Monte-Carlo methods for all-vs-all future LEO population evolution modeling

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ABSTRACT

Increasing traffic and space debris population in Earth orbit present a difficult environment for the safe operation of satellites and human space-flight. The planned deployment of so-called mega-constellations in low-Earth orbit (LEO): Starlink, Kuiper, OneWeb, etc. are introducing many technical and political challenges. Accurately modeling the number and distribution of resident space objects (RSOs) in orbit is important in understanding the various inputs to the environment and their consequences.

MIT Orbital Capacity Tool (MOCAT) has been developed with both methods to leverage the SSEM method's simplicity and computational efficiency and the MC method's comprehensiveness. The MC model is called MOCAT-MC, which has been developed to analyze the future LEO population in a modular and computationally efficient manner and to understand the future orbital environment and to validate other types of evolutionary models.

In this paper, the capabilities of the sub-modules of MOCAT-MC is described and analyzed for their fidelity and computational efficiency with particular focus on the future megaconstellation launch model as well as Lethal Non-trackable (LNT) objects. The tens of thousands of object currently in the SATCAT catalog is limited to objects that are detected by SSA sensors and are tracked using association algorithms, yet are often not modeled due to computational cost as well as the stochastic nature of the orbits of objects that are not tracked.

The MC scenario results are tested against different future launches scenarios to assess the evolution of the LEO population. Several variations for the sub-modules and assumptions are considered, such as various atmospheric model, propagator fidelity, active satellite station-keeping policies, new launches, reentry, post-mission disposal, explosions and collisions. Fragmentation effects are modeled as a modified version of the NASA standard break-up model. The proposed MOCAT-MC is tested with different launch rate scenarios, including the "no future launches" scenario. Performance and accuracy are analyzed and discussed in this paper, including the sampling-based and deterministic collision statistics, comparison to historic data on collisions, overall all-vs-all LEO population performance, and the effect of propagator fidelity with varying orbital perturbations. Variation to the time-step and collision cube size and shape are analyzed. The assumed future launch profile and the parameters of payloads are varied. Policies at the national and international level are examined to understand the effect, such as the recent 5-year deorbit rule and its effect on the *orbital rain* experienced by the VLEO operators. Lastly, the effect of an increased LEO population near the orbital capacity is analyzed for increased computational load placed on the SSA operators in terms of conjunction assessment, association and correlation issues, uncorrelated target processing and data processing computation requirements.

Keywords: Monte Carlo methods; on-orbit collisions; orbital capacity; low-earth orbit environment

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1. INTRODUCTION

The space environment has historically been understood a vast resource that can be exploited for military, political and economic gain. Though technological barrier had limited the use of space to a handful of governments, the recent development in the commercial space sector and falling launch costs have brought about the so-called New Space Age, led largely by commercial space actors. Economies of scale and market forces have allowed large constellations to become commercially viable. Technological innovation has also enabled a better use of LEO compared to missions and services that had only been viable in other orbits.

The rise in the number of objects in space come with consequences, however. The number of conjunction assessment by SSA service providers and conjunction avoidance maneuvers by satellite operators have risen quickly, and the number of collisions has also been growing steadily over the years. Space may not be as invulnerable and vast as once imagined, and equitable and safe allocation of such common resource has become a priority for space-faring and non-space-faring nations alike. LEO as a resource is similar to other global common goods such as clean air and electromagnetic spectrum allocation, where tragedy of the common is a problem that must be addressed.

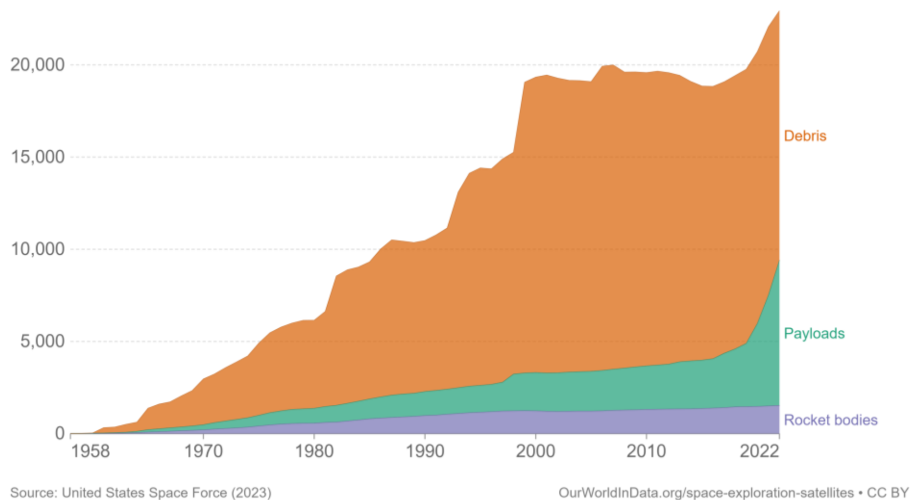

Fig. 1. Number of tracked objects in LEO by type with data from space-track.org [CITE]

There has been a rapid growth in the number of payloads launched into space, and with it the number of conjunctions. Even if a payload is successfully removed from the environment through a successful deorbit after its lifetime, there are objects left in space after a launch such as mission-related debris and rocket bodies. Conjunction assessment and warnings are often given by agencies such as NASA CARA and the 18th Space Defense Squadron to relevant satellite operators, and there are many logistical, operational and technical challenges to a successful conjunction maneuver; however, there are cases when the objects at risk are non-controllable – as in the case of payloads without maneuver capabilities – or two debris objects colliding. This problem is exacerbated when objects that cannot be tracked are taken into consideration as there may be no warning against such collisions. The European Space Agency estimated in 2021 that there were more than 130 million space debris objects larger than 1 millimeter.

It becomes increasingly clear that methods for estimating of the future LEO population due to launches, collisions, and orbital perturbations is an important step in understanding our LEO environment and long-term forecasting. Such modeling techniques can be largely be divided into two methods - Source Sink Evolutionary models (SSEM) and Monte Carlo (MC) methods. SSEM categorizes all modeled resident space object (RSO) into a few categories and represents the evolution of the population with coupled ODEs per altitude shell deterministically. In contrast, MC methods are a sampling-based method that propagates all objects' orbital states at some discrete time steps and determines collisions resulting in some collision dynamics. This method is computationally more intensive and requires the propagation of tens of thousands to millions of objects for timespans of over one hundred years. For shorter timespans, satellite users and SSA organizations currently use MC-like methods to predict conjunctions and plan conjunction avoidance maneuvers due to its fidelity and flexibility. Alternatively, approximation methods such as a source-sink evolutionary model (SSEM) can be exploited to alleviate this high computational demand, although at the cost of lower fidelity levels.

A number of MC models have been developed by space agencies and private entities over the years. Many of the existing research-level MC models are created by national space organizations and corporations and are close-sourced. LEO to GEO Debris model (LEGEND) has been developed by NASA [1], the DAMAGE model from the United Kingdom Space Agency (UKSA) [2, 3], the MEDEE model from Centre National d'Etudes Spatiales (CNES) [4], the DELTA model from the European Space Agency (ESA) [5], the LUCA model from Technische University at Braunschweig [6], and the NEODEEM model from Kyushu University and the Japan Aerospace Exploration Agency (JAXA), FAST [7], IMPACT [8], and more [9–11]. Although all codebases are proprietary, an IADC study in 2013 compared many of them in [12]. As noted, most of these models use the same assumptions, breakup models, etc., which may contribute to bias on the results, but it is also seen that even for very simple scenarios such as "no new launches" or "business as usual" the models can vary in its results due to differences in assumptions and sub-modules. The randomized initial sampling of the initial distribution of RSOs used by these MC methods prove to be important as seen by the fact that for all of the models, the results span a wide range of results. Also note that most of these tools have been used for analysis of trackable objects, typically regarded as objects larger than 10 cm objects.

2. MOCAT-MC MODEL

The MIT Orbital Capacity Assessment Tool (MOCAT) has been developed to assess the stability of the LEO environment in a generalized manner with varying fidelity. MOCAT has been developed with both SSEM and MC methods to leverage the SSEM method's simplicity and computational efficiency and also the MC method's comprehensiveness. The tool is open-source such that researchers can use a common model that is validated, robust, and efficient, allowing for collaboration amongst the community who are interested in using and developing this tool for a safer space operation.

The SSEM model has been used in many contexts including assessment of the orbital shell stability, estimation of orbital capacity, and improving its fidelity [13–19]. MOCAT-MC describes the MC model in MOCAT [20], which has been developed to analyze the future LEO population in a modular and computationally efficient manner and to understand the future orbital environment. It has been used to identify active debris removal candidates [21] and to validate other types of evolutionary models [22]. The main reason behind the development of the MOCAT-MC is to provide an open-source software, which can be accessed and employed by the scientific community with a common extendible tool. Particular regard is given to the computational speed of all the submodules of MOCAT-MC. One of the drawbacks of MC methods is the high computational time required to run the simulations, which prevents these methods to be tested against many different scenarios in terms of initial population, launch rate, collision and explosion events occurrences, etc. Modeling the future population and traffic of LEO is important in understanding the requirements put on the SSA community. Mature development of a validated model such as MOCAT-MC will allow for understanding of the changes to the requirements on the SSA community for a safe operation in space.

The MOCAT-MC model is described in greater detail in [20], and this section briefly describes the model and expands on the updates that enable the use for large constellations in the future as well as analysis into the LNT population. The overall schematic of the model is shown in Fig. 2.

As a Monte-Carlo tool, a simulation consisting of many episodes is run with some sampling of one or more random variables with associated given probability distribution functions (PDF). The random variables to be sampled and the PDFs can vary depending on the analysis to be performed. Several inputs are given for the simulation.

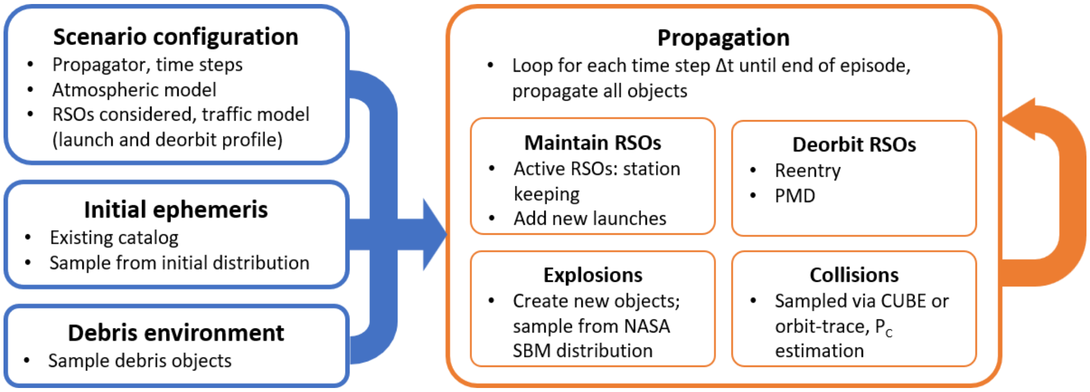

Fig 2. Schematic of the Monte-Carlo tool MOCAT-MC

After the initialization step, MOCAT-MC will enter the propagation loop. For each propagation step, the satellite states are propagated by the chosen time step Δt and a number of steps are taken. Active RSOs maintain their orbital altitude to counteract the atmospheric drag. New launches adds RSOs to the simulation as determined by the launch method used. Some RSOs are deorbited and removed from the simulation. Objects with altitudes below 200 km are removed due to atmospheric reentry. Active satellites at the end of the lifetime are removed due to Post-Mission Disposal (PMD); however, some of these satellites will fail to PMD with some given probability, which will change its status to an inactive satellite. The RSOs will explode with some given probability following the Poisson process. A different rate of explosion can be used per object type. An explosion will spawn new smaller objects, and the quantity, direction and size of the new objects will be sampled from the NASA Standard Breakup Model EVOLVE 4 for low-intensity and high-intensity explosions [23]. Similar to explosions, collisions will produce new objects in the simulation. The parameters of the new objects resulting from the collision will follow EVOLVE 4, and are described in Eq. 1 for explosions and collisions. The cumulative number of objects created n_f for objects larger than the characteristic length l_c is:

$$n_f = \begin{cases} 6\, c_s\, \hat{\ell}_c^{-1.6} & \text{for explosions} \\ 0.1\, \hat{m}^{0.75}\, \hat{\ell}_c^{-1.71} & \text{for collisions} \end{cases} \quad (1)$$

$$\hat{m} = \begin{cases} \dfrac{m_t + m_p}{[\text{kg}]} & \text{for } \tilde{E}_p \geqslant \tilde{E}_p^* \\ \dfrac{m_p\, v_i^2}{1000[\text{kg}\,(\text{m/s})^2]} & \text{for } \tilde{E}_p < \tilde{E}_p^* \end{cases} \qquad \tilde{E}_p = \frac{m_p\, v_i^2}{2\, m_t} \quad (2)$$

Where c_s is the correction factor depending on the type of object that exploded, and $\hat{m}$ is the quantity described in Eq. 2, while m_t and m_p are the masses of the parent and projectile objects respectively, v_i is the relative velocity and E_p is the specific energy of the collision. EVOLVE uses E_p^* = 40 J/g.

To determine collision between two objects, the Cube method is used [24, 25], which follows Eq. 3 to describe the collision probability between two objects in the same cube. This Cube method describes two particles that are close together (within the same cube) to estimate the probability of collision with the kinetic theory of gas as shown in Eq 3.

$$P_{i,j} = s_i s_j V_{imp} \sigma dU \quad (3)$$

where s_i, s_j are the spatial densities of objects i and j, V_{imp} is the relative velocity between the two objects, σ is the collision cross-sectional area $(r_i + r_j)^2$, and the volume of the cube is dU.

2.1 Data-Sources and Initial Population

TLEs from the SATCAT of the 18th Space Defense Squadron is used for the correct scenario epoch. These TLEs provide the list of tracked objects and their orbital state. Note that analyst objects may also exist for objects that are not tracked reliably; however, these are discarded for this work. The physical parameters of these orbital objects such as mass and radius are provided by ESA's DISCOS database. The objects are often without a mass or radius, which are important to note for the Cube method or following the SBM for the number of debris generated. For these cases, the interpolated values of the same object type are used. The Appendix section shows the fit for the payload and debris class.

2.2 Launch Rate

Several options for future launches are available. Repeated launches of some past period, akin to the "extrapolated launch" scenarios implemented in [20, 26, 27]. This simply repeats the exact same launches as they exist in the initial population, though with user-defined parameters such as mission-lifetime and PMD success rate for payloads. The orbital states may be randomized to introduce more stochasticity. A table of constellations could be read in

2.3 Propagator and Atmospheric Model

The propagator, scenario duration and the propagation time step are chosen by the user. Commonly, the SGP4 propagator is employed to propagate the RSOs orbital motion. However, other semi-analytical and analytical propagators could represent a better choice in terms of a compromise between fidelity and computational time. MOCAT-MC uses an analytical approximation of the solution for the motion of RSOs in LEO, considering the atmospheric drag and the J_2 perturbation, is employed as the predominant perturbation effects relevant for long-term evolution of the orbital population as described in [28].

There are a couple of atmospheric models that can be used. One is the static exponential model which can be viewed as the average atmospheric density across solar cycles. A time-varying model has also been implemented using the interpolated density of the Jacchia-Bowman 2008 model that used a high solar cycle prediction. Note that this density value is repeated every ~11 years to follow the solar cycle. The comparison of the atmospheric density and its dependence on altitude and time is shown in Fig. 3.

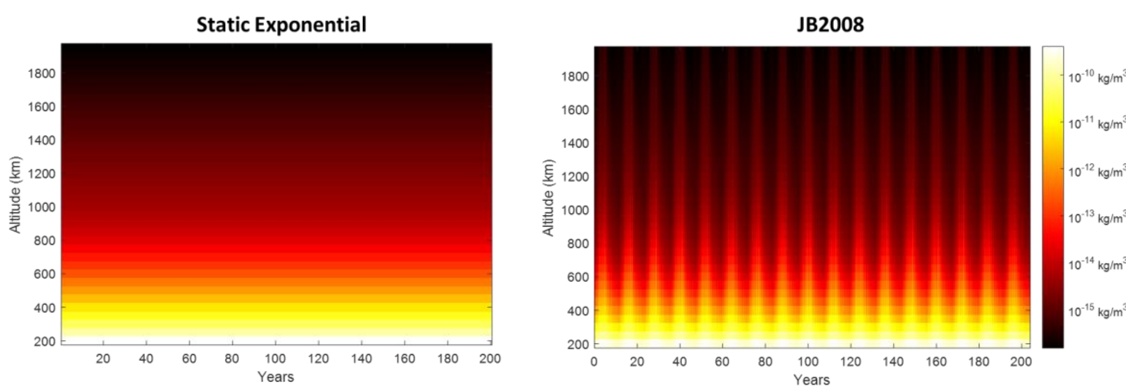

Fig. 3. Two atmospheric models available for MOCAT-MC

3. METHODOLOGY

3.1 Extension into Lethal Non-Trackable Objects

3.2 Megaconstellation Future Traffic Model

There has been numerous constellations exceeding 100 objects propoesd to various governing bodies over the past few years. Predicting which of these constellation will actually be financed, built and launched successfully is a difficult task. Many proposals have come and gone such as the Rwandan eSpace constellation that had 300,000 satellites that has lately been cancelled but may now be financed by France for a fewer number of satellites. As with any ventures, new constellations are constantly being proposed no matter the feasibility or the likelihood of such projects. Many financial, political, regulatory and competitive challenges exist in launching constellations of satellites even after the proposal. Mergers of the large constellation satellite operators and financiers have also led to even more uncertainty in the future launch landscape. SpaceX's Starlink constellation has continued to fill their constellation and has surpassed 5000 satellites launched since 2019. Though there are regulatory challenges governing these satellites, it is clear that there is economic benefit to producing and operating large constellations and such ventures are viable.

Even after filing with the regulatory body such as the ITU or FCC, plans may change depending on the evolving economic outlook or technological challenges. Despite these, an attempt at summarizing the proposed future megaconstellations has been made for this work. For this analysis, several sources of data are combined to create a few future launch scenarios along with some estimate of the physical properties of these satellites. Jonathan McDowell's database is a collection of many proposed satellite constellations [29] and various press releases and sources were used for updates to the numbers and timeline, or for the physical properties of the individual satellites. The cross-referenced data was then used for the creation of a launch model. The launch rate and the cumulative number of objects can be found in Fig. 4. More than 15 megaconstellations have been proposed, of which only two (OneWeb and Starlink) have had any substantial number of satellites launched to date. Note that the mission lifetime is all set at 8 years, while the payload collision avoidance probability $\alpha = 0.01$. Payload-on-payload collision is assumed to be 0, which has been true historically. PMD rate for constellations is set to 90% as used in [28]. A more detailed list of the constellations is shown in Table 1 in the Appendix.
Many satellite owners and operators have claimed that the first launch would be at a certain time, though that timeline has not been followed. For example, SpaceX hoped to begin launching Starlink v2 in 2022 but was unable to, as it needed the use of a larger launch vehicle such as the Starship. With the delay in Starship development, so has Starlink v2. Similar case can be found for some Chinese megaconstellation projects – the yet-unflown domestic super heavy lift vehicle may be needed for full deployment of the constellations. In all of these cases, noting the exact timeline of launches is difficult. Assumptions have been made in determining when these constellations could start to launch. To act as the lower bound, just the constellations with some proven launches are also used as a scenario.

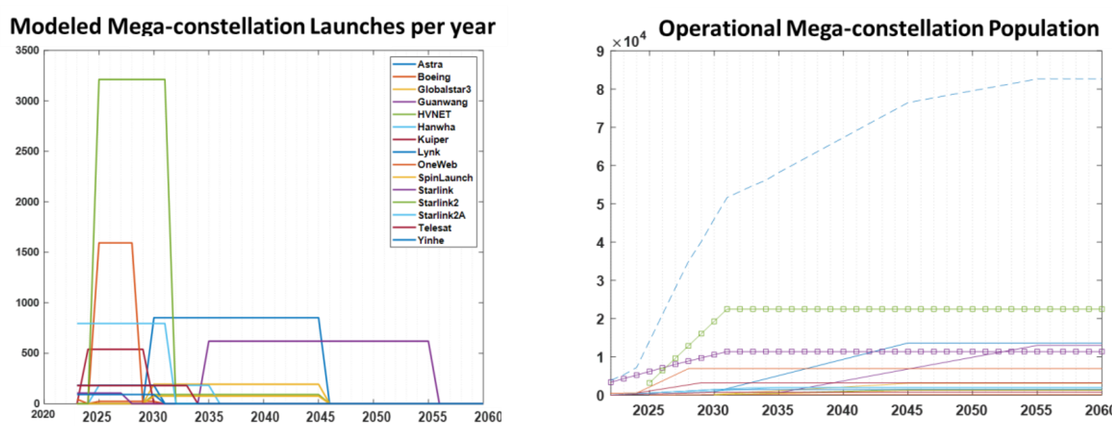

Fig. 4. Proposed megaconstellation launches in the next few decades modeled

The left plot in Fig. 4. shows the newly launched satellite cadence. As the existing satellites reach the end of life, the satellite will attempt to PMD or remain in orbit as a derelict object. No matter which option, a replenishment satellite is required to keep up the operating number of satellites in the constellation. Replenishing these satellites require additional launches, so the number of launches per year would in fact be higher than what is shown in the figure.
Assuming the ramp-up period for launches, the right plot shows the cumulative number of operational populations. The growth of payloads is substantial, and Starlink constellations have a head start as well as a large constellation planned.

4. RESULTS

The LNT numbers show a marked increase in the number of objects.

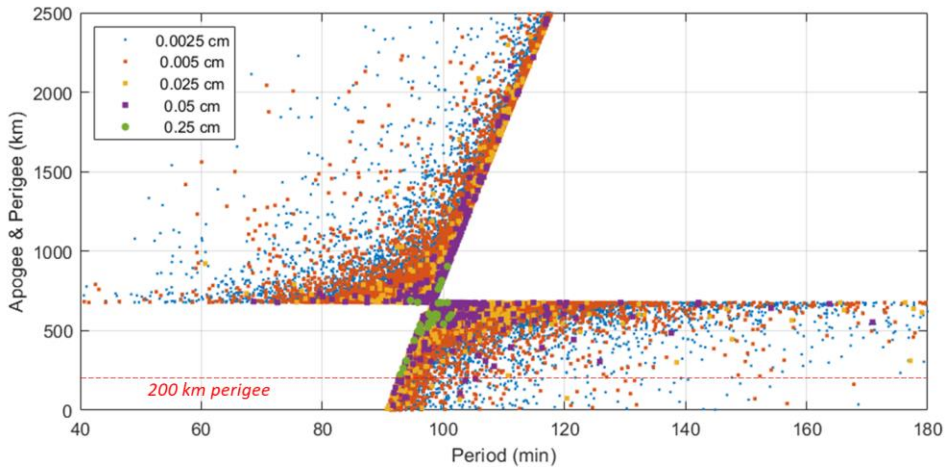

Fig 5. Gabbard diagram of a collision between 260 kg payload and 10 kg debris object at a 600 km altitude

It can be seen that after a collision, a large number of fragments gain a substantial amount of impulse and have either their perigee or apogee changed. Many objects deorbit immediately, which is also the case with collisions we see historically. Of note is the fact that the large objects do not gain as much delta-V as the smaller objects, as this is how the bi-modal distribution of delta-V in the EVOLVE SBM fragmentation model is implemented. This means the smaller objects, which often have higher area-to-mass ratio, may deorbit quickly even with the added impulse. Though the SBM states that the number of objects will follow the power-law relationship shown in Eq. 1, taking life-time into account, the small LNTs are removed from the environment faster.

The difference in the final population when involving LNTs just down to 5 cm compared to 10 cm is clearly seen in Fig. 6. The starting population is colored in orange, while the blue histogram shows the population at the end of a 50 year simulation. The number of objects grow substantially faster where there is a higher concentration of launches that result in collisions. Even after a few collisions, the number of debris in the system grows quickly because of the power-law relationship in the collision model.
The middle plots show the distribution of the size of the objects at the end of the scenario, where the large number of LNTs starts to show. The plots on the right shows the number of objects per type, where the payload fragmentation object dominate the LNT population. This shows that the LNT debris is mostly from collisions involving payloads or derelicts.

Various megaconstellation launch scenarios were run along with a No Future Launch case where all launches cease after this year. For the lowest number of megaconstellations, only the constellations that have shown manufacturing and funding for the constellation have been modeled. These include the Starlink v1 and v1.5, OneWeb and Kuiper, totaling 22228 satellites. The next scenario adds in the Starlink v2 constellations, for a total of 44716 satellites. Then lastly, all of the proposed megaconstellation is launched with a total of 84139 satellites. The assumptions for the orbital planes, number of objects and physical parameters can be found in Table 1. These results show 50 MC runs along with the median value.

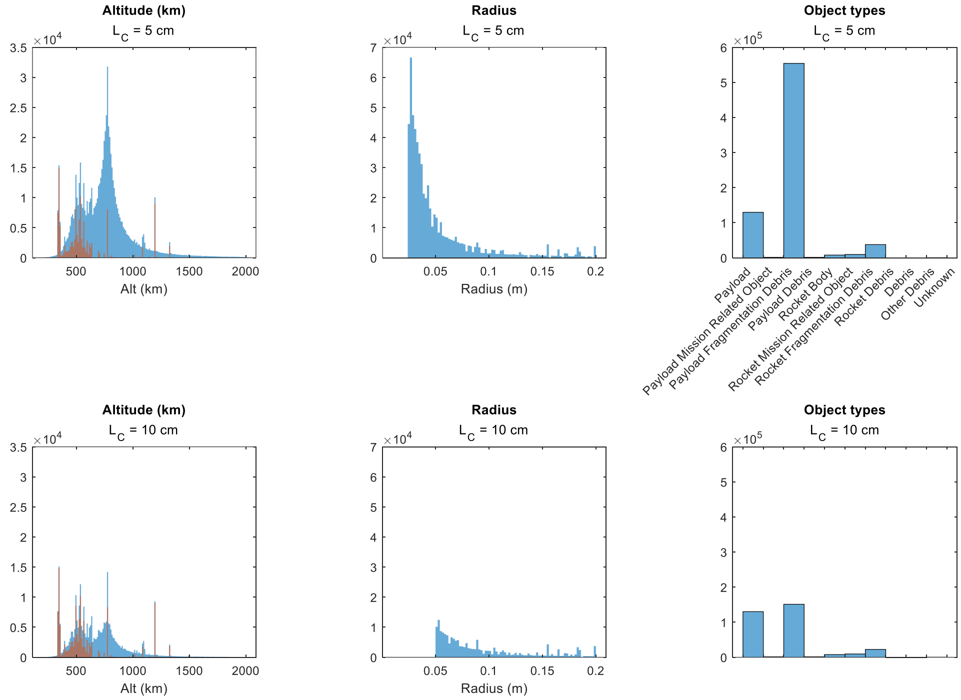

Fig. 6. Number of objects per object type for L_C = 5 cm and L_C = 10 cm

For these megaconstellation launches, Fig. 7. shows the growth in the number of objects. Of note are S (payload) and D (derelict) subplots – the number of objects grow with increased launch scenarios, but at the highest number of launches, the number of payloads start to decrease, despite the 1% failure to avoid a collision. That effect is more pronounced in the derelict class where such avoidance is not possible, and the number of derelict objects start to dwindle after 100 years.
It is also seen in these charts that the number of objects likely will grow even without new launches. This is in line with the findings from [20,27] and highlights the urgent need to limit the creation of derelict objects through higher PMD rates, and effective collision avoidance maneuvers to limit fragmentation events.

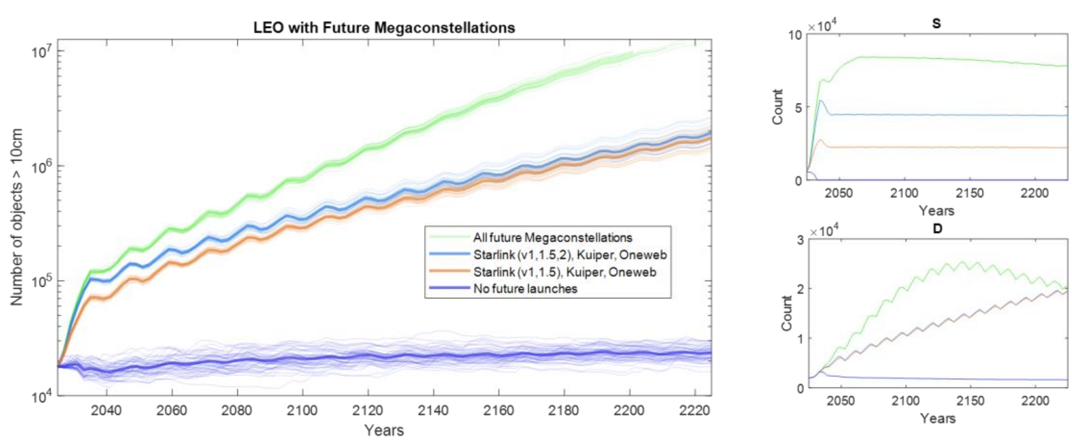

Fig. 7. 200 year propagation of various megaconstellation launches

5. CONCLUSION

It is clear that the consideration of LNTs is crucial in understanding the long-term evolution of the LEO population and sustainable use of space. The non-trackable objects make collision avoidance difficult, yet every collision produces a large number of LNTs, exacerbating the difficult problem. Though simulations that only assumed objects that are large enough for detection may show some orbits that are stable or "safe", the LNTs show a different picture with collision risk growing in regions that were previously thought to be benign.

The large number of megaconstellations that have been proposed in the past few years will also have a large impact on space sustainability. Even while assuming that the operational challenges of coordinating all of the payloads is possible, even more care is needed in collisions avoidance between these payloads and other debris objects. A static PMD number that follows historic statistics would yield a large number of derelict objects that grow linearly with the number of new satellites launched. A much better PMD level compared to historic trends is needed to keep the orbital debris low, including passivated rocket bodies and payloads to reduce the risk of explosions.

All these analyses were possible due to the computationally and memory efficient MOCAT-MC tool. The tool has been used for many other analyses, and its easily extendible and open-source nature allows for flexibility in being used for many different scenarios involving long-term evolution of the LEO environment.

Next steps would include adding other options for propagation, SSA efficacy in tracking objects, alternative collision models, closed-looped ADR model that is assumed to remove highly dangerous objects, and adaptive PMD and collision avoidance factors to enforce some constant collision rate and/or economic loss metrics.

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Appendix

A select proposed megaconstellation parameters are shown in Table 1. The data may not reflect the true state of the constellations and therefore is an approximate representation of the actual constellations. For the "all future megaconstellations" case a few additional constellations are also included: Guanwang, Yinhe, Hanwha, Lynk, Astra, Boeing, Telesat, HVNET, SpinLaunch, Globalstar3. These additional constellations total 39423 satellites as shown in Fig. 4. The total number of megaconstellation after full deployment for the "all future megaconstellations" case is 84139 satellites. The data for these additional constellations are taken from [29].

Table 1. Select Future Megaconstellations Modeled

Constellation Name	Altitude (km)	Incl (deg)	Total Planned	First Launch	Last Launch	Mass (kg)	Radius (m)
Starlink	550	53	1584	2018	2027	260	2
Starlink	570	70	720	2018	2027	260	2
Starlink	560	97.6	348	2018	2027	260	2
Starlink	540	53.2	1584	2018	2027	260	2
Starlink	560	97.6	172	2018	2027	260	2
Starlink2A	530	43	2500	2023	2031	750	2
Starlink2A	525	53	2500	2023	2031	750	2
Starlink2A	535	33	2500	2023	2031	750	2
Starlink2	340	53	5280	2025	2031	1250	4
Starlink2	345	46	5280	2025	2031	1250	4
Starlink2	350	38	5280	2025	2031	1250	4
Starlink2	360	96.9	3600	2025	2031	1250	4
Starlink2	530	43	860	2025	2031	1250	4
Starlink2	525	53	860	2025	2031	1250	4
Starlink2	535	33	860	2025	2031	1250	4
Starlink2	604	148	144	2025	2031	1250	4
Starlink2	614	115.7	324	2025	2031	1250	4
OneWeb	1200	87.9	588	2019	2023	150	0.5
OneWeb	1200	55	128	2019	2023	150	0.5
OneWeb	1200	87.9	1764	2025	2028	150	0.5
OneWeb	1200	40	2304	2025	2028	150	0.5
OneWeb	1200	55	2304	2025	2028	150	0.5
Kuiper	590	33	782	2024	2029	700	1.5
Kuiper	590	30	2	2024	2029	700	1.5
Kuiper	610	42	1292	2024	2029	700	1.5
Kuiper	630	51.9	1156	2024	2029	700	1.5

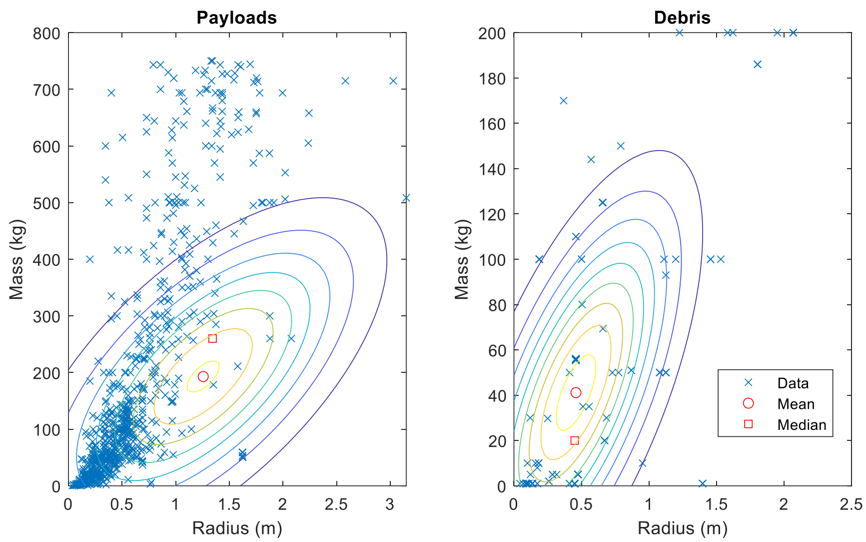

Fig. 8. Distribution of mass and radius from ESA DISCOS for tracked objects