Space Environment Pathways (SEPs) Reference Scenarios Data File Description Document (Version 0.2.0)

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# Document Purpose

The purpose of this document is to describe the data contained with the Space Environment Pathways reference scenario object files and provide explanation for methods and choices made, as well as details on how to interpret the data. This document corresponds to the preliminary draft release of the reference scenarios. This release is intended to provide data products and information about their format for community feedback. We invite comment on the products, including the selected scenarios, the technical methodologies used to compile them, the provided data fields, usability of the products, and any other aspects that stakeholders wish to share. A separate document will provide a list of targeted questions to inform feedback, but we welcome all comments, criticisms, suggestions, and corrections. It is hoped that these inputs will gradually evolve to become a widely used consensus community product.

These data products are intended to support a wide range of space environment modeling applications including full-scale Monte Carlo evolutionary space environment models, simplified lower-fidelity source-sink and similar models, and space traffic coordination simulations. Where indicated, there is future work planned to make improvements to the scenarios and add more detail. Some fields are placeholders at this time until that information is added in future releases.

This document will reference key passages from Lifson, et al [1] , and will expand on the specifics of the data file contents. Various updates have been made between the publication of Lifson et al. [2] (which discusses the motivation for a set of reference scenarios), Lifson et al. [1] (which describes the methodology), and this document. Where content in the documents conflicts, information in this document (or information in the later publication) should be considered authoritative. A updated, unified paper describing the final methodology will accompany the official release of Version 1.0.0 of the SEPs.

# Motivation for the SEP Reference Scenarios

These scenarios are intended to provide a resource to the space environment modeling community as a free, openly available set of inputs to represent plausible futures for the space environment. They are intended to address the fact that compiling such inputs is tedious and time-consuming, often requires access to non-public data sets, and demands considerable subject matter expertise. While the full motivation for this project is described in more depth in Lifson et al. [2], it is hoped that a set of public consensus modeling inputs can help accelerate the development of greater consensus on expected trends for the future space environment and the best actions to help manage this increasing level of traffic.

The scenarios will be periodically updated to reflect changes to the space environment, new systems that have been deployed, and revised understandings of likely future systems and trends.

# How to use the SEP Reference Scenarios

The SEP design team is unable to predict the future. The SEP reference scenarios do not attempt to forecast the future of the space environment over the next 200 years. Doing so would be an almost impossible task. Rather, they seek to provide a set of reasonable, expert-informed bounds for plausible evolutions of space activity planned over the next approximately 20 years and continues those trends and fully deployed traffic levels continuously for the next 200 years. This timescale is chosen because it represents a common timeframe for evolutionary space environment modeling in order to capture effects that take can take decades to manifest due to the relatively slow speed at which long-term space environmental effects tend to manifest. The scenarios are thus intended to be suited to assessing environmental responses to plausible levels of traffic and behaviors.

# Acronyms

|  |  |
| --- | --- |
| ADEPT | Aerospace Debris Environment Projection Tool |
| ADR | Active Debris Removal |
| ALT | Altitude |
| ARGP | Argument of Perigee |
| C2R | Control-To-Reentry |
| CA | Collision Avoidance |
| CLEF | Constellation Likelihood Evaluation Framework |
| CMLS | Compilated Master Launch Schedule |
| COLA | Collision Avoidance |
| CSA | Cross-Sectional Area |
| DO | Disposal Option |
| ECC | Eccentricity |
| ECI | Earth-Centered Inertial Coordinate Frame |
| FCC | Federal Communications Commission |
| FLM | Future Launch Model |
| GEO | Geosynchronous Orbit |
| IAC | International Astronautical Congress |
| IADC | Inter-Agency Space Debris Coordination Committee |
| INC | Inclination |
| IPM | Initial Population Model |
| ITU | International Telecommunication Union |
| LCOLA | Launch Collision Avoidance |
| LEO | Low Earth Orbit |
| LLC | Large LEO Constellation |
| MA | Mean Anomaly |
| MEO | Medium Earth Orbit |
| MJD | Modified Julian Date |
| MRO | Mission-Related Object |
| NORAD | North American Air Defense Command |
| OoM | Order of Magnitude |
| Pc | Probability of Collision |
| PMD | Post-Mission Disposal |
| RAAN | Right Ascension of the Ascending Node |
| R/B | Rocket Body |
| RIC | Radial, In-Track, Cross-Track Coordinate Frame |
| S/C | Spacecraft |
| SEP | Space Environment Pathway |
| SMA | Semi-Major Axis |
| SSA | Space Situational Awareness |
| SSC | Space Safety Coalition |
| TCA | Time of Close Approach |

# List of Files

The reference scenarios are distributed into a set of 9 comma-delimited \*.csv files that all start with “ref\_scen\_”. The Space Environment Pathway (SEP) scenario corresponding to each file is the end of the file name, as shown in Table 1.

Table 1. Files and their associated scenarios

|  |  |
| --- | --- |
| Filename | Scenario |
| ref\_scen\_SEP1.csv | SEP1: No Future Launch |
| ref\_scen\_SEP2.csv | SEP 2: Continuing Current Behaviours |
| ref\_scen\_SEP3M.csv | SEP 3 M: Space Winter (**M**edium Sustainability Effort) |
| ref\_scen\_SEP3H.csv | SEP 3 H: Space Winter (**H**igh Sustainability Effort) |
| ref\_scen\_SEP4.csv | SEP 4: Strategic Rivalry |
| ref\_scen\_SEP5M.csv | SEP 5 M: Commercial-driven Development (**M**edium Sustainability Effort) |
| ref\_scen\_SEP5H.csv | SEP 5 H: Commercial-driven Development (**H**igh Sustainability Effort) |
| ref\_scen\_SEP6M.csv | SEP 6 M: Intensive Space Demand (**M**edium Sustainability Effort) |
| ref\_scen\_SEP6H.csv | SEP 6 H: Intensive Space Demand (**H**igh Sustainability Effort) |

The sizes of these files varies significantly, as the low traffic scenarios such as “No Future Launch” have very few objects relative to the high traffic scenarios such as “Intensive Space Demand”, which projects a very large level of future large constellation traffic. Note that a specific methodology relying on a rubric and accompanying point system to assess constellations for inclusion was described in Lifson et al. [1] but was heavily adapted in this data release to produce a better spread of traffic across the six scenarios.

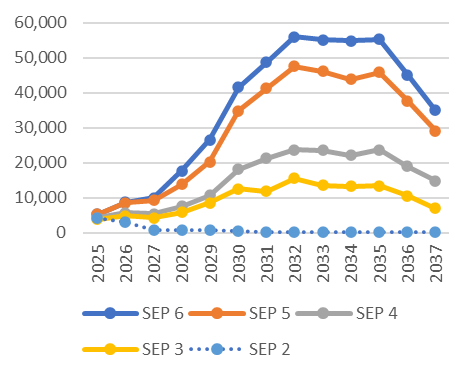


Figure 1. Estimated New Satellites Deployed by Year (IAC paper [1] Figure 7)

Two additional files are provided but may or may not be required for your use case. These are primarily of relevance to people 1) using space traffic coordination simulators or other models that require constellation RAAN and Mean/True Anomaly data to actively maintain constellation geometry, a level of fidelity not maintained in the reference scenario files, as described in the “Mission Phase Modeling” section of this document; 2) who simply need a listing of large constellation shells as a function of altitude, or 3) who wish to engage with detailed aspects of the Constellation Likelihood Evaluation Framework (CLEF) ratings. **CLEF ratings are a high-level quantification of objective rubric-defined factors that can be evaluated for a particular operator organization based on open-source information concerning actions taken by an entity to date and do not represent an Aerospace assessment of the credibility, economic viable, or future prospects of any assessed constellation or organization. CLEF ratings should not be considered investment advice.**

The excel file “ITU\_registrations\_2024\_08\_28 with Evals.xlsx” contains tabs for evaluated constellations. The “Summary” tab contains a list of filings derived from ITU filings. The “Due Dilligence Data” tab contains information about satellite launches used to bring filings into use. “Orbit Data” contains de-duplicated information about filings distributed across various orbital planes. “Shell Data” groups this information into specific shells. The “README” tab contains information regarding field mapping and explanations. “EMAC Evals” contains per-filing CLEF ratings. These ratings and processing steps follow the method in Lifson et al. [1]. The file “System Deployment Status Notes for Evals 20240828.docx” contains notes and sources corresponding to the evaluations in the “EMAC Evals” tab of the spreadsheet document.

# Object Schema Description

Table 2 below is a comprehensive listing of the columns contained within each file. The “Col” count number starts with 0 in the far left column and counts up to 58 in the far right column. Some more details about the object fields are provided after the table, but first a few quick notes regarding the file schema and its contents:

* Boolean (True/False) flags are represented by integer values of 1 or 0, respectively, to simplify data storage
* Fields highlighted in red are currently considered to be secondary or optional data fields. In this release, most of these will be blank. All remaining fields should be populated with a value.
* The data fields in future releases are subject to change pending feedback from the community and further development of the models.

Table 2. Reference Scenarios Object Fields Schema

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | | Col | Name | Type | Unit | Notes |
| Identifying Information | | 0 | Unique ID | int/str |  | Unique 18-digit ID |
| 1 | Mission Phase Desc | str |  | Objects can have multiple phases with different characteristics, like ascent/commissioning/ops/disposal/etc. |
| 2 | Mission Phase | int |  | An integer value associated with the mission phase 0 = ascent 1 = commissioning 2 = operations 3 = disposal (successful) 4 = debris/derelict (including failed disposal) |
| 3 | Parent ID | int/str |  | Debris fragments or other derivative objects that are whole or part of parent object. N/A for original object. |
| 4 | Operating Agency | str |  | Name of operator, which may have multiple constellations |
| 5 | Constellation Name | str |  | Unique constellation name to distinguish from other that an operator may own |
| 6 | Constellation Shell ID | int/str |  | Operators often have multiple constellation shells - integer value to identify, in average altitude order |
| Physical Characteristics | | 7 | Mass | float | kg |  |
| 8 | CSA | float | m^2 | Average cross-sectional area |
| 9 | Diameter\_LCOLA | float | m | The maximum dimension (used for LCOLA)  d\_lcola = sqrt(3)\*A = 1.732\*A for cube of side A |
| 10 | Diameter\_Tumbling | float | m | The diameter based on tumbling cross sectional area  d\_tumb = sqrt(6/pi)\*A = 1.382\*A for cube of side A |
| 11 | Diameter\_Characteristic | float | m | NASA’s characteristic diameter  d\_char = 1.539\*A for cube of side A |
| 12 | Object Type | int |  | 1 = Rocket bodies  2 = Payloads  3 = Debris  4 = MROs (Mission-Related Objects)  5 = Crewed  6 = NaK, slag, liner, ejecta, etc. |
| 13 | Length | float | m | Longest rectangular dimension |
| 14 | Width | float | m | Intermediate rectangular dimension |
| 15 | Depth | float | m | Shortest rectangular dimension |
| Behaviors | | 16 | Active | int |  | Satellite is active/operational or not (not necessarily the same as maneuverable) 0=False  1=True |
| 17 | Maneuverable | int |  | Operational satellites capable of COLA manevuers. 0=False  1=True |
| 18 | Stationkeeping | int |  | Assumes Active/Maneuverable 0 = none  1 = GEO E-W stkp  2 = GEO E-W & N-S stkp  3 = LEO maintain altitude  4 = Reference Control Box |
| 19 | Stationkeeping Box Radial | float | km | RIC Stationkeeping control box (cube relative to the reference trajectory) radial component |
| 20 | Stationkeeping Box In-Track | float | km | RIC Stationkeeping control box (cube relative to the reference trajectory) in-track component |
| 21 | Stationkeeping Box Cross-Track | float | km | RIC Stationkeeping control box (cube relative to the reference trajectory) cross-track component |
| 22 | Disposal Type | int |  | 0 = Undefined (Not a disposed object) 1 = Successful R/B disposal 2 = Failed R/B disposal 3 = Successful S/C disposal 4 = Failed during ascent S/C disposal 5 = Failed in orbit S/C disposal 6 = Failed during disposal S/C disposal 7 = Undefined (for derelict initial population objects) |
| 23 | Control to Reentry  (C2R) | int |  | Operator maintains control of satellites during disposal decay phase to perform COLA. 0=False  1=True |
| 24 | Pc threshold | float |  | If Maneuverable = True, the collision probability threshold to perform a maneuver (ex: 1e-4) |
| 25 | Pc goal | float |  | If Maneuverable = True, goal for post-maneuver acceptable Pc (ex: 1e-6) |
| 26 | Maneuver  Commit Point | int/float | hours | If Maneuverable = True, Minimum time before TCA at which a maneuver is performed or a preferred time before TCA to perform the maneuver. |
| 27 | Max maneuver dV | float | m/s | If Maneuverable = True, Pc reduction subject to a certain maximum deltaV |
| 28 | In-track dV Flag | int |  | If Maneuverable = True, whether to constrain maneuvers to only be along velocity vector 0=False  1=True |
| Epoch(s) | Phase Start | 29 | Year | int | year | Initial epoch of the phase this object is in (launch, start of ops, disposal, etc.) |
| 30 | Month | int | month |
| 31 | Day | int | day |
| 32 | Hour | int | hours |
| 33 | Minute | int | minute |
| 34 | Second | float | second |
| 35 | MJD | float |  | Modified Julian Date |
| Phase End | 36 | Year | int | year | Final epoch of the phase this object is in |
| 37 | Month | int | month |
| 38 | Day | int | day |
| 39 | Hour | int | hours |
| 40 | Minute | int | minute |
| 41 | Second | float | second |
| 42 | MJD | float |  | Modified Julian Date |
| Orbit State Epoch | 43 | Year | int | year | Instantaneous epoch that is associated with the orbit state data that follows. |
| 44 | Month | int | month |
| 45 | Day | int | day |
| 46 | Hour | int | hours |
| 47 | Minute | int | minute |
| 48 | Second | float | second |
| 49 | MJD | float |  | Modified Julian Date |
| Orbit State at Epoch | Classical Orbital Elements | 50 | SMA | float | km | Semi-major Axis |
| 51 | ECC | float |  | Eccentricity |
| 52 | INC | float | deg | Inclination |
| 53 | RAAN | float | deg | Right Ascension of the Ascending Node |
| 54 | ARGP | float | deg | Argument of Perigee |
| 55 | MA | float | deg | Mean Anomaly |
| ECI Cartesian Coordinates | 56 | ECI\_X | float | km | ECI X-coordinate position |
| 57 | ECI\_Y | float | km | ECI Y-coordinate position |
| 58 | ECI\_Z | float | km | ECI Z-coordinate position |
| 59 | ECI\_Vx | float | km/s | ECI X-coordinate velocity |
| 60 | ECI\_Vy | float | km/s | ECI Y-coordinate velocity |
| 61 | ECI\_Vz | float | km/s | ECI Z-coordinate velocity |

## Additional Object Fields Information

Additional information on the object fields is presented below where appropriate. Each heading below starts with the zero-indexed column number. Additional information may be added for clarification based on community feedback.

### 0. Unique ID

The 18-digit ID is a format developed for the Aerospace Debris Environment Projection Tool (ADEPT) [2] , and is being repurposed out of convenience for this product. Details on how to interpreted the digits of the ID are presented in the “Object ID Interpretation” section below.

### 1. Mission Phase Desc

Mission phases are currently limited to operations, disposal, and debris/derelict in this version. The plan for future versions is to include additional phases such as ascent, commissioning, etc., depending on how relevant these are determined to be for long-term modeling.

### 2. Mission Phase

See Mission Phase Desc.

### 3. Parent ID

There are two main ways the parent ID is used for an object. The first is due to the way different mission phases are handled. Rather than trying to account for multiple mission phases for a single object on a single ID, a different row of object data is provided for each mission phase, and therefor a unique ID. The parent ID is the way to link objects together to describe the full lifecycle of an object as it moves through different phases. A disposed satellite would have a parent ID that links it to the object entry for when it was an operational satellite. The same will be done for linking the operational satellite back to ascent, commissioning, and any other mission phase type that is added in future versions of these scenarios.

For a few examples:

* The Future Launch Model (FLM) GEO successfully disposed satellite with object ID: 000002610000137344 has the parent ID: 000002010000037344, the operational GEO satellite prior to disposal.
* The FLM LEO successfully disposed satellite with object ID: 000001418010017859 has the parent ID: 000001018000017859, the operational LEO satellite prior to disposal.
* The failed LLC disposal satellite with object ID: 000007919261310715 has the parent ID: 000007019260310715, the operational LLC satellite prior to disposal.

The other main reason for the parent ID is to link breakup debris back to the parent object that either exploded or collided with another object. This will show up in future versions of the scenarios.

### 4. Operating Agency

When available, the operating agency of the satellite is given. This is exclusively done for future constellations in this version of the reference scenarios. Future versions may include additional operator data, particularly where requested by the user community.

### 5. Constellation Name

A name is given for constellation objects in the future constellation model.

### 6. Constellation Shell ID

In general, constellations have multiple shells of satellites, each with a unique common altitude and inclination. To differentiate them for a specific constellation, each is given an integer value. This integer value is roughly increasing with altitude, but that isn’t always the case. Those details are included in the initial state orbital elements of this data schema.

### 7,8. Mass & CSA

Mass and Cross-sectional Area (CSA) for Initial Population Model (IPM) objects are inherited directly from an internal object database based on publicly available data, and for future objects are based on models of constellation objects and the background traffic to match recent catalog traffic.

### 9,10,11. Diameter

The diameter also comes from the same data sources as mass and CSA, but there are three diameter types captured here, which all have different uses and may be preferable by different users. The LCOLA (Launch Collision Avoidance) diameter is used for LCOLA risk analysis and is the most conservative (largest) value. Tumbling diameter and NASA’s characteristic diameter are also provided for use in other types of analysis.

### 12. Object Type

The first four values for object type come from definitions used in the Inter-Agency Space Debris Coordination Committee (IADC). A few more types are added to identify objects in more detail. More object types can be added pending community feedback.

### 13,14,15. Dimensions

Length, width, and depth dimension columns are included in the object data schema as a placeholder but not currently populated as this level of detail isn’t readily available and convenient to include at this time.

### 16,17,18. Active, Maneuverable, & Stationkeeping

The determination for active, maneuverable, and stationkeeping of catalog objects is done using as much open-source information as possible but should not be taken as truth for objects on orbit. Regardless, these models are meant to be representative of the current on-orbit population, not a truth model. NORAD IDs are also not used for these objects to avoid associating the modeled objects exactly to real-world objects.

### 19,20,21. Stationkeeping Box RIC

Additional variables to define a stationkeeping box are included as placeholders. Community feedback is requested to help determine what specifications here would be most valuable.

### 22. Disposal Type

The disposal type flag is only valid for disposed satellites and rocket bodies and identifies either the successful disposal type or the phase at which a failure occurs.

### 23. Control to Reentry (C2R)

C2R is the mitigation approach of maintaining active control and maneuverability of a satellite during the orbit decay phase post mission disposal, allowing for COLA maneuvers to prevent collisions. In practice, this concept is already in use by certain LLC operators, and therefor C2R is applied to those disposed satellites in the future launch model. This option only applied to successfully disposed satellite, as failures would imply loss of function or control of the satellite. This option may be applied to more operators in subsequent versions of these scenarios.

### 24,25. Probability of Collision (Pc) Threshold and Goal

The Pc values here are applied as default values to all maneuverable satellites depending on the specifications of the scenario. If actual operator values are made publicly available, they can be substituted in for subsequent versions.

### 26,27,28. Maneuver Commit Point, Max Maneuver dV, & In-track dV Flag

These operator behavior variables are included as a placeholder in this version. Community feedback is requested for reasonable default values and actual operator values where available.

### 29-49. Epochs

Three epochs are provided for each object.

The phase start epoch is when the current phase of this object actual begins. For IPM objects, the orbit state epoch is always at or close to concurrent with the initial epoch of the scenario, which is in 2024 for this version. The phase start epoch may be many years in the past since these are modeled after catalog objects that are launched well before the initial scenario epoch. For FLM objects, the phase start epoch is concurrent with the orbit state epoch.

The phase end epoch is a fixed duration after the phase start epoch for operational satellites, representing the operational lifetime of the satellite. For disposed or derelict objects, the phase end epoch is set to the end of the scenario (200 years into the future). These objects must be propagated using gravitational models that include sufficient perturbations and an atmospheric model to determine if the object reenters the atmosphere prior to the scenario end epoch.

The orbit state epoch is associated with the initial state values that follow. It is identical to the phase start epoch in many cases.

### 50-55. Classical Orbital Elements

This is the original format in which object initial states are generated. Note that the orbit elements as presented are meant to be used in statistical analyses and do not necessarily reflect the actual position of real objects or maintain appropriate spacing in RAAN and MA consistent with an operational constellation. Analyses such as linkage and coverage should use high fidelity models and inputs as appropriate for the spacecraft system being considered.

### 56-61. ECI Cartesian Coordinates

For convenience, all the classical orbital elements are converted to Cartesian coordinates.

# Methods, Assumptions, and Caveats

The paper presented at IAC [1] provides details on how the various population models within the reference scenarios were developed, and where the data originates from. Unless otherwise noted, the reader should assume the data within these files comes from the sources cited in that paper. In particular, satellite physical characteristics, epochs and ephemeris, and constellation configuration data comes from those sources. The following sections will add more clarification on how fields were populated and what differences to expect in the various scenario files. The epoch of the reference scenarios is July 4, 2024.

***Physical Parameters of Objects***

The physical parameters of the satellites and rocket bodies in the files are based on publicly available information. These are maintained in an Aerospace database similar to ESA’s DISCOS. The Aerospace database contains the shapes, dimensions, and masses of individual objects, and are classified into three general groups: rocket bodies (upper stages, kick motors, etc.), simple satellites (those without solar panels or significant antennas), and complex satellites (those with solar panels and/or significant antennas). Rocket bodies are assumed to be simple cylinders with diameter, length, and mass maintained. Simple satellites are maintained as geometric shapes with shapes varying as cubes, boxes, cylinders, spheres, or other simple geometric solids. For complex satellites, the areas of the solar panels and antennas are retained along with the type of antenna (either comm or SAR). Also, the overall dimensions of the box circumscribing the complex satellite is kept.

For fragmentation debris, the mass, area, and size estimates are handled in a separate manner. Since these objects are created on-orbit via collisions and explosions, there is no way to know the dimensions of the fragments nor the mass. Instead, the radar cross-section values present on the SATCAT files provided through [Space-Track.org](http://space-track.org/) are utilized to compute an average RCS value along with a standard deviation. From this, a collision radius useful for both operational COLA and for environment modeling can be computed. To gain a reasonable value for the mass, historical events have been examined to establish a relation between the average RCS and the observed decay of debris fragments (i.e., area-to-mass ratio) that can be used to estimate the mass for new fragments.

DISCLAIMER: There are over 26,000 intact objects in the database (not including the fragmentation debris). For some of these objects, especially older and foreign satellites and rocket bodies, actual values for the physical parameters are not available. In these cases, an estimate has been performed sometimes based upon simply a picture of the satellite, or that the satellite is being deployed by a certain upper stage that has a known fairing size, or that the satellite is carried aboard a launch vehicle with a certain mass capability. The values in the database should NOT be taken as indicative of the true values, but as reasonable estimates usable for modeling purposes.

## Future Launch Traffic Levels

The references scenarios are broken down into the six Space Environment Pathways (SEP) shown in Table 3. Each of these SEPs is defined by traffic levels and operator behaviors governed by the non-market demand, market demand, and level of sustainability effort columns shown in that table. Note that SEPs 3, 5, and 6 have both a primary and secondary level of sustainability effort, where the primary is meant to be the baseline assumption for that scenario, and the secondary is included as an optional assumption. See [1] for more details. Each of the files provided was developed with its unique combination of options. As shown previously in the list of files, there are in fact nine total scenario files because three of SEPs have primary and secondary levels of sustainability effort.

Table 3. Space Environment Pathway Scenarios (IAC paper [1] Table 8)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 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 Behaviours | Current | Current | Current | Current behaviours (NOT trends) continue indefinitely |
| SEP 3 M/H:  Space Winter | Low | Low | **Medium (primary)** | Anticipated additional constellation demand fails to materialize, continuation of existing constellations into the future |
| High (secondary) |
| 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 | **Medium**  **(primary)** | Significant commercial demands drives expansion of space traffic. |
| High  (secondary) |
| SEP 6 M/H:  Intensive Space Demand | High | High | Medium  (secondary) | A combination of geopolitical tensions and validation of commercial business cases leads to doubly intensive space demand |
| **High**  **(primary)** |

The Market Demand column describes different levels of traffic for both future large constellations and background traffic. The background traffic can be thought of as a continuation of recent defense, civil, commercial, research, scientific, etc. traffic that does not fall into the category of large constellations. Table 4 indicates the constellation and background traffic levels that correspond to the market demand categories.

The multipliers in the background traffic column are factors used to duplicate that recent traffic into the future. Individual files for these background traffic levels were generated separately and imported into the reference scenarios according to Table 3.

Table 4. Market Demand for Space Services (IAC paper [1] Table 3)

|  |  |  |
| --- | --- | --- |
|  | Future Large Constellations | Background Traffic |
| Current | Existing Large LEO Constellations (LLCs) finish deployment | 1x |
| Low | Only “high” constellations | 1.5x |
| Medium | “high” and “medium” constellations | 2x |
| High | “high”, “medium”, and “low/plausible” constellations | 3x |

The future large constellation traffic populations come from a series of Aerospace-produced Compilated Master Launch Schedule (CMLS) populations that vary the amount of future constellation traffic significantly. Table 5 is a listing of the CMLS populations that correspond to the SEP traffic levels in those SEPs. Numerous adjustments were made to the process of developing the launch scenarios for each scenario relative to the process described in Reference [1]. It was determined that the method described in Reference [1] alone produced insufficient differentiation between scenarios and potentially overestimated traffic in most cases. Certain constellations that are assessed to have state-backing are treated explicitly in SEP4 to reflect strategic rivalry-related considerations, but the point system augmentation approach in Reference [1] is not employed.

Table 5. Mapping of Space Environment Pathway to Compilated Master Launch Schedule (CMLS)

|  |  |
| --- | --- |
| Space Environment Pathway | # Future Ops (Total) |
| SEP6 | 460K |
| SEP5 | 385K |
| SEP4 | 210K |
| SEP3 | 126K |
| SEP2 | 13K |
| SEP1 | 0K |

Beyond that, there are 5 levels of traffic with the names given in the table, which combine the market and non-market demand inputs given to those pathways. Also shown is a rough number of future large constellation operational satellites that are maintained in those populations. The remaining SEPs are described in reverse order, beginning with the largest projection and then describing how this projection is reduced in the smaller cases.

SEP6 uses an optimistic projection that includes approximately 460,000 satellites sourced from FCC or ITU filings, with CLEF ratings of high, medium, or low. The CLEF methodology is described in Reference [1] and assesses 1) Constellation Deployment Status, 2) Financial Resources/Stability, 3) Legal & Regulatory Status, and 4) Business History for the constellation operator. These satellites are distributed across 349 unique orbital shells, i.e., each having unique combination of inclination and altitude.

To generate the demand for this project, we used prior Aerospace analysis of existing large constellation FCC filings and added ITU data focused primarily on shells having 1,000 or more satellites. Our initial analysis of ITU filings identified approximately 2.2 million potential satellites, which was deduplicated to ~1.6 million potential satellites, following the methodology in Reference [1]. This was still such a large number, that we decided to focus our efforts mainly on filings having 1,000 or more satellites in a shell. We rated these constellations using the Constellation Likelihood Evaluation Framework (CLEF) methodology from Reference [1] which assesses Constellation Deployment Status, Financial Resources/Stability, Legal & Regulatory Status, and Business History for the constellation operator. We then attempted to match satellites with current and forecasted available launch vehicles. Based on this analysis, we determined that approximately 530,000 satellites, including satellites already accounted for in FCC filings, needed to be considered in our forecast. However, due to time and resource constraints, the optimistic scenario features ~460,000 satellites and excludes approximately 74,000 satellites from constellations larger than 1,000 satellites per shell that would otherwise qualify. Given considerable uncertainty about future large constellation traffic, it is not clear that the comprehensive approach would yield a higher fidelity forecast than the version employed in the draft data release.

The most notable ITU filing with an assessed high CLEF total and greater than 1,000 satellites that is missing from the forecast is OneWeb’s L7A filing of 4,608 satellites. Other notable ITU filings with assessed medium CLEF totals and greater than 1,000 satellites that are missing from the forecast include:

* Spire Global’s LEMUR-2-3 filing of 1,792 satellites
* Telesat’s TELSTAR-LEO-V-2 filing of 1,671 satellites
* Eutelsat’s F-SAT-NG-13 filing of 1,728 satellites
* Eutelsat’s F-SAT-NG-16 filing of 1,336 satellites
* Eutelsat’s F-SAT-NG-11 filing of 1,107 satellites
* HISPASAT’s HISPASAT-LEO-BB-1 filing of 1,600 satellites
* HISPASAT’s HISPASAT-LEO-NB filing of 1,160 satellites
* LYNK Global’s USASAT-NGSO-10 filing of 5,110 satellites
* China Transport Telecom & Information Center’s MOTS 1 filing of 4,366 satellites
* China Transport Telecom & Information Center’s MOTS 2 filing of 4,510 satellites
* China Satellite Network Group’s CSN-L7 filing of 3,600 satellites
* China Satellite Network Group’s NT-1 filing of 3,600 satellites
* Airbus Defense & Space’s AST-NG-NC-CL3 filing of 2,784 satellites
* Airbus Defense & Space’s VHF-ADS filing of 2,252 satellites
* Hughes Network System’s D-LEG1-1 filing of 1,385 satellites
* Hughes Network System’s D-LEG1-2 filing of 1,694 satellites
* Hughes Network System’s D-LEG1-3 filing of 1,385satellites
* Hughes Network System’s ENGSO LEO-2 filing of 1,440 satellites

SEP5 includes those satellites that had a CLEF value of medium or high but not low.

SEP4 reduces the number of satellites being launched by assuming that most constellations would only partially deploy. SEP4 assumed roughly about half of the full size of the constellations, with some exceptions for constellation already being deployed, or with known launch contracts. We also fully deployed selected constellations for nation state actors such as Russia and China.

SEP3 further reduces the partially deployed constellations further to around 25 percent.

SEP2 uses a pessimistic traffic projection that essentially includes only constellations that are already being deployed or have confirmed launch contracts. We also included selected Russian and Chinese constellations in SEP2.

SEP1 is the “No Future Launch” pathway, and therefor contains no future launch traffic, indicated by Ok in Table 5.

## Mission Phase Modeling

The reference scenario data schema approaches different mission phases by using a different entry for each phase of a single mission. If a mission has five distinct mission phases in different orbits with different behavioral assumptions, then there will be five unique entries in the data files each with a unique object ID.

Presently, **all mission phases prior to satellite operations, which would include launch, ascent, commissioning, etc., are not modeled, and instead objects are added instantaneously at the start of mission operations**. Constellation satellites are distributed in mean anomaly and right ascension of the ascending node, but are currently NOT maintained in operational orbital planes. For applications requiring precise modeling of constellation spacecraft, these orbits should be derived directly from FCC and/or ITU filings or other sources. Depending on the type of launch vehicle assumed, upper stage rocket body hardware may also be added to the population at the time of the launch in a disposal orbit.

If enough operator detail is provided, the pre-operations phases may be added in future iterations of the reference scenarios, each phase with its own entry into the data file. A single mission object is then defined by linking each phase by the parent ID column. For example, a single constellation satellite may be deployed into a staging orbit below the operational orbit to perform checkout and commissioning for 30 days. This would be an object entry with start and end epoch separated by 30 days, and all assumptions about behaviors would be specified for that phase. Once the satellite moves to its operational orbit, it is replaced with a new entry with a new ID, but linked back to the previous phase using the parent ID field. This method would continue into any other phases the satellite may have, including alternate operations and post-mission disposal.

It is assumed the transition between these phases is instantaneous, and the only options for the trajectory during each phase is either to do stationkeeping or simply drift along with perturbations and drag. Future versions could include specifications for low transfer orbits or low thrust trajectories that transition from one orbit to another over a prescribed duration.

## Levels of Space Sustainability Effort

The final column in Table 3 that we must deal with is the level of sustainability effort. The detailed description of these levels is shown in Table 6. The following sections will walk through details of some of these rows individually.

A few notes on the rows do not need a detailed discussion:

* Under Collision Avoidance, all sustainability categories assume “No active maneuver collision avoidance (COLA) failures”. This assumption means when an operational, maneuverable satellite should be modeled as 100% successful when performing COLA maneuvers to avoid trackable objects. This does not have any effect on the fields in these data files.
* Medium and High levels include adoption of the Space Safety Coalition (SSC) Rules of the Road. This does not have any effect on the fields in these data files.
* The spacecraft shielding value is fixed at 1cm for all level. This assumption is relevant for modeling collisions with objects smaller than that threshold but does not have any effect on the fields in these data files.
* The “SSA – trackable object size” row similarly has no bearing on the object fields in the reference scenario files. However, these values vary by SEP and should be accounted for in collision modeling.

Table 6. Levels of Space Sustainability Effort (IAC paper [1] Table 6)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sustainability Category | Current  (Current behaviour) | 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 CA [1, pp. pp. 12, sec. 5.c]  Space Safety Coalition (SSC) Rules of the Road [1, 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 CA [1, pp. pp. 12, sec. 5.c]  SSC Rules of the Road [1, pp. 15-17, sec. 8]  CA if >5-year post mission disposal lifetime, in constellation, or prox. ops. [2, 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 R/B [3]  0.35% of Satellites [3] | 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 |
| SSA – Trackable Object Size | 10 cm | 10 cm | 5 cm  All sats trackable | 5 cm  All sats trackable |
| Post-Mission Disposal | Compliance Time Limit: 25 years  Defence/Civil: 65% [4, p. 93]  Commercial/Amateur/  Cubesat: 95% [4, p. 102]  R/B: 90% [4, pp. 98-100] | Compliance Time Limit: 25 years for non-constellation traffic  5 years for constellations\*  Defence/Civil: 70%  Commercial/Amateur/  Cubesat: 98% [4, p. 102]  R/B: 90% [4, pp. 98-100] | Compliance Time Limit: 5 years\* [1, pp. 15, sec. 7.i]  General PMD: 90% [2, p. 5.4.1.1a]  LLCs use check-out altitudes [2, p. 5.4.2.4]  Commercial/Amateur/Cubesat: 98% [4, p. 102]  R/B: 90% [1, pp. 11, sec. 3.f] | LLCs use check-out altitudes, checkout alt. lifetime <= 5 years [2, p. 5.4.2.4a]  LLC LEO PMD: 99% w/in 5 years\*  LEO PMD w/in 5 years: 95% [1, pp. 12, sec. 5.a]  LEO PMD w/in 25 years: 99% [1, pp. 12, sec. 5.a]  R/B: 98% [2, p. 5.4.1.1a] |
| Active Debris Removal  (2030 onwards) | None | 5 large objects per year | 10 large objects per year | 15 large objects per year |

Items in red are features that are not yet implemented in the current version

Items in purple are available features but are not active in the current version

## Collision Avoidance

The Probability of Collision (Pc) threshold values shown are passed through to all operational, maneuverable satellites in the future population model in column 21, “Pc threshold”.

The Post-Maneuver Risk Mitigation Reduction is shown as an Order of Magnitude (OoM) reduction from the Pc threshold. In this version of the reference scenarios, the reduction is set to 1.5 OoM for all cases. Column 22, “Pc goal” is derived by using log10­ scaling on the “Pc threshold” according to the OoM indicated. As an example, starting with Pc threshold = 1e-4, a 1.5 OoM reduction results in Pc goal = 3.162e-6.

Medium and High levels include a rule that new sats > 400 km can do CA. This rule is applied to all new future population model operational satellites with an average altitude > 400 km by setting column 14, “Maneuverable” to 1 (True).

High level includes a requirement that collision avoidance (CA) during the decay phase is required by constellation operators or proximity ops satellites if post-disposal lifetime is >5 years. This is equivalent to the Control-To-Reentry (C2R) option in column 20 on Table 2 This had been marked in purple to indicate that it is not an active option in this version due to the PMD option also highlighted in purple not being active. This will be discussed in the Post-Mission Disposal section.

## Explosions

Explosion have not yet been included in this version. When they are added, they will be applied to FLM satellites and R/Bs at the rates indicated in this table. Information on the explosion object, epoch, and energy will be provided in a separate set of complementary files, and debris fragments generated by Aerospace’s IMPACT model will also be included in the reference scenario object files.

## Post-Mission Disposal (PMD)

As indicated in the table, each sustainability level calls for a different level of PMD success. In the scenario data, every operational satellite object also has a disposed copy that models the post-mission phase. This can either be a successful disposal or a failed one, and the ID and initial state of that disposed object reflects whether it was a success or failure. The Object ID Interpretation section goes into a bit more detail on how to identify those objects. These success rates are distributed differently to different population types according to the sustainability level.

The levels also prescribe different disposal duration targets for LEO satellites of either 5 years or 25 years. Two distinct populations of disposal objects were generated for all LEO satellites and rocket bodies to target those durations. They were then sampled according to the sustainability levels to choose the appropriate disposal for successful attempts.

The High level provides an option for non-LLC LEO satellites of 5-year disposal with 95% success OR 25-year disposal with 99% success. For this version, only the first option is modeled, and the 25-year option is highlighted in purple to indicate it is not active. This omission renders the CA requirement in the High level inactive as well, as previously discussed.

## Active Debris Removal (ADR)

Active debris removal has not yet been included in this version. The intent is to begin modeling ADR in 2030 at a set rate by targeting high-priority objects. Initially, the targets for ADR action will only come from the IPM catalog, since there are already numerous candidate objects. In subsequent versions, an option can be added to remove FLM failed disposal objects that are deemed to be high priority.

ADR targets will be prioritized either by using a probability-severity index that considers both the likelihood that the derelict object will be involved in a collision with other traffic and the consequence of the object being involved in a collision. A file with a listing of the objects removed via ADR and the epoch of the removal will be included with each scenario object file. The scenario object file will also be modified by simply changing the end epoch of the derelict object to correspond to the ADR epoch. These will be modeled as instantaneous removals for simplicity.

# Object ID Interpretation

These scenarios use an 18-digit ID number borrowed from the Aerospace Debris Environment Projections Tool (ADEPT) to provide a unique identification for each object. This ID number contains information about the object type, disposal option, and other parameters. The breakdown of each column, and their dependencies is summarized here.

## Example IDs

It’s useful to start with some example IDs before getting into the details.

Table 7. Object ID Examples

|  |  |
| --- | --- |
| ID | Descripton |
| 000000000000012988 | Initial Population Model (IPM) object from catalog |
| 000000000000127087 | Modeled IPM subtrackable debris object |
| 000001011000017056 | Future Launch Model (FLM) LEO background traffic operational satellite |
| 000002610000137344 | FLM GEO successfully disposed satellite |
| 000006208771210375 | Large LEO Constellation (LLC) disposed rocket body |
| 000007015830011728 | LLC operational satellite |
| 000007919261310715 | LLC failed disposal satellite |
| 200370000008630781 | 630,785th GEN2 collision fragment in MC 37 |

There are three main categories of object populations represented in Table 7, separated with different cell shading, and each have distinct ID interpretations.

### Initial Population Model (IPM)

The first two rows in green are objects that are present at the initial epoch of the scenarios. These will have many leading zeroes and then a simple incrementing counter to give the object a unique ID. Objects that come from the public catalog will have 5 non-zero digits, corresponding roughly to the number of objects in the catalog. These are based off of real objects from the catalog, but an arbitrary counting number is used for their IDs rather than NORAD ID.

There are also modeled objects that are not trackable and therefore would not be in the catalog. These have at least 6 non-zero digits to distinguish them from catalog objects.

### Future Launch Model (FLM)

The next five rows in Table 7 with blue shading are FLM objects. These are modeled future satellites and rocket bodies in LEO, MEO, and GEO, including large constellation objects and background traffic (all other traffic not categorized as constellation traffic). These are the main focus of the ID column description in the next section. FLM objects will always have 5 leading zeros and then a non-zero digit in the 6th column to indicate the specific population. Details to follow in the next section.

### Breakup Debris

The last row shaded in orange is an example of a breakup debris fragment. In this initial version of the reference scenario files there are no included debris objects. In future versions, there will be explosion included and fragments from those explosions.

The first 5 digits are reserved for debris, where the first digit is set aside to indicate the collision feedback generation the fragment belongs to, and the next 4 digits are for Monte Carlo sampling bookkeeping.

## FLM ID Column Descriptions

### Columns 1-5

Reserved for breakup debris, and are therefore all “0”

### Column 6

Future Launch Model (FLM) Flag

* 1: LEO background traffic object
* 2: MEO/GEO object
* 3: Unassigned
* 4-9: Large LEO Constellation (LLC) object

### Column 7

Disposal option (DO) flag for the object

* A DO flag of 0 represents no disposal option
* There are 9 other disposal options, which depend on the study
* For example, a DO flag of 1 could represent a 25-year decay orbit

### Column 8-9

Future launch repetition number

* 01 corresponds to the first repeated launch cycle, etc.
* Starts in column 9 and expands to column 8 until a maximum launch repetition number of 99
* If the object is already in orbit (from catalog), the future launch repetition number is 00

Column 10-11

FLM specific constellation shell flag. Used in combination with the FLM flag in column 6. Per above examples:

* FLM flag = 6, columns 10-11 = 77, indicates an LLC shell at ALT = 610 km, INC = 42 deg
* FLM flag = 7, columns 10-11 = 83, indicates an LLC shell at ALT = 350 km, INC = 38 deg
* FLM flag = 7, columns 10-11 = 26, indicates an LLC shell at ALT = 1200 km, INC = 40 deg
* Etc.

### Column 12

Disposal failure/success flag

* 0: either an operational satellite or a successfully disposed object
* 1: an object that failed, either during ascent, during operations, or during a disposal attempt

See the column 14 description below for more detail on the failure type.

### Column 13

Disposal failure grouping number or success grouping number. Used to group objects into percentile groups for convenient post-mission disposal (PMD) success rate filtering.

### Columns 14-18

These are used as an object counter beginning at a value of 1 (00001) with a maximum counter of 99999.

# References

1. M. Lifson, B. Chen, G. Henning, A. Baset, M. Miyamoto, G. E. Peterson, B. Weeden, G. Williams, I. Brownhall, M. G. Burgess, D. Kaffine, M. Holzinger, M. Moretto and A. Rao, "Methods for Generating Publicly Releasable Modelling Inputs to Support Development of Reference Space Environment Scenarios," in 75th International Astronautical Congress, Milan, 2024.
2. Lifson, Miles, Aniqua Baset, Grant Cates, Bill Chen, Angelo Connor, Carson Coursey, Gregory Henning, et al. “Development of Reference Scenarios and Supporting Inputs for Space Environment Modeling.” Maui, HI: Maui Economic Development Board, 2024.
3. G. A. Henning, M. E. Sorge, A. B. Jenkin, G. E. Peterson, D. L. Mains, J. C. Maldonado and D. G. Bologna, “ADEPT: Calculating the Infinite Multiverse of Future Space Environments,” in Second International Orbitl Debris Conference, Sugarland, TX, 2023.
4. Cates, G.R., Houston, D.X., Conley, D.G., and Jones, K.L., “Launch Uncertainty: Implications for Large Constellations,” The Aerospace Corporation, November 2018. [[<https://csps.aerospace.org/sites/default/files/2021-08/Cates-Houston-Conley_LaunchUncertainty_12032018_0.pdf>](https://csps.aerospace.org/sites/default/files/2021-08/Cates-Houston-Conley_LaunchUncertainty_12032018_0.pdf)](https://csps.aerospace.org/sites/default/files/2021-08/Cates-Houston-Conley_LaunchUncertainty_12032018_0.pdf)
5. Federal Aviation Administration, Report to Congress on the Risk Associated with Reentry Disposal of Satellites from Proposed Large Constellations in Low Earth Orbit. September 22, 2023. See Table 1 in the appendix provided by The Aerospace Corporation. [[<https://www.faa.gov/sites/faa.gov/files/Report_to_Congress_Reentry_Disposal_of_Satellites.pdf>](https://www.faa.gov/sites/faa.gov/files/Report_to_Congress_Reentry_Disposal_of_Satellites.pdf)](https://www.faa.gov/sites/faa.gov/files/Report_to_Congress_Reentry_Disposal_of_Satellites.pdf)