Development of Reference Scenarios and Supporting Inputs for Space Environment Modeling

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Abstract

Models are widely used to understand potential futures of the space environment and space sustainability risks. In other domains, these models have often been combined with shared reference scenarios to support the development of effective policy solutions. Evolutionary space environment modeling is sensitive to modeling assumptions and inputs, but these inputs often rely on controlled information or are simply not disclosed. At the same time, a lack of a set of common modeling assumptions complicates communication across organizations and interpretation of detailed modeling results from different entities. This work describes preliminary efforts to develop a set of indicative reference scenarios for evolutionary space environment modeling, supported by publicly-releasable input sets. Community feedback is solicited on the proposed scenarios, parameter choices, and data formats. Dubbed, the "Space Environment Pathways" (SEPs), a set of six scenarios are defined along three axes: market demand for space services, non-market demand for space services, and level of space sustainability effort. Various modeling inputs are provided including narrative descriptions of the scenarios, an initial population model, future traffic model, and solar inputs for atmospheric density models. The process by which the scenarios and axes were defined is described. It is argued that a set of shared scenarios would provide multiple benefits to the modeling community including making it easier to develop, verify, and validate new models, supporting integrated assessment modeling, improving public communication about space sustainability, and enabling future adaptive management and governance structures for the space domain.

1. Introduction

As Bohr noted, prediction is very difficult, especially about the future. This paper describes a project to develop a set of 6 potential futures "scenarios" for the space environment, dubbed "The Space Environment Pathways" (SEPs). Scenarios can be thought of as 'if-then' statements. If we make a given set of assumptions about key economic, technological, and policy parameters, scenarios explore the consequences of these assumptions. In this way, scenarios serve as agenda-setting tools for research and policy (e.g., [1] describes how scenarios are used in climate-change research). The SEPs do not attempt to predict the exact future we will experience; rather, they attempt to identify key behaviors and potential outcomes that might influence the direction the space environment evolves and to provide an accessible, open set of data products to the community to model those potential futures. This paper describes the preliminary phases of work to develop these scenarios with the objective of beginning what we hope will be a community discussion on assumptions, methodologies, formats, and outputs for what we hope will eventually become a set of community standard outputs for evolutionary modeling of the space environment. The scenarios and inputs are intended for release in October 2024.

This paper focuses on articulating the value of having a set of standardized community reference scenarios for evolutionary space environment modeling, describing the methodology used to develop the 6 chosen scenarios and the scenarios themselves. While the various components that make up the inputs for each scenario are briefly described in this paper, they will be described more fully with underlying technical methodologies in a paper by this same team to be presented at the International Astronautical Congress [2] in a few weeks.

In wider literature and across research domains, developing scenarios to focus research community efforts is a common exercise [3] [4] [5]. Most notable are the Representative Concentration Pathways (RCPs) [6] and the Shared Socioeconomic Pathways (SSPs) [7] for climate change, which were central to the fifth and sixth assessment reports, respectively, of the Intergovernmental Panel on Climate Change (IPCC). The RCPs and SSPs were developed through community efforts to define ranges of socioeconomic, technological, and policy pathways that would create different greenhouse-gas emissions trajectories throughout the twenty-first century. The ranges of assumptions explored in the SSP and RCPs were chosen based partly on what relevant domain experts thought of as plausible, but also based on specific needs of climate researchers and policymakers. For example, the SSPs include scenarios consistent with limiting global warming to 1.5 degrees Celsius by 2100, as this is an aspirational goal of the 2015 Paris Agreement [7], even though the sociotechnical assumptions required to achieve that goal may be implausible (e.g., [8] [9]). Conversely, the scenarios with highest emissions—RCP8.5 and SS5-8.5—were originally intended to explore extreme upper bounds (despite widespread subsequent misuse), which can be useful in exploratory research and are also widely thought to be implausible [10] [9].

The RCPs focused mainly on providing emissions pathways specifically [6]. The SSPs focused on explicitly defining socioeconomic scenarios—which affect energy demand and technological progress—as a framework for exploring emissions scenarios. Figure 1, reproduced from O'Neill et al. [11] and Riahi et al. [7], illustrates this. The SSPs defined five socioeconomic pathways (SSP1,... SSP5) (Figure 1A), within which different stringencies of global climate policies could produce different emissions pathways, compared to 'baselines' with no climate policy (Figure 1B). Given that socioeconomic conditions also affect society's ability to adapt to climate change and cope with its consequences, foregrounding the socioeconomic assumptions in the SSP scenario framework was useful to research jointly exploring climate change pathways and their societal consequences (e.g., Moyer et al. [12]). However, given that some climate change research only needs emissions as an input (e.g., physical climate modeling), and many emissions pathways can be produced by multiple sets of socioeconomic assumptions (Figure 1B), the ongoing effort to develop scenarios for the upcoming seventh IPCC assessment report has reverted to foregrounding emissions pathways [13].

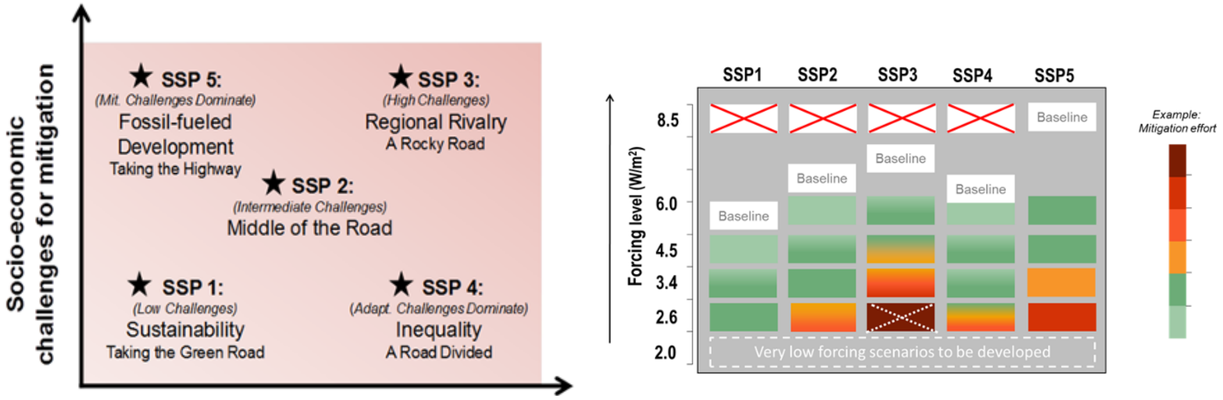

Figure 1 A: Overview of Shared Socioeconomic Pathways (SSPs). B: Scenario Matrix specified by SSPs and forcing levels. Scenarios populate individual cells providing information about mitigation benefits and costs [7].

The RCPs and SSPs have been extremely successful in providing a common framework for climate change research. For example, between 2014-2019, at least 1,378 analyses were published that used or continued to develop the scenarios [1]. Retrospective reviews by the RCP and SSP architects (e.g., [11] [13]), and critical reviews by others (e.g., [10]; [9]; [14]) make several recommendations, with clear analogs to other domains such as the space environment—the focus of our work. These recommendations include: distinguishing key axes of scenario assumptions that can vary separately (e.g., emissions and economic development) [13], distinguishing scenarios intended to be considered plausible from those intended to be considered exploratory [10] [9], developing widely accessible and user-friendly online repositories to catalyze collaboration and capacity building ([1]; see also IIASA, 2022 [15], for an example), avoiding insularity in scenario development that limits the scope of models and futures that can be explored [14], and having frameworks that allow scenarios to be regularly updated in light of new information and sociotechnical developments [10] [16].

There are clear analogs between the needs for common scenarios in climate modeling and modeling of the future of the space environment. It is well known that the outputs of evolutionary space environment models depend strongly on the chosen inputs. Without agreement on inputs, it can be difficult to compare models and studies and understand the potential consequences of choices or interventions. The presence of a common baseline of assumptions would be invaluable for the evolutionary space environment modeling community as it grapples with numerous sources of rapid change including a dramatic increase in the active space population and supporting launch rates, significant concern about space sustainability and orbital capacity and proposals for new mitigation and remediation requirements, and heightened geopolitical tensions as a backdrop for future space development. This idea is not new in a space context. The Inter-agency Space Debris Coordinating Committee (IADC) has long used standardized inputs for model cross-validation and prediction, such as the 2013 study by Liou et al. [17]. However, it does not make those inputs public, the inputs are not intended to fully span a range of potential futures, and relatively little of this work has been published. In this paper we take the idea of the SSPs and associated design recommendations as an inspiration but adapt it for suitability to the space environment. It is hoped that these scenarios and the associated inputs and methodology can help support improved modeling, and ultimately decision-making.

2. Methods

This section describes the process used by the SEP definition team to develop and validate the set of SEP scenarios, as well as the associated scope and goals for the project: a set of a manageable number of exploratory scenarios for potential space futures supported by publicly available model inputs.

One of the first tasks for the SEP definition team was to determine an appropriate process to develop our initial proposal for the SEPs. While this project was partially inspired by the previously mentioned SSPs for the climate research community, it quickly became evident that the SSPs would not provide an appropriate procedural example to emulate. Defining the SSPs in the climate research community followed an elaborate formal process with multiple preparatory conferences, papers, and participants and a considerable level of organizational infrastructure. The SSPs progressed from a proposal for development that was submitted to the community and ultimately obtained formal approval. The space environment modeling community is considerably smaller than the climate community, and we determined that the level of organization infrastructure used for that process would be overly inhibitive and unnecessary for a community of our size. We also determined that there is not yet a critical mass of support for reference scenarios within our community, which would complicate efforts to build a truly community-wide process from the start. Instead, we concluded that the best first step would be to gather a group of experts with experience in astrodynamics, orbital capacity, debris modeling, policy, space and resource economics, as well as experience with the development of and lessons learned from the SSP process. This group could then develop a preliminary proposal that would be provided to the broader space community for iterative feedback.

This group, the SEP definition team, is composed of Miles Lifson, Indigo Brownhall, Matthew Burgess, Marcus Holzinger, Daniel Kaffine, Mark Moretto, Akhil Rao, and Brian Weeden. It was responsible for defining the axes for exploration across the various scenarios, the points where each scenario would be placed on each axis, the narrative descriptions of each scenario, and overall direction of the project. A broader research team at The Aerospace Corporation lent technical expertise and support and developed detailed methodologies and data products in line with the direction from the SEP definition team. Miles Lifson coordinated the overall project and coordinated between the two teams. Having established the SEP project team, we make several early decisions concerning the objective and course of the project:

First, the scenarios and inputs to the project need to be publicly released and available openly to the full community. We felt this was important to achieve multiple objectives for the project even though it would impose limitations on the types of data sources and methodologies that could be used to construct modeling inputs. The entire team felt that associated losses in input fidelity were more than offset by the benefits of openness, and members noted that modeling using closed inputs would invariably continue alongside modeling of the open reference cases.

Second, the purpose of the reference scenarios should be exploratory and clearly conveyed as such. When conducting modeling and constructing scenarios, multiple objectives are possible. Exploratory modeling seeks to understand how a system responds to certain inputs. Such modeling can be used in a variety of ways including seeing how a system responds to possible environment inputs (which may be controlled or uncontrolled) and to understand how the system will respond to certain behavior and policy choices. Exploratory modeling can be distinguished from predictive modeling, which seeks to identify the actual future state of the modeled system, and normative modeling, which seeks to specify what should happen [18]. While a single set of scenarios can be used in multiple ways, we determined that the critical need for the community was a set of scenarios that would reasonably explore the set of potential futures to help inform model-development and policy decision-making. We viewed predictive modeling as impossible to achieve over the relevant time horizons, and normative modeling being too actor-specific to support generalization in common reference scenarios.

Third, we should provide a manageable number of scenarios that are conceptually distinct, recognizing that this handful of scenarios would be unable to sample all combinations of states on all axes of interest. In the case of the SSPs, a set of primary and secondary scenarios were identified that combine the socioeconomic aspects of the SSPs with various levels of radiative forcing from the RCPs [1].

Fourth, we identify several limits in scope to keep the project manageable for the first iteration. These limitations include constraining our focus to Low Earth Orbit (LEO), excluding future governmental large constellations, except where reported to the International Telecommunication Union (ITU) or Federal Communications Commission (FCC), and excluding commercial space stations and/or crewed space vehicles except insofar as these vehicles are captured in the replicated historical non-constellation launch traffic. We also decided not to include the modeling of the outcomes of a significant space conflict and/or future debris-producing anti-satellite missile tests. There are several reasons for this. First, we viewed the utility of such a scenario as limited. While the specific consequences of a significant conflict in outer space are highly dependent on the specific technical dimensions of that conflict, the result would be disastrous for other operators and the long-term space environment. This is widely understood and does not require a community consensus model to understand. With regards to debris-producing direct-ascent anti-satellite missile tests, the reprise of another FY-1C event appears remote due to emerging international norms and the widespread condemnation of that event. Recent anti-satellite missile tests have occurred at much lower altitudes and produced more limited and shorter-term environmental contexts. Additionally, the United States has announced a voluntary moratorium on such tests that has been joined by more than 30 additional countries [19].

Having defined the broad outlines of the task, we developed a process beginning with an open-ended discussion of key themes that we believed would influence the potential evolution of the space environment. From this discussion, we down-select a set of largely independent axes that corresponded to potential variation that we might see in future behaviors. As part of this process, we collapse and merge axes that are correlated and eliminate axes that we felt are of secondary importance. We then define points on each axis and identify combinations that corresponded to the most important combinations of potential states. At this point we construct paragraph narratives for each of the scenarios. These narratives describe the “what” that each scenario seeks to capture, emulating similar narratives for the SSPs. In our case, these narratives also provide context to assist modelers who wish to include factors not already specified in the scenario definition. In these cases, such individuals can use their judgment to identify additional parameters as necessary that correspond to scenario narrative of interest.

2.1 Preliminary Validation

To assist with preliminary validation, an initial concept for the SEPs was presented in June 2024 for preliminary feedback at the 7th International Workshop on Debris Modeling and Remediation. Feedback was positive and generally noted the usefulness that such a dataset would provide to the community, and desirability of eventually integrating such efforts into internationally coordinated work on space environment modeling through organizations such as the IADC. To ensure that the scenarios covered were robust to future behaviors, The Aerospace Corporation's Strategic Foresight Team [20] was asked to examine the scenarios and provide feedback. They determined that the scenarios were defined at an appropriate level of detail, responsive to major identified behaviors, and were developed using a reasonable methodology.

2.2 Selected Literature Review of Evolutionary Space Environment Modeling Assumptions

To further assist with validation, a selected literature review of evolutionary space environment modeling work was conducted. Evolutionary space environment modeling is a broad field with significant international work over the course of multiple decades. In defining a set of shared scenarios that wrap in various assumptions made in the modelling process, it was critical to understand what assumptions others have made in developing evolutionary models of the space environment and to confirm the general perceptions of the SEP definition team. To reduce the change that this analysis would be distorted by the pre-formed opinions of the SEP definition team, this literature review process was conducted by an additional researcher who was not involved with the SEP definition team. The intention of this literature review was not to be comprehensive, but to provide insight into the types of assumptions and choices commonly made in high-quality modeling work and to identify the types of data products that would need to be provided to support common modeling tasks. A number of papers ranging in publication year from 2002 to 2023 and origin were reviewed. A subset of these papers that included a robust outline of the assumptions adopted were used to generate a matrix of assumptions and studies from which overarching conclusions were drawn.

Some assumptions endure across almost all studies, even those with different goals. Launch traffic was always based on historical behaviors and was almost always a repeat of the last 8 years [21, 22, 23, 24, 25, 26, 27, 28, 29, 30]. Unless the effects of explosion rate were being evaluated, the explosion rate was commonly held to 0% [21, 22, 23, 17, 29]. This is similarly true for collision avoidance maneuvers; many earlier studies assume none [22, 17, 29, 31]. However, in the first 6 months of 2024 Starlink, a LEO constellation, reported over 50,000 [32]. Some efforts assumed no collision avoidance maneuvers only after successful post-mission disposal [21], and several studies varied the rate of collision avoidance maneuvers to evaluate its impact [28, 27]. 200 years is by far the dominant simulation timespan, reflecting that 200 years is thought to be long enough for relevant behaviors and results to become clear [21, 22, 23, 25, 17, 28, 29, 30, 31, 33]. Minimum object size is often held at 10cm, in keeping with the current understanding of what non-cooperative space situational awareness sensors are able to reliably detect and maintain [21, 25, 27, 26, 28, 29, 30, 31, 33]. This size may be decreased in years to come, particularly in parts of LEO, as the capabilities of the US DOD's Space Fence system are better understood. Spacecraft mission lifetime was most commonly 8 years [21, 22, 26, 29, 30, 34, 33]. Solar and geomagnetic effects were always rooted in past data, either by using a random combination of datasets, the mean, highs, or varied across a study effort to detect sensitivity [22, 24, 26, 30, 34]. Initial populations are often pulled from some standard catalog, such as DISCOS, MASTER, or the US DOD's catalog [21, 22, 26, 30, 33], and sometimes includes a freshness check to ensure only objects with recent states were ingested [24, 25]. When mentioned, crewed objects were excluded, as they are presumed to maneuver more often and operate with a more conservative collision risk posture [24, 25]. When LEO is the primary study regime, this is commonly defined as a perigee between 200km and 2000km [24, 26, 28, 29, 31, 34].

Post-mission disposal (PMD) timelines and rates are often set to 25 years with 90% success, reflecting longstanding standards [23, 26, 28, 30, 33]. However, this is also frequently varied to predict the state of the space environment given various levels of compliance for various types of spacecraft. For example, 0%, 50%, 60%, 75%, 99.5%, and 100% were all investigated [21, 25, 27], and rocket bodies were assumed to not be disposed in one case to demonstrate this impact [31]. As the most recent study reviewed was from 2023, but many were from before this, a 5-year rule was not often included as an assumption. Similarly, active debris removal (ADR) is typically not discussed, unless its effect is being evaluated in the study [28].

In some cases, where the effort is primarily interested in the relationship between a specific class of spacecraft (e.g., CubeSats or large LEO constellations) and the environment, assumptions are made about the attributes and behavior of these spacecraft. This often include the profile and length of the orbit raising and lowering periods, spacecraft shapes, sizes, masses, propulsion methods, and deployment/replenishment models [25, 27, 31, 33].

3. Results

To define the scenarios, axes were established to bound the dimensions on which the reference scenarios would be built. These axes are categorized into two main groups: the future population model and sustainability efforts. The future traffic model is further divided into Commercial and Non-Commercial demand. Non-Commercial launches encompass satellites built to meet inherent consumer demands commonly driven by governments, such as Earth Observation (EO), scientific, Position Navigation and Timing (PNT), and other Defense payloads. In contrast, Commercial demand launches are driven by market users and include internet or communication constellations, as well as private market PNT (LEO) and EO constellations. In both cases, demand is modeled exogenously, i.e. satellites are pre-specified based on criteria rather than being the function of internal economic logic within the model. The second category addresses the level of mitigation and sustainability efforts. This axis is crucial for developing regulations, guidelines, and improvements in space operations. An example of an action along this axis could be investing in ADR to remove high-risk rocket-bodies or inactive payloads. Finally, a proposed axis for atmospheric density and solar activity/space weather was considered but ultimately rejected due to the project design team’s opinion that atmospheric density variability was less important for exploration than the existing axes, would additionally complicate interpretation of results, and that limited scientific understanding of the probabilities associated with various solar activity excursion cases meant that it would be likely that a solar axes would have modest effects or overly explore fairly unlikely cases.

3.1 Definition of Scenario Axes

Table 1 Scenario Axes Breakdown.

	Market Demand for Space Services	**Non-Market Demand for Space Services**	**Level of Sustainability Effort**
Current	Existing Large LEO Constellation (LLC) shells finished, 1x 10-year repeated launch cycle	Existing LLC shells finished, 10-year repeated launch cycle.	Current behavior
Low	Only “high” likelihood constellations. 1.5x repeated traffic.	No additional constellations	Current trend
Medium	“High” and “medium” likelihood constellations. 2x repeated traffic.	Boost status of constellations from major miliary spending states* by 1 point	Improved vs. current behavior, but below aspirational goals
High	“High”, “medium” and “plausible” constellations. 3x repeated traffic.	Boost status of constellations from major military spending states by 2 points	Best practices implemented

**Major military spending state is defined as the top 20 states by defense spending in 2023, as calculated by Stockholm International Peace Research Institute’s Military Expenditure Database.*

3.1.1 Commercial Demand for Space Services

The project team quickly realized that the level of space traffic and its properties would be one of the most important inputs to a set of reference scenarios. In recent years, the overwhelming majority of traffic in LEO has been commercial, driven primarily by large commercial communications constellations. SpaceX and Eutelsat OneWeb have both deployed very large constellations, with future generations of their constellations already proposed. Multiple other operators have also proposed ambitious constellations. The team generally agreed that there is considerable uncertainty about the level of demand for space services that will emerge in the coming years, and the number and distribution of satellite constellations and satellites that this demand will support. We accordingly prioritized future commercial traffic as a key axis for our model.

Most space environment evolutionary modeling paradigms and implementations require specific information about particular spacecraft orbits, engineering properties, and behaviors for the duration of the modeling span, which is often 100-200 years. Naturally, this level of precision cannot feasibly be obtained with any level of fidelity based on the information available today for points a decade from now, much less centuries into the future. When faced with such uncertainty, M. Granger Morgan [35] describes a process first proposed in a paper by Casman, Morgan, and Dowlatabadi [36] whereby models with different levels of fidelity are fused to provide an estimate over differing timespans, with transitions between detailed modeling, order-of-magnitude estimation, and bounding analysis. For a project that seeks to support a wide variety of modeling paradigms with common inputs, we cannot insist on such capabilities in the models themselves. However, we can design the inputs to provide appropriate inputs to test information over these timeframes, starting with more detailed information where it exists and extrapolating into the future while recongizing that over intermediate and long-term time horizons, the specific outputs obtained are more appropriate for order of magnitude and bounding analysis rather than detailed predictive outcomes. This objective informs the approach we take to estimating the future launch population.

In predicting future space traffic, we wanted to provide a set of inputs based on defensible, objective criteria that could be plausibly updated on a regular cadence while tracking shifts in the nature of the space environment. We determined that the best way to do so would be approach rooted in regulatory filings for large constellations and a repeated historical non-constellation model. FCC and ITU filings were downloaded and processed to produce a list of unique physical satellites proposed in those filings. This list was categorized into a set of constellation development tiers based on a quasi-objective rubric for constellation deployment status, financial resources/stability, legal and regulatory status, and business history. The full methodology is described in Lifson et al. [2]. Ratings were applied on a per-company rather than a per-constellation basis. These constellations were then assigned to representative launch vehicles with a deployment schedule based on the required ITU deadlines for bringing their spectrum into use, assuming continued replenishment for the duration of the scenario. This is accompanied by a non-constellation traffic model that repeats launches from recent years with a multipler based on the level of demand provided as an input, concentrating traffic over a shorter time period between repetitions for multipliers greater than one. This is a coarse model of future demand but is designed as a leading indicator to roughly reflect the continued behavior of near-future constellation proposals, recognizing that there is wide variance in the likelihood of various filings and that a method based only on deployments to date would ignore significant future constellations, even high likelihood systems. It produces fairly detailed information about near-term satellite deployments as a function of estimated level of demand for satellite services, but transitions to a more approximate estimate of traffic on longer time-scales that may underestimate traffic in the far future. Nonetheless, the chosen approach still provides useful input on the question of how current levels of traffic demand and behaviors will influence the long-term sustainability and space operational assurance of the space environment. This question is one of the most important outcomes for long-term environmental modeling.

3.1.2 Non-Market Demand for Space Services

In addition to satellites and constellations driven by market demand, there will also be other satellites and constellations that do not respond to market-driven economic logic. These are primarily government missions developed for civil or national security purposes. Such missions are likely to be driven by different demand factors than commercial economic demand (even if at least some services are provided by commercial satellites). At the same time, non-market demand will be related to and benefit from economies of scale and technical innovation in the commercial market. As a reminder and as described in the scope limitations for the project in Section 2, the focus for this axis is describing the peaceful environmental consequences of non-commercial demand rather than explicitly simulating the environment consequences of kinetic space conflict.

We note that the satellites and constellations providing such services are likely to be subject to increased sensitivity about the nationalities of object ownership and operation and that, particularly in a national security context, political leaders may be willing to relax space sustainability requirements for missions with national security imperatives, particularly if such requirements are perceived as delaying or diminishing important mission's capabilities. We also determined that we did not wish to try to model potential future purely government owned and operated constellations. There are not, to our knowledge, great open data sources to characterize such constellations and attempts to guess their properties are likely quite fraught, particularly if our guesses were to closely resemble the eventual design of actual classified government satellites.

As a result, we opted for the approach seen in Table 1, where the level of non-market demand acts as a modifier that increases the likelihood status of commercial constellations associated with nations with substantial defense spending as identified by a respected third-party methodology. This approach captures the recognition that the primary driver for non-market demand for large constellation traffic will be national security rather than civil, even though new civil large constellations may also emerge.

3.1.3 Level of Sustainability Effort

In addition to the *level* of traffic, the *behavior* of that traffic strongly influences the evolution of the space environment. The extent to which space traffic fails to dispose promptly and successfully at end of mission, fails during operational lifetime, and/or experiences spontaneous explosions all provide strong influences on the future for the debris environment. We sought to create an axis that reflects levels of effort in this domain, ranging from current behavior to strongly improved behavior at the levels posited to be necessary to ensure long-term sustainability. Along this axis, we included two additional levels: one corresponding to an extrapolation of today's trends to reflect weak but incremental improvement over current practices, and another corresponding to considerable but not aspirational levels of improvements aligned largely to industry recommendations about improvements. While a variety of sources were consulted, the values in Table 3 drawn primarily on current practices and best practices as documented in the ESA Space Environment Report [33] and IADC Space Debris Mitigation Guidelines [37], the Space Safety Coalition's Best Practices for the Sustainability of Space Operations, and the newly revised ESA Zero Debris Charter [38]. These values were selected by the Aerospace technical team without Office of Space Commerce consultation and do not constitute an official statement of endorsement or preference by the Office of Space Commerce for the Traffic Coordination for Space System, policy, or more generally. While these sources were consulted, they are not encoded literally. Certain aspects of the requirements in these documents, for instance conditioning mitigation requirements on levels of estimated orbit-specific cumulative collision risk as calculated with third-party tools would be too onerous to impose as a requirement intended to be broadly compatible with multiple modeling tools that operate are widely varying levels of fidelity. For the same reason, we opted to make the values on level of the axis constant rather than time-varying. In practice, slow improvements are likely to occur over time, with factors like PMD rates increasing as engineering improves and older missions are replaced by newer satellites with greater sustainability focus. Nonetheless, it is likely that only a subset of models will be able to support time-varying behaviors for mitigation actions (which in at least some models are set by a single global parameter). Because of the importance of broad compatibility, we opt for the easier to implement, but lower-fidelity alternative. The use of constant values also simplifies interpretation of outcomes versus a time-varying outcome, in alignment with this project's focus on exploratory rather than predictive scenario design.

Perhaps controversially, our methodology combines both mitigation and remediation into a combined single axis. One of the design principles for this project was to minimize the number of axes while covering the most important and truly distinct axes. We reasoned that a world that seeks to commit effort to address space sustainability concerns is also one that will likely begin operational remediation to some degree. Most contemporary analysis argues that mitigation is a necessary but insufficient condition for long-term sustainability and that remediation will also be necessary. At the same time, remediation concepts continue to mature technically while continuing to face significant economic and policy questions. Remediation, particularly ADR, will likely continue to be a more expensive way to remove risk than mitigation. Values were set based on the group's informal judgment concerning levels of ADR that were potentially plausible but also environmentally significant. While most high-risk objects currently on-orbit are high-altitude derelicts from the Soviet space program, we do not currently impose any limitations on the nationality of objects that are removed. Over the timeframes countenanced in these scenarios, accounting for contemporary space capabilities, economic scale, and political alignment is overly precise relative to the scale of other assumptions. Similar to the description of mitigation actions, we impose a constant rate of removal at each level of the axis. This is again less realistic than an increasing slope but simplifies analysis and is in line with the options explored in [39, 40]. Nevertheless, variable rates of ADR activity are likely more easily implementable across the broad scope of evolutionary space debris models than PMD and this is a factor that could be revisited based on community feedback.

3.2 Scenarios

Ultimately, at least 6 scenarios are necessary to cover key potential futures. These scenarios and narrative descriptions are present in Table 2. The position of each scenario along the three axes is described in Table 3. The scenarios range from a highly synthetic to plausible extrapolations of current behaviors. All scenarios feature the same shared initial population model and time-varying solar activity indices, described in more detail in Lifson et al. [2].For each scenario, the goal was to find a possible outcome that develops from changing hypothetical positions along the axes:

SEP 1 is a synthetic scenario that, although extremely unrealistic, is highly useful for model comparison and troubleshooting. “No future launch” scenarios have been used for model comparison in an IADC context as they limit the number of additional variables and degrees of freedom that need to be coordinated across models and make it easier to identify problematic discrepancies or modeling errors before additional complexity is added [17]. Furthermore, evolutionary studies have shown that there is currently enough debris in LEO that the number of inactive objects will rise even in a baseline scenario – providing an outcome to model policy and potential mitigations for future studies [25].

SEP 2 follows another common idea in evolutionary studies, which is the extrapolation of the current behavior: what would happen if we continued to operate as we are today. Note that this scenario reflects current behavior, rather than current trends, so that factors such as gradually increasing compliance with post-mission disposal guidelines will not be reflected. Rather, today’s compliance rates are continued for the duration of the scenario, along with current rates of explosions for rocket bodies and satellites and no ADR.

SEP 3 describes a scenario in which commercial and governmental interest in using space declines substantially. Some combination of easing political tensions, the development of cheaper substitutes (e.g., proliferated high-altitude balloons), and rising economic uncertainty reduces the importance of space development on national and international agendas. Though national security demand from large nations with developed space programs continues, the influx of new space actors and investments diminishes considerably. The significant reduction in space activity in this scenario is accompanied by medium (primary) or high (secondary) space-related environmental policies in the two sub-scenarios, with a heavier focus on maintaining existing operations than on ensuring future growth in space environment usage is sustainable.

SEP 4 and 5 consider two large variations in the sources of demand for space activity in LEO. SEP 4 is a scenario where there is a new space race or cold war and interest in LEO comes primarily from governments, military and defense organizations and market demand (i.e., for satellites serving non-governmental customers) is weaker. Strategic imperatives lead to low sustainability effort, as outcompeting rivals attains more national importance than long-term sustainability. SEP 5 is the opposite: a scenario in which commercially-driven development of LEO increases while government-driven investment decreases. In SEP 5, there is a steady increase in constellations and satellites, without a corresponding build-up in non-commercial demand. Here, two cases are considered with medium or high sustainability effort, with medium effort being considered the primary scenario.

Finally, SEP 6 was included as possible outcome where both market and non-market demand drive an extremely busy and operationally complex space environment. This interest drives increased sustainability behavior, with high sustainability effort being the primary case, and medium effort as the secondary case.

Table 2 Narrative Descriptions of the Space Environment Pathways

Space Environment Pathway (SEP)	Description
SEP 1: No Future Launch	A reference scenario where, from today, there are no further launches either from the commercial or governmental sectors. Existing satellites complete their missions then are deorbited subject to post-mission disposal success assumptions. Constellations and other missions are not replenished. Over the long term, debris continues to grow from explosions, fragmentations and inactive object collisions. Initially, there will be a drop in LEO objects that decay and re-enter Earth's atmosphere over time. Sustainable measures and policies are not practiced or developed.
SEP 2: Continuing Current Behaviors	The world follows a path that maintains current behaviors, with existing partially-deployed large constellations finishing their deployments and then replenishing over time, along with a continuation of recent historical launch traffic. Commercial interest in internet connectivity and lower launch costs drive the growth of satellites, with a few constellations satisfying market demand. There are no advancements to sustainability guidelines or practices beyond today's behaviors.
SEP 3: Space Winter	The space bubble pops - after a period of rapid growth, the demand for commercial and governmental space activities crashes. Easing political tensions and rising economic uncertainty diminishes the importance of space development on national and international agendas, resulting in limited future investments in the sector and new space launch. 3M: The drop in space traffic leads to limited interesting in improving sustainability effort beyond today's trends by most actors. Limited ADR begins to occur. 3H: Despite the low level of traffic, sustainability practices continue to increase with global and national institutions as well as operators working to improve sustainability practices to achieve long-term outcomes. Significant ADR begins to occur.
SEP 4: Strategic Rivalry	A rise in tensions between major space nations leads to significant government-backed demand, while predicted future commercial market demand for space services fails to materialize. Some LEO Earth observing, communications and Position, Navigation and Timing (PNT) constellations are deployed and maintained, but through government funding rather than commercial demand, with a focus on nationally-affiliated satellites. Urgent perceived self-interest among nations results in a low level of effort being applied towards space sustainability.
SEP 5: Commercially Driven Development	Non-market demand for space services declines, but the demand for commercial space-based activities such as internet, earth-observation imagery, and PNT steadily increases, leading to the expansion of multiple existing and new large LEO constellations. 5M: The complex operating environment spurs ongoing interest in sustainability, improving somewhat over current trends. Some ADR begins to occur. 5H: The complex operating environment spurs strong sustainability effort including greatly improved PMD, reduced explosions, and significant ADR

SEP 6: Intensive Space Demand	Driven by both rising international tensions and robust commercial market demands for satellite services, innovative technologies and reduced launch costs lead to growth in market and non-market demand for satellites. The space economy rapidly becomes the next trillion-dollar industry. LEO becomes an even busier environment, with a significant increase in both maneuverable and non-maneuverable objects, creating challenges for space traffic management and sustainability. 6M: Operational complexity drives interest in sustainability, improving on current trends. Limited ADR begins to occur. 6H: Sustainability policy and regulation increases due to increased complexity of operations, as well as additional government funding and pressure from the public. Significant ADR begins to occur

Table 3 Space Environment Pathway Scenarios

Scenario	Non-Market Demand for Space Services	Market Demand for Space Services	Level of Sustainability Effort	Notes
SEP1: No Future Launch	None	None	Current	Used primarily for model vs. model comparison
SEP 2: Continuing Current Behaviors	Current	Current	Current	Current behaviors (NOT trends) continue indefinitely
SEP 3 **M**/H: Space Winter	Low	Low	**Med (primary)** High (secondary)	Anticipated additional constellation demand fails to materialize, continuation of existing constellations into the future
SEP 4: Strategic Rivalry	High	Low	Low	International tensions lead to significant government-backed non-market demand, with backsliding on sustainability effort. Predicted increased commercial demand for satellite services fails to materialize
SEP 5 **M**/H: Commercial-driven Development	Low	High	**Med (primary)** High (secondary)	Significant commercial demands drives expansion of space traffic
SEP 6 M/**H**: Intensive Space Demand	High	High	Med (secondary) **High (primary)**	A combination of international tensions and validation of commercial business cases leads to doubly intensive space demand

4. Conclusions and Future Work

As seen in other environmental modeling disciplines, community-agreed reference scenarios have the potential to provide multiple benefits. They reduce barriers to entry for the development, verification, and validation of new modeling approaches and improve comparability between modeling methods and tools. They also help promote better integrated modeling across issue areas and disciplines—for instance, unifying assumptions (and potentially models) for assessing multiple types of negative externalities or integrating economic decision-making and environmental modeling. Reference scenarios can additionally facilitate improved public communication about likely future behaviors subject to different societal choices and support the development of necessary workflows for adaptive, or other model-informed, space environment management strategies.

This paper presents a preliminary set of six proposed reference scenarios for community feedback and discussion. The scenarios are intended to be distinct while broadly spanning the range of plausible futures for the space environment. Each proposed reference scenario is framed with a narrative context and supported by associated modeling inputs which will be released alongside the scenarios. The process used to develop these scenario concepts was validated with a conference presentation to experts, literature review, and review by strategic foresight experts.

Key inputs include the initial population model, future launch model, atmospheric model and inputs, and operator behavioral assumptions. The focus of this paper is on the reference scenarios themselves and the high-level choices that feed into them. The chosen methods are intended to support a wide variety of potential approaches to space environment modeling, be transparent and defensible in their assumptions and choices, and avoid a reliance on controlled information. The workflow to develop these inputs is being designed to sustainably support a periodic update cadence.

The project team hopes to continue to improve the scenario methodology over future iterations, including transitioning the non-constellation satellite model to an endogenous function of economic and environmental factors (building on the approach by Rao et al. [41]), rather than relying purely on recent historical launch traffic. In many cases we have had to apply coarse assumptions for object properties, particular satellite mass and cross-sectional area for future systems. We also hope to improve the quality of this data and reduce the importance of assumptions by gathering additional inputs as they become available, including from the designs of such satellites and constellations.

Initial development of the SEPs proceeded as a shared project team but outside the aegis of a formal governance organization. We believe that this choice was prudent to allow us to develop a preliminary proposal for community feedback. That being said, we recognize that broader community feedback, contributions, and ultimate adoption, particularly at an international level, would benefit from and may require a more formalized process and institutional home. One putative organizational home would be the Inter-Agency Space Debris Coordination Committee (IADC), which is composed of representatives from a select set of national space agencies, with access to high quality data and considerable experience and expertise. Particularly if there was an IADC structure that could support broader community involvement beyond national space agencies, it could be an ideal institutional home for the continued development and stewardship of the SEPs.

Future work will simulate each reference scenarios using the provided modeling inputs and different evolutionary space environment models to help validate the project concept and design choices. After the scenario designs are finalized, a set of modeling outputs for each scenario will be generated to support secondary modeling and derivative analysis.

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Appendix A.

Table 4: Levels of Sustainability Effort

Sustainability Category	Current (Current behavior)	Low (Current trend)	Medium (Improving trend)	High (Best practices)
Collision Avoidance	No Active Man. Collision Avoidance (COLA) failures Probability of Collision (Pc) Threshold: 1e-4 Post-Maneuver Risk Mitigation Reduction: 1.5 Order of Magnitude (OoM)	No Active Man. COLA failures Pc Threshold: 1e-4 Post-Maneuver Risk Mitigation Reduction: 1.5 OoM	No Active Man. COLA failures Pc Threshold: 1e-5 Post-Maneuver Risk Mitigation Reduction: 1.5 OoM New sats > 400 km can do COLA [42, pp. pp. 12, sec. 5.c] SSC Rules of the Road [42, pp. 15-17, sec. 8]	No Active Man. COLA failures Pc Threshold: 1e-5 Post-Maneuver Risk Mitigation Reduction: 1.5 OoM New sats > 400 km can do COLA [42, pp. pp. 12, sec. 5.c] SSC Rules of the Road [42, pp. 15-17, sec. 8] COLA if >5 year post-failure lifetime, in constellation, or RPO [43, p. 5.3.2.2.c]
Spacecraft Shielding	1 cm lethal	1 cm lethal	1 cm lethal	1 cm lethal
Explosions (lifetime rate, non-passivated objects)	2.8% of Rocket Bodies (R/B) [44] 0.35% of Satellites [44]	2% of R/B 0.3% of Satellites	1.5% of R/B 0.2% of Satellites	1% of R/B 0.1% of Satellites
Trackable Object Size (char. length)	10 cm	10 cm	5 cm All sats trackable	5 cm All sats trackable
Post-Mission Disposal (PMD)	Compliance Time Limit: 25 years Defence/Civil: 65% [33, p. 93] Commercial/Amateur/Cubesat: 95% [33, p. 102] R/B: 90% [33, pp. 98-100]	Compliance Time Limit: 25 years for non-constellation traffic 5 years for constellations* Defence/Civil: 70% Commercial/Amateur/Cubesat: 98% [33, p. 102]	Compliance Time Limit: 5 years* [42, pp. 15, sec. 7.i] General PMD: 90% [43, p. 5.4.1.1a] Large LEO Constellations (LLCs) use check-out altitudes [43, p. 5.4.2.4]	LLCs use check-out altitudes, checkout alt. lifetime <= 5 years [43, p. 5.4.2.4a] LLC LEO PMD: 99% w/in 5 years* LEO PMD w/in 5 years: 95% [42, pp. 12, sec. 5.a] LEO PMD w/in 25 years: 99% [42, pp. 12, sec. 5.a]

		R/B: 90% [33, pp. 98-100]	Commercial/Amateur/Cubesat: 98% [33, p. 102] R/B: 90% [42, pp. 11, sec. 3.f]	R/B: 98% [43, p. 5.4.1.1a]
ADR (2030 onwards)	None	5 large objects per year	10 large objects per year	15 large objects per year

*Unless operator has committed to better.