Studying the impact of large constellations on the space environment using a space debris metric

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Space capacity allocation for the sustainability of space activities, Milan, 6th June 2023

Background

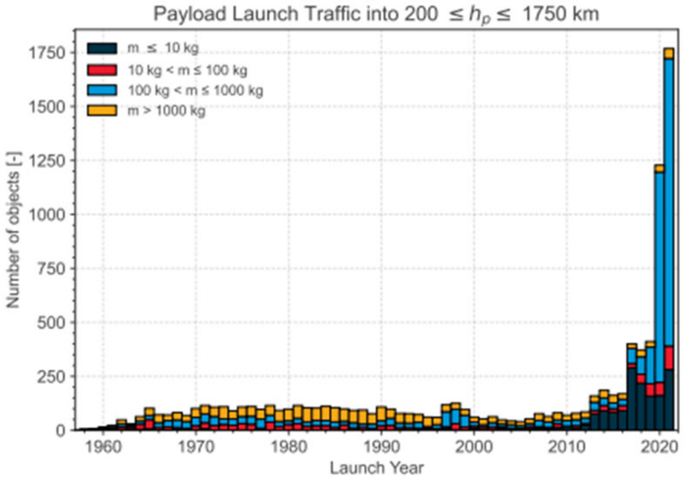

Fig. 1 - Evolution of the launch traffic near LEO per mass category

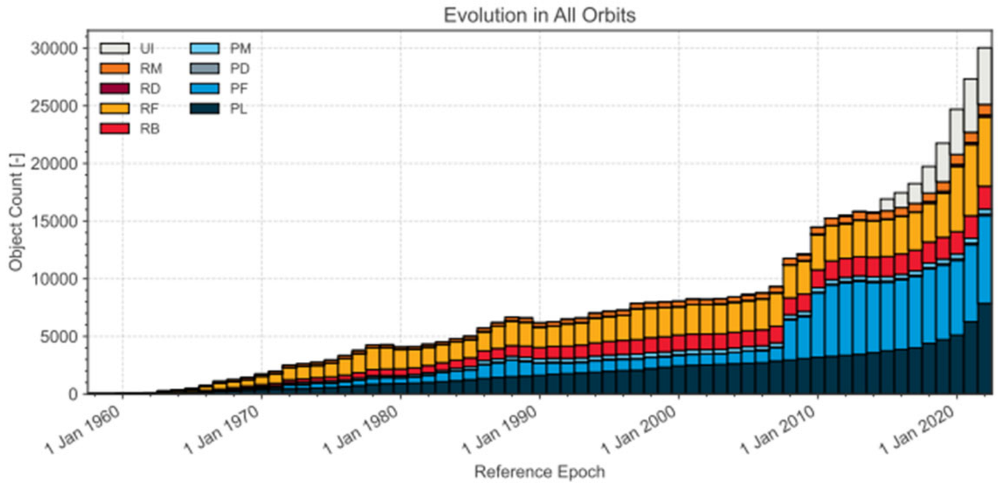

Fig. 2 - Evolution of the number of objects

THEMIS software to monitor the sustainable evolution of the space environment

- Assessing the **impact** of **missions**

  1. Effects of fragmentation on the population of orbiting objects
  2. Environmental index computation

➢ **ESA, "ESA'S ANNUAL SPACE ENVIRONMENT REPORT", 2022**
➢ **Colombo, C. et al. "Evaluation of the Space capacity share used by a mission", 73rd IAC, Paris, France, 2022, September 18-22**

THEMIS index

General overview

- **Risk metric** in terms **of probability** and **severity**
- **Mission** profile divided into **phases** (e.g., operational, deorbiting, etc.)
- **Originally** defined for **LEO region** (currently being extended to other orbital regions)

$$I = \int_{t_0}^{t_{EOL}} I(t)dt + \alpha \cdot \int_{t_{EOL}}^{t_{end}} I(t)dt + (1-\alpha) \cdot \int_{t_{EOL}}^{t_f} I(t)dt$$

Generic phase: $\int_{t_0}^{t_{EOL}} I(t)dt$

Post Mission Disposal (PMD): $\alpha \cdot \int_{t_{EOL}}^{t_{end}} I(t)dt + (1-\alpha) \cdot \int_{t_{EOL}}^{t_f} I(t)dt$

Reliability of the PMD: α

t_0: Mission start epoch
t_{EOL}: Mission EoL epoch
t_{end}: Nominal re-entry epoch
t_f: Failed EoL re-entry epoch

- Letizia, F., Lemmens, S., Bastida Virgili, B., & Krag, H. "Application of a debris index for global evaluation of mitigation strategies", Acta Astronautica , 2019, 161, 348-362.
- Colombo, C. et al. "Evaluation of the Space capacity share used by a mission", 73rd IAC, Paris, France, 2022, September 18-22
- Muciaccia, A. et al. "Environmental impact of large constellations through a debris index analysis", 73rd IAC, Paris, France, 2022, September 18-22

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Collision probability

- **Flux-based model** of the space debris environment
- ESA MASTER 8 for **debris flux** and impact **velocity**

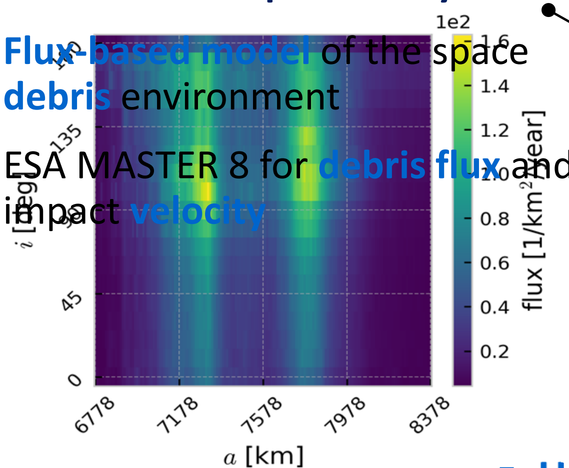

Fig. 3 - Debris flux - LEO

Space debris index

$$I(t) = p_c \cdot e_c + p_e \cdot e_e$$

Explosion probability

- **Historical data** from ESA DISCOS database
- Kaplan-Meyer estimator (estimate the survival rate)

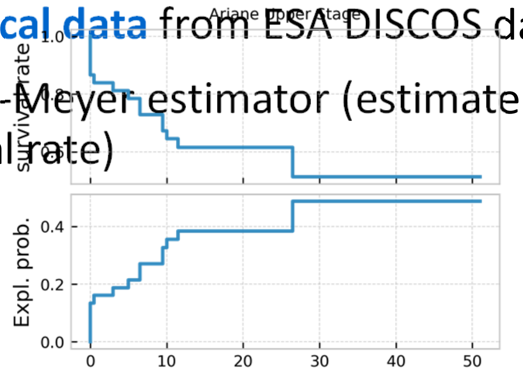

Fig. 4 - Survival rate (above) and explosion probability (below) evolution over time - Kaplan-Meyer.

Fragmentation effects maps

- **Reference objects** from the population of active satellites
- **Density based model** (Starling2.0) to generate artificial fragmentations
- Evaluation of the **cumulative collision probability** over time

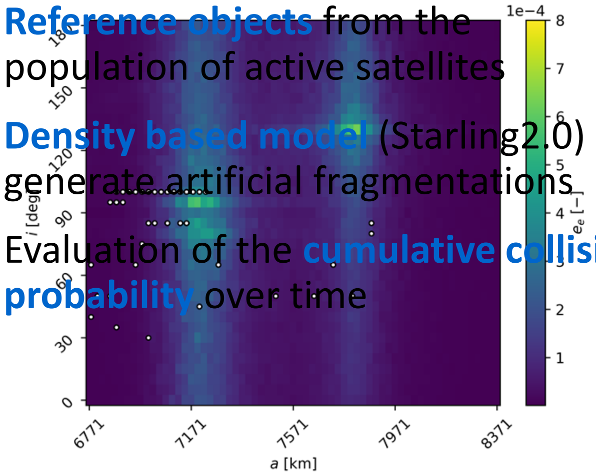

Fig. 5 - Payload explosion effects map - LEO

THEMIS index

Fragmentation effects maps

How we obtain them

- **Active objects** properties from DISCOS
- Definition of **representative targets** on a **grid** in terms of **Keplerian orbital elements** (semi-major axis and inclination for LEO)
- Generation of a **fragmentation** (either an explosion or a collision) in **each cell** of the grid, and **propagation** of the generated **cloud** using a **continuum approach**
- Evaluation of the **cumulative collision probability** between the generated cloud and the representative targets over time
- $e = \frac{1}{A_{TOT}} \sum_{i=1}^{N_t} P_c(t = 15ys) A_i$

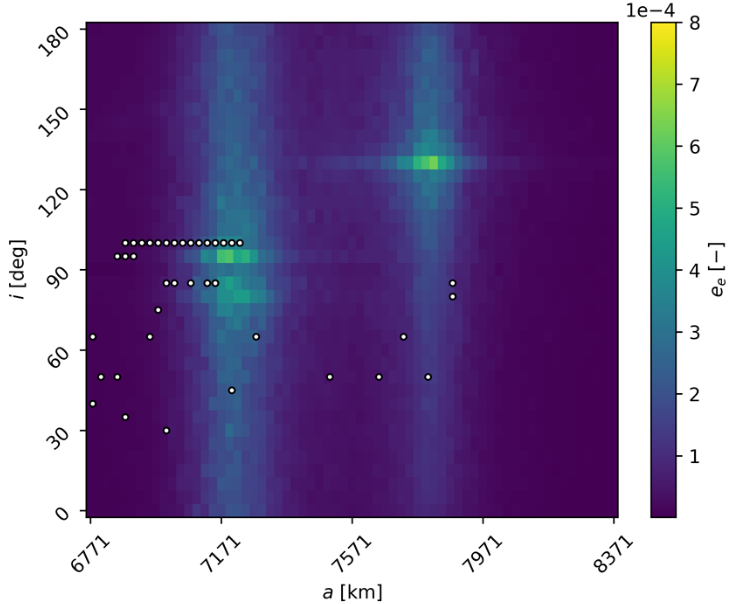

Fig. 6 - Payload explosion effects map (white dots are the representative targets)

- Letizia, F., Colombo, C., Lewis, H. G., & Krag, H. (2016). Assessment of breakup severity on operational satellites. Advances in Space Research, 58(7), 1255-1274
- L. Giudici, M. Trisolini and C. Colombo, "Phase space description of the debris' cloud dynamics through continuum approach," in 73rd International Astronautical Congress, Paris, France, 2022.

Objective 1

FRAGMENTATION MAPS EVOLUTION

Fragmentation maps evolution

- **Investigate** the **influence** of **large constellation** on the **fragmentation maps**
  1. Analyse the **impact** of a single **large constellation** during its **deployment phase**
  2. Analyse the **impact** of the **location** of the **constellation** (in terms of semi-major axis and inclination) when **fully deployed**
- Results in terms of
  - Representative targets selected
  - Location of the peak
  - Value of the peak

Targets and effect maps evolution

Fragmentation effects map – LEO

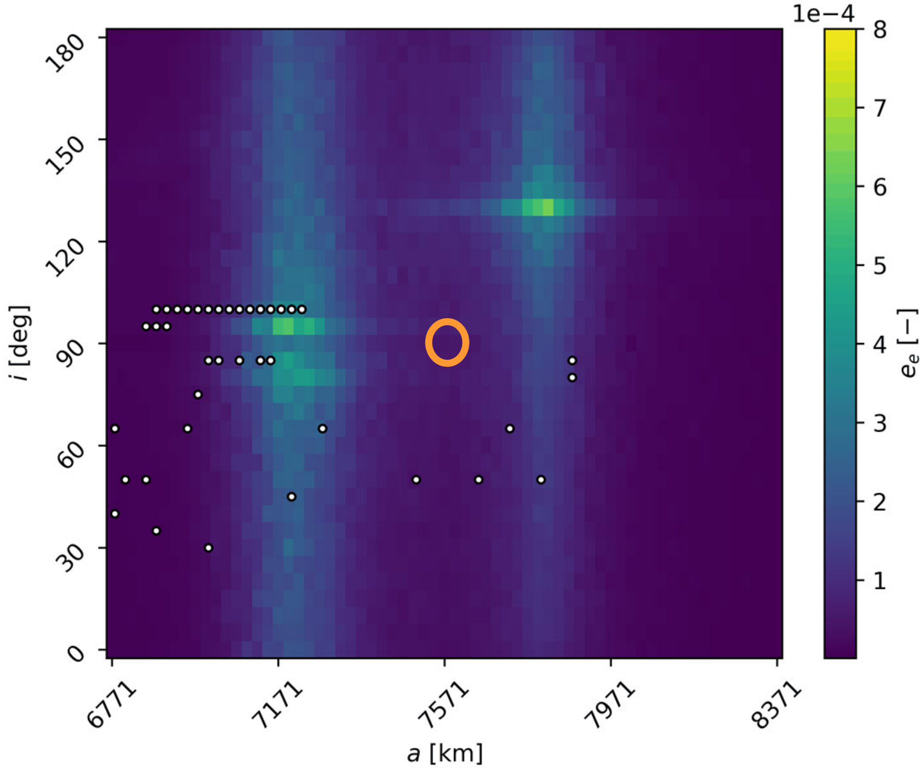

Fig. 7 - Payload explosion effects map evolution with the deployment of the constellation – 1 year snapshot

Constellation parameters

- **Location**
  - Altitude: 1200 km
  - Inclination: 89.7°
- **Satellites physical properties**
  - Mass: 200 kg
  - Area: 5 m^2
- **Deployment plan**
  - 30 satellites per month
  - Fully deployed in 4 years (1440 satellites)

Targets and effect maps evolution

Fragmentation effects map – LEO

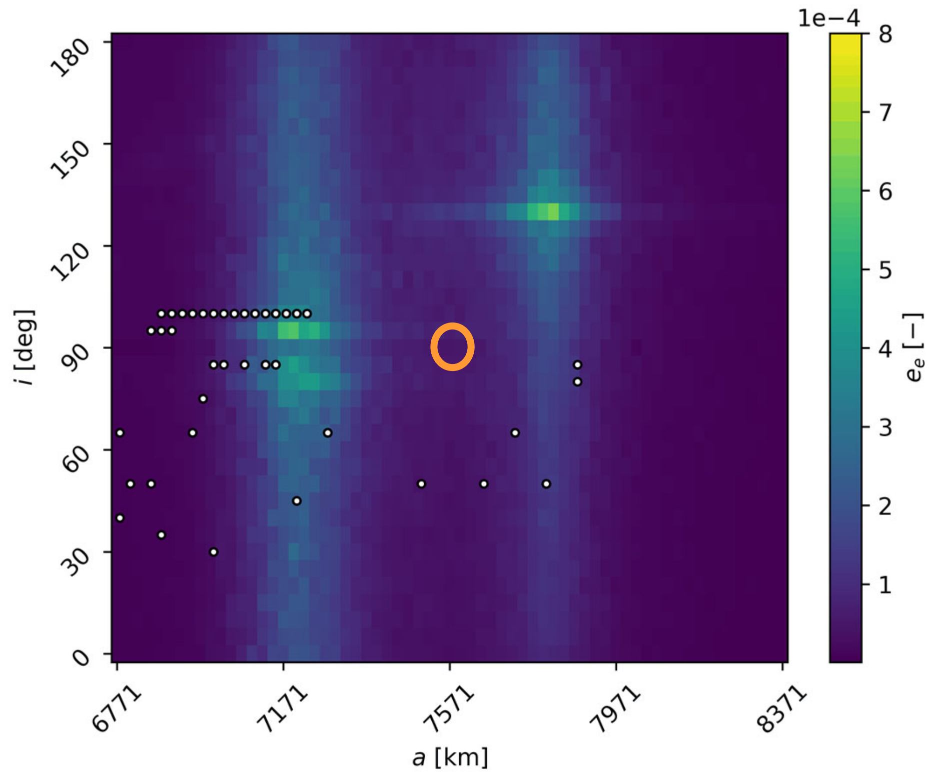

Fig. 7 - Payload explosion effects map evolution with the deployment of the constellation – 1 year snapshot

- Generation of a third vertical band
- Change in peak value
  - Flux distribution
  - Impact velocity between fragments and targets

Targets and effect maps evolution

Constellation different location - LEO

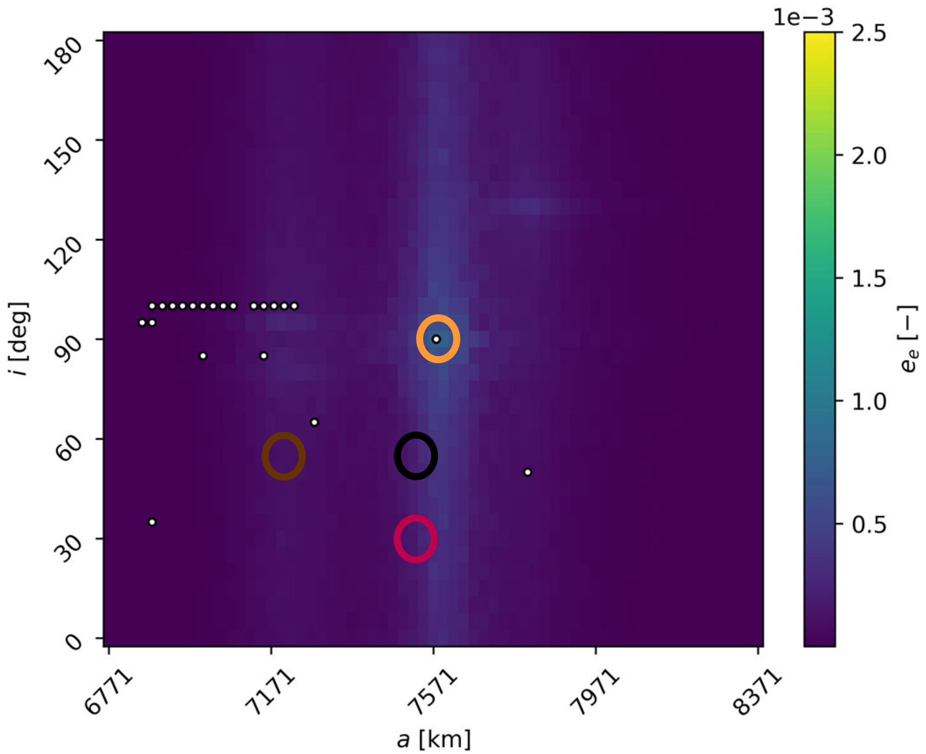

Fig. 8 - Payload explosion effects map according to the location of the constellation – 4 different cases

	Altitude [km]	Inclination [°]
Constellation 1	1200	89.7
Constellation 2	1150	55
Constellation 3	1145	30
Constellation 4	830	55

Number of satellites: 1440

- Peak moves with the constellation
  - Symmetry with respect to 90° of inclination
- Change in peak value
  - Flux distribution
  - Impact velocity between fragments and targets

Objective 2

ENVIRONMENTAL INDEX EVALUATION

Environmental index evaluation

- **Computation** of the **environmental** space debris **index** of
  - 1812 Inactive Payloads
  - 2278 Active Payloads
  - 918 Rocket Bodies
  - 1440 Satellites Constellation (total)
- **Index computed** considering
  - **5 years** (2023 – 2027) to follow the constellation deployment (only one constellation)
  - Each time **new fragmentation effects maps** (to include the constellation) are generated to model a **feedback effect on the constellations** themselves

Index value for objects in LEO

Objects index evolution over time – constellation deployment

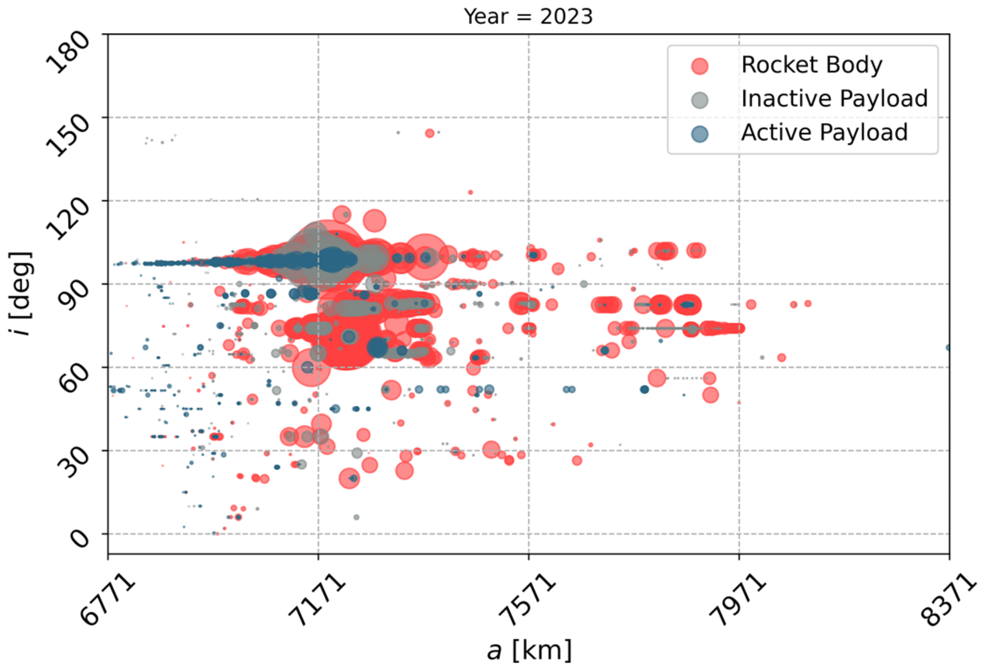

Fig. 9 - Index value for objects in LEO over time – constellation deployment

- Objects distribution in a semi-major axis inclination grid
- Evolution of the index of the objects over time (**marker size** is proportional to the **index of the object**)
- **Constellation** deployment tends to **influence the impact of other missions** on the space environment

Index value for objects in LEO

Distribution of the total index among object categories

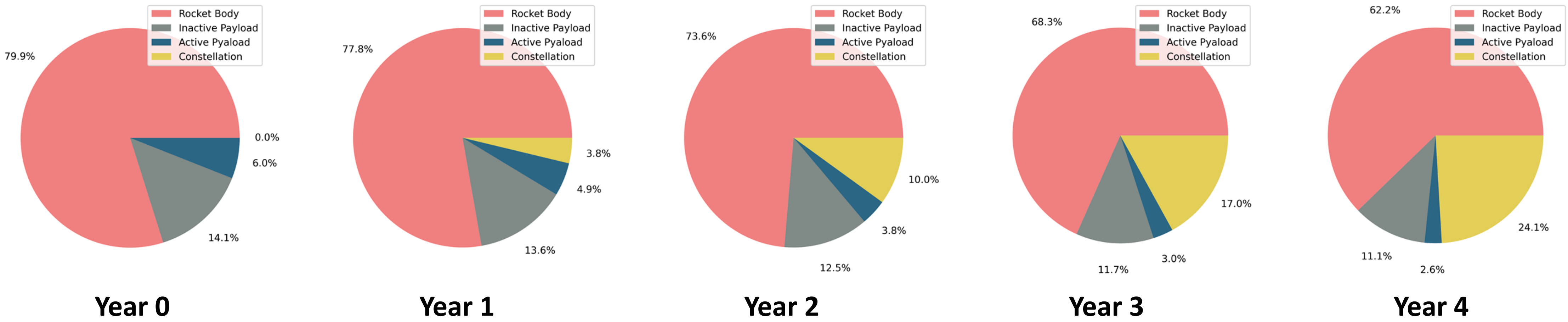

Fig. 10 - Distribution of the total index among object categories over time

Conclusions

- Assessing the impact of all the missions on the space environment is a key task
- Introduction of constellation can generate areas at risk, perhaps precluding the use of other areas different from that of constellation
- Future activities
  - Computation of the index value using other constellations' characteristics
  - Computation of the index value in other orbital regions
  - Further investigation and improvement of the severity term

Managing the space as a resource and driving the definition of mitigation rules is one of the challenges and responsibilities to which as space debris community we are called in the coming years

CREDITS: ISTOCKPHOTO

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