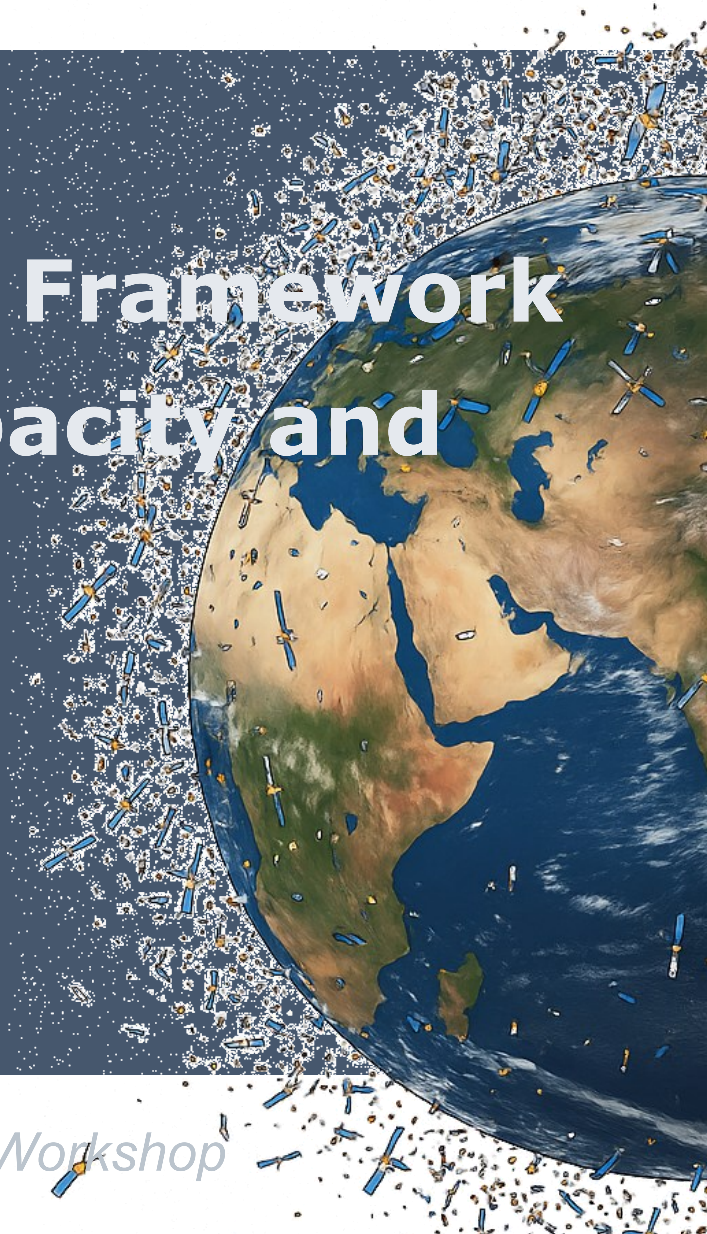
Consiglio Nazionale delle Ricerche

SDM 6.0: A Modernized Evolutionary Framework for Assessing Long-Term Orbital Capacity and Mitigation Strategies



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Second Space Capacity Allocation For The Sustainability Of Space Activities Workshop

Assessing Space Carrying Capacity

The Management Dilemma

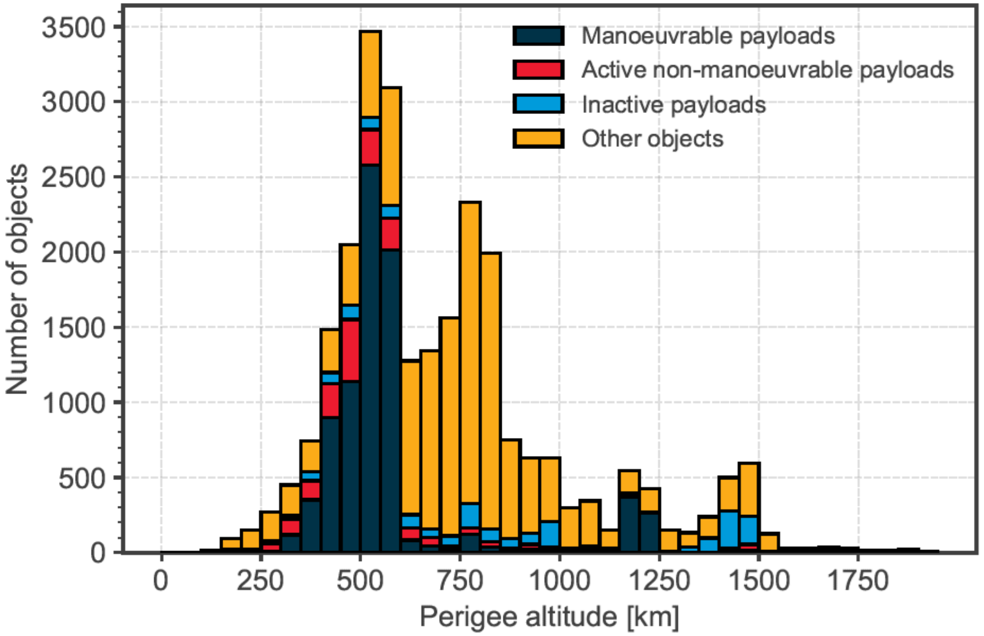
- Navigating between short-term space traffic coordination and long-term environment health targets requires distinct metric dimensions.

CSI : Analytical Diagnostic Scale

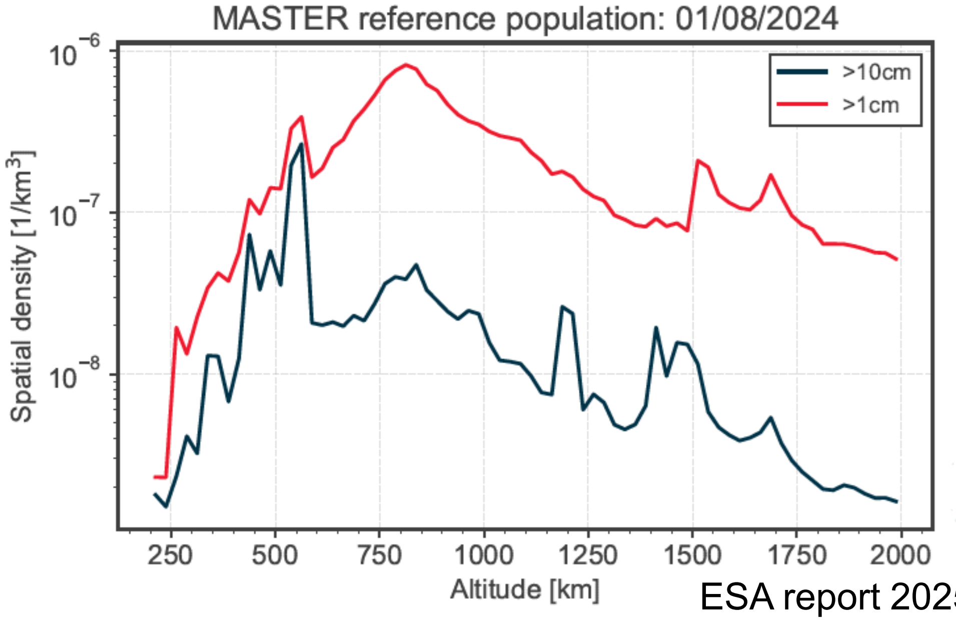
- Evaluates individual spacecraft and altitude shells via instantaneous epoch snapshots.

SDM : High-Fidelity Evolutionary Engine

- Simulates macro-environmental trends by coupling multi-regime physical mechanisms.



Letizia, ActaA 2026



ESA report 2025

Criticality of Spacecraft Index (CSI)

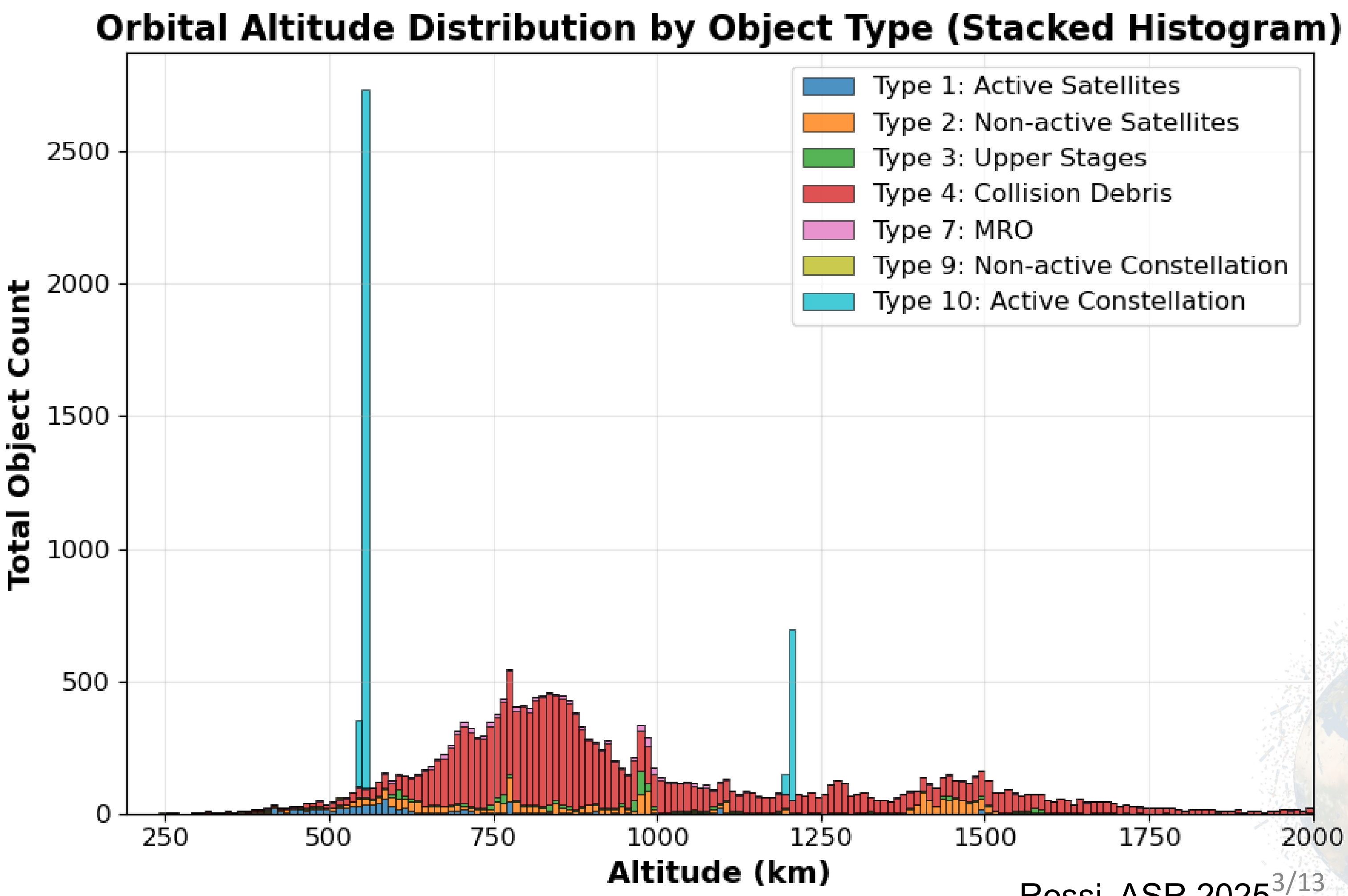
Formulation

$$\Xi = \frac{A}{A_0}\frac{M}{M_0}\frac{\rho(h)}{\rho_0}\frac{\mathrm{L}(h)}{\mathrm{L}(h_0)} f(i)$$

- Quantifying individual object environmental criticality.

Dataset Setup

- 2025 LEO environment extrapolated via SDM5, based on MASTER-2009.
- Background density computed down to d >= 5 cm
- Target population filtered at d >= 10 cm



Rossi, ASR 2025

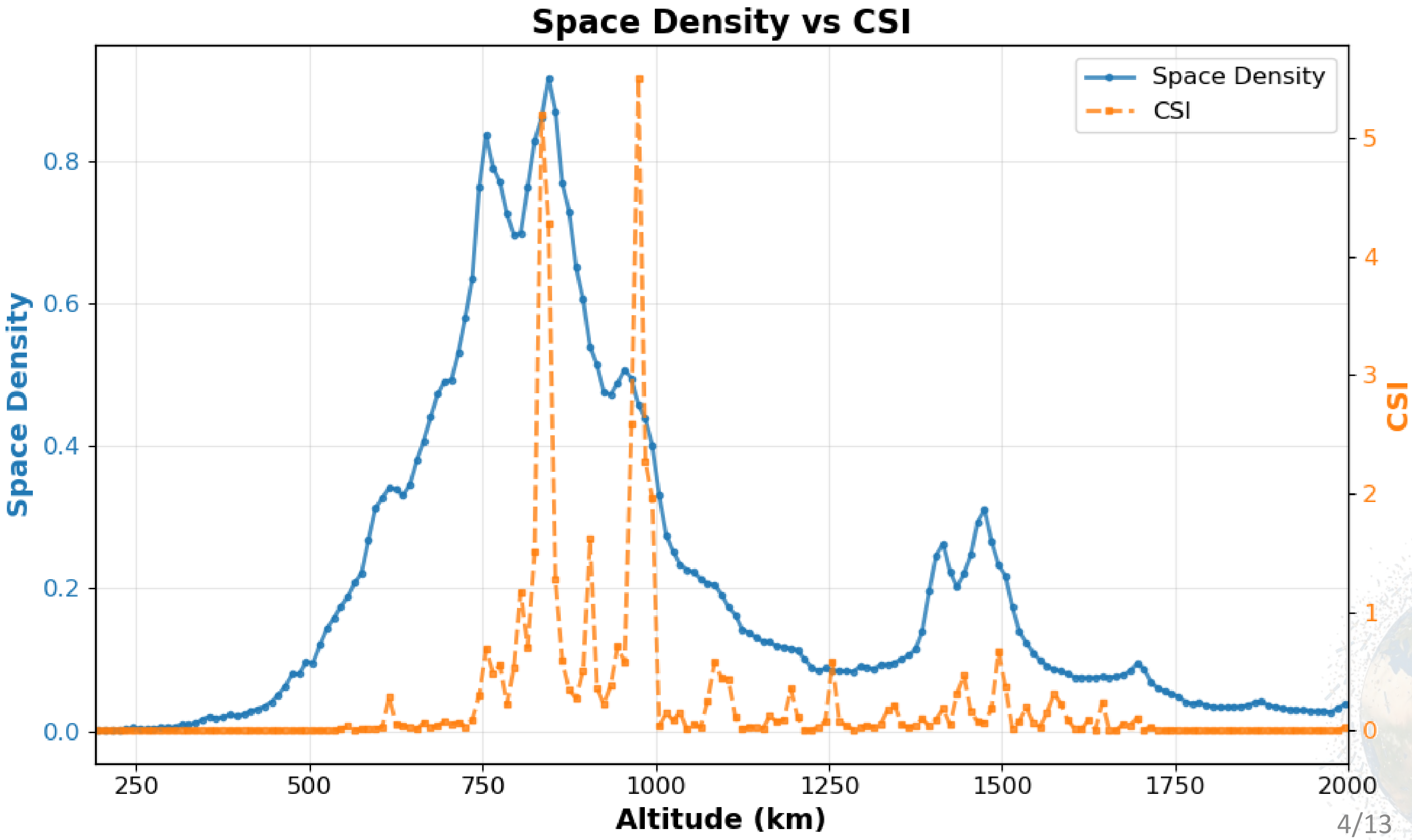
Criticality of Spacecraft Index (CSI)

$$\Xi = \frac{A}{A_0}\frac{M}{M_0}\frac{\rho(h)}{\rho_0}\frac{\mathrm{L}(h)}{\mathrm{L}(h_0)} f(i)$$

Normalization References

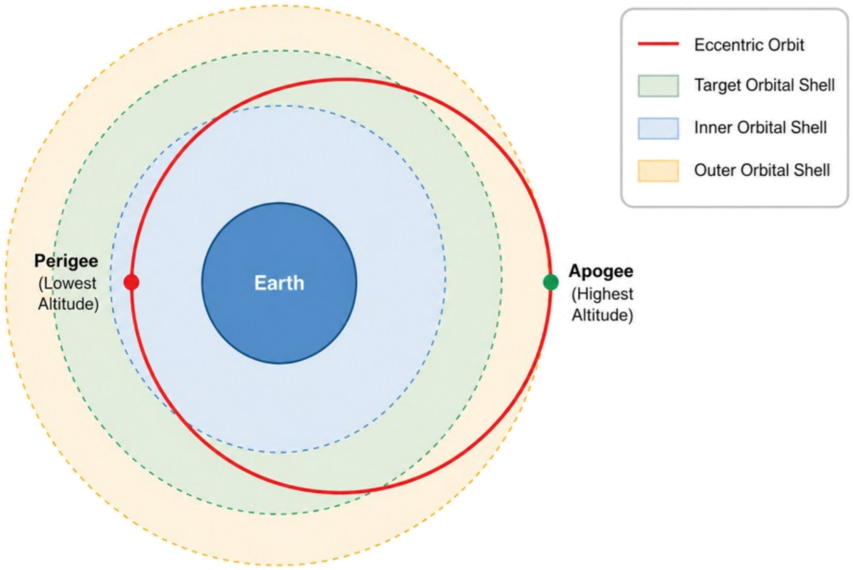
$$A_0 = 1\ \mathrm{m}^2$$
$$M_0 = 10000\ \mathrm{kg}$$
$$\rho_0 = \rho(770\ \mathrm{km},\ \mathrm{year}\ 2009)$$
$$\mathrm{L}(h_0) = \mathrm{L}(1000\ \mathrm{km})$$

$$\boxed{\Xi_{\mathrm{LEO},\,k} = \sum_{j=1}^{p(k)} \Xi_j}$$

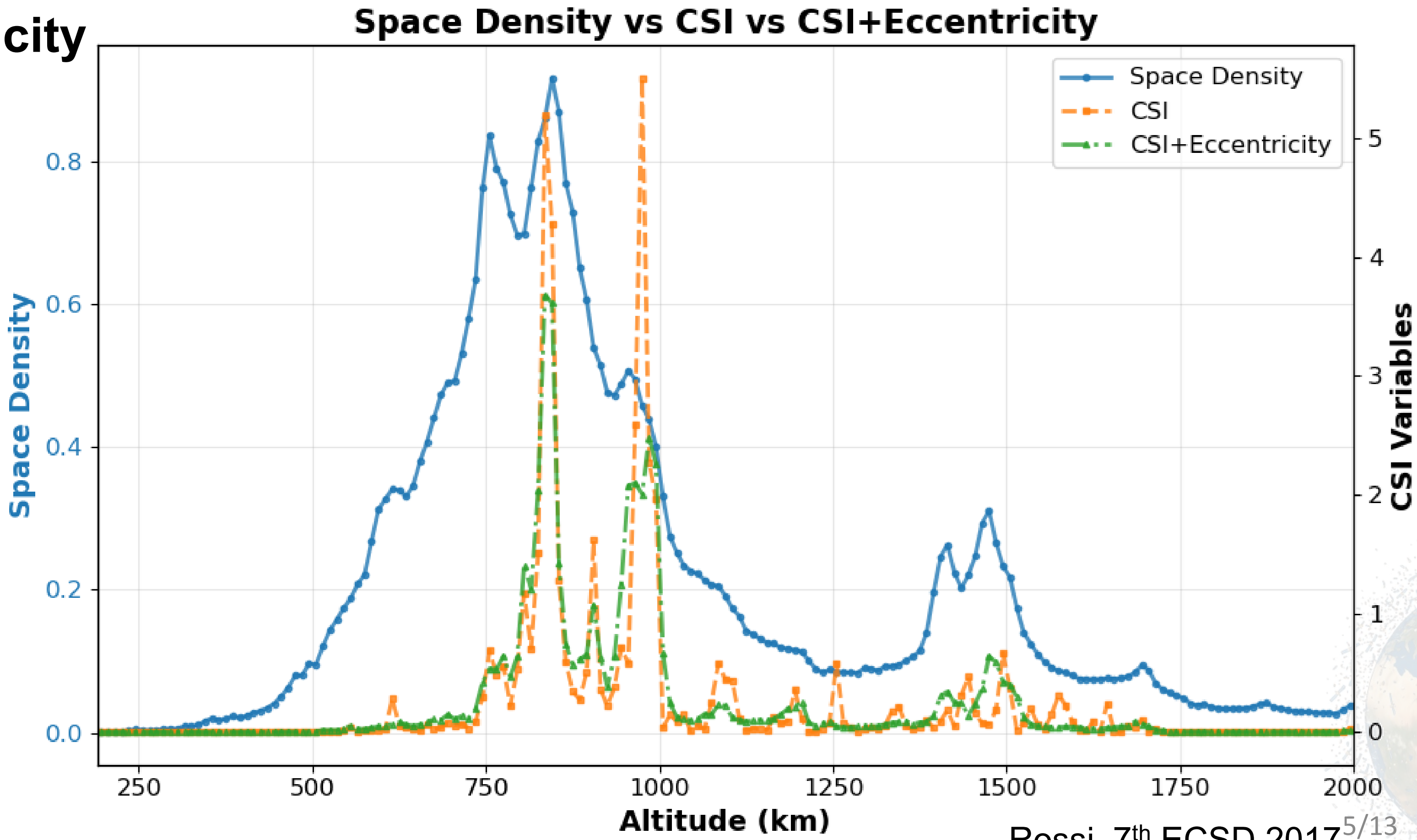


$$\Xi_{k,j} = \frac{A}{A_0}\frac{M}{M_0}\frac{\rho(h_k)}{\rho_0}\frac{\mathrm{L}(h_a)}{\mathrm{L}(h_0)} f(i) \,, \quad \Xi_k = \sum_{j=1}^{p(k)} \Phi_{k,j}\Xi_{k,j} \,, \quad \Xi_j = \sum_{k=1}^{N_j} \Phi_{k,j}\Xi_{k,j}$$

Accounting for Orbital Eccentricity via Altitude Layering



$$\Phi_{k,j} = \Phi_{k,j}(a,e)$$

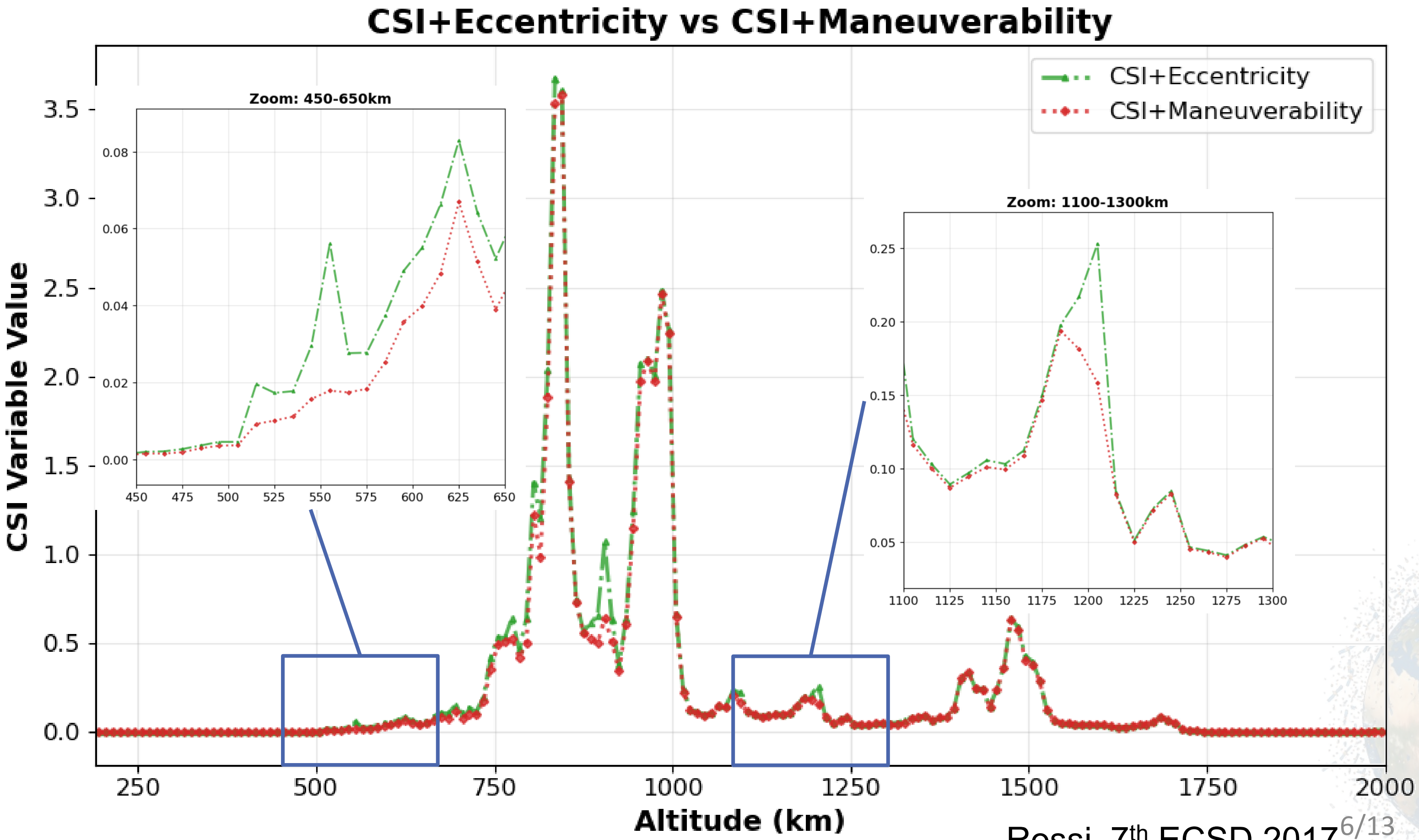


$$\Xi_{k,j} = \frac{A}{A_0}\frac{M}{M_0}\frac{\rho(h_k)}{\rho_0}\frac{\mathrm{L}(h_a)}{\mathrm{L}(h_0)}\eta_{avoid} f(i), \quad \Xi_k = \sum_{j=1}^{p(k)} \Phi_{k,j}\Xi_{k,j}, \quad \Xi_j = \sum_{k=1}^{N_j} \Phi_{k,j}\Xi_{k,j}$$

Maneuverability Scaling Factor

- $\eta_{avoid} \in [0, 1]$
  0.1 = 90% mitigation success rate (10% failure risk)

- Operational satellites d>50cm
  $\eta_{avoid} = 0.2$
- Active megaconstellations
  $\eta_{avoid} = 0.02$
- All other objects / debris η_{avoid} = 1

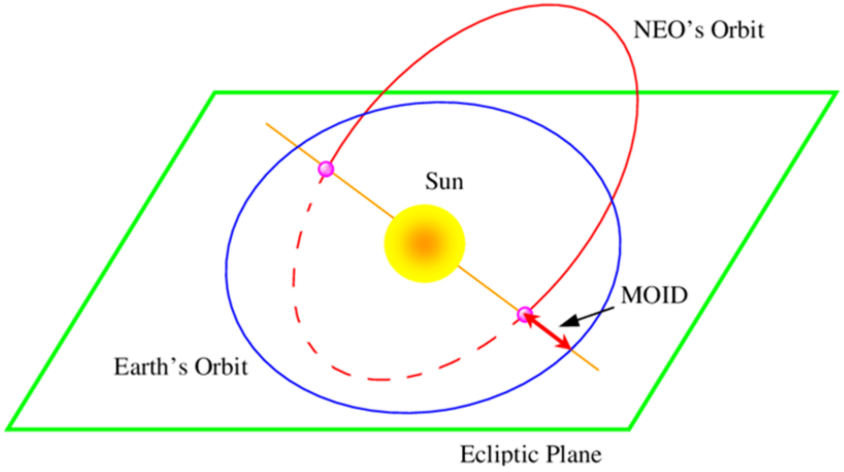


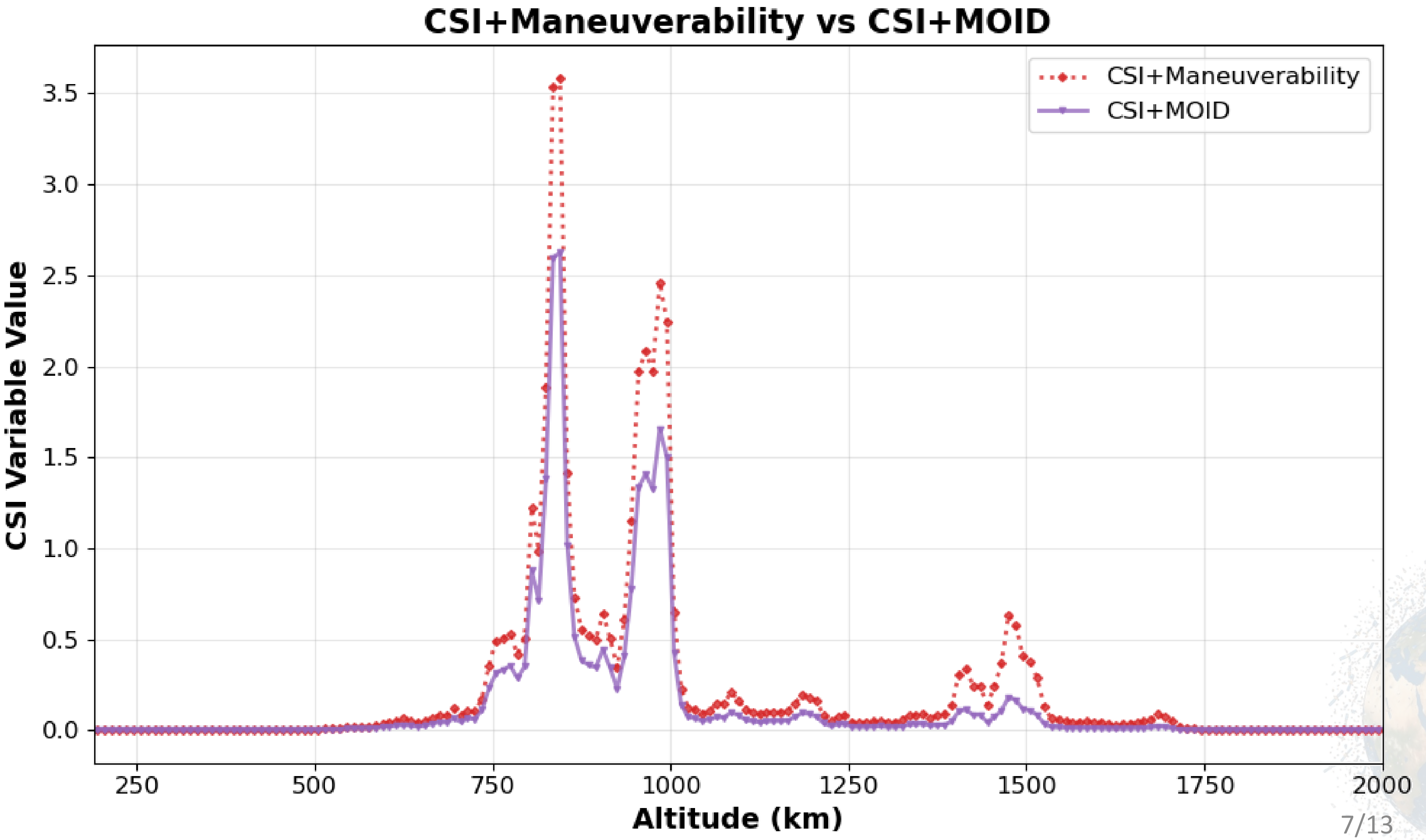
Rossi, 7th ECSD 2017

$$\Xi_{k,j}=\frac{A}{A_0}\frac{M}{M_0}\frac{\rho(h_k)}{\rho_0}\frac{\mathrm{L}(h_a)}{\mathrm{L}(h_0)}\eta_{avoid}\eta_{MOID}f(i)\ ,\quad \Xi_k=\sum_{j=1}^{p(k)}\Phi_{k,j}\Xi_{k,j}\ ,\quad \Xi_j=\sum_{k=1}^{N_j}\Phi_{k,j}\Xi_{k,j}$$

MOID (Minimum Orbital Intersection Distance)

$$\eta_{MOID}=\frac{\min(\mathrm{med}(\mathrm{MOID}))}{\mathrm{med}(\mathrm{MOID})_j}$$





Comprehensive Analysis of Improvements

Eccentricity Smoothing

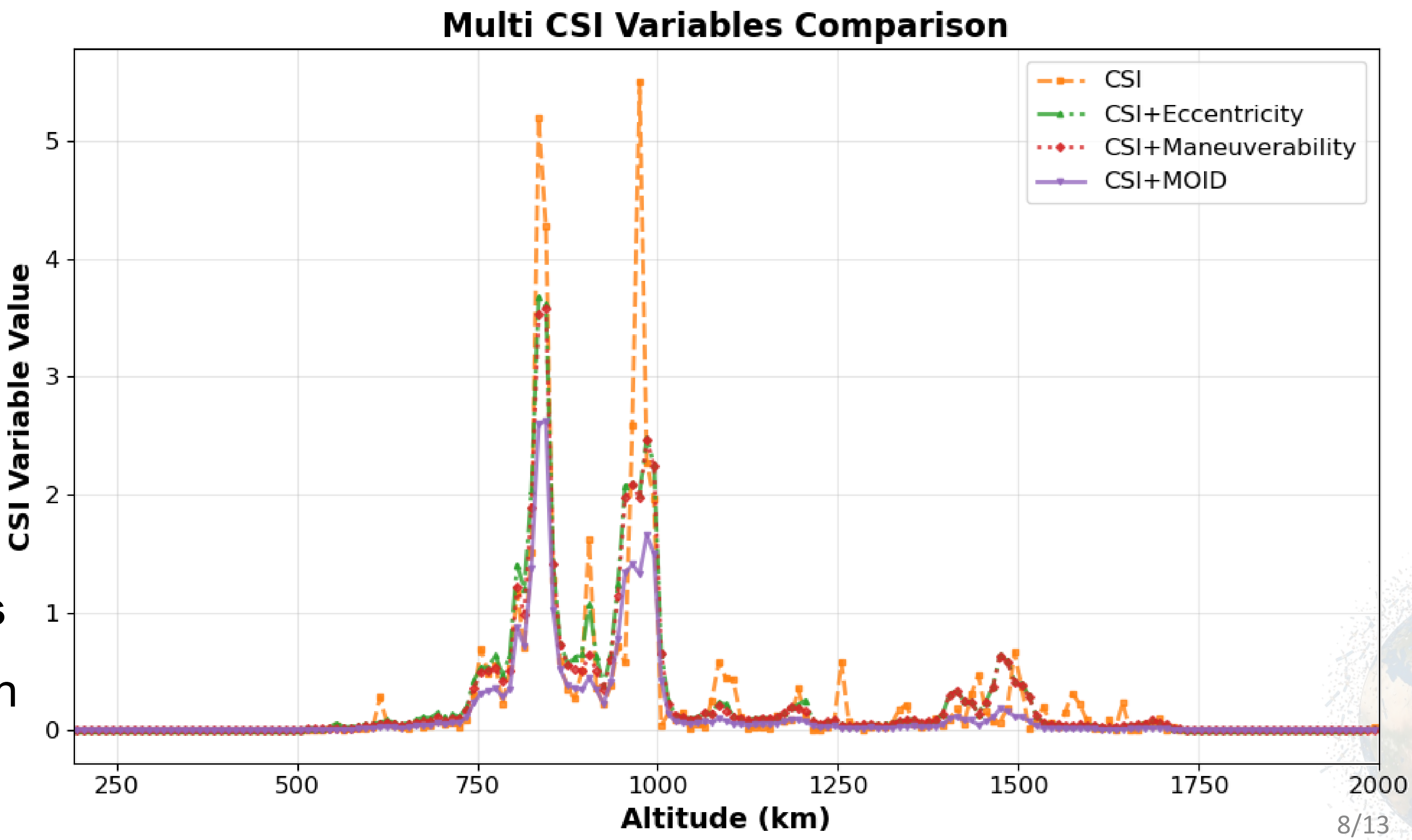
- Eliminates artificial sharp peaks, smoothing the macro capacity profile.

Maneuverability Credit

- Quantifies capacity release in mega constellation shells.

MOID Geometric Constraints

- Prevents risk overestimation in highly coordinated regimes.



Space Debris Mitigation (SDM) model

Fast Long-Term Propagation

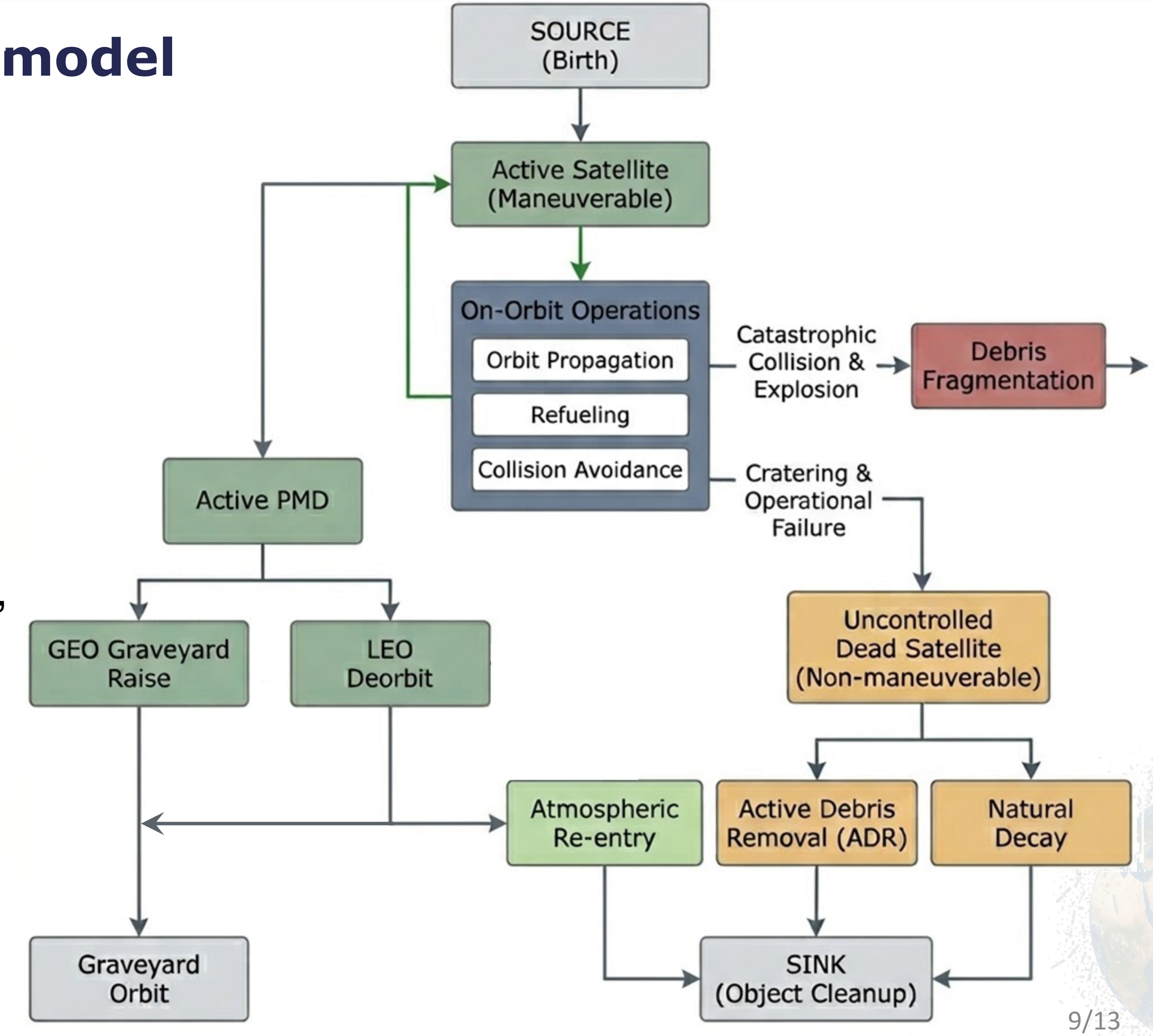
- Centurial orbit simulation of centimeter-scale objects from LEO to GEO using multi-regime integrators.

Full-Spectrum Source/Sink Dynamics

- Coupled modeling of launches, refueling, failures, explosions, collisions (catastrophic/cratering), PMD, and ADR.

Policy Sensitivity Analysis

- Quantitative evaluation of PMD rates, ADR targets, and coordination rules to support mitigation standard-setting.



SDM6.0 : Object-Oriented Refactoring for Commercial Space & STM

Drivers	Solutions	Capabilities
Next-generation satellites present complex attributes such as collision avoidance, deorbiting, and flexible appendages.	Encapsulates *SpaceObject* derived type and implements dynamically extensible control tags for customizable control logic.	Decouple control logic, high-fidelity validating emerging PMD and ADR regulatory policies.
Commercial megaconstellation deployment	Introduced constellation derived data type *ConstState*, on-demand dynamic memory allocation and persistent tracking of satellite lifecycle IDs.	Supports full-lifecycle STM simulations including tailored launch schedules, on-orbit refueling, and automated replenishment management.
Exponential catalog growth of trackable space objects	Modular subroutines. Optimized via Swap-and-Pop, achieving $O(1)$ complexity for rapid deallocation of inactive objects.	Minimized processing latency, paving the technical path toward million-scale catalog extrapolation.

SDM6.0 : Object-Oriented Refactoring for Commercial Space & STM

100% Inherited Physical Mechanisms

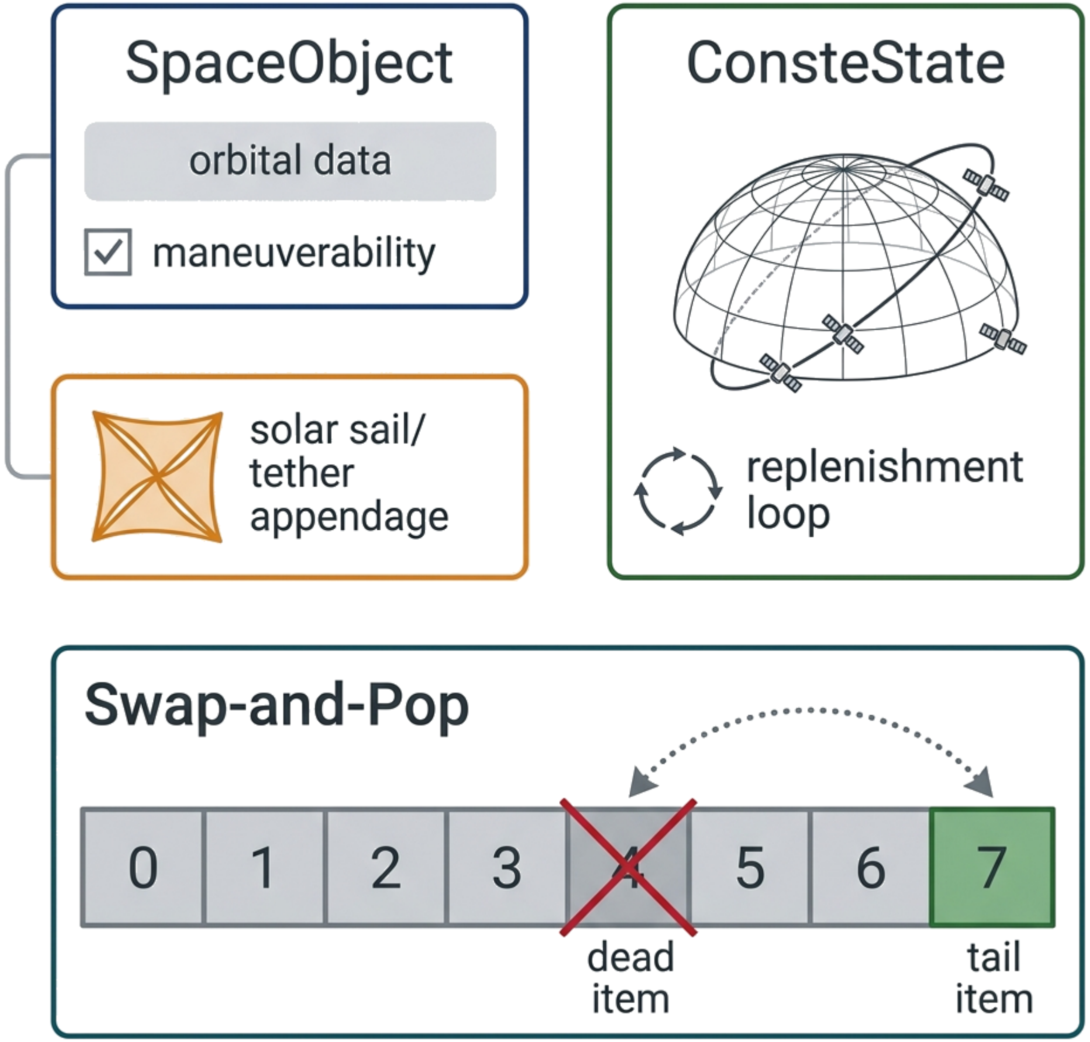
- Orbital perturbation dynamics, NASA Standard Breakup Model / EVOLVE-4 model, de-orbiting logistics, etc.

Unit Verification

- Orbital Extrapolation
- Breakup (Explosion/Collision) Events
- De-orbiting / Decay
- Constellation Deployment.

Benchmarking

- Long-term evolutionary stability fully verified.



Methodological Discussion

Metric/Framework	Strengths	Limitations	Targeted Scenarios
CSI (Analytical Scale)	Zero-latency analytical formula.	Relies on external baseline models for ongoing environment feed.	Mission-Level auditing for example constellation licensing. Active Debris Removal (ADR) candidate profiling.
SDM6.0 (Evolutionary Engine)	Simulates complex, full-spectrum source-sink dynamics (launches, explosions, cratering).	High computational cost by intensive multi-run Monte Carlo simulations required to capture stochastic evolution behaviors. Highly dependent on input parameters (e.g., failure risks, and PMD compliance rates).	Capacity policy standard setting (e.g., 5-year vs 25-year rule evaluation).

Summary

CSI Enhancements:

Integrates considerations of eccentricity, maneuverability, and MOID, revealing the authentic risk characteristics and differentiated regulatory requirements across distinct orbital regimes.

SDM6.0 Refactoring:

Completes the object-oriented refactoring and unit verification, establishing a extendable architecture for long-term maintenance and the future integration of emerging physical models.

Future Works:

Algorithm upgrade, massive stochastic simulation, SDM+CSI coupling analyzation.

Thank you !

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