ADEPT: Calculating the infinite multiverse of future space environments


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Abstract

The Aerospace Debris Environment Projection Tool (ADEPT) developed at The Aerospace Corporation models the long-term space environment, subject to varying initial conditions and future space traffic scenarios that influence collision frequency and debris population growth. The results of ADEPT analyses have been used to inform U.S. and international Space Traffic Management (STM) and debris mitigation policies, as well as for numerous studies on the effects that current and future activity will have on the sustainability of the space environment. This paper will walk through the ADEPT workflow and describe each component process used to propagate object orbits, compute conjunction probabilities and generate collisions, create debris fragments (as small as >1 cm) from breakups, down-sample the fragments to a manageable population, and feed those fragments back through the process to create a superset database of multiple generations of collisions and debris. Scenario-specific results are then extracted from the database using a unique post-processing approach that enables the comparison of results for an unlimited number of scenarios.

1 INTRODUCTION

ADEPT employs a unique approach of simulating multiple scenarios simultaneously to minimize the amount of computational resources needed to make meaningful comparisons among those multiple scenarios. This approach circumvents the need to run simulations more than once per Monte Carlo (MC) by including disposed and undisposed versions of post-mission objects and generating collisions between all possible pairs of objects in a population model that includes the objects needed to define all the potential scenarios of interest.

The main benefit of this “Schrödinger’s Cat” process is that a single run through the core ADEPT simulation process provides an infinite multiverse of future space environments that can be used continuously to extract new results and insights. The only additional work that needs to be done is to define new scenarios based on the questions to be answered and re-run post-processing routines that pull scenario results data from the results superset. This approach allows the ADEPT team to analyze numerous variations to inputs while minimizing the use of computational resources.

This paper provides an overview of the current ADEPT process, describing the various component tools used in the process, the inputs and outputs to conduct the environment projections, the unique approach used to investigate numerous scenarios efficiently, and challenges faced with this approach.
2 AEROSPACE DEBRIS ENVIRONMENT PROJECTION TOOL (ADEPT) OVERVIEW

The ADEPT simulation process generates representations of the future orbital population. The model includes orbit trajectories, sizes, and masses for a complete set of Earth orbital objects as defined by a population model. Descriptions and results of earlier versions of ADEPT can be found in [1], [2], [3], [4], [5], and [6]. A sample of some typical ADEPT analysis results are shown below in Fig. 1, Fig. 2, and Fig. 3.

![ADEPT Simulation Process]

Fig. 1. Example ADEPT results (a) Visualization of hypothetical future Earth-orbiting environment. (b) Altitude distribution of trackable object collisions in Low Earth Orbit (LEO) with varying Post-Mission Disposal (PMD) success rate across multiple scenarios

![ADEPT Results](image1)

Fig. 2. Example ADEPT results (a) All 100 MCs and statistics of object count vs. time for a single scenario. (b) Stack chart of object count vs. time showing distribution of future debris generations

![ADEPT Results](image2)

Fig. 3. Example ADEPT results (a) Distribution of Undisposed Mass Per Year (UMPY) over numerous scenarios used in a study. (b) Object count vs. UMPY future snapshot for hundreds of scenarios
2.1 ADEPT’s Unique Batch Processing Approach

Aerospace is one of many international organizations performing future debris environment projection analysis, including many recent studies of the impact of large constellations [7], [8], [9], [10], [11], [12]. All these organizations have capabilities like ADEPT, but their implementations differ.

A typical environment projection approach might start by defining a single scenario, running a discrete event simulation where the population is propagated forward, and generating collisions with a conjunction-finding algorithm. When a collision occurs, a breakup model replaces parent objects with fragmentation debris and propagation continues, stopping at each breakup to add debris until the simulation end. This process would then be repeated for any number of MCs and different scenarios.

This straightforward approach has significant computational challenges, particularly with high traffic scenarios that lead to many collisions and exponential debris population growth. The set of objects the program must track quickly becomes large, and the complexity of finding close approaches between all objects increases rapidly. The simulation may slow significantly as the population becomes too large to handle. This serial simulation must then be run for multiple MCs to obtain good statistics, and each scenario that is to be considered must be simulated on its own through the same process.

ADEPT circumvents the need to run simulations more than once per MC by generating collisions between all possible pairs of the objects needed to define all the potential scenarios of interest including both properly disposed and failed disposal alternatives to accommodate variations in post-mission disposal (PMD) success. All these collisions are generated concurrently, as a batch, without regard to their chronological order or the logic of one collision preventing or enabling another.

In brief, ADEPT starts by propagating all initial population model (IPM) and a future launch model (FLM) objects using mean elements (MEANPROP) [13] for the duration of the study (typically 100-200 years). An Orbit Trace Crossing (OTC) [14] method is used to compute probability of collision (Pc) between all objects pairs that could intersect in the study, and a set of 100 MCs of collisions is generated based on each Pc. The tool IMPACT [15] models breakups associated with collisions and adds a debris fragment population to the simulation. Section 4 has more detail on these processes. The debris is fed back into the OTC method to generate more collisions with the original object population. This loop can be repeated to create multiple generations of collisions and their resultant debris fragments.

The result of this process is a superset containing all possible collisions and debris that could exist in scenarios bounded by the population model. Now, a very large number of scenarios may be defined by future traffic level, PMD methodologies and success rates, collision avoidance capability (influenced by object trackability), or various disruptions like on-orbit failures, intentional breakups, or active debris removal (ADR) efforts, so long as those variations were captured in the initial population model. The accounting of collisions and debris in a specified scenario is done in post-processing by parsing which input objects exist, and therefore which collisions can occur, from the results superset.

3 STUDY SETUP

The first step in an ADEPT study is to define study constraints, like the study duration (typically 100+ years), minimum object size to consider (ADEPT can currently model >= 1cm objects), and which orbit regimes to include (LEO/MEO/GEO/etc.). The next step is to generate a population model that contains all objects needed to represent the full range of possible scenarios that will be considered.

3.1 Population Model

The ADEPT population model was first described in detail in [2]. The methodology is largely the same, with modifications to account for the changing space environment, briefly described here:
• **IPM (Initial Population Model)** consists of three sub-populations: (1) unclassified USSPACECOM catalog of resident space objects; (2) “unknown” filler population randomly drawn from the catalog to bring the count of trackable objects to the stated total; and (3) a sub-trackable model

• **FLM (Future Launch Model)** replicates recent launch traffic for different orbital regimes:
  - CRC (Continuously Replenished Constellations) – the continuation of current constellations such as Iridium, ORBCOMM, Globalstar, Starlink, and OneWeb in LEO and O3b, GLONASS, GPS, Beidou-M (a.k.a. COMPASS), and Galileo in MEO
  - GEO (Geosynchronous) – all activity in and around the GEO belt, including GEO Transfer Orbit (GTO) trajectories and disposal in the GEO graveyard orbit
  - NonCRC – a periodic continuation of all other current traffic not captured in CRC or GEO
  - FCM (Future Constellation Model) – future constellations from FCC fillings [16] and/or public releases, or follow-on versions of CRCs if they are different than the CRC versions
  - Associated rocket bodies and satellite disposals are included for all FLM objects

3.2 The ADEPT_ID

Extracting specific scenarios from the projection superset requires traceability of debris generated through collisions and explosions, which enables identification of objects that would exist in a particular scenario and the removal of those that would not exist. This is accomplished by using the ADEPT_ID, an 18-digit string that encodes information that identifies and characterizes each object. Every IPM and FLM object is given an ADEPT_ID following strict format rules.

IMP catalog object ADEPT_ID is NORAD ID with leading zeroes appended. E.g., Hubble Space Telescope’s NORAD ID = 20580, so ADEPT_ID = 00000000000020580. Modeled non-catalog object have values >50000 (beyond the latest catalog NORAD IDs), not to exceed the first 12 digits of the ID.

FLM objects are identified with a non-zero 13th digit (1=NonCRC, 2=GEO, 3=CRC, 4=FCM). E.g., an object with ADEPT_ID = 000003006110020301 is a CRC. The digits after the 3 are other identifying information such as the constellation it belongs to (e.g., Iridium), the constellation orbit plane, whether it is an operational satellite, a rocket body, or an inactive disposed satellite, when it is launched, etc.

Debris fragment ADEPT_IDs have the breakup generation in the first digit, followed by its MC. Remaining digits increment up from 1, ensuring unique IDs. E.g., a fragment with ADEPT_ID = 20037000000008399 is the 8,399th fragment from MC 37 in the 2nd generation. Detailed breakup files generated by OTC contain fragment traceability information back to the original IPM/FLM object(s) that spawned them.

4 BREAKUP AND FRAGMENTATION GENERATION PROCESS

The initial batch process of generating all the explosions, collisions, and their resultant debris fragments is summarized in the flow chart in Fig. 4. The portion in the yellow box includes the study setup steps already discussed, as well as propagation and downsampling of the IPM, and generation of explosions (based on observed historical rates) to add to the simulation. The portion in purple is a loop that flows through the OTC, IMPACT, and MEANPROP tools to create a generation of collisions, debris fragments, and trajectories for those fragments. This loop can be repeated until the debris generated by the feedback is no longer significant. A flow chart of this process is shown in Fig. 4.

4.1 Object Propagation Using MEANPROP

MEANPROP is Aerospace’s long-term orbit prediction and stationkeeping software. MEANPROP performs orbit prediction and stationkeeping through mean element propagation theory based on the highly accurate and efficient Draper Semi-Analytic Orbit Propagator (SAOP) developed by the Computer Sciences Corporation and Draper Laboratory. More details on this theory can be found in [13].
4.2 Collision Finding using OTC

The OTC method is used to compute $P_c$ and generate collisions. For each object pair, all orbit trace crossings (OTC events) over the study time interval are found. Orbit trace evolution is accounted for in MEANPROP orbital element files. The $P_c$ at each OTC event is computed assuming object mean anomalies (MA) are uniformly distributed over 360°, because the MA value decades in the future is very sensitive to small variations in semi-major axis (SMA). This assumption allows a formulation that is much less computationally intensive than a detailed close approach analysis, facilitating a long-term analysis. The mean number of collisions is determined by summing collision probabilities of all OTC events in the assessment time interval. A description of OTC and a comparison with other methods are shown in [14].

4.3 Debris Fragment Generation using IMPACT

ADEPT uses the IMPACT fragmentation model to generate fragments from breakup events. IMPACT is a semiempirical model used at Aerospace for more than 30 years. It produces representative numbers, masses, area-to-mass ratios and spreading velocities for debris fragments from breakup events based on the characteristics of the events including specific energy, object types, material composition, and completeness of the breakup. More details on the IMPACT model can be found in [15].

4.4 Object Downsampler

The number of fragments generated by IMPACT for all collisions in 100 MC cases is too large to post-process. This is especially the case when fragments down to 1 cm are retained. This problem is addressed by down-sampling to a smaller, weighted population by binning objects by mass in log space. Retained objects are given a weighting factor that represents the number of similar objects they represent. More detail on the downsampler can be found in [17].
5 ADEPT SIMULATION POST-PROCESSING PROGRAM (ASPPP)

The result of the breakup and fragmentation generation loop is a superset of all possible input objects, 100 MCs of all possible breakups involving those objects, a downsampled debris fragment population that result from those breakups, and multiple generations of additional collisions and fragments from the feedback loop. This superset represents the future space environment “multiverse”, where any realistic scenario is a subset representing a possible discrete universe. To explore this infinite multiverse, we sample it with finite scenarios. A flowchart of the process is shown in Fig. 5.

5.1 Scenario Definition

A scenario is defined by a certain traffic level, PMD practice and success rate, and other detailed inputs or adjustments made to the FLM. Traffic level is defined by which FLM populations to include or exclude in a scenario. The PMD success rate and disposal practice is then set for each object included, either by full constellations, single constellation shells, or even single satellites. Other adjustments can be made to alter the activity level for a particular population. Ultimately, the scenario-specific model of future traffic will be used to filter the breakup events to only those that are possible for that scenario and MC run.

5.1.1 PMD Success Rate

The default PMD success rate for an object or population of objects is either set by the scenario default value or specifically for that population. This allows for different success rates for different populations within a scenario. E.g., the FCM Starlink population could be set to 99%, while CRC Iridium could be 95% and all NonCRC satellites could be 90%. Regardless of how it is defined, the method for including the correct distribution of successful and failed disposed satellites in a scenario is identical.
For every FLM operational satellite modelled, there are at least three copies in the object database: one for the station-kept operational satellite that exists through the mission duration to end-of-life and two more that replace it for the post-mission disposal duration. One post-mission option is a successful disposal, which will be compliant with the disposal duration, and the other is a failed disposal, left in or near the operational orbit, and generally non-compliant. Both disposal objects begin at the end-of-life of the operational satellite and remain on orbit until atmospheric drag, ADR, or a breakup removes them. Both are subject to interactions with other inactive objects and may have collisions modelled by OTC.

<table>
<thead>
<tr>
<th>ADEPT_ID</th>
<th>PMD Type</th>
<th>Start Epoch</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>00000400164020301</td>
<td>Operational Satellite</td>
<td>1 APR 2027</td>
<td>12.0 years</td>
</tr>
<tr>
<td>00000400164020301</td>
<td>Successful Disposal (DISP)</td>
<td>1 APR 2039</td>
<td>5.0 years</td>
</tr>
<tr>
<td>00000400164010301</td>
<td>Failed Disposal (FAIL)</td>
<td>1 APR 2039</td>
<td>18.5 years</td>
</tr>
</tbody>
</table>

Take the Large LEO Constellation (LLC) object example in Tab. 1. The three IDs represent an operational satellite, a successfully disposed copy (DISP), and a failed disposal copy (FAIL) of the same satellite. The ADEPT_ID column 7 (yellow) value is the PMD option (0 = operational satellite, >0 = disposed satellite). For a disposed satellite, column 12 (cyan) indicates successful or failed (0, 1), and column 14 (red) indicates a failure type. Column 13 (green) is a randomly distributed failure group, such that PMD success rate is in a set of 50%-100%, according to the binning in Fig. 6. Remaining columns are identical.

Fig. 6. Default PMD success rate failure group distribution

Half of all FLM satellites are in group 0, 10% are in group 1, and so on according to the percentages in the colored boxes. The far-right bins are smaller for more resolution at higher PMD percentiles, as only 4% are in group 8, and 1% in group 9. The OPS, DISP, and FAIL boxes underneath the failure group indicate which groups are modelled (No failed copies group 0 since minimum PMD success rate is 50%).

To choose end-of-life options associated with a given PMD success rate, ADEPT considers “Schrödinger’s Satellite,” a reference to the paradox of quantum superposition, where the satellite may be considered simultaneously successfully disposed or not, and its true state is only determined when a scenario is defined. When a PMD success rate for a population is specified, the scenario filter, described in more detail in the next section, selects the DISP and FAIL objects from the superset that yield the correct PMD success rate, according to their failure group. E.g., PMD = 75% has DISP objects from groups 0-3, and FAIL objects from groups 4-9, ensuring there is exactly one disposed copy for each operational satellite.

5.1.2 Active Debris Removal, Control-To-Reentry, and Other Scenario Inputs

A scenario definition may include additional modelled activities such as ADR, reduced disposal duration, extended operational lifetime, enhanced rocket body reentry, and “control-to-reentry” (C2R). All of these can be applied to any population or individual object modelled in the FLM.

ADR can be done in the “Classical ADR” mode, prioritizing large derelict resident objects, or “Enhanced-PMD ADR” mode, focusing on specific constellation satellites that failed to dispose. For both, the inputs required are a start year and a rate of ADR missions per year.

The C2R concept is like the capability that some LLCs already have, which is to maintain active control of disposed satellites until atmospheric re-entry, allowing COLA maneuvers if there are conjunctions with other inactive objects during the descent trajectory of the disposed object, thus preventing collisions.


5.2 Scenario Filtering

Scenario filtering begins with the superset of all IPM and FLM objects and then filtering out excluded populations and disposed satellites that don’t match the PMD rate according to the logic previously discussed. This is also where modifications to object start or end epoch, weighting factor, or physical characteristics are applied. This population subset forms the initial populations for scenario MC filtering.

An event list is created for each MC, with explosions and collisions from all generations merged and sorted chronologically. The algorithm steps through time determining which events to keep or discard in this timeline for various reasons. The simplest reason is that a breakup parent object was excluded. Another example is that a collision is avoided if the C2R flag is true for a parent object. When an event is possible, it is added to an output event list, the resultant debris fragments are added to the object set, and a breakup is recorded for the parent objects. If the number of breakdowns exceeds the weighting factor for an individual object, no more breakdowns for that object can occur, and the object’s end epoch is set to the breakup epoch. Next-generation collisions involving breakup fragments can only occur if both parents exist in the timeline, which is only true if the previous generation breakup occurred.

ADR is implemented by removing objects according to the input ADR rate and prioritized target list. ADR events are added to breakup events to compare to the weighting factor, as above, to end the object’s life early. The real-world situation that is being modeled is that the object has been removed either by reentering the atmosphere early (ADR) or being replaced by a cloud of debris (breakup).

All scenarios and MCs are run in parallel on an Aerospace-internal computing cluster, resulting in a database of unique timelines of events and objects that represent a multiverse of discrete future debris environment projections. The scenario filtering process can be rerun on a new scenario without the need to redo the breakup and fragmentation generation process. Scenario filtering is orders of magnitude quicker than the heavy-duty computing required to propagate, find collisions, and model breakups, so only having to do the breakup computations once for a study is hugely beneficial.

5.3 Post-processing and Visualization

The main goal of ASPPP is to generate metrics from the event lists and object sets that can be used to assess scenarios. The metrics include object counts by year, collision rates and cumulative collisions over time, spatial density by altitude bin and year, COLA and LCOLA rates for given trajectories, etc.

Object and breakup count files by year and altitude bin are generated for each scenario MC, which are combined to yield statistics and scenario averaged values. E.g., Fig. 2 (a) shows object count variance, where faint gray lines are MCs, and bold colored lines are various statistics.

A new ADEPT feature generates and averages future environment snapshots for each scenario, which can be used like a future catalog. The snapshots can also be simulated visually with SOAP, Aerospace’s satellite orbit analysis program, as shown in Fig. 1 (a). This feature enables the ADEPT Standard Environment Model (ASEM), a projection with reasonable assumptions about near-term future traffic that is used to perform analysis on the interaction between future space systems and the environment.

Previous work [5],[6] formulated a simple metric, called Undisposed Mass Per Year (UMPY), for relating the characteristics of components of a scenario (e.g. constellations) or the entire scenario population and behavior to the consequences for the environment. UMPY allows ADEPT to compare many independent scenarios on an apples-to-apples basis and formulate strategies for targeting desired results by manipulating UMPY. An example comparison of scenario results vs. UMPY is shown in Fig. 3.
6 CHALLENGES AND FUTURE DEVELOPMENT

The unique method used by ADEPT is not without challenges. Significant research and development effort has been, and continues to be, expended to improve the implementation to work through roadblocks and improve data quality.

The downsampling step is unavoidable and necessary to computationally handle the immense number of modelled objects in a reasonable amount of processing time. But the more downsampling done, the larger weighting factors become, particularly for low-mass objects. Use of a single object to represent many other objects eliminates some variability in object orbits and lifetimes. Weighting factors can make object count statistics look very noisy when they are high for certain objects. The weighting factor is also used to amplify the P. the OTC collision-finding processes, which can lead to an overwhelming number of collisions attributed to a single object. Averaging results from 100 MCs can smooth out data when weighting factors are low, but this can start to break down at higher weighting factors.

Another issue arises when filtering scenarios with very low traffic compared to the full study superset. In such cases, a large portion of the traffic and events are filtered out, leaving a very sparse data set with high weighting factors due to downsampling, which may yield very noise results. A possible solution is to significantly increase the number of MCs, but that would drive the computational burden of the breakup and fragmentation generation process, where the most CPU time is already needed. Some balance must be struck between downsampling results data sparseness. Some other challenges include:

- Tendency for feedback generations of collisions to grow exponentially in the superset, limiting the number of generations that can be reasonably run
- Complexity of bookkeeping events and ancestors of multiple generations of debris fragments
- Proliferation of near-intact parent debris objects resulting from multiple low-energy collisions that exacerbate the higher generation growth in debris
- Superfluous collisions generated by OTC that never show up in a real timeline during the scenario MC filtering, but still contribute to the downsampled weighting factors

Many of these challenges have been partially mitigated by implementing processes to screen and prune out superfluous collisions prior to running IMPACT, which suppresses the debris fragment weighting factors. These improvements, along with others to reduce data file sizes, increase parallel processing speed, and enhance output products, have produced an ADEPT that is far more efficient, produces cleaner data results, and generates a variety of results that previously required significant manual work.

Future development plans are focused primarily on streamlining the ADEPT process. Some pieces of the process are still dependent on human-in-the-loop steps, and there are subprocess interfaces that should be simplified. Part of this effort involves modernizing the codebase, which originates from decades-old Aerospace legacy tools. The source code is also being made more modular and portable so that we may leverage other high-power computing environments. A sustainment effort to improve the quality of the output products, add new tables, figures, and charts, and incorporate new scenario filtering features to reflect real-world on-orbit activities is ongoing, with a goal to make scenario definitions infinitely flexible.

ADEPT has undergone many forms and iterations over its development lifetime, and is now in its most capable state to date, able to perform complex analysis that used to take days, weeks, or months in a matter of hours. ADEPT is ready to tackle the biggest questions about what effects our actions (or inaction) today will have on the space environment of tomorrow.
7 References


