Space Environmental Governance and Decision Support using Source-Sink Evolutionary Environmental Models

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ABSTRACT

Existing U.S. orbital debris rules largely focus on imposing certain minimum technical standards and disclosure requirements on operators. While such rules undoubtedly help reduce orbital risk and limit blatantly irresponsible behavior, they are only indirectly tied to actual policy objectives around preservation of the long-term sustainability of the Low Earth Orbit environment.

We argue that ensuring space sustainability will require a transition away from a reliance on fixed per-spacecraft or per-system rules to a process that combines both rules for generally responsible behavior and integrated environmental modeling to understand consequences of decisions for overall capacity and the space environment.

Adaptive management and governance processes provide structured decision-making mechanisms to facilitate collaborative action to robustly achieve goals in the presence of uncertainty and change. Adaptive processes can help regulators and stakeholders ensure compatibility between actions and their sustainability goals, understand efficacy of various interventions, respond nimbly but predictably to unexpected events, and more efficiently adjudicate trade-offs between stakeholders.

We sketch out a notional adaptive space environment management process, using a source-sink evolutionary model (SSEM) from the MIT Orbital Capacity Assessment Tool to demonstrate potential roles for integrated modeling. Several potential use cases and scenarios are described. SSEMs simulate broad trends for the evolution of the space environment by aggregating consideration of general classes of objects such as active satellites and debris into large spatial bins. Despite inherent limits to fidelity, SSEMs have several attractive features for use in adaptive governance processes including low computational cost, simplicity, accessibility, and generality.

1. INTRODUCTION

Existing U.S. orbital debris rules largely focus on imposing certain minimum technical standards and disclosure requirements on operators. Such rules are fairly simple and derived at least in part from expert advice informed by high-fidelity, if sometimes dated, modeling. The benefits of such an approach are clear: rules are easy for operators to understand and give regulators a clear yardstick against which to measure behavior. Because for many years it was only irresponsible orbital use that threatened to exceed the capacity of the orbital environment, regulating to enforce responsible use was an adequate solution.

However, driven by new technology and economics, continuously increasing levels of traffic may begin to be sufficient to implicate sustainability concerns—even if new operators comply with norms of responsible behaviors at rates higher than legacy traffic [18, 27]. Faced with a credible supposition, but not definitive evidence, that this claim is true, stakeholders are left with an uncomfortable vacuum where the previous approach is potentially inadequate but the alternative is not necessarily clear.

This paper argues that a logical solution is to explicitly incorporate environmental modeling into decision-making on orbital use by individual stakeholders, multi-stakeholder coordination groups, and regulators. Such modeling has, of course, always informed expert comments to regulatory organizations and discussions within the U.S. Government inter-agency process. What is different, and we argue necessary, is bringing that modeling capability more directly and accessibly into stakeholder discussions and decision-making and in an iterative and responsible way that exceeds the cadence feasible under a model predicated on expert studies that occur over months to advise rulemaking processes that take years.

A conceptual process is described, discussing how accessible environmental models could be integrated into workflows for decision-making about orbital use as a decision-support tool. For concreteness, key steps in the process are demonstrated using a relatively simple and low to moderate fidelity modeling tool from the MIT Orbital Capacity Assessment Tool (MOCAT) called the MOCAT Source-Sink Evolutionary Model (MOCAT-SSEM). While this specific model is used to demonstrate the approach, the discussion about the role of models in space environment management is intended to be largely agnostic to the chosen model(s). It is important that any model is accessible to, usable by, and trusted among stakeholders. Stakeholders should drive the appropriate level of fidelity, complexity, accuracy, and precision for modeling, rather than a model-first approach that dictates what questions stakeholders can ask.

The process of incorporating such modeling tools is described, referencing learning from terrestrial resource management and mistakes made in previous American attempts to manage natural resource systems. Rather than transition from fixed rules to a centralized expert-driven process of scientific management with adversarial dispute resolution, we recommend the embrace of adaptive management and adaptive governance philosophies shown to yield fairer, more efficient, more stable, and wiser outcomes [39, pg. 145].

This paper makes three main contributions to the literature:

1. It seeks to provide the most comprehensive description to date about how adaptive management and governance concepts could be applied in the space environment management context.
2. It advances the notion of orbital capacity as a constrained optimization across multiple distinct, stakeholder-defined constraints.
3. It provides a demonstration of the use of an SSEM model to consider multiple kinetic safety constraints to orbital use.

The rest of this section briefly describes the source-sink evolutionary modeling approach used in this paper and introduces adaptive management and adaptive governance concepts.

1.1 Source-Sink Evolutionary Models

Source-sink Evolutionary Models (SSEMs) are a low to medium fidelity space environment modeling approach that makes several simplifying assumptions. By making these assumptions, it is possible for even a commodity laptop computer to be able to simulate the evolution of the space environment over hundreds of years in seconds or minutes. Accordingly, they permit a level of iterative exploration in near real-time that is impossible with higher fidelity evolutionary modeling approaches that require supercomputers and hours or days of computational time to complete a simulation. Furthermore, because they abstract away much of the detail contained in the real world, they are simpler to understand and use, and can often simulate diverse analysis problems with relatively minor modifications as compared to higher fidelity modeling approaches that need to simulate phenomena in greater detail to understand effects.

SSEMs work by representing shifts in populations of various species of objects through sets of coupled ordinary differential equations (ODEs). SSEMs have long been used to provide rough modeling of the evolution of the space environment, with key papers including [43], [28], and [41]. Whereas higher-fidelity space environment evolutionary models typically semianalytically propagate individual space objects, perform conjunction screening, and simulate collisions using a break-up model, SSEMs aggregate objects into common species with set physical properties and interaction rates. Preliminary work has been done to investigate calibrating SSEM models [28, 33] against higher-fidelity three-dimensional Monte Carlo models, but more work will be needed to develop SSEMs with generalized correlation that retain accuracy and fidelity across diverse modeling conditions. Such calibration is likely necessary for the models to obtain stakeholder acceptance to support the use cases demonstrated in this paper.

Several source-sink models have been developed as part of MOCAT incorporating various phenomena and analysis methods including system-wide optimization, non-trackable debris, mass-binned species, and orbit-raising and deorbiting [10, 11, 12, 16, 20, 30, 37]. In [31], a new modeling framework called MOCAT-SSEM was described, which is being used to integrate the various analysis methods and features from previous individual models while providing an object-oriented interface and automatic equation compilation. As compared to higher-fidelity models, these SSEM models within MOCAT make several significant simplifying assumptions: All objects are placed in concentric circular orbits, collision and break-up fragments are deposited into the circular altitude bin of the parent objects, and collisions are assumed to occur at rates derived from an analogy to the kinetic theory of gases rather than a higher-fidelity method that accounts for the physical details of object orbits (which are not modeled in the SSEM). These simplifying assumptions are generally acceptable for most analysis, but struggle to represent the interactions of rocket bodies (which typically exist in elliptical orbits) and accurately calculate collision flux changes from specific fragmentation events. We believe that some of the shortcomings of these modeling assumptions could be addressed in future work while retaining the computational benefits of this approach.

The equations that describe the population quantities and flows for a set of object species in MOCAT-SSEM are defined using a system of ODEs:

$$\dot{\boldsymbol{P}} = \dot{\boldsymbol{\Lambda}} + \dot{\boldsymbol{C}}_{PMD} + \dot{\boldsymbol{F}} + \dot{\boldsymbol{C}} \tag{1}$$

where the change in the population of each species, $\boldsymbol{P}$, is a function of launch rate, $\boldsymbol{\Lambda}$, post-mission disposal, $\dot{\boldsymbol{C}}_{PMD}$, atmospheric drag, $\dot{\boldsymbol{F}}$, and collisions, $\dot{\boldsymbol{C}}$. Each of these terms is a time-varying quantity with quantities associated with each of a set of consecutive fixed-width interacting concentric orbital altitude bins. In this paper specifically, $\boldsymbol{\Lambda}$ is defined as a linear interpolation of exogenously-determined altitude-binned object launches divided across various species.

$\dot{\boldsymbol{C}}_{PMD}$ is modeled as:

$$\dot{\boldsymbol{C}}_{PMD} = -\frac{Q_i}{\Delta t} \tag{2}$$

for each active satellite species, simulating a certain portion of satellites being de-orbited from each altitude bin at each time based on the assumed orbital lifetime, Δt. For a debris species corresponding to each active satellite species, a percentage failure in post-mission disposal is modeled as occurring at each time step according to:

$$\dot{\boldsymbol{C}}_{PMD} = \frac{1 - P_M}{\Delta t} Q_i \tag{3}$$

Atmospheric drag is modeled as in previous work, with inactive objects and active objects without propulsion experiencing drag according to:

$$\dot{\boldsymbol{F}} = \left[\dot{F}_{d,Q_1}, \ldots, \dot{F}_{d,Q_N}\right] \tag{4}$$

Where Q refers to the species in the system. $\dot{F}_{d,Q}$ is written as follows for species with drag:

$$\dot{F}_{d,Q} = -\frac{Q_+ v_+}{d} + \frac{Qv}{d} \tag{5}$$

In Equation 5, d is the thickness of an altitude bin, the subscript + indicates quantities related to the bin immediately above the current one, and v is the rate of change of the semi-major axis, expressed as:

$$v = -\rho B \sqrt{\mu R} \tag{6}$$

where $B = c_D \frac{A}{m}$, defaulting to a flat-plate ballistic coefficient of $c_D = 2.2$ [40]. A is the drag area of the object, and m is the mass of the object. Atmospheric density ρ can be computed using either a static exponential model based on CIRA-72 [44, pg. 537] or as a time-varying dynamic atmospheric density based on interpolation and down-sampling of the Jacchia-Bowman 2008 model [3] following the approach described in [12]. In this case, ρ lacks a closed-form expression, but can still be integrated using standard numerical ODE solvers.

Collisions are modeled according to the approach in [31], where the NASA Standard Break-up Model (SBM) [22, 25] is used to estimate and bin fragments created as a result of a collision between any two species across the set of debris species included in the model.

The two colliding objects are decremented according to

$$\dot{C}_i = \Gamma_{ij} \phi_{ij} Q_i Q_j \tag{7}$$

$$\dot{C}_j = \Gamma_{ji}\phi_{ji}Q_jQ_i \tag{8}$$

where the collision modifier Γ_{ij} is -1, augmented by collision avoidance terms α_i (for collisions versus an inactive object j) or $\alpha_{active_i}\alpha_{active_j}$ (for collisions between two active objects). For collisions between two objects subject to coordinated mutually exclusive orbits, an additional factor $(1-\zeta)$ based on slotting effectiveness factor ζ is applied following the approach in [30].

Following [40] and others, the kinetic theory of gases is used to estimate intrinsic collision frequency between species i and j, ϕ_{ij}, modeled as

$$\phi_{ij} = \pi\frac{v_r(h)\sigma_{ij}}{V(h)} \tag{9}$$

where $v_r(h)$ represents the relative impact velocity, assumed as 10 km/s. While not used in this work, MOCAT-SSEM has the ability to set the parameter on an altitude-bin by altitude-bin basis. $V(h)$ is the volume of the altitude bin and σ_{ij} is the impact parameter for species i and j:

$$\sigma_{ij} = (r_i + r_j)^2 \tag{10}$$

Specifically, for a set of one or more debris species, the k-th debris species N_k is incremented by

$$\dot{C}_{N_k} = w_k\Gamma_{ij}\phi_{ij}Q_iQ_j \tag{11}$$

where the Γ_{ij} term incorporates reductions to collision probability associated with the species i and j. Note that Γ_{ij} is assumed to be symmetric and equivalent to Γ_{ji}, since no meaningful distinction is modeled by one object being considered the primary versus the secondary. Weighting factor w_k is computed from the fragment mass distribution produced by the NASA SBM via the nearest-neighbor method.

1.2 Adaptive Management and Adaptive Governance

Describing the concepts of adaptive management and adaptive governance concisely and with precision is tremendously challenging. Both terms are used by multiple authors in different contexts to mean different things [42]. Brunner cautions, "adaptive governance is a pattern of practices [that] cannot be reduced to any one thing without serious distortion" [4, pg. 19]. This section seeks to briefly describe both concepts, as well as the management context in which they were developed, with an emphasis on factors relevant to the application to space governance discussed in the next section. Readers desiring a more comprehensive treatment should consult [4, 5, 6, 42].

1.2.1 Avoiding the Trap of Scientific Management

Scientific management is a technocratic approach to centralized planning of resource management decision-making that delegates objective definition and management to a small set of experts. At first blush, this may seem like a reasonable way to incorporate environmental modeling into decision-making: trust the experts to rise above parochial interests and politics and make the "right" choices. Indeed, the approach dominated American national resource management for the first half of the twentieth century. Resource management, it promises, can be depoliticized by delegating management authority to scientific experts. Those experts will then craft an impartial objective against which changes to the natural environment will be assessed to guide decision-making to ensure the most rational, efficient outcome.

Unfortunately, this appealing technocratic ideal fails in several ways when implemented in practice [4, ch.1.] [5] [15] [42]. Centralized management excludes non-scientific stakeholders and their sources of practical knowledge. The selected management indicator is often reductive since it must be amendable to modeling. Technical experts fail to understand and incorporate stakeholder objectives and priorities and may fail to identify, much less make reasonable trades, when multiple stakeholder interests conflict. Management goals may become less relevant to stakeholders over time (if they were even relevant in the first place).

Because scientific management regimes frequently lack systems for internal adaptation, stakeholder dissatisfaction undermines the legitimacy of management system and encourages stakeholder recourse to legal or political processes

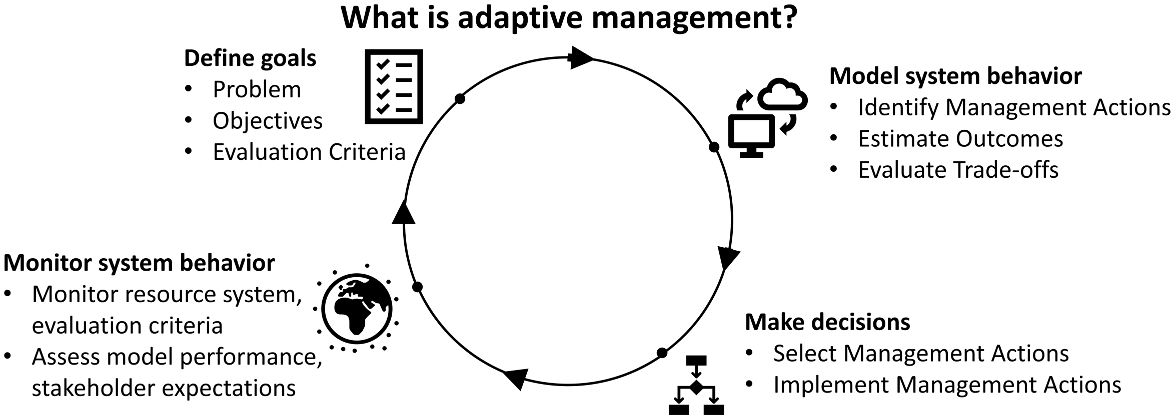


Fig. 1: A Potential Adaptive Management Cycle

that undermine the stability and effectiveness of the management regime. Worse still, the American approach to resource governance tends to pair scientific management regimes with dispute resolution through adversarial legal processes, encouraging ideologically short-term zero-sum thinking at the expense of long-term cooperation, while simultaneously imposing large negotiation costs, side payments, and regulatory uncertainty [4, ch. 7] [1] [39, ch. 21] [23].

1.2.2 Adaptive Management

Adaptive management emerged in response to the failures of scientific management. It stresses inclusive decision-making processes, multiple stakeholder objectives, and iterative learning from experimentation in management actions. Adaptive management strategies recognize the existence of limited knowledge and irreducible uncertainty across multiple factors relevant to the management of a natural resource system, including the ecological dynamics of the system under management and future behavior/resource use by stakeholders. Adaptive management seeks to achieve robust, resilient outcomes in the presence of uncertainty. It does so through a flexible management philosophy featuring cyclical learning and periodic adjustments to management actions based on observations of environmental response and improvements to supporting models and parameters. Adaptive management is particularly suitable when stakeholders broadly agree on management goals, but not necessarily on means to achieve those outcomes [39, pg. 5]. While there is no consensus on a single set of steps for adaptive management, one possible diagrammatic breakdown is presented in Fig. 1.

One critical benefit of adaptive management is the potential for contingent agreement, whereby stakeholders that disagree on the likelihood of different outcomes can jointly agree to management rules to guide responses to environmental trends that ultimately manifest without having to agree on a specific shared future environmental forecast a priori[39, pg. 147]. In the space context, for instance, a stakeholder who believes Large Low Earth Orbit (LEO) Constellation (LLC) failure rates are likely to be 10% of spacecraft might reach consensus with an operator who believes their failure rate will be sub-1% with initially more lenient post-mission disposal timelines that become more strenuous should failure rates exceed a particular threshold.

A Department of the Interior technical guide [14] on adaptive management lists nine criteria that must be met for adaptive management to be appropriate:

1. Management decisions must be made
2. Stakeholders can be engaged
3. Management objectives must be explicitly describable
4. Decision-making must be subject to uncertainty about the impacts of potential management actions

5. It must be possible to model relationships between resources and management actions
6. Monitoring can feasibly inform decision-making
7. Progress towards achieving management objectives must be measurable
8. Management actions must be adjustable in response to learning
9. The process must be feasible within legal constraints

These criteria all reasonably hold true for space environment management. Decisions about mission authorization and debris mitigation/remediation need to be selected from among a variety of economically, legally, politically, and environmental feasible options. Operators and other stakeholders are highly interested and want to be engaged. Sustainability-related objectives can be described at a high level, and indeed have been in the internationally-accepted definition of the long-term sustainability of the space environment. There is considerable uncertainty about both future conditions and relationships between management actions and the future debris population. Monitoring is possible, both directly for trackable space objects and indirectly using satellite failures and other proxies for lethal non-trackable (LNT) object strikes. Additionally, data collected by satellite operators for sub-lethal collisions that can be used to infer other portions of the non-trackable population. Figures of merit can be measured against management objectives, as will be demonstrated in Section 2. Management actions can be adjusted over time in response to learning by stakeholders or through revisions to rules. Legal constraints on an adaptive management process for space are perhaps the hardest to characterize, absent a specific proposal for a governing body and governing structure. Nothing in principle would prohibit adaptive management on a voluntary opt-in basis by a group of concerned satellite operators. While adaptive approaches have been embraced by other portions of the U.S. government, adaptive management regimes are largely incompatible with the linearity and rigidity required for much of U.S. administrative law [1]. We lack the expertise to determine whether such a structure could exist within existing Federal Communications Commission or Department of Commerce authorities and constraints, or if adaptive processes would require additional authorization from Congress. Resolving this issue is an important question that has strong implications for implementation.

1.2.3 Adaptive Governance

Adaptive governance expands adaptive management from seeking resiliency in the presence of uncertain ecological dynamics of a managed system to feature additional resiliency in the presence of economic, social, and political change [42]. It aims to facilitate coordination of resource use among users in a way that improves joint gains while reducing negotiation costs and ensuring sustainable outcomes [39, pg. 2]. A theoretic construct embraced by Elinor Ostrom and others conceptualizes adaptive governance as a set of nested management layers, with increasing burdens to change rules at each higher level [36, 42]. Within this structure, adaptive management forms the innermost loop where the adaptive management system makes routine operational decisions about system monitoring, enforcement, resource appropriation, and information sharing. A collective rules layer provides mechanisms to revise resource management policies applied at the operational level. A highest constitutional level governs participation in the adaptive governance process and the governance structures used to make decisions regarding collective rules. This is visualized in Fig. 2.

1.2.4 Previous Work on Adaptive Governance and Space

Adaptive governance for space has been mentioned in several contexts, but usually at a high level of abstraction. Oltrogge and Christensen [35] note the potential relevance of adaptive governance philosophies for the space domain to help achieve underlying stakeholder objectives in the presence of evolving economic, societal, and environmental contexts. Ezell conducts a high level survey of existing space governance, generally favoring the adoption of more adaptive space governance mechanisms [13]. Keles recommends implementation of adaptive governance by the United Nations Office of Outer Space Affairs and the International Telecommunications Union [24]. Keles also highlights Dynamic Adaptive Policy Pathways (DAPP), an approach introduced by [17] that identifies tipping points to key indicators and uses the performance of those indicators to inform shifts between various management strategies. While not explicitly framed in terms of adaptive governance, a recent European Space Policy Institute report on orbital capacity describes the use of European Space Agency (ESA) Space Environment Capacity Concept to support coordination for

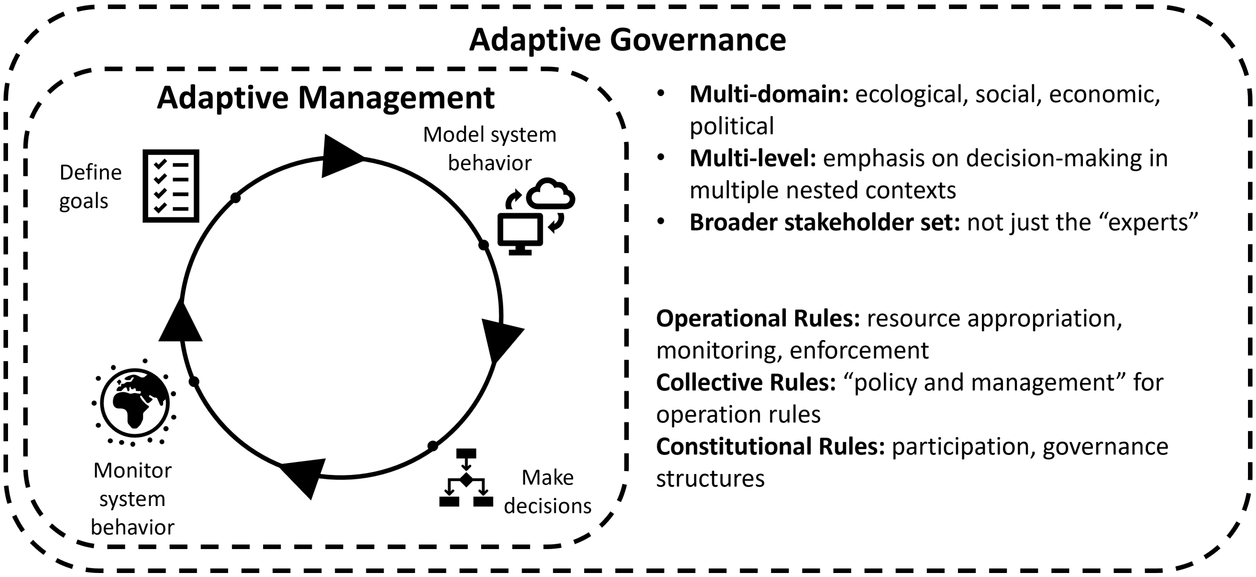


Fig. 2: Adaptive Governance Overview

sustainable orbital use in similar terms [38]. While these works all recognize the potential for adaptive management and governance in the space context, [34] notes that the space policy literature has "stopped short of extending those arguments into current governance frameworks that can be operationalized."

2. METHODOLOGY

In this paper, the MOCAT-SSEM is used as a quantitative evolutionary space environment modeling tool to demonstrate several forms of support such a model could play to an adaptive governance process.

2.1 A Sketch of an Adaptive Space Environment Management Regime

There is not a single checklist to successfully implement adaptive management and governance. Rather, the process itself is context-dependent and should be responsive to both technical and process learning. In this section, we will lay out a notional process and structure for adaptive space environment management and governance. The purpose of this description is to help concretize the description of these concepts provided earlier, while fully recognizing that during an actual implementation, preconceived notions should give way to outcomes of participatory collaborative stakeholder involvement processes.

The discussion in this section is informed by multiple sources including [1, 4, 14, 42], but does not explicitly follow a single structure from any of these works. While the discuss focuses primarily on adaptive management rather than adaptive governance, adaptive governance elements involve similar thinking but also permit changes to stakeholder sets and governance systems to ensure continued effectiveness and responsiveness.

2.1.1 Leadership

A management regime needs an actor to implement and coordinate the process, building buy-in among stakeholders and facilitating participation in the governance structure. In the space debris context, two main kinds of stakeholders are perhaps the best fit.

The first would be a well-respected non-government organization with domain expertise that is widely respected by operators and other stakeholders and perceived as impartial. They could potentially partner with another group with deeper expertise in adaptive management and governance for natural resource systems, but likely without the same familiarity with space debris or the space community. Because such an organization or partnership is unlikely to have funding sufficient to support a long-term process, they would likely also have to attract a source of funding sufficient to sustain the process for at least several years. Such funding could come from corporate, government, or foundation sources. Funding would be necessary to support the activities of personnel from the supporting organizations, to fund technical experts and supporting modeling work, as well as to pay costs associated with travel and meetings to convene stakeholders. Funding might also be needed to support participation of stakeholders who are important to the process but lack financial resources to participate at their own cost.

Another option would see a government entity acting in the leadership and convening role. This could be a regulatory entity, subject to compliance with relevant administrative law requirements, or an entity with domain knowledge but that does not serve as a regulator. Personnel familiar with adaptive management could be detailed from the Department of the Interior or elsewhere to help support the process. The entity would need to ensure any necessary authorization to pursue the effort, as well as to maintain funding necessary to support the program over a multi-year initial period.

2.1.2 Stakeholder Engagement and Recruitment

One of the earliest tasks for the executive leadership team will be to develop awareness and interest in participation among relevant stakeholders. This group should includes those who make use of the managed resource system: namely satellite operators, as well as those impacted by management decisions concerning resource allocation. Relevant cleavages among stakeholders may include orbit regime, earth observation vs. communications payloads, academic vs. commercial operators, operators of large constellations vs. small numbers of bespoke satellites, and between large constellations of dozens of satellites (who may still rely on more manual processes to some extent) and megaconstellation operators (where scale means they must leverage even greater levels of autonomy). A key task for the recruited stakeholder group is to agree on scope, objectives, and feasible management actions. The management scheme would likely involve primarily commercial users, and may be constrained to nations with particular geopolitical allignments. A failure to obtain global participation or global scope is not necessarily a problem. For instance, a set of LEO-only operators may feel they will be better able to make progress discussing rules for their own regime if GEO operators, who compete with LEO operators in the communications market and have sometimes tried to leverage sustainability concerns for competitive reasons, are excluded. A process that involves only Western operators may still establish norms and best practices and improve the environment, even without full participation from geopolitical rivals.

2.1.3 Problem and Goal Identification

Once a stakeholder group is assembled, a key early step is to identify a problem and an associated high-level goal or goals.

A reasonable starting point is concern that various factors will limit the ability of humans to conduct space activities. A potential high level goal can be found in the United Nations Committee on the Peaceful Uses of Outer Space's Guidelines on the Long-Term Sustainability of Outer Space Activities and their definition of the "Long-Term Sustainability of Outer Space Actitivies" as "the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations" [7].

Nevertheless, this definition alone is not sufficient. Multiple factors potentially constrain human ability to make use of the space environment over time. In the realm of kinetic space safety there are concerns related to the long-term sustainability of the space environment, operational threats to spaceflight safety and associated mitigation burden, and orbit coordination and cross-constellation orbital compatibility. Other potential limitations include access to communications spectrum to send and receive information between satellites and the ground, the risk to air and ground users from space debris that survives re-entering the Earth's atmosphere, changes to climate from increasingly large amounts of aluminum and other materials being vaporized in the Earth's upper atmosphere during post-mission disposal, and the carbon cost of spaceflight and associated terrestrial activities.

Kinectic space safety is likely where any such effort will start, but the stakeholders must decide what, if any, additional areas to include and what additional technical expertise or additional stakeholders will need to be included to satisfactorily consider such goals.

2.2 Objective Definition

It is necessary to translate potentially qualitative problems and goals into objectives that can be expresses unambiguously in a feasible and measurable manner. This definition in turn drives necessary modeling capabilities to support the adaptive management process. As distinct from scientific management, there are likely multiple objectives with differing importance to different stakeholders.

2.2.1 Defining Potential Management Actions

There are many ways to influence the space environment including through new launches, through promoting, disincentivizing, or coercing certain behaviors, through monitoring and interacting with objects in space, and through removing objects. While kinetic space safety actions are often divided between space debris mitigation and remediation, a plethora of more specific options are available. Some such topics include requirements for satellite maneuverability above a certain altitude threshold, system-wide limits on aggregate ground causality risk, requirements to remediate failed spacecraft that exceed a particular orbital lifetime or lifetime probability of collision, and conditional mission authorization based on model-derived compliance with management objectives. Stakeholders may decide that one or more of these actions are appealing and should be encouraged or required.

The set of identified potential management actions again creates requirements for supporting technical modeling.

What distinguishes the selection of such management actions in an adaptive management process from business as usual is several-fold: 1) the decision is being made through a participatory governance structure with strong buy-in from stakeholders; 2) technical expertise is provided to assist stakeholders in independently understanding and assessing the likely quantitative effect of proposed changes; and 3) decisions are regularly revisited as part of a structured decision-making process.

2.2.2 Model Identification and Adoption

Once objectives and potential management actions are identified, one or more modeling approaches need to be selected to support efforts to simulate management actions, estimate outcomes, and identify trade-offs.

Technical assistance will often need to be provided by experts to develop models, explain their limitations and sources of uncertainty, and ensure that suitable modeling approaches are identified that can measure the objectives of interest and other consequences of management actions. In many cases more than one modeling approach may be used. In the space context, lower fidelity SSEMs and heuristic methods used for discussion and preliminary evaluation could be augmented by higher fidelity full-scale 3D Monte Carlo techniques for final decision making.

As part of this process, there will be a need to develop consensus on multiple modeling parameters including initial starting populations, future solar weather predictions (which influence drag, the only natural sink on the space environment), launch models, and spacecraft physical and behavioral properties. Where possible, representative consensus values should be defined, with ranges of several values used for parameters where there is significant uncertainty and the environment is sufficiently sensitive to merit additional modeling runs. Launch models will likely begin as exogenous deterministic or stochastic models, but evolve over time to be economically=informed to better reflect reality.

2.2.3 Estimating Outcomes and Trade-offs

Stakeholder intuition and models can be used to estimate the results of various management actions, either alone or in combination. The models can then be used to understand results for objectives relevant to stakeholders. In some cases multiple objectives can be simultaneously be accommodated through properly selected management actions, while in others stakeholders will need to explicitly trade between different at least partially incompatible objectives.

2.2.4 Selecting Management Actions

From a set of enumerated management actions and their modeled outcomes and trade-offs, it will be necessary for stakeholders to select a set of management actions. These actions will be periodically re-visited, but generally used to guide routine administration by system managers. As part of the selection of management actions, stakeholders will need to balance the desirability of stability and therefore predictability vs. flexibility to accommodate unexpected behavior and outcomes [9].

2.2.5 Implementing Management Actions

Once decisions are made, these management actions will need to be implemented. Depending on the management action, this implementation may be anything from almost self-executing to extremely complex and time-consuming.

2.2.6 Monitoring

As part of the adaptive regime, stakeholders will need to agree to a monitoring plan. Monitoring can be used to understand the status of the selected objectives, the state of the resource system, to compare stakeholder predictions vs. actual environmental evolution, and to calibrate and improve models.

2.2.7 Assessment

This step studies the results of management actions and uses learning from the adaptive management process to inform changes during the next iteration of the management loop.

2.3 Model Specifications

The previous subsection briefly described elements that might exist for adaptive management and governance of the space debris environment. In this section, several of these elements will be demonstrated explicitly using MOCAT-SSEM.

As explained previously, an adaptive management process relies on translating a problem and qualitative objectives into specific technical evaluation criteria that can be evaluated in a model run. As described above, such goals must be defined through broadly inclusive processes that understand and address differing needs among different sets of stakeholders. For the demonstration in this section, several nominal goals are demonstrated and implemented as indicator variables in MOCAT-SSEM.

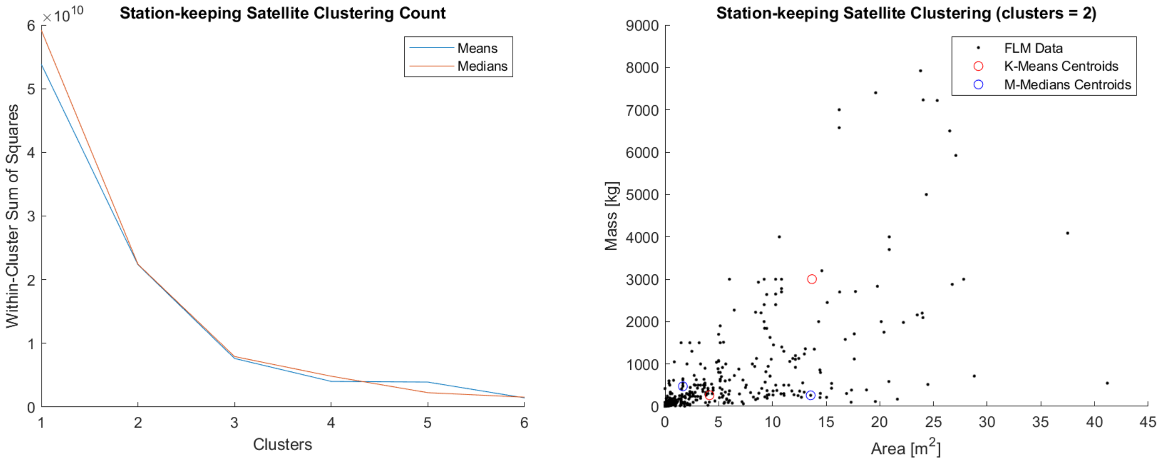
In the MOCAT-SSEM framework, global properties are set for certain scenario-wide attributes as seen in Table 4. Other properties are set on a species-wide basis, as seen in Table 3. Equations are generated according to the general processes described in the introduction.

2.3.1 Initial Population and Launch Traffic

An initial traffic and future launch model is compiled and used in all simulation runs.

The initial population is extracted from all two line elements available with epochs between 2023-01-01 and 2023-01-03 with mean motion greater than 3 revolution per day (to capture LEO objects), excluding analyst objects and the ISS (since its modules skew property statistics for satellite species). This approach ignores the population of initial non-trackable debris, although it is possible to incorporate this population using counts from ESA's MASTER or NASA's ORDEM. If an object has multiple available states in this interval, the latest state is selected. Physical properties are estimated through fusion with the European Space Agency's DISCOS database, with interpolation laws used for missing objects as described in [21]. Object areas are derived from radius information subject to a circular area assumption, which is also used for the drag term B* for each object with drag coefficient C_D of 2.2 as commonly used for satellites [45].

A synthetic launch profile is created by fusing several sub-profiles. A baseline recurring launch rate is generated by repeating injection of launched objects each year from 2018 to 2022, with the date of launch randomized to occur sometime during the corresponding year of the recurring launch model. To this background population, a set of selected LLCs is added based on the values in Table 5. LLCs are assumed to replenish satellites at the end of mission lifetime for the duration of the simulation. A piece-wise interpolated launch rate is created by binning the future



(a) Residual vs. Clusters

(b) 2 Cluster Fit

Fig. 3: Area vs. Mass Analysis for Station-keeping Satellites

launch traffic model by altitude and mass-binned species, discretized with time resolution equivalent to the model output reporting criteria.

2.3.2 Modeled Species

More species improve fidelity but increase the number of modeled collision pairs, increasing computational cost and analysis burden. The species for the simulation were chosen through a combination of analysis and judgment. As a preliminary step, k-medians and k-means residuals were calculated for a combined set of initial and future launch model data for 1 to 6 clusters per class. Based on diminishing returns in these results, as well as the relative population size of various satellite types as seen in Table 2, a certain number of species were selected. The values for mass, area, radius, and lifetime were then set based on these results. Results for mass and area only are visualized for a class in Fig. 3. Because the debris population is not known a priori and a relatively small portion of the dataset, values were selected to model sub-trackable debris, as well as trackable debris and derelicts for active species. The chosen species and properties are displayed in Table 3.

2.4 Indicator Variables

In addition to the features previously described, a new feature called indicator variables was added to MOCAT-SSEM. These are non-species quantities that can be customized to model, extract, and visualize behavior of interest that does not necessarily correspond to the population of one or more species. In this work indicator variables are constructed to measure quantities associated with potential indicators for various space environment goals that constrain orbital capacity. When compared against consensus targets for permissible values for these indicators, they provide feedback on the acceptability of environmental evolution in a given simulation. The modeled indicators in this work include long-term debris trends, active satellite losses to collisions, satellite maneuvers, and the amount of orbital space physically saturated by large constellation deployment.

As implemented in MOCAT-SSEM, indicator variables can be computed using additional ODEs (that are integrated by the chosen numerical integrator), as arbitrary functions of system state information at a particular moment in time, or as a numerical derivative of system state outputs. Helper functions were implemented that automatically compile each of these indicator variables depending on model scenario variables and species. The generic implementation is intended to support future research and stakeholder use with differing goals. For instance, the debris-induced cost model from [8] could be used to quantify the cost associated with debris as predicted by MOCAT-SSEM.

2.4.1 Long-term Sustainability

A long-term sustainability constraint is intended to ensure the amount of debris does not experience problematic long-term growth over the simulation period.

In this demonstration, an indicator is implemented to ensure that the increase in the numerical derivative of the number of debris objects in any given altitude bin for any given species does not increase at the end of the simulation. Because the use of a density-informed drag model results in local periodic oscillations, this is evaluated using a linear fit to the total number of debris objects of each species in each altitude bin, evaluated over the last quarter of the simulation period (150-200 years). Numerous other decisions could be reasonable here: looking at aggregate debris count or debris counts in broader regions of LEO rather than the specific altitude bin structure used in this simulation, quantifying debris in terms of kilograms or kilogram-years, or accepting a slight amount of growth or requiring decreases. For greater security, it would also be possible to impose a stability constraint, requiring the orbital solution to be able to accept an impulse of a certain quantity of debris at a particular altitude or altitudes without violating the constraint.

2.4.2 Operational Risk

This constraint seeks to ensure that short-term ”pain” to satellite operators caused by debris does not exceed some impermissible threshold. This is evaluated in terms of both the estimated number of collision maneuvers that a given satellite must perform, as well as the percentage of active satellites in a particular altitude bin that are lost to collisions in a given year.

Collisions are evaluated following the approach described in [30] and summarized in the introduction. Collisions between two active maneuverable spacecraft species are reduced by a factor α_{active}^2, while collisions between an active satellite and a trackable non-manueverable or inactive object are reduced by a factor of α. For conjunctions between two species with slotted orbit coordination effectiveness, ζ, a reduction of $1-\zeta$ is applied to reflect the physical separation achieved by this coordination. There is no reduction in collisions that occur between inactive objects or between an active object and an LNT object.

Recall that for a pair of species, Q_i and Q_j, the populations in each altitude bin are decreased by:

$$\dot{C}_i = \Gamma_{ij}\phi_{ij}Q_iQ_j \tag{12}$$

$$\dot{C}_j = \Gamma_{ji}\phi_{ji}Q_jQ_i \tag{13}$$

to model collisions. By summing the number of collisions generated for each species pair involving a species Q_i, it is possible to calculate aggregate collisions per year for a particular species in each altitude bin as a function of time. This quantity can also be computed for Q_i as a percentage by multiplying by the factor of $100/Q_i$.

$$\dot{C}_{i_{tot}} = \sum_{j=1}^{k}\Gamma_{ij}\phi_{ij}Q_iQ_j \tag{14}$$

where $j = 1..k$ reflects the index values of all other species against which Q_i could experience a collision. Note that, while not explicitly indicated, $\dot{C}_{i_{tot}}$ is a time-varying quantify that is altitude-bin dependent.

For a collision to occur between a pair of trackable objects where at least one object is active, collision avoidance must have failed. Maneuvers per year are considered to occur for active maneuverable species at a rate corresponding to the portion of intrinsic collision probability that is not mitigated by Γ. The number of maneuvers for a collision pair in an altitude bin can thus be estimated according to:

$$\dot{M}_{ij} = (1+\Gamma_{ij})\phi_{ij}Q_iQ_j \tag{15}$$

For conjunctions between maneuverable slotted species with slotted orbit coordination effectiveness ζ, a correction factor of $\frac{1}{1-\zeta}$ is applied since the reduction in collision frequency due to this orbit coordination is assumed to occur without maneuvers due to physical orbit separation. For pairs of active objects, we divide the $\dot{M}_{ij}$ contribution evenly between the two species, but this modeling assumption could be modified based on empirical information, for instance if a particular species corresponds to an operator who prefers to maneuver during conjunction events.

The number of maneuvers per species per time period can then be summed across all relevant species pairs to estimate the number of maneuvers for a species per altitude bin at a particular time in Equation 16. This can also be calculated as a per-spacecraft quantity by dividing by the total population Q_i at that time. This per-spacecraft quantity is naturally more useful for collision avoidance burden assessment purposes.

$$\dot{M}_i = \sum^{n} \dot{M}_{ij} \tag{16}$$

It is important to note that while this modeling approach will produce a maneuver estimate corresponding to the model dynamics, it is subject to non-trivial countervailing sources of error. It will often tend to over-predict maneuvers and collision events due to a reliance on the kinetic theory of gases to model cross-species interaction and to under-predict collision events since it assumes perfect knowledge of when a maneuver is required with no wasted additional maneuvers. It further assumes that every maneuver is successful at preventing a collision.

In future validation work, the reliability of this indicator should be assessed against the number of potential collision "rolls" within a full-scale 3D Monte Carlo modeling using the cube method [32] for collision detection. The cube method similarly relies on the kinetic theory of gases but assumes objects can only potentially collide during periods where they overlap within small cubes of space rather than the expansive bins assumed by MOCAT-SSEM. Outputs from cube method data will naturally need to be scaled to correct for the artificial dependency between derived maneuver counts and cube size. Outputs from both models should be compared against higher fidelity data that either simulates time-varying object covariances and conjunction analysis pathways, or against real historical data on maneuver frequency.

2.4.3 Intrinsic Capacity

Large constellations are typically designed to ensure that satellites within the constellation do not pose a threat of physical collision, "fratricide", to other satellites within the same orbital shell of that constellation. Large constellations overlapping in orbital volume in an uncoordinated manner have the potential to generate significant numbers of close approaches that would necessitate analysis, coordination, and potential mitigation. To avoid this risk, it is reasonable to offset large constellations for mutual exclusion. Separation between large constellations was included as a recommended best practice within a recent set of recommendations compiled by OneWeb, Iridium, and SpaceX through the American Institute of Aeronautics and Astronautics [19]. If such separation is done using compatible frozen orbits for each constellation, such separation can be accomplished within a relatively modest orbital volume [29]. Assumptions for minimum acceptable spacing between satellites can be used to extrapolate the maximum number of allowable satellites in a particular orbital shell and the number of acceptable shells using power laws fit to empirical two-body results following the methods in [2, 29]. In [30], these methods were applied to place a constraint on satellites within an SSEM for the purpose of system-wide optimization.

Here, intrinsic capacity, or the number of geometrically allowable mutually-compatible satellites in an orbital volume, is computed on a shell-wise basis using the equation:

$$N_{sat}(i, \alpha_i) = \left(\frac{\alpha(i)}{c(i)} \right)^{\frac{1}{b(i)}} \tag{17}$$

where N_{sat} is the number of satellites that can fit within a single shell, α_i is the minimum allowable separation distance between satellites (expressed in terms of either an angle or arc-length converted to an equivalent angle, and c and b are coefficents used to fit the power law to the satellite distribution, following the approach in [29], based on the interval from 500 to 10,000 satellites using the 10 highest capacity solutions for each N_{sat}. Intrinsic capacity is then computed for each bin based on an assumed exclusive height for each shell. The unconsumed intrinsic capacity in a given altitude bin is found as:

$$I_{free} = \frac{d}{h} * N_{sat}(i, \alpha_i) - \Sigma_i^{N_s} S_i(t) \tag{18}$$

where d is the altitude range of each altitude bin, h is the exclusive height assumed to be occupied by a given orbital shell, N_s is the number of species of satellites subject to orbit coordination, and $S_i(t)$ is the population of species S_i at time t. This model ignores inclination-dependency, assumes a single allowable in-shell and between-shell separation distance, and does not consider the specifics of the physical geometry of each orbital shell subject to coordination. Nonetheless, it is helpful to limit capacity per altitude bin within the SSEM, recognizing that orbit coordination may impose constraints on orbital placement different than long-term sustainability, particularly if operators are assumed to conduct maneuvers to avoid collisions against trackable objects. This indicator is best used for first-pass analysis on plausibility of placement of large constellations in a compatible manner, to be replaced by actual constellation shell designs and physical geometry for specific overlap analysis for actual orbit coordination.

In this paper, intrinsic capacity is computed assuming an inclination of 40 degrees, a minimum in-shell separation distance of 60 km, an exclusive orbital volume of 5 km per shell. These numbers are chosen as a fairly conservative bound for intrinsic capacity. For large constellations with electric propulsion, technically achievable separation distances may be much smaller than these values [26].

2.5 Non-Zero Altitude Disposal Orbits

Most previous MOCAT modeling approaches have supposed the instantaneous disposal of de-orbited satellites by removing them from the system. Gusmini et al. explicitly modeled transitions between shells for satellites with low-thrust propulsion [16].

In this work, an intermediate approach is implemented by adding a property "disposal_altitude" as an optional parameter for active satellite species. For a species where a non-zero disposal_altitude is selected, satellites that successfully experience post-mission disposal at an altitude greater than the disposal altitude are incremented to $k-th$ altitude bin of the debris species, N_i, that corresponds to the chosen satellite species. This approach is useful to simulate disposal orbits corresponding to various allowable maximum post-mission orbital lifetime, e.g. a 25 year vs. 5 year rule assuming circular disposal orbits. It is less suitable for studying elliptical disposal orbits given the simplifications included in the current model.

Given a set of altitude bins, h, we can construct:

$$\text{altitude vector } h = \begin{pmatrix} h_1 \\ \vdots \\ h_i \\ h_{i+1} \\ \vdots \\ h_n \end{pmatrix}, \text{ disposal vector } l = \begin{pmatrix} l_1 = 1 \\ \vdots \\ l_i = 1 \\ l_{i+1} = 0 \\ \vdots \\ l_n = 0 \end{pmatrix}, \text{ and disposal altitude indicator } \iota = \begin{pmatrix} 0 \\ \vdots \\ \iota_i = 1 \\ \vdots \\ 0 \end{pmatrix} \tag{19}$$

We can add two additional term to $\dot{\boldsymbol{C}}_{PMD}$ for species N_i to represent passivated disposal at altitudes below the cut off and satellites from higher altitudes that maneuver to the disposal altitude before passivation:

$$\dot{\boldsymbol{C}}_{PMD} = \dot{\boldsymbol{C}}_{PMD} + lP_M \frac{Q_i}{\Delta t} + \iota P_M \frac{Q_i}{\Delta t} \Sigma_{j=i+1}^{n} C_j \tag{20}$$

If satellites were moved to a disposal altitude but retained collision avoidance capabilities, that would be modeled differently, with a transition between altitude bins for the same active species rather than to a debris species.

3. RESULTS

This section demonstrates several potential roles that modeling could play within an adaptive governance regime using MOCAT-SSEM: to assess marginal traffic for compatibility with environmental objectives, to model effects of environmental changes, and to estimate effects of various actions, either individually or in concert. While not demonstrated here, MOCAT-SSEM could also be used to assess the impact of different factors that change endogenous launch rates, examine impacts of changes on system-wide optimization solutions, and to evaluate the relative impact of a particular mission on the environment.

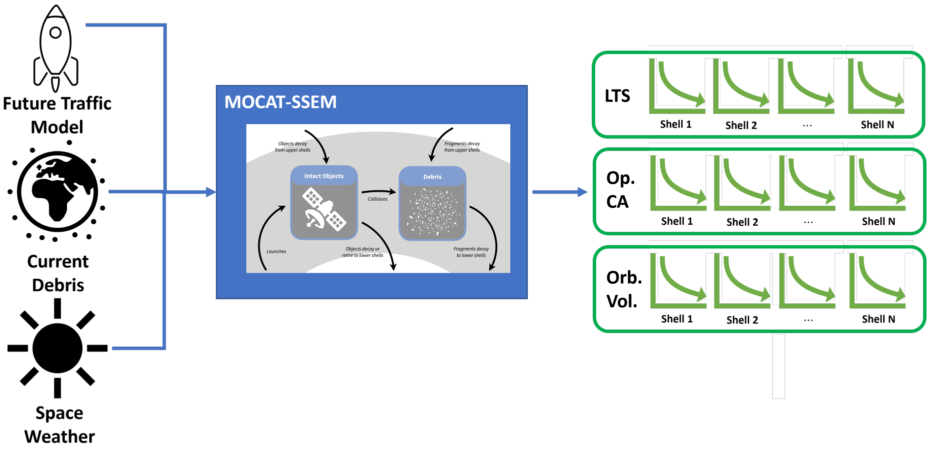


Fig. 4: Baseline Modeling Process Diagram

The purpose of these demonstrations are to show in concrete terms how evolutionary space debris modeling could be used to support an adaptive governance process. These examples are not intended to indicate that any particular management concept should be unilaterally implemented by a regulator, but rather to demonstrate how quantitative models could be used to support analysis and potential implementation of such management actions if they were endorsed by stakeholders in a relevant adaptive process.

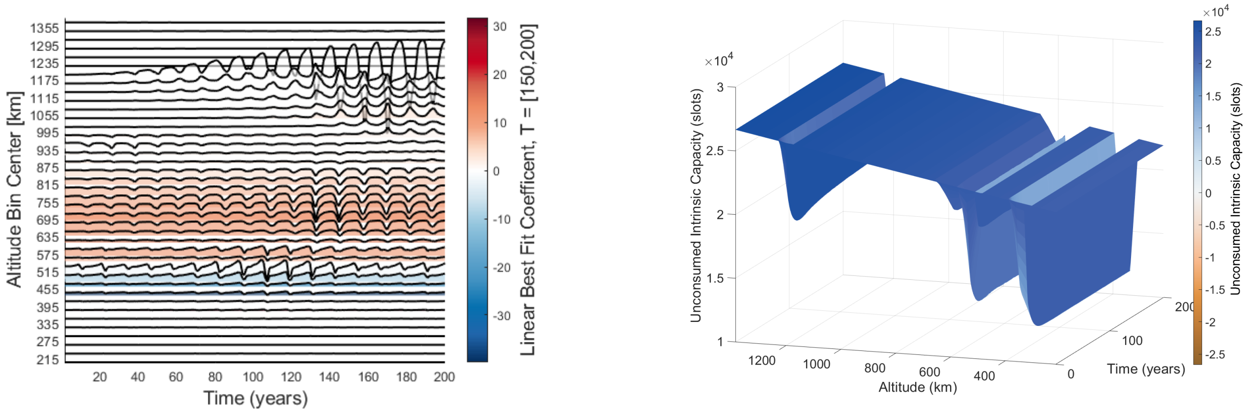
The results in this section are using an uncalibrated model built using the MOCAT-SSEM framework, which features multiple substantial simplifying assumptions. Verification and validation work is on-going, with only limited calibration work published to date [33] for simpler MOCAT SSEM models. Calibration is still being implemented into the full MOCAT-SSEM framework to support multiple mass-binned species and other features. In particular, because the uncalibrated MOCAT-SSEM model used in this work employs a collision model that assumes all fragments from a collision are deposited in the altitude bin where the collision occurs and that collision probability is dependent on the kinetic theory of gases, it tends to overstate the number of collisions that result. Accordingly the results from this work are at best indicative of potential trends and should not be used to inform decision-making without further verification.

3.1 Adaptive Authorization Pathway

In the first modeling approach under this section, MOCAT-SSEM is configured to measure indicators for long-term sustainability, operational collision avoidance, and intrinsic capacity. For the purpose of this example, the following constraints are assumed. In an actual adaptive process, these would be determined though a consensus approach based on discussions between stakeholders.

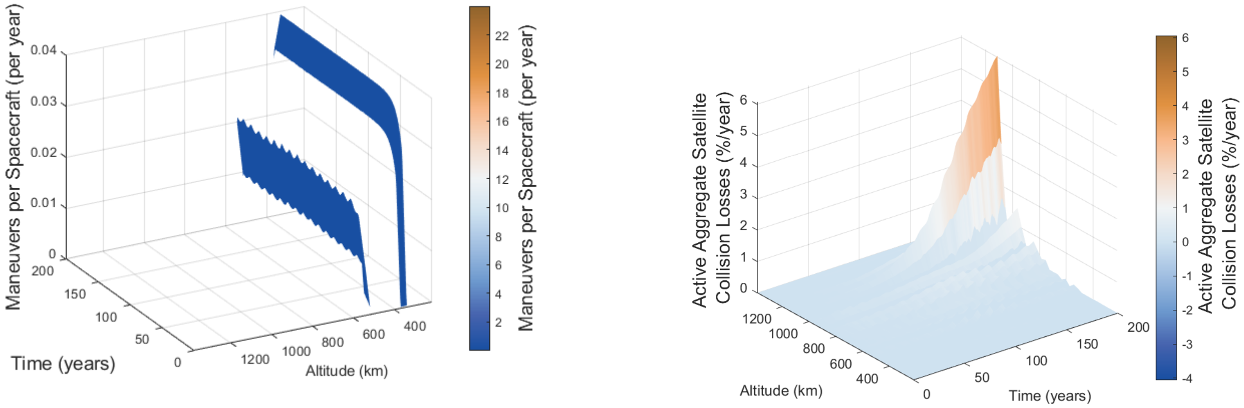
1. **Long-term sustainability**: The numerical derivative of the number of debris objects in any altitude bin for each species shall be non-positive, as measured by the slope coefficient of with a linear fit to the last fifty years of the simulation period. This fit period is used to avoid having periodic effects due to solar cycle expansion and contraction influence this indicator.
2. **Operational Collision Avoidance**: No more than 1% of satellites within any given species in any given altitude bin shall be lost in a given year to collision events. A given satellite shall not have to perform more than 12 collision avoidance maneuvers per year.
3. **Intrinsic Capacity**: The number of satellites within large constellations shall not exceed the quantity associated with preserving 60 kilometers between satellites within shells and 5 kilometers between shells.

The model is then run and these constraints are evaluated to assess whether or not they are met.



(a) Population Trends for LNT Debris Population

(b) Intrinsic Capacity



(c) Collision Avoidance Maneuvers per Spacecraft for S_{1250kg} species

(d) Aggregate Collision Losses for Active Spacecraft

Fig. 5: Baseline Constraint Satisfaction

3.1.1 Baseline Model

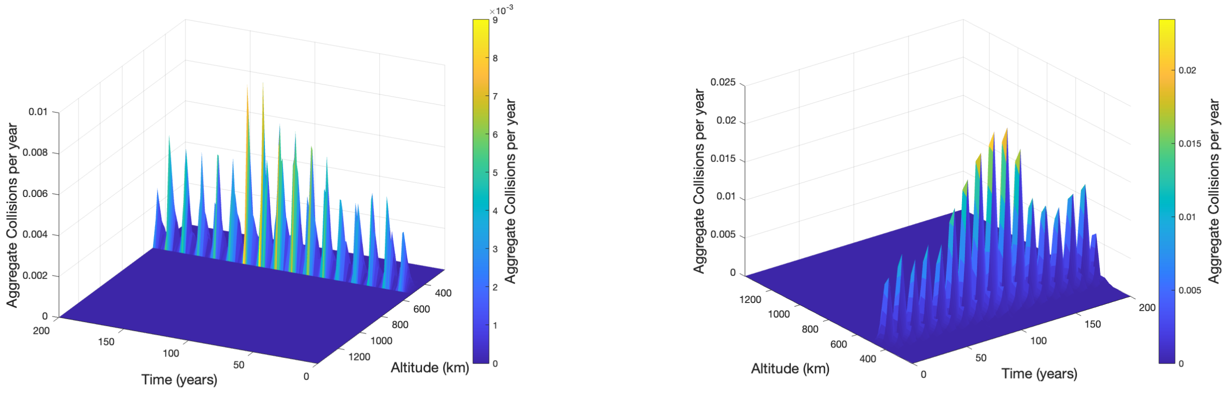
In Fig. 5 we see various outputs for the model run, with good values in blue and bad values in red. In Fig. 5a, we see data for the LNT species, indiciating that while there are strong oscilatory effects at high altitudes, but they do not necessarily violate the constraint. However, there is an altitude range in the middle of the graph where the constraint is not met. While only one species is displayed in this paper due to space limitations, in practice all populations would be reviewed, either individually or in aggregate. In Fig. 5b, we see dips in intrinsic capacity associated with the various modeled LLCs, but note that there is still remaining excess intrinsic capacity. In Fig. 5c, a per-species quantity is shown and we see that about 1 in 25 S_{1250} spacecraft will have to maneuver each year to avoid a collision with a tracked object, well below the threshold. In Fig. 5d, we see a violation of the operational collision avoidance constraint at high altitudes far into the future. Because high-altitude debris is not mitigated earlier in the simulation, it gradually fragments overtime into a large amount of LNT debris, making the orbit unacceptable dangerous. In this baseline model run we see that not all constraints are met. This indicates that action will be needed as part of the governance process. Stakeholders could choose to revise constraints on indicators, adopt additional mitigation or remediation actions, or limit traffic.

3.1.2 Safe-Harbor Review

In this example, we assume that the adaptive governance institution decides to implement a process whereby constellations are evaluated using the modeling tool to ensure the environment remains compliant with the goals for various indicators in the presence of the new traffic. We further assume that there is a regulator involved in the process with authority to approve or reject proposed traffic. This assumption simplifies the description of the workflow, but is not an inherent requirement. A similar process could be conducted on the basis of a processing round rather than per application. Likewise, similar review could be used to inform a safe harbor provision to avoid more detailed scrutiny of a constellation's orbital use rather than an approval or denial decision. For simplicity in this example (and not verisimilitude), a single constellation will be considered and the information from the SSEM model run alone is used to qualify for a safe harbor condition rather than to provide an approval or denial decision. As described here, the regulator only considers whether the added traffic remains within the capacity as defined by the chosen indicators. It does not make any evaluation on efficiency of orbital use or other trade-offs (although an adaptive governance system could impose such consideration).

The applicant, AstroCorp. proposes a consistently replenished satellite constellation of 200 24 kg 12U CubeSats without propulsion or maneuverability at 500 km. Satellites operate for one year. This is modeled with two new species, shown in Table 6. In the model, the paired derelict class is excluded from being spawned by collision events and the initial/future launch model to preserve traceability. AstroCorp. adds their mission to the baseline model run and finds that the net contribution from their mission to any of the constraints is negligible. They demonstrate as seen in Fig. 6 and 7 that the constellation produces few collisions and requires few maneuvers by other maneuverable actors to avoid either the satellites or debris. They do not use intrinsic capacity, and have negligible effect on LTS due to their altitude. The regulator thus permits AstroCorp. to use a streamlined capacity review process that waives certain analysis requirements.

While AstroCorp. received accelerated review, the opposite is also possible. A constellation that showed problematic changes to indicators could be subject to higher scrutiny or potentially be required to revise their constellation to comply with the modeling outcomes determined by the adaptive process.



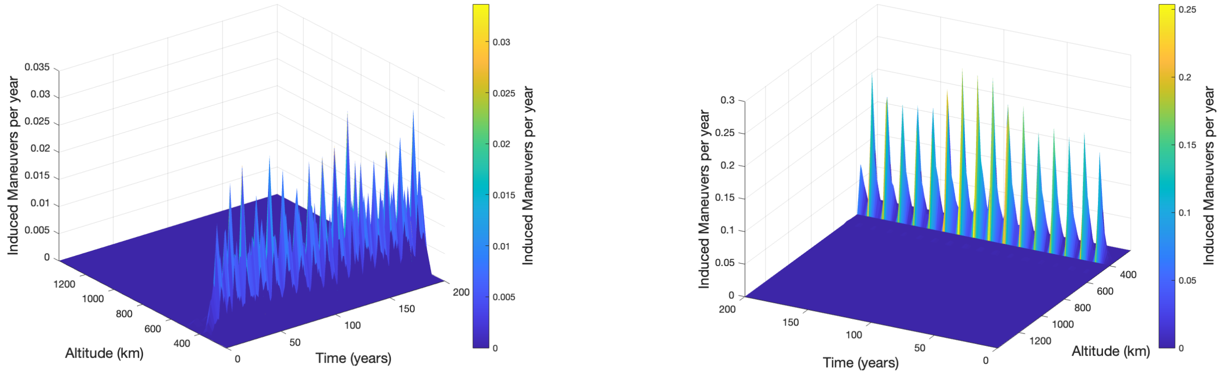
(a) Constellation (C)

(b) Constellation Derelicts (D)

Fig. 6: Additional aggregate collisions from the new constellation (C) and constellation derelicts (D)

3.2 Adaptation to Changes to Environmental Conditions

In this example, an anti-satellite (ASAT) missile test is modeled as occurring at 8.0402 years into the simulation at 800 km involving a 500kg 2 meter radius object and an 8000 kg object with a 32 meter radius. The event generates the fragment counts in Table 1. Those fragments are modeled as being deposited into the altitude bin containing 800 km, although this assumption is not particularly realistic. Recall also that our initial population excludes the substantial amounts of sub-trackable debris already at these altitudes. In comparing Fig. 8a and Fig. 8b, the sharp spike in debris creation due to the ASAT event is clearly visible, with the region already violating the LTS constraint and continuing to do so after the test. However, the long-term slope of the line remains similar. Based on predicted LNT collision rates and the background environment, adaptive management participants could discuss if they need to adapt any decision-rules in response to the event, such as discouraging traffic to impacted altitudes, encouraging additional spacecraft shielding, or pursuing enhanced in-situ monitoring to better estimate LNT flux.



(a) Constellation (C)

(b) Constellation Derelicts (D)

Fig. 7: Additional induced maneuvers from the new constellation (C) and constellation derelicts (D)

Table 1: Fragment Counts for the Simulated Anti-Satellite Missile Test

	$\mathbf{N_{0.0014137kg}}$	$\mathbf{N_{0.567kg}}$	$\mathbf{N_{6kg}}$
Fragments	56,037	608	45

3.3 Decision-Support to Changes to Behavior

Another major category where integrated modeling can be helpful is in assessing the approximate outcomes of various interventions. Comparing a model run with and without an intervention is valuable for assessing a wide range of potential interventions to understand trade-offs. Such interventions might include use of cross-operator orbit coordination between LLCs, greater or less compliance with PMD requirements, or changes to maximum post-orbit lifetime. Because behavior of individual spacecraft does not need to be explicitly simulated to represent such actions in an SSEM, it is often easy to represent such changes by altering parameters or with minimal additions to the model. This section provides an example using the non-zero altitude disposal introduced in Section 2.5.

3.3.1 Post-Mission Disposal Altitude

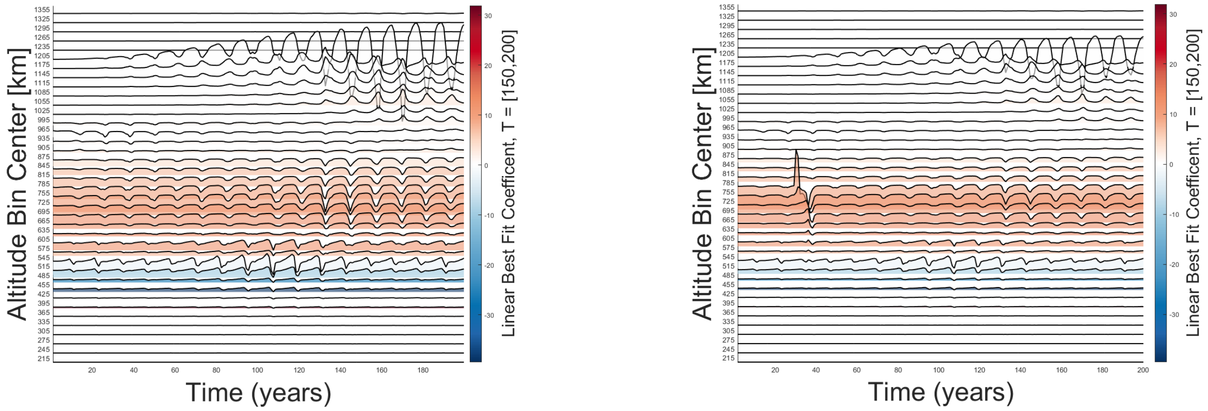
In this example, stakeholders are considering implementing a five year rule for maximum post-mission orbital lifetime. They assume that, despite requesting that people de-orbit as soon as possible, many users will passivate spacecraft at altitudes sufficient to comply. To model this effect, the PMD equations are changed so that maneuverable non-LLC spacecraft, S_u, that successfully complete PMD above the disposal altitude are no longer immediately removed from the scenario, but deposited into a disposal orbit sufficient to de-orbit in five years or less.

For each species of S_u this altitude was estimated by propagating a representative satellite until it reached 200 km using the Orekit astrodynamics library's implementation of the Draper Semi-analytical Satellite Theory with a modified HarrisPriester atmosphere model (429 km for S_{260kg} and 573 km for S_{473km}).

A comparison was conducted between instantaneous disposal and this new behavior. As seen in Fig. 9, we see the expected increases in derelict populations from the new policy. Fig. 10a shows the policy results in between 0.1 to 0.25 additional low-altitude collision events per year, while Fig. 10b shows up to about a half an additional maneuver per spacecraft per year for the Su_{473kg} species.

4. CONCLUSION

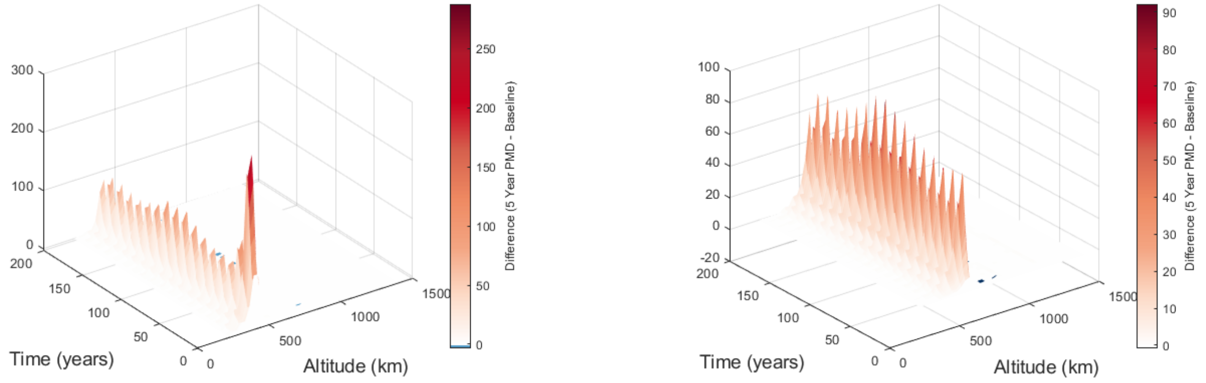
This paper has tried to place space environment management in the context of prior learning on governance of natural resource systems and demonstrate how evolutionary space environment models could be used to support adaptive management and governance processes. This role was demonstrated using MOCAT-SSEM and a set of notional



(a) No ASAT

(b) With ASAT

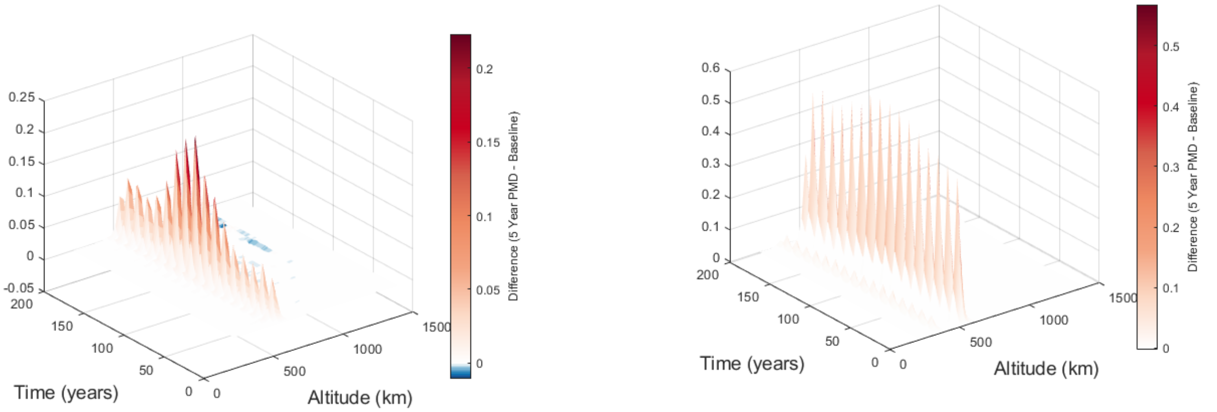
Fig. 8: Long-term Sustainability Constraint, evaluated with and without ASAT test



(a) N_{260kg} Population Difference

(b) N_{473kg} Population Increase

Fig. 9: Derelict population increases from 5 year rule vs. instantaneous disposal



(a) N_{473kg} Additional Collisions

(b) Su_{473kg} Additional Collision Avoidance Maneuvers per Spacecraft

Fig. 10: Derelict population burden from 5 year rule vs. instantaneous disposal

constraints to orbital capacity that capture different potential stakeholder interests. More technical work is needed to calibrate, verify, and validate MOCAT-SSEM and build community familiarity with the entire MOCAT.

This paper has further argued that incorporating evolutionary environmental modeling more directly into deliberations around orbital use is a necessary change if we want to improve the quality of our decision-making on space debris mitigation and remediation. Several steps are necessary to achieve this shift.

First, across a variety of fora, we need to develop consensuses around measurable technical definitions for what we mean by space sustainability, the factors we believe constrain our use of the space environment, relevant modeling assumptions, and indicators that capture the aspects that matter to different classes of stakeholders.

Second, we need to build community confidence in and ability to use modeling tools, as well as devote resources to make them available and usable to stakeholders. Trusted, accessible, sufficiently-capable models are a critical prerequisite for successful adaptive management.

Third, we need to start to incorporate notions of orbital capacity into our decision-making: whether because capacity constrains our actions or because the data show that it does not. Shared resources that are finite need to be understood and used efficiently and equitably. At the same time, it is important to avoid the siren's call of scientific management. Incorporating evolutionary space environment models more directly into management decision-making is important, but will likely not lead to success if used as part of a highly centralized process mediated by adversarial legal interactions between stakeholders.

Fourth and lastly, work is needed to socialize these ideas within the space community, determine potential convening organizations, and build stakeholder support and participation. Whether efforts coalesces around a convening government entity, a voluntary private effort, or another structure, it will take significant will and a groundswell of support to build and maintain relevant structures and institutions to support improved decision-making processes.

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Table 2: Objects in initial population and future launch model.

Species	**Count**	**Percentage**
Non-station-keeping Satellites	36,974	3.06
Station-keeping Satellites	7,182	0.59
Coordinated Satellites	1,120,127	92.77
Rocket Bodies	7,182	0.59
Debris (initial + exogenous)	35,954	2.98

APPENDIX

Table 3: Species and properties within the MOCAT-SSEM configuration chosen for this paper.

Symbol	**S**	$\mathbf{S_u}$	$\mathbf{S_{ns}}$	**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

Table 4: Scenario Properties

Field	Value
Start date	1 December 2022 0:00:00 UTC
Simulation duration [years]	200
Output steps	200
Density model	JB2008 Interpolated Density (generic high solar cycle prediction)
Number of shells	40
Minimum altitude [km]	200
Maximum altitude [km]	1400
Velocity of collisions [km/s]	10
Characteristic length [m]	0.01
Integrator	ode15s
Launch traffic model	Empirical fit to large constellation scenario

Table 5: Large Low Earth Constellations Included in Future Launch Model

Constellation	Altitude	Inclination	Sats on stn	Sats off stn	Sats down	Total Sats Planned	FirstLaunch	FinishLaunch	mass	radius
Starlink	550	53	1419	35	251	1584	2018	2027	260	2
Starlink	570	70	170	234	3	720	2018	2027	260	2
Starlink	560	97.6	233	0	0	348	2018	2027	260	2
Starlink	540	53.2	1544	23	68	1584	2018	2027	260	2
Starlink	560	97.6	0	0	0	172	2018	2027	260	2
Starlink2A	530	43	0	288	2	2500	2023	2031	750	2
Starlink2A	525	53	0	0	0	2500	2023	2031	750	2
Starlink2A	535	33	0	0	0	2500	2023	2031	750	2
Starlink2	340	53	0	0	0	5280	2025	2031	1250	4
Starlink2	345	46	0	0	0	5280	2025	2031	1250	4
Starlink2	350	38	0	0	0	5280	2025	2031	1250	4
Starlink2	360	96.9	0	0	0	3600	2025	2031	1250	4
Starlink2	530	43	0	0	0	860	2025	2031	1250	4
Starlink2	525	53	0	0	0	860	2025	2031	1250	4
Starlink2	535	33	0	0	0	860	2025	2031	1250	4
Starlink2	604	148	0	0	0	144	2025	2031	1250	4
Starlink2	614	115.7	0	0	0	324	2025	2031	1250	4
OneWeb	1200	87.9	499	133	2	588	2019	2023	148	0.5
OneWeb	1200	55	0	0	0	128	2019	2023	148	0.5
OneWeb	1200	87.9	0	0	0	1764	2025	2028	148	0.5
OneWeb	1200	40	0	0	0	2304	2025	2028	148	0.5
OneWeb	1200	55	0	0	0	2304	2025	2028	148	0.5
Kuiper	590	33	0	0	0	782	2024	2029	700	1.5
Kuiper	590	30	0	0	0	2	2024	2029	700	1.5
Kuiper	610	42	0	0	0	1292	2024	2029	700	1.5
Kuiper	630	51.9	0	0	0	1156	2024	2029	700	1.5

Table 6: Species and properties for additional species added for demonstration case

Symbol	**C**	**N_c**
Description	Candidate Constellation Streamlined Review (Section 3.1.2)	Paired Debris Class Streamlined Review (Section 3.1.2)
Cd	2.2	2.2
Mass [kg]	24	24
Radius [m]	0.261	0.261
Area [m^2]	0.681	0.681
Active	true	false
Slotted	false	false
Drag	true	true
Maneuverable	false	false
Trackable	true	true
Mission lifetime	1	N/A
Post-mission disposal	.N/A	N/A
Disposal altitude	N/A	N/A
Efficacy of collision avoidance vs. inactive	N/A	N/A
Efficacy of collision avoidance vs. active	N/A	N/A
Rocket body	false	false
Launch rate	empirical fit (200 sat @ 500 km, replenished every 1 years)	N/A