POLITECNICO MILANO 1863

S2-SD-02 Extended Methods for Space Debris Consequence and Space Capacity Analysis

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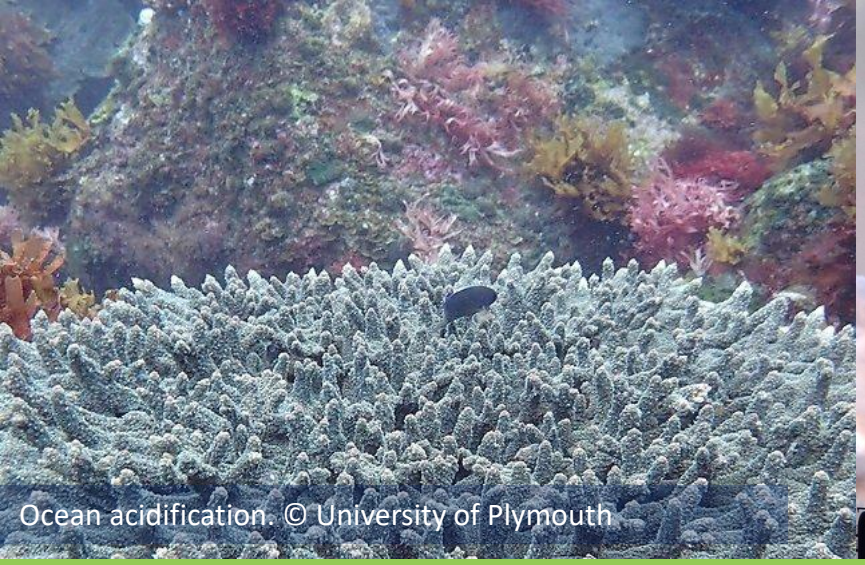
ESA Clean Space Days 2026, 02/07/2026

THEMIS PROJECT



Ocean acidification. © University of Plymouth

CO_2 emission. © Picture alliance/dpa

Amazon rainforest deforestation. © REUTERS/Bruno Kelly

Is the space debris problem as an environmental issue?

Credit background: iStock.com/slavemotion

Space sustainability

Orbital congestion and space debris risk

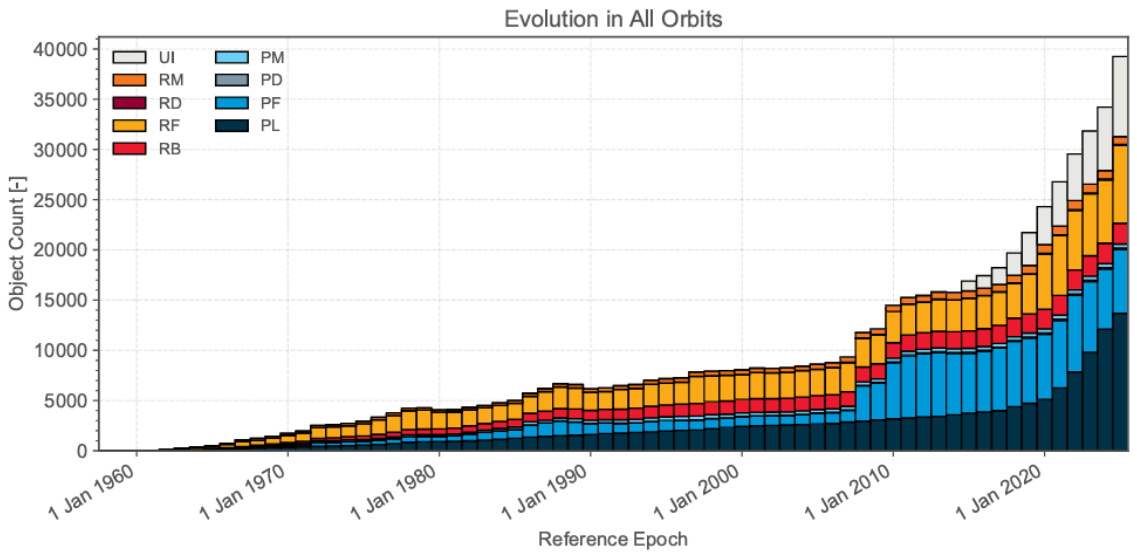


Fig. 1 Time evolution of the number of objects orbiting Earth.

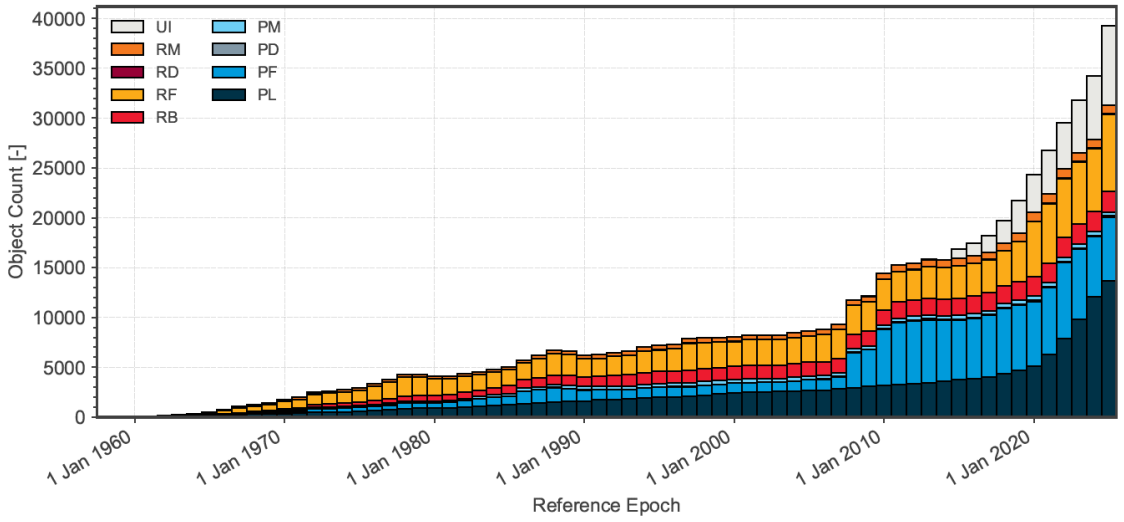
- Launch traffic increase
- Large constellations
- Increased risk of collisions

➢ Source: ESA's Space Environment Report 2024.

Introduction

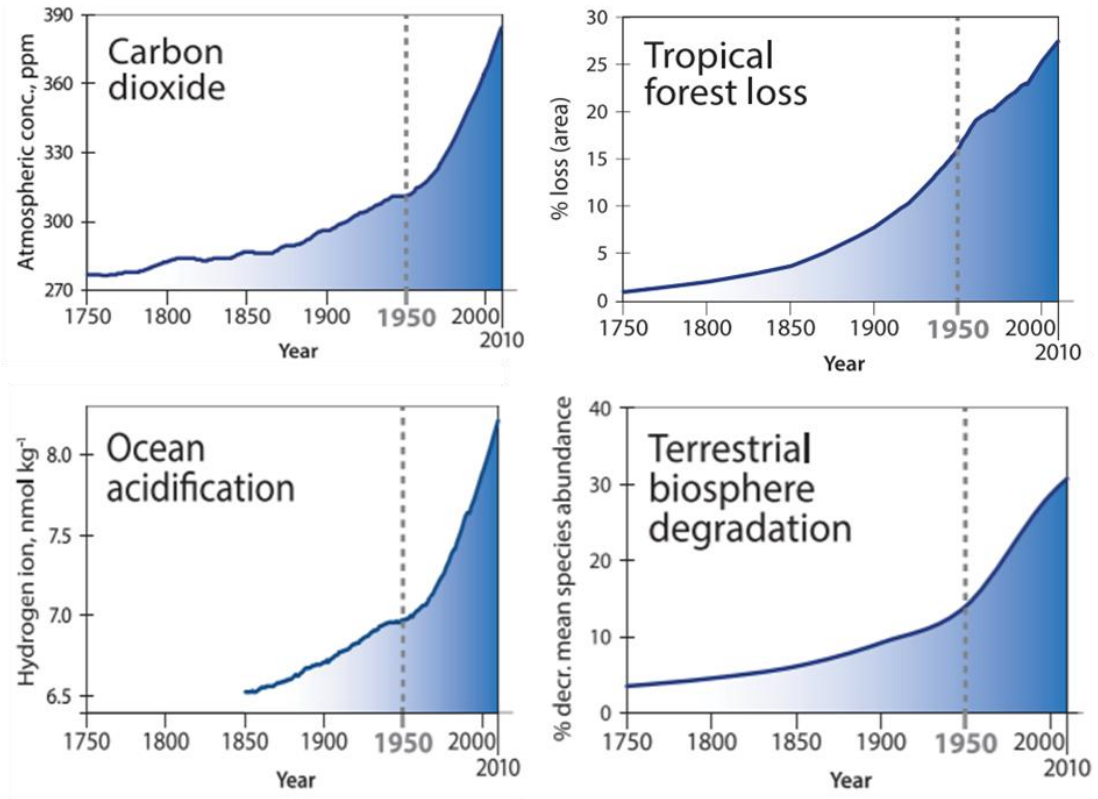
Is the space debris problem as an environmental issue?

Orbital environment trend: space debris tracked by space surveillance networks.



➢ Source: ESA's Space Environment Report 2024.

Earth system trends: environmental stressors



➢ Earth system trends: environmental stressors. Maury T., Loubet P., Trisolini M., Gallice A., Sonnemann G., Colombo C., "Assessing the impact of space debris on orbital resource in Life Cycle Assessment", Science of the Total Environment, 2019.

Introduction

How to measure the contribution to Space missions to the space debris environment

Mission-based indicator approach

Aim

- To assess the impact of a space mission on the space environment based on mission information
- To determine the share of the capacity of Space used by the mission under analysis

Applications

- Support operators in the early phases of mission design trade-off process
- Rank derelict objects for future ADR missions
- Facilitate the environmental evaluation of missions during the licencing process

Space capacity approach

Aim

- To measure the overall space capacity used by orbiting objects
- To analyse possible definitions and thresholds of the space capacity

Applications

- Give an indicator of how the global situation is
- Support the evaluation of future mitigation guidelines

Shall we link the single mission contribution to the global evaluation of the space capacity?

Introduction

How to measure the contribution to Space missions to the space debris environment

Mission-based indicator approach

Aim

- To assess the impact of a space mission on the space environment based on mission information
- To determine the share of the capacity of Space used by the mission under analysis

Why

- How the space traffic management operations are implemented (i.e. CAM, PMD reliability)
- Which debris mitigation are implemented (i.e. PMD, passivation, system reliability)

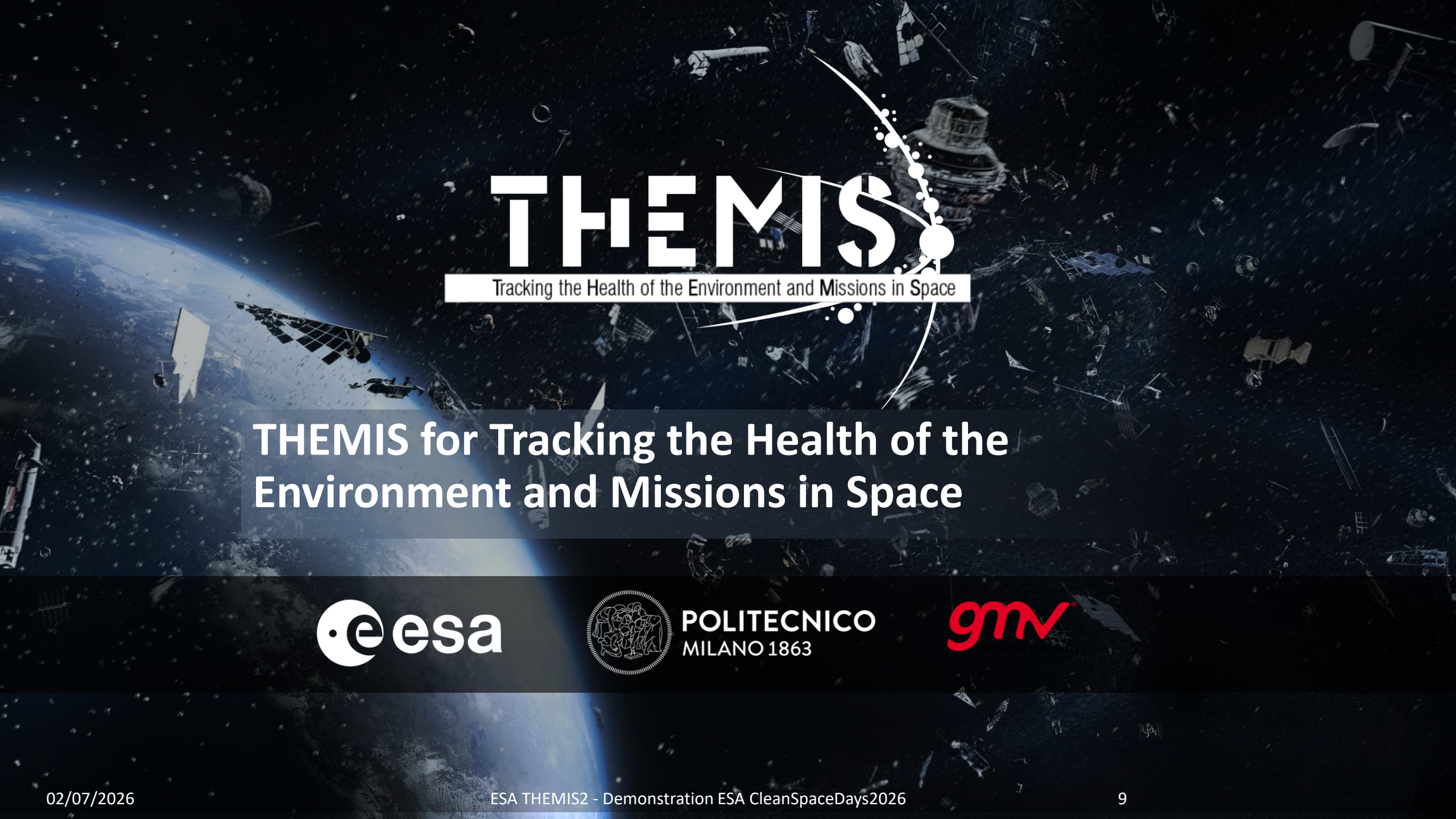
Space capacity approach

Aim

- To measure the overall space capacity used by orbiting objects
- To analyse possible definitions and thresholds of the space capacity

Why

- Harmonise short term space traffic management with long term space sustainability
- Long term evolution depends on single mission contributions



THEMIS for Tracking the Health of the Environment and Missions in Space

THEMIS software tool

Software modes

Space debris mode

to allow different users to assess the impact of a space mission on the space environment based on mission information such as orbit, mass, cross-section, and risk of fragmentation due to accidental collisions or explosions.

to determine the share of the capacity of space used by that mission under analysis.

Space capacity mode

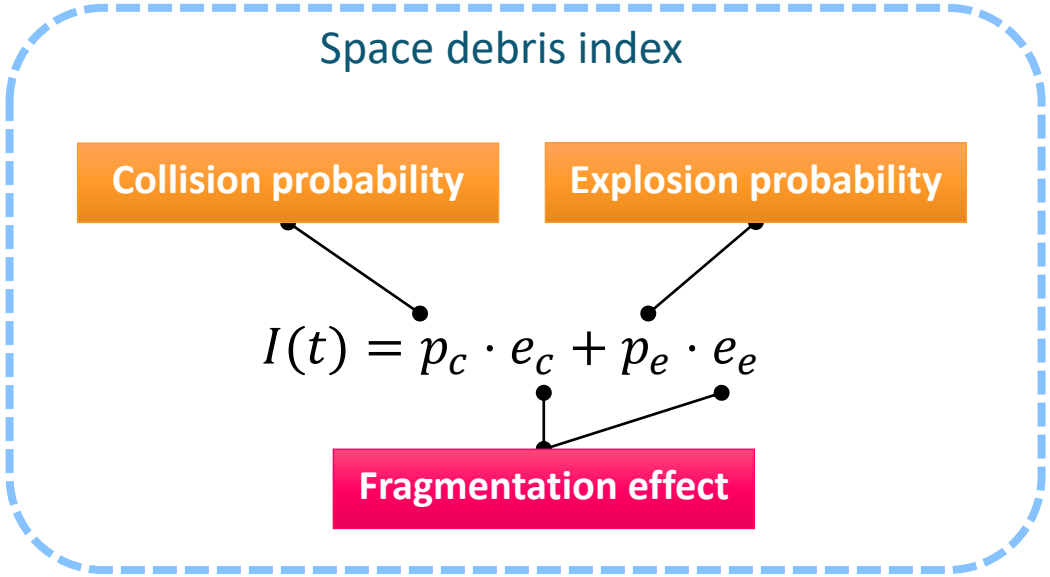
to allow the computation of the overall space capacity used by orbiting spacecraft.

to analyse possible definitions and proxy of the capacity threshold

THEMIS Space debris index

How to measure the impact of a space mission on the space environment?

ECOB formulation index to assess the risk = probability x severity



p = probability
e = effects (severity)

- Letizia F., Colombo C., Lewis H.G., Krag H., "Extending the ECOB Space Debris Index with Fragmentation Risk Estimation", 7th European Conference on Space Debris, ESA/ESOC, Darmstadt, Germany, 18-21 Apr. 2017.
- Colombo C., Muciaccia A., Giudici L., Gonzalo J.L., Masat A., Trisolini M., Del Campo B., Letizia L., Lemmens S., "Tracking the health of the space debris environment with THEMIS", Aerospace Europe Conference 2023, 10th EUCASS – 9th CEAS, July 2023.ù

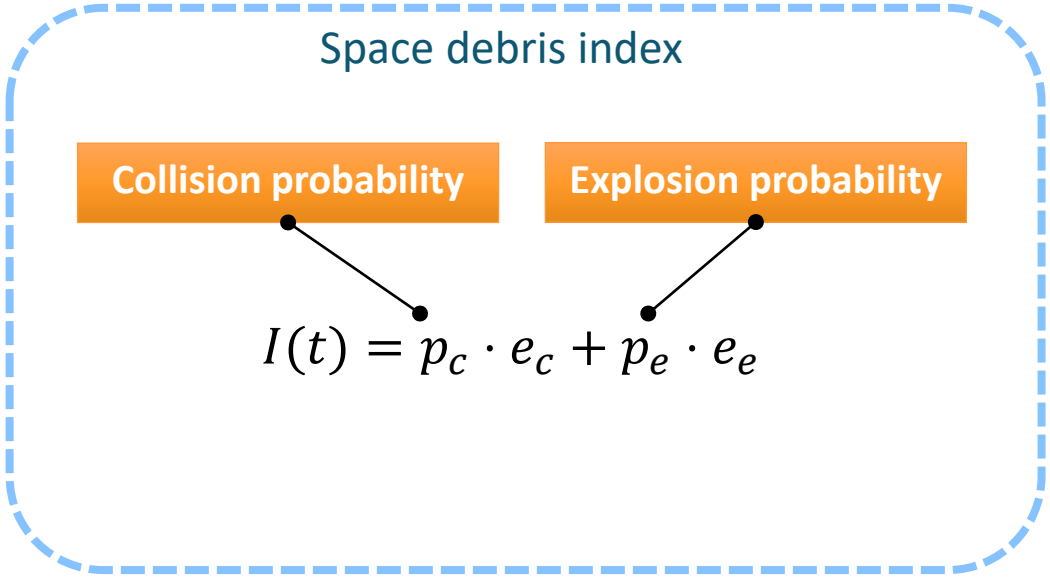
THEMIS Space debris index

Causes: collision and explosion probability

ECOB formulation index to assess the risk = probability x severity

Collision probability:
Probability of an object to collide with the debris population while in orbit during the mission lifetime

- Computed from debris flux and impact velocities from MASTER
- Considers the capability of a spacecraft to perform CAM (i.e. avoid trackable debris objects → reduced collision risk computed with ARES)



Explosion probability:
Probability of an object to explode while in orbit during the mission lifetime

- Estimated statistically from DISCOS historical data using the Kaplan-Meier estimator

➢ Colombo C., Muciaccia A., Giudici L., Gonzalo J.L., Masat A., Trisolini M., Del Campo B., Letizia L., Lemmens S., "Tracking the health of the space debris environment with THEMIS", Aerospace Europe Conference 2023, 10th EUCASS – 9th CEAS, July 2023.ù

THEMIS Space debris index

Effects: collision risk caused on active spacecraft population

ECOB formulation index to assess the risk = probability x severity

Collision probability:
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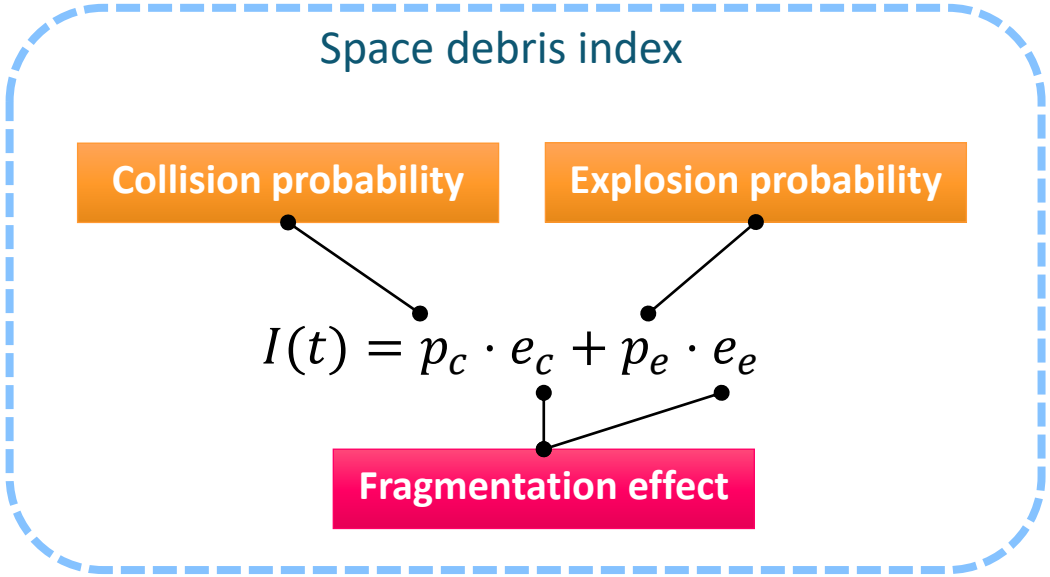

Explosion probability:
Probability of an object to explode while in orbit during the mission lifetime

- Estimated statistically from DISCOS historical data using the Kaplan-Meier estimator

Fragmentation effect:
When an object fragment in orbit all the active population of object is affected by the generated debris cloud.

➢ Colombo C., Muciaccia A., Giudici L., Gonzalo J.L., Masat A., Trisolini M., Del Campo B., Letizia L., Lemmens S., "Tracking the health of the space debris environment with THEMIS", Aerospace Europe Conference 2023, 10th EUCASS – 9th CEAS, July 2023.ù

THEMIS Space debris index

Effects: collision risk caused on active spacecraft population

Cloud evolution in physical space

Fragmentation effect:

When an object fragments in an **orbital slot**, the entire population of **active objects** is affected by the generated debris cloud as:

- A debris cloud is generated and **reaches in time different orbital slots**
- This causes an increased operational effort due to an **increased collision risk**

THEMIS Space debris index

Effects: collision risk caused on active spacecraft population

Cloud evolution in physical space

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When an object fragments in an **orbital slot**, the entire population of **active objects** is affected by the generated debris cloud as:

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Computation

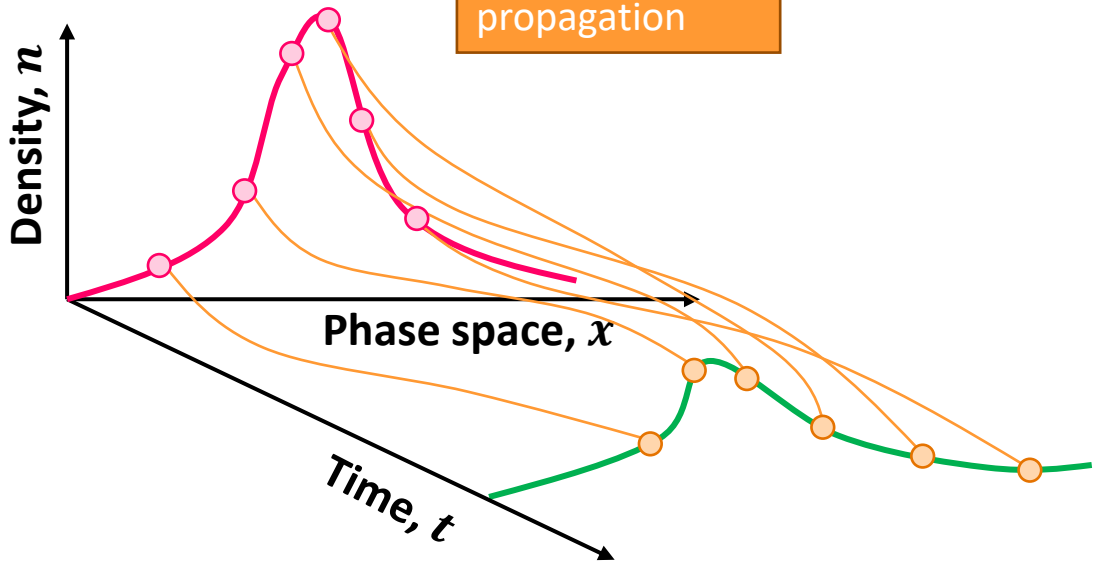
3. Simulation of **breakup event** (collision or explosion) for each cell of the grid
4. Fragments' **cloud propagation** for **user-defined period (e.g. 15 years)**
5. Evaluation of **cumulative collision probability** with target objects representative of the active satellites

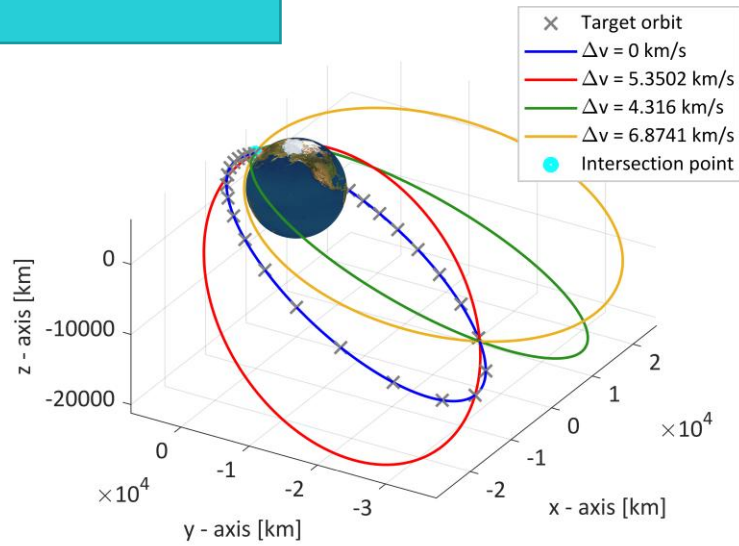
Cloud propagation and collision risk estimation

Starling method

1. Density distribution in orbital elements and area-to-mass ratio at fragmentation epoch
2. Density distribution in orbital elements and area-to-mass ratio over time
3. Impact rate and collision probability between the debris' cloud and given target objects

NASA Standard Breakup model in probabilistic terms → Fragment density propagation → Collision risk estimation

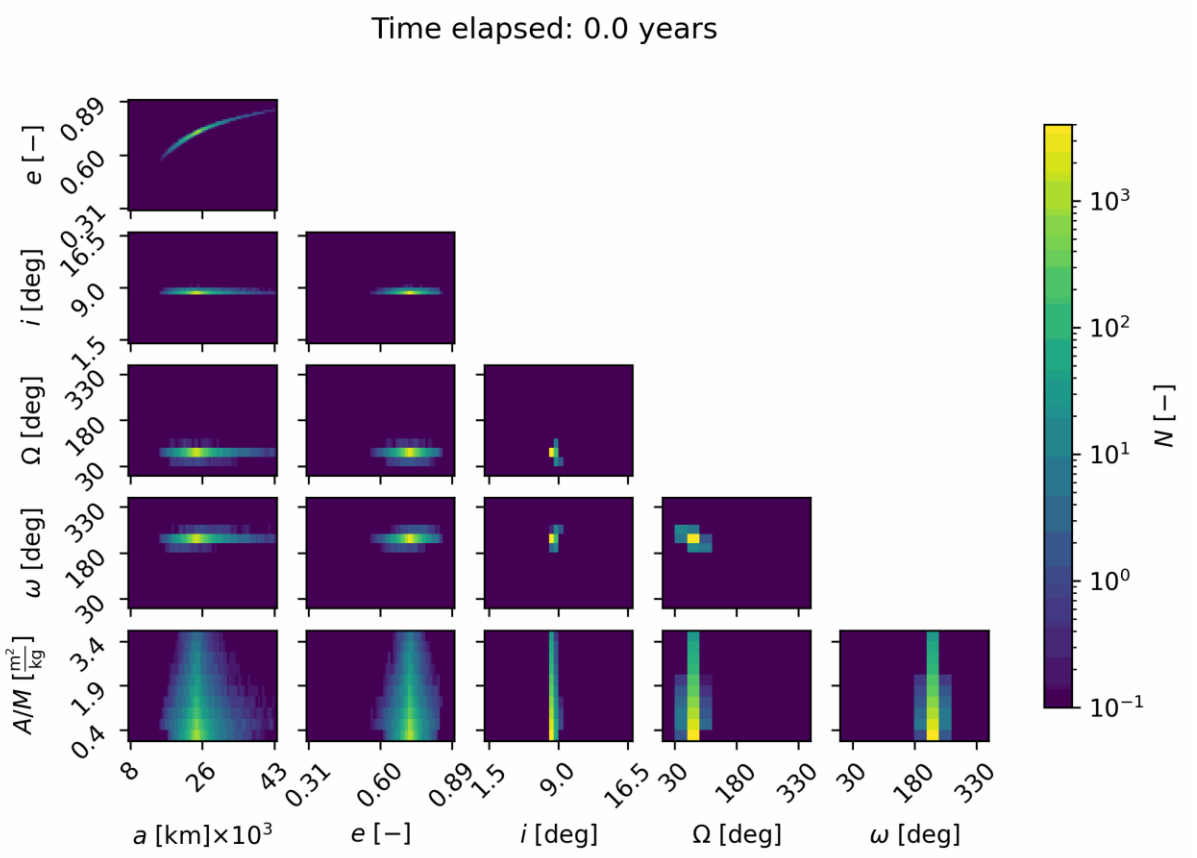




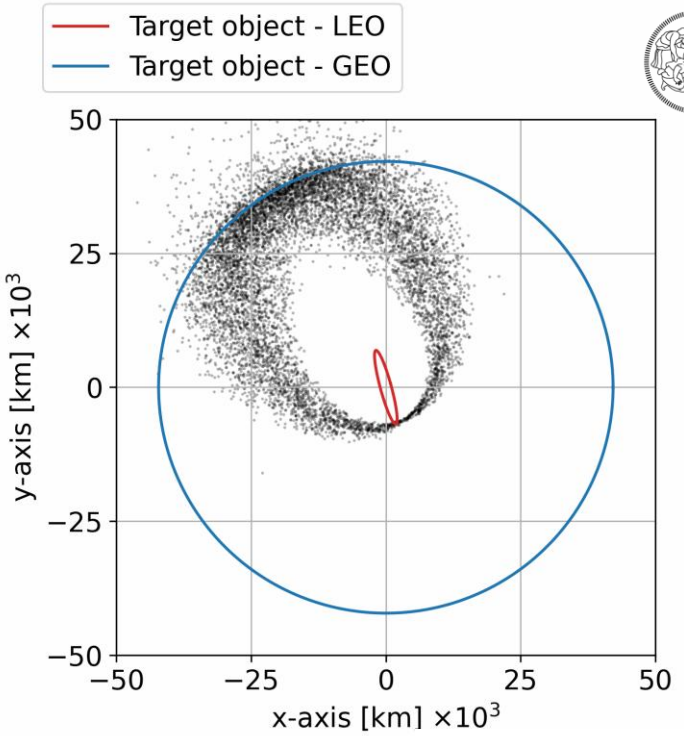
- Frey S., Colombo C., Transformation of satellite breakup distribution for probabilistic orbital collision hazard analysis, Journal of Guidance, Control, and Dynamics, 2021.
- Giudici L., Trisolini M., Colombo C., Probabilistic multi-dimensional debris cloud propagation subject to non-linear dynamics, Advances in Space Research, 2023.
- Giudici L., Gonzalo J. L., Colombo C., Density-based in-orbit collision risk model extension to any impact geometry, Acta Astronautica, 2024.

Fragmentation modelling

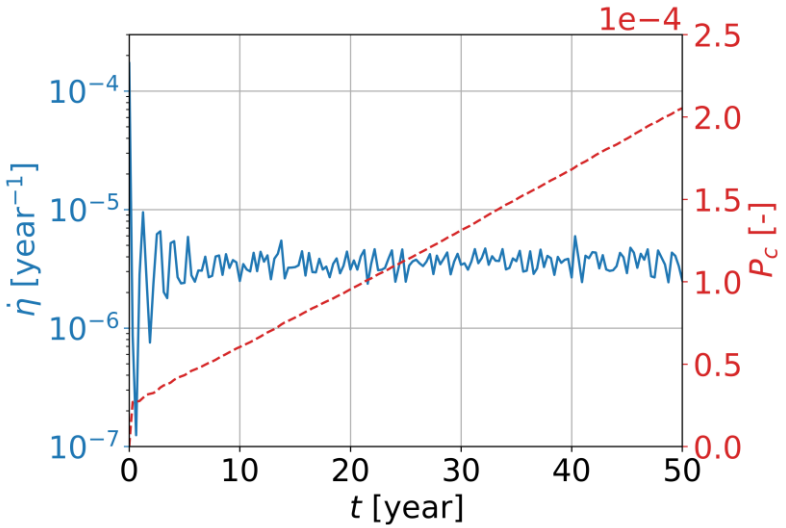
Long-term cloud evolution and effect



Density distribution over time.
Ariane 2 third-stage fragmentation in GTO



Cloud evolution in physical space



Collision probability with LEO satellite

THEMIS Space debris index

Effects: collision risk caused on active spacecraft population

Cloud evolution in physical space

Fragmentation effect:

When an object fragments in an **orbital slot**, the entire population of **active objects** is affected by the generated debris cloud as:

- A debris cloud is generated and **reaches in time different orbital slots**
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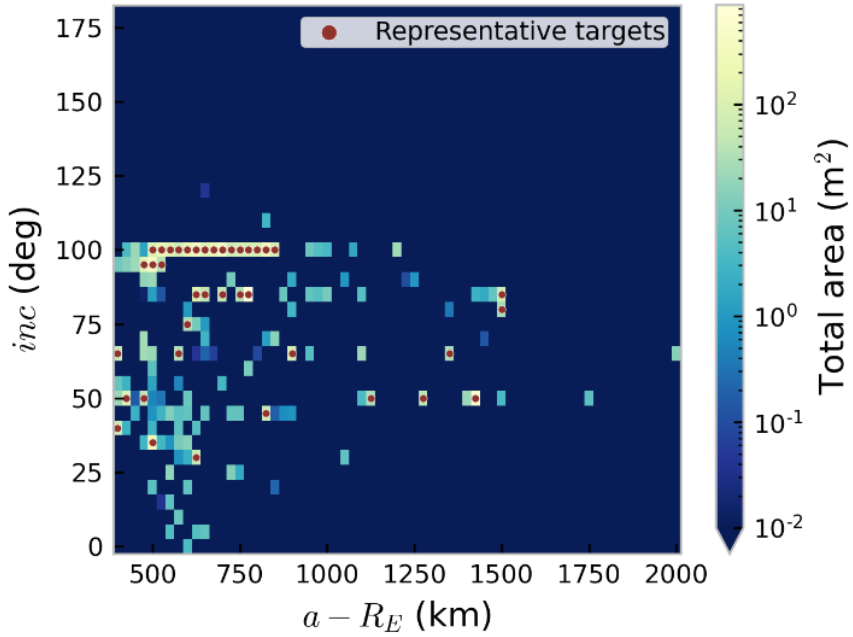


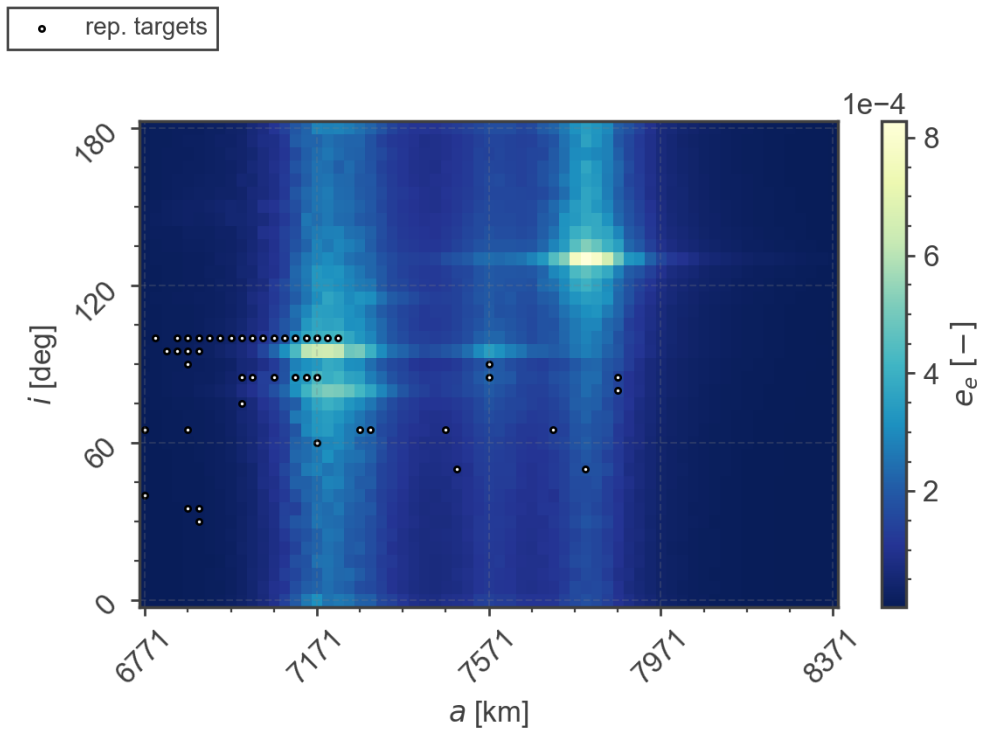
Representative targets in low-Earth orbit

THEMIS Space debris index

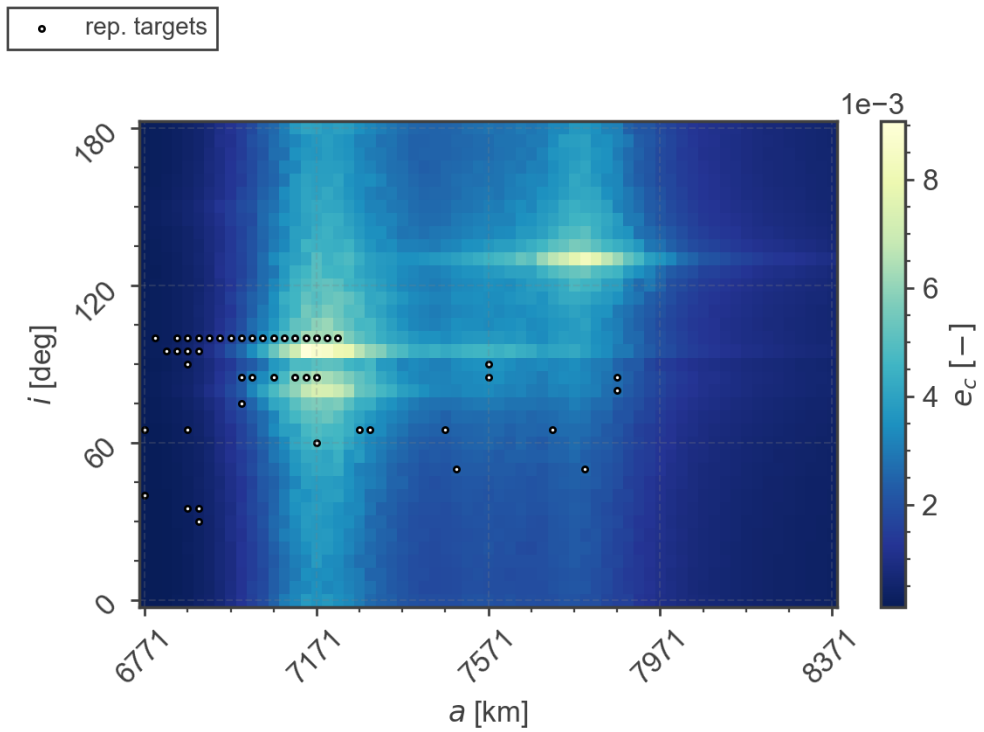
Fragmentation effect maps in LEO

- Effects map in LEO is formulated in semi-major axis a and inclination i
- Impact of a fragmentation in LEO is evaluated against LEO active satellites population

Explosions effects map



Catastrophic collisions effects map



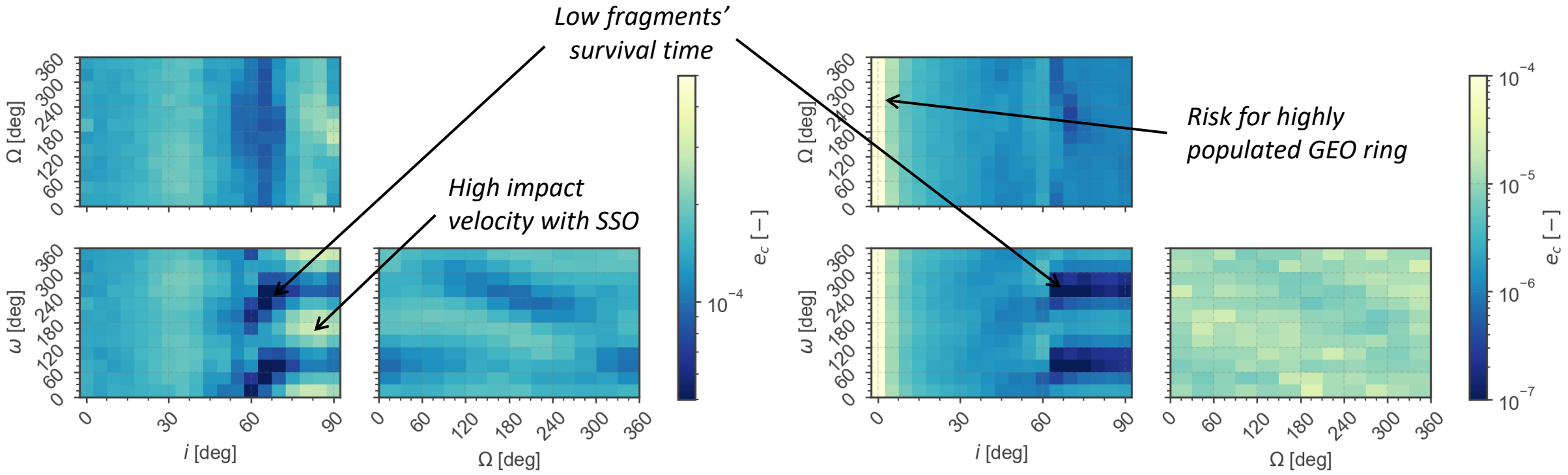
THEMIS Space debris index

Fragmentation effect maps in GTO

- Effects map in GTO is formulated in the three angular elements (i, Ω, ω)
- Impact of a fragmentation in GTO is evaluated against LEO and GEO protected regions

Effect on LEO active satellites

Effect on GEO active satellites



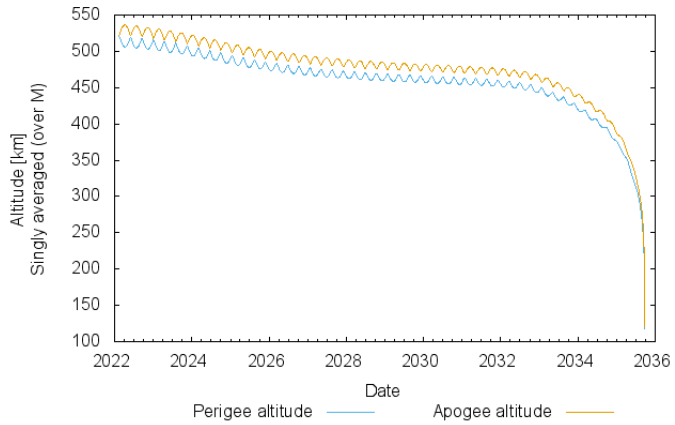
THEMIS Space debris index

Mission profile

DRAMA

OSCAR

- **Disposal scenarios**



Space debris index

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

Operational phase

Post mission disposal

Reliability of the PMD

t_{end} = epoch at which the disposal ends

t_f = epoch at which the object would naturally decay from its initial orbit

➢ 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.

THEMIS Space debris index

Mission profile

THEMIS frontend

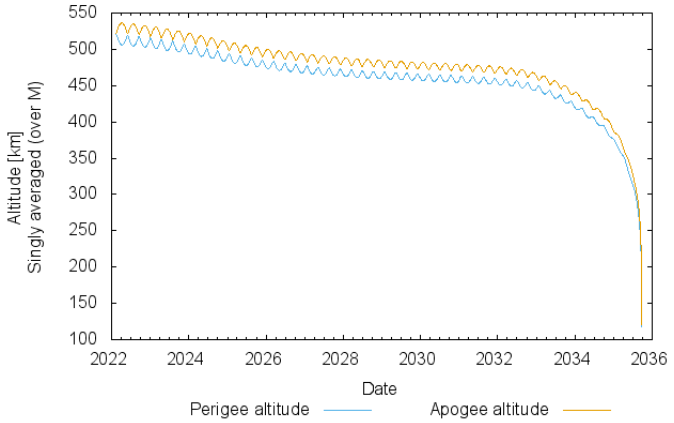
Web GUI

- Disposal scenarios
- Mission phases
- Spacecraft parameters

DRAMA

OSCAR

- **Disposal scenarios**



Space debris index

$$I = \underbrace{\int_{t_0}^{t_{EOL}} I(t)dt}_{\text{Operational phase}} + \alpha \cdot \underbrace{\int_{t_{EOL}}^{t_{end}} I(t)dt + (1-\alpha) \cdot \int_{t_{EOL}}^{t_f} I(t)dt}_{\text{Post mission disposal}}$$

Reliability of the PMD

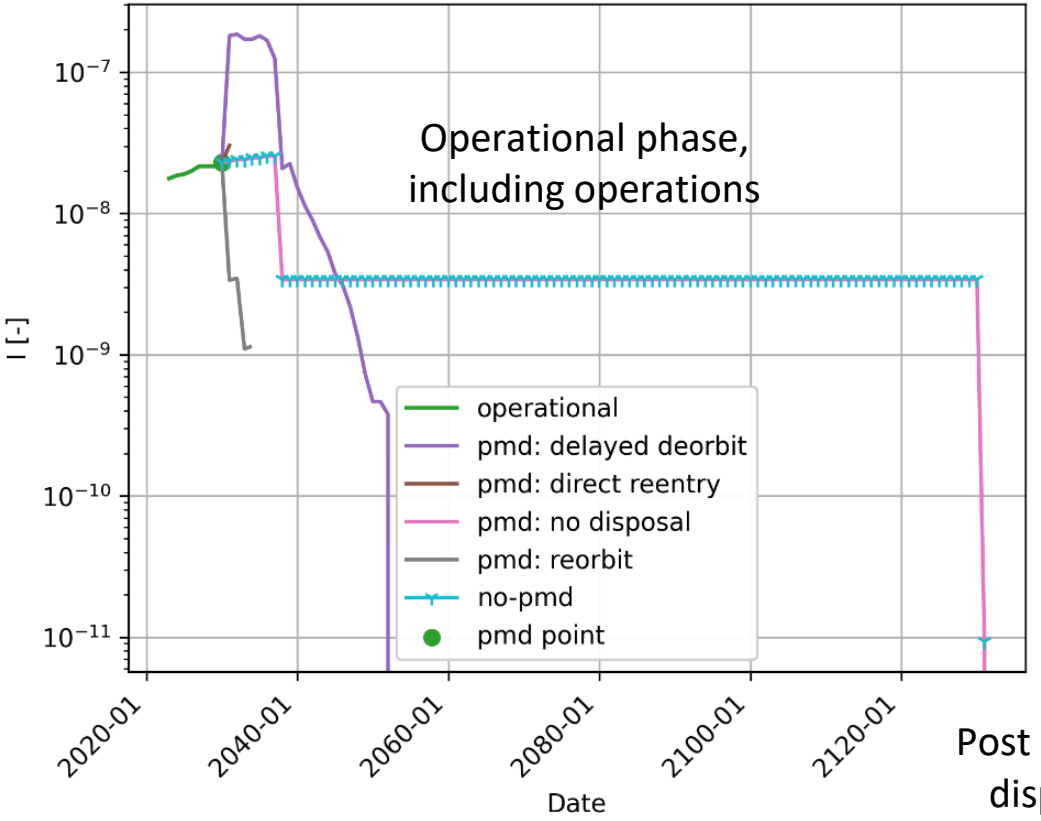
tend = epoch at which the disposal ends

tf = epoch at which the object would naturally decay from its initial orbit

➢ 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.

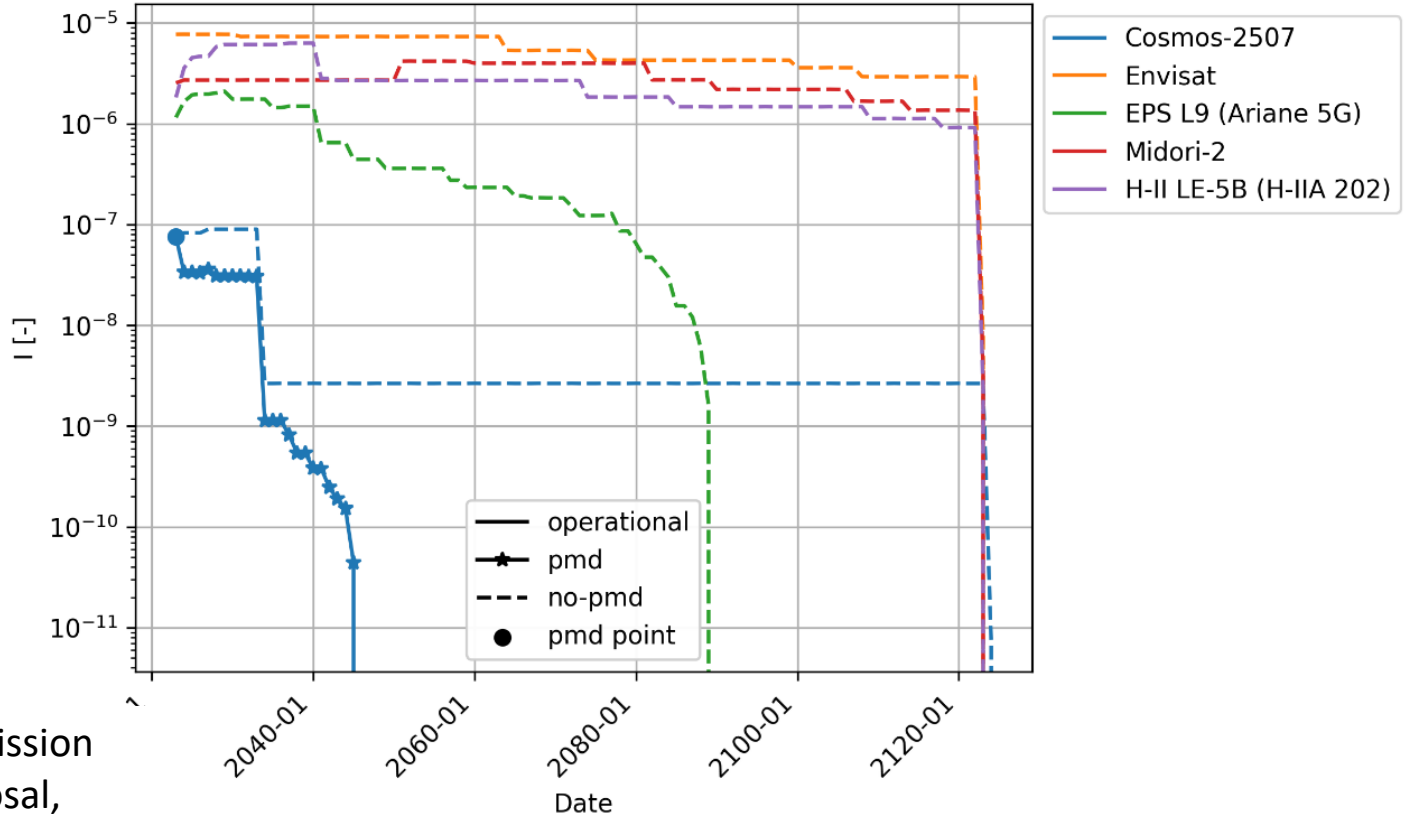
THEMIS Space debris index

Example



Index profile for a single OneWeb satellite considering several disposal options

Post mission disposal, including failures



Index evolution for different missions in LEO

Colombo C., Muciaccia M., Giudici L., Gonzalo J. L., Masat A., Trisolini M., del Campo B., Letizia F., Lemmens F. "Tracking the health of the space debris environment with THEMIS, EUCASS-CEAS Conference 2023, 9-13 Jul. 2023, Lausanne.

THEMIS software tool

THEMIS frontend

To analyse missions and their impact

To have an overview of the overall status of the space environment

For **registered users** to submit user-defined mission for evaluation of its environmental impact both in terms of index and capacity consumption

For **operators** to declare new missions' profiles

THEMIS backend

Computation of the environmental index:

- Create and propagate a mission profile
- Compute the collision probability
- Compute the explosion probability
- Determine the collision effect
- Determine the explosion effect
- Interface with ESA tools

Computation of the space capacity:

- Long-term propagation using ESA DELTA
- Compute the available capacity of the space environment

THEMIS for Tracking the Health of the Environment and Missions in Space

Debris risk metric:

- Collision/explosion probability
  - Orbit
  - Cross-area
  - CAM reliability
  - PMD
  - Failures
  - Fragment trackability
- Effects
  - Orbital region where the possible fragmentation takes place
  - Mass
  - Positions and area of other active spacecraft
  - Relative orbit geometries

Debris risk metrics can be used to quantitively assess the debris-generating impact of a space missions for several applications:

Mission design

Impact of a space mission on the space environment based on mission information

Capacity evaluation

Aggregate over all objects in the population to measure the orbital capacity

Mitigation guideline

Drive de definition of mitigation guidelines

Licence procedure

Could be integrated into licencing process (e.g. ITU)

Insurance evaluation

Depending on the orbital slot the risk is very different

Colombo C., Muciaccia M., Giudici L., Gonzalo J. L., Masat A., Trisolini M., del Campo B., Letizia F., Lemmens F. “Tracking the health of the space debris environment with THEMIS, EUCASS-CEAS Conference 2023, 9-13 Jul. 2023, Lausanne.

Space sustainability

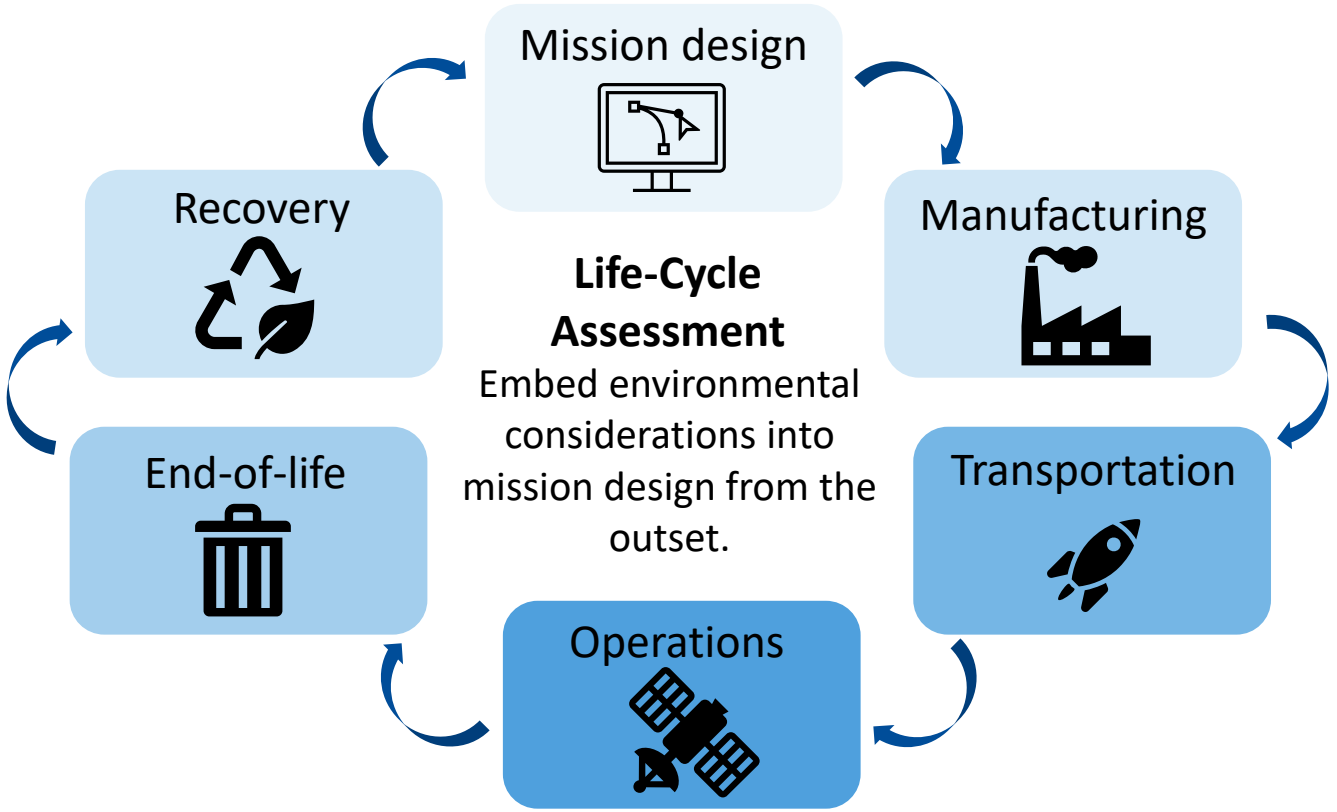
Environmental issue

Environmental issue

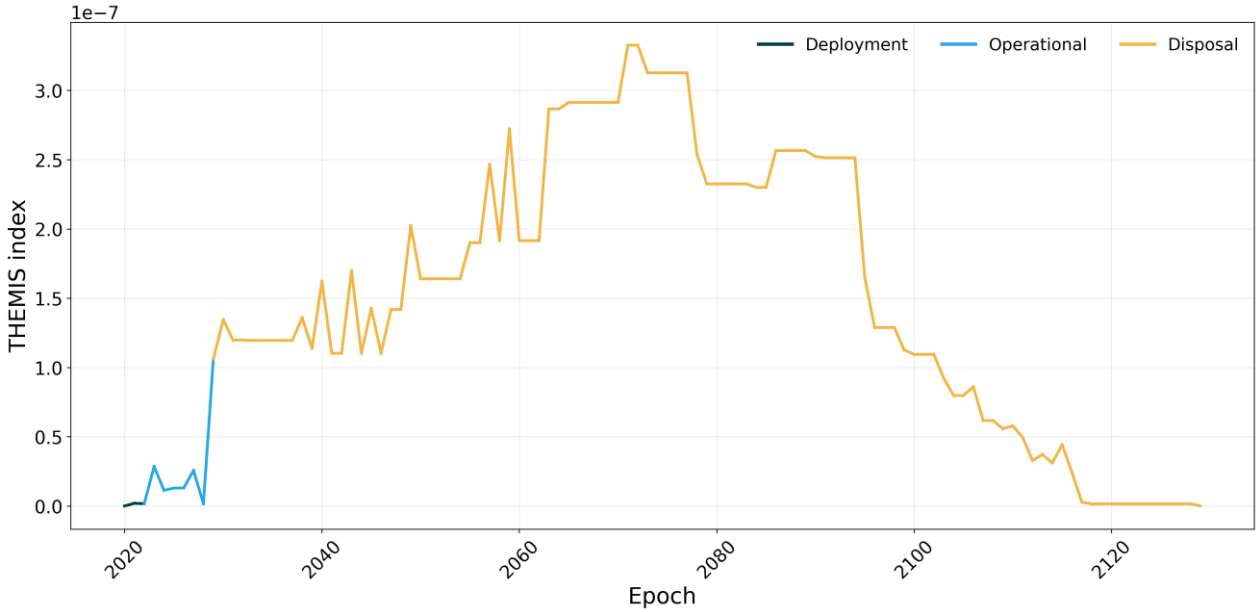
Need for a more sustainable approach to space operations, one that embeds environmental considerations, such as end-of-life disposal, into mission design from the outset.

Environmental footprint indicators

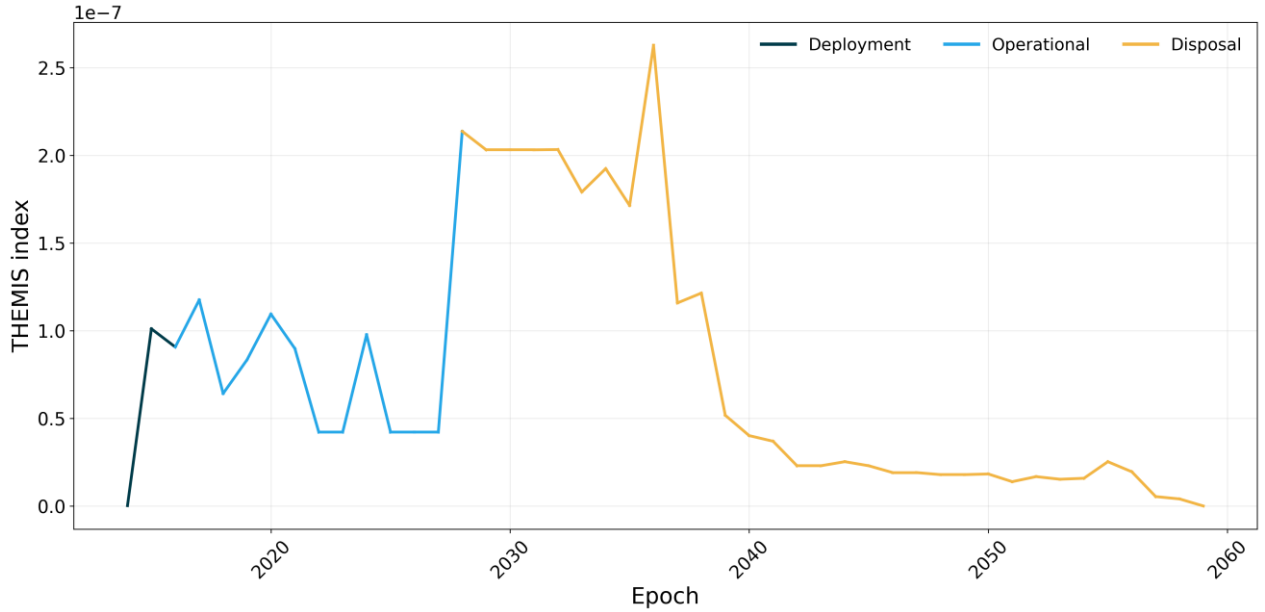
Quantify life-cycle environmental impact of missions and assess the broader state of the space environment.



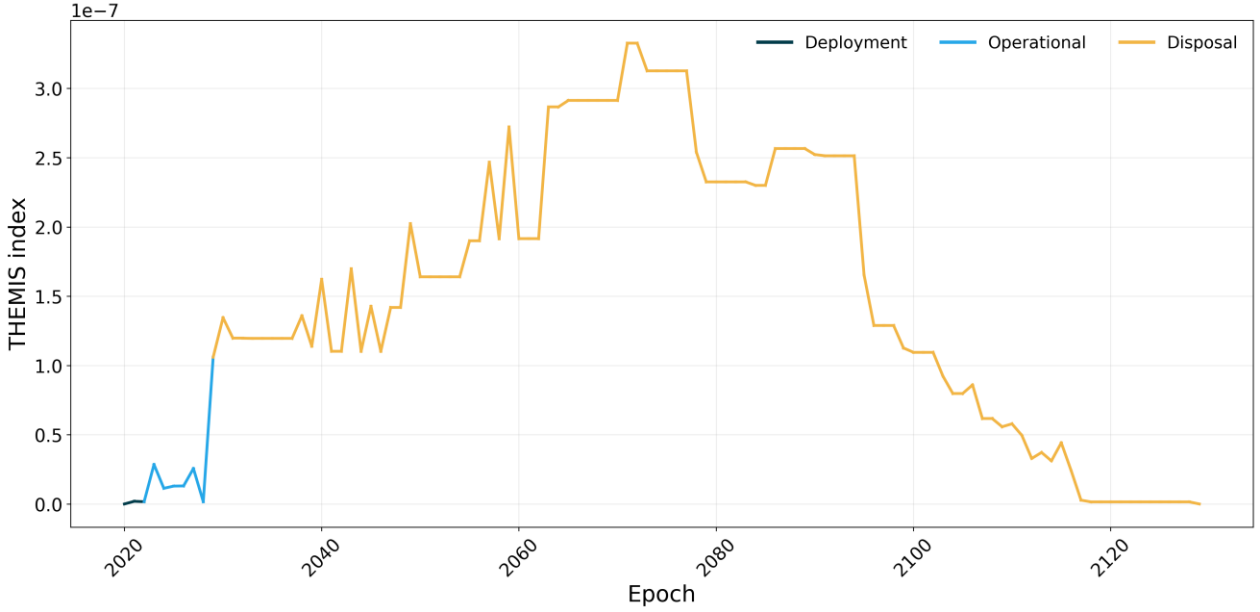
SENTINEL-6A



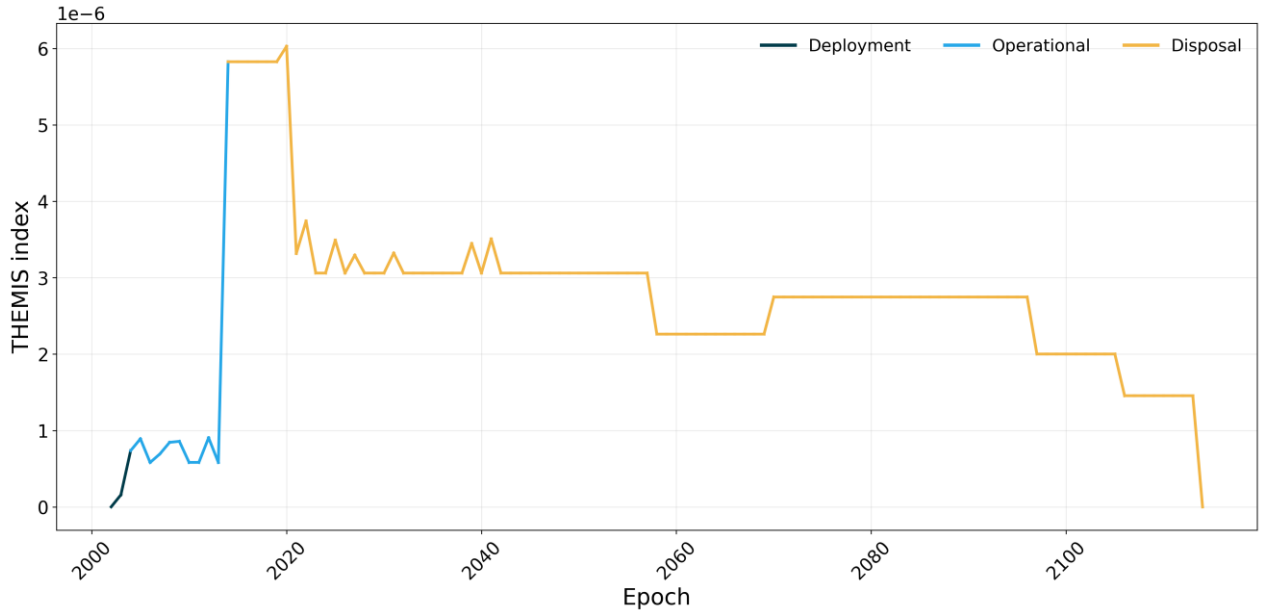
SENTINEL-1A



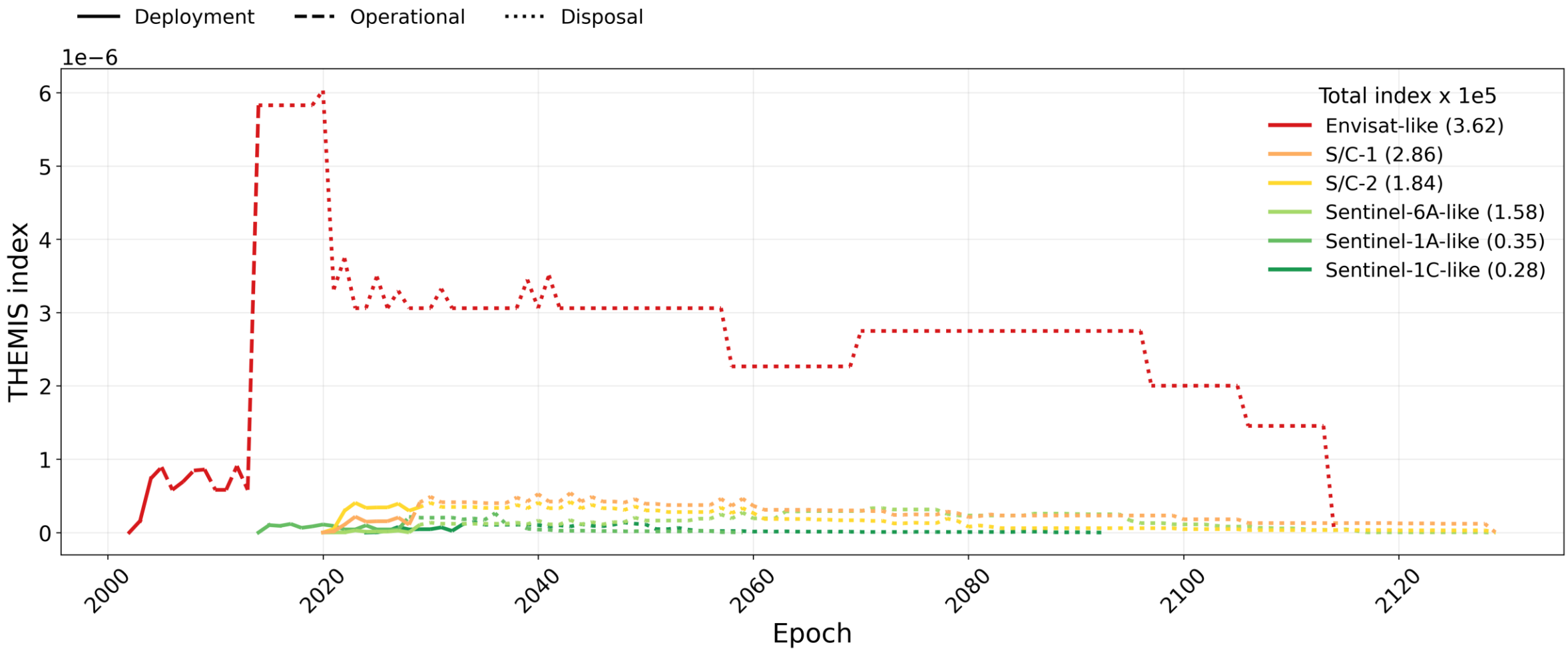
SENTINEL-1C



ENVISAT



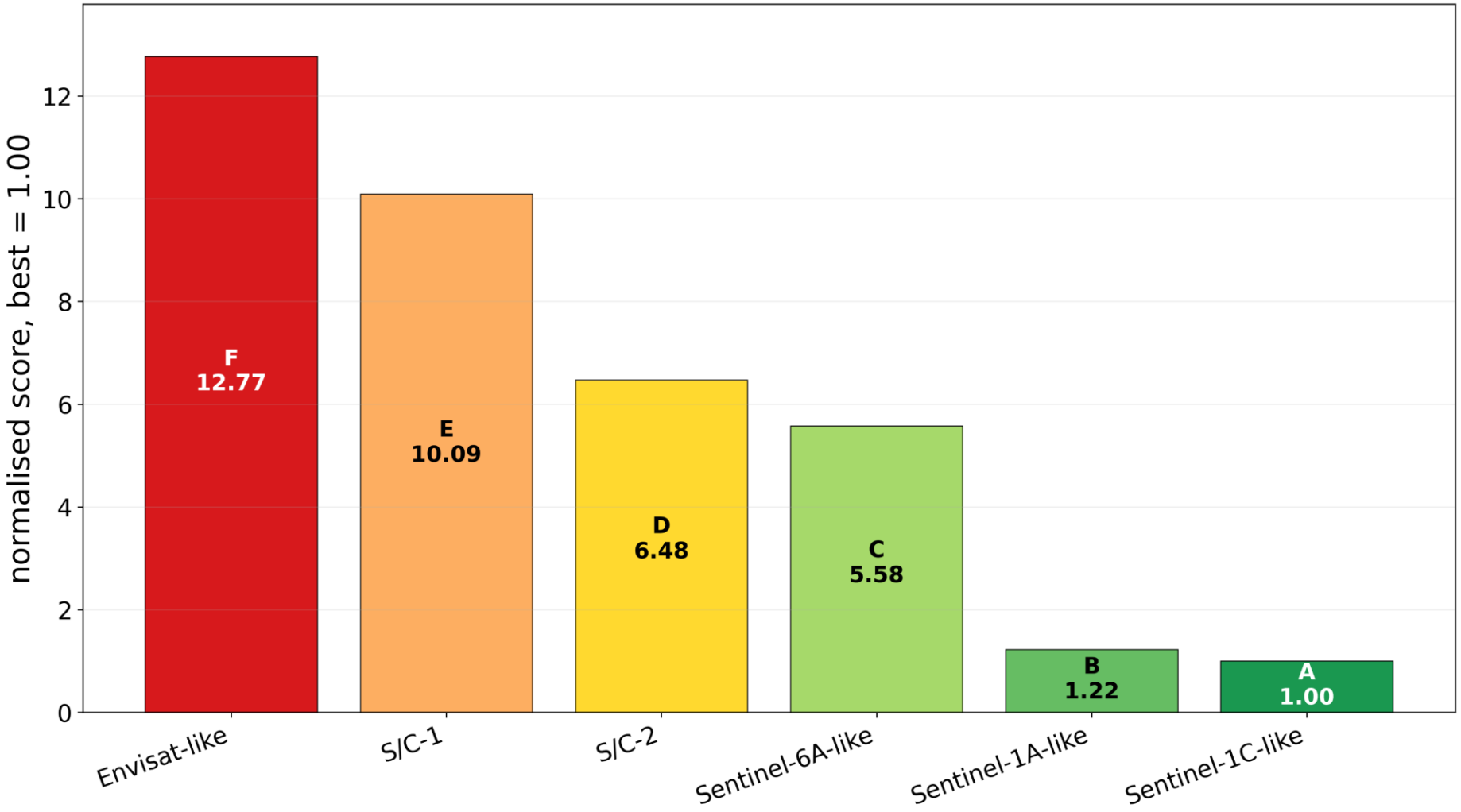
Space debris risk evaluation could be included in LCA assessment of space mission for in-orbit phase assessment
!Example only!



Toward space mission labelling

Normalised index score

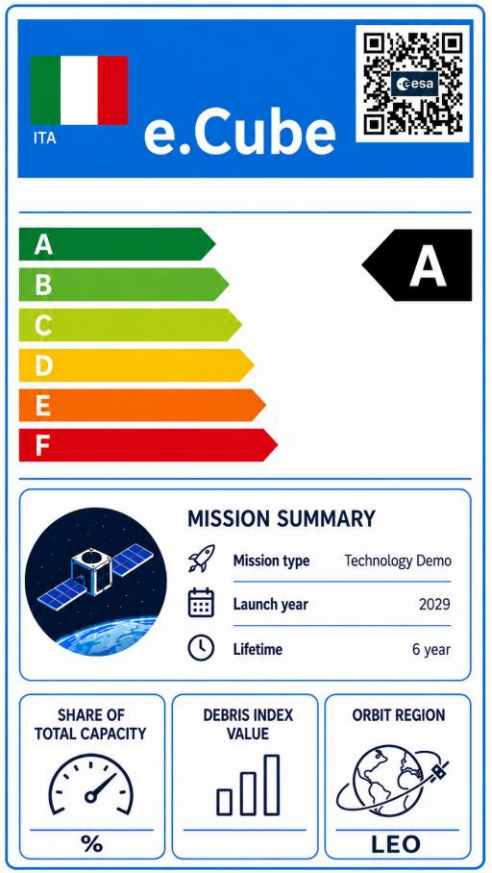
$I_{tot,THEMIS} = I_{tot,THEMIS}/I_{min}$, where I_{min} is relative to the mission with lowest environmental impact.



Towards spacecraft labelling

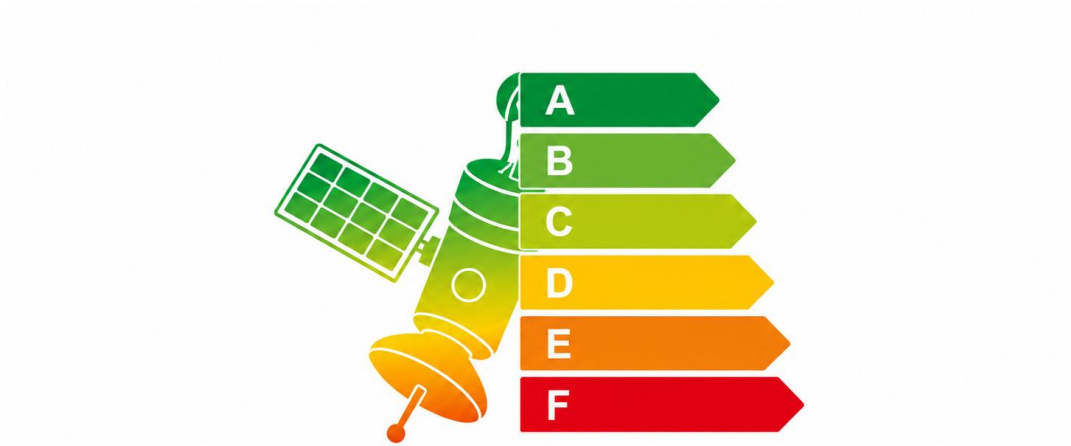
Proposed Space Label for the e.Cube mission

The label class is derived from the normalized THEMIS total index score. Additional elements: mission-level information such as capacity share, debris index, orbit region, mission details, and a QR code to the THEMIS front-end.



Simplified Space Label concept

The simplified version shows a proof-of-concept A–F classification scale based on the normalized THEMIS total index score. The displayed thresholds are illustrative and should not be interpreted as definitive classification boundaries.



A	B	C	D	E	F
<=1	<=3	<=6	<=9	<=11	>=12

Space sustainability

Environmental issue

Light pollution indicator [1]

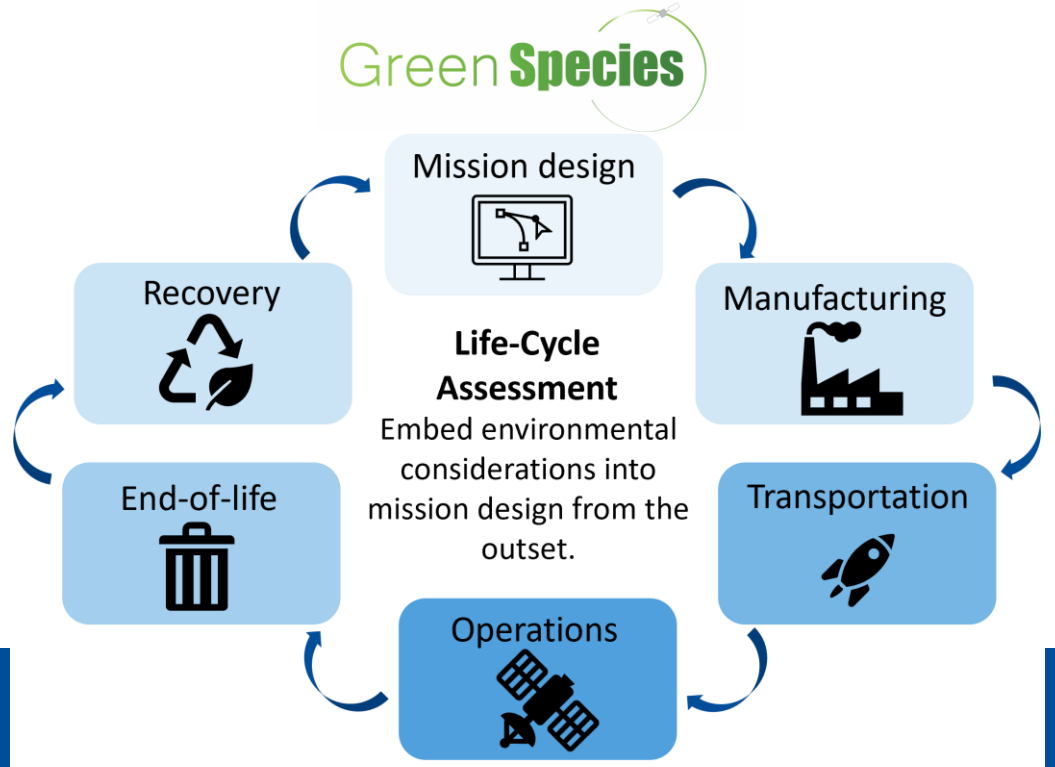
Space debris indicator for in-orbit segment [3]

Orbital resource use [2]

Casualty risk at re-entry [2]

Social benefit of a mission [4]

Atmosphere pollution for re-entry



1. Gerardo Littoriano, Camilla Colombo, Alessandro Nastasi, Carmelo Falco, “Modelling of spacecraft apparent brightness A study on OneWeb constellation satellites”, Advances in Space Research, Vol. 74, Issue 3, 2024, pp. 1392-1409, ISSN 0273-1177
2. Colombo, Camilla, Letizia, Francesca, Trisolini, Mirko, Lewis, Hugh G., Chanoine, Augustin, Duvernois, Pierre-Alexis, Austin, Julian and Lemmens, Stijn (2017) Life cycle assessment indicator for space debris. 7th European Conference on Space Debris, , Darmstadt, Germany. 18 - 21 Apr 2017
3. Colombo C., Muciaccia M., Giudici L., Gonzalo J. L., Masat A., Trisolini M., del Campo B., Letizia F., Lemmens F. “Tracking the health of the space debris environment with THEMIS, EUCASS-CEAS Conference 2023, 9-13 Jul. 2023, Lausanne.
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Conclusion

- Development and consolidation of the different building blocks required for the definition of space debris environmental index
- Validation campaign with respect to some representative cases.
- The space debris indicator developed in THEMIS can be applied to all the other orbital regions beyond LEO, in MEO, GTO and GEO.
- The THEMIS debris indicator is computed to all the objects in the debris population to compute the overall space capacity.

THEMIS SOFTWARE FUTURE USES

THEMIS software use

Future uses

Space debris mode

to allow different users to assess the impact of a space mission on the space environment based on mission information such as orbit, mass, cross-section, and risk of fragmentation due to accidental collisions or explosions.

to determine the share of the capacity of space used by that mission under analysis.

Space capacity mode

to allow the computation of the overall space capacity used by orbiting spacecraft.

to analyse possible definitions and proxy of the capacity threshold

THEMIS software use

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Support the definition of a capacity threshold

Support the definition of new mitigation guidelines

Facilitate the environmental evaluation of single missions during the licencing process

Support the definition of spacecraft mission insurance process for the on-orbit segment

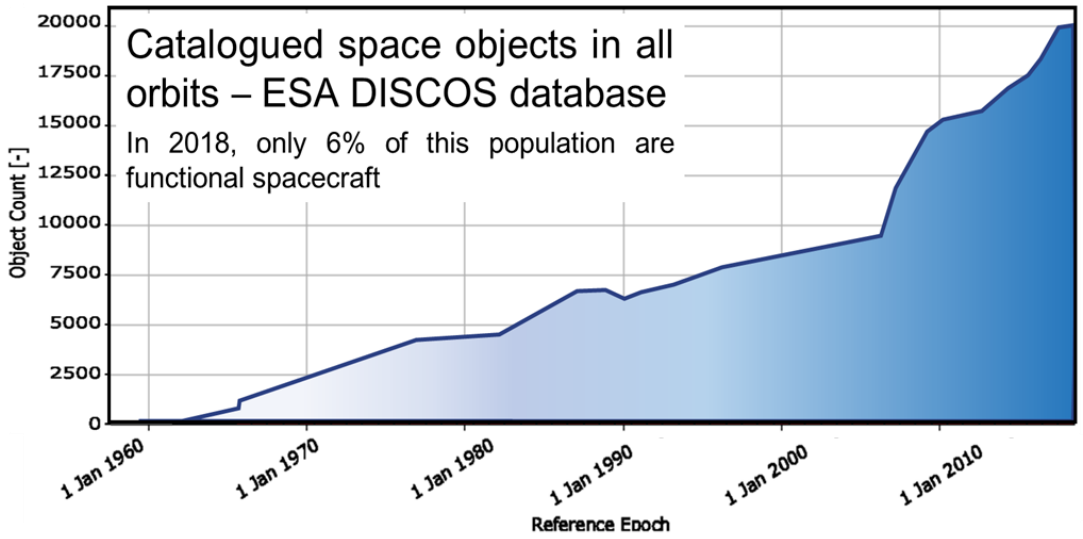
THEMIS software use

Future uses: Support the definition of a capacity threshold

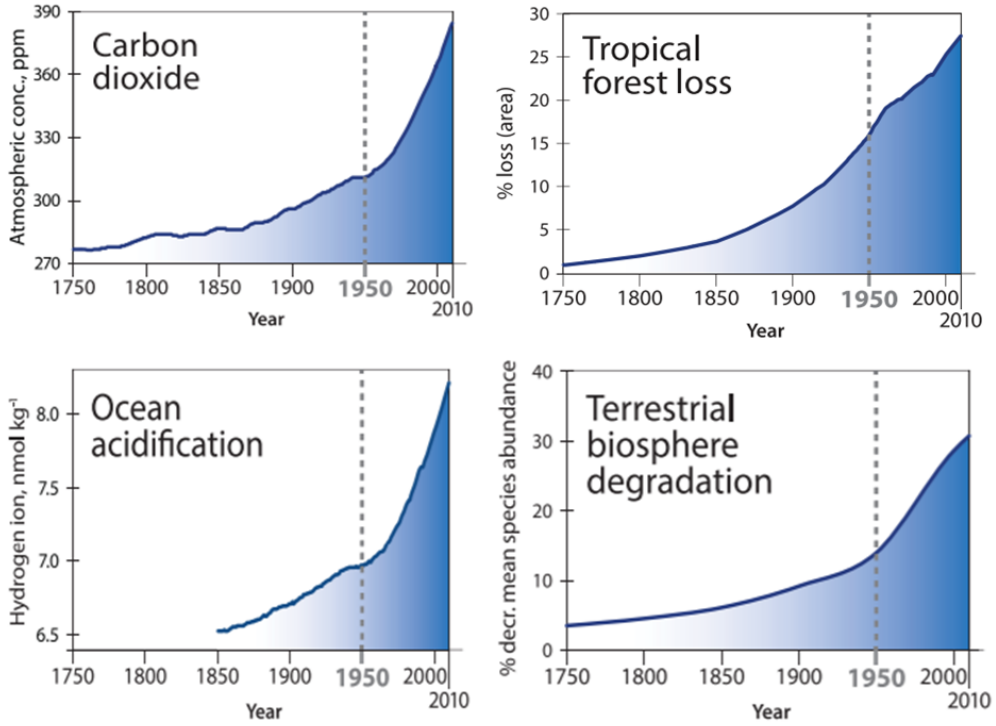
Support the definition of a capacity threshold

Space debris like other environmental issues

Orbital environment trend (space debris growth)



Earth system trends (environmental stressors)



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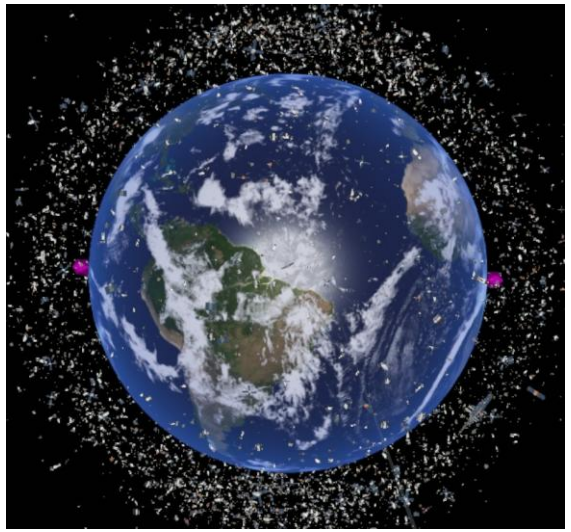
THEMIS software use

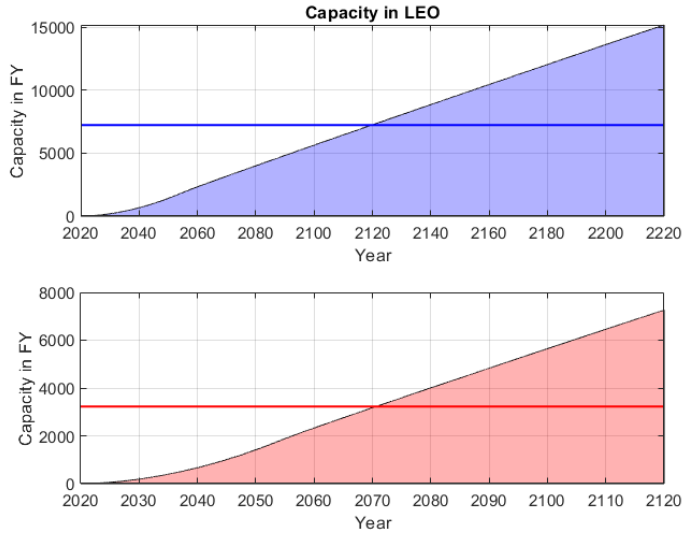
Future uses: Support the definition of a capacity threshold

Support the definition of a capacity threshold

AIM:

- To define an internationally recognised and accepted approach to measure the Space capacity
- To support in the definition of the threshold for such a capacity
- To link such measure to the contribution that each new and already flying mission apport to it





➢ Trozzi V., Trisolini M., Colombo C., "Analysis of possible definitions of the space environment capacity to pursue long-term sustainability of space activities," 72nd International Astronautical Congress, 25-29 October 2021, Dubai

THEMIS software use

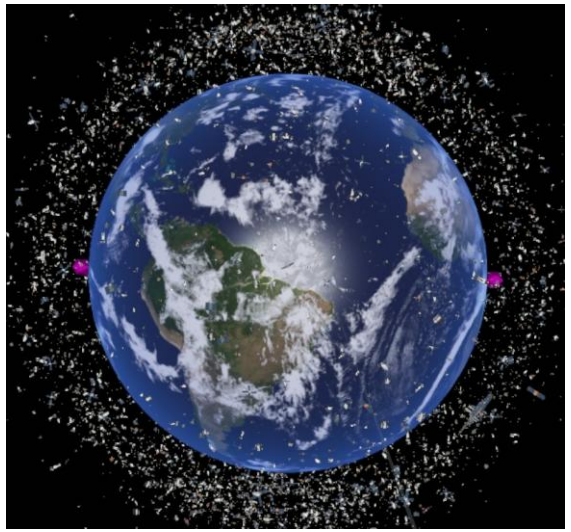
Future uses: Support the definition of new mitigation guidelines

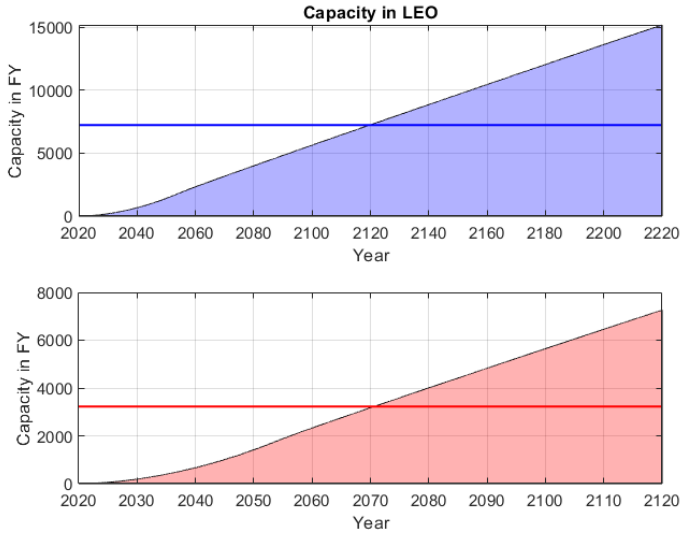
Support the definition of new mitigation guidelines

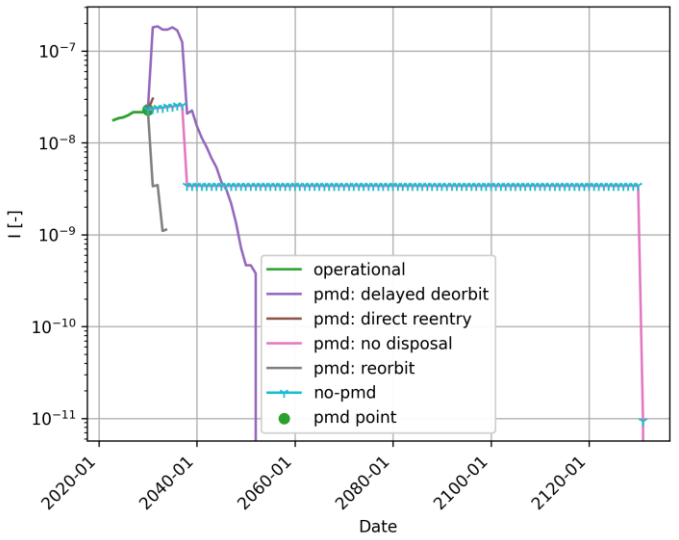
THEMIS for supporting mitigation guidelines

- THEMIS can assess the space debris index associated to each phase of the mission
- It can include at some extent the operational aspects
- THEMIS can compute the share of the overall capacity used up by a mission

THEMIS can support the monitoring of adherence to mitigation guidelines







➢ Trozzi V., Trisolini M., Colombo C., "Analysis of possible definitions of the space environment capacity to pursue long-term sustainability of space activities," 72nd International Astronautical Congress, 25-29 October 2021, Dubai

THEMIS software use

Future uses

The use of an index-based evaluation can simplify

- The evaluation of the **adherence to mitigation guidelines**
- Facilitate the environmental evaluation of single missions during the **licencing process**
- Support the definition of spacecraft mission **insurance process** for the on-orbit segment

We see this in

Bio food, electrical appliances and house energy classifications, cars pollution evaluation, etc. etc.

BETA TESTING

Would you like to be a beta tester?

Beta testing phase

A. Please contact us
B. Register to the ESA SSO account https://sdup.esoc.esa.int/
C. Send us your email address for the ESA account
D. We will share with you an account and some tests
E. You can test your own missions
F. One-to-one meeting for feedback
G. Possible licences

THEMIS FRONTEND TUTORIAL

POLITECNICO MILANO 1863

THANK YOU!

BETA tester THEMIS software

POLITECNICO MILANO 1863

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S2-SD-02 Extended Methods for Space Debris Consequence and Space Capacity Analysis

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