Using Satellite Movements to Predict Orbital Debris Risk[1]

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Untracked orbital debris poses a risk to the growing number of satellites. The authors demonstrate how debris smaller than the width of a pencil can be detected by examining changes in a satellite's attitude.

Introduction

Untracked orbital debris is a serious risk to the survivability of satellites, particularly those in low Earth orbit (LEO). Acknowledging the growing threat such debris poses to space operations, U.S. National Space Traffic Management Policy (also known as Space Policy Directive-3) calls for "advancing the S&T [science and technology] of critical SSA [space situational awareness] inputs such as observational data, algorithms, and models necessary to improve SSA capabilities" (National Space Traffic Management Policy 2018, 28970). Guidelines for doing so should minimize SSA deficiencies "in regions with limited sensor availability and sensitivity in detection of small debris" (National Space Traffic Management Policy 2018, 28971).

Existing NASA models for characterizing small orbital debris in LEO depends on interpolating between impact counts from short duration Shuttle missions (under 1 millimeter in size) and radar data (above 3 millimeter in size), leaving a critical gap in predicting impact with particles 1–3 millimeters in size. This gap is small but important because this size regime can kill a small satellite when impacting at orbital velocities, and the number of satellites in LEO is expected to increase dramatically in the next decade (NewSpace 2018). NASA's Orbital Debris Engineering Model (ORDEM) 3.0 indicates that satellites in LEO by 2029 will face potential collision with more than 16,000 pieces of orbital debris of 1 millimeter or larger each year. Further, many of those satellites will be in orbits where debris under 1 centimeter in size is both untrackable and dangerous.

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Survival of new satellite constellations in LEO will depend on the accuracy of debris prediction models. Some new method of gathering data for predicting satellite impacts with debris of all sizes is needed to calibrate existing NASA orbital debris models. This paper outlines a technique for using 1–20 meters changes in satellite mean altitude to calculate the size of small, untrackable orbital debris particles that impact satellites.

Converting Satellite Perturbations into Orbital Debris Environment Predictions

A 2017 technical study for NASA compared predictions of satellite failures from impact with debris against observations of satellite anomalies from impact with

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debris (Squire et al. 2017). The failure predictions and anomaly observations were limited to sudden leaks in pressurized batteries and propulsion tanks—failures that were most likely to be caused by sudden orbital debris impact. Between 8 and 11 failures were predicted, but only two anomalies were actually reported. This indicates either the model is overpredicting failures or satellite owner-operators are underreporting them. The range of orbital debris sizes causing failure varied from 1.5 to 4 millimeters—the range where the least information exists about the orbital debris environment. This implies a need for better observed data in this range.

For the same NASA study, an IDA-developed prediction technique (Williamsen and Evans 2017) was used to correlate impacts with orbital debris of various sizes to reported motion of satellites in LEO. IDA used hydrocode analyses to determine the effects of different orbital debris sizes, masses, velocities, and directionalities on plates that simulate subsequent layers in general satellite construction. (Hydrocodes model the fluid-like response of solid materials to short-duration loading from much higher velocity impact.) Using this technique, IDA established that the momentum enhancement factor (MEF) of the impacting particle varies between 1.5 and 3, depending on the structure hit. MEF relates how much the backward flow of debris material reduces the satellite's forward velocity and thus lowers the average satellite altitude. Thin structures, for example, do not react strongly to orbital debris impact because the debris tends to go through them without multiplied momentum.

Satellite mean altitude is the average of the satellite's altitudes at perigee (the portion of the orbit closest to Earth) and at apogee (the portion farthest from Earth). The change in altitude after collision for satellites in circular orbits is called the delta semi major axis (dSMA). A mathematical illustration of the magnitude of the collision's effect on dSMA follows. For this illustration, assume the satellite is in a circular Keplerian orbit (Earth at the center of the circle).

$$v^2 = (1/2)\, v_e^{\,2}\, (2/r - 1/a)\ , \tag{1}$$

where v is the orbital velocity, v_e is the escape velocity from Earth, and r and a are the spacecraft orbital radius and semi-major axis, respectively (both unitless, as a fraction of the Earth's radius, with $r = a$ for circular orbits).

Following impact with debris, a satellite enters an elliptical orbit (Earth at either end of the ellipsis) with a new mean altitude or semi-major axis. Equation 1 computes the orbital velocity for both the original circular orbit at radius r and immediately after impact, still at radius r but with the perturbed semi-major axis a. From the change in satellite velocity dV, the debris particle's mass can be calculated using equation 2:

$$m_0 \times v_0 \times MEF = M \times dV\ , \tag{2}$$

where m_0 is the debris particle's mass, v_0 is the velocity component approaching opposite to the satellite's velocity vector, MEF is the momentum enhancement factor, and M is the satellite's mass.

Table 1 correlates calculated changes in satellite altitude following impact with orbital debris to the size of the debris particle for satellites of the following sizes made of both aluminum and steel:

- Minisatellites: 150 kilograms and 1 square meter
- Microsatellites: 37 kilograms and 0.3 square meters
- Nanosatellites: 1.5 kilograms and 0.1 square meters

Table 1. Changes in Satellite Altitude Relative to Debris Particle Size

	Diameter (in millimeters) of debris causing designated dSMA upon impact with satellite						Predicted occurrences of designated dSMA per 1,000 satellites		
	Aluminum debris			Steel debris			Aluminum and steel debris combined		
dSMA (meters)	Minisatellite	Microsatellite	Nanosatellite	Minisatellite	Microsatellite	Nanosatellite	Minisatellite	Microsatellite	Nanosatellite
20	3.30	2.07	0.71	2.32	1.46	0.50	2	21	34
15	3.00	1.88	0.65	2.11	1.32	0.46	6	35	43
10	2.62	1.54	0.56	1.84	1.26	0.40	16	68	57
5	2.08	1.30	0.45	1.46	0.92	0.32	69	172	87
3	1.75	1.10	0.38	1.24	0.78	0.27	167	303	113
2	1.53	0.96	0.33	1.08	0.76	0.23	306	454	135
1	1.22	0.76	0.26	0.86	0.68	0.17	732	868	175
0.5	0.97	0.51	0.23	0.68	0.43	0.15	1,491	1,487	216

Notes: Based on impact with debris particles in near-polar circular orbit (~50% of flux) traveling 14.94 kilometers per second at an altitude of 800 kilometers. More occurrences are possible if all flux directions are considered.

The table shows that debris detectability varies with the material it is made of, the size of the satellite it impacts, and the dSMA. For example, an aluminum particle as small as 1.75 millimeters in diameter that impacts a minisatellite can be detected by observing a dSMA of 3 meters. Likewise, a steel particle as small as 1.24 millimeters can be detected based on the same dSMA in a minisatellite. A nanosatellite weighs much less than a minisatellite, so debris particles as small as 0.38 millimeters for aluminum and 0.27 millimeters for steel cause a dSMA of 3 meters.

This information, coupled with information about a satellite's exposed area and shields, allows us to compare the predicted number of orbital changes with the observed number of a given size. Table 1 also provides expected occurrences of each dSMA, as predicted using ORDEM 3.0. Given large constellations, hundreds of hits from particles of 1–3 millimeters are expected, if NASA's model is correct.

Potential Methods to Detect Satellite *Perturbations*

A variety of methods are available for determining the magnitude of vertical satellite movement (perturbations) of 1–20 meters following debris hits of 1–3 millimeters. Among them are:

- **Ground-Based Radar and Laser Ranging**: The U.S. Space Command's Space Surveillance Network contains the largest collection of LEO-observing ground-based radar. The Combined Space Operations Center uses object tracking and radar characterization data from the Space Surveillance Network to determine a space object's location and trajectory. In turn, these location and trajectory data are used in propagation models to predict orbital positions. However, the margin of error in the orbital propagation prediction with these data exceeds the small altitude change experienced by minisatellites, microsatellites, and nanosatellites when struck by millimeter-sized space debris.
- **Monitoring Satellite Crosslinks in Constellations**: Many current and planned future satellite constellations communicate first through uplinks that send information from the ground, through crosslinks, and finally through a downlink to the recipient satellite. Sudden loss of these connections or changes in the transmission antenna's pointing angle indicate a change in a satellite's position, possibly from impact with debris. However, variation in satellite guidance or response can also be the cause of the position change.
- **Monitoring Global Positioning System (GPS) Information**: Continuous monitoring of GPS information for LEO satellites is becoming a feasible way to detect sudden changes in their mean orbital altitude. Some current GPS receivers for LEO, such as General Dynamics' Viceroy-4, have positional accuracies better than 15 meters. The newer General Dynamics' Sentinel M-Code has LEO positional errors of less than 4 meters. Furthermore, studies show that 1 meter accuracy is achievable with commercial off-the-shelf signal-frequency GPS receivers for LEO, and that accuracy can be improved down to 0.3 meters using post-processed GPS orbit and clock products (Montenbruck et al. 2012, 527).

Of these methods, the most promising are monitoring a satellite's GPS position and its ability to maintain communication crosslinks with neighboring satellites in a constellation. Using reported data on internal spacecraft anomalies (failures) that accompany a rapid change in orbital position would further improve confidence in orbital debris model predictions.

Clearly, capabilities exist that can detect and resolve the magnitude of satellite movement after an orbital debris impact, which will allow more data to be gathered on the environment. The ability to make these comparisons have ramifications for satellite design and risk perception and management.

Collecting and Distributing Anomaly Data

To best address the potential risk from orbital debris, and to help improve debris models (particularly the ORDEM model), satellite owners and operators need to share data and other satellite information within a common framework. Currently, satellite owners and operators rely on the ORDEM 3.0 debris model to predict satellite anomalies or failures. Sharing anomaly data would allow for a more realistic assessment of the true debris environment.

In line with its goals to create a safer operating environment and to establish new guidelines for satellite design and operation, Space Policy Directive-3 named the Department of Commerce as administrator of an open architecture data repository. Anomaly data could be an important part of this repository. To understand how anomaly data collection and distribution can be part of an orbital debris mitigation process, consider the following roles U.S. Government agencies have in monitoring and regulating the space environment:

- The Department of Defense (DoD) owns the U.S. Government sensors that identify and track space objects.
- NASA is leading the effort to establish new guidelines for satellite design and operation through the U.S. Orbital Debris Mitigation Standard Practices. NASA also represents the United States on the Inter-Agency Debris Coordinating Committee of the United Nations. This committee coordinates space debris research between members, reviews progress of ongoing cooperative activities, and identifies debris mitigation options.
- The Federal Communications Commission (FCC) is responsible for licensing radio transmissions from satellites owned by private companies. Under rules put into effect in 2005, FCC authorization requires communication satellites that transmit to U.S. receiver systems to submit documentation on their debris mitigation strategy. A debris mitigation strategy includes plans to limit both operational debris produced and the probability that the satellite itself will become a source of debris (Sorge 2017, 2–3).
- Within the Department of Transportation, the Federal Aviation Administration (FAA) Office of Commercial Space Transportation oversees, authorizes, and regulates launches and reentries of vehicles and the operation of launch and reentry sites for the United States. The FAA's debris mitigation regulation focuses primarily on reentry debris.
- The National Oceanic and Atmospheric Administration (NOAA) issues licenses for remote sensing space systems. To obtain a license, a licensee must assess and minimize the amount of orbital debris associated with the system's disposal.

DoD and NASA are both involved in assessing the orbital debris environment; NASA leads the effort and the DoD provides satellite object data. The FCC, the FAA, and NOAA are all involved in licensing U.S. commercial satellite systems; each agency has different degrees of oversight related to orbital debris.

Current orbital debris regulations focus on plans for mitigating production of debris and for properly disposing of debris that is produced. Absent from these regulations is a requirement for satellite owners or operators to provide data that will aid in assessing the debris environment. Figure 1 illustrates how anomaly data collection and distribution would fit into the agency roles and processes for orbital debris mitigation.

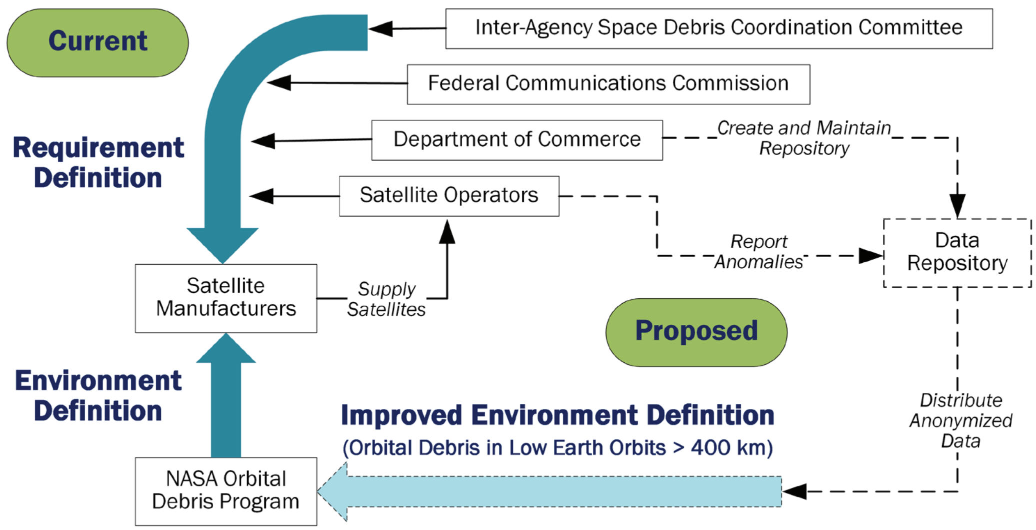

Figure 1. Relationship of Anomaly Data Collection and Distribution to Orbital Debris Mitigation

We propose that the Department of Commerce include in its data repository the location and tracking of objects and a mechanism to capture anomaly data caused by debris. Sharing anomaly data that has been tracked in a standard and consistent manner can lead to better understanding of the root causes of failures and, ultimately, to improved satellite designs.

Developing a transparent process and educating owners and operators about the benefits of submitting anomaly data to the data repository could motivate satellite owners and operators to take responsibility for fostering a safe space environment. Alternatively, the United States could make sharing anomaly data part of the mitigation portion of licensure applications or a prerequisite to receiving object catalog services. These data could be anonymized—the minimum data requirement would be satellite mass, original altitude, altitude change, and approximate time and location of impact. Satellite operators could voluntarily offer concurrent satellite information (system failures, satellite rotation, etc.) to strengthen the case for orbital debris impact as the source of the observed perturbation, and reduce uncertainties associated with the predicted orbital debris impact parameters.

Conclusion

Prior to launch, all U.S. Government agencies that operate satellites in LEO must meet requirements for assessing risks to a satellite from impact with debris smaller than 1 centimeter. The accuracy of risk assessments directly depends on the accuracy of orbital debris environment predictions. Overpredicting risk can lead to heavier satellites and higher launch costs.

NASA studies show that orbital debris 1–3 millimeters in size cannot be directly measured, but can be expected to cause serious or catastrophic damage to spacecraft in LEO, where the number of satellites is increasing rapidly. Current NASA orbital debris environment models and spacecraft assessment techniques for altitudes above 400 kilometers appear to overpredict the number of satellite impacts by a factor of 10 and the number of failures by a factor of 5. Clearly, better orbital debris environment data are needed for these altitudes to accurately predict the number of satellite impacts and failures, particularly as the use of LEO space expands.

NASA can use the technique outlined in this article to detect, validate, and improve ORDEM 3.0. Further, in line with the goals of Space Policy Directive-3, the Department of Commerce could incorporate anomaly data in its open architecture data repository to improve understanding of the orbital debris environment.

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