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Advances in Modelling Space Capacity with THEMIS

2nd Space Capacity Allocation For The Sustainability Of Space Activities Workshop

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Contents

Current approach

01

Current approach
Environment impact estimation

- Environment impact as product of fragmentation probability (p_c, p_e) and effect (e_c, e_e):

$$I = p_c \cdot e_c + p_e \cdot e_e$$

- Estimating Index for missions using reference epoch formulation for effect:

$$e(\Delta t) = \frac{\sum_{i=1}^{N_t} P_{c_i}(\Delta t) \cdot A_{t_i}}{A_{tot_0}}$$

- Representative targets defined by area, semi-major axis and inclination in LEO

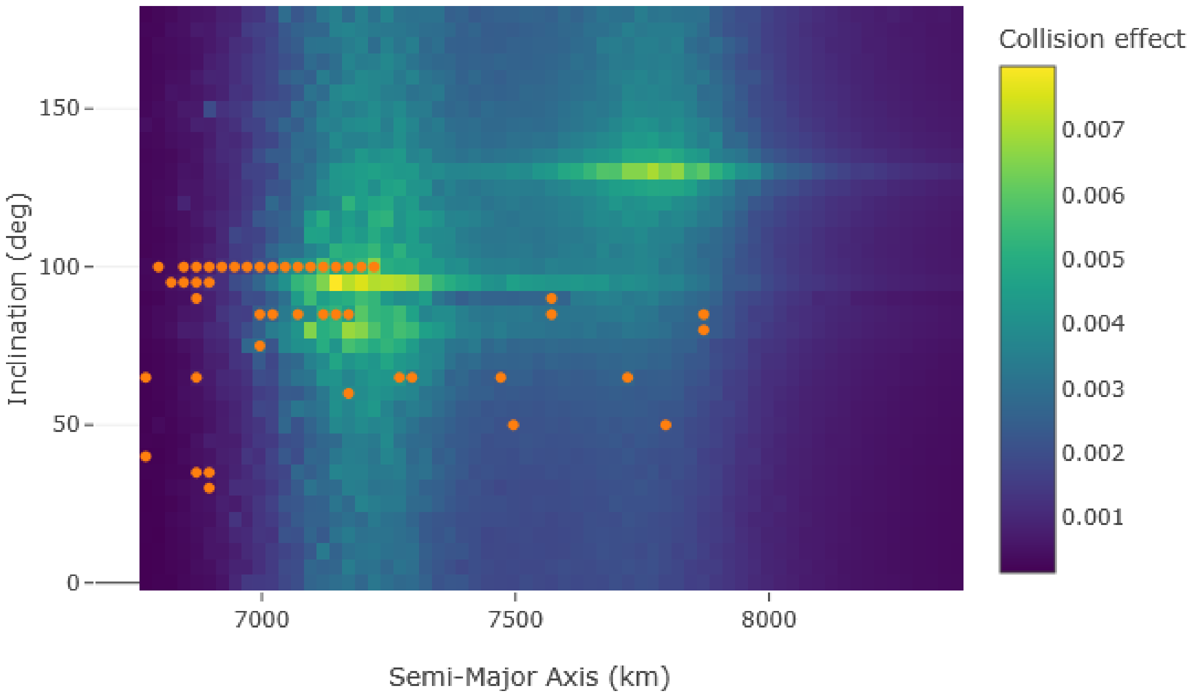

Fig.1 – Map of fragmentation effect over Inclination and SMA in LEO.

➢ Letizia F., Colombo C., Lewis H. G., Krag H., "Assessment of breakup severity on operational satellites", Advances in Space Research, 2016

Current approach
Capacity estimation principle

- Computation of the overall space capacity (C) consumed by orbiting objects and the contribution of each mission to it
  - Compute the impact of single objects
  - Aggregate the results of single objects
  - Provides scalar value for consumed capacity

$$C = \sum_{j=1}^{N_m} EI_j$$

- N_m: number of missions
- EI_j: environmental impact of the *j-th* mission

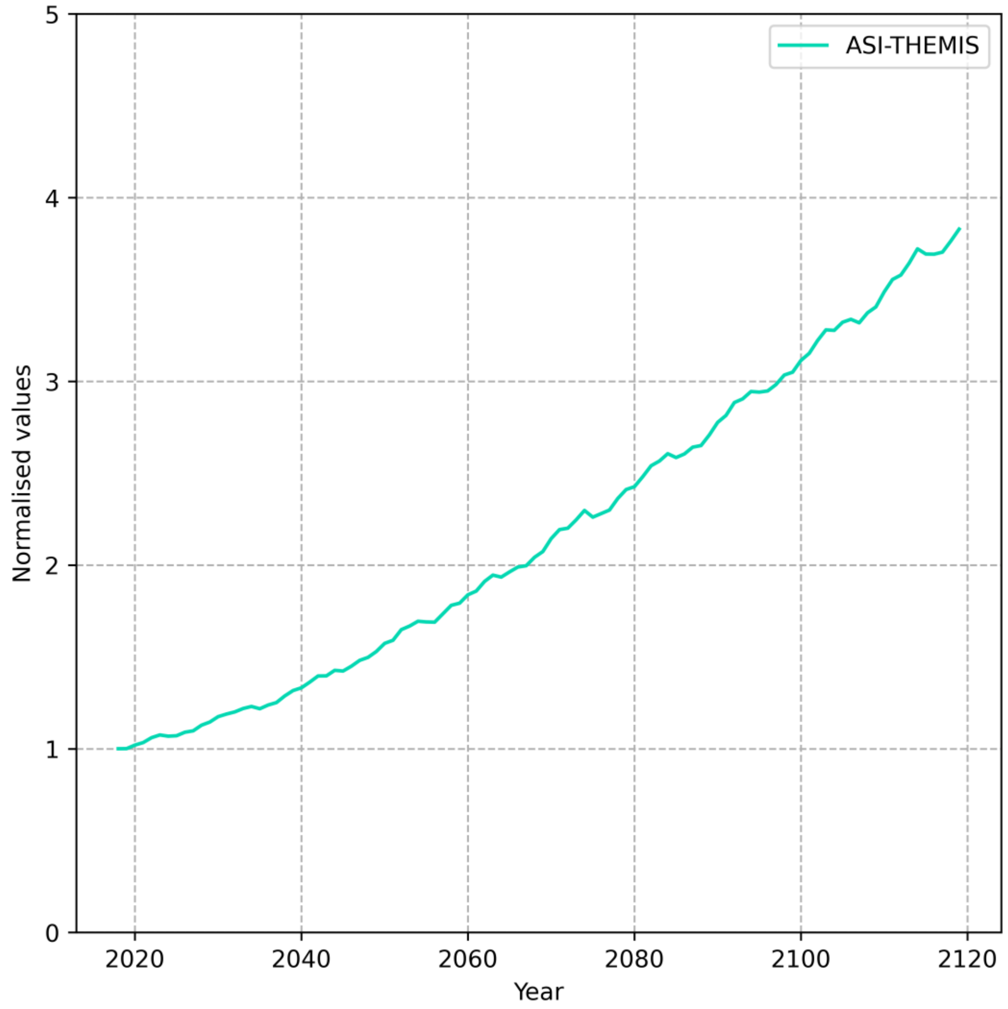

Fig.2 – Consumed capacity evolution over time.

- Letizia F., Colombo C., Lewis H. G., Krag H., "Assessment of breakup severity on operational satellites", Advances in Space Research, 2016
- Colombo C., et al. "Evaluation of the Space capacity share used by a mission", 73rd International Astronautical Congress (IAC), 2022
- Muciaccia A., et al., "Low Earth Orbit capacity thresholds investigation for a sustainable use of the space environment", 75th International Astronautical Congress (IAC), 2024

Current approach
Gaps

- Only consumed capacity is considered not available capacity
- Single, averaged scalar for capacity
  - Effect might affect certain region more
  - Averaging hides peaks
  - Unclear where highest impact would happen
- Approach takes a long time to evaluate (~1 hour per scenario)
- Contributions from secondary collision (a collision caused by a previously generated fragment) is not accounted for
- Potentially difficult to interpret results

Changes

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Proposed changes
Overview

- Breaking down the effect on each representative target
- Introducing new Effect terms
- Using representative objects
- Considering 2nd order effects

Proposed changes
Per bin Effects

- Estimate effect on individual representative targets
- Form a vector of effects in each bin
- Re-using the same formulations but avoiding aggregation across bins
- Improves interpretation of results
- Avoids averaging of highly affected bins
- Most affected region can be identified

$$\vec{e} = \begin{bmatrix} \frac{P_c(\Delta t)\cdot A_{t_1}}{A_{tot}} \\ \frac{P_c(\Delta t)\cdot A_{t_2}}{A_{tot}} \\ \vdots \\ \frac{P_c(\Delta t)\cdot A_{t_N}}{A_{tot}} \end{bmatrix}$$

Proposed changes
New effect terms

- When using the per satellite effect vector possible effect terms:
  - Collision avoidance manoeuvres (CAMs) per satellite per year
  - Per satellite probability of damage/destruction before end of mission
  - Number of objects/fragments/collisions in environment to compare to proxy values
- Improves interpretation of results for operators and allows better setting of upper limits

Proposed changes
Per Bin Satellite properties

- Not evaluating individual objects
- Use representative objects described via:
  - Area, Mass, SMA, inclination, number of satellites
- Evaluate effect of each average object on other average targets and store in effect matrix $\boldsymbol{e}$
- Evaluate p_c for each average target
- Find Capacity vector $\vec{C}$ through multiplication

$$\boldsymbol{e} = \begin{pmatrix} e_{1->1} & e_{2->1} & e_{3->1} \\ e_{1->2} & e_{2->2} & e_{3->2} \\ e_{1->3} & e_{2->3} & e_{3->3} \end{pmatrix}$$

Proposed changes
Per Bin Satellite properties

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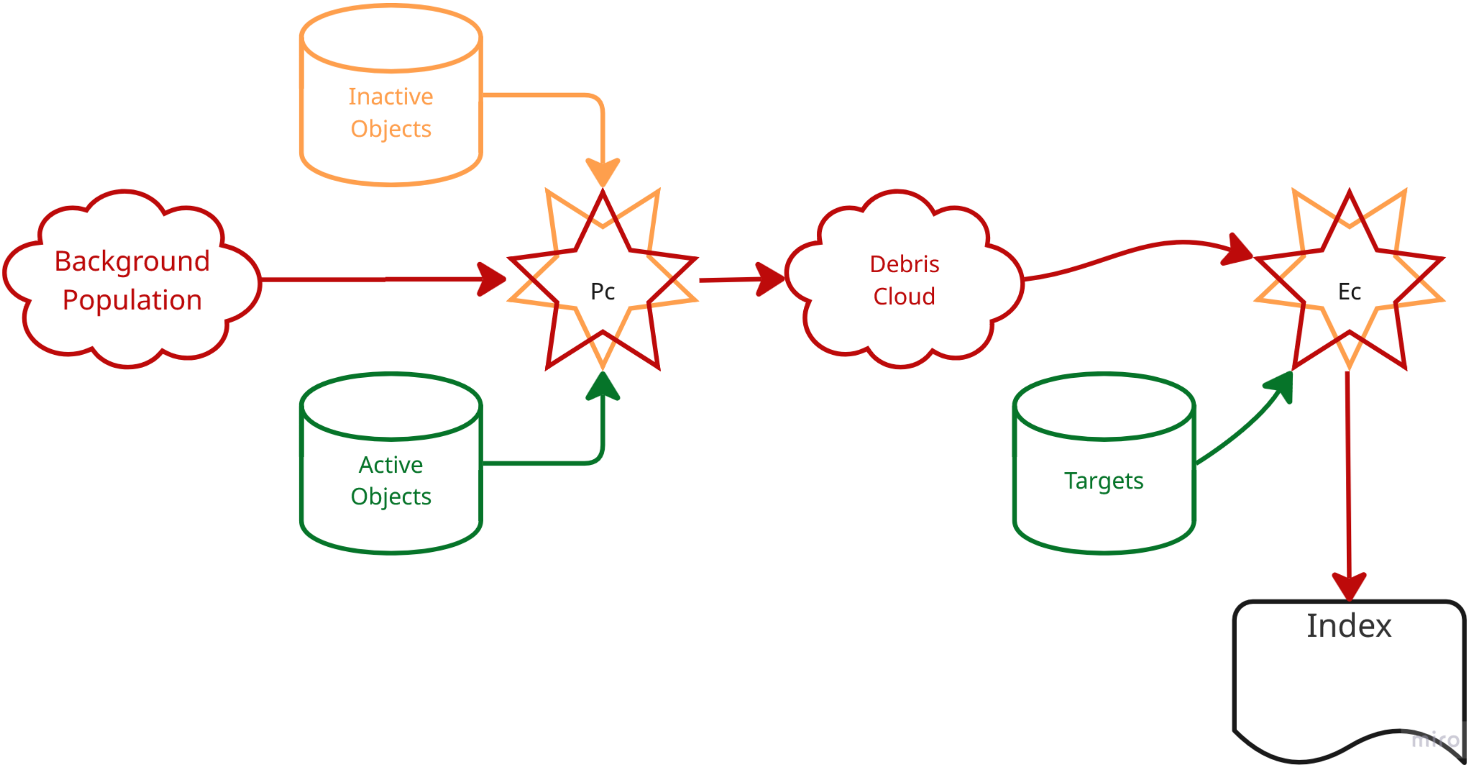
$$\vec{p_c} = \begin{bmatrix} \left(1 - e^{-\phi \cdot A_{t_1} \cdot \Delta t}\right) \cdot n_1 \\ \left(1 - e^{-\phi \cdot A_{t_2} \cdot \Delta t}\right) \cdot n_2 \\ \vdots \\ \left(1 - e^{-\phi \cdot A_{t_N} \cdot \Delta t}\right) \cdot n_N \end{bmatrix}$$

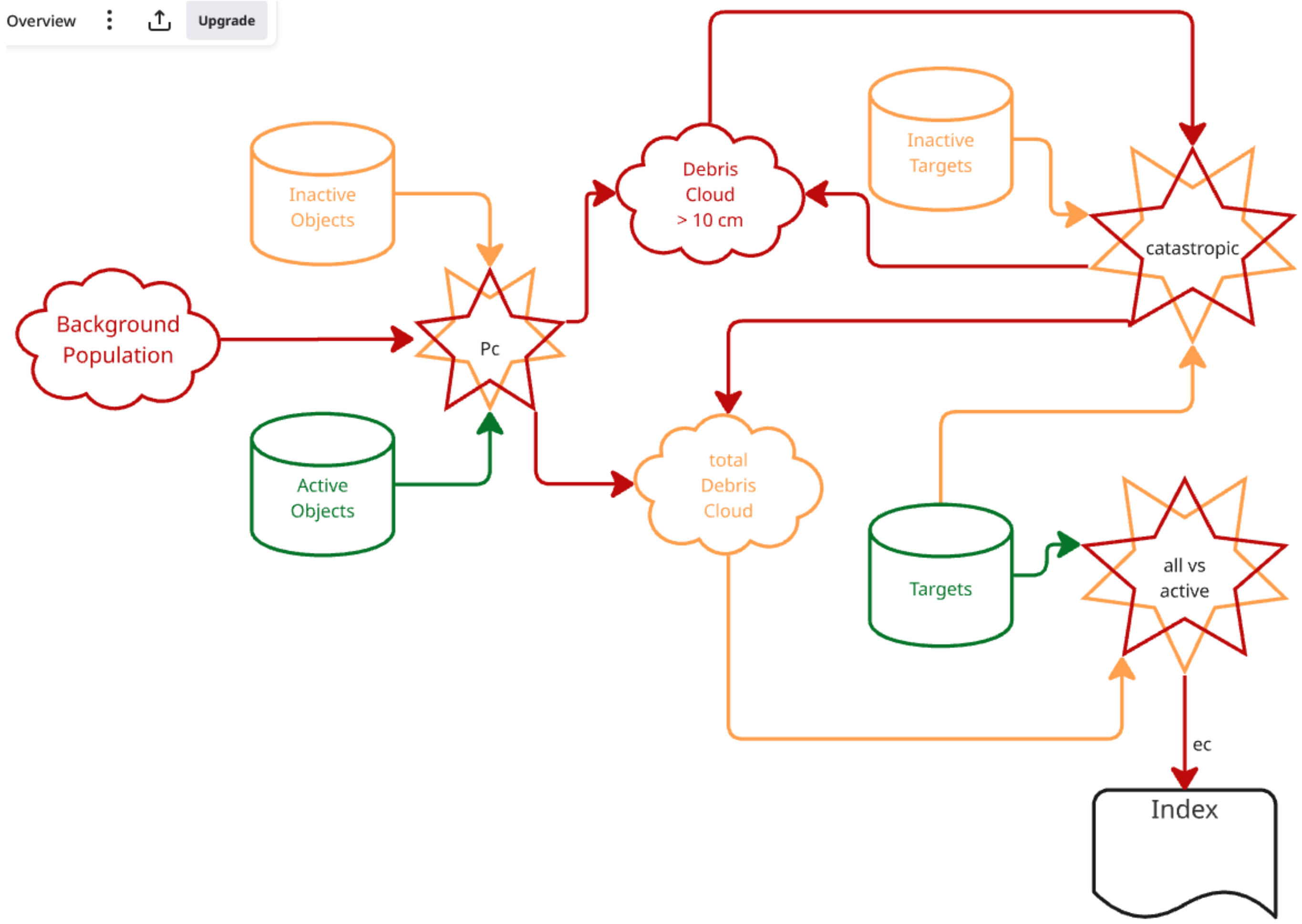
$$\vec{C} = \boldsymbol{e} \cdot \overrightarrow{p_c}$$

Proposed changes
Secondary Collisions



- Estimate direct effect of fragmentation on representative targets
- Fragmentation of Targets not taken into consideration
- Fragments capable of causing a catastrophic collision would need to be modeled separately

Proposed changes
Secondary Collisions



New Capacity approach

e_{tot}: Effect including secondary effects
E: Expected number of catastrophic collisions
e_p: Effect of primary fragmentations
e_s: Effect of secondary fragmentations

$$e_{tot} = e_p + E_p \cdot e_s + E_p \cdot E_s \cdot e_s + E_p \cdot E_s \cdot E_s \cdot e_s + \ \dots$$

$$e_{tot} = e_p + E_p \cdot (e_s + E_s \cdot (E_s \dots))$$

$$e_{tot} = e_p + E_p \cdot \sum_{n=0}^{\infty} E_s^n \cdot e_s$$

$$e_{tot} = e_p + \frac{E_{cat,p} \cdot e_s}{1 - E_{cat,s}}$$

Proposed changes
Secondary Collisions

- Approach works best in vector form to account for different relations between objects

$$\vec{C} = \boldsymbol{e} \cdot (\boldsymbol{I} - \boldsymbol{E})^{-1} \cdot \overrightarrow{p_{c,cat}}$$

- Allows very fast evaluation of the stability of a scenario
- Single evaluation for a “static” environment
- Consumed capacity goes to infinity for an unstable environment

Preliminary results

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Proposed changes
Per bin Effects

- Effect shown over different bins
- Large variation of effect
- Difference between least affected bin and most affected bin is larger than factor 10

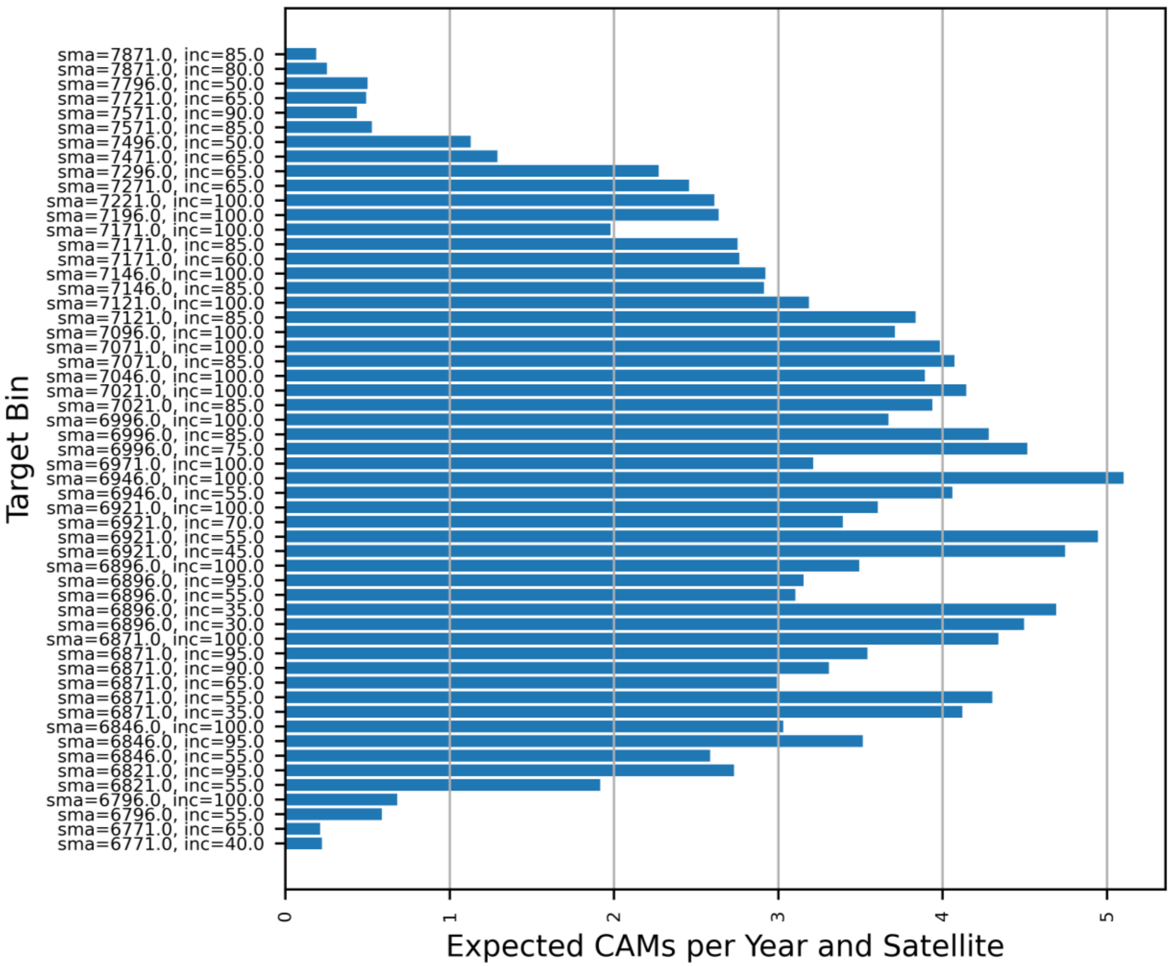

Fig.3 – Effect of a fragmentation broken down by representative targets.

Preliminary results
Capacity over object number

- Population based on 2023 active only population
- Scaling up population as is
- 10 cm as catastrophic collision threshold
- 540 kg per object
- 90% CAM efficacy
- Exponential capacity growth when considering 2nd order effect, linear growth without
- Capacity limit depends on environment settings

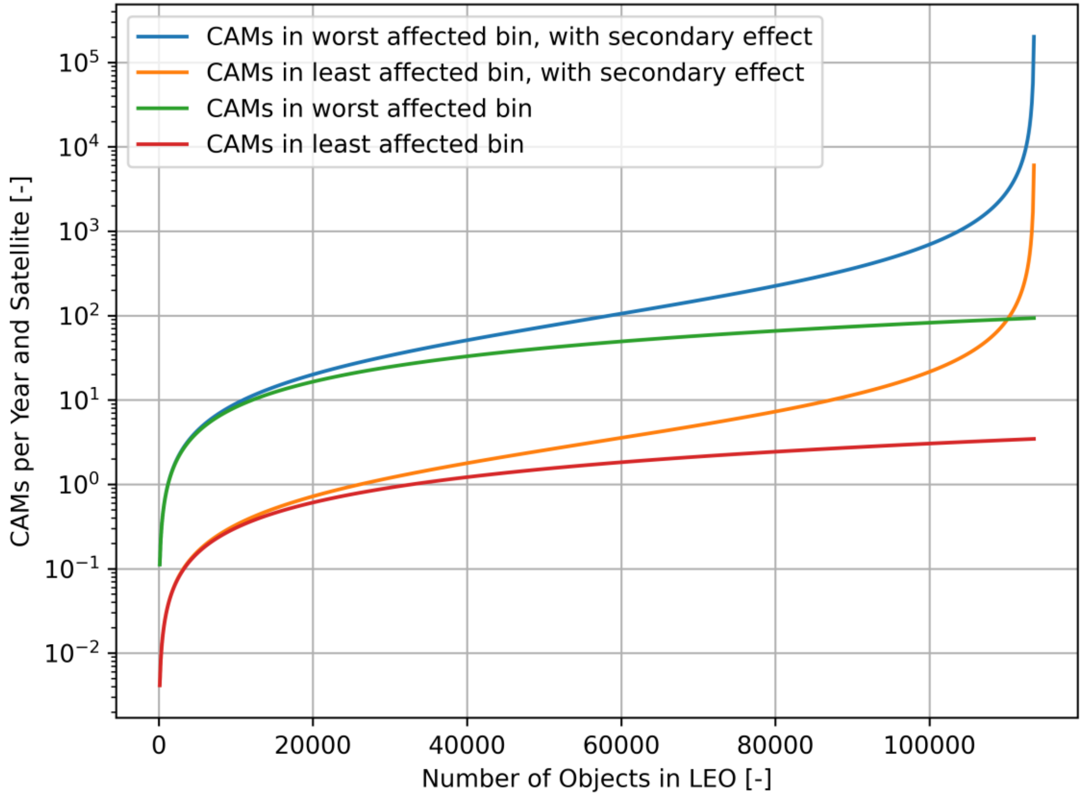

Fig.4 – Consumed capacity over number of objects in LEO.

Conclusion

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Conclusion
Applicability and Shortcomings

- Approach provides the consumed capacity for a given, static scenario
- Limitations:
  - Effect of Fragments is assumed to disappear after propagation time (15-year default)
  - Effect with 2^{nd} order effects is after an infinite time
  - Use of average objects
  - Fixed threshold for catastrophic collisions
  - Objects are assumed to be replaced immediately
- Next steps:
  - Gather more up to date data on current distribution of objects (including inactive)
  - Determining realistic values for parameters to set
  - Integration in THEMIS
  - Definition of Thresholds for sustainability

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Thank you for your attention

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Backup
Capacity limit over CAM efficacy

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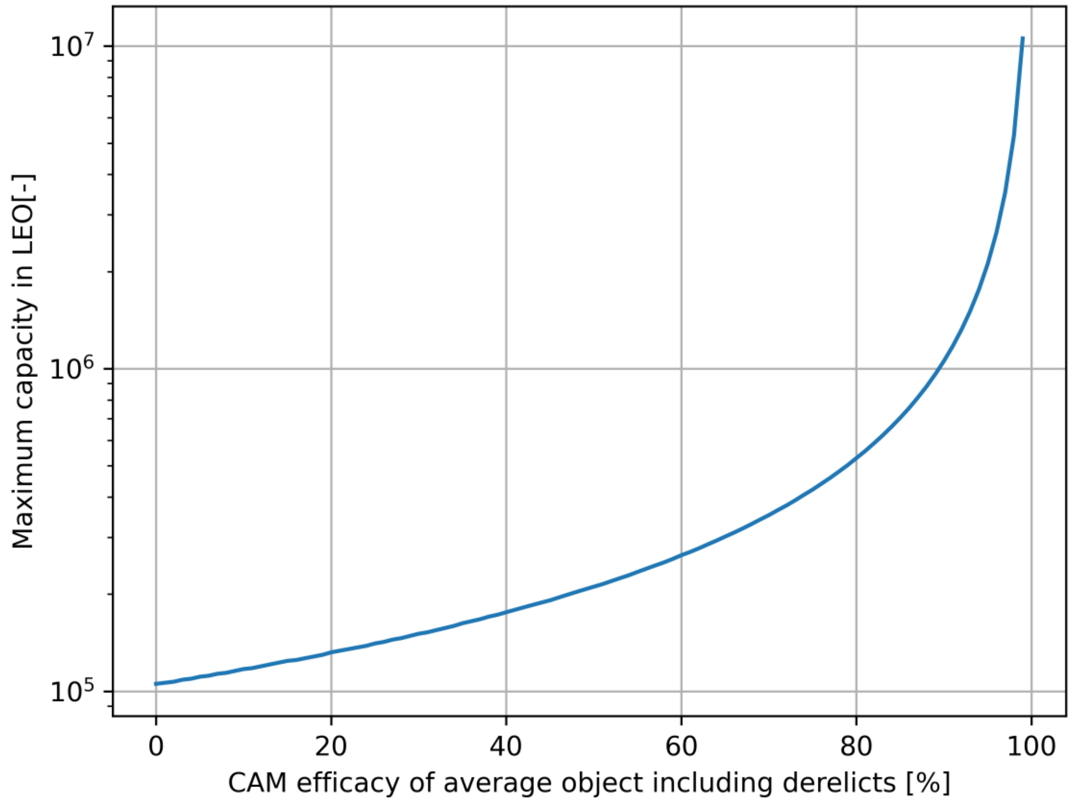

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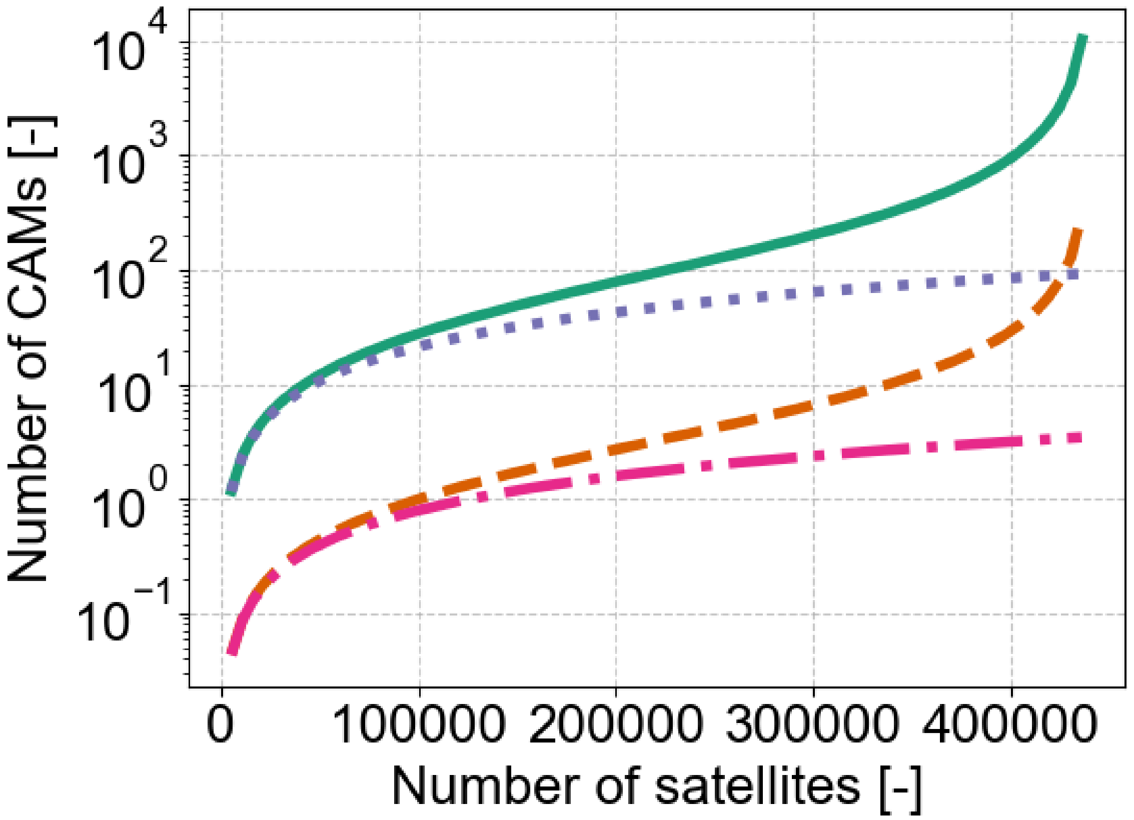

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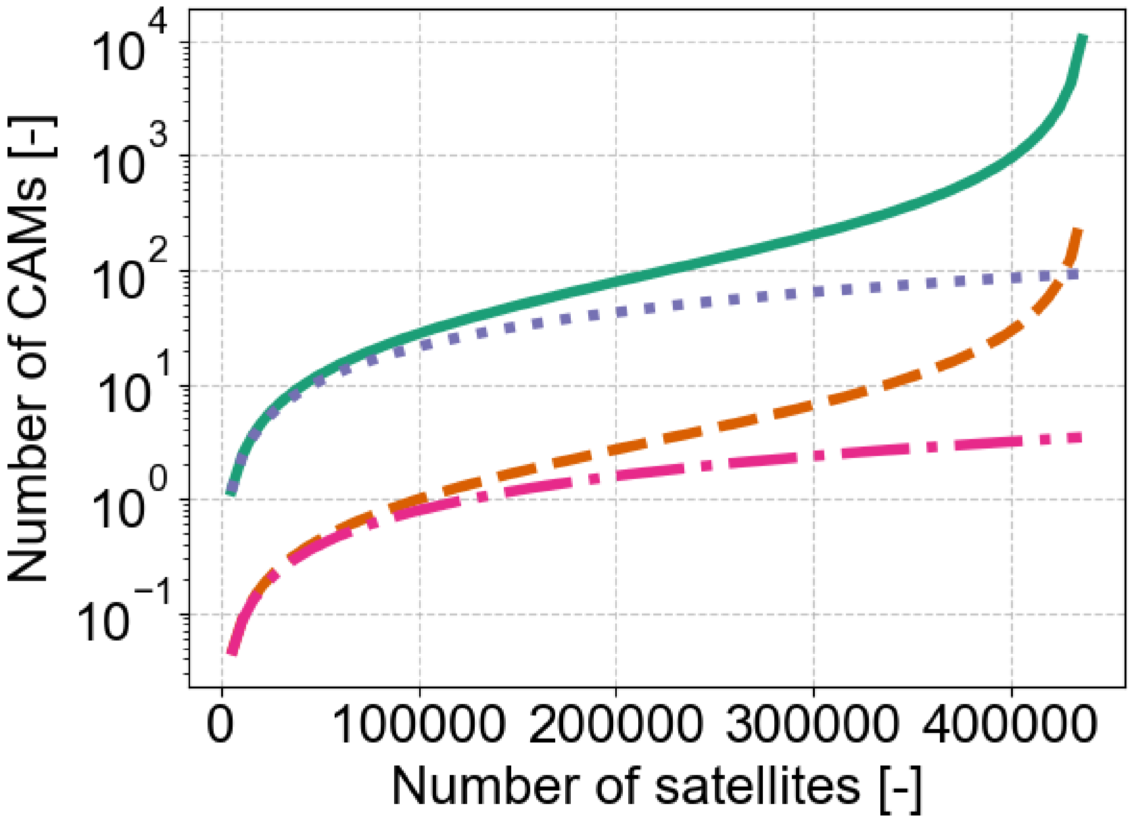

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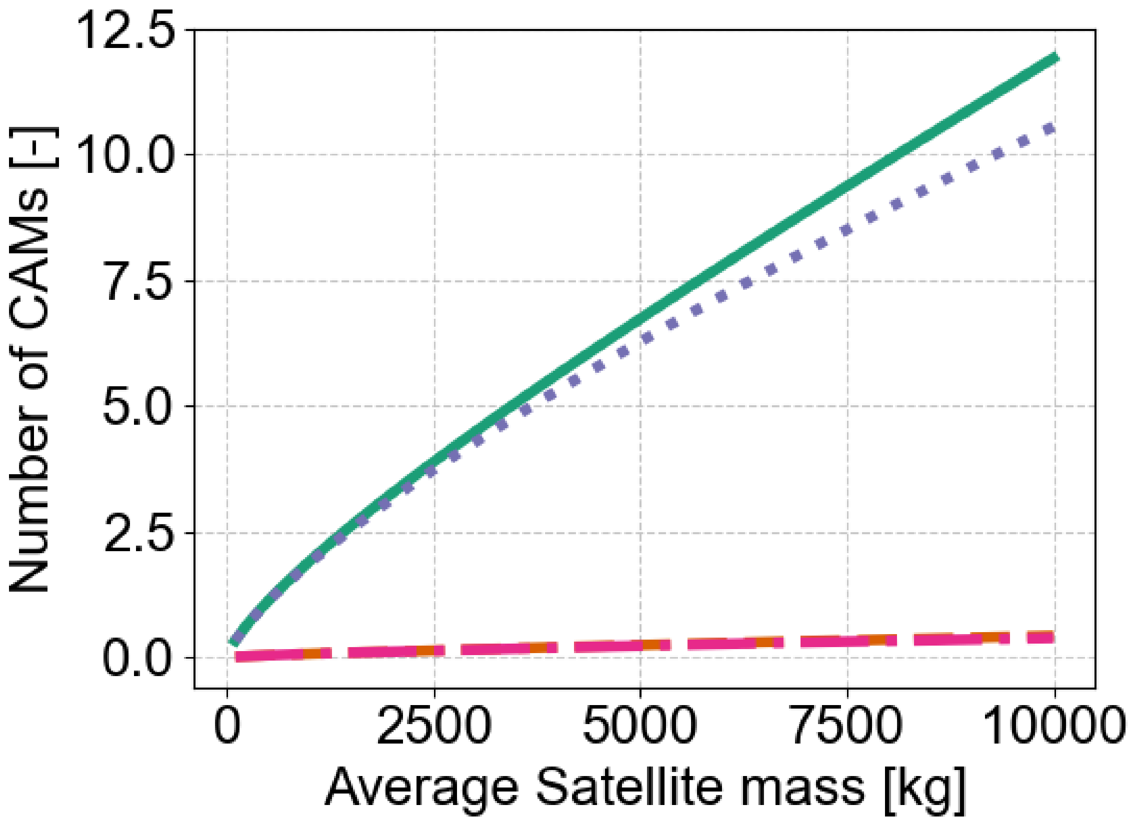

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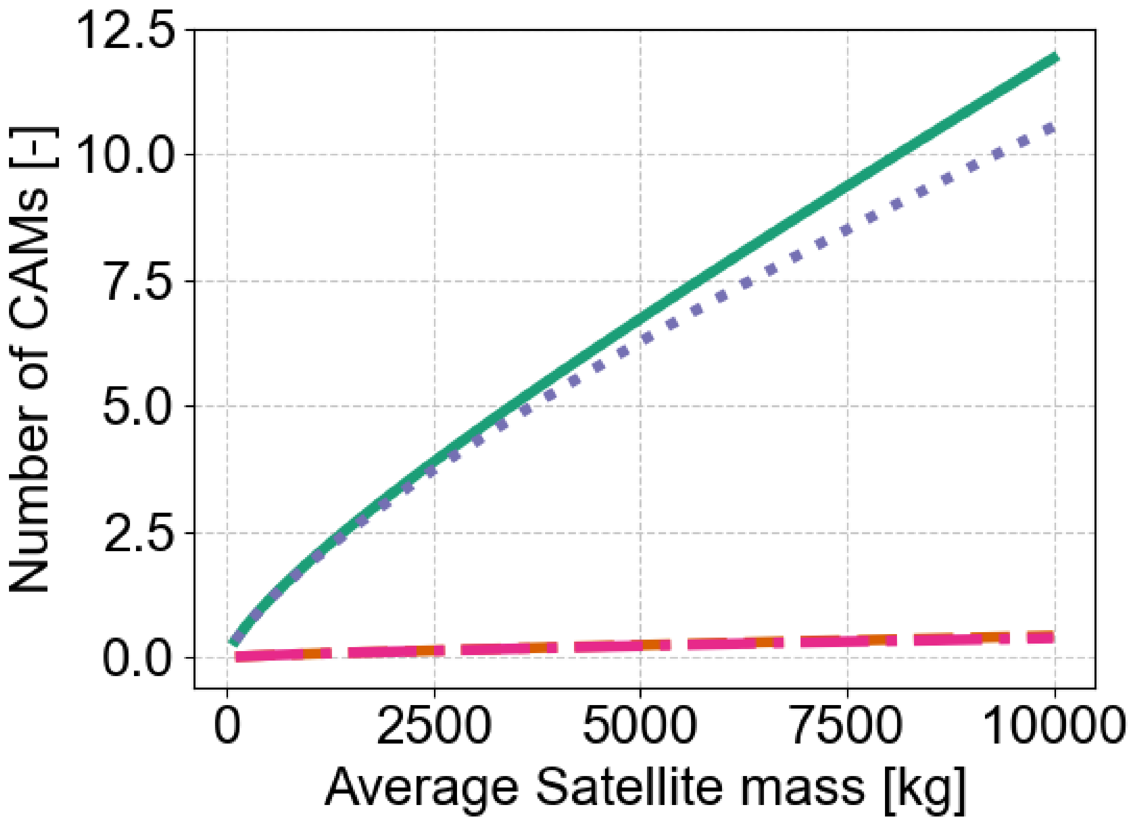

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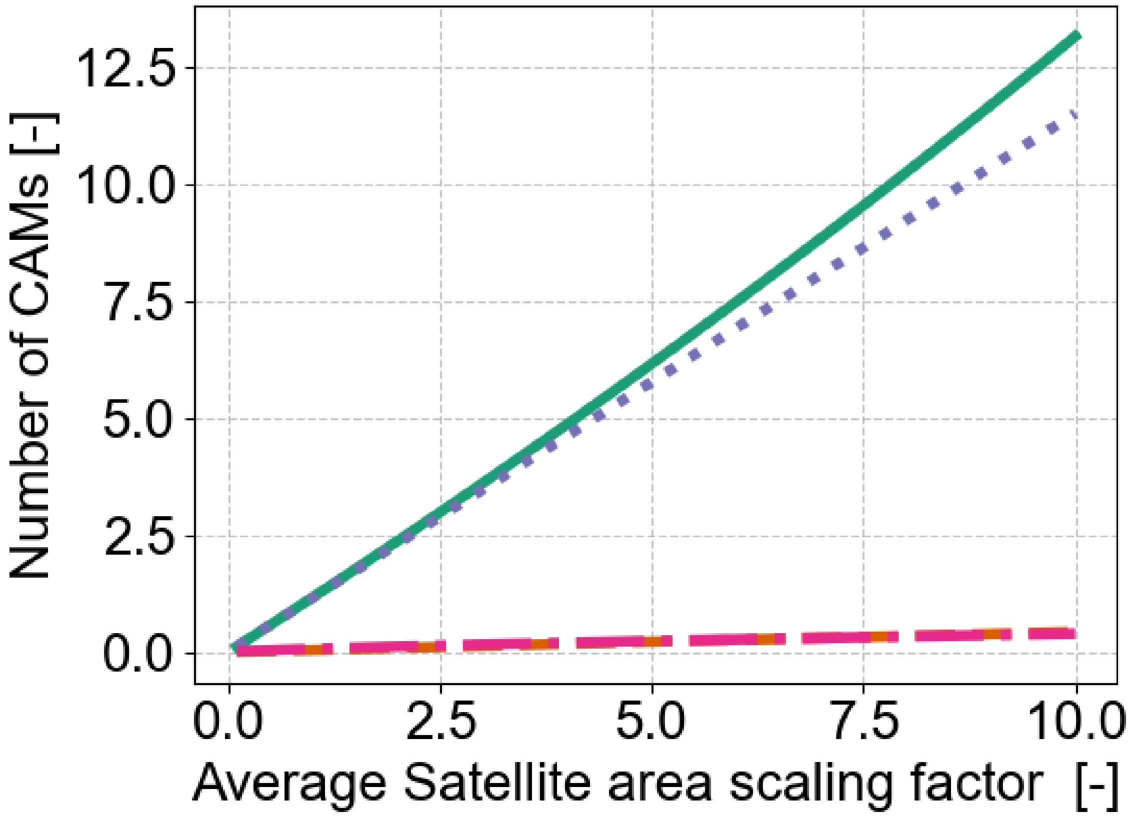

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