Characterizing the Orbital Debris Environment Using Satellite Perturbation Anomaly Data

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ABSTRACT

The untracked orbital debris environment is as one of the most serious risks to the survivability of satellites in high-traffic low Earth orbits, where acute satellite population growth is taking place. This paper describes a method for correlating observed satellite orbital changes with orbital debris impacts, and demonstrates how populations of small debris (< 1 cm) can be characterized by directly examining the orbit and attitude changes of individual satellites within constellations. The paper also presents means for detecting unusual movements and other anomalies (e.g., communication losses) in individual satellites and satellite constellations using space surveillance sensors and in situ methods. Finally, the paper discusses how an anomaly data archive and policy repository might be established, supporting an improved definition of the orbital debris environment in harmony with the President's Space Policy Directive 3.

1 SATELLITE CONSTELLATIONS AND UNTRACKED ORBITAL DEBRIS: A COLLISION COURSE

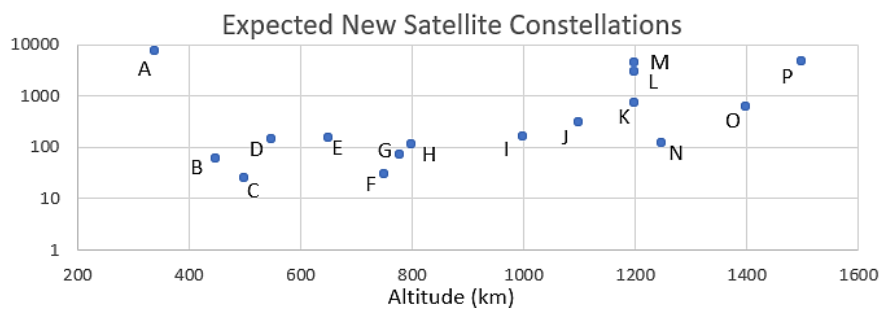
"Space Policy Directive 3: National Space Traffic Management Policy" calls for the timely and actionable characterization of space objects and their operational environments to support safe, stable, and sustainable space activities. The directive's goals include advancing the science and technology of critical space situational awareness (SSA) inputs, such as observational data and models to improve SSA capabilities; minimizing deficiencies in SSA capability, particularly in coverage regions with limited sensor availability and sensitivity for detection of small debris; updating debris mitigation guidelines, standards, and policies to mitigate the operational effects of orbital debris; and establishing new guidelines for satellite design and operation [1].

Historically, the National Aeronautics and Space Administration (NASA) Orbital Debris Program Office has taken a leading role in the characterization of small, mostly untrackable orbital debris in low Earth orbit (LEO), producing the Orbital Debris Engineering Model (ORDEM) [2]. ORDEM depends on post-flight observations of Shuttle radiators and windows to predict small orbital debris impacts—unfortunately, this source produced almost no data on impacts above 1mm in size. Ground-based staring radars, such as Goldstone and Haystack [3], can measure and predict orbital debris sizes down to 3 mm at the ISS orbit, leaving a critical gap in prediction for particle sizes of 1 mm to 3 mm. At higher altitudes (400 to 2000 km), this gap in prediction capability grows—not only because radar capability to detect small debris sizes deteriorates with altitude, but also because there has been no way to gather in situ data on smaller orbital debris strikes (< 1 mm) at these higher, critical altitudes. It is also noteworthy that existing in situ data based on post-flight observations of Shuttle impacts ceased with the last Shuttle flight in 2011. Some new method of gathering in situ data for impacts of all sizes under 3mm is clearly needed in order to calibrate existing NASA orbital debris models.

Why is examination of this 1mm – 3mm gap important? Table 1 and Figure 1 show that the number of satellites to be placed in LEO is expected to grow more than tenfold in the next decade [4]. Many of these satellite constellations will be placed into orbits where orbital debris (1 mm to 1 cm in size) is both untrackable and dangerous to satellite survivability. Although the precise design of these future satellites remains unknown, Table 1 shows the expected number of 1 mm, 3 mm, and 1 cm impacts these satellites would experience if they fall into the 1 m^2 "minisat" size regime (where the predicted number of impacts is computed by multiplying the expected flux × area × time).

Table 1. Expected Satellite Constellations [4] and Their Orbital Debris Impact Predictions Using ORDEM 3.0

				Debris Impacts per Year (2029) Assuming 1 m^2 Satellite Body		
Operator	**Number**	**Average Altitude (km)**	**Origin**	**≥ 1 mm**	**≥ 3 mm**	**≥ 1 cm**
A - SpaceX Vband	7518	340	US	211	0.1	0.009
B - Black Sky	60	450	US	6	0.0	0.000
C - Planet	24	500	US	5	0.0	0.000
D -Kepler	140	550	US	28	0.1	0.004
E - Spire	150	651	US	139	0.2	0.012
F - Orbcomm	30	750	US	51	0.1	0.006
G - Iridium	72	780	US	72	0.4	0.014
H - Theia	112	800	US	260	0.4	0.033
I - Xingyun	156	1000	China	317	0.3	0.017
J - Hongyan	300	1100	China	321	0.4	0.020
K - SpaceX Starlink	4425	1200	US	2496	4.6	0.174
L - Boeing	2956	1200	US	1667	3.0	0.116
M - OneWeb	720	1200	ESA	406	0.7	0.028
N - Telesat LEO	117	1248	Canada	45	0.1	0.005
O - Astrome Tech	600	1400	India	804	0.9	0.020
P - Samsung	4600	1500	Korea	9476	7.1	0.141
		Predicted Totals per Year		**16303**	**18**	**1**



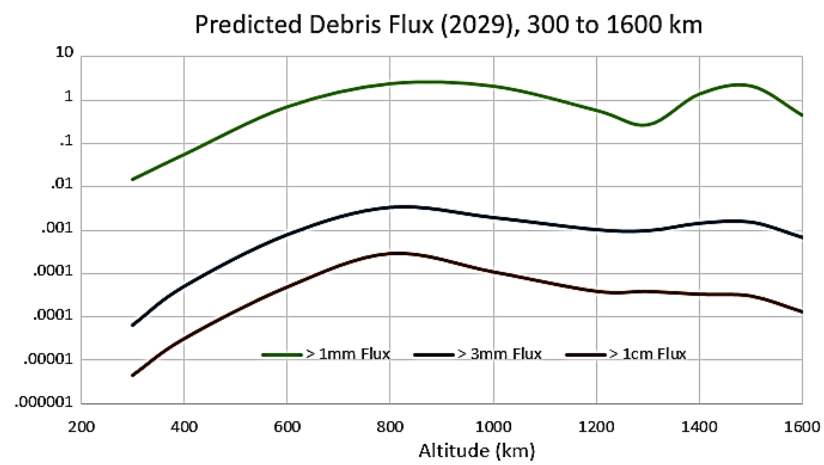


Figure 1. Predicted debris flux (particles/m2/year) and expected satellite constellations and their altitudes for the year 2029 [2] [4]. The letters shown in the top panel correspond to the letter designations of the new satellites given in Table 1.

As the chart shows, huge satellite constellations are being placed into altitudes where predicted orbital debris populations dangerous to satellite survivability (above 1mm) are high. But are these predictions accurate?

2 COMPARING ACTUAL SATELLITE FAILURES AND ANOMALIES TO THE PREDICTED ORBITAL DEBRIS ENVIRONMENT

Based on debris flux predictions from ORDEM 3.0, the new population of satellites expected in LEO by 2029 will face more than 10,000 orbital debris impacts of 1 mm size or larger each year (see Table 1). For these new satellite constellations, the prediction accuracy of the > 1 mm orbital debris size regime is vital to the survivability of these systems.

In 2017, the NASA Engineering and Safety Center (NESC) published a technical study, titled "Evaluation of Micrometeoroid and Orbital Debris Risk Predictions with Available On-Orbit Assets" [5]. The study compared observed anomalies across three operational satellite types that were attributed to micrometeoroid and orbital debris (MMOD) impacts with predictions of how many of those failures should have occurred using NASA's MMOD risk assessment methodology and tools. The NESC team used two methods. First, they compared actual satellite anomaly data to the predicted number of failures, considering a total of 73 separate spacecraft of three types at high-inclination orbits (> 85°) between 700 km and 900 km. The failure predictions and comparisons to anomaly observations were limited to one clearly defined failure mode—sudden leaks in pressurized batteries and propulsion tanks—that was most likely to be caused by a sudden orbital debris impact, and where the well-established pressurized tank design was not likely to leak from other causes. Considering this satellite group, a total of between 8 and 11 failures were predicted versus two anomalies actually reported, indicating that the orbital debris failure prediction process (either the environment, penetration assessment, or both) likely is overpredicting failures (or satellite owner-operators are underreporting anomalies). The range of orbital debris sizes causing failure differed from spacecraft to spacecraft, but varied from 1.5 mm to 4 mm—right in the range where the least information exists about the orbital debris environment—implying the desperate need for better in situ data on flux distributions in this critical size regime.

In this same NASA study, the researchers used a second methodology—an IDA-developed prediction technique—to correlate impacts with orbital debris of various sizes to reported motions of satellites in LEOs [6]. The relative velocity distribution of orbital debris particles, in 800 km nearly polar orbits, varies from approximately 1 km/s to 15 km/s for debris impacting the "side" and "front" of a spacecraft (perpendicular and normal to the velocity vector). Over 50% of impacts between 14 and 15 km/s occur nearly parallel and opposite to the spacecraft velocity vector (see Figure 2). When impacts occur under these conditions, there is a momentum exchange between the orbital debris particle and the satellite that causes the satellite to lose orbital velocity and, averaged over an orbital period, orbit at lower altitude (the average between apogee and perigee). The loss in average satellite altitude (delta satellite mean altitude) that results is highly dependent on the mass, velocity, and direction of the impacting particle, as well as the design of the satellite body that is impacted.

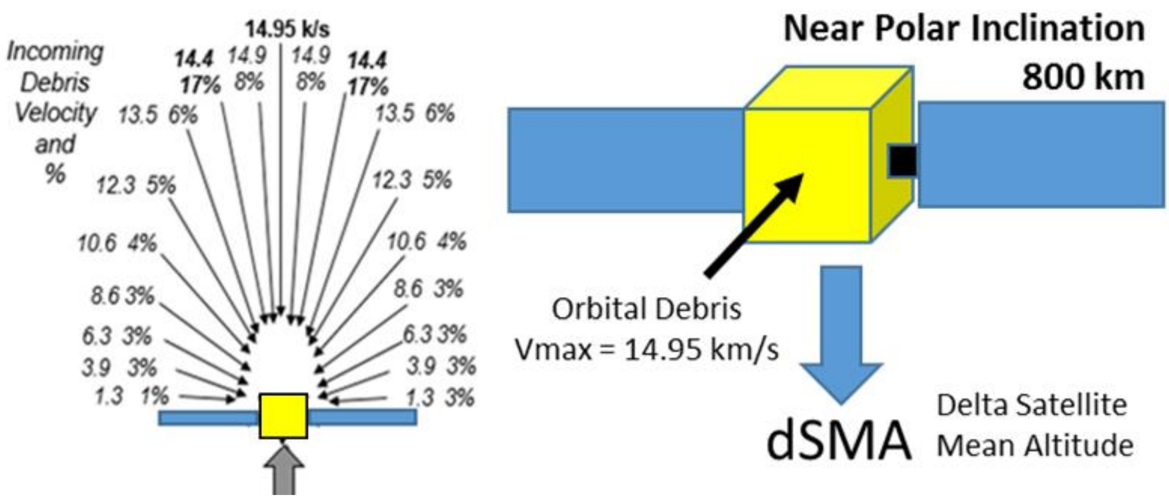


Figure 2. Predicted orbital debris relative impact velocities for an 800 km circular orbit [6]

IDA used hydrocode analyses (see Figure 3) to determine the effects of different orbital debris sizes, masses, velocities, and directionalities on both single plates and dual plates. These plates simulate subsequent layers in general satellite construction. Using this technique, IDA verified that the momentum of the impacting particle actually "multiplies" by a factor > 1 due to some of the original impacting debris and target material flowing backward, out of the damaged spacecraft, to act like a small rocket motor that further reduces the spacecraft's forward velocity and thus lowers the average satellite altitude. IDA established that this momentum enhancement factor (MEF) varies between 1.5 and 3, depending on spacecraft structure. Thin structures, such as spacecraft solar arrays, do not react as strongly to orbital debris impact, because the debris tends to go through them without depositing multiplied momentum.

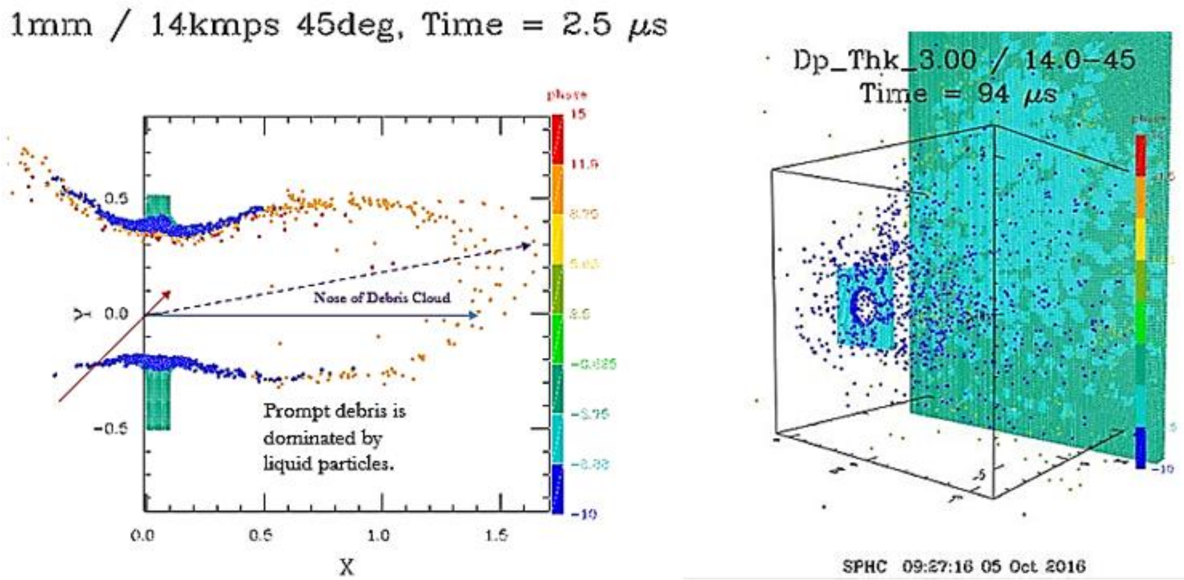


Figure 3. Debris clouds produced by simulated orbital debris impacts at 14 km/s [6]. Note that debris ejected backwards, outside the original first surface, causes a momentum multiplication effect relative to the original momentum of the orbital into the satellite. The x-axis and y-axis in the above graphs indicate distances in centimeters, and particle colors represent the physical phase of the produced debris cloud.

As stated earlier, the satellite mean altitude is defined as the average of the satellite's altitudes at perigee and at apogee (this average is equivalent to the semi-major axis), and is a useful term for expressing and computing the change in mean altitude before and after collision (i.e., the delta satellite mean altitude (dSMA)). For a simple illustration of the magnitude of the collision's effect on dSMA, IDA assumed the satellite initially is in a circular Keplerian orbit. The mathematics for relating orbital debris impact characteristics to changes in spacecraft velocity and altitude are given below. The instantaneous orbital velocity of the spacecraft is related to the spacecraft altitude as shown in Equation 1,

$$v^2 = (1/2)\, v_e^2\, (2/r - 1/a), \qquad (1)$$

where v is the orbital velocity, v_e is the escape velocity from Earth (11,200 m/s), and r and a are the spacecraft orbital radius and semi-major axis, respectively, both in units of the Earth's radius (6370 km, and with r = a for circular orbits).

After colliding with debris, the satellite will enter an elliptical orbit and have a new mean altitude or semi-major axis. Equation 1 allows for the computation of the original orbital velocity in circular orbit at radius a and of the orbital velocity immediately after impact, still at radius r but with the perturbed semi-major axis, a.

From the change in satellite velocity, dV, the mass of the impacting particle is then calculated using Equation 2, assuming near-normal incidence,

$$m_0 \times v_0 \times MEF = M \times dV, \qquad (2)$$

where m_0 is the impacting debris mass, v_0 is the impacting debris velocity, MEF is the momentum enhancement factor, and M is the mass of the satellite.

Table 2 shows how changes in altitude following orbital debris impact may be correlated for each satellite class to the size of the impacting particles (in this case, at a near-polar circular orbit and 800 km altitude for a 14.94 km/s impact). The detectable impacting particle size varies with the type of debris (steel or aluminum), the size and mass of the satellite, and the amount of orbit reduction (dSMA, in m) that can be detected by the satellite operator, the U.S. Space Command, or other entity. For example, it is possible to detect a 1.75 mm diameter or larger aluminum sphere, or a 1.25 mm steel orbital debris particle, impacting a minisat by means of a 3 m change in dSMA in the minisat's altitude. A nanosat weighs 100 times less, so it is possible to detect much smaller dSMA changes (0.38 mm aluminum, 0.27 mm steel) from impacting orbital debris size for an observed 3 m change in altitude. Knowing the design of a satellite's shields and its exposed area, one can compare the observed number of orbit changes of a given size over time (due to multiple debris impacts over time) to the expected number of orbit changes using the predicted orbital debris environment models (e.g., ORDEM 3.0 [2]). Usng this technique, we now have a way to compare the debris prediction models to the actual 1 to 3 mm debris population. This, in turn, has numerous ramifications, ranging from satellite design (shielding weight, spacecraft cost) to risk perception and management.

Table 2. Predicted Changes in Altitude from Orbital Debris Strikes for Three Satellite Classes at 800 km

	Minisat	Microsat	Nanosat
Mass (kg)	150	37	1.5
Body Area (m^2)	1	0.3	0.01

	Aluminum sphere dia (mm) at max velocity (~15 km/s) that causes dSMA		
dMSA (m)	Minisat	Microsat	Nanosat
20	3.30	2.07	0.71
15	3.00	1.88	0.65
10	2.62	1.64	0.56
5	2.08	1.30	0.45
3	1.75	1.10	0.38
2	1.53	0.96	0.33
1	1.22	0.76	0.26
0.5	0.97	0.61	0.21

	Steel sphere dia (mm) at max velocity (~15 km/s) that causes dMSA		
dMSA (m)	Minisat	Microsat	Nanosat
20	2.32	1.46	0.50
15	2.11	1.32	0.46
10	1.84	1.16	0.40
5	1.46	0.92	0.32
3	1.24	0.78	0.27
2	1.08	0.68	0.23
1	0.86	0.54	0.18
0.5	0.68	0.43	0.15

Total Steel plus aluminum	Expected dSMA occurrences for 1000 spacecraft, 800 km polar orbit, per year*		
dMSA (m)	Minisat	Microsat	Nanosat
20	2	21	34
15	6	35	43
10	16	68	57
5	69	172	87
3	167	303	113
2	306	454	135
1	732	868	175
0.5	1491	1487	216

*Based on impacts > 14 km/sec in orbit plane (~50% of flux). More occurances are possible considering all flux directions

The number of expected orbital changes (dSMA occurrences), as predicted using NASA's ORDEM 3.0 model, is listed at the bottom right of Table 2. Given large constellations, hundreds of hits of 1-3 mm particles are expected, if NASA's orbital debris model is correct. Clearly, a capability to resolve dSMA after an orbital debris strike will allow more data to be gathered on the orbital debris environment.

3 METHODS TO DETECT SATELLITE MOVEMENTS AND OTHER ANOMALIES

3.1 Ground-Based Radar and Laser Ranging

The U.S. Space Command's Space Surveillance Network (SSN) contains the largest collection of LEO-observing ground-based radars. The SSN sends object tracking and radar characterization data to the Combined Space Operations Center (CSpOC). The CSpOC uses the data to determine a space object's location and trajectory. For the majority of tracked objects, U.S. Space Command publicly distributes this orbital information (via www.space-track.org) in the form of two-line element sets (TLEs). The TLE data format contains the satellite's orbital elements and is used to predict orbital positions through propagation models. For a spacecraft in LEO, the accuracy that can be obtained with the current orbit models is on the order of kilometers within a few days of the epoch of the element set. The typical error growth for TLEs propagated with an analytical propagator is 1.5 km per day. The prediction error growth can be reduced to 100 m per day by treating TLE data as "pseudo-observations" and fitting an object's orbit to the pseudo-observations using a high-precision special perturbations propagator and traditional batch least-squares [7].

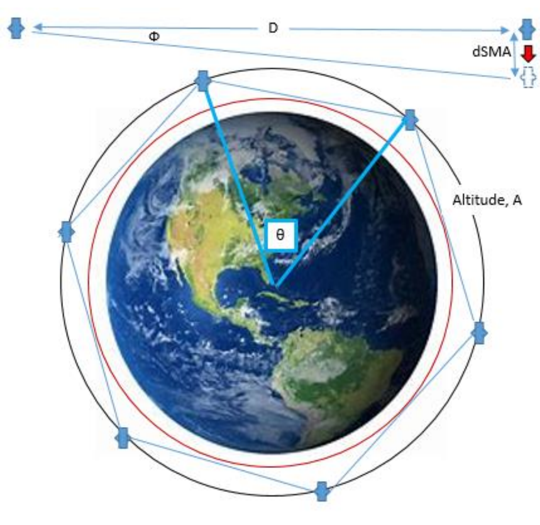
Although a 100 m (and even a 1 km) error is sufficiently small enough for radars to find and track specific objects, it is one to two orders of magnitude larger than the 0.5 to 20 m mean altitude change experienced by mini-, micro-, and nanosats when struck by millimeter-sized debris. The sensitivity and large field of view of Space Fence (an improvement to the SSN) will provide precision object tracking and increase the number of tracks per day, leading to both more precise knowledge of a space object's location and a better estimate of its trajectory. But unless a debris impact happens between two observations closely spaced in time (Space Fence and another radar), the error in the orbital propagation prediction may easily exceed the 0.5 to 20 m mean altitude change experienced by a satellite hit by millimeter-sized debris.

The CSpOC space object catalog contains a small number of well-understood satellites with accurately known positions (measured within 1 m), determined from either laser ranging or onboard beacons [8-9]. Some of the most precisely tracked satellites are geodetic satellites that are orbited for the purpose of establishing high-accuracy reference frames for precise measurement of Earth locations. Geodetic satellites carry various aids to facilitate their precise tracking to an accuracy of less than one m [10], well under the 20 m altitude change that may occur from a debris impact. These aids include laser reflectors, radio frequency transponders, and impulse light sources. These satellites are good candidates for monitoring sudden changes in altitude due to debris strikes. However, a mechanism needs to be established to ensure they are routinely lased and any deviations are reported so a potential debris strike can be investigated.

3.2 Monitoring Satellite Crosslinks in Constellations

Many current and planned future satellite constellations communicate through uplinks that send information from the ground to a satellite, satellite-to-satellite crosslinks that relay the information to a satellite near the intended recipient of the message, and a final downlink from that satellite to the recipient satellite. Sudden changes in satellite positions can be detected through loss of these crosslinks, whose beam widths (and sensitivity to changes in satellite position) vary with the technology used to transmit information. Optical methods send information through laser crosslinks. Because of their narrow beam angles, optical antennas require a pointing precision in the range of microradians, so they could easily detect a satellite position change of a meter or less and infer the minimum debris size that would cause such a change. For radio frequency links, pointing is less precise than with optical antennas since the radio frequency beam angles are much wider (generally on the order of 0.5 milliradians) [11].

Figure 4 shows the changes in pointing angle associated with typical satellite position changes from impacts of 1 to 20 dSMA. The times in green and yellow, in the associated table, show the linkage between changes in mean altitude and changes in pointing error that can be detected by broken Radio frequency and optical links. There is no way to directly measure the change in pointing angle; once the satellite rotates enough to break the link, the link is broken, but we don't know by how much. It's important to note that a simple loss of signal does not mean the satellite has moved, but might be associated with a change in guidance or reaction wheel response.



Sudden Change in Crosslink Pointing Angle Induced by dSMA for Various Satellite Constellations, Φ, milliradians (mr)

Altitude = 400 km — Number of Satellites in Plane

dSMA	6	7	8	9	10	11	12
20	NP*	NP*	NP*	NP*	4.77	5.24	5.70
10	NP*	NP*	NP*	NP*	2.39	2.62	2.85
5	NP*	NP*	NP*	NP*	1.19	1.31	1.43
3	NP*	NP*	NP*	NP*	0.72	0.79	0.86
1	NP*	NP*	NP*	NP*	0.24	0.26	0.29
Inter-Satellite Distance, km	NP*	NP*	NP*	NP*	4189	3819	3508

Altitude = 800 km — Number of Satellites in Plane

dSMA	6	7	8	9	10	11	12
20	NP*	3.21	3.64	4.07	4.51	4.94	5.38
10	NP*	1.61	1.82	2.04	2.25	2.47	2.69
5	NP*	0.80	0.91	1.02	1.13	1.24	1.35
3	NP*	0.48	0.55	0.61	0.68	0.74	0.81
1	NP*	0.16	0.18	0.20	0.23	0.25	0.27
Inter-Satellite Distance, km	NP*	6229	5494	4910	4436	4045	3716

Altitude = 1200 km — Number of Satellites in Plane

dSMA	6	7	8	9	10	11	12
20	2.64	3.04	3.45	3.86	4.27	4.68	5.10
10	1.32	1.52	1.72	1.93	2.14	2.34	2.55
5	0.66	0.76	0.86	0.96	1.07	1.17	1.27
3	0.40	0.46	0.52	0.58	0.64	0.70	0.76
1	0.13	0.15	0.17	0.19	0.21	0.23	0.25
Inter-Satellite Distance, km	7578	6576	5800	5184	4683	4270	3923

*NP = Not possible to have this few equally spaced satellites in a plane at this altitude, because crosslink signal will pass through earth atmosphere (< 50 km altitude)

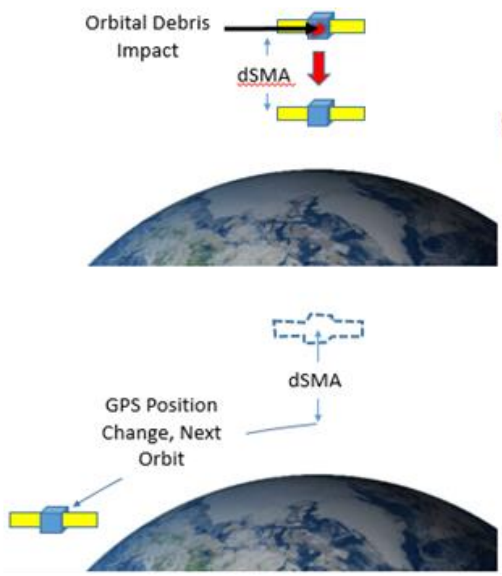
Movement induces > 0.50 milliradians pointing error, movement detection range for RF or laser crosslinks.

Movement range that would likely break laser-based crosslinks, but not RF-based crosslinks.

Figure 4. Change in crosslink pointing angle associated with sudden movement of satellites following debris impact

3.3 GPS Methodologies

The continuous monitoring of Global Positioning System (GPS) position information for LEO satellites is becoming a feasible way to detect sudden changes in their mean orbital altitude. Satellites in LEO can receive signals from GPS satellites, and because they have signal availability, signal navigation, and timing performance similar to that of terrestrial GPS users, they may compute their own position over the earth. Current GPS receivers for LEO that use dual antennas are advertised to have positional accuracies better than 15 m [12]. This error is too large to detect mean altitude changes less than 15 m, but new M-code GPS receivers are expected to have LEO positional errors of less than 4 m [13], allowing for the detection and estimation of altitude changes greater than and equal to 5 m (this indicates the art of the possible for mass produced operational receivers). Furthermore, studies show that 1 m accuracy is achievable with commercial off-the-shelf signal-frequency GPS receivers for LEO, and that accuracy can be improved down to 0.3 m using post-processed GPS orbit and clock products [14]. Figure 5 shows that a change of 0.5 m in altitude renders an along-track change in observed position along its track of about 1.5 m after just one orbital period, which should be detectable using commercial off-the-shelf signal-frequency GPS receivers for LEO. The satellite or ground station would continuously record its GPS position, and sudden changes to that position could then be correlated to potential debris strikes.



Change in Expected GPS Position in One Orbit (m)
Induced by Orbital Altitude Change (dSMA, m)

	Altitude, km		
dSMA, m	400	800	1200
-20	64.7	62.8	61.2
-15	48.5	47.1	45.9
-10	32.3	31.4	30.6
-5	16.2	15.7	15.3
-3	9.7	9.4	9.2
-2	6.5	6.3	6.1
-1	3.2	3.1	3.1
-0.5	1.6	1.6	1.5

Figure 5. Change in expected GPS position in one orbit induced by orbital altitude change.

3.4 Other In Situ Methods for Detecting and Reporting Anomalies

The attribution of altitude changes to debris impacts may be supported by correlating the altitude changes with changes in satellite telemetry state-of-heath [15, 16] and waveform characteristics (e.g., gain fluctuations and Doppler frequency shifts) [17], monitoring reaction wheel responses to sudden changes in the satellite's orientation, and detecting communication outages between satellites within constellations. The latter two possible data sources would both arise in response to sporadic changes in satellite orientation due to momentum transfer from debris. Reaction wheels would respond to the orientation change in order to maintain attitude control and, if the change in orientation is large enough, communications between adjoining satellites within a constellation could be interrupted.

4 COLLECTING AND DISTRIBUTING ANOMALY DATA

In addition to calling for the identification of new means to catalog debris data, Space Policy Directive 3 calls for the creation of minimum standards for safe satellite operation and mitigation of any associated debris. Furthermore, the policy directs the U.S. Government to provide guidelines to satellite and constellation owners and operators that consider maneuverability, tracking, reliability, and disposal, and that encompass all stages of satellite operation from design to end of life. A major focus of the policy is improving SSA data interoperability, including satellite and debris tracking as well as location predictions, to make the SSA environment safer to operate within [25]. All U.S. Government agencies (Department of Defense (DoD), NASA, National Oceanic and Atmospheric Administration

(NOAA), etc.) that operate satellites in LEO currently are required prior to launch to assess risks to the satellite (from loss of control or from loss of ability to dispose of the satellite at the end of the mission) from impacts with small debris (< 1 cm).

In the United States, different agencies have various roles in monitoring and regulating the space environment. The 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, the international group that coordinates space debris research activities between member space agencies, reviews the 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 operational debris produced during the mission and to limit the probability that the satellite will become a source of debris [18]. 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. A major focus of FAA debris mitigation regulation is reentry debris. NOAA issues licenses for remote sensing space systems, and one requirement is that the licensee assess and minimize the amount of orbital debris associated with the satellite's disposal.

The FCC, FAA, and NOAA are all involved in the licensing of U.S. commercial satellite systems, with each agency having different oversight related to orbital debris. DoD and NASA are involved in assessing the orbital debris environment, with NASA leading the effort and relying on DoD to provide satellite object data. Current orbital debris regulations focus on plans to mitigate against creating debris and plans to properly dispose of debris that is created. Absent from these regulations is a requirement for satellite owners or operators to provide data that will aid in assessing the debris environment. Figure 6 shows the potential relationship of anomaly data collection and distribution to satellite design and operating processes for orbital debris risk assessment and mitigation.

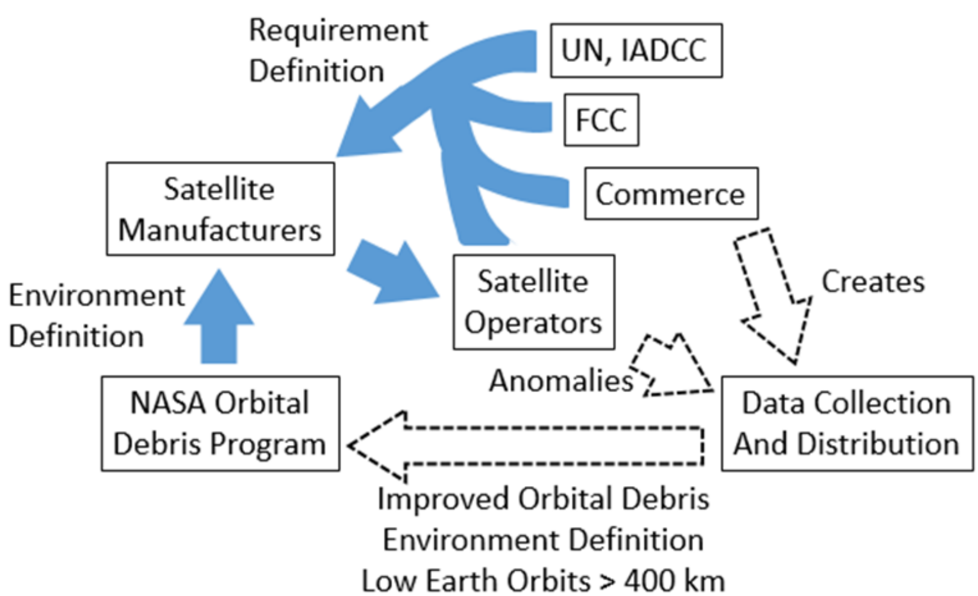


Figure 6. Relationship of anomaly data collection and distribution to design processes for orbital debris mitigation

We propose the creation of an anomaly data archive to support an improved definition of the orbital debris environment in harmony with Space Policy Directive 3. Anomaly data are relevant within Space Policy Directive 3 because of its goal to create a safer operating environment as well as to establish new guidelines for satellite design and operation. Currently, satellite owners and operators rely on the ORDEM 3.0 debris model to predict the number of anomalies or failures. Collecting and tracking satellite anomaly data will greatly improve the model and allow for a more realistic assessment of the true debris environment. Also, anomaly data could be an important aspect of the open architecture data repository called for in Space Policy Directive 3. In fact, tracking anomaly data in a standard and consistent manner and sharing the data with satellite owners and operators can ultimately lead to improved designs and a better understanding of the root causes of failures. As the Department of Commerce (DoC) develops the SSA data repository architecture, they should not only include the location and tracking of objects but also consider a mechanism to capture anomaly data caused by debris. Figure 10 shows the potential relationship of an independent anomaly data collection and distribution entity to the existing orbital debris design community. Educating owners and operators about the benefits of submitting such anomaly data may convince them to submit their data to help create a safer operating environment for their satellites as well as for other satellites.

Creating a transparent, simple process for submitting anomaly data to DoC's data repository might be sufficient to motivate satellite operators to take responsibility for fostering a safe space environment. However, if the goodwill approach is not enough, the U.S. could adopt requirements into the space regulatory environment that compel U.S. owners and operators to provide anomaly data. The FCC, FAA, and NOAA could extend the debris mitigation plan portion of their licensure application process to require owners or operators to provide anomaly data to the DoC data repository. Alternatively, agreeing to share anomaly data could be made a requirement for receiving DoC object catalogue services (currently provided by DoD). Anomaly data could be anonymized—all that would be required is satellite mass, original altitude, the altitude change, and the approximate time and orbital location of impact. Other concurrent satellite failure information could be offered by satellite operators on a voluntary basis to strengthen the case for orbital debris impact as the source of the observed perturbation.

5 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

The 2018 national Space Policy Directive 3 calls for "advancing the science and technology of critical space situational awareness inputs such as observational data…[and] models necessary to improve SSA capabilities…particularly in coverage regions with limited sensor availability and sensitivity in detection of small debris…[and updating] debris mitigation guidelines, standards, and policies…to mitigate the operational effects of orbital debris" [1]. Prior to launch, all U.S. Government agencies (DoD, NASA, NOAA, etc.) that operate satellites in LEO must meet requirements for assessing risks to a satellite (from loss of control or from loss of ability to dispose of the satellite at the end of the mission) from impacts with small debris (< 1 cm). The accuracy of risk assessments is directly dependent 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 mm to 3 mm in size cannot be directly measured, but can be expected to cause serious or catastrophic damage to spacecraft in LEO, where acute growth of satellite numbers is occurring. Current NASA orbital debris environment models and spacecraft assessment techniques for altitudes above 400 km 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.

This paper has outlined a technique for using small changes (1 to 20 m) in satellite mean altitude to calculate the size of small, untrackable orbital debris particles that impact satellites. NASA can also use these mean altitude changes as a "detector" to validate and improve their orbital debris model (ORDEM 3.0), which is the primary tool used to perform required satellite risk assessments. A variety of techniques are available for determining the magnitude of vertical movement (from 1 to 20 m) of satellites following debris hits of 1 to 4 mm (depending on satellite design). Some of the most promising include monitoring a satellite's GPS position and its ability to maintain communication crosslinks with the neighboring satellites in a constellation. Using reported data on internal spacecraft anomalies (failures) that accompany a rapid change in orbital position would also improve confidence in current orbital debris models.

A major goal of Space Policy Directive 3 is to improve data collection and data processing to better track and predict locations of satellites and debris. 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 anomaly data and other satellite information within a common framework. Improved debris models will lead to a better understanding of the debris environment and more accurate predictions. Creating an easy, transparent process for submitting anomaly data to DoC's data repository could be sufficient to motivate satellite operators to take responsibility for fostering a safe space environment. If not, however, the U.S. government could adopt requirements into the space regulatory environment; U.S. owners and operators could be mandated to provide anomaly data. The FCC, FAA, and NOAA could extend the debris mitigation plan component of their licensure application process to require owners and operators to provide anomaly data to the DoC data repository.

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