Debris cloud analytical propagation for a space environmental index

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SPACE DEBRIS ENVIRONMENT

metrics for the impact of fragmentations

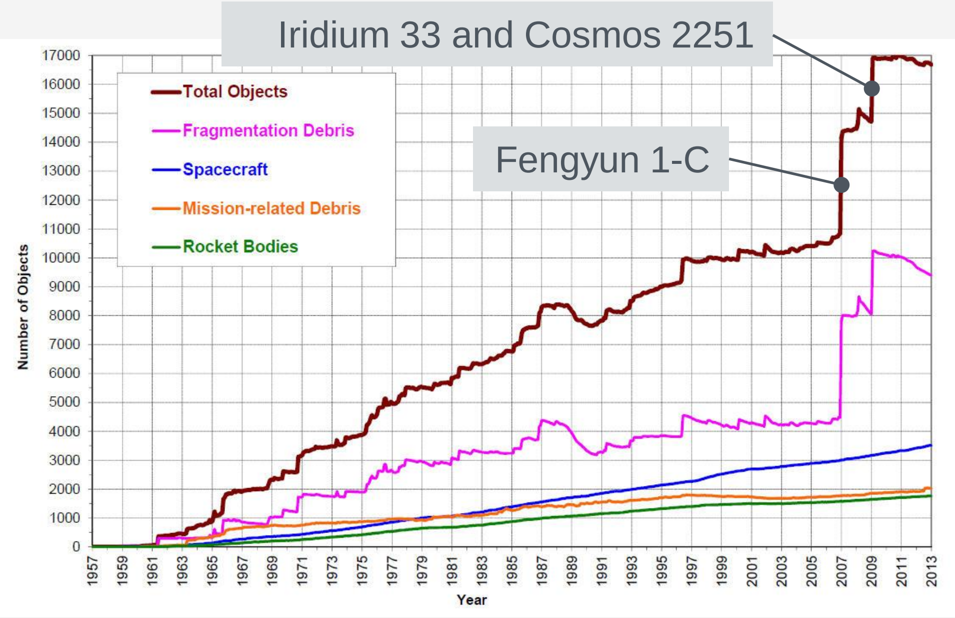
Long term evolution of space debris environment highly affected by the **fragmentations of massive objects**

Different **metrics** to rank space objects depending on their **impact on the environment** considering several factors
(e.g. mass, orbit, residual lifetime)

> Utzmann et al. 2012, Bastida Virgili and Krag 2013, Lang et al. 2013, Lewis 2014, Rossi et al. 2015,

Possible application:
identification of good **candidates** for **active debris removal** missions

Growth of the catalogued population of objects in Earth orbit (IADC)



eco_B

Environmental Consequences of Orbital Breakups

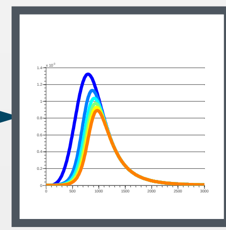
It measures how the **fragmentation** of the spacecraft will affect the collision risk for **operational satellites** in LEO

Object's parameters

Targets' trajectories

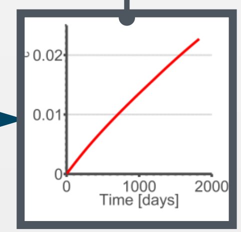
Breakup model

NASA model for catastrophic collisions



Analytical propagation

Continuity equation to model the effect of atmospheric drag



Collision probability

Analytical formulation based on the kinetic theory of gas

CiELO
Cloud debris Evolution for Low Earth Orbits

> Letizia, Colombo, Lewis, *JGCD*, 38(8), 2015 | *JGCD*, 09/2015 | *ASR*, 12/2015

OUTLINE

INTRODUCTION

01

Target selection

Definition of a set of targets representative of operational satellites

02

Index computation

Structure of the tool and computation for the objects in DISCOS

03

Applications

Connection between the index and the severity of breakups

CONCLUSIONS

Target selection

1

TARGET SELECTION

algorithm

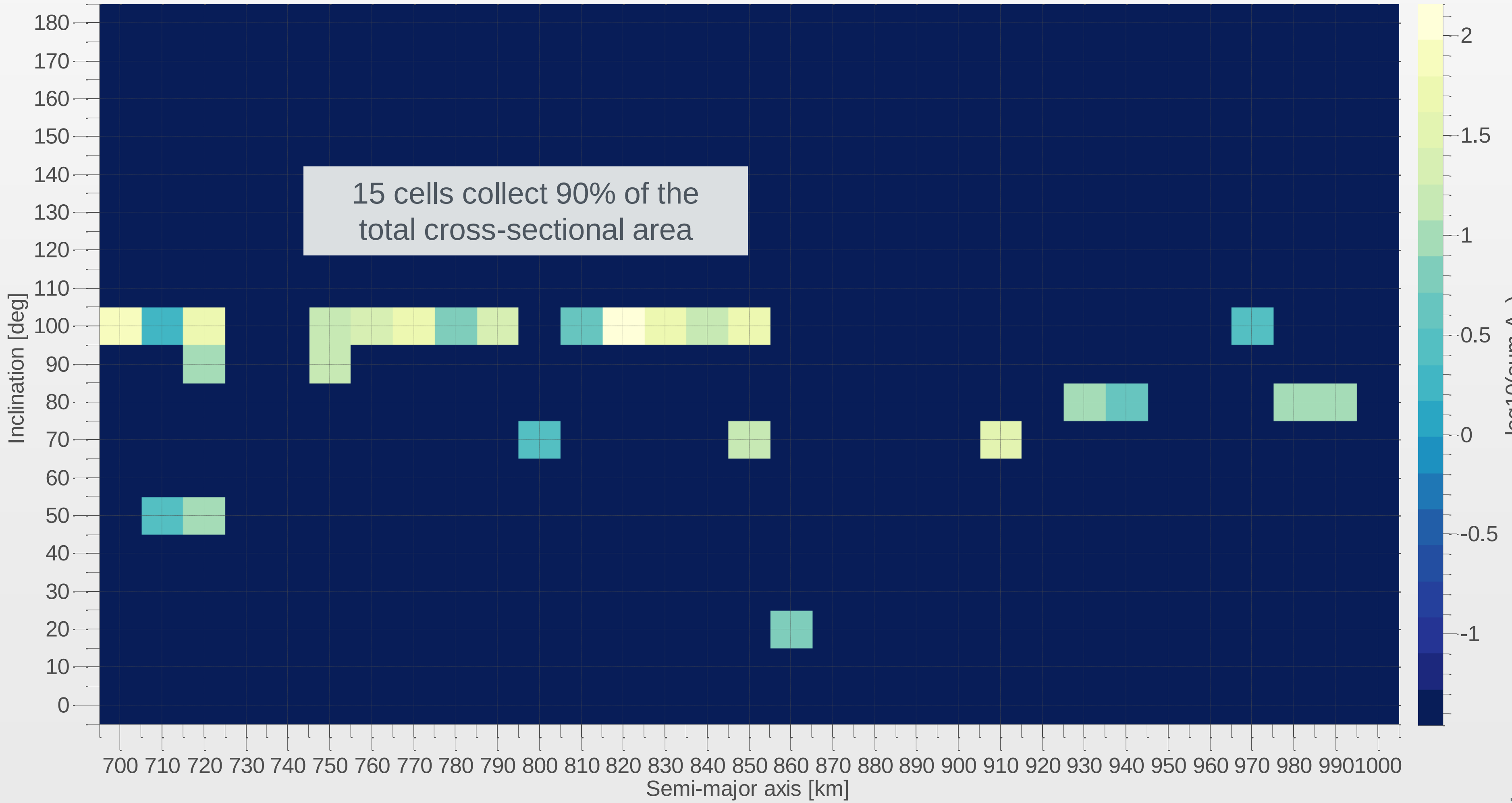
1. Input: **database** with all possible **targets**
2. Definition of a **grid** in **altitude** (semi-major axis) and **inclination** and computation of the **total cross-sectional area** in each cell

TARGET SELECTION

distribution of the cross-sectional area

2

spacecraft launched in the last 10 years,
in orbit between 700 and 1000 km (DISCOS)



TARGET SELECTION

algorithm

1. Input: **database** with all possible **targets**
2. Definition of a **grid** in **altitude** (semi-major axis) and **inclination** and computation of the **total area** in each cell
3. **Selection** of top cells and definition of **representative objects**
   area-to-mass ratio equal to cell average
   semi-major axis and inclination equal to the cell centre

TARGET SELECTION
algorithm

1. Input: **database** with all possible **targets**

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   area-to-mass ratio equal to cell average
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4. **Index** = sum of the collision probability for the reference targets

$$I = \sum_{j=1}^{N_T} w_j \, p_{c,j}$$

$$w_j = \frac{(A_c)_{\mathrm{cell},j}}{(A_c)_{\mathrm{tot}}}$$

weighting factor based on how relevant the cell is compared to the total population

$$p_{c,j}$$

cumulative collision probability for the *j* object after **25** years

Index computation

2

INDEX COMPUTATION

variation with orbital parameters and mass

Index computed for **synthetic** objects on a grid of **semi-major axis**, **inclination**, **mass**

INDEX COMPUTATION

variation with orbital parameters and mass

Index computed for **synthetic** objects on a grid of **semi-major axis**, **inclination**, **mass**

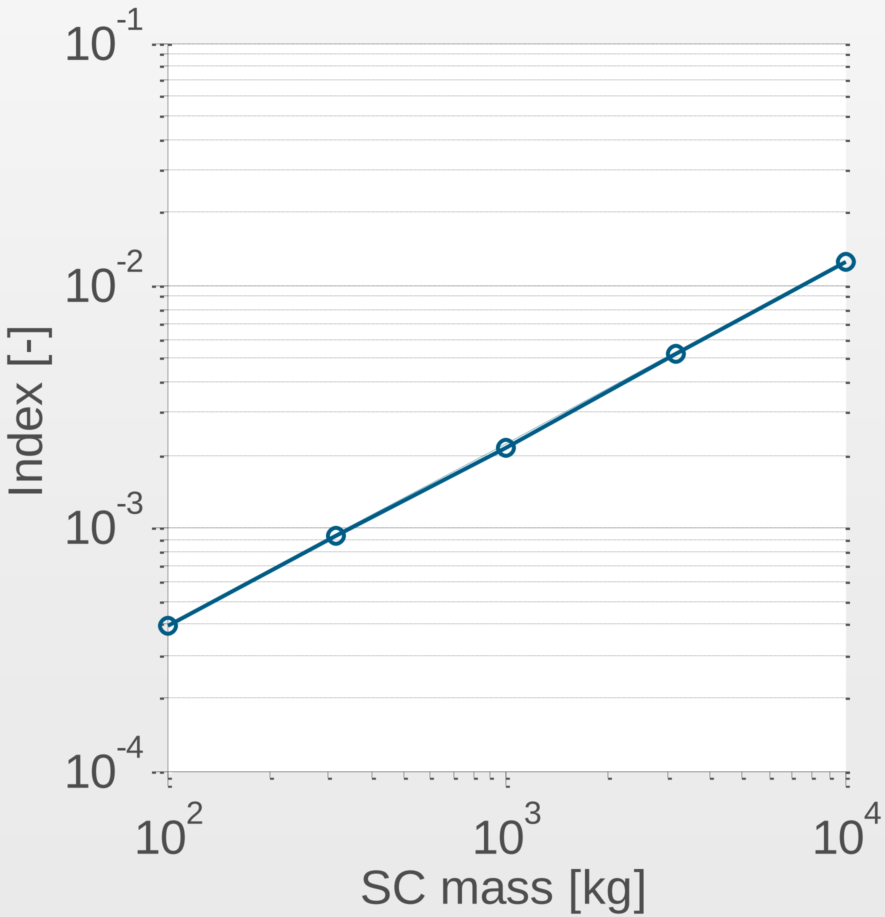
The variation of the index with the **mass** follows the same **power law** that describes the **number of fragments** as a function of the fragmenting mass

Index ~ $M^{0.75}$

N_F ~ $M^{0.75}$ (NASA breakup model)

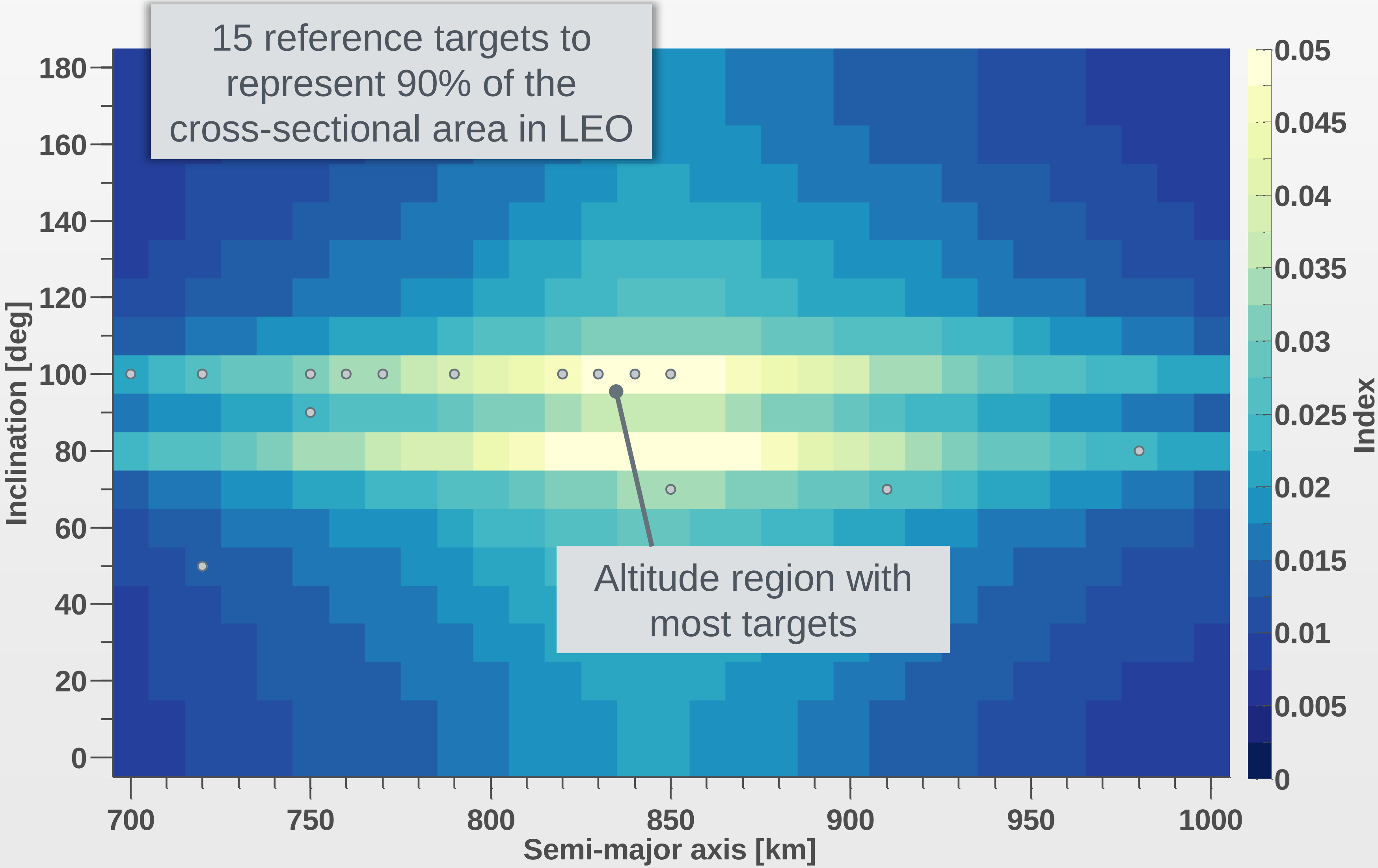
The index can be computed for a **reference mass** and **rescaled**

The variation of the index with the spacecraft mass



INDEX COMPUTATION

reference layer for fixed mass value (10000 kg)



INDEX COMPUTATION

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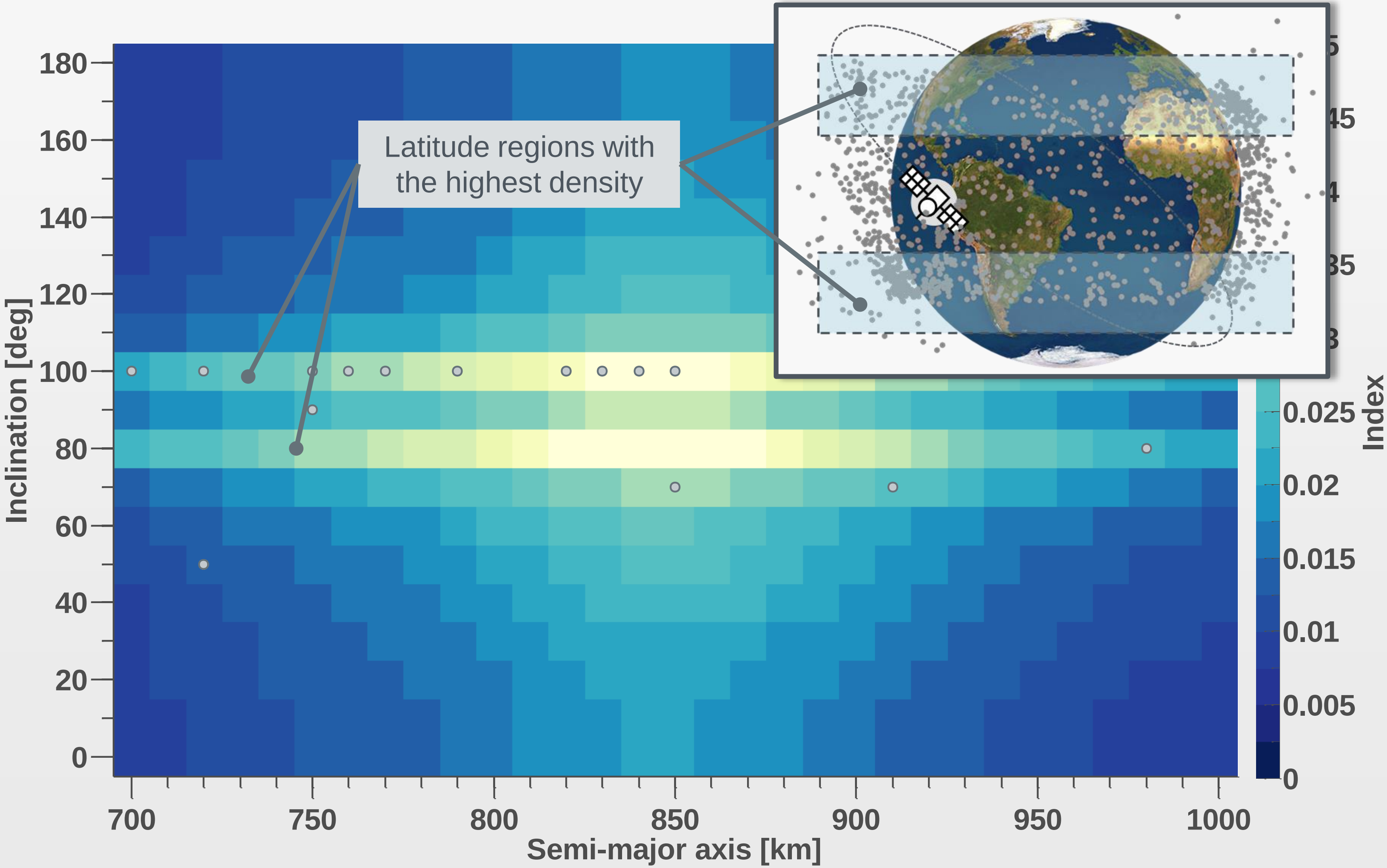
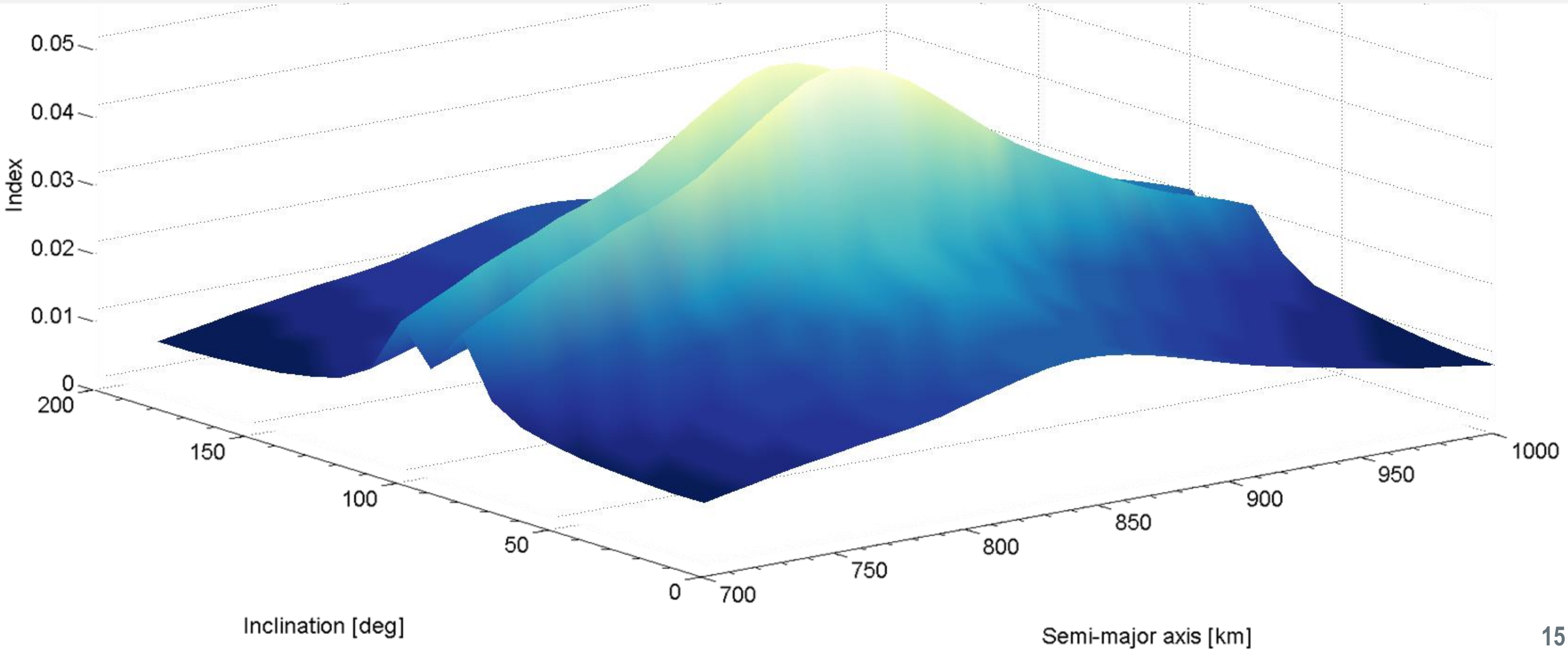


INDEX COMPUTATION

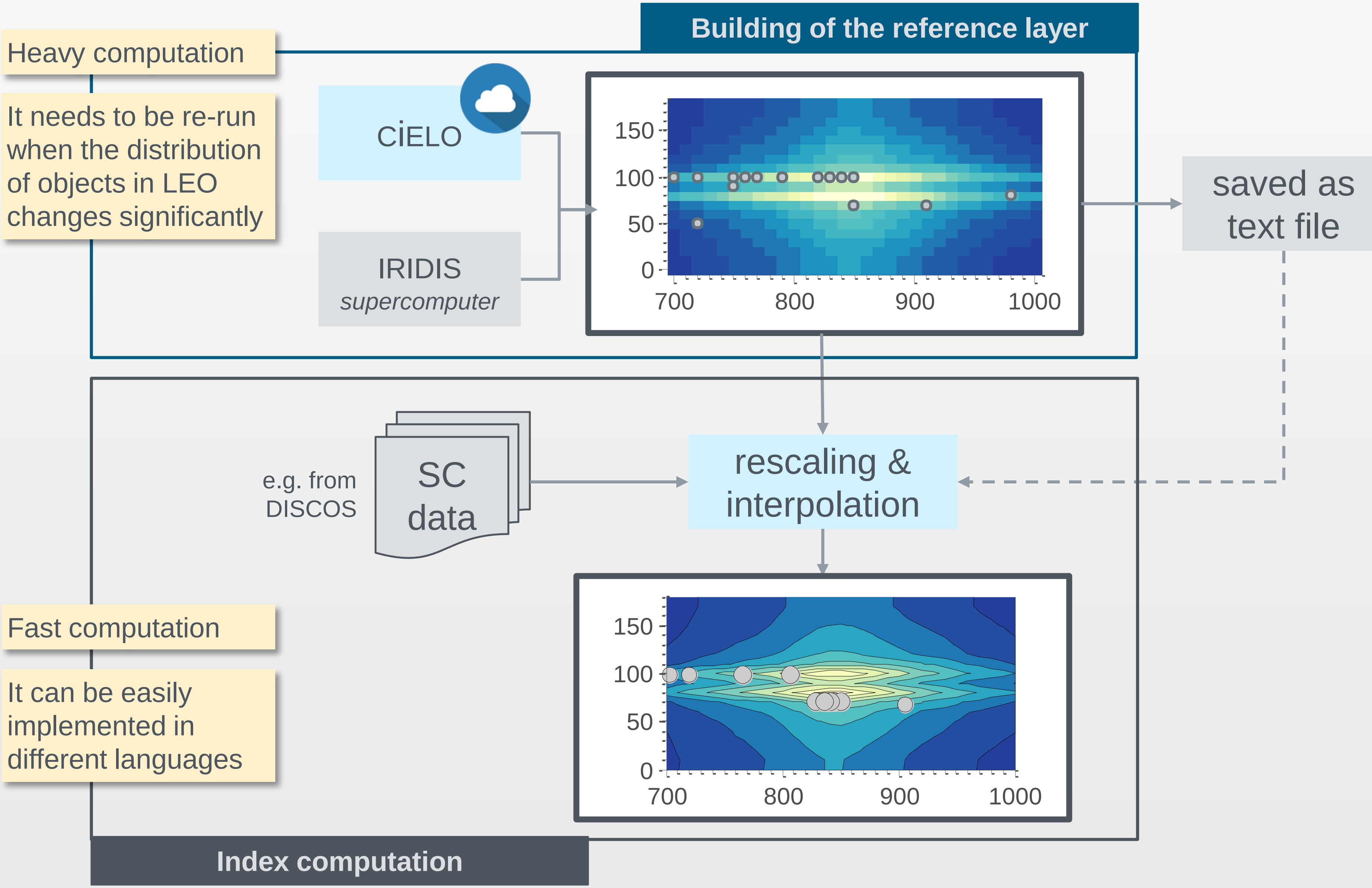
two-step process

Computation of the index for any space object

1. **Rescaling** of the *reference layer* according to the **mass** of the object
2. **Interpolation** of the value on the grid points, to obtain the index considering the value of **semi-major axis** & **inclination**



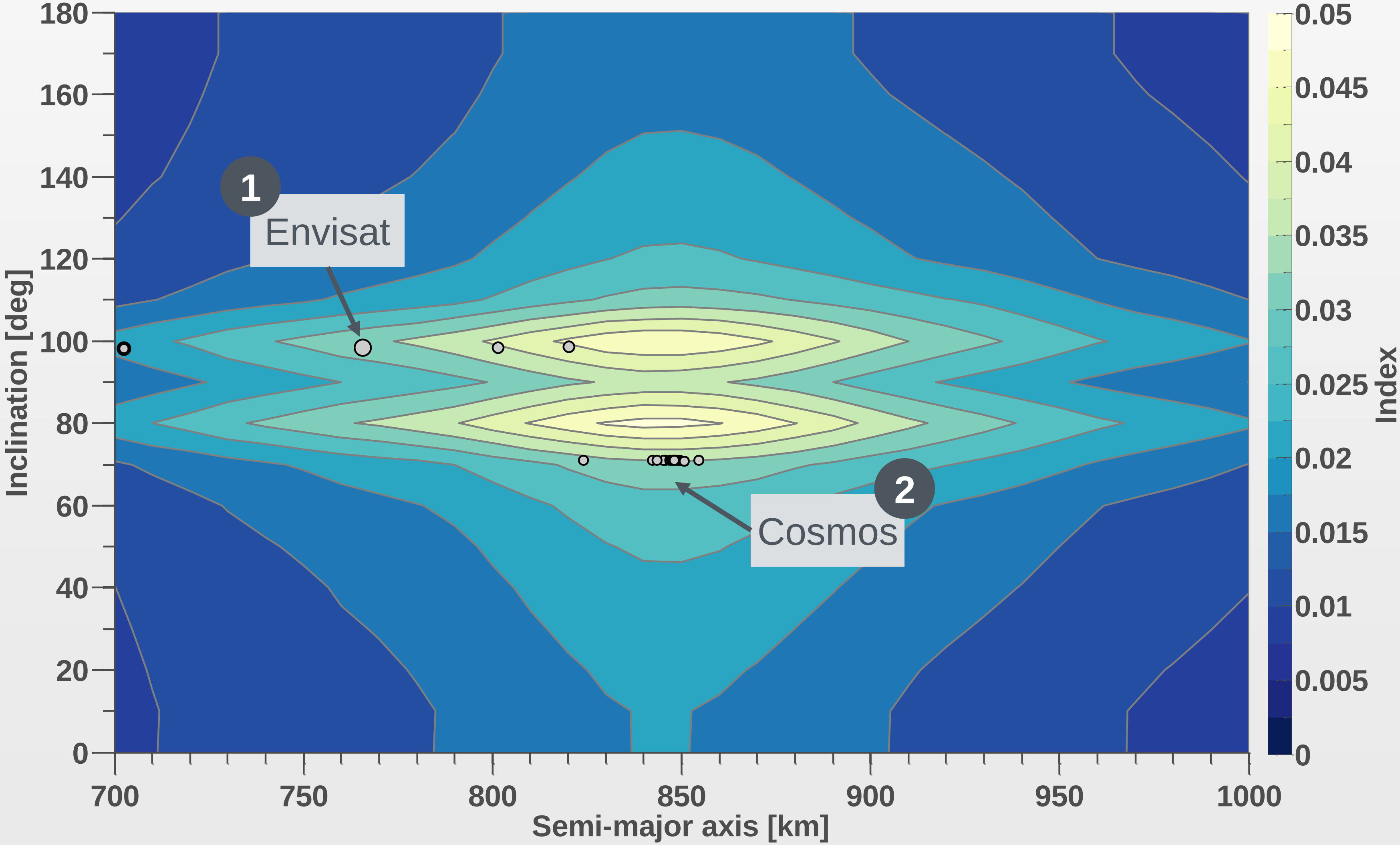
STRUCTURE OF THE TOOL



INDEX COMPUTATION

combination with DISCOS database

Input = payload launched more than 10 years ago



Applications

3

EXAMPLE OF APPLICATION

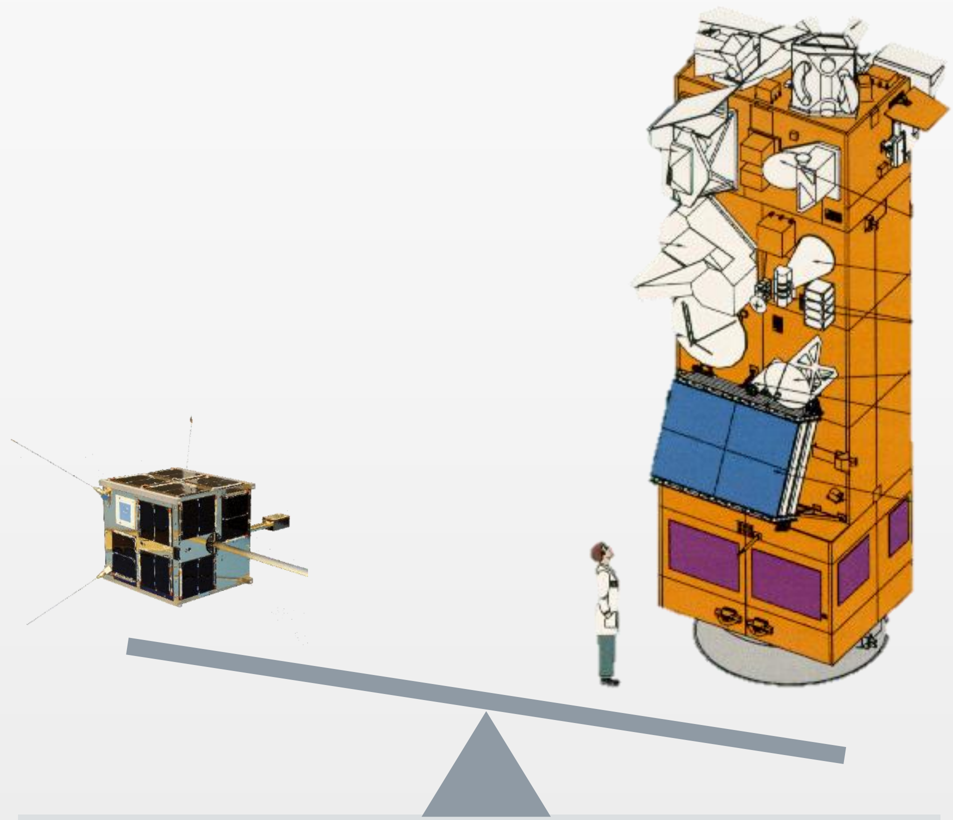
licensing process

Possible applications of the index

- candidates for **active debris removal**
- support to **spacecraft licensing**

It could be apply to distinguish **different classes of satellites** and **orbital regimes** when evaluating the compliance with **end-of-life requirements**

Interest in creating a **standard licensing procedure** to encourage commercial investors



100 kg 700 km low inclination	4000 kg 850 km polar orbit

INTERPRETATION OF THE INDEX

severity categories

Connection between the index and the severity categories in FMECA (Failure Modes, Effects, and Criticality Analysis)

Severity	Dependability effects	Safety effects	Breakup consequences
Catastrophic	Failure propagation	Severe detrimental environment effects	Subsequent collisions
Critical	Loss of mission	Major detrimental environment effects	Major increase in collision risk
Major	Major mission degradation		Increase in collision warnings
Minor	Minor mission degradation		Negligible

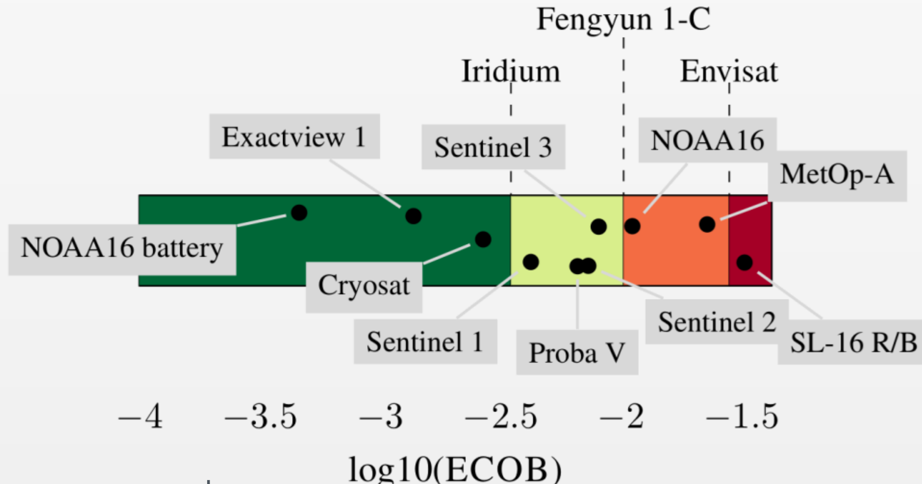
European Cooperation for Space Standardisation, "Space product assurance: Failure modes, effects (and criticality) analysis," ESA Requirements and Standards Division, ECSS-Q-ST-30-02C, 2009

CLASSIFICATION OF MISSIONS

severity categories and criticality matrix

The link between index & severity cannot be based on the numerical value only
(it depends on the set of targets)

Definition of **reference breakups** as thresholds of the severity levels
(e.g. Iridium, Fengyun 1-C, Envisat)



Flux of debris objects
Reliability of end-of-life strategy

The severity categories are combined with the probability level in the **criticality matrix**:
orange cell = critical element suggested design review

Severity category	SNs	Probability level			
		10^{-5}	10^{-3}	10^{-1}	1
		PNs			
		1	2	3	4
catastrophic	4	4	8	12	16
critical	3	3	6	9	12
major	2	2	4	6	8
negligible	1	1	2	3	4

CONCLUSIONS

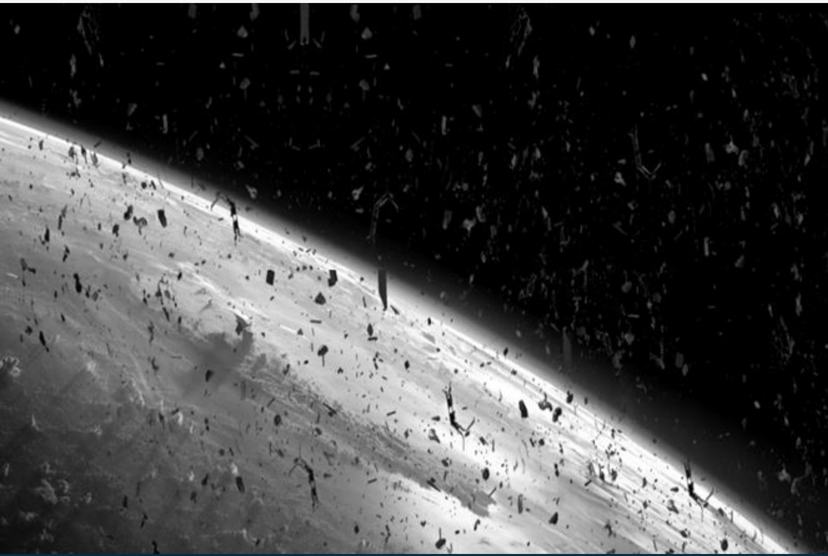
eco_B

An environmental index based on the assessment of the effect of breakups on **operational satellites** is proposed.

A set of **representative targets** is defined starting from the distribution of **cross-sectional area** in semi-major axis and inclination. The index is obtained as sum of the collision probability for the targets.

The index is initially computed for a fixed **mass** value and on a grid of points in **semi-major axis** and **inclination**. The index for studied spacecraft is obtained by **interpolation** of the values on the grid points.

The index can be combined with a database of spacecraft to identify good candidates for **active debris removal**. It can also be applied to the **licensing** phase of satellites by connecting the value of the index to the definition of severity categories.



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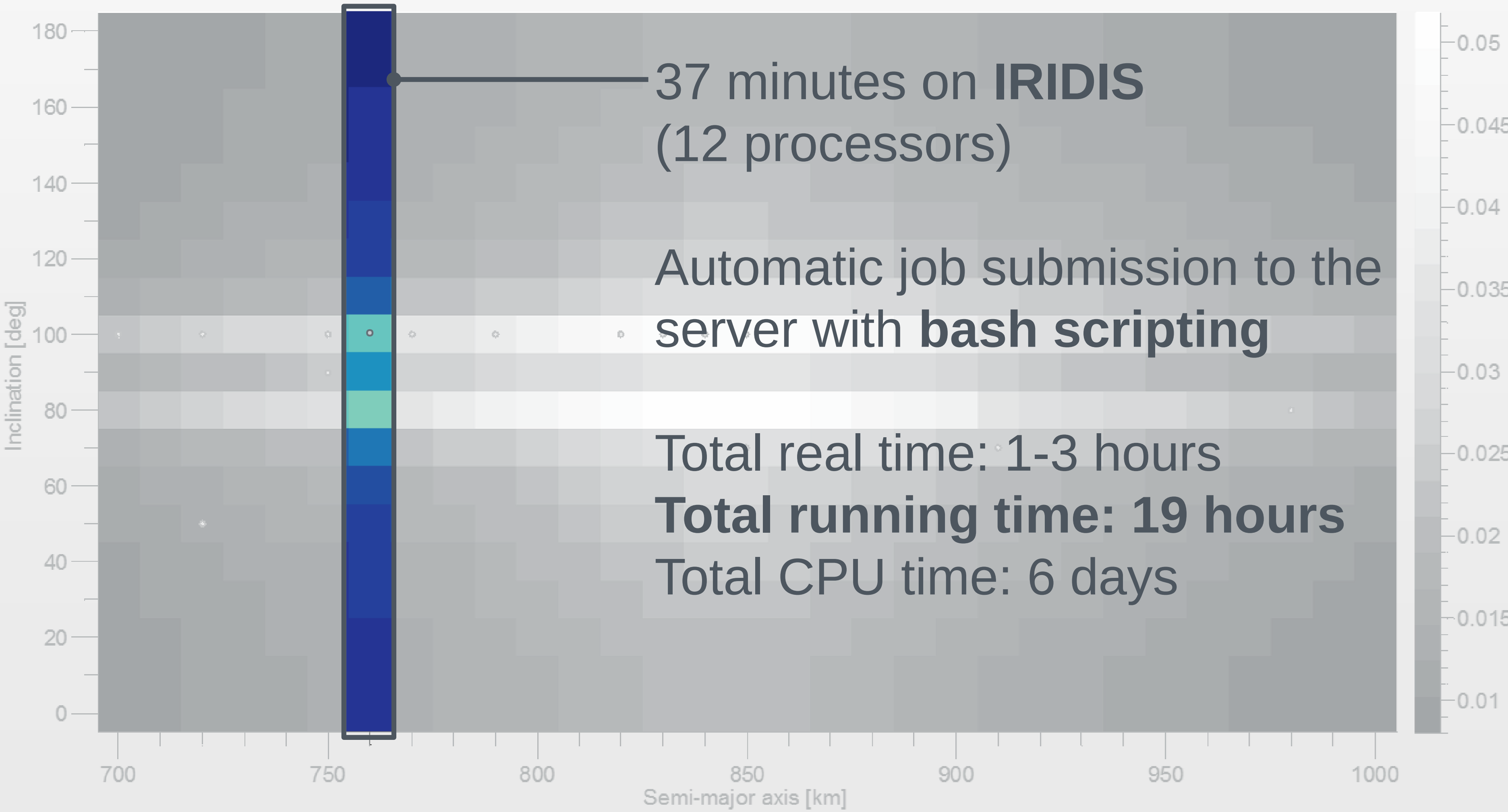
Backup slides

Computational time
Comparison with other formulations

A

COMPUTATIONAL TIME

MATLAB parallel + IRIDIS



37 minutes on **IRIDIS**
(12 processors)

Automatic job submission to the server with **bash scripting**

Total real time: 1-3 hours
Total running time: 19 hours
Total CPU time: 6 days

COMPARISON WITH OTHER INDICES

Figure of Merit (FOM)

$$\mathrm{FOM} = \Phi(h) A_c m^{0.75} \Delta t(h)$$

> Utzmann et al,
Ranking and characterization of heavy debris for active removal, IAC, 2012

Criticality of Spacecraft Index (CSI or Ξ)

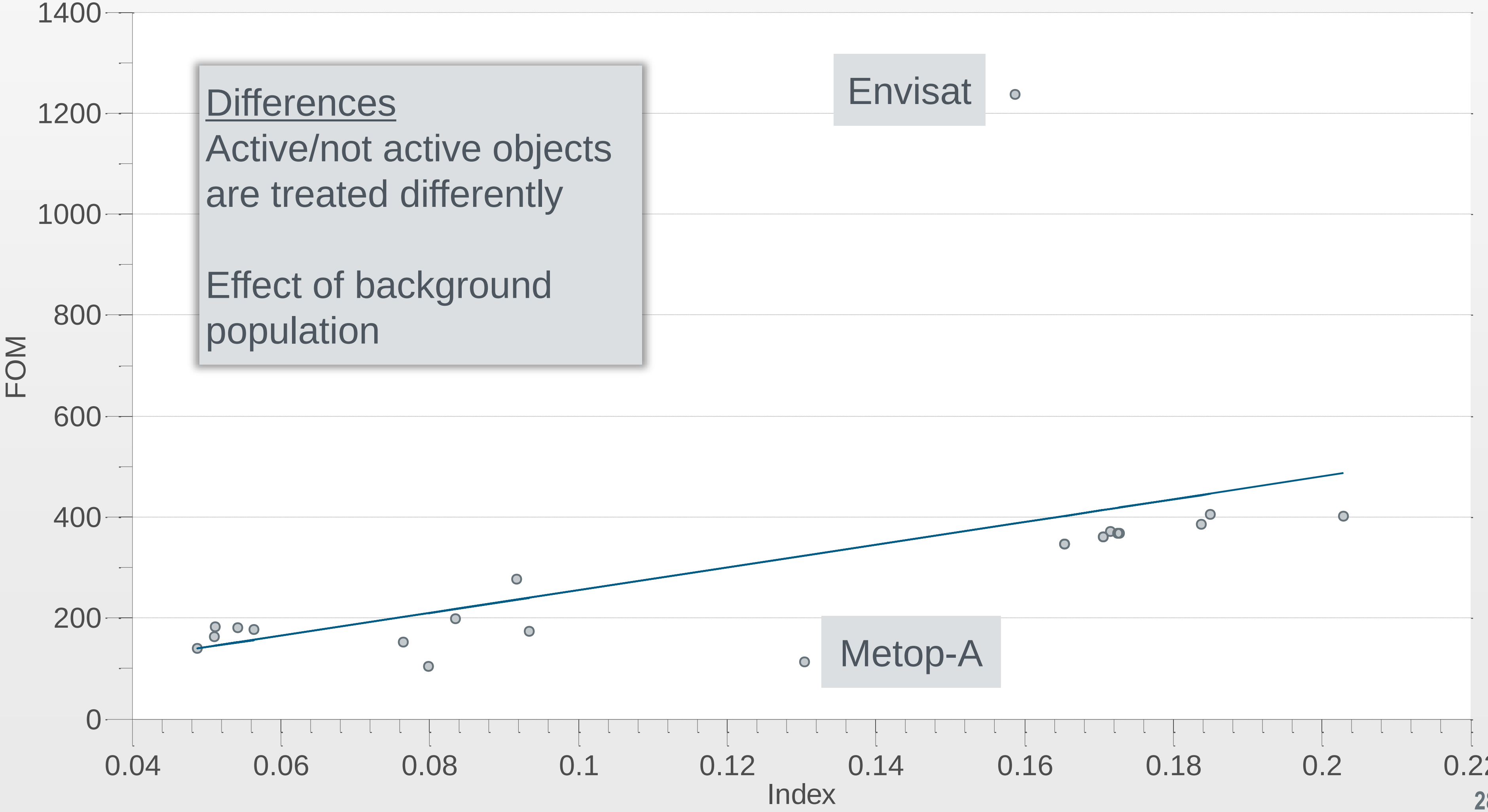
$$\Xi = \frac{m}{m_0} \frac{D(h)}{D(h_0)_c} \frac{\Delta t(h)}{\Delta t(h_0)} \frac{1 + k\Gamma(i)}{1 + k}$$

> Rossi et al,
The Criticality of Spacecraft Index, ASR 56(3), 2015

Yes (Flux, Φ)	**Environment**	Yes (Density, D)
Yes	**Cross sectional area (A_c)**	No
Yes	**Mass (m)**	Yes
Yes	**Lifetime (Δt)**	Yes
No	**Inclination**	Yes

COMPARISON WITH OTHER INDICES

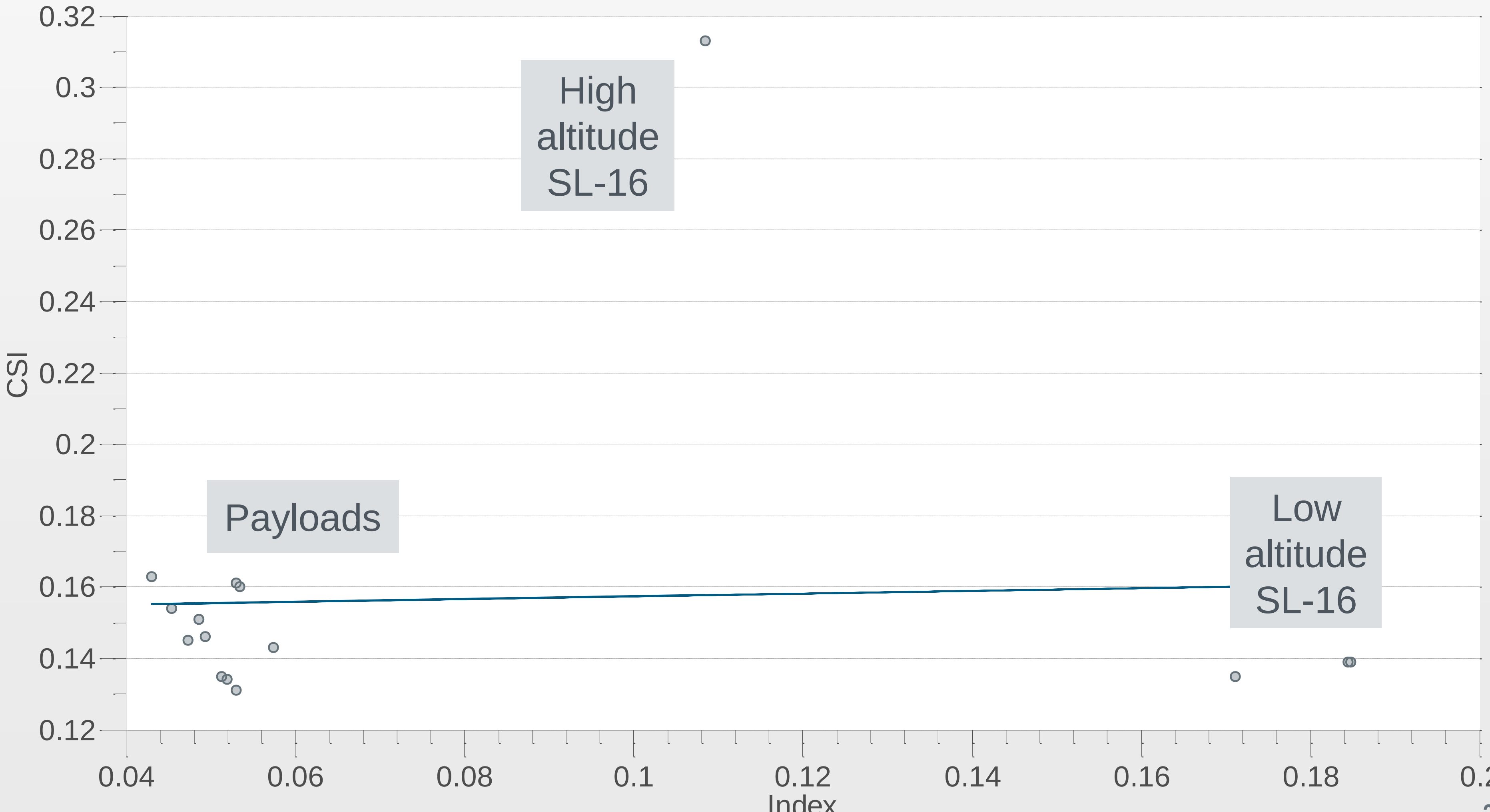
correlation with FOM



COMPARISON WITH OTHER INDICES

correlation with CSI

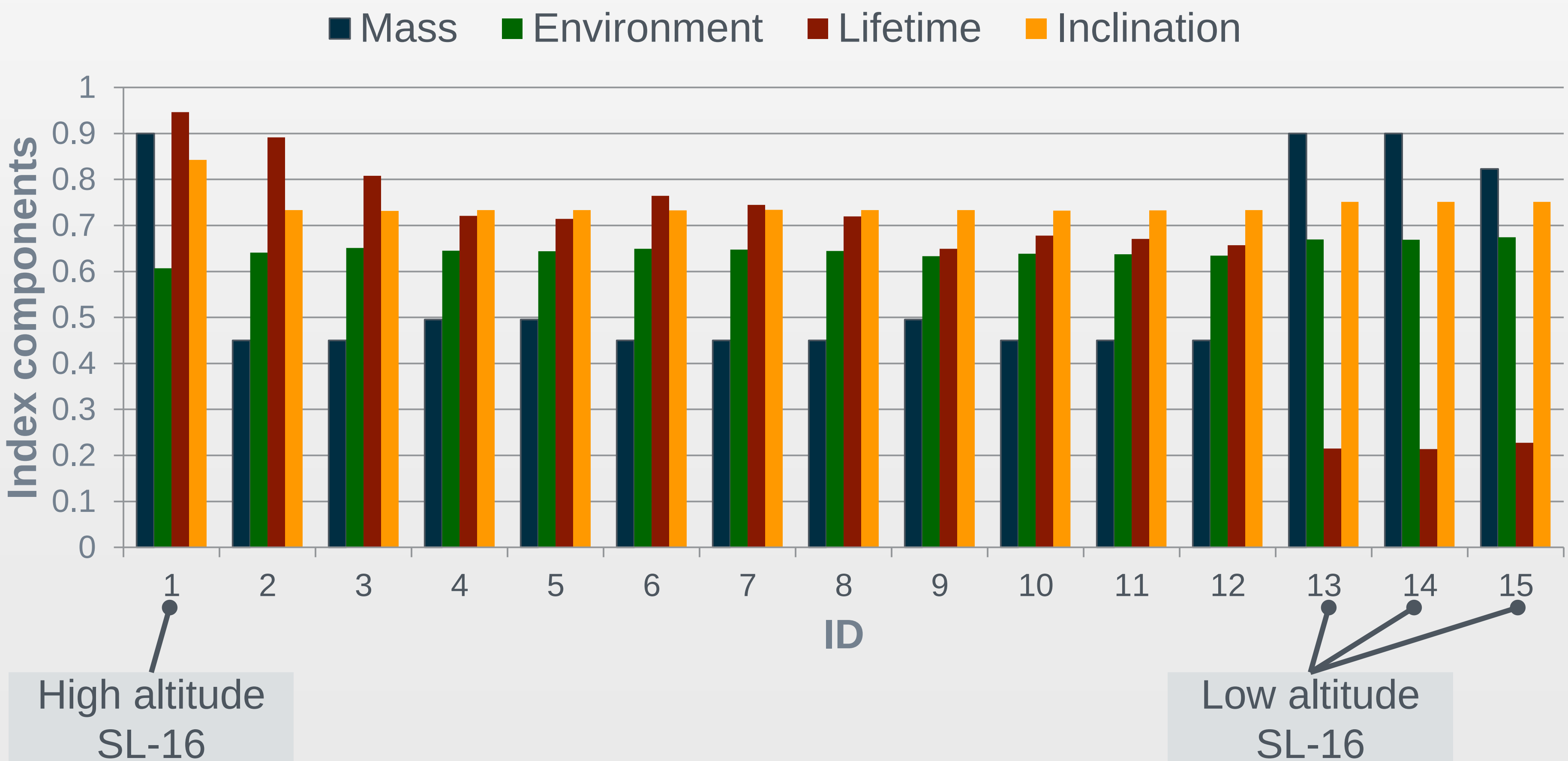
> Rossi et al,
The Criticality of Spacecraft Index,
ASR 56(3), 2015



COMPARISON WITH OTHER INDICES

components of CSI

$$\Xi = \frac{m}{m_0} \frac{D(h)}{D(h_0)_c} \frac{\Delta t(h)}{\Delta t(h_0)} \frac{1+k\Gamma(i)}{1+k}$$



COMPARISON WITH OTHER INDICES

CSI objects distribution

Difference
The altitude plays a different role in the two indices:
in CSI (mainly) lifetime,
in *I* distance from targets