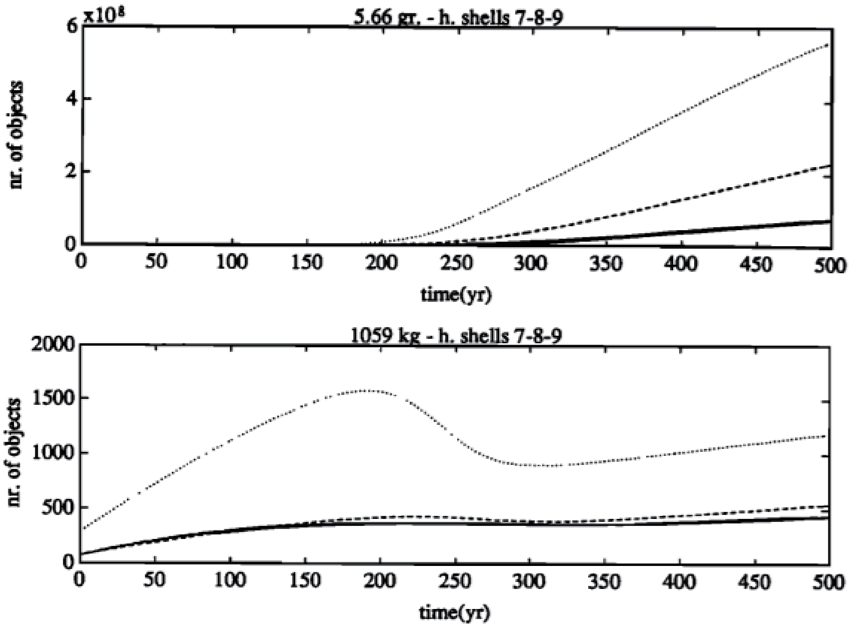
JAXA - 8TH SPACE DEBRIS WORKSHOP

TOKYO, 3-5/12/2018

Acknowledgments

- The work presented here was done mostly in collaboration with:
  - Elisa Maria Alessi (IFAC-CNR, Italy)
  - Giulia Schettino (IFAC-CNR, Italy)
  - Giovanni Battista Valsecchi (IAPS-INAF, Italy)
- Wherever noted, work from the ReDSHIFT partners is also presented.

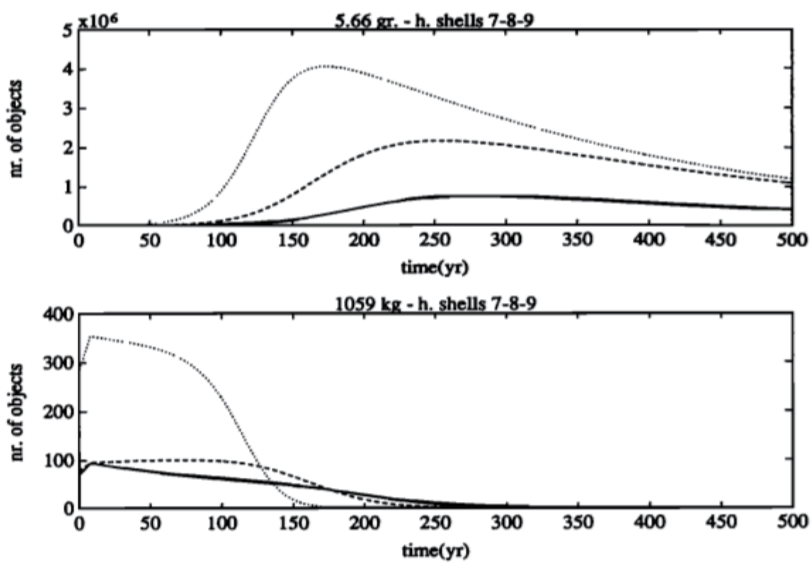
Space debris long term evolution: reference



From Rossi, Cordelli and Farinella, JGR, 1994

Space debris long term evolution: No Future Launches

ROSSI ET AL.: EVOLUTION OF EARTH'S ORBITAL DEBRIS CLOUD



From Rossi, Cordelli and Farinella, JGR, 1994

European Commission

Space debris long term evolution: reference case scenario

ReSHIFT

- Epoch of beginning of the simulation: Jan 1st 2013
- Launch scenario: repeating the 8-year historical cycle
- Explosions: 2-3 events per year until 2028
- LEO: All active satellites perform collision avoidance with 80 % success rate against all other objects.
- LEO: All active objects, which do not comply naturally, perform an end-of-life manoeuvre to an eccentric orbit with residual life of 25 year *(25-year rule)* with a 60 % compliance rate per object after 8 years of mission lifetime.
- 50 Monte Carlo runs

IFAC

European Commission

Space debris long term evolution: improved scenarios

ReSHIFT

- Epoch of beginning of the simulation: Jan 1st 2013
- Launch scenario: 8 years repeating of historical cycle
- Explosions: 2-3 events per year until 2028
- LEO: All active satellites perform collision avoidance with 80 % success rate against all other objects → 100 %
- LEO: All active objects, which do not comply naturally, perform an end-of-life manoeuvre to an eccentric 25 year orbit *(25-year rule)* with a 60 % compliance rate per object after 8 years of mission lifetime →90 % compliance to a 10-year rule
- 50 Monte Carlo runs

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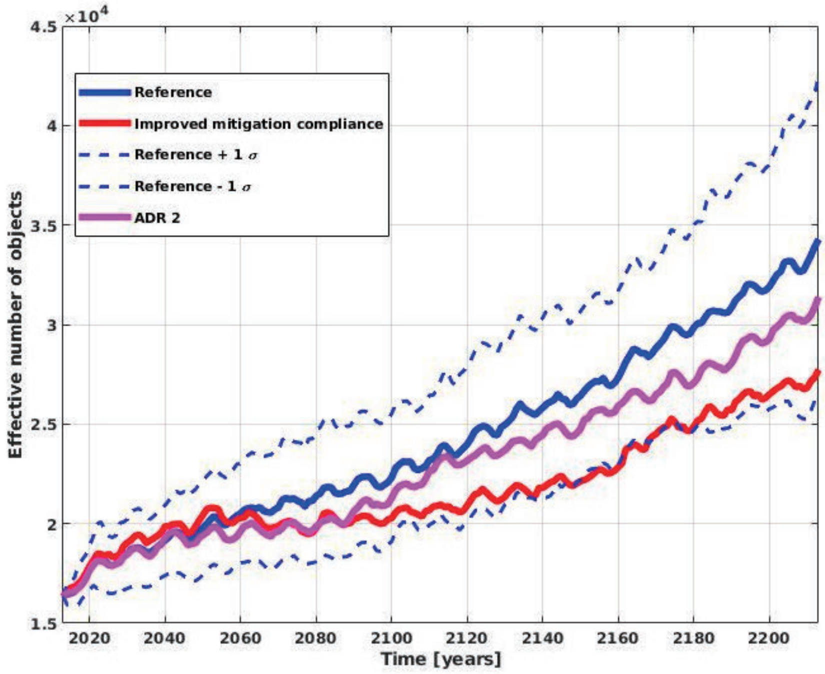
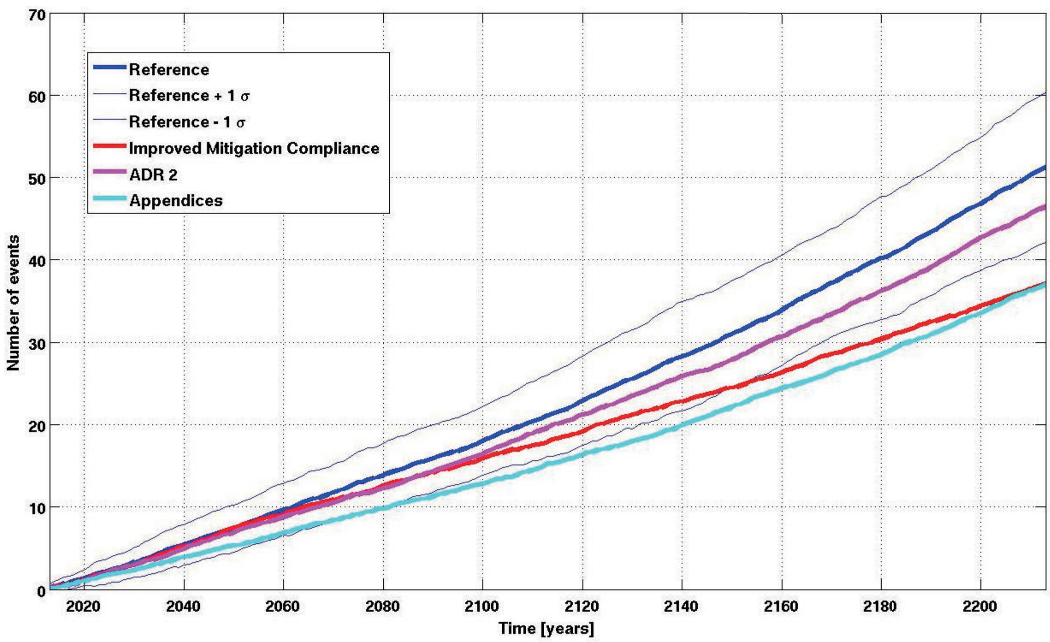
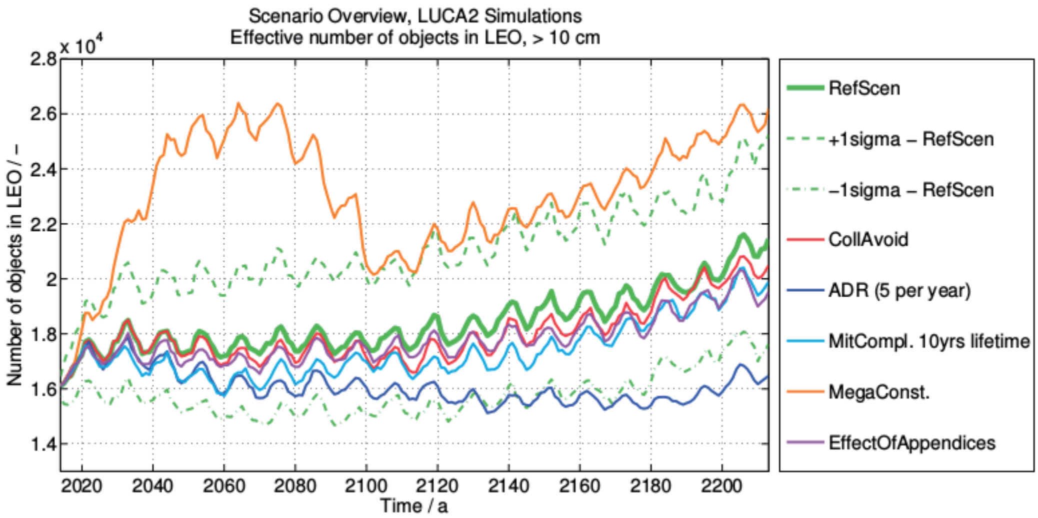
Space debris long term evolution: number of objects in LEO



Space debris long term evolution: number of fragmentations in LEO



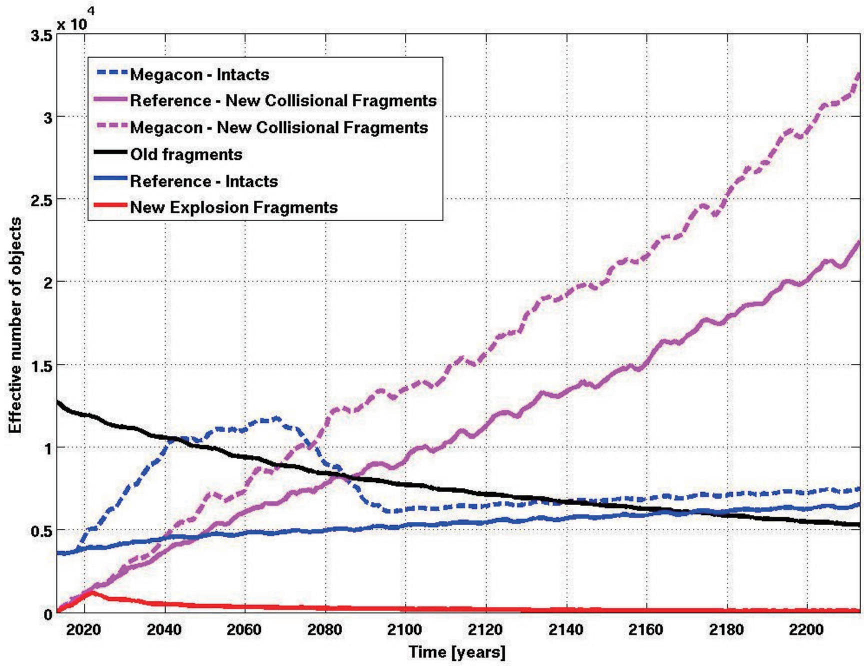
Space debris long term evolution: mitigation measures



Results from TUBS (V. Schaus, J. Radtke, E. Stoll, A. Rossi, C. Colombo, S. Tonetti ,I. Holbrough, 7th SDC, 2018)

Space debris long term evolution: troubles ahead?

- 1080 satellites in 20 orbital planes
- Circular orbits at 1100 km of altitude and 85 degrees inclination
- M= 200 kg
- Area = 1 m²



Statistical evaluation of results

ReSHIFT

- There are uncertainties associated with the long term evolution models and there is a statistical variability related to the Monte Carlo process.
- It is possible to bound the MC statistical variability by means of the *statistical moments* such as mean, variance, etc., or by percentiles.
- The "criticality norm" (Rossi et al., *Adv. Spa. Res.*, 2015):

$$C_i = \left(\frac{n_{FRAG}(i) - n_{REF}(i)}{\sigma_{REF}(i)}\right) \qquad \text{if } (n_{FRAG}(i) - n_{REF}(i)) \geqslant 0 \text{ else } C_i = 0;$$

can help to quantify and visualize if two long term evolutions are statistically independent and allow the ranking of the scenarios by summing the norm over the MC runs ➔

$$C^* = \sum_{i=1}^{N} \frac{C_i}{N} = \sum_{i=1}^{N} \left(\frac{n_{FRAG}(i) - n_{REF}(i)}{\sigma_{REF}(i)}\right) \Big/ N$$

- More sophisticated methods: the Wilcoxon signed rank test is a non-parametric test which does not assume normality in the data and, given two samples, allows to assess whether their population mean ranks differ (Rossi et al., *Proc. 7th European Space Debris Conference*, 2017).

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Number of objects in LEO: norm

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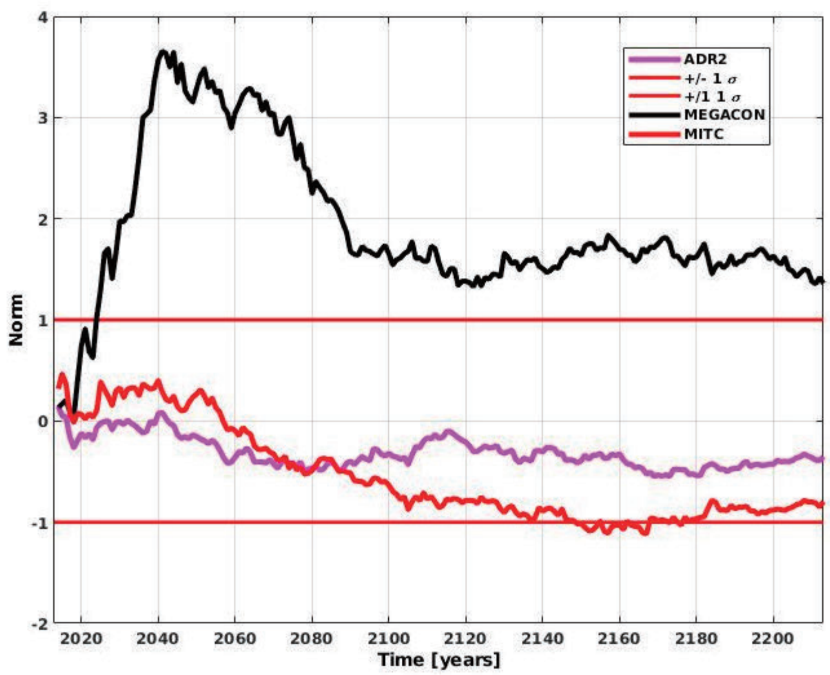

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Mitigation measures: some considerations…..

- As confirmed by a number of previous studies (e.g., IADC WG 2 joint simulation efforts), the LEO environment appears "unstable", with the population growing notwithstanding the currently adopted mitigation measures.
- More aggressive mitigation measures can slow down the growth pace, but not stop or revert it ➔ ADR?
- The use of super-LEO storage zone should be "handled with care", to avoid accumulation of uncontrolled objects possible leading to unavoidable collisions on the long term.

Mitigation measures: some considerations…..

- Collision avoidance can be performed only if at least one of the objects involved is active ➔ in the Reference case (80 % of efficiency of C.A. procedures) on average there are 5 avoided collisions over 200 years (out of ~ 52).
- Moving the efficiency from 80 % to 100 % the decrease in number of objects in LEO after 200 years is around 4 % but there is no stabilization of the population nor a noticeable change in the growth pace of debris.
- The planned mega constellations might represent a big issue in the future of the LEO environment, hence a careful look should be kept on them and on the way their operations are handled.

Environmental indexing

- For a given object, the Criticality of Spacecraft Index (CSI) can be written as (Rossi et al., *Adv. Spa. Res.*, 2015):

$$\tilde{\Xi} = \frac{A}{A_0}\frac{M}{M_0}\frac{\rho}{\rho_0}\frac{\mathcal{L}}{\mathcal{L}_0}f(i)$$

- *A*: area of the satellite
- *M*: mass of the object;
- *ρ*: spatial density associated with the given shell in the given year
- *L*: lifetime of the object at the altitude corresponding to the shell
- *f(i)*: a function of the orbital inclination *i*.
- A_0 , M_0 , ρ_0 , and L_0 are normalizing factors

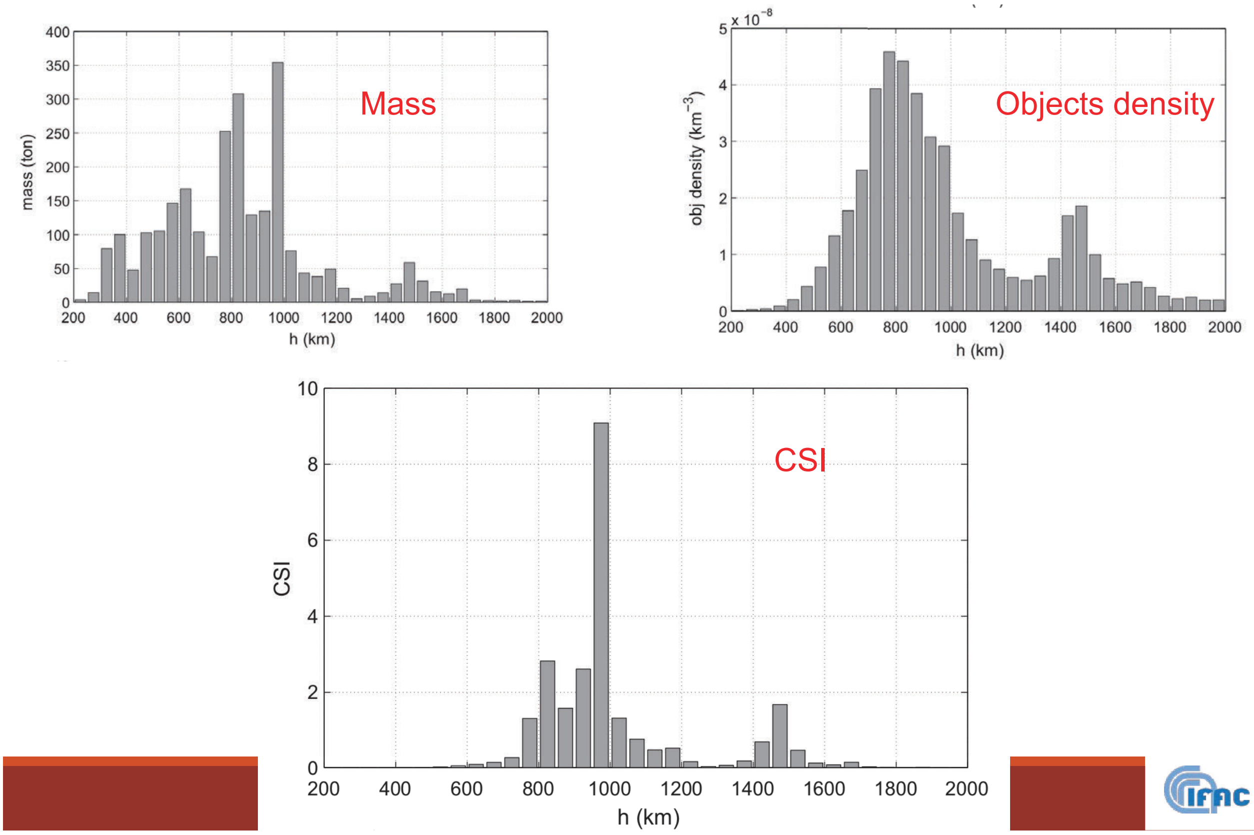
Environmental indexing

- The CSI of the LEO region (or for a given altitude shell) for a given year is (Rossi et al., *Proc. 7th European Space Debris Conference*, 2017):

$$\tilde{\Xi}_{LEO} = \sum_{i=1}^{N}\sum_{j=1}^{p(i)} \Phi_{i,j}\tilde{\Xi}_j$$

- where *p(i)* is the number of objects moving through the LEO shell, and $\Phi_{i,j}$ denotes the percentage of the orbital period spent by the object *j* in the shell *i,* which is a function of the semi-major axis *a* and the eccentricity *e* of the object.

Representing LEO in terms of CSI index



Mega-constellations: environmental impact index (CCI)

(Rossi et al., *Proc. 7th European Space Debris Conference*, 2017)

Aim: to depict the variation of $\tilde{\Xi}$ LEO caused by the mega constellation, according to hypotheses on its composition, building, maintenance and disposal practices, as defined by:

- (*a, e, i*), M, A for all the satellites of the constellation;
- collisional avoidance capability (*C*) and probability of failure (*F*) for all the satellites of the constellation in the operational phase;
- the same two quantities (C_d and F_d) during the de-orbiting phase;
- first and last year of launch, duration of the building phase, satellite life;
- number of launches and number of satellites per launch during building and replenishment phases;
- initial pericenter and apocenter for the de-orbiting phase, and duration of the de-orbiting phase.

Mega-constellations: environmental impact index (CCI)

(Rossi et al., *Proc. 7th European Space Debris Conference*, 2017)

The CCI for a given year can be written as the sum of two terms:

- a direct contribution which is the sum of the $\tilde{\Xi}$ of the spacecraft of the mega constellation, either operational or de-orbiting, weighted for their collision avoidance capabilities and their probability of failure;
- an indirect contribution which is instead due to the variation of the density of each shell caused by the presence of new spacecraft

$$CCI = CCI^{dir}_{LEO} + CCI^{non-dir}_{LEO}$$

The cumulative CCI is the sum of the CCI over all the years, until all the satellites have cleared the whole LEO region.

Mega-constellations: environmental impact index (CCI)

(Rossi et al., *Proc. 7th European Space Debris Conference*, 2017)

- Direct contribution:

$$CCI^{dir}_{LEO} = \sum_{i=1}^{N_O}\sum_{j=1}^{p_o(i)}[(1-\mathcal{C})(1-\mathcal{F})+\mathcal{F}]\Phi_{i,j}\tilde{\Xi}_j +$$
$$\sum_{i=1}^{N_D}\sum_{j=1}^{p_d(i)}(1-\mathcal{F})[(1-\mathcal{C}_d)(1-\mathcal{F}_d)+\mathcal{F}_d]\Phi_{i,j}\tilde{\Xi}_j +$$
$$\sum_{i=1}^{N_O}\sum_{j=1}^{p_d(i)}\mathcal{F}\Phi_{i,j}\tilde{\Xi}_j,$$

- Indirect contribution:

$$CCI^{non-dir}_{LEO} = \sum_{i=1}^{N}\sum_{j=1}^{p(i)}\Phi_{i,j}\frac{A}{A_0}\frac{M}{M_0}\frac{\Delta\rho}{\rho_0}\frac{\mathcal{L}}{\mathcal{L}_0}f(i)$$

where *p* here includes the historical existing objects, plus the operational and the de-orbiting objects of the mega constellation, and the density variation is weighted as a function of *C*, *Cd* , *F*, *Fd* .

Basic Mitigation measures

- Stop explosions ➔ spacecraft and upper stages design
- Reduce number of collisions ➔ collision avoidance
- Reduce collision output ➔ shielding and spacecraft design
- Improve compliance to de-orbiting at the end-of-life ➔ exploit astrodynamics + improved de-orbiting devices and propulsion

ReDSHIFT (http://redshift-h2020.eu)

EU H2020 funded project started on 1/1/2016, ending on 31/12/2018

Great Britain:

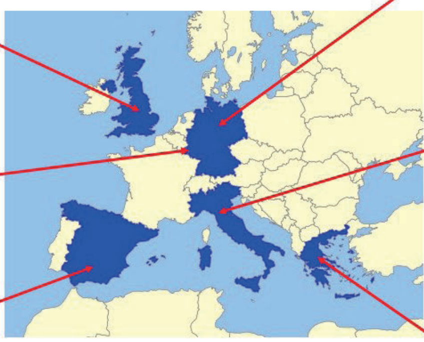
- University of Southampton
- Belstead Ltd.
- PHS Space Ltd.

Luxemburg:

- LUX Space

Spain:

- Deimos Space
- Elecnor Deimos Satellite Systems



Germany:

- Technical University of Braunschweig
- Deutschen Zentrums für Luft- und Raumfahrt
- University of Cologne

Italy:

- IFAC-CNR (coordinator)
- Università di Padova
- Politecnico di Milano

Greece:

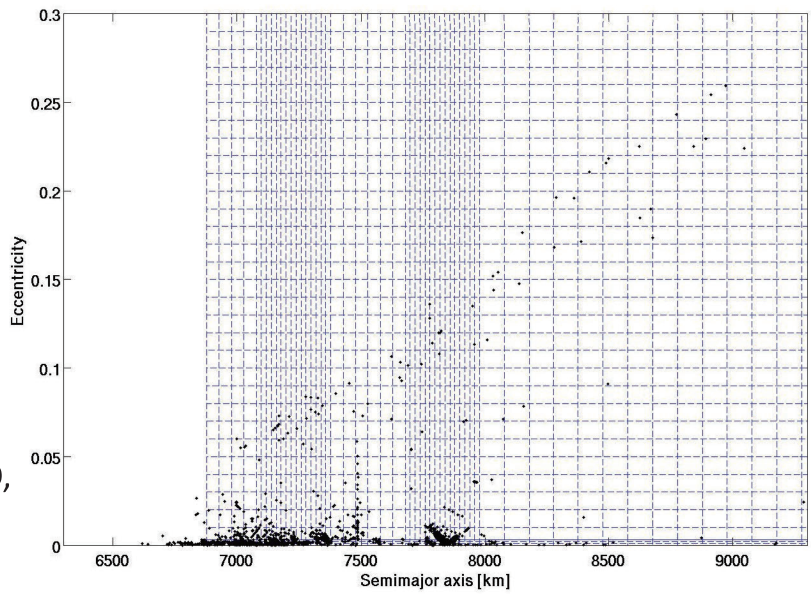
- University of Thessaloniki

ReDSHIFT: Mitigation from the cradle to the grave

- **Simulations**: Simulate the evolution of the current space environment with standard procedures and, later on, with the proposed advanced procedures.
- **Astrodynamics**: a “cartography” of the phase space in the Earth vicinity will be performed looking for de-orbiting highways (coupled with non-standard propulsion means) using modern celestial mechanics and astrodynamics tools.
- **3D-printing**: produce and test prototypes of small spacecraft (or part of) with novel solutions (protection, design-for-demise,....) based on the theoretical findings.
- **Legal framework**: propose advances to the current mitigation guidelines on the basis of the results obtained.

LEO to GEO resonance mapping as a preferential route to de-orbiting

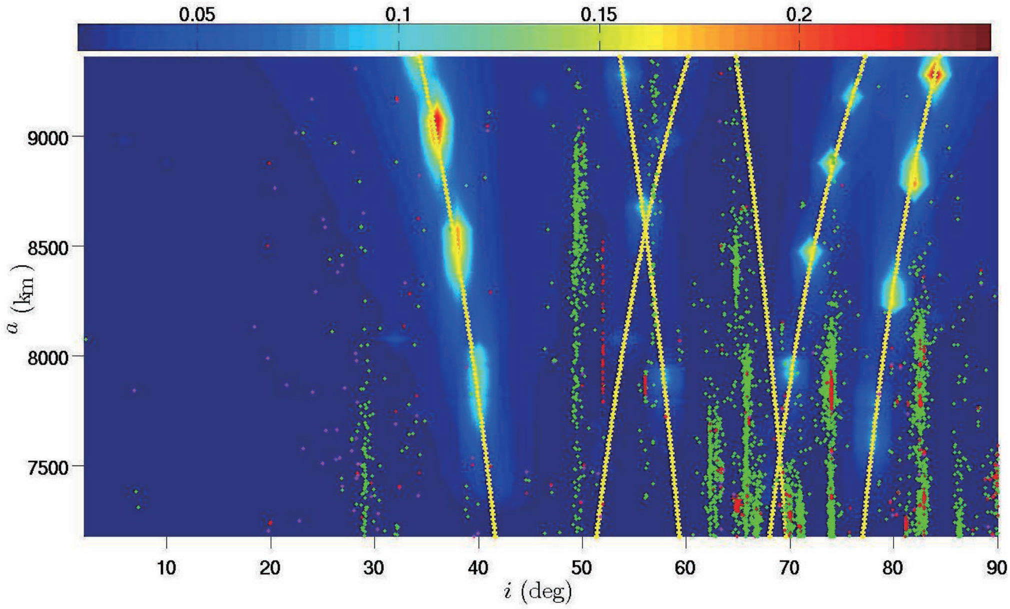
- A variable grid was defined from LEO to GEO.
- Several tens of millions of orbits were propagated.
- Different computational models, including all the relevant gravitational and non gravitational perturbations, were used for the three regimes (LEO, MEO, GEO).
- Two A/M values:
  - A/m = 0.012 m^2/kg
  - A/m = 1 m^2/kg



- All the maps are currently available and downloadable from: http://redshift-h2020.eu/results

LEO: resonance mapping as a preferential route to de-orbiting

Maximum eccentricity map for objects with enhanced A/M = 1 m^2/kg



Note that the mapping was also done for the MEO (by **University of Thessaloniki**) and GEO (by **Politecnico di Milano**) regions (not shown here).

LEO to GEO resonance mapping as a preferential route to de-orbiting

The most important resonances affecting the eccentricity evolution in the LEO region.

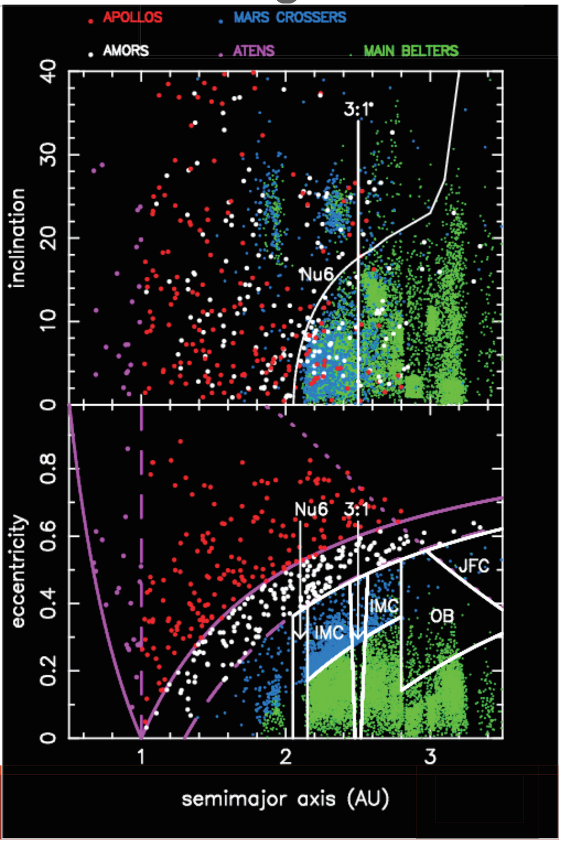
- $\dot{\psi} = 2\dot{\omega} + \dot{\Omega} - 2n_S$, associated with singly-averaged solar gravitational resonance (n_S is the apparent mean motion of the Sun);
- $\dot{\psi} = 2\dot{\omega} + \dot{\Omega} \approx 0$, associated with doubly-averaged lunisolar gravitational perturbations;
- $\dot{\psi} = \dot{\omega} \approx 0$, associated with lunisolar perturbations but also with higher-degree terms in the geopotential;
- $\dot{\psi} = \alpha\dot{\Omega} \pm \dot{\omega} \pm n_S \approx 0$, associated with SRP ($\alpha = 0, 1$).

If an orbit is far from resonance, e evolves on a time-scale $\sim 2\pi/\dot{\omega}$, depending solely on the geopotential. Inside or near a resonance, e follows a longer secular time-scale, $\sim 2\pi/\dot{\psi}$.

LEO to GEO resonance mapping as a preferential route to de-orbiting

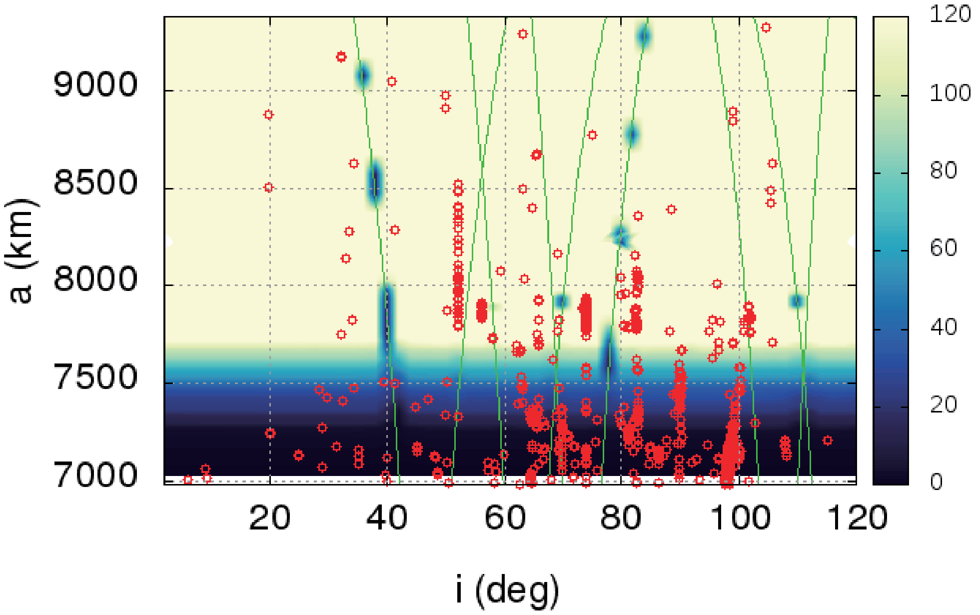
Asteroid resonances

Orbital distribution of main belt asteroids (green), Intermediate Mars Crossers (blue) and NEOs (white, red and magenta)
(From: B. Bottke *et al.*, Understanding the distribution of NEAs).



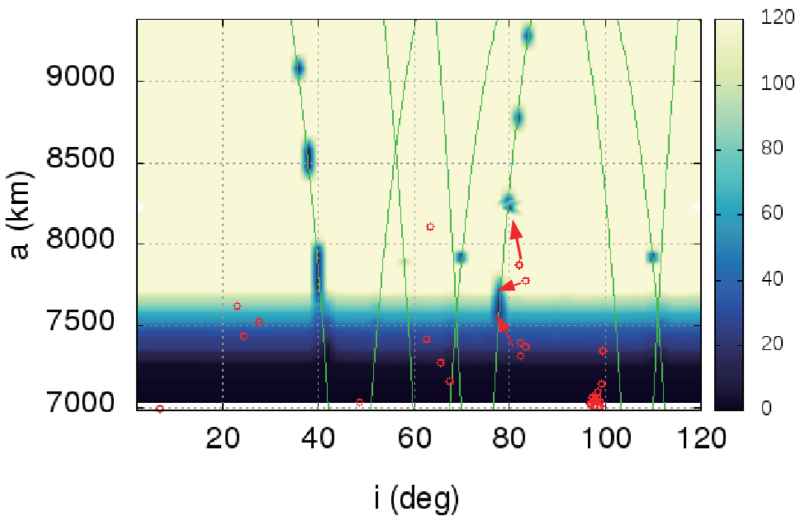
LEO: resonance mapping as a preferential route to de-orbiting

Residual lifetime for objects with enhanced A/M = 1 m^2/kg



LEO: resonance mapping as a preferential route to de-orbiting

Steer traffic launch towards the reentry corridors (compatibly with mission requirements)



LEO to GEO resonance mapping as a preferential route to de-orbiting

The natural dynamics is enhanced via impulsive manoeuvres, solar and drag sailing and a combination of manoeuvres and solar and drag sailing.

For LEO disposals:

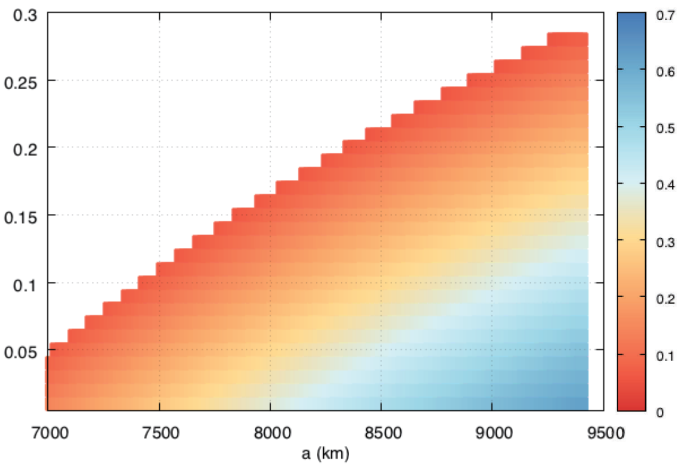
- compute the possible displacements in (*a*,*e*,*i*) for a given ΔV provided in input, in order to identify the most suitable final orbit that can be achieved with that ΔV.
- The maximum ΔV considered for the simulation is the one corresponding to a direct re-entry manoeuvre down to 80 km of altitude.
- In this way, all the possible target orbits are selected and, among them, the one that will naturally evolve toward re-entry in a time less than 50 years are chosen.
- For all these cases, the required *ΔV* is computed as a single burn manoeuvre in case the two orbits are intersecting.
- A solar radiation pressure-augmented case, (A/M= 1 m^2/kg) is considered too.
- In this case the corresponding resonant inclination are targeted.
- This corresponds to a two-phase deorbiting strategy: a relatively small manoeuvre is performed to reach a resonance where the atmospheric drag or the solar radiation pressure can then be exploited to re-enter by means of a passive stabilised sail.

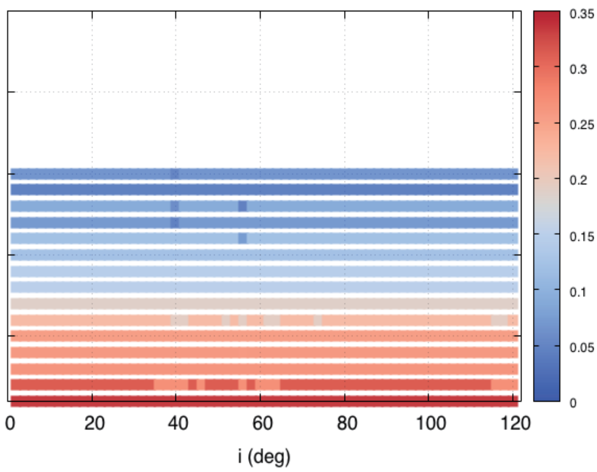
LEO to GEO resonance mapping as a preferential route to de-orbiting

The natural dynamics is enhanced via impulsive manoeuvres, solar and drag sailing and a combination of manoeuvres and solar and drag sailing.

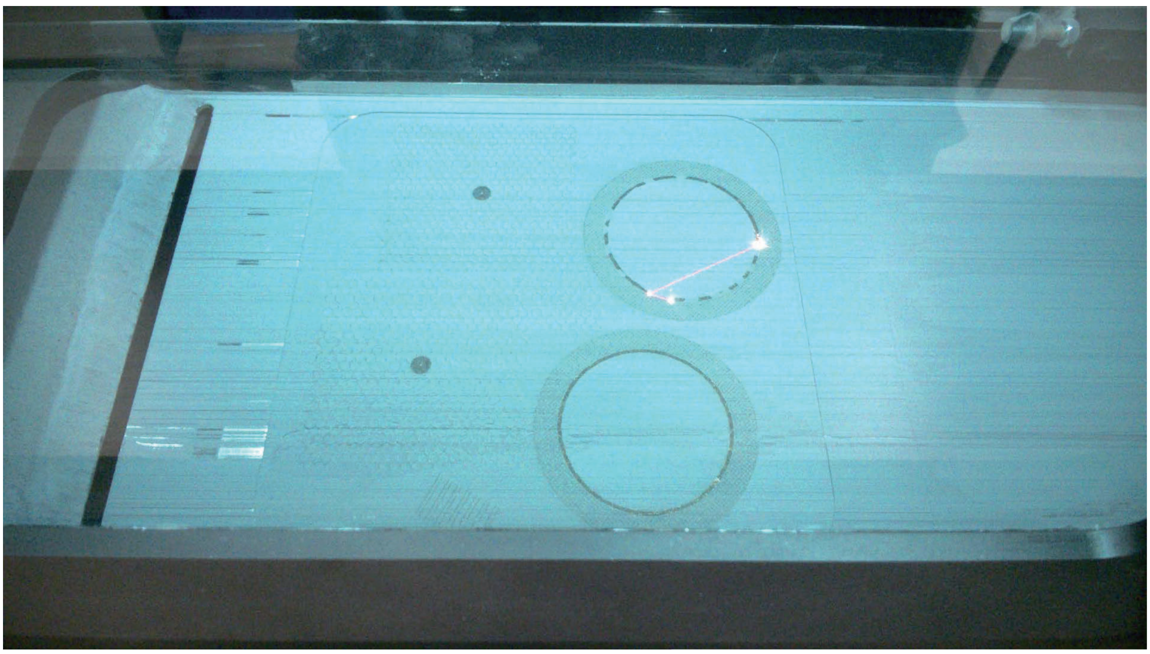
Results for the direct re-entry solutions.

Minimum-cost re-entry solutions, a0 = RE +1520 km



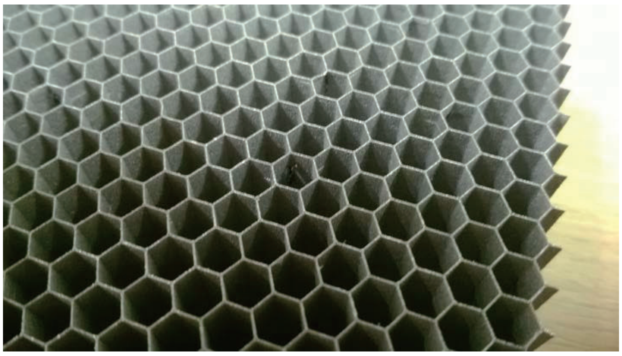


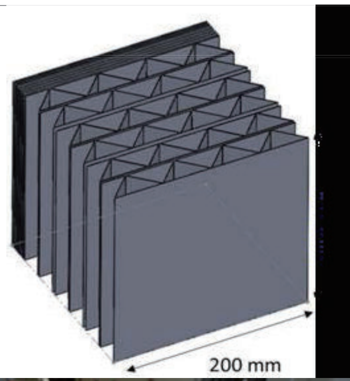
3D printing of spacecraft parts and shields at University of Southampton



3D printed material: tests

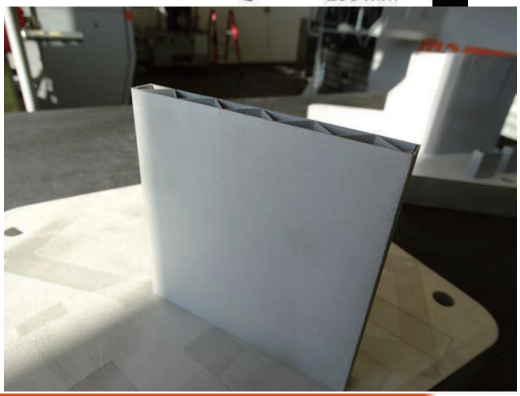
ReSHIFT





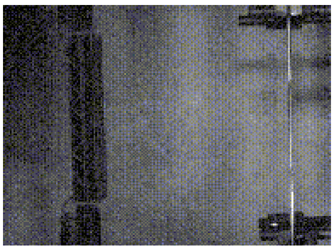
Shields designed and tested by **PHS Space and University of Padova**.
The 3D printed parts are undergoing a series of tests:

- D4D at DLR
- Radiation and hypervelocity impact tests at Univ. of Padova.

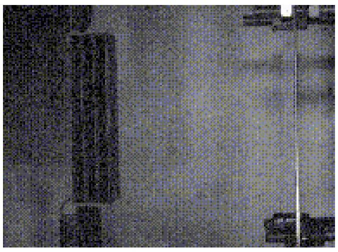


3D printed material: HVI tests

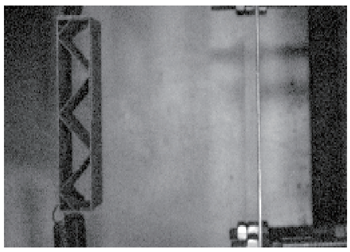
ReSHIFT



d_p = 2.9 mm - v = 4.60 km/s

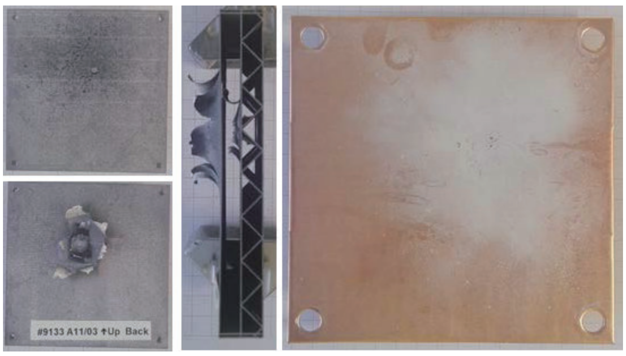


d_p = 2.9 mm - v = 4.79 km/s

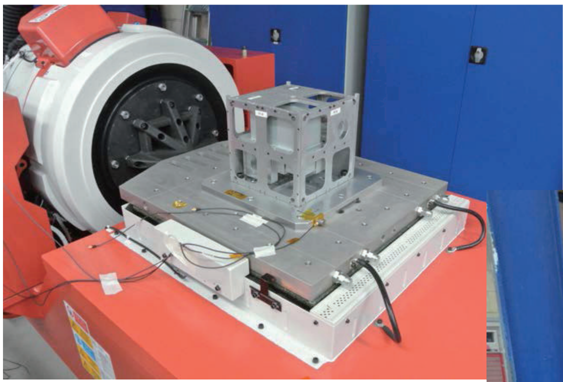


d_p = 2.9 mm - v = 4.87 km/s

- Radiation and hypervelocity impact tests at **Univ. of Padova**.
  - **Excellent projectile fragmentation** (causing a very marginal damage on the witness plate) despite the large damage on the panel
  - → **High protection capability for spacecraft internal equipment**



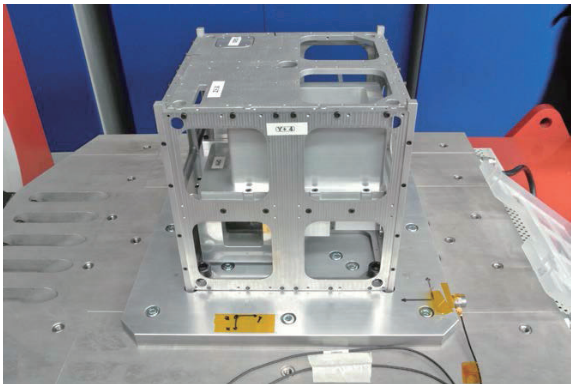
3 prototype spacecraft



- 3 spacecraft assembled/printed at **Elecnor Deimos Satellite Systems**

- The 3 spacecraft underwent launch vibration tests by EDSS

3 prototype spacecraft



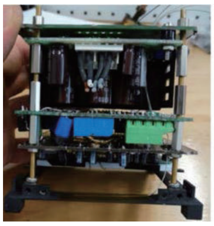
- The 3 spacecraft underwent launch vibration tests
- All the spacecraft passed the tests.

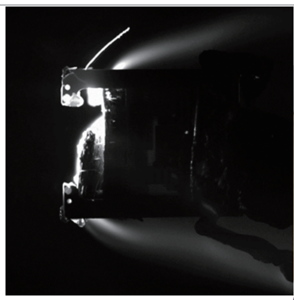
- The outcome shall be used to optimize the design of a spacecraft fully optimized for 3D printing

Design for Demise (D4D) Tests

- The spacecraft (or parts of it) should not survive during the atmospheric re-entry!
- Test campaign performed at the DLR L2K facility, by the **Belstead Ltd.** and the **DLR** teams.

D4D Tests – A number of "firsts"



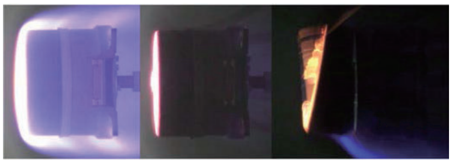


- First tests of aluminium thin structures:
  - Top hat, Plate, CubeSat Structure, Reaction Wheel Housing.
- First demise test of a full CubeSat mockup:
  - Demise expected, but maybe not as easily as previously thought:
    - Structure melts;
    - steel rods for mounting can support structure
    - GFRP electronics cards more robust than expected

D4D Tests – A number of "firsts"

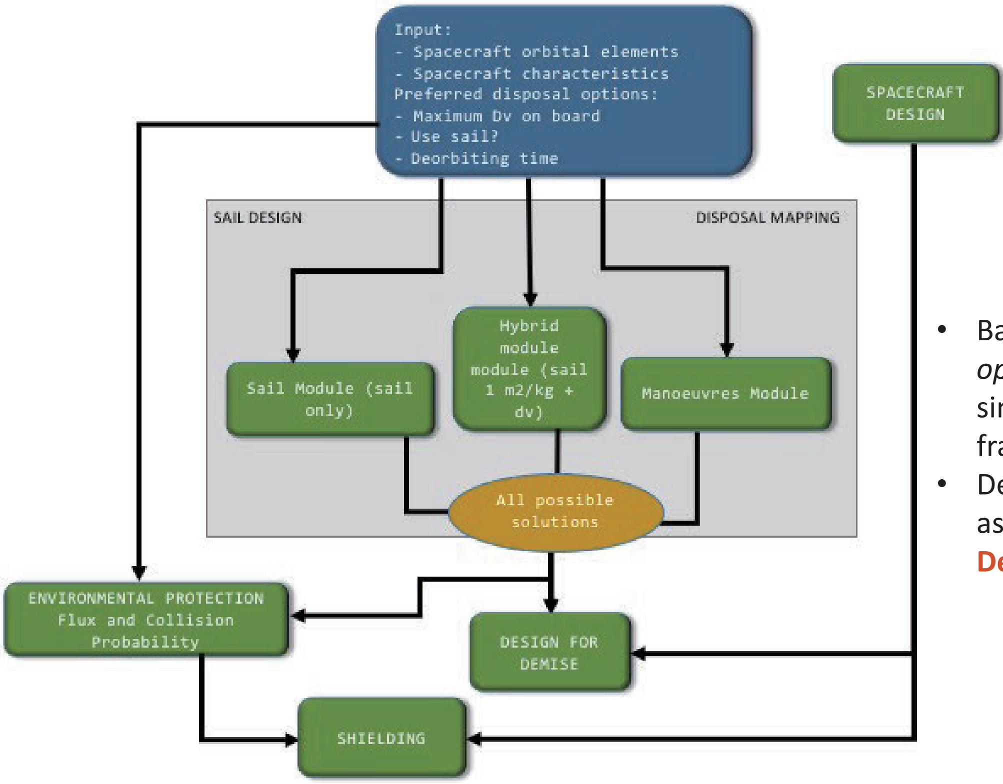
ReDSHIFT

- **First demise test of an engineering model of a reaction wheel:**
  - demise process very different from models
  - Many small parts produced
  - Not quite as bad for demise as it looks…
  - Massive steel objects are clearly an issue



ReDSHIFT software tool

ReDSHIFT



- Based on the *openSF* simulation framework
- Designed and assembled and at **Deimos Space**.

CONCLUSIONS

- The mitigation of the space debris problem needs a global approach from several different point of views.
- Different indicators can be devised to properly quantify the benefits of the mitigation measures and the state of the space environment as a whole.
- The effectiveness of the passive means for mitigation can be enhanced by the proper exploitation of the orbital dynamics features.
- The whole design of a space debris compliant mission can benefit from innovative manufacturing processes.
- In the frame of the EU ReDSHIFT project most of these aspects are analyzed and will be implemented in a publicly available software suite, soon available on:

http://redshift-h2020.eu/

European Commission

ReDSHIFT

Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies

HTTP://REDSHIFT-H2020.EU/

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