The MOCAT Ecosystem: An Overview of the MIT Orbital Capacity Assessment Tool Suite

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MIT AEROASTRO

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MOCAT Motivation

The growing demand for space **requires** modeling **techniques** that can **support** effective **operational** and **policy decision-making.** Two leading methods:

Source-Sink Models

- **Objects categorized into few species**
- **Generalized physical and orbital parameters**
- **Collision probability as input**
- **Low computational cost**

MIT Orbital Capacity Assessment Tool (MOCAT)

Monte Carlo Methods

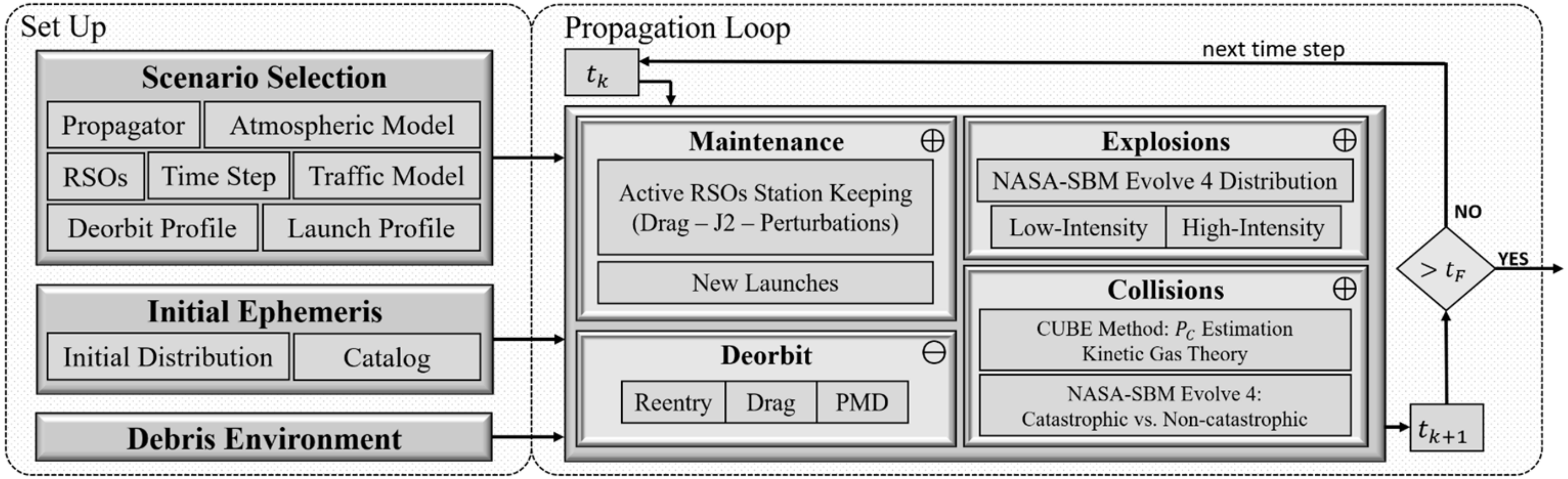
- **Model individual objects, parameters and orbits**
- **Individualized modeling possible for fragmentation**
- **Estimate collision probability**
- **High computational cost**

Goal: prediction of space objects evolution, sustainability assessments, policy optimization.

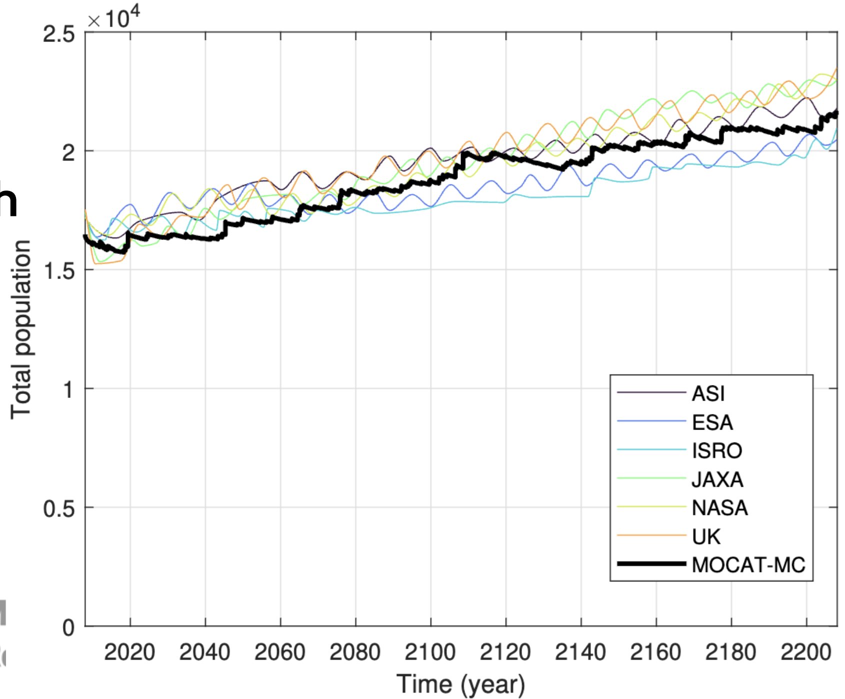
MOCAT-MC is openly and freely available!

MOCAT-MC

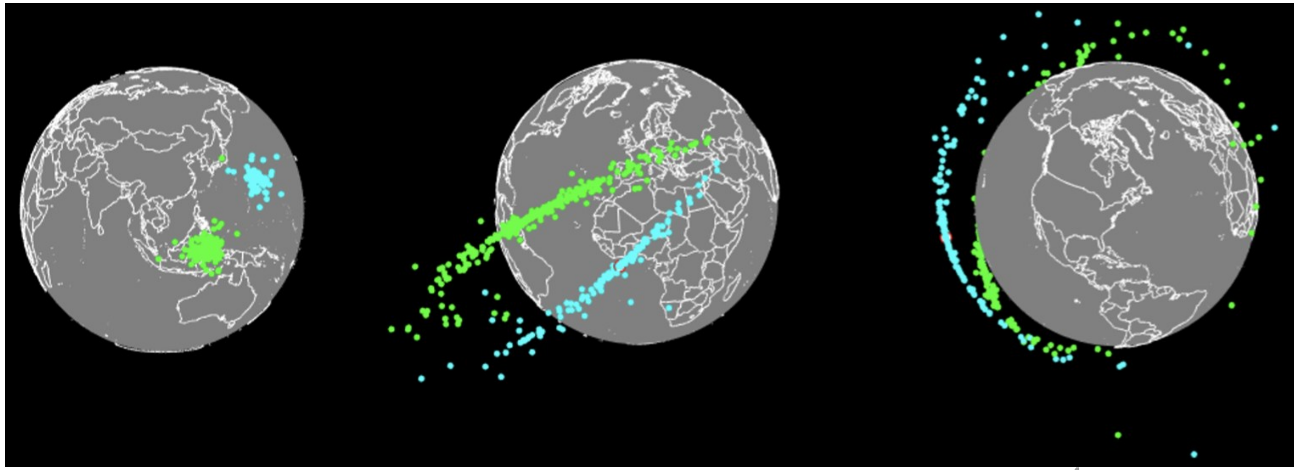
Architecture



Validation campaign with other space agency MC models

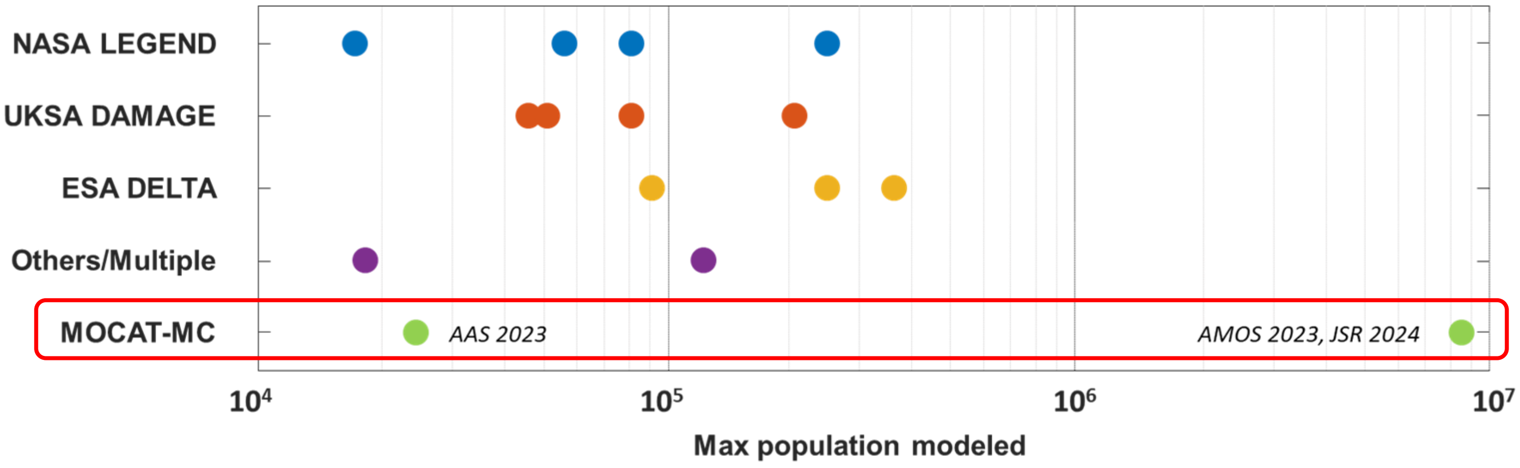


Graphical view of collision

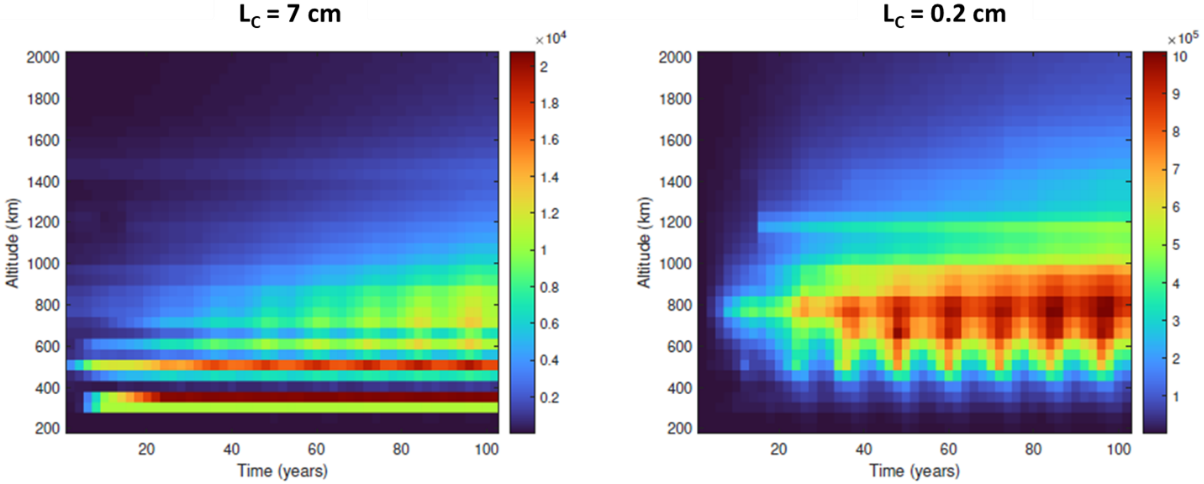


Capabilities

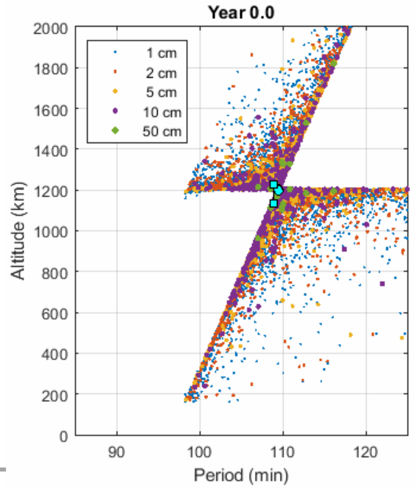
- MOCAT-MC is a validated SoTA MC model for long-term LEO population evolution.
- Millions of objects must be modeled for small debris and future megaconstellations.
- SSEM validation is possible with the MC.



MOCAT-MC is able to track Lethal Non-Trackable Objects due to its linear scalability



MC can validate the SSEM model and bridge the gap: Gabbard Plot of collision debris



MOCAT-SSEM is also openly and freely available!

MOCAT-SSEM

Motivation and Methodology

High-Fidelity Methods (e.g., stochastic MC) can track every space object individually, but are computationally slow.

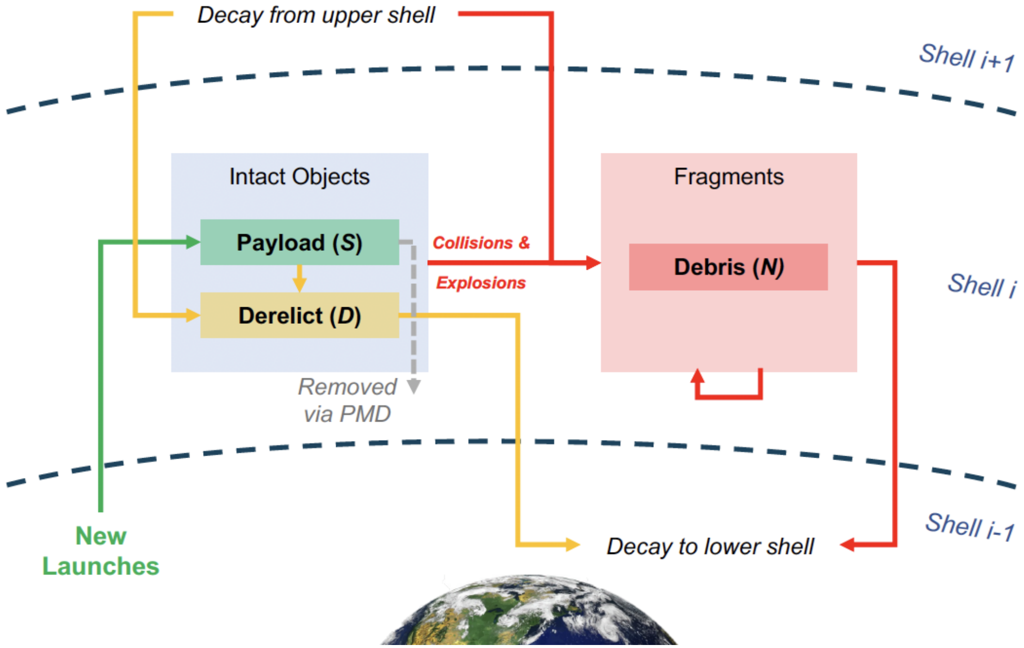
Source-Sink Evolutionary Method (e.g., SSEM):

- Down-sample space objects into species and model population growth/decline.
- Lower-fidelity but computationally efficient: up to minutes for setup (if considering many species and additional features), then seconds for a run.
- System of ordinary differential equations.
- Several applications with runtimes of seconds to minutes: economic, control, environmental, etc.

Species: Active Satellites (S, Su, Sns), Derelicts (D), Debris (N), Rocket Body (B).

Sources: Launch rate

Sinks: Post mission disposal rate, Collisions (& Explosions), Atmospheric Drag



Symbol	S	S_u	S_{ns}	N	B
Description	Active station-keeping satellites, orbit-coordinated	Active station-keeping satellites	Non-station-keeping satellites	Debris (plus derelicts for S, S_u, S_{ns})	Rocket body
Cd	2.2	2.2	2.2	2.2	2.2
Mass [kg]	148, 750, 1250	260, 473	6	.0.00141, 0.5670	1783.94
Radius [m]	0.5, 2.0, 4.0	0.73, 2.08	0.11	0.01, 0.1321	2.69
Area $[m^2]$	0.79, 12.57, 50.26	1.67, 13.56	0.035	3.1416e-4, 0.0548	22.70
Active	true	true	true	false	false
Slotted	true	false	false	false	false
Drag	false	false	true	true	true
Maneuverable	true	true	false	false	false
Trackable	true	true	true	false, true	true
Mission lifetime	8	8	3	N/A	N/A
Post-mission disposal	.99	.65	N/A	N/A	N/A
Disposal altitude	0	0	N/A	N/A	N/A
Efficacy of collision avoidance vs. inactive	1e-5	1e-5	1e-5	N/A	N/A
Efficacy of collision avoidance vs. active	1e-5	1e-5	1e-5	N/A	N/A
Rocket body	false	false	false	false	true
Launch rate	empirical fit	empirical fit	empirical fit	N/A	empirical fit

Capabilities and Research Directions

MOCAT-SSEM is aimed to be an **open source toolkit** to **enable transdisciplinary** research, e.g. policy and socio-economic modelling.

Model improvements:

- Debris fragment spreading after collisions across shells.
- Elliptical orbits and collisions.
- Time/shell varying quantities (PMD, orbital lifetime), with/without uncertainties.

Research directions:

(1) Optimization capabilities to **optimize** number of **satellites** that fit in the LEO region **under** dynamical system **equilibrium** and **sustainability constraints**.

(2) **Validation** of MOCAT-SSEM with MOCAT-MC.

(3) Launch Rate and Active Debris Removal **feedback controllers** (PD and NMPC for optimization).

(4) MOCAT-SSEM with EVDT as **policy engine** and **techno-economic** calculator.

(1)

$$\min_{S_{h_i}(t),D_{h_i}(t),N_{h_i}(t),\lambda_{h_i}(t)} J = -\sum_{i\in\mathcal{H}} \log(S_{h_i}(t)),$$

Equality constraints

$$g^{eq} = \begin{cases} \dot{S}_{h_i}(t) = 0, \\ \dot{D}_{h_i}(t) = 0, \\ \dot{N}_{h_i}(t) = 0, \end{cases}$$

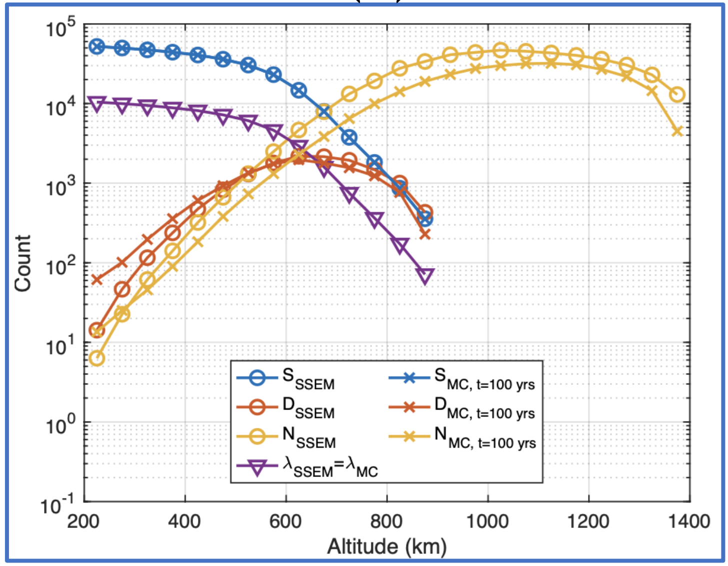
Lower boundary

$$g^{lb} = \begin{cases} S_{h_i}(t) \geq 0, \\ D_{h_i}(t) \geq 0, \\ N_{h_i}(t) \geq 0, \\ \lambda_{h_i}(t) \geq 0, \end{cases}$$

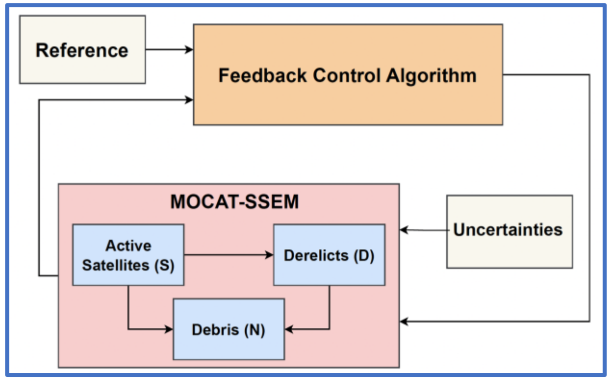
Sustainability constraints (e.g., failure rate, max debris per shell width)

$$g^{su} = \begin{cases} \lambda_{h_i}(t)\Delta t(1-\chi_{max}) - S_{h_i}(t) \leq 0 \\ D_{h_i}(t) - D_{max} \leq 0, \\ N_{h_i}(t) - N_{max} \leq 0, \end{cases}$$

(2)



(3)



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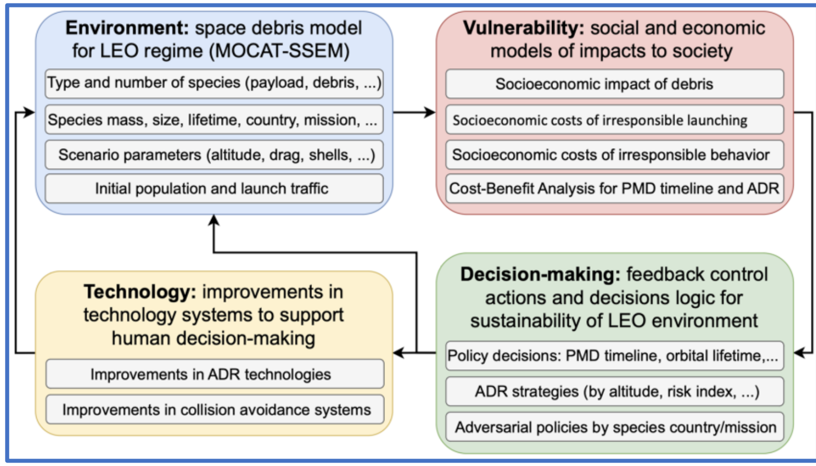
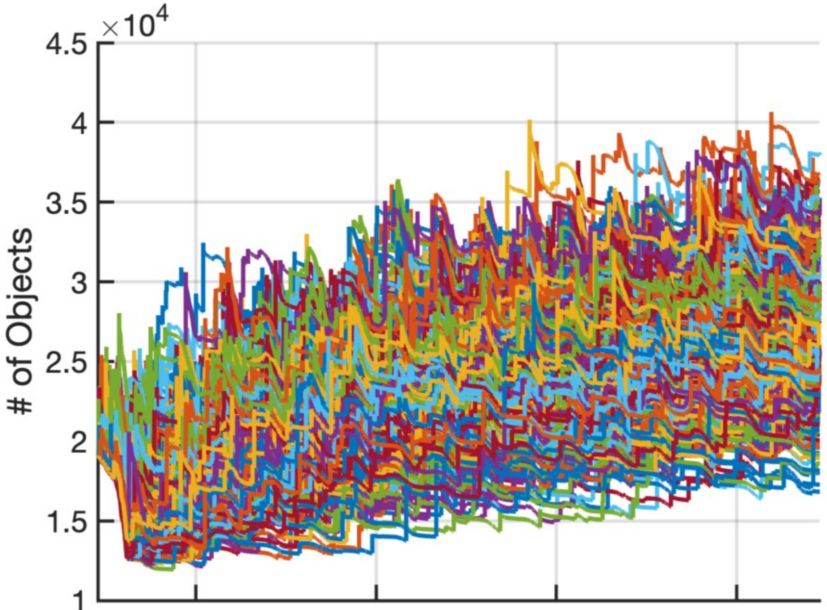
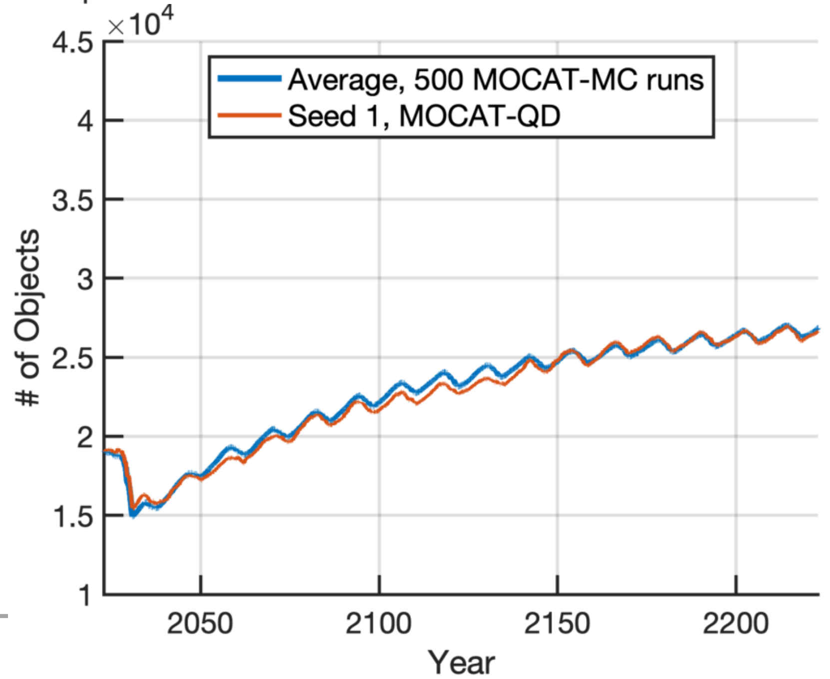


MOCAT-QD

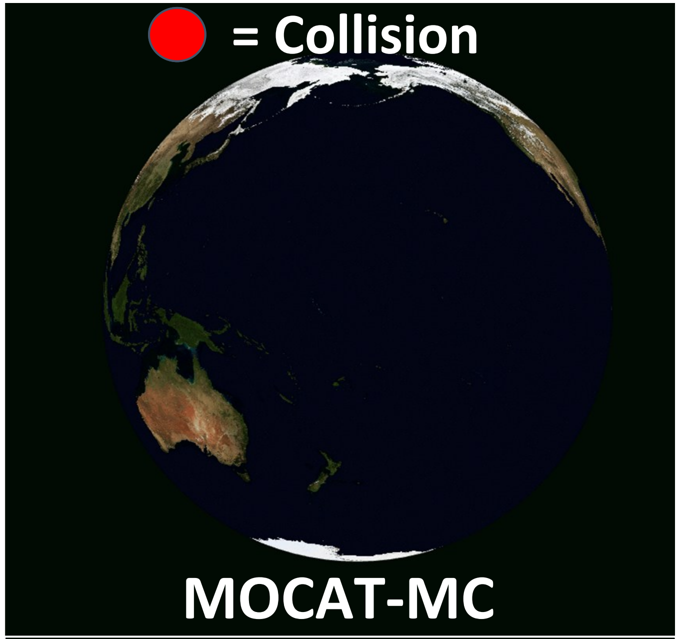
Architecture

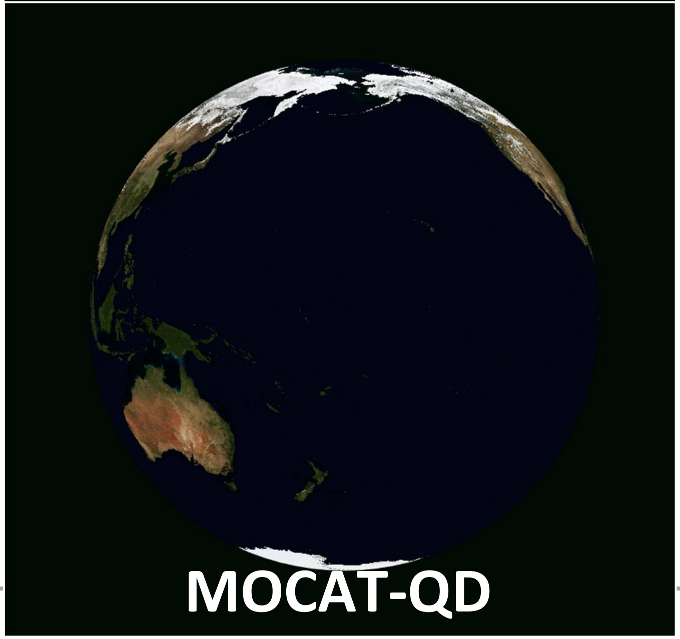




Methodology:
(1) Replaces binary "all-or-nothing" collision events with "virtual" debris generation at every conjunction.
(2) Instead of rolling dice, the number of fragments generated in a conjunction is scaled directly by the actual Probability of Collision.
(3) Mathematically engineered to ensure that the cumulative population matches the statistical average of thousands of Monte Carlo runs.
(4) Combines deterministic physical propagation with a continuous fragmentation logic to maintain the computational speed of all-vs-all simulators.

Key Takeaway: MOCAT-QD provides the statistical stability of 1,000+ Monte Carlo runs in the time it takes to run just one.





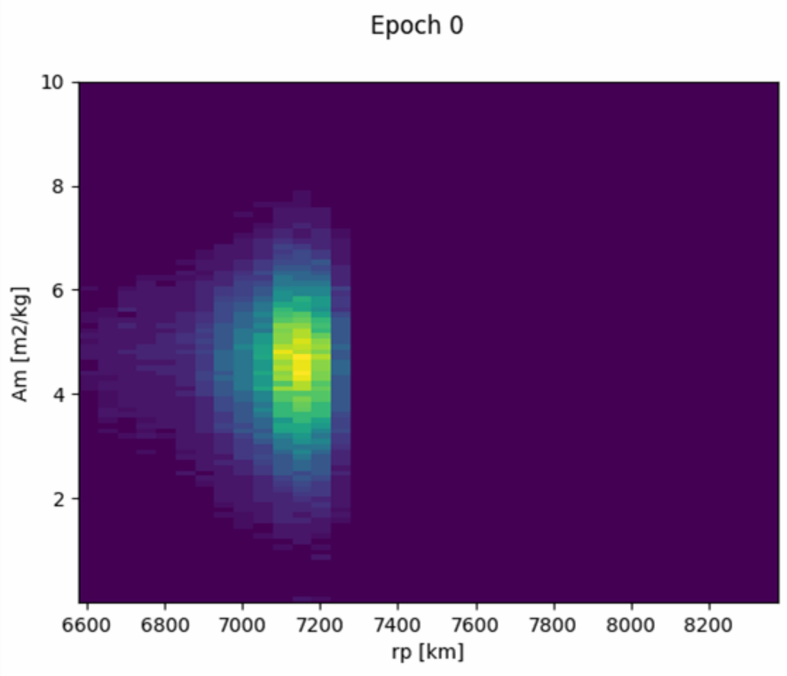
MOCAT-ML is also … ok, you got it ;)

MOCAT-ML

Idea and Methodology

Graphical and intuitive representation of number of objects along time. Data are represented in phase space with:

- area-to-mass ratio (A/m), discretized in 99 bins [10^{-5} m^2/kg, 10^1 m^2/kg]
- perigee radius (r_p), discretized in 36 bins [200 km, 2000 km]

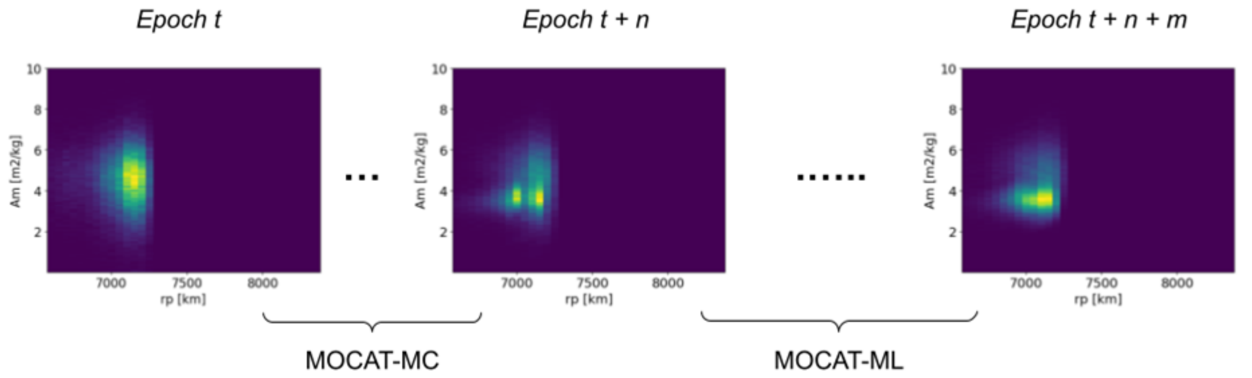


Idea: initial epochs of the evolution are provided by MOCAT-MC, then a fast ML-based density forecasting model completes the propagation/prediction:

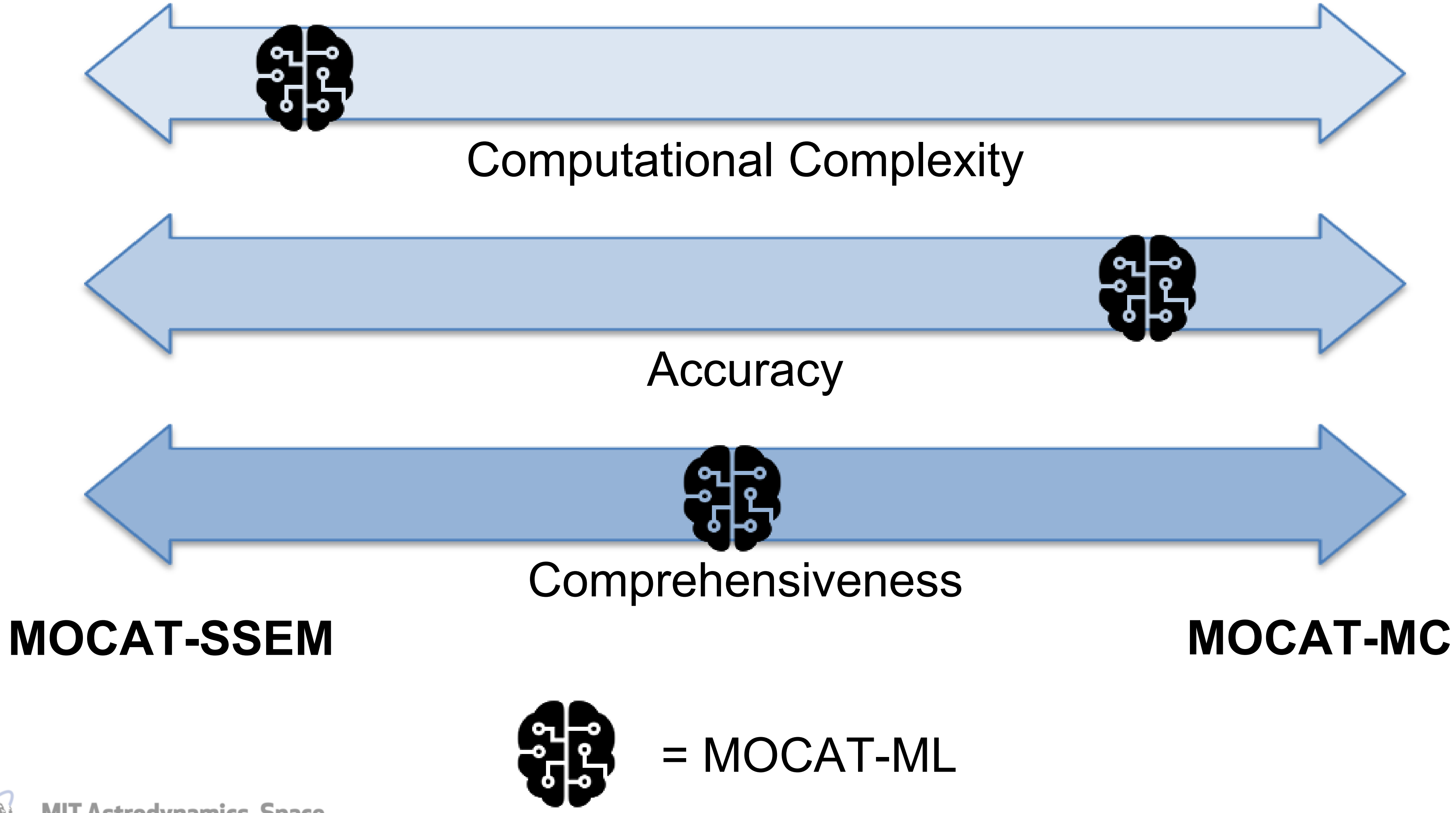
- Input: Past n densities
- Output: Future n+m densities

Basically, a forecasting problem with density distributions instead of time series.

MOCAT-MC is used to generate training data.



MOCAT-ML vs MC and SSEM



Thank you for your attention!

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