Modeling of the orbital debris environment risks in the past, present, and future

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ABSTRACT

Despite of the tireless work by space surveillance assets, much of the Earth debris environment is not easily measured or tracked. For every object that is in an orbit we can track, there are hundreds of small debris that are too small to be tracked but still large enough to damage spacecraft. In addition, even if we knew today's environment with perfect knowledge, the debris environment is dynamic and would change tomorrow. Therefore, orbital debris scientists rely on numerical modeling to understand the nature of the debris environment and its risk to space operations throughout Earth orbit and into the future. This talk will summarize the ways in which modeling complements measurements to help give us a better picture of what is occurring in Earth orbit, and helps us to better conduct current and future space operations.

1.0 INTRODUCTION

The orbital environment represents many risks to operators of robotic and crewed spacecraft. For nearly 60 years, humans have continued to launch more objects and mass into space than is removed from orbit by natural drag processes. As a result, Earth orbit regimes – especially low-Earth orbit (LEO) below about 2000 km – continues to get more crowded. The natural questions arise of "how do we know what is happening up there?" and "what are the hazards due to orbital debris?" In this presentation and the accompanying presentation on measurements, I will attempt to outline how we answer these kinds of questions.

2.0 MODELING

The problem with measuring the orbital debris environment is that we seldom measure all the things we wish to measure. We wish to know debris size and mass, and we measure radar cross section with a radar or brightness of reflected sunlight with a telescope. The ability to take the data from instruments and to turn it into useful information requires the use of mathematical models.

In many cases, we are limited to looking at a sub-set of the debris environment limited in size and location, and try to deduce what is happening elsewhere in Earth orbit. However, even if we could perfectly know what the environment looks like today, we would still be limited in predicting what will be happening in the future, because the orbital environment is a very dynamic environment, and is constantly changing by human activity and the evolution of the orbital debris complex. Extrapolating to regimes of limited data or out into the future requires mathematical models.

The purpose of this presentation is to provide a summary of the major modeling tools used by the NASA Orbital Debris Program Office to define the orbital debris environment, but also to describe how we use the modeling tools to help us determine policies and procedures to limit the accumulation and risk form orbital debris into the future.

3. LEGEND

The LEGEND (<u>LE</u>O-to-<u>GE</u>O <u>En</u>vironment <u>D</u>ebris) model is a three-dimensional orbital debris evolutionary model that is capable of simulating the historical and future debris populations in the near-Earth environment. In many ways it is the "workhorse" of the NASA orbital debris efforts, as it provides information on how and why the current environment evolved the way it did and how it will evolve into the future. The LEGEND model itself grew out of the pioneering work that was done on NASA's Evolve model.

The historical component in LEGEND adopts a deterministic approach to reproduce the known historical populations. Historical launches of rocket bodies, spacecraft, and mission-related debris (shrouds, bolts, etc.) are added to the simulated environment as they occurred over time. The orbits of these objects are also evolved under the influences of atmospheric drag and solar radiation pressure. This allows researchers to study and calibrate how orbit population have grown over time, and provides tools how these populations will develop in the future. Known historical breakup events are reproduced, and fragments down to 1 mm in size are created to simulate the growth of the small particle environment.

For large satellites, the model keeps track of each object individually, but for small debris the program tracks a subset of the population, where each object is "representative" of a specific number of other similar debris objects that are not individually tracked. This avoids bookkeeping and computer speed problems that can occur with large number of small debris.

Future launch activity is usually simulated by repeated past launch traffic cycles. However, any types of future launch activity can be parameterized and simulated, such as the explosive growth of cubesats or future planned "mega-constellations" of satellites.

We have known for a long time that the single most important factor that will affect future populations is catastrophic collisions between large satellites in space. The high velocities in orbit create extremely energetic collisions that will be an unprecedented source of future debris.

The LEGEND future projections adopt a Monte Carlo approach and use an innovative pair-wise collision probability evaluation algorithm to simulate the future breakups and the growth of the debris populations. This algorithm is based on a new "random sampling in time" approach that preserves the likely locations and conditions of collisions and captures the rapidly changing nature of the orbital debris environment.

The LEGEND model has been used to test various types of mitigation scenarios, including the so-called "25 year rule", where satellite users design their mission so that all spacecraft and rocket bodies are removed from the LEO environment within 25 years of the end of mission life.

In addition, LEGEND has been used to examine the efficacy of removing large orbiting objects from the environment, a technique known as Active Debris Removal (ADR). The studies have shown that targeted removal of certain massive rocket bodies and satellites over time can significantly alter the future collisional growth of the orbital debris environment.

Note that the LEGEND model requires a number of sub-models in order to model the past and future. One of those models is the NASA breakup model – a numerical distribution that characterizes explosion and collision (each handled separately) breakup clouds in terms of particle size, ballistic coefficient, and delta-velocity.

The program also uses a special orbit propagator called PROP3D. Most orbit propagators are optimized for high-precision, short-term propagation, and are generally slow or inaccurate for long-term propagation over decade time intervals. PROP3D is optimized to sacrifice short-term precision for fast and accurate long-term propagation, in order to model how old satellites will decay from the environment in the future. The future propagation model also needs a future solar activity model, which is based on the latest NOAA predictions, as well as projection of historical activity into the future.

4. ORDEM

Spacecraft users are usually not interested in long-term environment evolution, but in how the current and near-future environment will affect their satellites. For this purpose, NASA's Orbital Debris Program Office has created a family of "engineering models", known as ORDEM (Orbital Debris Engineering Model). The most recent engineering model, known as ORDEM 3.0, uses a pre-computed orbit distribution of debris and intact satellites down to 10 μm in size, and in orbits up to 40,000 km altitude. It also breaks down the debris into discreet density families, including "low density" (plastics, $\rho = 1.3$ g/cm^3), "medium density" (aluminum, $\rho = 2.8$ g/cm^3), and "high density" (steel, $\rho = 7.9$ g/cm^3). It projects these populations out to 2035. ORDEM 3.0 is a Microsoft Windows application made available to the general public, free of charge.

There are two calculation modes for ORDEM. One is the "spacecraft mode" which computes the flux on a spacecraft in a particular defined orbit in terms of direction and velocity in the spacecraft frame. The second is "telescope mode" which computes what a ground-based radar or optical telescope pointing to the sky would be expected to see.

Unlike LEGEND, ORDEM is intended to be primarily an empirical model, where the orbit populations are computed as much as possible using empirical data. My other presentation in this series will discuss the empirical data used in the construction of the ORDEM populations. The model also preserves uncertainty information on the populations that can be used to understand the accuracy in spacecraft risk calculations.

The primary purpose for the environment model is to be able to use the information on the debris to estimate spacecraft risk. This is usually done using a model known as Bumper. This is used to construct a 3D model of the spacecraft, in order to understand how different parts of the spacecraft "shield" or "shadow" other parts. In addition, each element of the spacecraft is

assigned a damage equation. These semi-empirical equations, based on hypervelocity tests of test articles identical to the spacecraft surfaces, describe whether a particle of a given size, density, speed, and direction can perforate and damage that section of the spacecraft. ORDEM provides the environment, but Bumper computes the risk probability, usually given as "probability of no penetration".

The debris orbit populations created for ORDEM are based on empirical data, but data that is mostly statistical sampling made by various instruments. A number of statistical models are used to extract the desired information from these statistical samples. For instance, one of our chief tools for understanding the centimeter-sized debris environment is radar. A radar returns a measure of the reflected electromagnetic energy known as radar cross section (RCS), not size. In order to convert to size, we use a "Size Estimation Model" (SEM), based on ground radar range lab data of a series of 39 fragments from a laboratory collision test. There is not necessarily a one-to-one correspondence between RCS and size, but this tool gives us a statistical way to convert a distribution of RCS values into a distribution of size values with reasonable confidence. Similar models for estimating solar albedo of debris allow us to use the measurement of optical magnitude by a telescope to estimate debris size.

For *in situ* data, the problem is similar. What we measure is impact damage on a detector surface. That damage is a complicated function of the particle size, mass, shape, density, speed, and impact angle. We use statistical tools to try to untangle these various parameters to arrive at the parameters we want to know.

For all these data sources, there are orbit regions and size regimes where we cannot measure, so we rely on tools like LEGEND to help us extrapolate to regions with limited or no data.

5. Collision Avoidance

Because orbiting objects larger than about 10 cm in size can be tracked, we can know where such objects will be at a later time to some precision. The work of tracking in the United States is accomplished by the Space Surveillance Network (SSN), operated by the Department of Defense. During the Space Shuttle era, the SSN began issuing collision avoidance warnings for human spaceflight. For the International Space Station, this technique was perfected, with NASA help, to compute accurate uncertainties on future predictions. These uncertainties, given as statistical covariance matrices, allow spacecraft users to compute a probability of collision, and use that probability to make decisions concerning the maneuver of the space asset to avoid the collision. The small risk of collision must be weighed against the effect the maneuver will have on the mission of the spacecraft.

Note that even though, in principle, collision avoidance can effectively remove most of the collision risk of a spacecraft with any tracked space object, for every object we can track, there are many more we cannot track that could do serious damage to a spacecraft. So, while collision avoidance is prudent for many spacecraft users, its efficacy is limited.

Note that there are future plans to augment the SSN with more sensitive sensors that have the potential to lower the minimum trackable size. While this will allow a spacecraft to avoid more

debris than they currently do, a drastic increase in the number of collision warnings may cause unforeseen problems in spacecraft mission planning.

6. Reentry Risk Assessment

Another area of modeling interest is the prediction of space objects reentering in an uncontrolled manner and their risk to people and structures on the ground. This risk is primarily from large objects that can be tracked, however, our models have limitations on the precision with which they can predict reentry locations. As a result, it is very difficult to isolate a particular ground risk to even a hemisphere, let alone a country or city.

One of the tools we have used is the gridded global world population produced by Columbia University. With this database, we can superimpose the expected ground tracks from a particular orbit to estimate the probability of a ground casualty. However, this requires an accurate understanding of what portions of the disintegrating spacecraft may be expected to reach the ground.

NASA uses the ORSAT tool to take spacecraft information from the spacecraft designer – information such as the size, shape, material types, and geometry of different elements of the spacecraft – and computes which parts of the spacecraft will be expected to survive reentry. ORSAT uses a relatively simple method to model the various elements, for instance assuming that the elements are either in fixed orientation or randomly tumbling, rather than trying to model the complex and chaotic aerodynamic behavior during reentry, to arrive at estimates of what will survive or not. Studies between NASA and international colleagues show there are great similarities between models, despite very different modeling philosophies. However, there are also a number of basic assumptions about reentry physics that still need to be studied and better understood to improve our reentry predictions.

7. Conclusion

As can be seen in this discussion, modeling efforts permeate every aspect of orbital debris studies. The mathematical models using the power of the computer can help us interpret data from instruments, extrapolate debris populations in regions and times where we have no data, and allow spacecraft designers and operators make their spacecraft safer and more reliable. However, models are only as good as the data that goes into them and the quality of the assumptions made. The NASA Orbital Debris Program Office has a unique team consisting of measurements and modeling experts to pull this data together to produce information and tools for the spacecraft manufacturers and operators as well as policy-makers to make better-informed decisions.