An holistic approach to the space debris mitigation

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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.
MITIGATION: LONG TERM SIMULATIONS

- The scope here is a critical analysis of the strength and weaknesses of the currently adopted mitigation measures.
- Moreover the simulations will set the reference for further analysis in the second phase of the project, to evaluate the environmental benefits of the new solutions.
- Several different long term evolution scenarios were simulated. First a Reference scenario, mimicking the current operational and mitigation procedures, was simulated, against which to compare the results of the modified scenarios.
Mitigation: long term simulations

Modified scenarios were devised to highlight the effect of a single parameter on the long term evolution of the population:

- widespread use of collision avoidance, for the active satellites;
- increased compliance with the currently proposed mitigation measures (such as the 25-year rule), from 60% to 90%;
- reduced residual lifetime after disposal (from 25 to 10 years);
- active debris removal (one case with 2 objects per year and one with 5 objects per year);
- launch of a mega-constellation of satellites in LEO;
- considering complex satellites shapes, with appendages (e.g., antennas, panels, etc), in the computation of the collision probabilities and of the collision consequences.
Mitigation: Long Term Simulations

- Initial Population: MASTER population, objects ≥ 10 cm
- Projection time frame: 200 years
- Monte-Carlo Runs: 50
- Launch traffic: Standard IADC, 8 year repeating cycle
- Collision activities: Both catastrophic and non-catastrophic collisions are modelled
- Explosions: $N > 2 - 3$ expl. until 2028, then 0
- Collision avoidance: Active Satellites (80% success rate)
- Post Mission Disposal:
  - compliant with the IADC guidelines (25-year rule and IADC disposal for GEO) with 60% compliance level
  - compliant with the IADC guidelines (25-year rule and IADC disposal for GEO) with 90% compliance level
MITIGATION: number of objects > 10 cm in LEO
MITIGATION: NUMBER OF CATASTROPHIC FRAGMENTATIONS IN LEO

![Graph showing the number of catastrophic fragmentations over time from 2020 to 2200. The graph includes lines for Reference, Reference + 1 σ, Reference − 1 σ, Improved Mitigation Compliance, ADR 2, and Appendices. Each line represents a different scenario, with the number of events increasing over time.]
Mitigation: Obj. > 10 cm in LEO, Megacon
Mitigation: Fragmentations in LEO, Megacon
MITIGATION: RE-ENTRY OF OBJECTS
MITIGATION: RE-ENTRY OF OBJECTS

From: Schaus, Radtke, Stoll, Rossi, Colombo, Tonetti, Holbrough (2017)
MITIGATION: SPATIAL DENSITY OF OBJECTS
MITIGATION: SPATIAL DENSITY OF OBJECTS

Dynamics disposal!
MITIGATION: SPATIAL DENSITY OF OBJECTS

- Above \( \sim 1400 \) km it becomes energetically more convenient (less \( \Delta V \)) for an operator to send the satellite in a circular graveyard orbit above the protected LEO region, at \( \sim 2000 \) km.

- The accumulation of spent, uncontrolled spacecraft in a restricted region of space leads inevitably to a significant number of collisions.
MITIGATION: DISTRIBUTION OF FRAGMENTATIONS

![Graph showing distribution of fragmentations with MIT compliance and reference lines.](image-url)
Mitigation: Spatial Density of Objects

- Above ~ 1400 km it becomes energetically more convenient (less $\Delta V$) for an operator to send the satellite in a circular graveyard orbit above the protected LEO region, at ~ 2000 km.
- The accumulation of spent, uncontrolled spacecraft in a restricted region of space leads inevitably to a significant number of collisions.
- We aim at showing that there might be less energetically demanding trajectories to facilitate the compliance with the 25-year (or XX-year,...) rule.
MODEL AND SIMULATION SETTINGS

FOP: averaged eqs. of motion, multi step, variable order propagator

- Geopotential: $5 \times 5$
- Sun & Moon
- Solar Radiation Pressure: spherical model including shadows
- Atmospheric drag: Jacchia-Roberts 77, assuming an exospheric temperature of 1000 K and a variable solar flux.
  - $A/m = 0.012 \text{ m}^2/\text{kg}$
  - $C_R = 1 \div 2$
  - $C_D = 2.1$

The time history of $(a, e, i, \Omega, \omega)$ is recorded at a step of 1 day. Maximum and minimum values attained by $(a, e, i)$ are stored. The orbit is considered to have re-entered the atmosphere whenever $h_p < 300 \text{ km}$. 
MODEL AND SIMULATION SETTINGS: FINAL GRID

- $a \in [R_E + 500 : R_E + 3000]$ km
- $e \in [0 : 0.28]$ s.t. $e < 1 - (R_E + 300$ km$)/a$
- $i \in [2° : 120°]$
- $M = 0°$

The non-uniform grid is refined in the most crowded orbital zones.

| $h$ (km)       | $\Delta a$ (km) | $\Delta e$                   | $\Delta i$ | $\Delta \Omega/\omega$ |
|----------------|-----------------|------------------------------|------------|-------------------------|
| [500 : 700]    | 50              | $10^{-3}$ up to 0.01, then 0.01 | 2°         | 90°                     |
| [700 : 1000]   | 20              | $10^{-3}$ up to 0.01, then 0.01 | 2°         | 90°                     |
| [1000 : 1300]  | 50              | $10^{-3}$ up to 0.01, then 0.01 | 2°         | 90°                     |
| [1300 : 1600]  | 20              | $10^{-3}$ up to 0.01, then 0.01 | 2°         | 90°                     |
| [1600 : 2000]  | 50              | 0.01                         | 2°         | 90°                     |
| [2000 : 3000]  | 100             | 0.01                         | 2°         | 90°                     |

A similar grid was defined for the MEO and GEO regions.
Area Augmentation Devices

▶ The possibility to exploit area augmentation devices was explored too.
▶ These devices can act either as solar sails in higher orbits or as drag sails when interacting with the atmosphere.

Image courtesy of LUX Space
(All rights reserved)
AREA AUGMENTATION DEVICES

- The simulations were therefore repeated for an $A/m = 1 \text{ m}^2/\text{kg}$, which can be considered as a realistic value possible to achieve with a drag or solar radiation pressure enhancing device with the present technology.

- Note that the additional collision risk associated with these kind of devices is currently under evaluation in the framework of a different study too.

Image courtesy of LUX Space
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**ORBITAL LIFETIME**

We took the **LIFETIME** computed for a given initial condition as the main reference to evaluate the outcome.

This helps, in particular, in discriminating between the cases which could naturally comply with the 25-year rule thanks to a given (enhanced or not) perturbation and the cases which cannot.

![Expected lifetime for a circular orbit as a function of h and A/m.](image-url)
**RE-ENTRY ECCENTRICITIES**

$$(A/m) = 0.012 \, \text{m}^2/\text{kg}, \, \Omega = 180^\circ, \, \omega = 0^\circ, \, \text{Epoch: 2020}$$
LIFETIME MAPS: $\alpha = R_E + 1200 \text{ km}$

Epoch 2018 \hspace{1cm} (A/m) = 0.012 m$^2$/kg

$\Omega = 90^\circ, \omega = 0^\circ$ \hspace{1cm} $\Omega = 270^\circ, \omega = 0^\circ$
LIFETIME MAPS: $\alpha = R_E + 2000$ km

Epoch 2018 - $(A/m) = 0.012$ m$^2$/kg

$\Omega = 0^\circ, \omega = 180^\circ$

$\Omega = 90^\circ, \omega = 270^\circ$
**MAXIMUM ECCENTRICITY:** $a = R_E + 1200$ km

Epoch 2018 - $(A/m) = 0.012$ m$^2$/kg

$\Omega = 90^\circ, \omega = 0^\circ$

$\Omega = 270^\circ, \omega = 180^\circ$
Maximum eccentricity: \( a = R_E + 2000 \text{ km} \)

Epoch 2020 - \((A/m) = 1 \text{ m}^2/\text{kg}\)

\[ \Omega = 90^\circ, \; \omega = 0^\circ \]  
\[ \Omega = 270^\circ, \; \omega = 180^\circ \]
LIFETIME CLOSE TO RESONANCES

\( i = 40^\circ \quad a \in [7678.14 : 7978.14] \text{ km} \)

Epoch 2020, \( C_R(A/m) = 0.024 \text{ m}^2/\text{kg} \), \( \Omega = 0^\circ \), \( \omega = 90^\circ \)
LEO RESONANCES

A detailed analysis over all the initial values of semi-major axis in the grid has allowed to recognize the most important resonances affecting the eccentricity evolution in the LEO region.

Previous results on the subject include (in a non exhaustive list....):

- Musen (1960)
- Cook (1962)
- Hughes (1977, 1980, 1981)
- Breiter (1999)
- Colombo et al. (2012, 2016)
- Celletti et al. (2017)
- ...
Starting from the expression for the SRP disturbing function as written in (Krivov et al, 1996):

\[ R_{SRP} = \frac{3}{2} P C_R \frac{A}{m} a e [T_1 + T_2 + T_3 + T_4 + T_5 + T_6] \]

where \( T_j \) are (sin and cos) functions of the spacecraft orbital elements (\( i, \Omega, \omega \)) and of the the longitude of the Sun measured on the ecliptic.

Assuming that the resonances are isolated, then we can write the variation in \((e, i)\) as due to only one of the \( j \)th term \( T_j \).

Applying the Lagrange planetary equations we get the expression for the time derivatives of \((e, i, \Omega \) and \( \omega)\) due to the effects of \( J_2 \) and SRP, from which it is possible to identify a series of resonances.
LEO RESONANCES

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 SRP Resonances: Location for e = 0.02**

Top: \( A/m = 0.012 \text{ m}^2/\text{kg} \).

Middle: \( A/m = 1 \text{ m}^2/\text{kg}, \psi = 0^\circ \).

Bottom: \( A/m = 1 \text{ m}^2/\text{kg}, \psi = 180^\circ \).

- **Blue**: \( \dot{\omega} - n_S = 0 \).
- **Red**: \( \dot{\Omega} + \dot{\omega} - n_S = 0 \).
- **Green**: \( \dot{\Omega} - \dot{\omega} - n_S = 0 \).
- **Purple**: \( \dot{\omega} + n_S = 0 \).
- **Yellow**: \( \dot{\Omega} - \dot{\omega} + n_S = 0 \).
- **Cyan**: \( \dot{\Omega} + \dot{\omega} + n_S = 0 \).
LEO RESONANCES CROSSINGS

Two main overlapping between SRP resonances. For quasi circular orbits we have:

- an overlapping between $\dot{\psi} = \dot{\omega} - n_S = 0$ and $\dot{\psi} = \dot{\Omega} + \dot{\omega} + n_S = 0$ at $a \approx r_\oplus + 2200$ km and $i \approx 56^\circ$;
- an overlapping between $\dot{\psi} = \dot{\omega} + n_S = 0$ and $\dot{\psi} = \dot{\Omega} - \dot{\omega} + n_S = 0$ at $a \approx r_\oplus + 1180$ km and $i \approx 69^\circ$.

We do not observe chaotic islands in the neighborhoods of these crossings.

The overlapping of resonances can, in some cases, modify the relative importance of specific resonances.
LEO RESONANCES RANKING (AMPLITUDE IN $\dot{e}$)

1. $\dot{\Omega} + \dot{\omega} - n_S = 0$
   (emanating from $i \approx 44^\circ$ at $r_\oplus$)
2. $\dot{\Omega} - \dot{\omega} - n_S = 0$
   (emanating from $i \approx 75^\circ$ at $r_\oplus$)
3. $\dot{\omega} - n_S = 0$
   (emanating from $i \approx 60^\circ$ at $r_\oplus$)
4. $\ddot{\omega} + n_S = 0$
   (emanating from $i \approx 66^\circ$ at $r_\oplus$)
5. $\dot{\Omega} + \dot{\omega} + n_S = 0$
   (emanating from $i \approx 50^\circ$ at $r_\oplus$)
6. $\dot{\Omega} - \dot{\omega} + n_S = 0$
   (emanating from $i \approx 71^\circ$ at $r_\oplus$)

Amplitude corresponding to the variation in $e$ at the given SRP resonances for $a \in [r_\oplus : r_\oplus + 3000]$ km, $e = 0.02$, and $A/m = 1$ m$^2$/kg.
MAXIMUM ECCENTRICITY AND RESONANCES

\( e = 0.1, \Omega = 0^\circ, \omega = 0^\circ \)

Epoch 2018, \( C_R(A/m) = 0.024 \text{ m}^2/\text{kg} \)

Epoch 2020, \( C_R(A/m) = 1 \text{ m}^2/\text{kg} \)
MAXIMUM ECCENTRICITY AND RESONANCES

For the high value of area-to-mass ratio the only resonances which matter are those associated with SRP.
Main frequencies as a function of $i$

$h = 1400 \text{ km}, e = 0.02, \Omega = 0^\circ, \omega = 90^\circ, \text{epoch: 2020}, A/m = 0.012$
Main frequencies as a function of $i$

$h = 1400 \text{ km}, e = 0.02, \Omega = 0^\circ, \omega = 90^\circ$, epoch: 2020, $A/m = 0.012$
i vs e: MEM CONTOUR MAPS FOR EPOCH 2020

$h = 500 \text{ km}$
**RE-ENTRY ECCENTRICITIES**

\[(A/m) = 0.012 \text{ m}^2 /\text{kg}, \Omega = 180^\circ, \omega = 0^\circ, \text{Epoch: 2020}\]
**MEO Dynamics: Unstable Orbits**

- Very hard to define initial conditions leading to an Earth re-entry.
- This is due to the fact that, in practice, we do not have the freedom to change $(\Omega, i)$ to get a more favourable positioning and, more importantly, to the intrinsic dynamics of the MEO region.

Galileo: nominal initial inclination (56°). Values of $\omega$ ensuring reentry for a given $t_0$ and $\Omega$ (white means “no reentry found”)

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**Resonances**

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MEO DYNAMICS: DYNAMICAL STRUCTURES

From: Rosengren, Daquin, Tsiganis, Alessi, Deleflie, Rossi, Valsecchi, MNRAS, 2017
**Dynamics: ongoing work**

- All the maps produced are being collected in an “atlas” displaying the preferential routes to de-orbiting (the “de-orbiting highways”) from a selected orbital region.
- The atlas will be made public on the ReDSHIFT web site (http://redshift-h2020.eu).
- The maneuvers needed to reach the highways entrances from neighboring orbits are being computed and will be offered as de-orbiting solutions in the final ReDSHIFT software tool (publicly available on the ReDSHIFT web site (http://redshift-h2020.eu) at the end of the project.
- The improvements on the mitigation scenarios obtained with the proposed dynamical de-orbiting solutions will be tested with the long term evolution codes (by repeating the previous scenarios with the new ΔV requirements).
3D PRINTING: ReDSHIFT STRUCTURAL MODEL

- 8U-cubesat
- $226.30 \times 226.30 \times 227.00$ mm
- compatible with the Additive Manufacturing system at the University of Southampton.

Image by EDSS
3D PRINTING: ReDSHIFT STRUCTURAL MODEL

- CAD model and manufacturing drawings completed by EDSS
- 3 different models with different number of components and materials
- A number of features will be tested on these models:
  - Shielding
  - Controlled Break Up
  - Design for Demise (D4D)
- Different tests will also be performed on them:
  - D4D, in heated wind tunnel;
  - Impact, with hypervelocity gas guns;
  - Radiation tests.
  - Vibrational test.
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