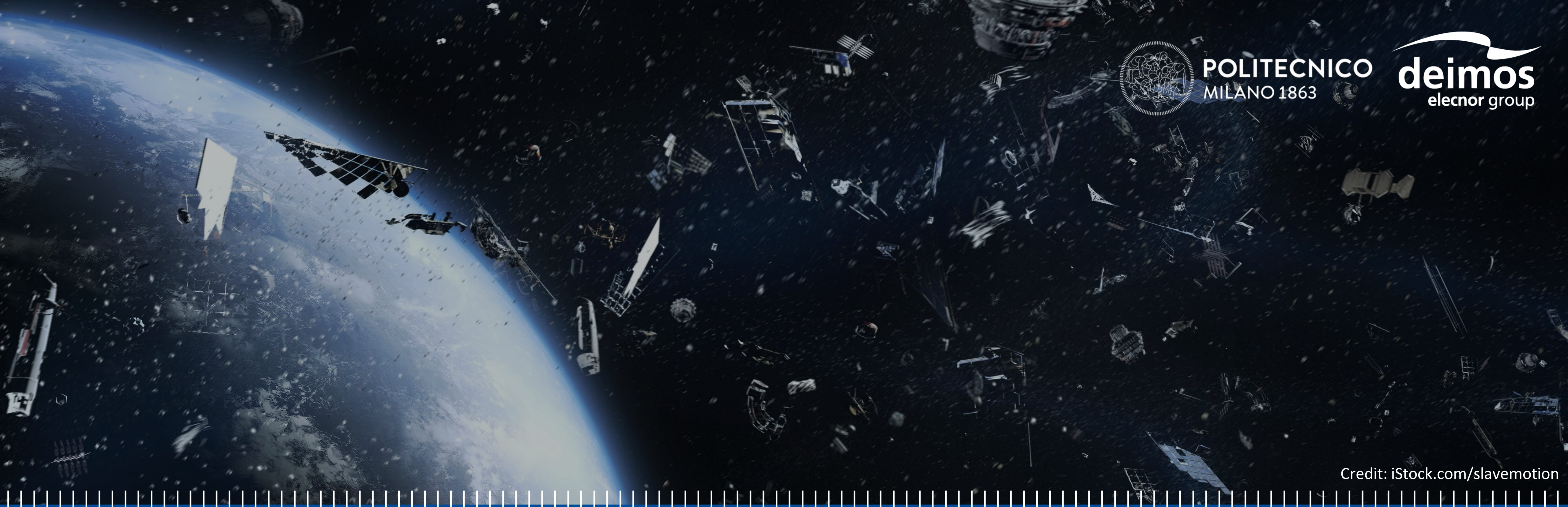


Credit: iStock.com/slavemotion

THEMIS: Tracking the health of the environment and missions in space

Camilla Colombo [1], Andrea Muciaccia[1], Mirko Trisolini [1], Lorenzo Giudici [1], Juan Luis Gonzalo [1], Stefan Frey [2], Borja del Campo [3], Francesca Letizia [4], Stijn Lemmens [4]

[1] Politecnico di Milano, [2] Vyoma, [3] Deimos Space, [4] European Space Agency

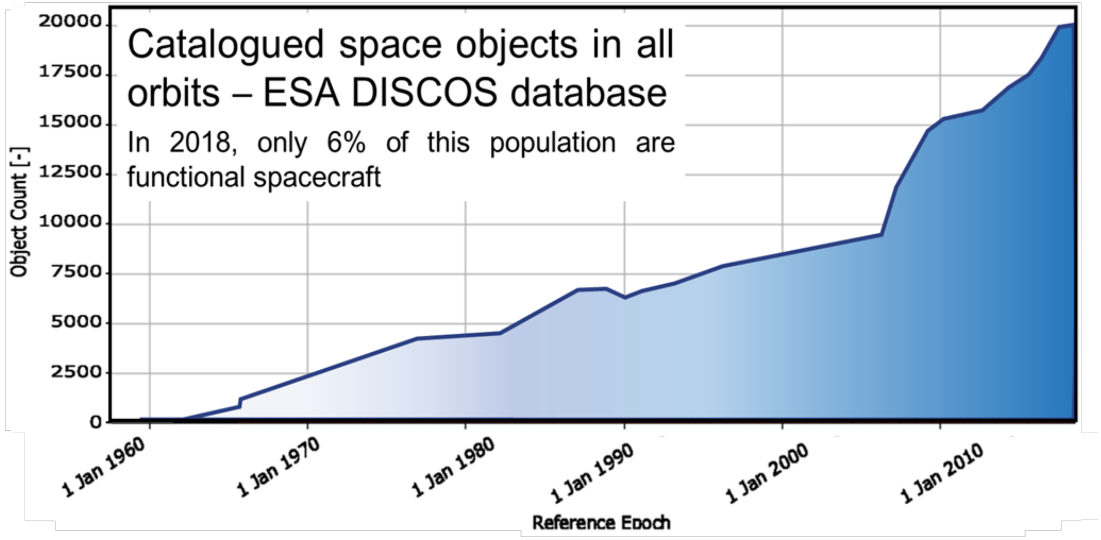
6th European Space Debris modelling and Remediation workshop, Milano, 18-20 May 2022

Apollo mission 2019. Simulation COMPASS Virtual Reality game. Actual space debris orbits, artistic representation of objects

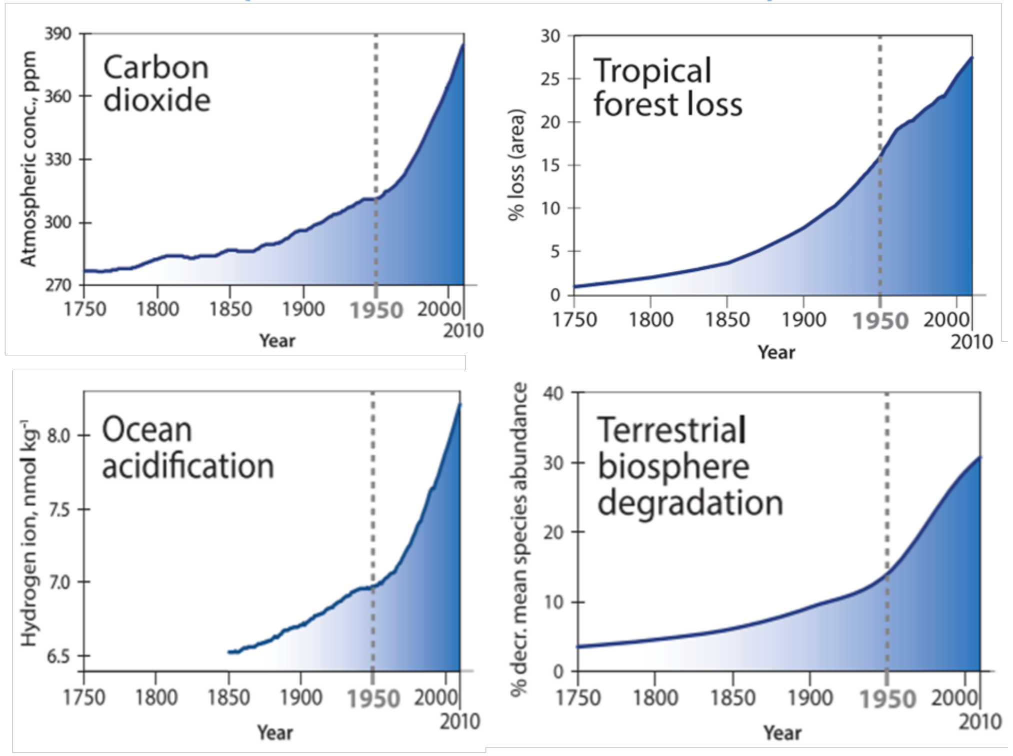
Introduction

Space debris like other environmental issues

Orbital environment trend (space debris growth)



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: a proposed method and case study", Science of the Total Environment, 2019. Earth system trend original image by Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the anthropocene: The great acceleration. Anthropocene Review, 2(1), 81–98. https://doi.org/10.1177/2053019614564785

Introduction

Goals and novelties

Goals:

- To assess the impact of a space mission on the space environment
- To assess the overall Space capacity and the contribution of each mission to it

Scientific development:

- A statistical density-based approach used for propagating explosion and collision fragments
- Definition and extension of space debris index to all orbital regions, including LEO, GEO, MEO, GTO, HEO
- Analysis of possible capacity proxy and capacity threshold

Software development:

- Integration with existing ESA tools such as DISCOS, MASTER, DRAMA, OSCAR
- Single score output of the environmental analysis in the ESA database DISCOS for reporting analyses and for integration into a life cycle assessment procedure
- Develop a web-based interface for the submission and evaluation of the space by several users

THEMIS SOFTWARE TOOL

THEMIS software tool

Tracking the Health of the Environment and Missions In Space

Space debris mode

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

Software design

THEMIS frontend

Interface for external users:

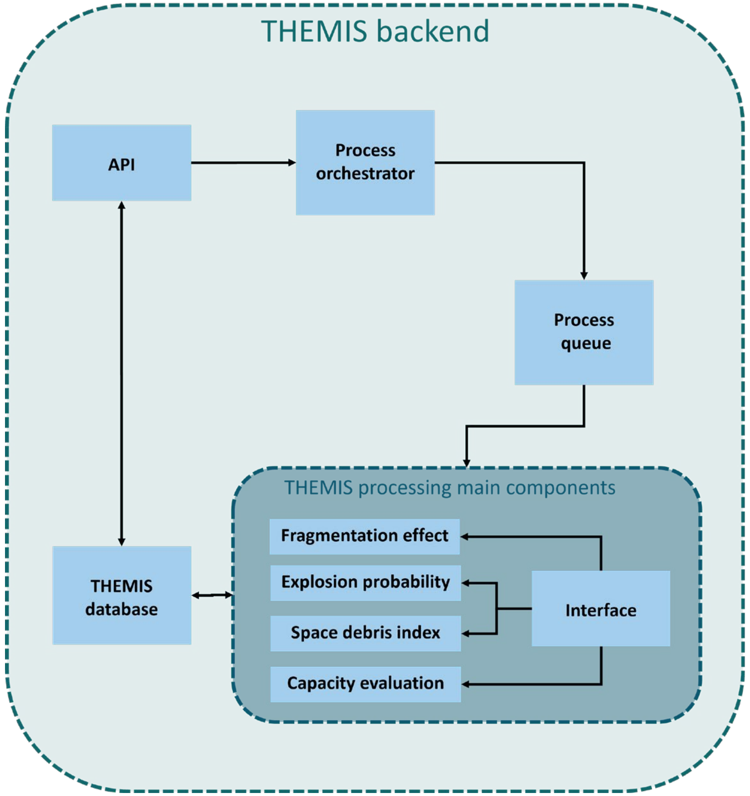
- to analyse missions and their impact
- to have an overview of the overall status of the space environment
- for registered users to submit user-defined mission for evaluation of its environmental impact both in terms of index and capacity consumption
- for operators to declare new missions profiles

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 effects
  - Interface with ESA tools
- Computation of the space capacity:
  - Long-term propagation using ESA DELTA
  - Compute the available capacity of the space environment

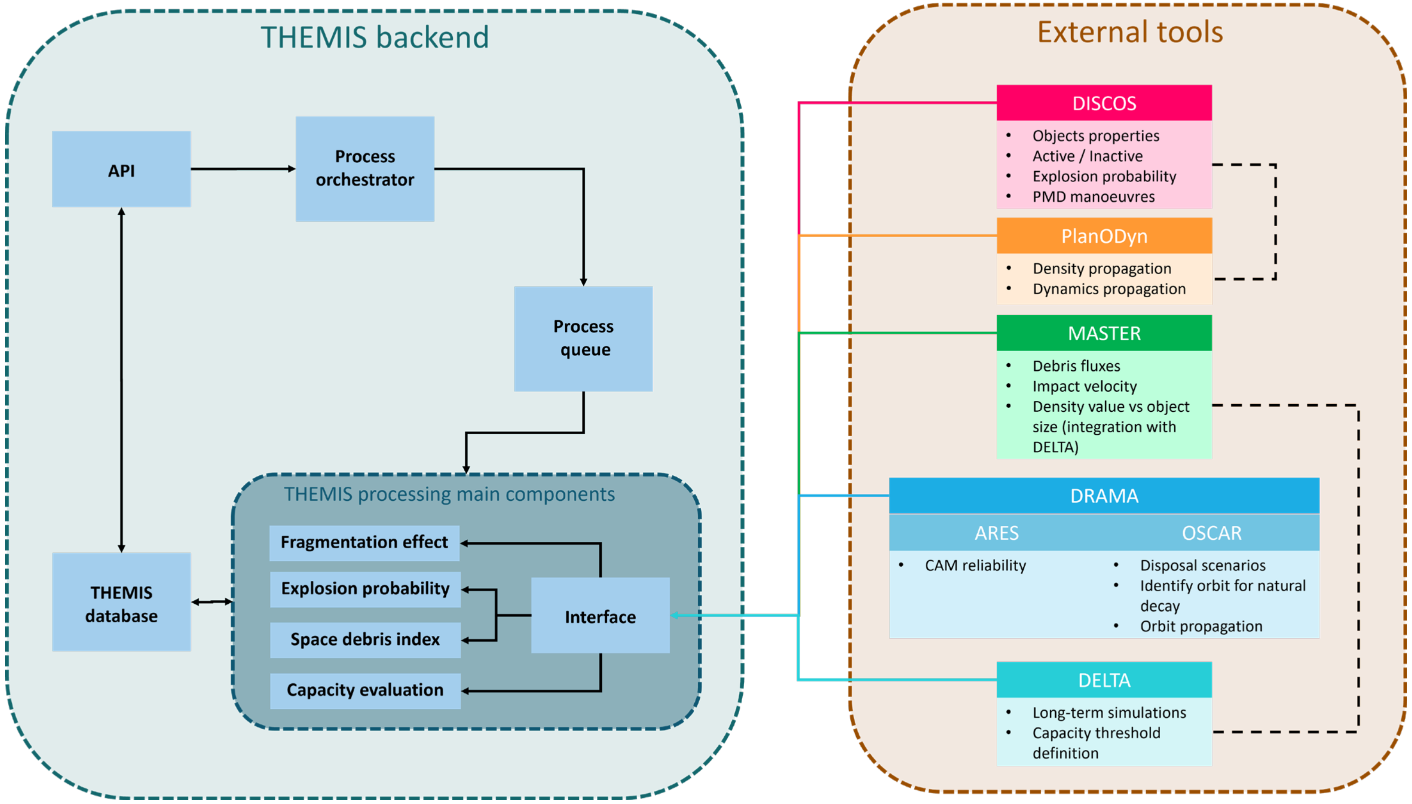
THEMIS software design

Overall software design and flow



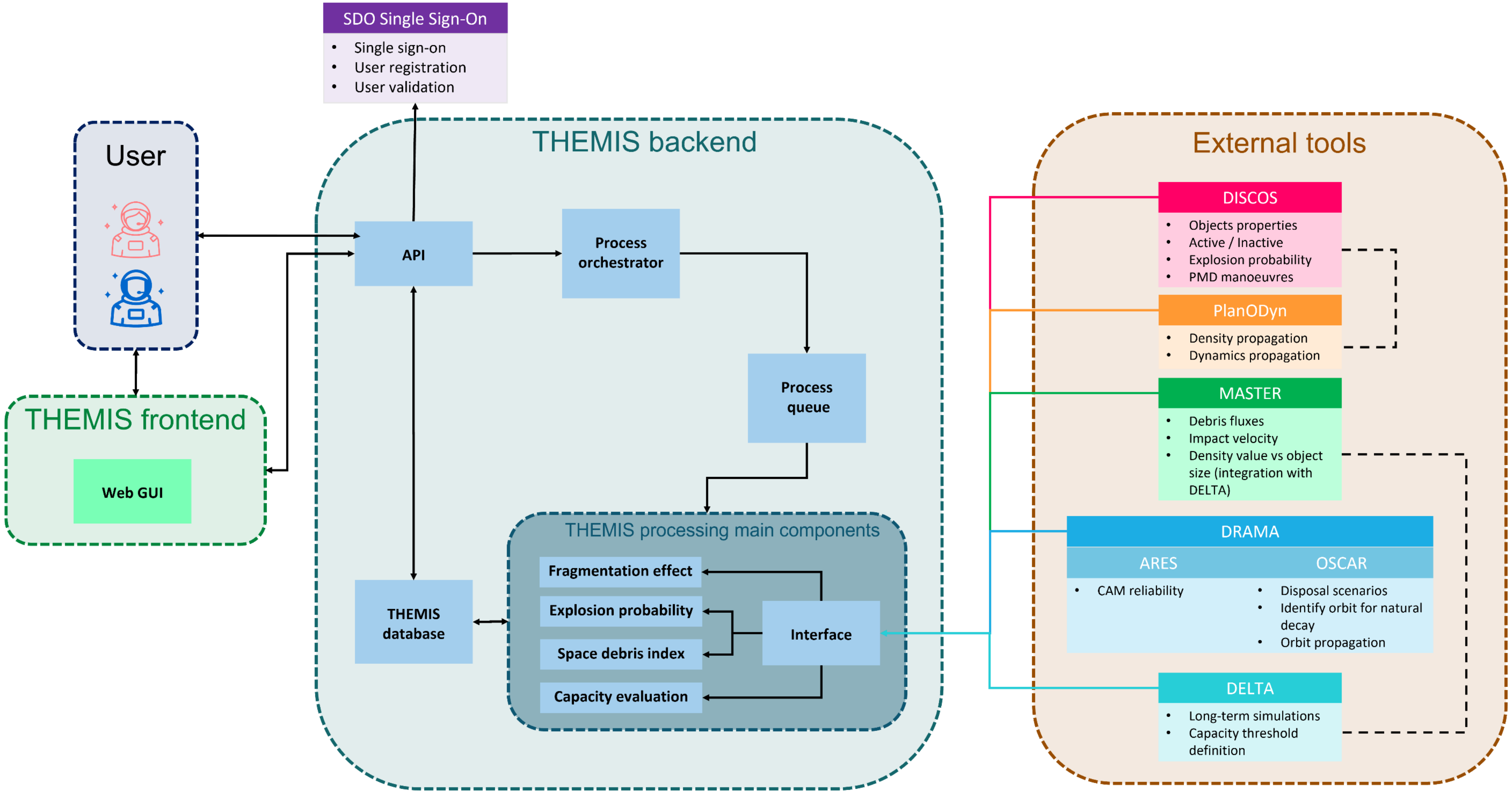
THEMIS software design

Overall software design and flow



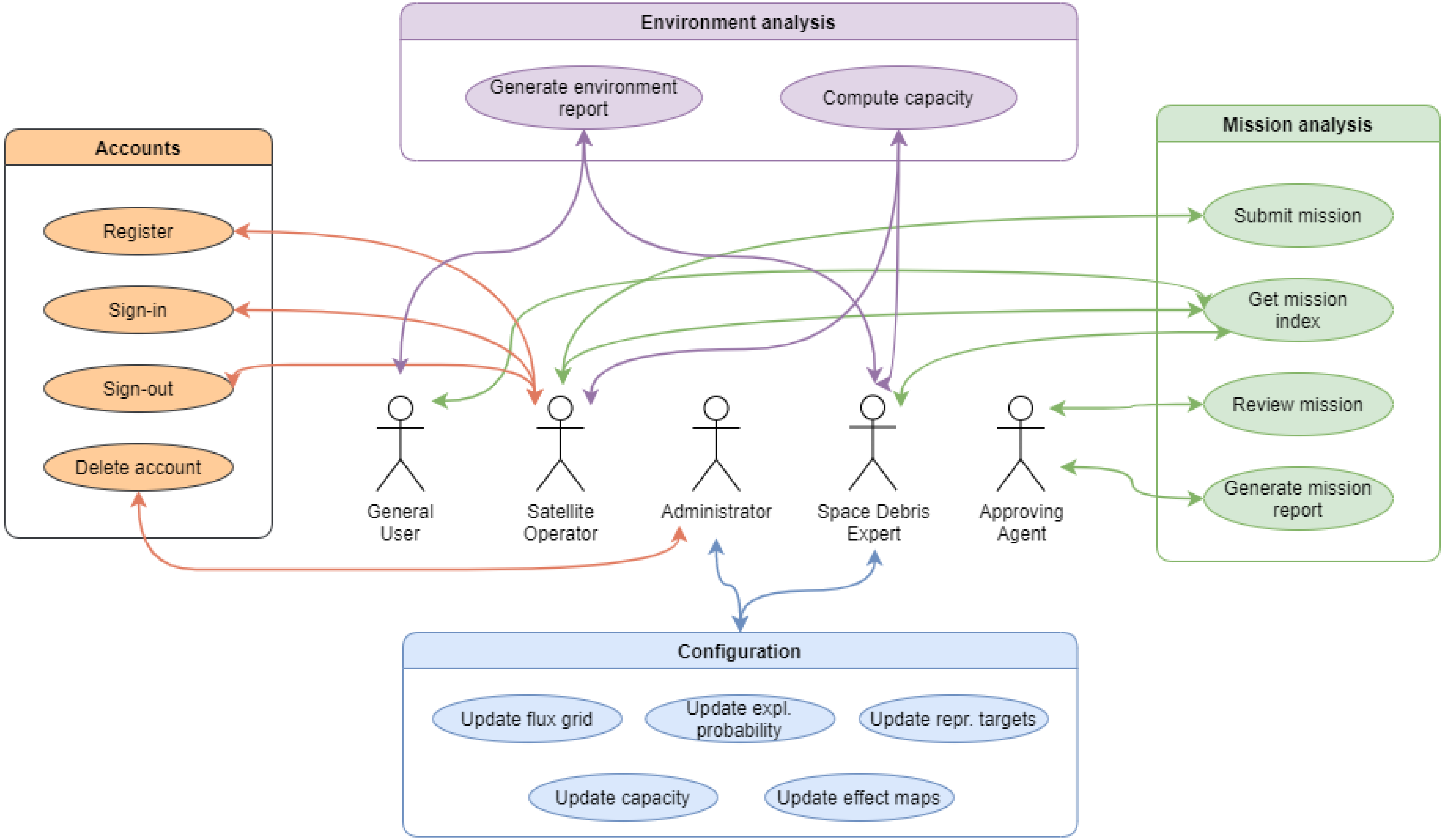
THEMIS software design

Overall software design and flow



THIS software tool

Basic functional analysis of the system subdivided by sections



SPACE DEBRIS INDEX

Space debris index

Index formulation

- ECOB formulation index to assess the risk = probability x severity

p = probability
e = effects (severity)

Space debris index

Collision probability | **Explosion probability**

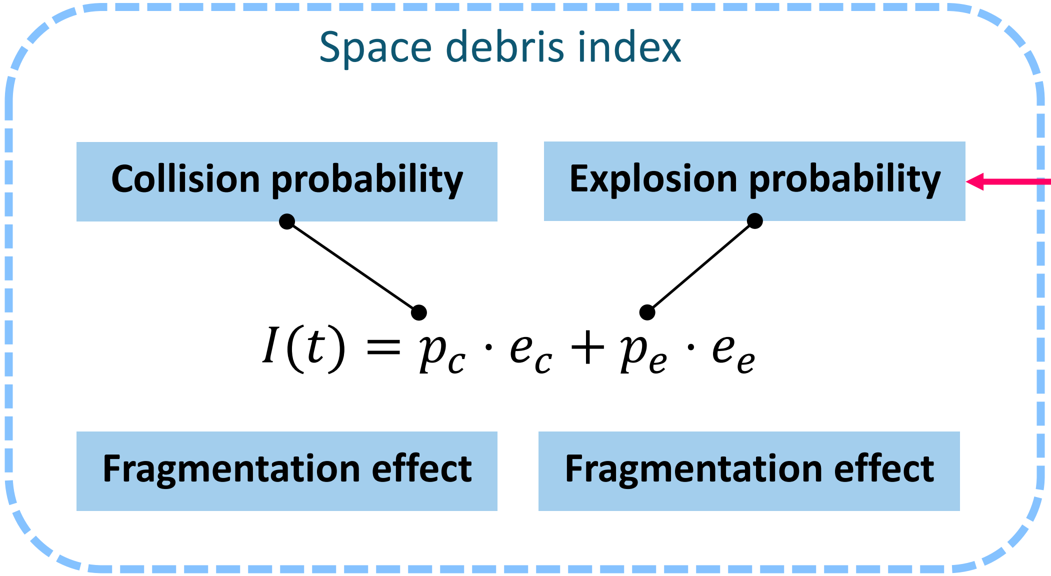
$$I(t) = p_c \cdot e_c + p_e \cdot e_e$$

Fragmentation effect | **Fragmentation effect**

➢ 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.

Space debris index

Explosion probability

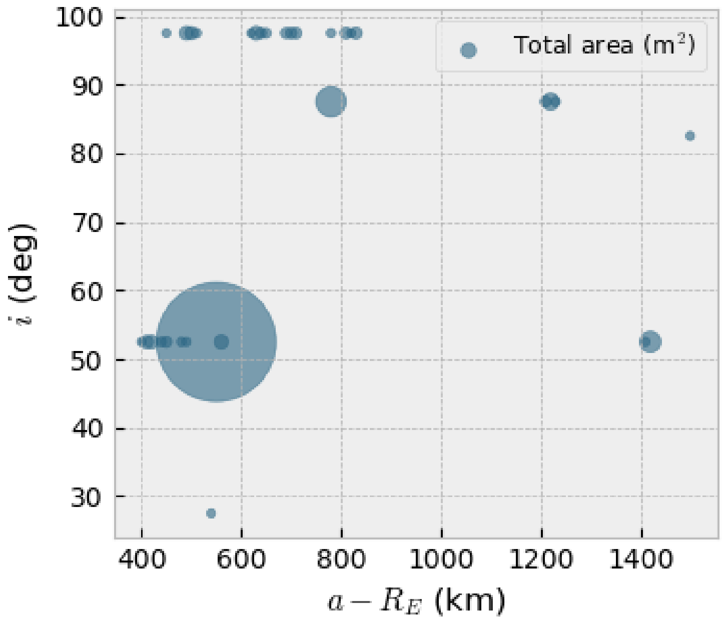


DISCOS

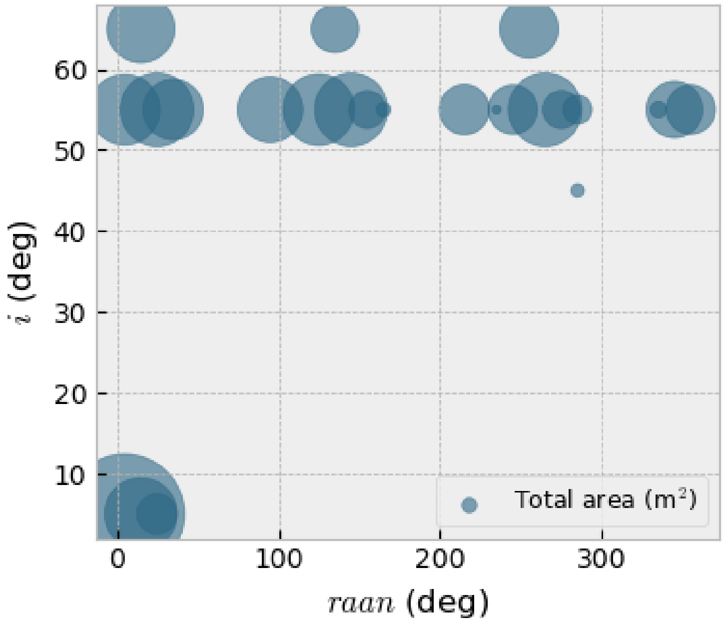
- Objects properties
- Active / Inactive
- **Explosion probability**
- PMD manoeuvres

Space debris index

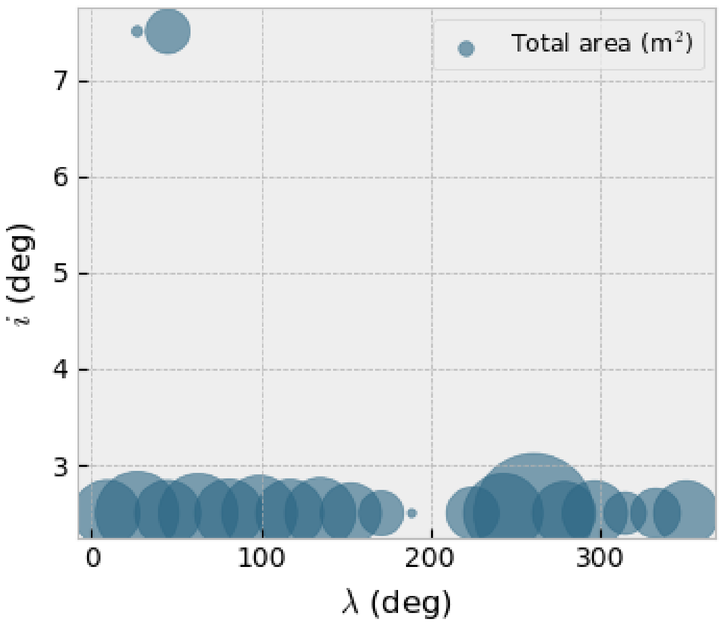
Representative targets



LEO region representative targets in a semi-major axis and inclination grid



MEO region representative targets in a right ascension of ascending node and inclination grid



GEO region representative targets in a longitude and inclination grid

Space debris index

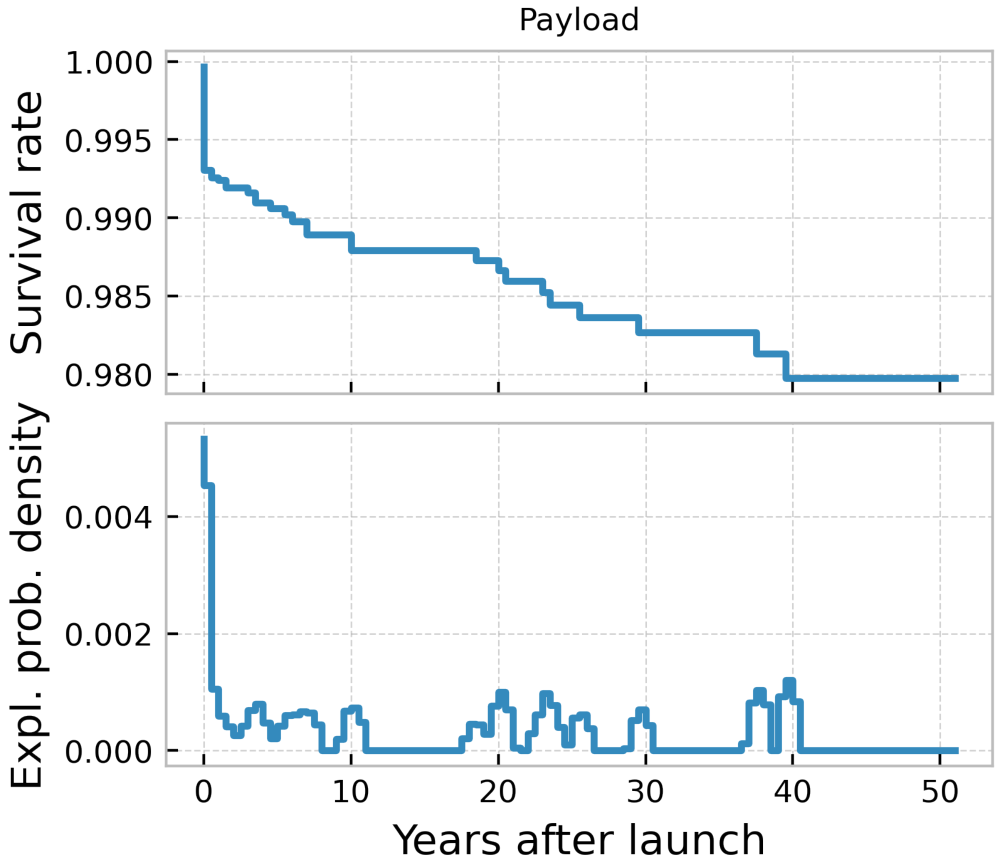
Explosion probability

Survival rate evaluated using the **Kaplan-Meyer** estimator

$$S(t) = \prod_{t_i<t}\left(1 - \frac{d_i}{n_i}\right)$$

Explosion probability evaluated using the **Nelson-Aalen** estimator

$$H(t) = \sum_{t_i<t}\frac{d_i}{n_i}$$



- Kaplan, E. L., Meier, P . (1958), Nonparametric Estimation from Incomplete Observations. Acta Astronautica, 53(282), 457-481.
- O. Aalen, (1978), Nonparametric Inference for a Family of Counting Processes. The annals of statistics, 6(4), 701-726.

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MASTER

- **Debris fluxes**
- **Impact velocity**
- Density value vs object size (integration with DELTA)

DRAMA

ARES

- CAM reliability

Space debris index

Collision probability | **Explosion probability**

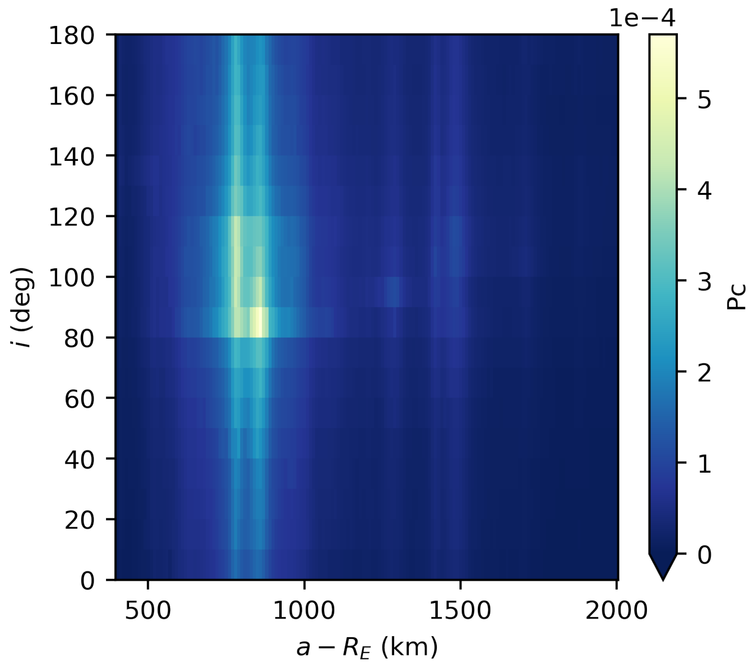
$$I(t) = p_c \cdot e_c + p_e \cdot e_e$$

Fragmentation effect | **Fragmentation effect**

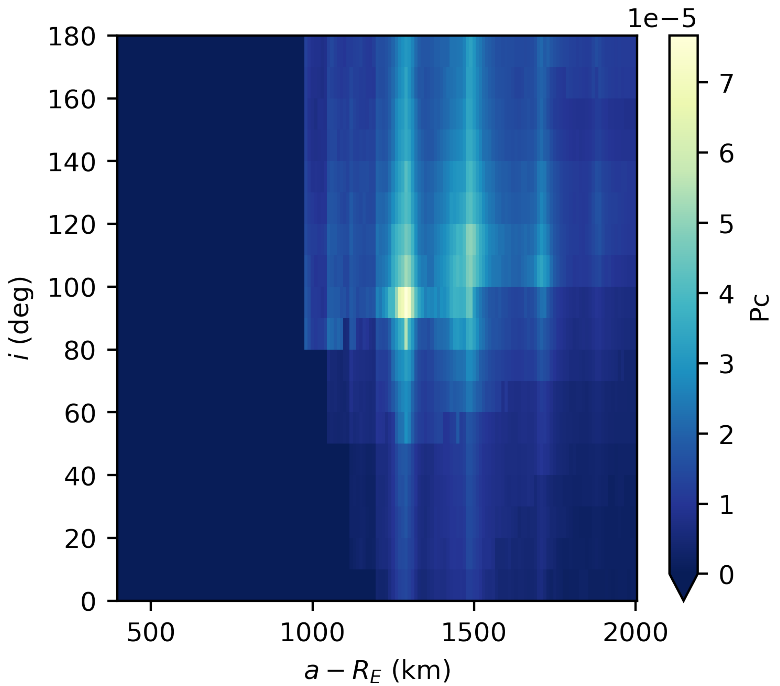
THIS software design

Subcomponent: index evaluation – collision probability

Collision probability without CAM capability



Collision probability considering CAM capability



Collision probability evaluation as function of the semi-major axis and inclination considering:

- Cross-section = $10\ m^2$
- Time discretisation = 1 year

Space debris index

Collision probability

Explosion probability

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

Fragmentation effect

STARLING

PlanODyn

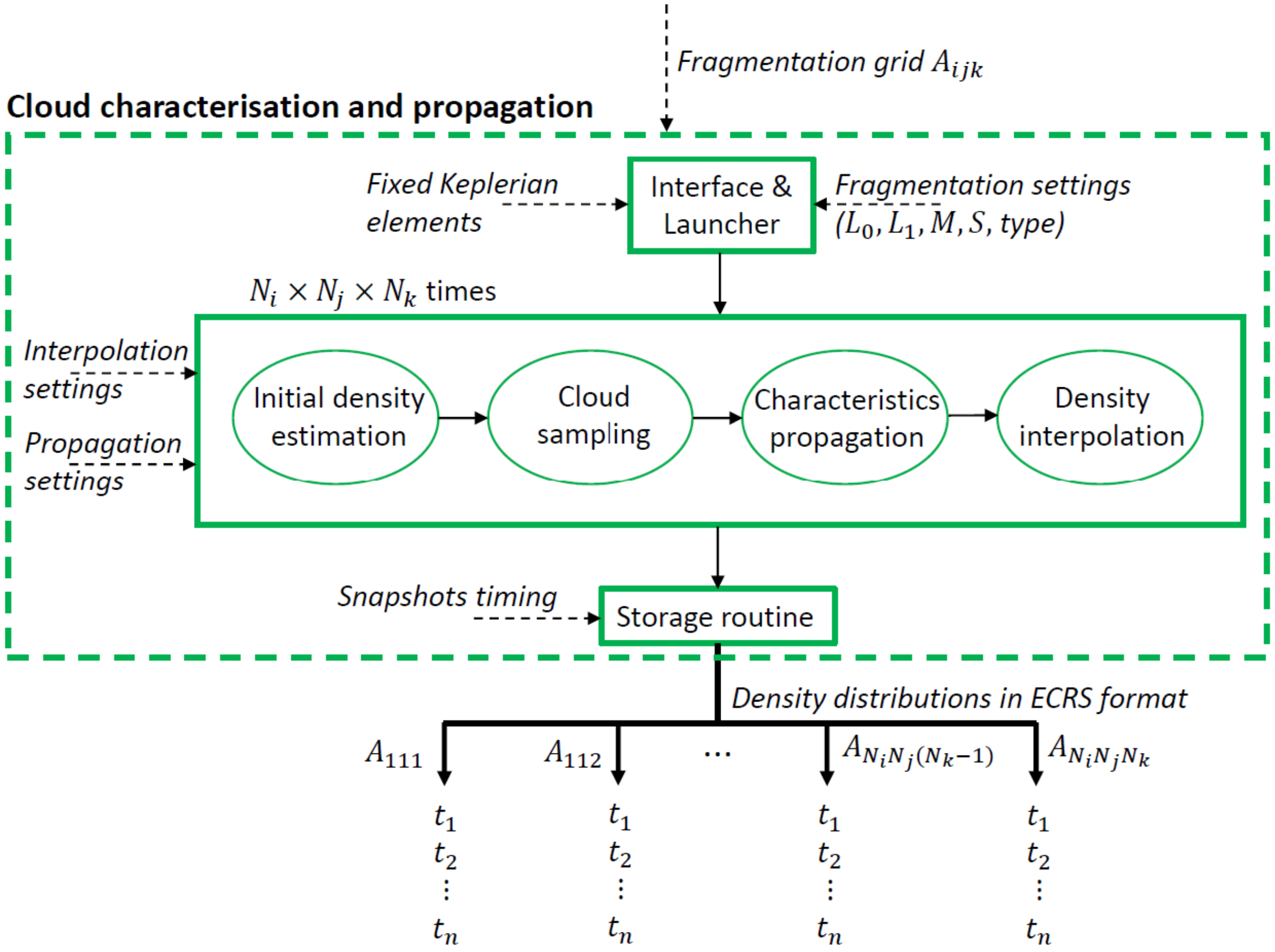
- Density propagation
- Dynamics propagation

DISCOS

- **Objects properties**
- **Active** / Inactive
- Explosion probability
- PMD manoeuvres

THIS software design

Cloud characterisation and propagation



Input:

- **Fragmentation grid**: coordinates of the subset of characteristic Keplerian elements of the orbital region under analysis

Output:

- **Density distributions**: density values stored in ECRS* format, for each fragmentation at each time snapshot

*Compressed row storage applied to extended Karnaugh map representation of the density array

THEMIS software design

Subcomponent: initial density estimation and sampling

Inputs:

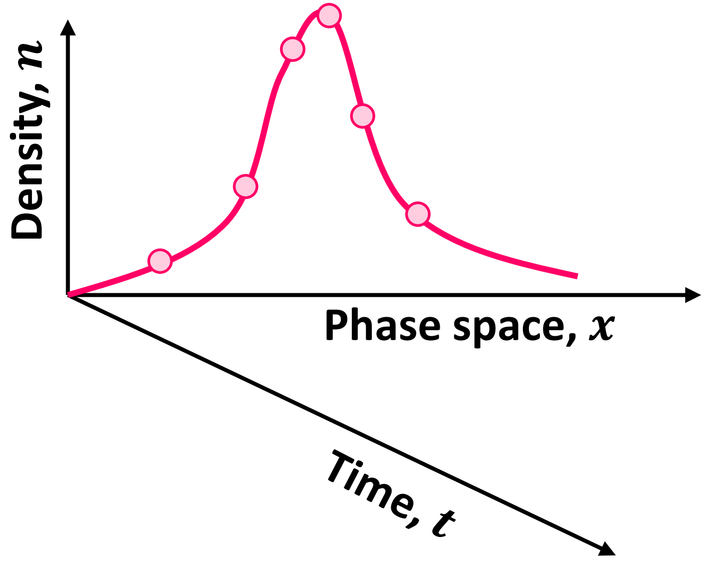
- **Fragmentation settings** specifying:
  - Parent orbit
  - Fragmentation type
  - Parameters (mass, fragments' size, scaling factor)
- **Interpolation settings** specifying:
  - Interpolation variables
  - Step-sizes for binning
  - Method (Monte Carlo or Weighted Monte Carlo)
  - Re-entry altitude

Process:

- Probabilistic definition of the phase space domain
- Estimation of the density distribution through a binning approach
- Characteristics' sampling according to bins' size and (possibly) expected dynamical behaviour of the cloud

Output:

- **Initial characteristics**: coordinates $(a, e, i, \Omega, \omega, M, A/M_d, A/M_{srp})$ and density value of each characteristic to be propagated



THIS software design

Subcomponent: characteristics' propagation

Inputs:

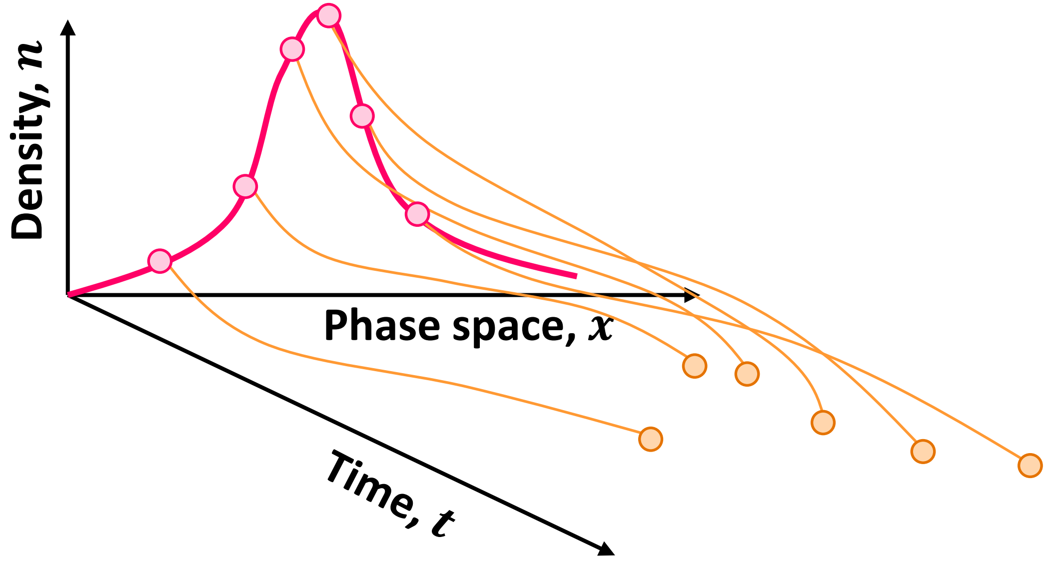
- **Initial characteristics**: coordinates (a, e, i, Ω, ω, M, A/M_d, A/M_{srp}) and density value of each characteristic to be propagated
- **Propagation settings** specifying:
  - Snapshots' times (start, end, step-size)
  - Integration settings (tolerances, solver)
  - Dynamical model (parameters and flags, Jacobian, density model, ephemerides)

Process:

- Propagation of characteristics using PlanODyn (semi-analytical tool) with set perturbations
- Storing in at some specified epochs

Output:

- **Propagated characteristics**: coordinates and density values at each snapshot time



THIS software design

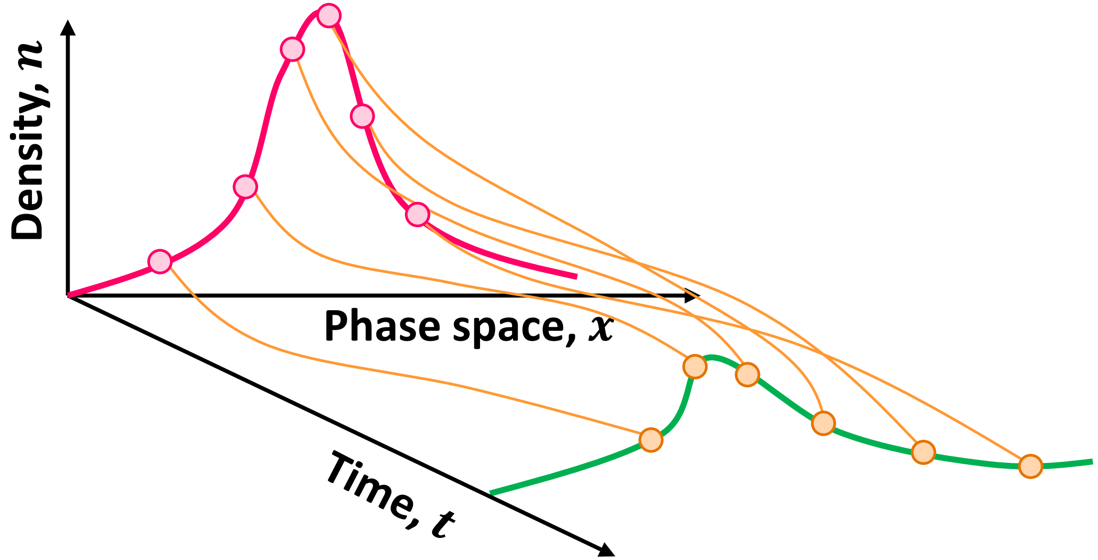
Subcomponent: density interpolation

Inputs:

- **Interpolation settings** specifying:
  - Interpolation variables
  - Step-sizes for binning
  - Method (Monte Carlo or Weighted Monte Carlo)
  - Re-entry altitude
- **Propagated characteristics**: coordinates and density values at each snapshot time

Output:

- **Density distributions** at each specified snapshot time stored in ECRS format

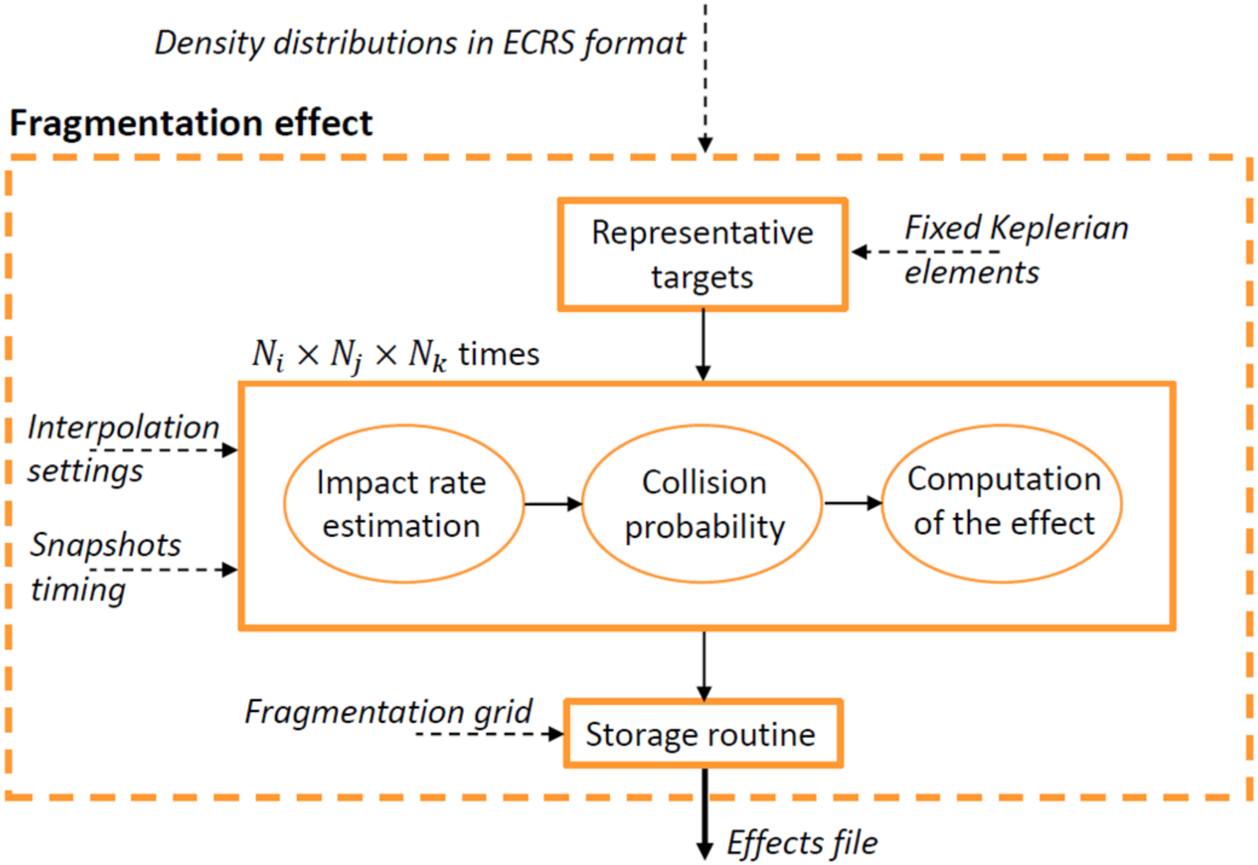


Process:

- Density distributions are recovered from the propagated characteristics through binning in an (up to) 6D phase space
- Nearest-neighbour – like interpolation among neighbouring bins is implemented to avoid missing data in the distribution

THIS software design

Main block: fragmentation effect



Input:

- **Density distributions** at each specified snapshot time stored in ECRS format

Output:

- **Effects**: coordinates of one fragmentation defined in the fragmentation grid and the relative effect on the representative targets

THIS software design

Subcomponent: representative targets

Inputs:

- **DISCOS active objects**
- **Grid** parameters:
  - Keplerian elements ranges and steps
  - Orbit type
- **Target settings** specifying the fixed Keplerian elements

Output:

- **Representative targets:** Keplerian elements, area, and total area of each representative target

Process:

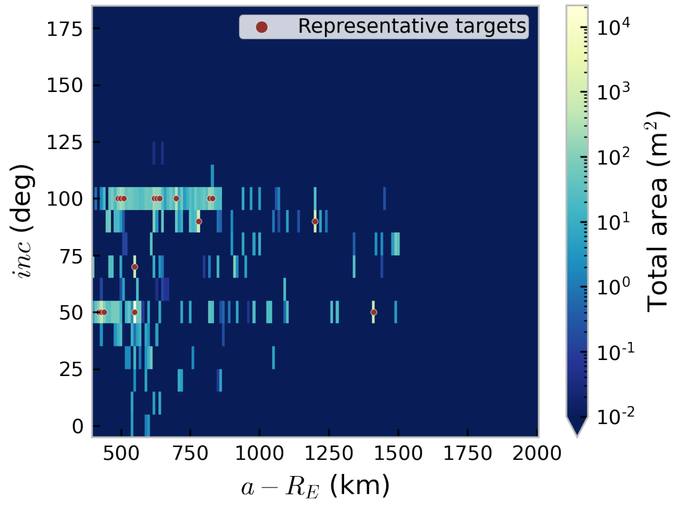
- Reading DISCOS file with active objects
- Generation of the grid in Keplerian elements (according to the orbital region) and computation of the total and average areas in each cell of the grid
- Identification of the representative targets considering the cells containing the 90% of the cumulative cross-sectional area

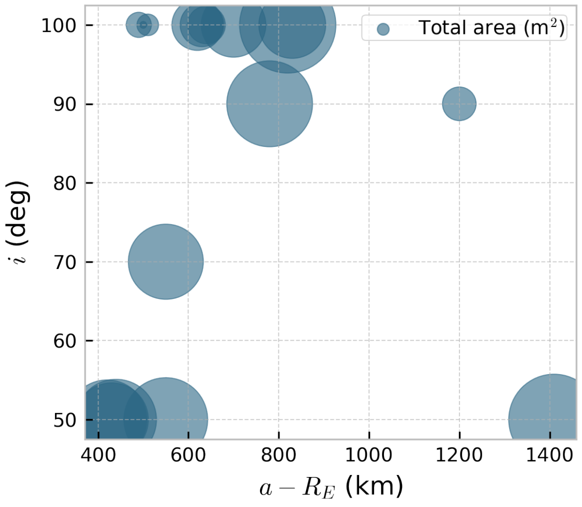
THEMIS software design

Subcomponent: representative targets

Grid parameters:

- Semi-major axis range: $[6778 \ - \ 8378]$ km
- Semi-major axis step: 10 km
- Inclination range: $[0 \ - \ 180]$ deg
- Inclination step: 10 deg

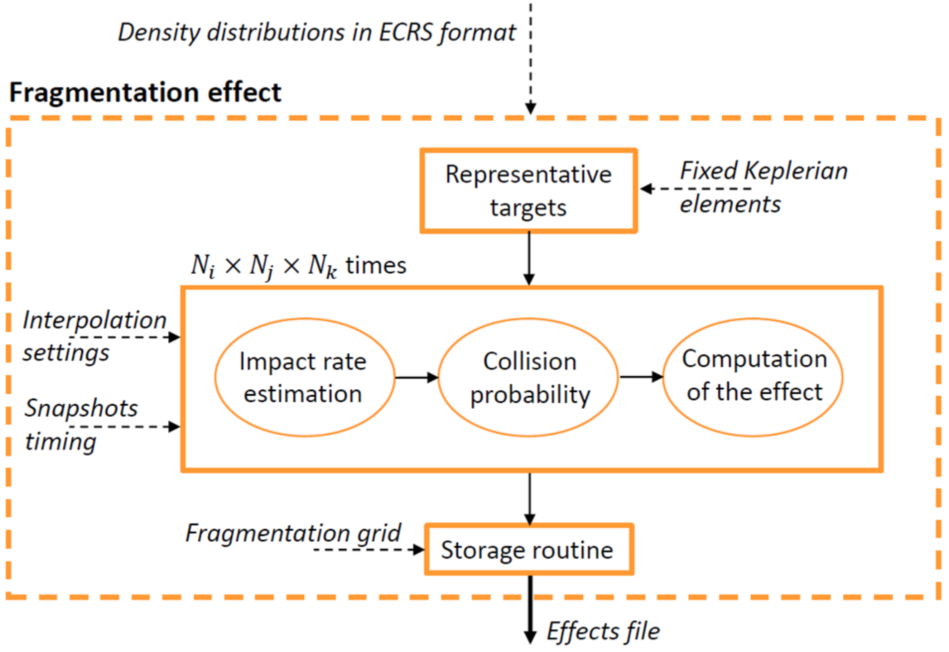




Representative targets in LEO region - 14/02/2022

THIS software design

Main block: fragmentation effect



Impact rates:

$\dot{\eta}$ for different target positions (according to an equally-spaced grid in mean anomaly) at each specified snapshot time

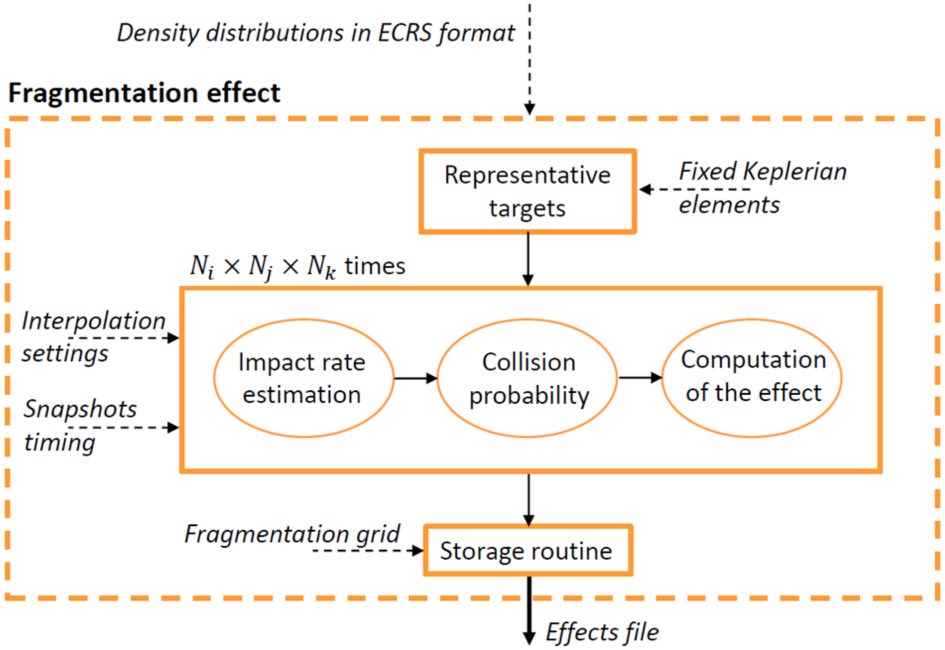
$$\dot{\eta} = A_c \int_{\mathbb{R}^3} \sum_{k=1}^{4} \frac{n_{\boldsymbol{\alpha}}\left(\boldsymbol{\alpha}_{13}, \boldsymbol{\alpha}_{46}^k\right)}{|\det J^k|} \left\| \boldsymbol{v}\left(\alpha_{13}, \alpha_{46}^k\right) - \boldsymbol{v}^* \right\| \mathrm{d}\boldsymbol{\alpha}_{13}$$

Process:

- The density distribution is sampled in the subset of Keplerian elements (a, e, i)
- By imposing intersection with target position, the full set of samples' coordinates is retrieved
- The density values in correspondence of the samples' coordinates is computed
- The impact rate is evaluated by integrating the flux of fragments over the target area

THEMIS software design

Main block: fragmentation effect



Cumulative collision probability:

$p_c(t)$ at each specified snapshot time

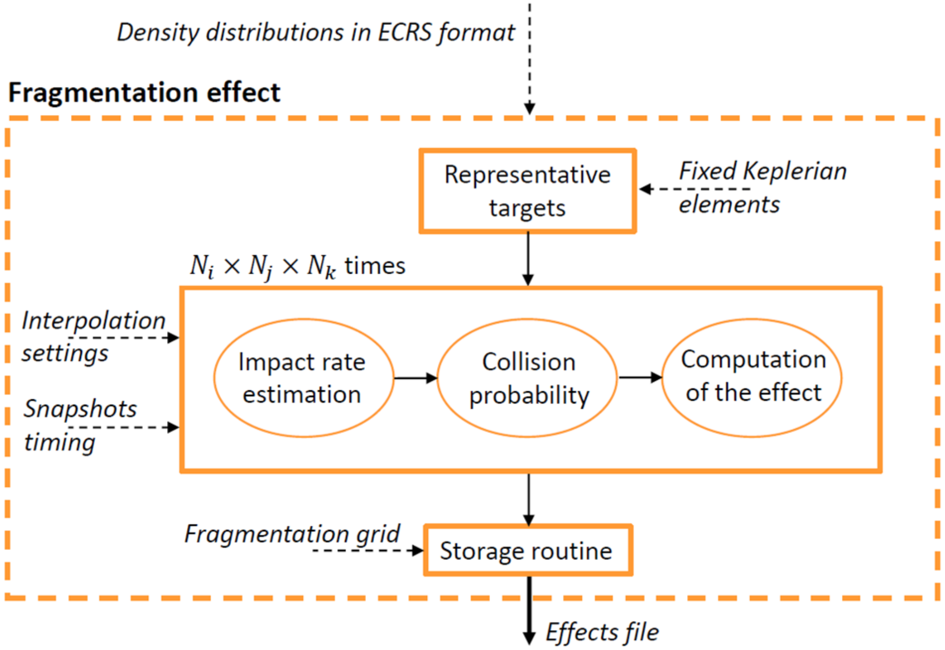
$$p_c(t) = 1 - \exp(\eta(t)) = 1 - \exp\left(\int_{t_0}^{t} \dot{\eta}(\boldsymbol{r}^*, \boldsymbol{v}^*)\mathrm{d}s\right)$$

Process:

- The number of impacts with the target is estimated through midpoint integration
- The probability of collision is computed from the cumulative number of impacts at final time, through an analogy with kinetic gas theory

THEMIS software design

Main block: fragmentation effect



Fragmentation effect:

e: weighted (according to shared area) cumulative collision probability of one fragmentation with the representative targets

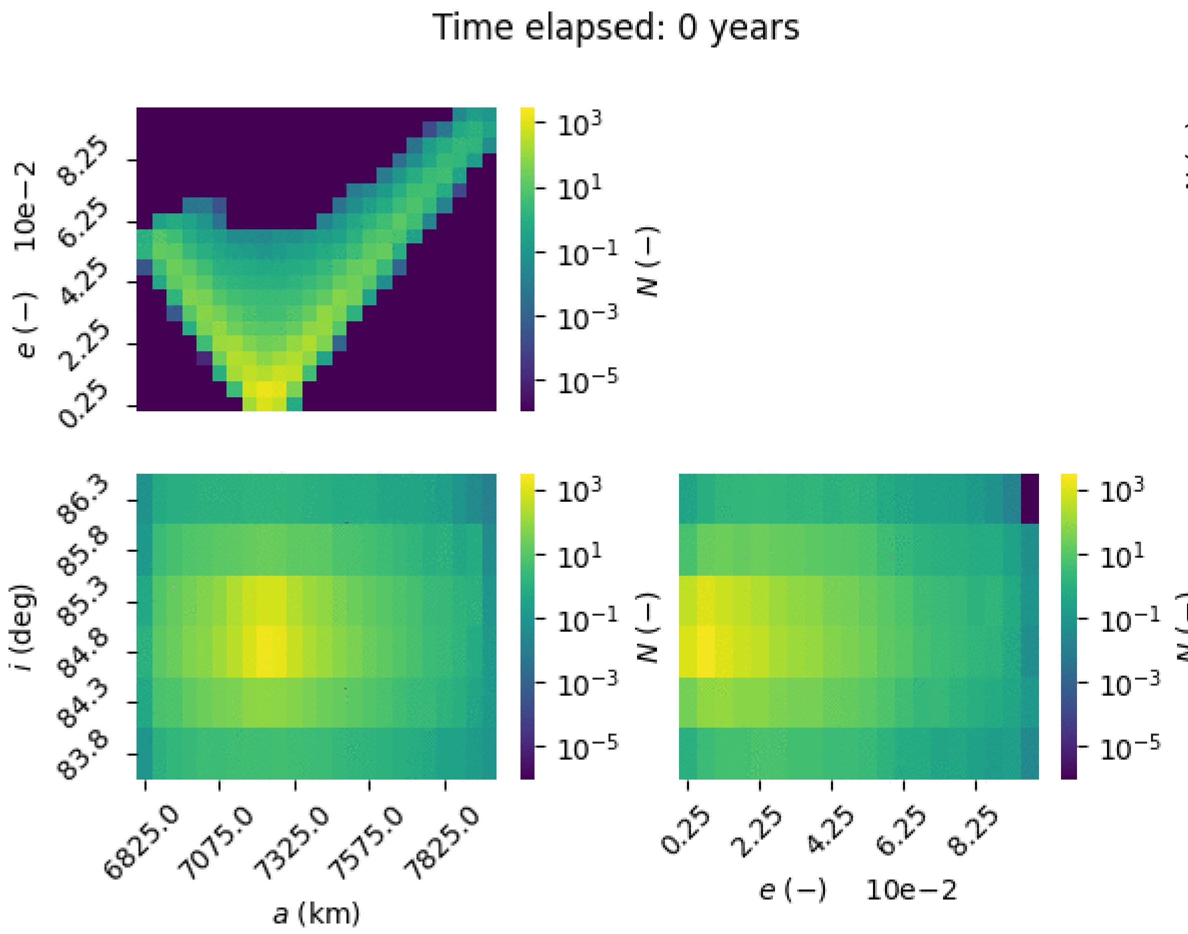
$$e = \sum_{k=1}^{N_t} \frac{A_c^k}{A_c^{\text{tot}}} p_c^k(t_f), \qquad A_c^{\text{tot}} = \sum_{k=1}^{N_t} A_c^k$$

Process:

The effect of a fragmentation is computed as the weighted sum of the collision probabilities according to the share of overall cross-sectional area of each target

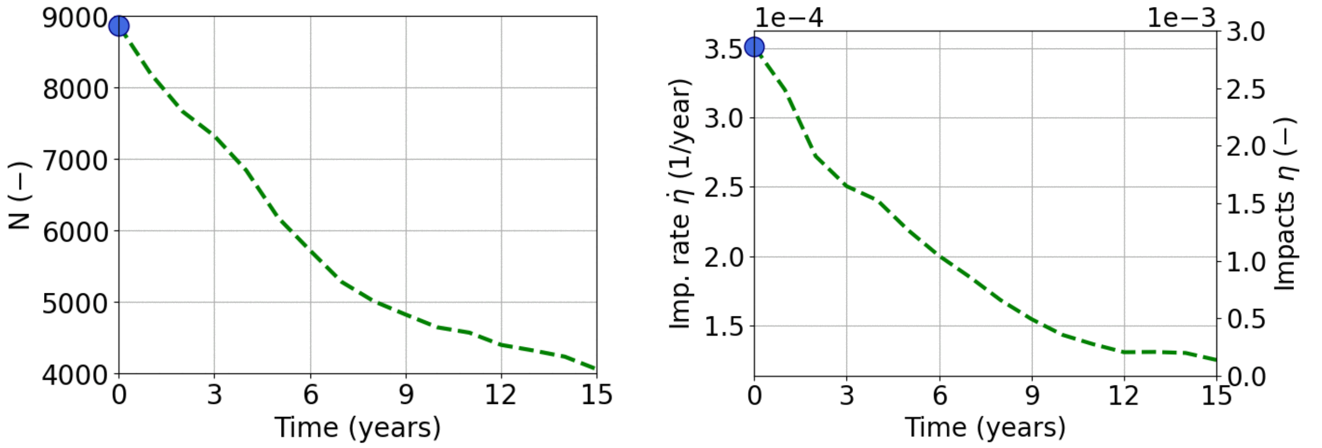
Fragmentation example

Payload explosion in low-Earth orbit



Fragments' number (N) distribution over time – heatmaps in a, e and i

Fragments number (N), impact rate ($\dot{\eta}$) and number of impacts (η) over time

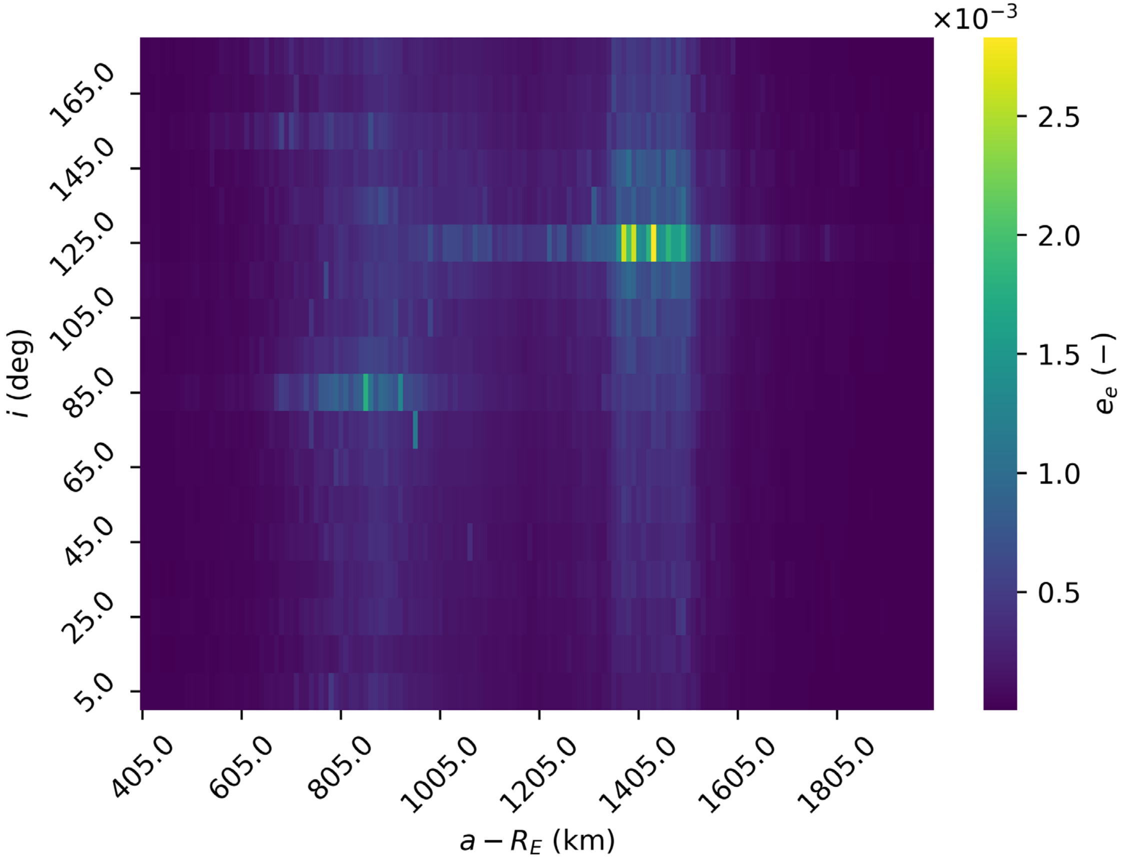


- **Fragmentation orbit:** $a = 7236$ km, $e = 0.001, i = 85$ deg
- **Target orbit:** $a = 7226$ km, $e = 0.001, i = 75$ deg

- **Perturbation model:** J_2 and drag
- **Collision probability:** randomisation in ω, Ω, M assumed

Effects map

Payload explosions in low-Earth orbit



Cumulative collision probability at 15 years from fragmentation on 48 representative targets

Space debris

POLITECNICO MILANO 1863 deimos elecnor group

ECOB formulation overview

- The index assessed over time to get its evolution and cumulative value for the mission lifetime

$$I = \int ECOB\ dt$$

- Each mission profile is divided in mission phases: e.g. launch, injection, orbit raising, operational orbit, deorbiting etc.
- The basic formulation expanded to include the reliability of post-mission disposal (PMD) manoeuvres with a coefficient (α)

$$I = \int_{t_0}^{t_{EOL}} ECOB\ dt + \underbrace{\alpha \cdot \int_{t_{EOL}}^{t_f} ECOB\ dt}_{\text{disposal}} + \underbrace{(1-\alpha) \cdot \int_{t_{EOL}}^{t_f} ECOB\ dt}_{\text{no disposal}}$$

➢ 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 frontend

Web GUI

- Disposal scenarios
- Mission phases
- Spacecraft parameters

Space debris index

Collision probability **Explosion probability**

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

Fragmentation effect **Fragmentation effect**

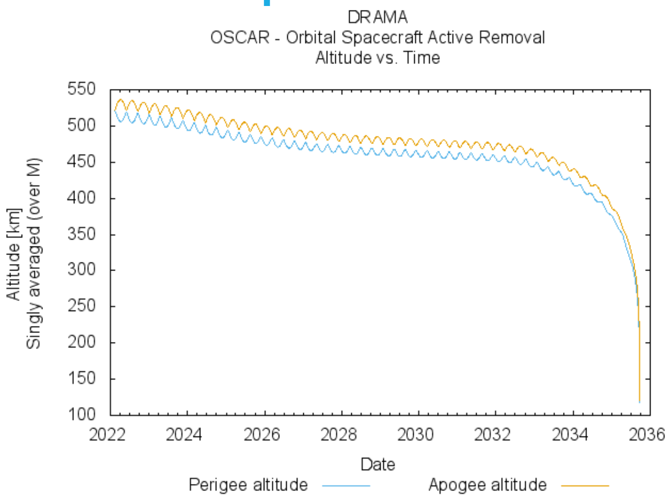
Integrate along the trajectory

- Collision probability
- Explosion probability
- Fragmentation effects

DRAMA

OSCAR

- **Disposal scenarios**
- Identify orbit for natural decay
- **Orbit propagation**



PMD reliability

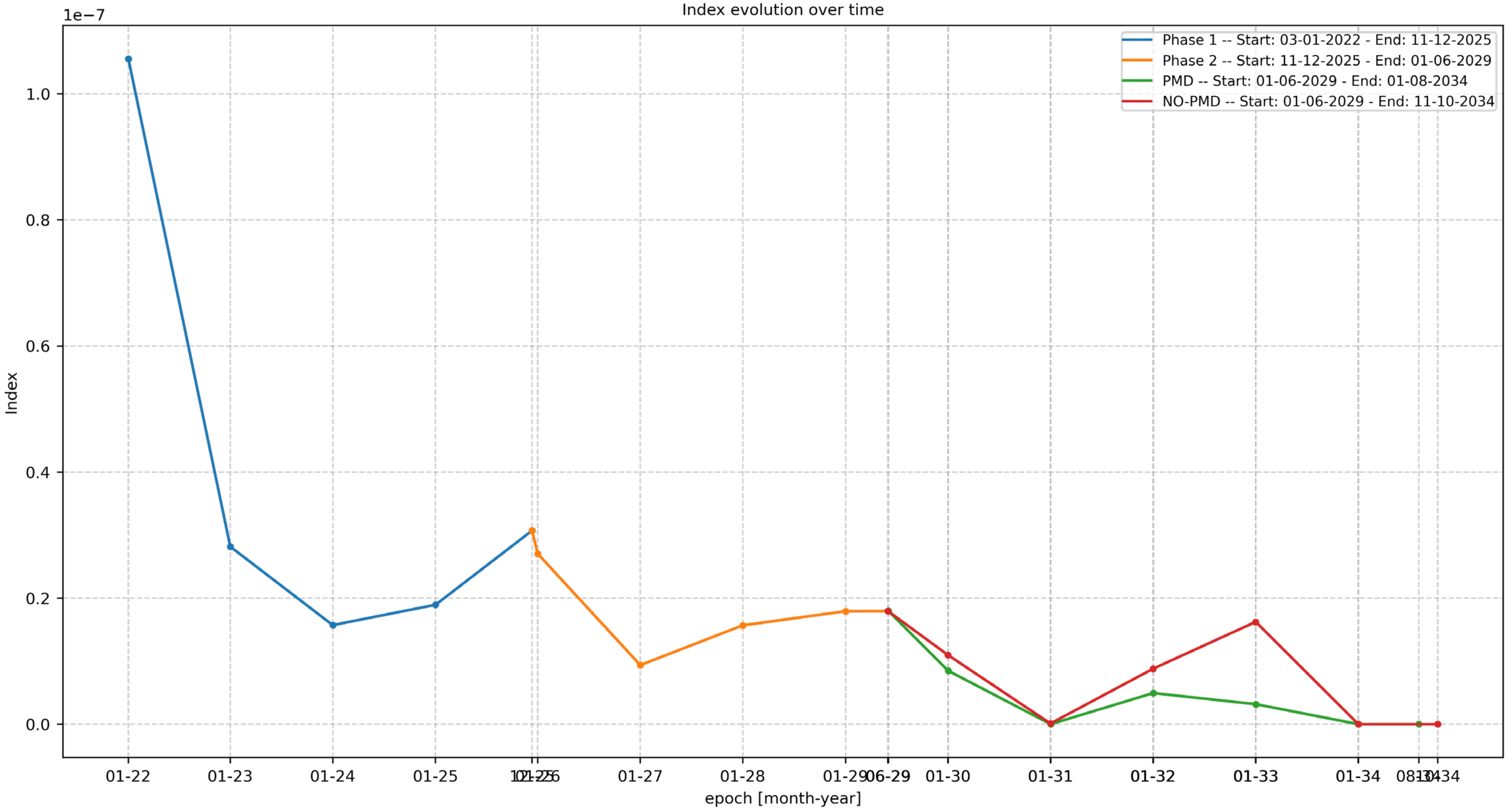
$$I = \int_{t_0}^{t_{EOL}} ECOB\, dt + \alpha \cdot \int_{t_{EOL}}^{t_f} ECOB\, dt + (1-\alpha) \cdot \int_{t_{EOL}}^{t_f} ECOB\, dt$$

➢ 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.

THIS software design

Index evolution – **dummy** mission

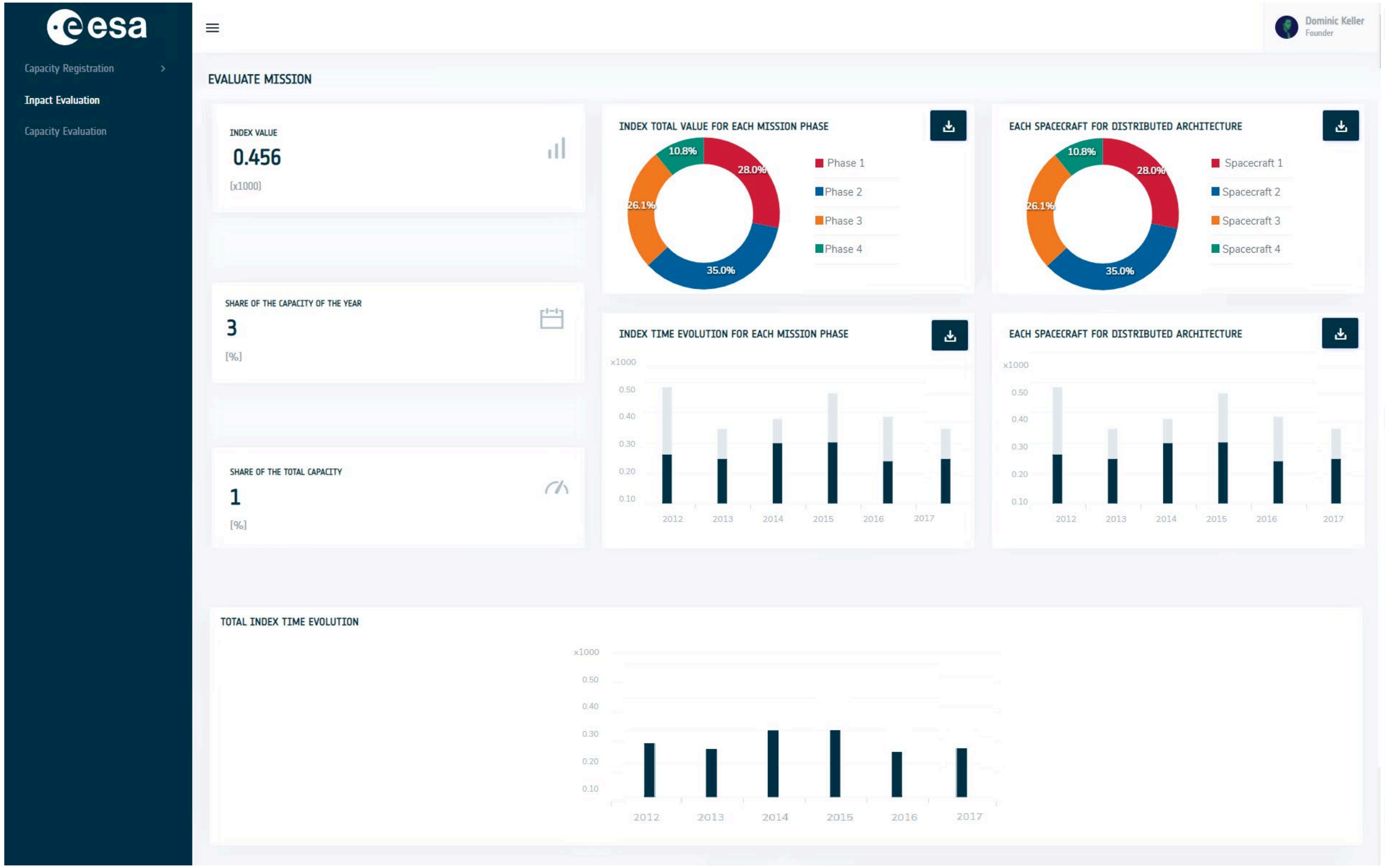
- **Phase 1:** Keplerian elements from an .oem file
- **Phase 2:** constant Keplerian elements
- **PMD/NO-PMD:** OSCAR propagation, considering a Re-orbit at 500 km using chemical propulsion

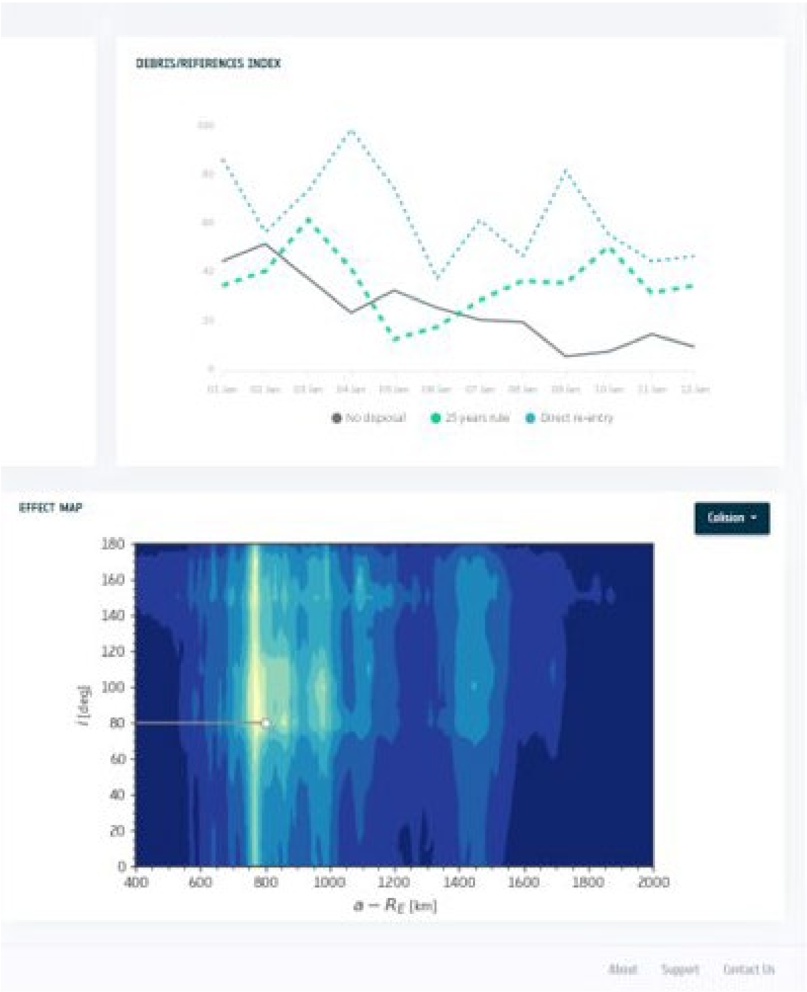


Index evolution over time – each color represents a single phase of the mission, and the index is computed at each time epoch

THIS software design

Frontend – Evaluation Output View





CONCLUSIONS

Conclusions

Steps completed

- Staling 2.0 tool applied to computation of the space debris index
- Space matrix approach for efficient binning
- Development of space debris ingredients for any orbital region
- Interfaces with ESA tools: DISCOS, MASTER, DRAMA

Next steps

- Space debris implementation and validation
- Capacity formulation and definition of capacity threshold
- Engaging with the space community…stay tuned

This project has received funding from the European Space Agency contract 4000133981/21/D/KS

THEMIS: Tracking the health of the environment and missions in space

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6th European Space Debris modelling and Remediation workshop, Milano, 18-20 May 2022

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