An Exploration of Metrics for Orbital Capacity Modeling

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Abstract

Orbital capacity (OC) modeling has an important role in enhancing space safety and space sustainability. This paper details three different OC models: empirical risk mapping, simple regulatory algorithms, and risk balance (posed and abated) and discusses the general value, observations, and facilitation of active debris removal (ADR) operations of each. Analysts and operators must nonetheless be wary of the unintended negative consequences of applying capacity modeling to Low Earth Orbit (LEO). Current trends toward shorter post-mission disposal (PMD) thresholds, more investment and interest in active debris removal missions, and better communications among satellite owners and operators (O/O) to streamline space traffic coordination (STC) interactions should not be short-circuited by OC modeling results. For example, stating that certain orbits have "excess capacity," thus obviating the need for more mitigation, remediation, and STC advances, would be detrimental to current initiatives and space safety and space sustainability as a whole; the term "capacity" should not be interpreted too literally. However, the examination of several OC models reinforces the deleterious effects of massive derelicts, the importance of persistence, and the criticality of responsible constellation operators.

Background on Models

Before examining the OC models, it is useful to discuss model development in general. A proposed framework for models is shown in Figure 1. A model can be forensic (looking back), diagnostic (current), or predictive (looking forward); usually forensic and diagnostic versions are created prior to establishing the validity of a predictive capability.

It is proposed there are two general classes of models: reductive and reflective. A reductive model has the fewest factors possible as a means to create the simplest representation. Sometimes concise and compelling is better than complete and fewer features need not mean a less accurate representation. When it comes to models, sometimes bigger is not better.

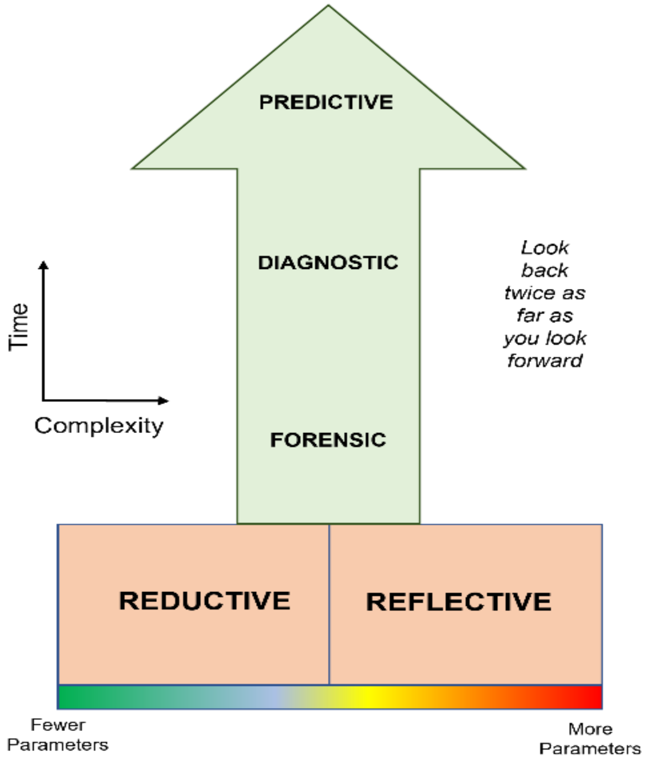

Figure 1. A framework of models displays how models vary in the number of parameters included and time considered.

At the other end of the spectrum are reflective models. These include an exhaustive number of parameters as a means to elucidate all possible relationships. While reductive models may "assume away" many terms, or simply eliminate them for convenience, reflective models will strive to be complete. A sensitivity analysis of the reflective model may be able to ascertain whether or not leaving out those parameters in the reductive model is appropriate.

There is no right or wrong choice between reductive or reflective models (or any model along the spectrum between the two); it largely depends on the application. If trying to represent a complicated technical phenomenon to introduce concepts for a nontechnical audience, a reductive model might be most helpful. However, if examining the same situation for a scientific team using the model to drive engineering decisions, a reflective model might be the better option.

While predictive models are the most advanced, they are built upon diagnostic and forensic models and are fueled by empirical data. From previous examinations of forecasting[1], we suggest it is best to only look forward half as far as a model can "look back". This is an actual flaw in some orbital debris modeling; some analysts develop 200-year models to examine tradeoffs between certain actions to be taken now to minimize the growth of orbital debris over centuries. The first space launch occurred only ~65 years ago and space activity can be viewed as at least three distinctly different phases, limiting projections based on the former phases and shortening the "looking back" window even more:

- The first 20 years of the space age was largely experimentation and exploration. This phase consisted of attempting to see if Earth satellites were viable and what designs and approaches made the most sense.
- The next 20 years was a push by governments to establish services to support civil and national security priorities. This era was represented by many large spacecraft deployed for a wide variety of applications to a wide variety of orbits by a few space agencies.
- The last phase of the space age has been one of commercialization, where a large number of small payloads, often deployed in synchronized constellations, now dominate operational space systems in LEO.[2] This commercial trend has also accelerated the number and diversity of countries involved in the last decade. This rapid change in the space population complicates any attempts at long-term predictive modeling.

With the current dynamic state of affairs, the best modeling one can even attempt is to project just five to ten years before the error bars ovderwhelm the results from the models.

The performance characteristics of these families of models have been informed by a variety of trials and tribulations involving space safety, infectious disease outbreaks, global catastrophes, and other major events. Just as "all models are wrong, some are useful"[3], that "all metrics are wrong, some are useful" also applies.

Our hypothesis is a valuable model is coherent and compelling (i.e., logical, actionable, cumulative, and

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[1] McKnight, D., "Forecasting", Cognovation Dialogues, September 2018.

[2] In geostationary orbit (GEO), the very large monolithic satellite is still the norm.

[3] Paraphrased from Box, G.E, "Science and Statistics", Journal of the American Statistical Association, Vol. 71, No. 356. (Dec76), pp. 791-799.

accurate).[4]

- Logical: a logical model is understandable, and all assumptions are stated clearly. Units and parameters are self-consistent. Putting in extreme values for parameters produces expected results. The model covers the full range of possible inputs and outputs.
- Actionable: an actionable model produces a useful outcome. It avoids unintended negative consequences and does not include extraneous, irrelevant factors. It naturally produces the results in the appropriate timeframe and specificity of action for use.
- Cumulative: a cumulative model serves a role of knowledge accumulation, creates value beyond algorithmic models, and will hopefully advance the output from beyond information to wisdom.
- Accurate (enough): an accurate model is built with algorithms that are not false. Further, a greater amount of quality data produces better (i.e., more useful) results. The terms and relationships are consistent with the domain in which the model is applied.

OC Model 1 of 3: Empirical Risk Mapping

As part of the LeoLabs data analytics efforts, the debris-generating potential (i.e., risk = probability of collision (PC) x mass involved) is plotted in the LeoMap tool. Figure 2 depicts the distribution of the aggregate risk by altitude for all cataloged objects for events grouped in space traffic management (STM) and space debris management (SDM) risk for 1 January 2022 to 30 June 2022 (upper panel) and for 1 January 2022 to 15 May 2023 (bottom panel).

STM represents all conjunctions in LEO involving at least one operational payload where the probability of collision exceeded 1E-6. Conjunctions between operational spacecraft of the same constellation are excluded. SDM conjunctions are between two non-operational objects (i.e., rocket bodies, non-operational payloads, mission-related debris[5], and fragments). The aggregate risk is summed up for over 665,000 representative conjunction data messages (CDMs) from 1 January 2022 to 15 May 2023. A "representative" CDM is the LeoLabs-derived CDM nearest to the time of closest approach (TCA) based on radar-derived positional uncertainty derived by LeoLabs radars for non-operational objects, while operator ephemerides are used for operational satellites, when available.

The growth of the Starlink peak from the first half of 2022 to the entire period in comparison to the SDM peaks (at ~770 km, ~840 km, and ~980 km) is significant. There is even some variation among the SDM peaks as is expected when aggregating purely empirical observations. This variation occurs for two primary reasons. First, any ensemble of derelict orbiting objects in the same altitude range will have some predictable long-term encounter rate over decades, however, over short timeframes (i.e., months to years) the encounter rates (i.e., number of CDMs for a given PC threshold) may vary drastically from the long-term average due to the stochastic (i.e., random) encounter dynamics. Secondly, derelict objects may migrate to lower altitudes due to atmospheric drag, derelicts may be removed by ADR, and new derelicts may be added by either payloads failing, or rocket bodies being abandoned.

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[4] This framework was developed as a best practice of the LeoLabs Data Analytics Team.

[5] For our depictions, mission-related debris is combined into the "fragments" family.

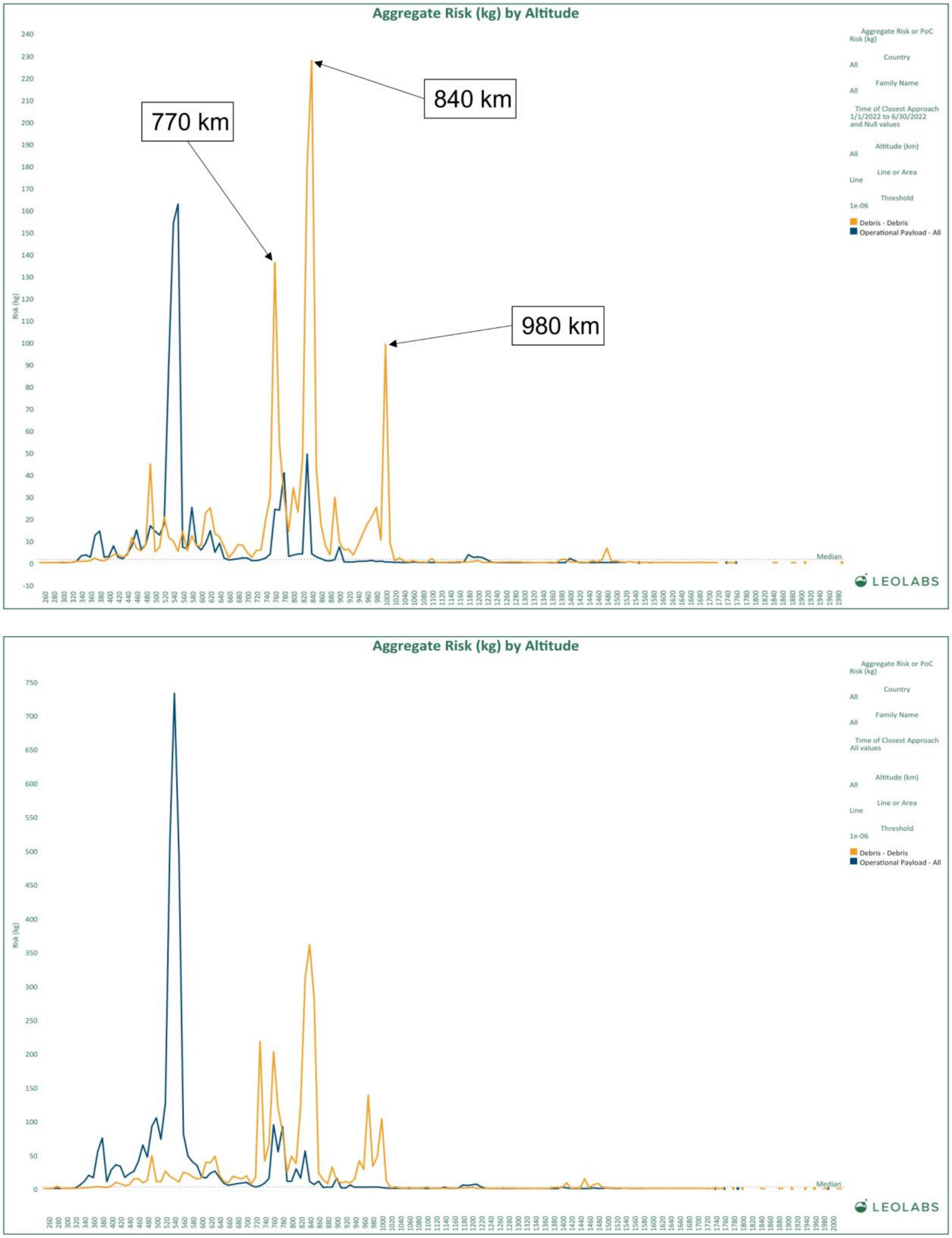

Figure 2. Aggregate risk using LeoMap for STM vs SDM conjunctions shows several distinct peaks. The upper panel depicts the situation for the first six months of 2022 while the lower panel shows the current cumulative situation (i.e., summing the events from 1 January 2022 to 15 May 2023).

This model depiction does not directly account for atmospheric drag (i.e., orbital lifetime). However, the two large SDM peaks are the result of many abandoned rocket bodies and non-operational payloads deposited before the turn of the century that have not been largely affected by drag. The data used in this analysis are compiled for 16.5 months, which does not provide a very long period for drag effects to show up in the evolution of this data set.

Clearly, as long as commercial constellations in LEO continue their track record of managing collision risk well and maintaining their current high satellite reliability performance, the blue curve in the aggregate risk may not be relevant to OC modeling[6]. Could we have imagined even five years ago there would be over 7,000 operational satellites operating in LEO without mission-ending collisions occurring? A tenfold increase in operational systems with no collisions! However, the SDM peaks are real and concerning, and are the most likely locations of a catastrophic collision. These peaks reflect orbits with the greatest debris-generating potential and with easy means for risk abatement (i.e., ADR is not easy!), a fair surrogate for orbital capacity.

Examining the change of the debris-generating potential over time provides some interesting insights. In comparing data from the first quarter of 2022 to the first quarter of 2023, the median SDM aggregate risk increased by ~22% while the STM peak at 540 km increased by 400%. The growth of the Starlink STM peak is noticeably increasing over time. This growth is expected, as about half of all operational payloads in LEO are in this altitude region.

Conversely, the SDM peaks showed significant fluctuation over time, with the 840 km SDM peak having half the magnitude in the first quarter of 2023 compared with the first quarter of 2022. This does not mean collision risk decreased but illustrates the variability of these regions in an empirical assessment. Over the last 16.5 months, the SDM peak at 840 km is clearly the most concerning, but that does not mean it is always the most concerning zone at any given time. In fact, 840 km and 760 km had nearly identical peak aggregate risk in the first 4.5 months of 2023.

OC Model 2 of 3: Simple Regulatory Model(s)

As a proposal to update the way the U.S. Federal Communications Commission (FCC) imposes regulatory authority on space systems, we believe that debris mitigation guidelines should be (1) simplified, (2) based on actual safety burden from the space system (on the environment and on other space systems), and (3) be enforced immediately by stopping further launches of a constellation that is non-compliant.

In order for constellations, or even individual space systems, to continue to launch a regulator could consider a simple safety burden calculation of object-years (e.g., two derelict objects whose orbital lifetimes are each 60 years create a safety burden of 120 object-years). A preliminary threshold of 100 object-years to require cessation of further space launches was included in the original FCC filing[7] to show the math and value of such an approach; an actual threshold for use in regulatory efforts should be derived through detailed technical analysis and operational discussions with O/O.[8]

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[6] This will be quantitatively addressed in the third OC model.

[7] These models are based on several FCC filings by Darren McKnight for LeoLabs in 2022.

[8] It is hoped this paper serves that purpose.

The threshold for object-years was created by combining the 25-year rule with 90% reliability to determine a realized environmental burden (REB). The REB threshold is calculated as (probability of failure = 10%) x (25 years) x (number of satellites) = 2.5 x (number of satellites) in object-years. The REB is proposed to be calculated in advance and then monitored by the FCC. The threshold grows by the number of satellites in the system or constellation, as shown in the figure below, with a threshold at 100 object-years. In essence, the threshold is flexible for constellations of fewer than 40 satellites, but constant after that for all constellations, regardless of the number of satellites in the constellation.

The orbital lifetimes in this paper are derived from the analytic approach taken by Desmond King-Hele[9]. This approach permits simple excursions based on different altitudes, solar activity, and area-to-mass ratios. We do correct for the known variable coefficient of drag in LEO (2.1 near reentry up to 3.0 above 1,000 km altitude[10]) while King-Hele used a value of 2.1 throughout the orbital decay process. A typical intact object has roughly a 5-year orbital lifetime at 500 km and a 25-year orbital lifetime at 615 km, based on average solar activity. Solar radiation pressure is completely ignored by King-Hele, and thus neglected in our preliminary analysis.

For example, a 10-satellite constellation has a REB threshold of 25 object-years. If it is deployed to 500 km and one satellite fails at that altitude, then they have incurred a REB of 5 object-years, so launches to this system can continue. However, if the system had been deployed to 615 km and one satellite fails, the constellation's REB is 25 objects-years. As a result, the failed, non-operational payload needs to be removed or its orbital lifetime reduced before more launches by this operator can take place.

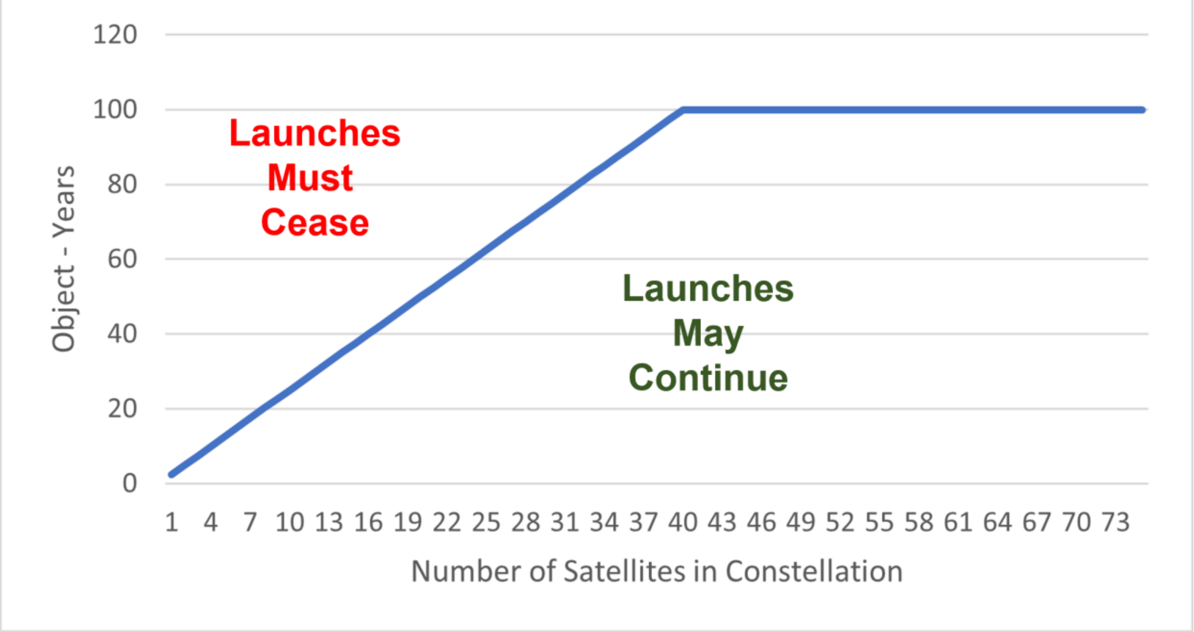

Figure 3. The object-years threshold grows at 2.5 object-years per satellite but maxes out at 100 object-years.

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[9] King-Hele, Desmond. Theory of Satellites in an Atmosphere. Blackie and Son Ltd, London, 1987.

[10] Used the C_D distribution provided by STELA, STELA | Connect by CNES

Mass can also be, and should be, considered in a REB evaluation; therefore, a second regulatory metric was proposed with units of object-metric ton-years. For the example scenario, assuming each satellite had a mass of 500 kg, then the deposition of one payload creates a REB of 12.5 object-metric ton-years. This is well below the 25 object-metric ton-years that would be the REB threshold for a 10-satellite constellation.

In the original FCC filing for this algorithm, a maximum threshold of 100 object-metric ton-years was shown as an example, however, just as with the object-years metric, concurrence among O/Os on the proper threshold is a required next step.

For this paper, we find it instructive to determine the actual levels of these two metrics in LEO as both a relevant context for a proper regulatory threshold and a potential useful depiction of orbital capacity. Figures 4 and 5 show object-years and object-metric ton-years by altitude, respectively. These were calculated using the LeoLabs satellite catalog, excluding operational satellites, as of 15 May 2023. This will slightly under-report the levels since some operational payloads do not have robust collision avoidance systems, making them part of the collision risk burden to others.

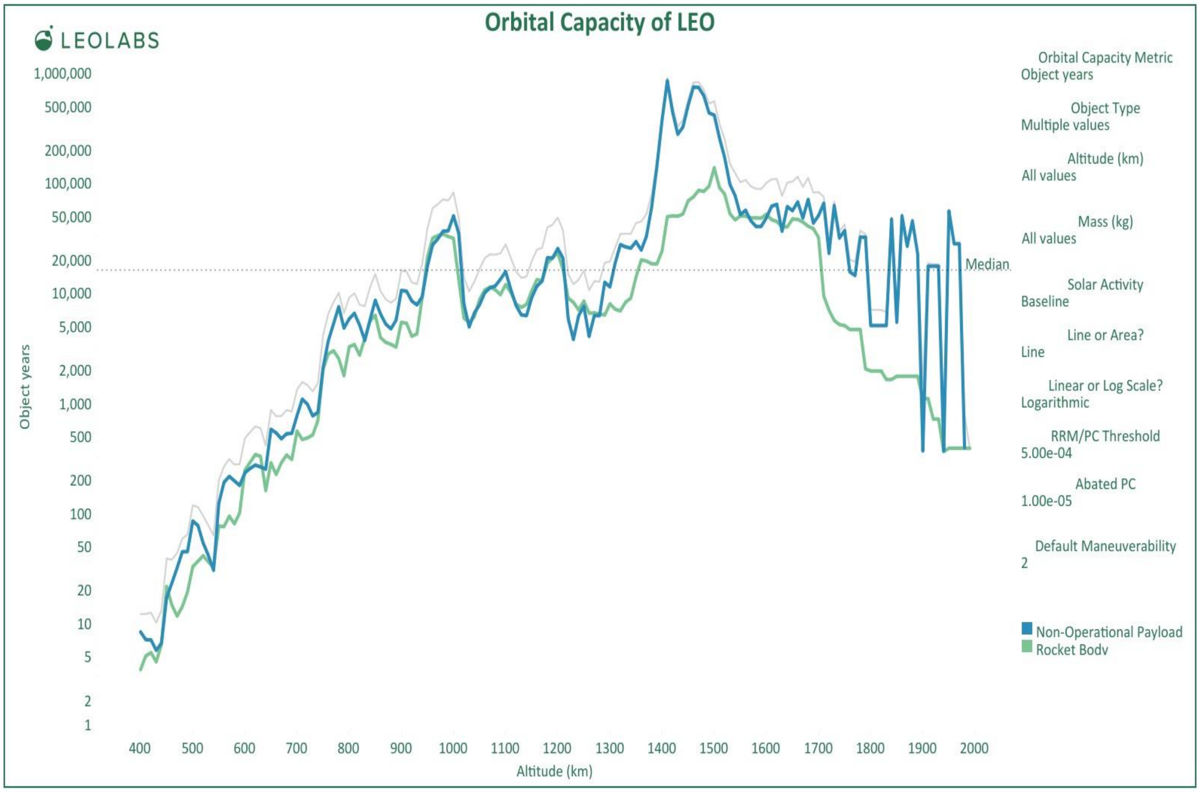

Figure 4. Object-years by altitude, without operational payloads, shows the significant effect the exponentially varying atmosphere has on these calculations. The same worksheet was built within Tableau for each of the three new OC models while filters for risk abatement thresholds shown in this figure are only used in the final OC model (i.e., risk balance).

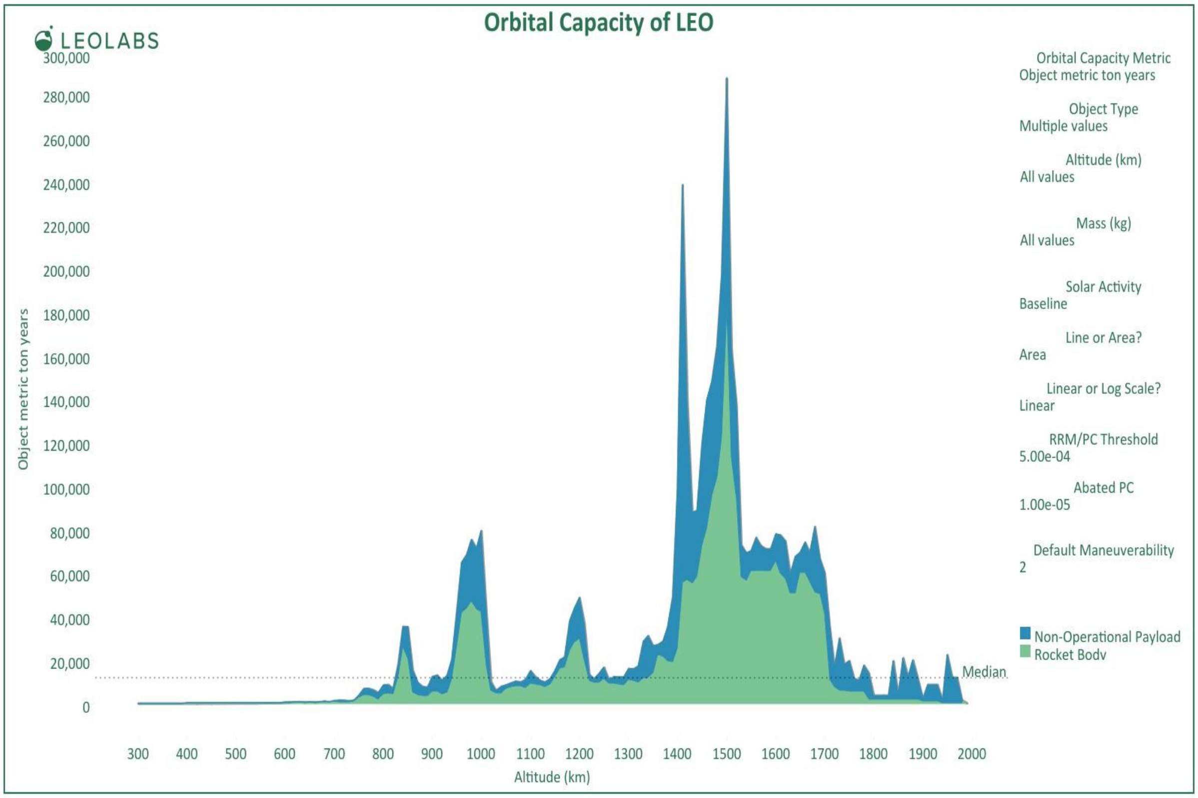

Figure 5. Object-metric tons-years by altitude without operational payloads accentuates the "bad neighborhoods" centered at ~840 km and ~975 km while reinforcing the persistence of the derelicts abandoned at ~1,500 km.

These figures provide perspective on the relevance of a 100 object-years threshold and highlight that altitude has a very large effect on the characterization of object-years, as would be expected.

The median object-years for the current LEO population is ~15,000 object-years while the peak is~ 840,000 object-years at between 1,400 km and 1,500 km. Considering only the altitudes from 700 km to 2,000 km, the median is ~25,000 object-years. Indeed, 100 object-years is an incredibly restrictive threshold considering the current state of affairs in LEO.

One might ask, does the peak value reflect a distressing situation, or is the relatively small level of object-years in other LEO orbits reflective of a wonderful situation? The authors propose this just begins to hint at the importance of persistence (i.e., orbital lifetime) in measuring orbital capacity. Not considering the mass of the objects amplifies the effect of persistence.

Adding mass to create the object-metric ton-years plot produces a significantly different depiction, amplifying the "bad neighborhoods" centered at 840 km and 975 km, while the peak object-metric ton-year value still remains at the higher altitude region of ~1,400 to 1,700 km. It is also clear rocket bodies and non-operational payloads contribute equally to the persistence of debris-generating potential.[11] These dangerous, massive derelicts are also not being moved or removed by atmospheric drag due to

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[11] The ~1,400 km altitude is the only place non-operational payloads drastically outnumber rocket bodies.

their high altitudes; this is an unfortunate combination. The median object-metric ton-years for LEO is ~12,000 object-metric ton-years while the peak is ~287,000 object-metric ton-years at ~1,500 km. The median for 700 km to 2,000 km is ~17,000 object-metric ton-years.

OC Model 3 of 3: Collision Risk Balance (posed x abated x persistence)

A slightly more reflective model considers orbital capacity as a function of an ensemble of objects' risk burden and risk abatement for a given altitude. We must be wary of unintended negative consequences of orbital capacity modeling; as models get more complicated, peoples' confidence (rightly or wrongly) grows in the model.

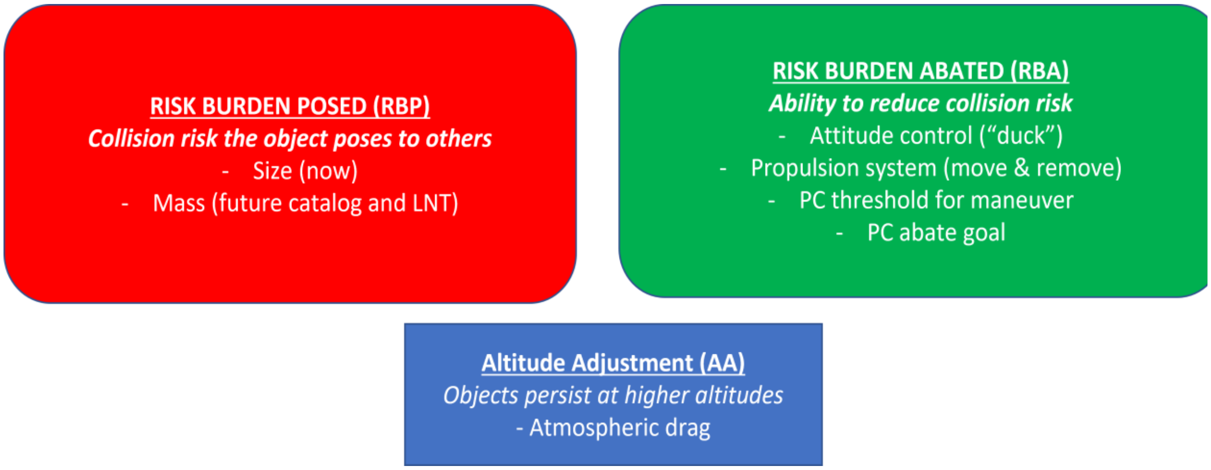

Figure 6. Orbital capacity can be modeled as a balance between risk posed and risk abated and adjusted by persistence (based on atmospheric drag characterized by altitude).

This model can be represented mathematically as:

$$OC = \Sigma\, [RBP * \{10 - RBA\} * AA]$$

RBP (intact object[12]) = mass x area

Assume area-to-mass ratio, A/M = 0.01 m^2/kg for intact object, so A = 0.01M as default but examine a larger A/M ratio (e.g., 0.05 m^2/kg) as typical of newer, larger constellations.

RBP (intact object) = 0.01 M^2

RBP (catalog fragments and LNT) are not covered in current model. [13]

RBA (intact derelict) = 0, means no risk is abated

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[12] Energetic sources onboard are ignored but could be added for future model developments.

[13] Catalog fragments and lethal nontrackable (LNT) debris will not be considered in this preliminary evaluation. However, if included RBP (fragment) = 0.025 kg, by assuming A/M (fragment) = 0.05 m^2/kg and mass(fragment) = 0.5 kg and RBP (LNT) = 2.5E-6 kg assuming A/M (LNT) = 0.10 m^2/kg and mass (LNT) = 0.005 kg. RBA (fragment or LNT) = 0

RBA (OPL[14]) = $2.15 \times \{MAN \times 0.33\} \times 2.15 \times \{1 - ([6 + \log_{10}\{RMM/PC\}]^2/10)\} \times 2.15 \times \{1 - ([7 + \log_{10}\{AbPC\}]^2/10)\}$

The constant 2.15 is the cube root of 10 – this is used to give each factor equal weight.

The maneuverability (MAN) taxonomy, scoring between 0 and 3, is included in Appendix A.

RRM/PC threshold is the probability of collision (PC) on which a risk reduction maneuver (RRM) is executed, with a minimum of 1E-6 and a default for uncrewed systems of 5E-4.

AbPC is the goal to which the conjunction PC is to be abated, with a minimum of 1E-7 and a default value of 1E-5.

AA = $1 + [(ALT-300)/100]^{3.85}$, adjusts for persistence at altitudes above 300 km due to less atmospheric drag.[15]

We calculate and plot OC as a function of altitude directly from the LeoLabs catalog. Figures 7 and 8 displays OC as a function of altitude with contributions from the current population of operational payloads, rocket bodies, and non-operational payloads. The upper panel illustrates the data in an area plot with a linear y-axis to show the total OC, while the lower panel is a line plot with log scale for the y-axis, displaying the contributions of each object type. The median OC from LEO is ~270,000,000 (~270M) with a peak value of ~31,000,000,000 (~31B) at 840 km. Note, the OC is a dimensionless term, and its value should not be compared to the values for object-years or object-metric ton-years.

This model is differentiated from the others because it includes both orbital lifetime and operational payloads and considers the payload capability to reduce collision risk (see Table 2). This more complete (i.e., reflective) model amplifies the criticality of the 840 km "bad neighborhood" compared with other orbital regimes. The second and third "bad neighborhoods" around 975 km and 1,500 km still pose a concern. It should be noted that all of these models assess the effect of derelict objects and operational satellites at each altitude at the current time. However, objects at higher altitudes will eventually go through all of the lower orbits in their natural decay or deorbiting process. This effect is not yet addressed or considered in the current model.

Table 2. The three OC models examined provide a diverse range of viewpoints.

Model	Aggregate Derelict Collision Risk	Aggregate Operational Payload Collision Risk	Orbital Lifetime
Risk Mapping	✓	✓	
Simple Regulatory	✓		✓
Collision Risk Balance: Posed, Abated, and Persistence	✓	✓	✓

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[14] OPL is operational payload.

[15] The exponent 3.85 was chosen to most closely match the atmospheric density profile in LEO.

This method also shows how Starlink and OneWeb operations reflect an overall smaller impact on orbital capacity on account of their RBA.

Many of the spikes across LEO are created not by constellations, but rather by an aggregation of hundreds of individual payloads not in constellations, and generally have less sophisticated collision avoidance, or specifics of their collision avoidance operations are not publicly known. Six large constellations account for 70% of the nearly ~7,200 operational payloads in LEO as of 15 May 2023. The remaining ~2,100 operational payloads may not be as rigorous about collision avoidance as the six largest constellations. This collective effect of non-constellation operational payloads reinforces previous public assertions about space sustainability: constellations are not the problem; they may well be the victim of future debris-generating events.

Other payload spikes in the OC below 700 km may be mitigated significantly over the next few years as solar activity is set to peak in 2024 and 2025.

This analysis assumes an A/M of 0.01 m^2/kg for all operational payloads, however, Starlink and many of the newer satellites are deploying with a larger A/M. Such a change will lead to faster orbital decay in the case of satellite failure and helps self-abatement of risk. Unfortunately, the larger area for a given mass will both increase the requirements for station-keeping and increase the collision cross-section and collision hazard. For this model, the increase in A/M leads to an increase in RBP, but a decrease in orbital lifetime, thus a decrease in the AA term.

To test boundary cases, all operational payloads were increased to an A/M of 0.05 m^2/kg. The lifetime calculation was also adjusted by changing the altitude adjustment (AA) coefficient from 3.85 to 3.25 to adjust the lifetimes appropriately for this higher A/M. The peak value altered very slightly as it was dominated by rocket bodies and nonoperational payloads and thus largely not affected by these changes. The median rose to 447M (a 10% increase); this counterintuitive result is exactly why we use models.

Examination of the results reveals that, for higher altitudes, the increased A/M produces a net decrease in overall risk, but, for lower altitudes, the AA adjustment gives a smaller net difference, increasing the overall risk slightly due to the larger exposed area. Overall, the larger A/M values for new constellation satellites ends up not making a large difference, good or bad, despite the seemingly obvious effect. However, the larger A/M provides more opportunity for lethal nontrackable (LNT) debris to adversely affect these satellites; this feature is not modeled in the current framework for the risk balance model. This issue will be addressed in future model developments.

These values clearly reflect the combination of “self-abatement” from lower altitude deployments and the benefit of a robust collision avoidance capability in reducing collision risk.

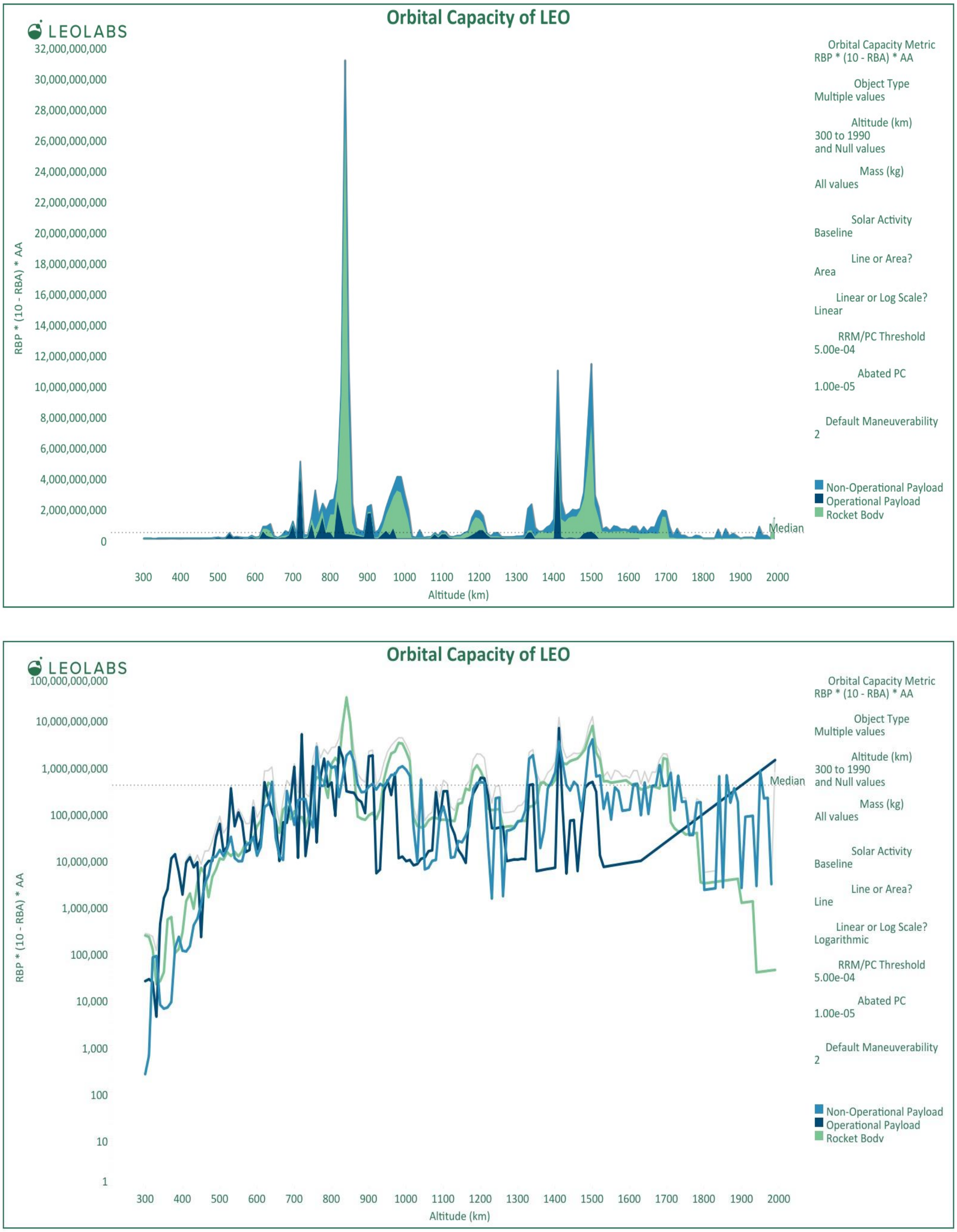

Figure 7. The collision risk posed/abated model as a function of altitude highlights concerns of the ~840 km "bad neighborhood" and the much higher altitude "bad neighborhood" in the ~1,400 to 1,500 km altitude range.

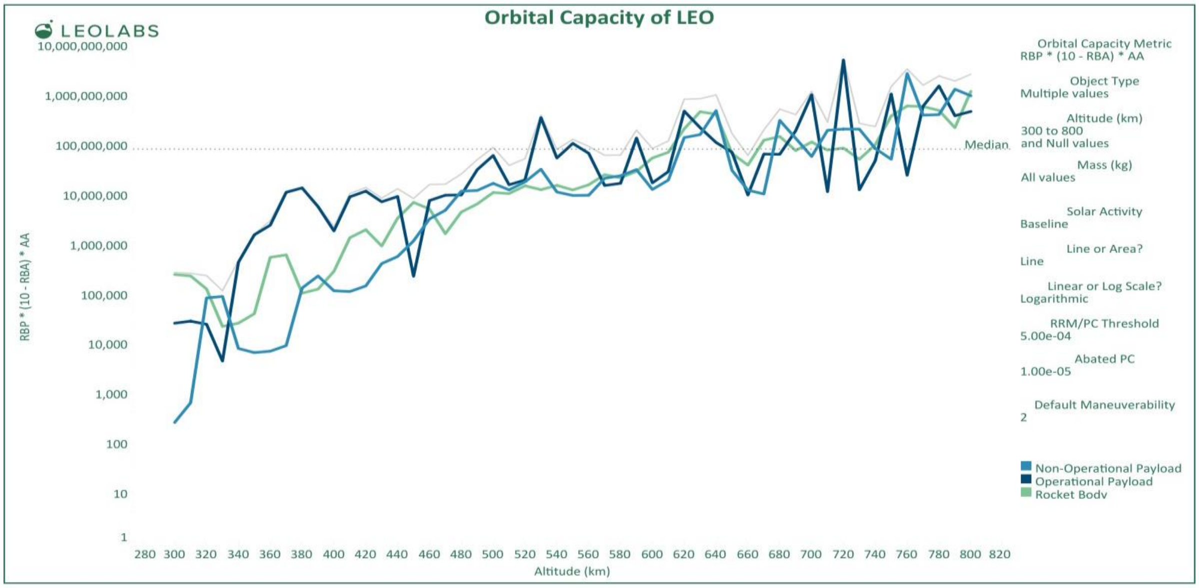

Figure 8. Zooming in on lower band provides insights into structure of the population in critical regions below 800 km where so many of the future constellations are slated to be deployed.

Further, if satellites switched from one constellation location to another, what effects would result? While this paper illustrates the risk balance across altitude regimes, the calculations can be applied to an individual satellite at an isolated altitude... So, what if we switched a Starlink and OneWeb satellite in LEO? A quick analysis determined the OneWeb at Starlink altitude had a 2.35 factor lower overall OC while the Starlink at the OneWeb altitude had a 2.35 OC larger than the OneWeb constellation. Switching satellites as above is more for investigating the flexibility of the model than for making evaluations of specific satellite systems. Since our model assumes all intact objects have an AMR of 0.01 m^2/kg, mass is the driving force behind the risk burden posed (i.e., RBP) portion of the model (i.e., OC is proportional to the square of mass of the satellite) while maneuver capability and altitude selection are the two primary ways of abating the risk. Comparing the Starlink and OneWeb constellations could provide a stark comparison. The levels for these terms are summarized below for convenience:

- Starlink: mass of 260 kg, orbital lifetime of 5 years[16], best maneuverability with risk values for action and abatement goal of 1E-5/1E-6
- OneWeb[17]: mass of 150 kg, orbital lifetime of 1,000 years, best maneuverability with risk values for action and abatement goal of 1E-5/1E-6

In essence, Starlink satellites have a mass ~70% larger than OneWeb satellites and an orbital lifetime

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[16] In reality, the orbital lifetime of a failed Starlink satellite is closer to 3 yr due to a larger physical AMR than the 0.01 m^2/kg assumed.

[17] In reality, the two-term representation of the OneWeb risk abatement process is a simplification of a series of thresholds and actions that they use in their operations. A more “reflective” model would be able to use these other factors.

200 times smaller, with identical risk abatement maneuver operations. As a result, the net effect of swapping out two satellites while keeping the number of satellites in the constellation the same, is the new OneWeb constellation with Starlink satellites would have a slightly increased OC while the new Starlink constellation with OneWeb satellites would have a decreased OC.

In summary, this excursion of the OC model reinforces the fidelity of this modeling approach and constellation design and operations are likely to be fine-tuned for the chosen altitude and constellation size.

A paper by Sweetser[18] provides an elegant alternative to risk burden abated through risk reduction maneuver operations that will be investigated in future research. It considers more parameters such as positional uncertainty and object size directly.

Implications for ADR

The OC modeling downplays the significance of identifying specific objects for removal (from the Top 50 papers [19]); the original top 50 list from the 2020 paper is shown in Table 1. Simply stated, this analysis demonstrates it is just as important to remediate an orbital regime as it is to look at individual objects for removal. The top 50 objects from the earlier papers indicate there are clear orbital regimes with collectively the greatest debris-generating potential that should be remediated. Some objects most likely to present the greatest debris-generating potential may not be available for removal either due to geopolitical or a combination of mass and tumble rate. Analytically, removing object #35 of the top 50 list now may be better than waiting years to go after #1. In reality, the difference in debris-generating potential, after the top 20 or so, is fairly small. In addition, the range of actual high-PC encounters varies drastically from object to object over time (as seen in the first OC model of empirical data), so the first collision event among the hundreds of massive derelicts may not include the top ranked object for removal.

Therefore, we need to start reducing the general debris-generating potential for the “bad neighborhoods” (e.g., 840 km, 975 km, and 1,500 km) regardless of relative rank.

It may be prudent to execute ADR by finding large, easily retrieved (i.e., no energy source and stable or slowly tumbling) objects centered within the peaks in spatial and mass density, representing peaks in orbital capacity. This process must be iterative, with a re-examination of the debris-generating potential by orbit, both empirically and statistically, each time a massive derelict is removed. For example, the cluster of 18 SL-16 rocket bodies (R/Bs) centered at 840 km is a high priority for removal; however, once several of them have been deorbited, the remaining SL-16 R/Bs may not be the “hot spot” any longer.

This will require constant monitoring, characterizing, and updating of priorities; however, the priorities will be more about the altitude regime than about individual objects. Since the major debris-generating potential local maxima (i.e., ~840 km, ~975 km, and ~1,400 to 1,500 km) are at such high altitudes it is

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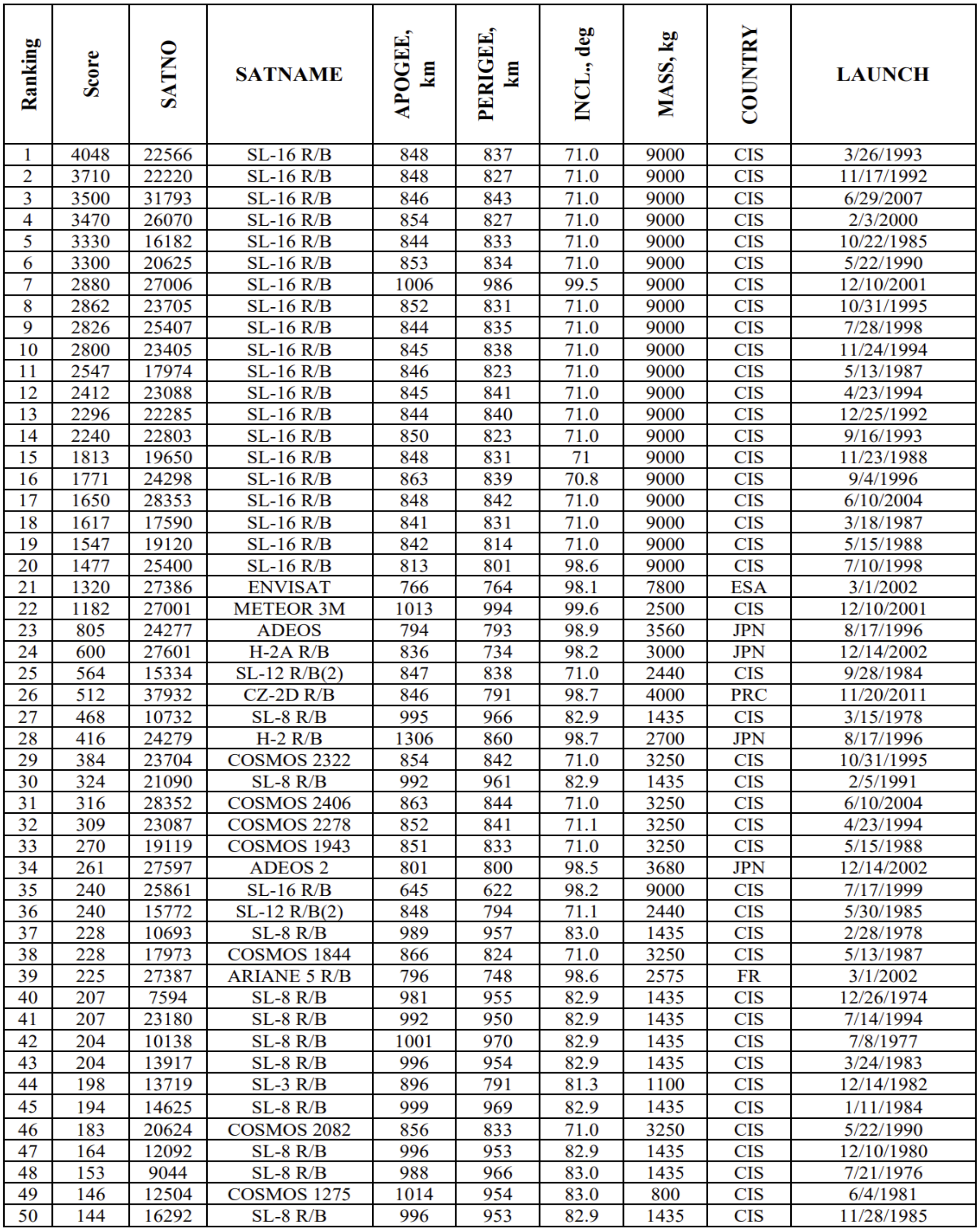
[18] Sweetser, T., Braun, B., Acocella, M., and Vincent, M., “Quantitative Assessment of a Threshold for Risk Mitigation Actions,” Journal of Space Safety Engineering, 9Aug2020, https://doi.org/10.1016/j.jsse.2020.07.009

[19] McKnight, D., et al, “Identifying the 50 Statistically-Most-Concerning Derelict Objects in LEO,” 71st International Astronautical Congress (IAC) – The CyberSpace Edition, Dubai, UAE, October 2020; and McKnight, D., et al, “A MAP OF THE STATISTICAL COLLISION RISK IN LEO”, 73rd International Astronautical Congress, Paris, France, Sept2022.

not likely these regions will benefit from anything other than ADR or derelict addition (i.e., increase in derelict population due to faulty operations).

Table 1. The scoring for the top 50 objects drops off quickly after the first 20 or so objects.



Ranking	Score	SATNO	SATNAME	APOGEE, km	PERIGEE, km	INCL., deg	MASS, kg	COUNTRY	LAUNCH
1	4048	22566	SL-16 R/B	848	837	71.0	9000	CIS	3/26/1993
2	3710	22220	SL-16 R/B	848	827	71.0	9000	CIS	11/17/1992
3	3500	31793	SL-16 R/B	846	843	71.0	9000	CIS	6/29/2007
4	3470	26070	SL-16 R/B	854	827	71.0	9000	CIS	2/3/2000
5	3330	16182	SL-16 R/B	844	833	71.0	9000	CIS	10/22/1985
6	3300	20625	SL-16 R/B	853	834	71.0	9000	CIS	5/22/1990
7	2880	27006	SL-16 R/B	1006	986	99.5	9000	CIS	12/10/2001
8	2862	23705	SL-16 R/B	852	831	71.0	9000	CIS	10/31/1995
9	2826	25407	SL-16 R/B	844	835	71.0	9000	CIS	7/28/1998
10	2800	23405	SL-16 R/B	845	838	71.0	9000	CIS	11/24/1994
11	2547	17974	SL-16 R/B	846	823	71.0	9000	CIS	5/13/1987
12	2412	23088	SL-16 R/B	845	841	71.0	9000	CIS	4/23/1994
13	2296	22285	SL-16 R/B	844	840	71.0	9000	CIS	12/25/1992
14	2240	22803	SL-16 R/B	850	823	71.0	9000	CIS	9/16/1993
15	1813	19650	SL-16 R/B	848	831	71	9000	CIS	11/23/1988
16	1771	24298	SL-16 R/B	863	839	70.8	9000	CIS	9/4/1996
17	1650	28353	SL-16 R/B	848	842	71.0	9000	CIS	6/10/2004
18	1617	17590	SL-16 R/B	841	831	71.0	9000	CIS	3/18/1987
19	1547	19120	SL-16 R/B	842	814	71.0	9000	CIS	5/15/1988
20	1477	25400	SL-16 R/B	813	801	98.6	9000	CIS	7/10/1998
21	1320	27386	ENVISAT	766	764	98.1	7800	ESA	3/1/2002
22	1182	27001	METEOR 3M	1013	994	99.6	2500	CIS	12/10/2001
23	805	24277	ADEOS	794	793	98.9	3560	JPN	8/17/1996
24	600	27601	H-2A R/B	836	734	98.2	3000	JPN	12/14/2002
25	564	15334	SL-12 R/B(2)	847	838	71.0	2440	CIS	9/28/1984
26	512	37932	CZ-2D R/B	846	791	98.7	4000	PRC	11/20/2011
27	468	10732	SL-8 R/B	995	966	82.9	1435	CIS	3/15/1978
28	416	24279	H-2 R/B	1306	860	98.7	2700	JPN	8/17/1996
29	384	23704	COSMOS 2322	854	842	71.0	3250	CIS	10/31/1995
30	324	21090	SL-8 R/B	992	961	82.9	1435	CIS	2/5/1991
31	316	28352	COSMOS 2406	863	844	71.0	3250	CIS	6/10/2004
32	309	23087	COSMOS 2278	852	841	71.1	3250	CIS	4/23/1994
33	270	19119	COSMOS 1943	851	833	71.0	3250	CIS	5/15/1988
34	261	27597	ADEOS 2	801	800	98.5	3680	JPN	12/14/2002
35	240	25861	SL-16 R/B	645	622	98.2	9000	CIS	7/17/1999
36	240	15772	SL-12 R/B(2)	848	794	71.1	2440	CIS	5/30/1985
37	228	10693	SL-8 R/B	989	957	83.0	1435	CIS	2/28/1978
38	228	17973	COSMOS 1844	866	824	71.0	3250	CIS	5/13/1987
39	225	27387	ARIANE 5 R/B	796	748	98.6	2575	FR	3/1/2002
40	207	7594	SL-8 R/B	981	955	82.9	1435	CIS	12/26/1974
41	207	23180	SL-8 R/B	992	950	82.9	1435	CIS	7/14/1994
42	204	10138	SL-8 R/B	1001	970	82.9	1435	CIS	7/8/1977
43	204	13917	SL-8 R/B	996	954	82.9	1435	CIS	3/24/1983
44	198	13719	SL-3 R/B	896	791	81.3	1100	CIS	12/14/1982
45	194	14625	SL-8 R/B	999	969	82.9	1435	CIS	1/11/1984
46	183	20624	COSMOS 2082	856	833	71.0	3250	CIS	5/22/1990
47	164	12092	SL-8 R/B	996	953	82.9	1435	CIS	12/10/1980
48	153	9044	SL-8 R/B	988	966	83.0	1435	CIS	7/21/1976
49	146	12504	COSMOS 1275	1014	954	83.0	800	CIS	6/4/1981
50	144	16292	SL-8 R/B	996	953	82.9	1435	CIS	11/28/1985

Note how, after the first 20 or so objects, the overall score (the second column) drops very quickly.

The regulatory models reviewed (i.e., object-years and object-metric ton-years) also provide a potential way to monetize the benefits of ADR. If a satellite operator or an ADR provider removes an object with 200 object-metric ton-years, they could sell that asset (or its associated credit) to an operator who needs "relief".[20] This might help catalyze ADR, but also may create the unintended consequence of concentrations in realized burden where operators bought object-metric ton-years from derelicts removed from an altitude different from their operational altitude.

The first stage of ADR implementation should be government-promoted so the ADR industry can be pushed into a stable operational mode, similar to earth observation satellites and space launch. In addition, early ADR successes should be examined from a long-term perspective to enable the next phase where multiple-satellites-per-mission removals can happen, as ADR mission prices decrease to be self-supporting either through incentives or directly by commercial firms that create less expensive and more flexible ADR solutions.

Synthesis

The concept of an orbit being "full" is controversial and fraught with cognitive danger. However, the examination of several potential OC models reinforces the deleterious effects of massive derelicts, the importance of persistence, and the criticality of constellation operators acting responsibly. The massive derelicts are a real threat and a hinderance to space sustainability. Constellation operators have, so far, been responsible and thus have not manifested the high aggregate operational payload risk some had anticipated before their satellites were deployed. If constellation failure rates start to increase due to collision risk from LNTs, then this positive situation could deteriorate.

The three models presented in this paper, and all of the "top ##" lists generated, agree on one observation: the cluster of SL-16 rocket bodies centered around 840 km poses a unique danger to LEO space safety and space sustainability. These 20 derelict objects[21] are much larger and more massive than typical derelicts; their orbital altitudes will keep them in orbit for centuries; and debris generated by collisions among them will linger for many decades. After that, the 975 km, and 1,500 km local maxima of derelict object clusters pose the greatest threat to enduring LEO space safety. ADR should be emphasized in these three regions; this is critical since collision events in these regions will affect much of LEO. For example, fragments from the 2009 Cosmos 2251 / Iridium-33 collision at 765 km continue to create 3,400 high-PC conjunctions over the last 15 months, 13 years after the collision, at altitudes ranging from 330 km to 1,600 km.

Third on the priority list are the nearly 2,100 operational payloads not in the six major constellations that may collectively pose a space safety concern. The good news is that many of these systems, and most of the major constellations, are below 700 km which makes events involving them much less persistent (due to atmospheric drag) than the three "bad neighborhoods," and the higher presence of

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[20] An examination of the pros and cons of carbon credits might be a worthy topic of conversation in a follow-on analysis.

[21] 18 of these massive SL-16 R/Bs reside in the notorious "bad neighborhood" centered around 840 km but two others also still orbit in other altitude regions in LEO.

operational payloads allows some of the risk to be mitigated.

Future research will help to understand how much more collision avoidance burden the major constellations could weather. For example, if two SL-16 rocket bodies were to collide, it would double the catalog population and create a large amount of LNT in an instant. Could current constellations' collision avoidance systems absorb this new risk? Would failure rates increase due to the increased LNT population?

It is important to remind the reader while we presented an orbital capacity model based solely on objects and the persistence in orbit (i.e., object-years), this model was only shown as part of the buildup to the more reflective modeling methods.

Further, as this paper started with a disclaimer about orbital capacity modeling, it is appropriate that it closes with a proposed definition for orbital capacity as proposed by Matthew Hejduk of the Aerospace Corporation: "Capacity is the number of spacecraft that can safely occupy a given orbital corridor/regime if all of the orbital safety best practices outlined in [some consensus or international document such as the NASA Orbital Safety Best Practices document] are embraced and followed."

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Appendix A. Maneuverability Taxonomy (developed cooperatively with David Goldstein, SpaceX)

Level	Name	Change Attitude (to reduce collision cross-section)	Manual Ingestion of CDMs	Differential Drag (change attitude to increase drag, very low ΔV and very low responsiveness)	Cold Gas or Degraded Full Propulsive (e.g., CP or EP) Maneuverability (low ΔV and moderate responsiveness)	Full Propulsive (EP or CP) Capability (high ΔV and very responsive)
0	Non-maneuverable					
1	Non-Propulsive Maneuverability	X	X	X		
2	Partial Propulsive Maneuverability	X	X		X	
3	Full Propulsive Maneuverability	X	X			X

EP: electric propulsion and CP: chemical propulsion

While discussions in developing this taxonomy included separating autonomous RRMs and the benefit of acting later in the process (i.e., maneuvering closer to TCA), it was determined there are multiple ways to execute RRMs. Eventually, the RRM PC threshold and abated PC goal were found to be the most important. We want to measure effectiveness in reducing risk, not efficiency of the process. By definition, as constellations grow efficiency is necessary.

RRM magnitude may range from ~ 5 mm/s to ~10 cm/s. Note, performing a RRM earlier may require a smaller magnitude impulse but will likely result in more maneuvers. The optimum response time and impulse budget is very system-specific, however, differences between operational systems with conjunctions do add extra challenges to the collaborative interactions to reduce individual event collision probabilities.

Appendix B. Terms Used in the Risk Balance Model

Constellation (# as of APR2023)	Maneuverability	PC RRM Threshold[22]	AbPC
Starlink (~3,900)	3	1E-5	1E-6
OneWeb (~615)	3	1E-5	1E-6
Flock (~165)	1	1E-3	1E-4
SpaceBee (~100)	0	--	--
Lemur 2 (~100)	0	--	--
Iridium (~75)	3	1E-4	3.2E-6[23]
Manned spaceflight	**3**	**1E-5**	**1E-6**
Default unmanned	**3**	**5E-4**[24]	**1E-5**

The tagging of maneuverability required several steps. The operators for the six constellations supplied the data in the table below. Then maneuverability flag in the 18th Space Defense Squadron's conjunction data message was used for all other operation payloads. Roughly 300 of the remaining operational satellites were marked as "maneuverable"; these were assumed to have a maneuverability score of 2. About 200 objects were marked as not maneuverable, these were assigned a maneuverability value of zero. Roughly 1,400 payloads were given a null value or unknown capability. In examining these objects, about 80% were cubesats and, as such, all nulls given no maneuverability; even though it is likely that some have some form of maneuverability. Incorporation of more detailed maneuverability specifics (both reported and empirically-derived from observations) will be investigated in the next iteration of this research.

The ISS does not follow a PC-based RRM threshold, but equivalent thresholds to their methods equate to 1E-5 and 1E-6. It is unclear what safety guidelines are used for the Chinese Space Station (CSS) but for this analysis, it is assumed they mirror the ISS. This may be overly optimistic. It is also important to note the large masses of the assembled modules for the ISS and to a smaller extent for the CSS, should not be considered as available for fragmentation since they are so large and loosely coupled.

Similarly, many of the risk reduction processes for the constellations shown above are more nuanced than two simple thresholds, however, for the purposes of this modeling activity these values were agreed upon as a reasonable assessment of how they manage collision risk.

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[22] A 2021 paper reviewed LEO RRM thresholds and found them at the time to be between 1E-5 to 1E-4: Alfano, S.; Oltrogge, D.; Arona, L., "SSA Positional and Dimensional Accuracy Requirements for Space Traffic Coordination and Management," AMOS Tech, Maui, HI, September 2021.

[23] For Iridium, the goal is to achieve an abated PC of 1E-6 but the NASA guideline of reducing the 1E-4 risk by 1.5 orders of magnitude (i.e., to 3.2E-6) is considered acceptable.

[24] Sweetser, T., Braun, B., Acocella, M., and Vincent, M., "Quantitative Assessment of a Threshold for Risk Mitigation Actions," Journal of Space Safety Engineering, 9Aug2020, https://doi.org/10.1016/j.jsse.2020.07.009