Assessing the Operational Impacts of Orbital Debris

Dr. Benjamin Skopic, Dr. Cameron Liang, Dr. Hannah Yi

Institute for Defense Analyses

ABSTRACT

Space is becoming more crowded with both satellites and orbital debris as more proliferated constellations come online. Although the risk of Kessler syndrome remains a topic of intense debate, the effects of increased maneuvering pose a significant risk to satellite operations. More frequent collision conjunctions in increasingly congested orbits will compel operators to perform more maneuvers; degrading a satellite's real-time performance and reducing its overall operational lifespan. To quantify these mission-level impacts, IDA developed the Space Environment Risk Prediction by Evaluating Numerical Simulations (SERPENS) model. SERPENS uses a numerical propagator to determine orbits, evaluate conjunctions, execute maneuvers, and perform mission tasks. Using SERPENS, we show how the operational availability (A_o) of the Flock constellation is impacted by the current debris environment and notional debris-generating events. Quantifying the operational impact of debris-generating events enhances the ability to forecast mission readiness and the on-orbit lifespan of satellites.

1. INTRODUCTION

Colliding with orbital debris is a significant and increasing hazard for satellites, with tens of measurable debris creating events occurring annually. Studies that extrapolate this hazard into the future agree that the rate of debris-generating collisions will increase [1, 2, 3], which may render entire orbital regions unusable [3]. As satellite constellations expand and orbital activity intensifies, understanding the implications of orbital debris on satellites is essential for sustaining safe and reliable space operations [4].

When two space objects are predicted to pass near each other and potentially collide, the U.S. Space Force's 18th Space Defense Squadron (SDS) sends a conjunction data message (CDM) to the satellite operator [5, 6]. The information in the CDM includes the probability that the conjunction will result in a collision (P_c). It is then up to the operator to decide what risk mitigating actions, such as an orbital maneuver, they may execute based on the operators' risk tolerance threshold [5]. The 18th SDS sends a CDM if the change the conjunction will result in a collision less than is 1 in 10,000 ($P_c > 10^{-4}$) but operators can assess their own risk tolerance threshold. SpaceX, for example, uses 1 in 1 million ($P_c > 10^{-6}$) [7]. Both CDMs and resultant collision avoidance maneuvers are becoming more frequent; in 2022, SpaceX was conducting six maneuvers per satellite per year on average [8]; in 2025, they are conducting 35 [7]. These maneuvers not only interrupt primary mission activities, leading to data collection gaps and temporary service outages, but also consume onboard fuel—reducing operational lifespans and limiting end-of-life disposal capabilities. The cumulative effect of these disruptions can degrade mission reliability and increase the total cost of operating a constellation of satellites. In worst-case scenarios, where warnings are missed or avoidance maneuvers are unsuccessful, the outcome—asset loss due to debris impact—yields a persistent and costly threat.

Existing orbital debris analyses focus on statistical trends or system-wide implications, leaving a gap in understanding for how debris risk translates into specific operational burdens for individual spacecraft [1, 3]. Without quantification on a satellite-by-satellite or constellation level, it's difficult to assess the interplay of mission design, orbit selection, and risk tolerance variables with debris-driven constraints. This lack of fidelity limits the development of tailored mitigation strategies and obscures the true cost of debris-related disruptions. The impact of these unknowns is further compounded when considering transient effects from debris-generating events such as collisions or anti-satellite (A-SAT) attacks. Work has been done to model hypervelocity impacts between objects in space [9, 10]. These models cannot capture the exact trajectory of a debris immediately following an arbitrary debris generating event, creating substantial uncertainty in the transient mission-level impacts on nearby satellites.

Here, we use the Space Environment Risk Prediction by Evaluating Numerical Simulations (SERPENS) model to quantify how the variability in debris cloud formation and propagation impact mission-level satellite operations in the hours immediately following a debris generating event. We first quantify the impact that the current orbital debris-environment has on a test constellation: Flock. To then investigate the compounded impacts of additional debris generating events, we simulate several events that add debris to the existing debris environment, and evaluate how the resultant environments change the operational availability (A_o) of the Flock constellation.

2. METHODOLOGY & ASSUMPTIONS

Satellite TLE data were obtained from CelesTrak.org on July 30, 2025 [11]. The debris TLE information was obtained from SpaceTrack.org January 30, 2025 [5]. SERPENS is a N-body simulation code that propagates objects, predicts collision probability, performs collision avoidance maneuvers, and predicts mission availability. SERPENS uses the TLE information to initialize orbits using the *hapsira* python package [12]. *Hapsira* is a numerical orbit propagator that provides accurate positioning information for all objects in SERPENS.

We determine potential conjunctions using the 18th SDS near-Earth conjunction calculation for P_c [13, 14]. For these calculations, one object is predetermined as the primary object and the other is the secondary. At the time of closest approach (TCA) between the two objects, the geometry of the collision can be reduced into a 2-dimensional plane where the primary object is at the origin. For computational efficiency, we use the first order approximation P_0 for P_c derived by reference [15]:

$$P_c \approx P_0 = \exp\left[-\frac{1}{2}\left(\frac{\mu_x^2}{\sigma_x^2}+\frac{\mu_y^2}{\sigma_y^2}\right)\right]\left[1-\exp\left(-\frac{R^2}{2\sigma_x\sigma_y}\right)\right], \quad \text{Eqn. 1}$$

where R is combined radii of the two objects as approximated as spheres, μ_x/μ_y are the coordinates of the secondary object in the collision plane (i.e., the radius of closest approach (RCA)), and σ_x/σ_y are the overlapping covariances of the two objects projected into the collision plane [16, 17]. σ_x/σ_y are calculated using the covariances of each object in the conjunction. In all simulations, we assume constant covariances for all satellite and debris independent of object size and time [18].

The present study assesses the impact that debris has on satellites. Therefore, we only consider conjunctions between satellites and debris, omitting satellite – satellite and debris – debris conjunctions. This has the added benefit of substantially reducing the number of conjunction computations required.

We use the calculated P_c from conjunction assessments to determine A_o on a satellite-by-satellite basis. Since operators have different risk tolerance thresholds, we conducted our analysis using: 10^{-8}, 10^{-6}, and 10^{-4}. When a conjunction assessment has a P_c value greater than the threshold, the satellite is threatened and we assume that the satellite is not available to execute its mission. The A_o calculation is:

$$A_o = \frac{\#\,satellites - \#\,satellites\ not\ avialable}{\#\,satellites}. \quad \text{Eqn. 2}$$

We assume a satellite is not mission available for 1 minute due to a potential conjunction. This assumption accounts for the necessary time to protect the satellite prior to a collision avoidance maneuver, the maneuver itself, and the time to begin operating the satellite again. The duration for mission unavailability due to this process is typically longer than one minute. Here, the short duration of unavailability is assumed to investigate the theoretical minimum impact due to these debris-generating events. In reality, the duration could be much longer and thereby further decreasing the time for normal operations [19]. We evaluate Eqn. 2 for every timestep of the simulation to determine $A_o(t)$.

The Flock constellation has 97 satellites, each at an altitude of 400–515 km and an inclination of 97° all in a single orbital plane. We selected this constellation because it has similar orbital parameters to other constellations such as Starlink, Amazon's Kuiper constellation, and the U.S. Space Development Agency's (SDA) tranches.

To notionally generate debris, we simulate a catastrophic event where all five NOAA satellites simultaneously collide with debris. The NOAA constellation resides at an altitude of 800 km and an inclination of 98° in different orbital planes. The debris is generated using the smooth hydrodynamics particle code (SPHC) [9, 10] based on the collision between a representative 150 kg satellite, with a 1 m^3 bus, and a 30 cm aluminum hollow sphere representing orbital debris. In this notional collision scenario, the satellite and debris are moving at 7 km/s and 3 km/s, respectively, for a head on 10 km/s relative velocity impact. SPHC generates 100k unique debris particles with masses ranging from 26 kg to 10 µg and effective diameters ranging from 0.5 m to 1 mm. Since the 18^{th} SDS can only track objects with effective diameters > 10 cm [5], we only simulate the largest 100 SPHC debris particles that are larger than 10 cm. The notional SPHC results were transformed into the position and velocity of the specific NOAA satellites at the instant we predetermine the notional debris generating events to occur. In all our simulations, the starting epoch is January 1, 2025 at midnight and the collisions occur simultaneously 10 minutes into the simulation. Although these synchronized collisions of a single constellation are unlikely, the scenario emulates an increasingly plausible case where multiple collisions occur within close proximity of each other in a short period of time [3].

We introduce variation into the notional debris generating scenario by perturbing the initial velocity of the calculated SPHC debris objects. The perturbed velocities are calculated by:

$$\vec{v}_{0,i} = \vec{v}_{SPHC,i} + \delta v, \qquad \text{Eqn. 3}$$

$$\delta v = rand[-1, 1] * \eta_v * \vec{v}_{SPHC,i}, \qquad \text{Eqn. 4}$$

where $\vec{v}_{0,i}$ is the velocity of each i debris object we initialize within SERPENS, $\vec{v}_{SPHC,i}$ is the velocity of each i debris object as calculated by SPHC, and η_v represents the maximum perturbation from $\vec{v}_{SPHC,i}$. In this study, we investigate $\eta_v = 0$, 0.15, and 0.3. The magnitude of the velocity perturbation for each i debris object is scaled by a random number between -1 and 1 to introduce uncertainty in the debris cloud generated by SPHC.

3. RESULTS & DISCUSSION

The existing debris environment causes the A_o of the Flock constellation to deviate from 100% depending on the risk tolerance threshold as shown in Fig. 1. The Flock constellation experienced 95 conjunctions with $P_c > 10^{-6}$ during the 18-hour period modeled. On average, per hour, each satellite has a ~5% probability[1] it will experience a conjunction with $P_c > 10^{-6}$. We used this result as a benchmark to validate the methodology. Exact conjunction information for the Flock constellation is publicly unavailable. However, historical conjunction data are available for the Starlink constellation, which includes satellites with orbits similar to the Flock constellation but also occupies many more diverse orbital planes. During a 6-month period at the end of 2024, SpaceX conducted 50,666 collision avoidance maneuvers for their ~7000 satellites in all orbital regimes when $P_c > 10^{-6}$ [7]. On average, per hour, each Starlink satellite has a ~0.2% probability it will experience a conjunction with $P_c > 10^{-6}$. This is about 10 times less frequent than we predict Flock will have conjunctions. Considering Starlink satellites are in many more orbital planes than Flock, with varying amounts of debris, we evaluate SERPENS to be accurate for order-of-magnitude evaluations of P_c for potential conjunctions and effects of orbital debris on satellites' A_o for large number of conjunctions and satellites.

---

[1] Probability was calculated by dividing the number of conjunctions the constellation experiences with $P_c > 10^{-6}$ within a given time period by the number of satellites within the constellation and the given time period in hours (e.g., (95 conjunctions with $P_c > 10^{-6}$ per 18 hours for Flock constellation / 97 satellites in the Flock constellation) / 18 hours).

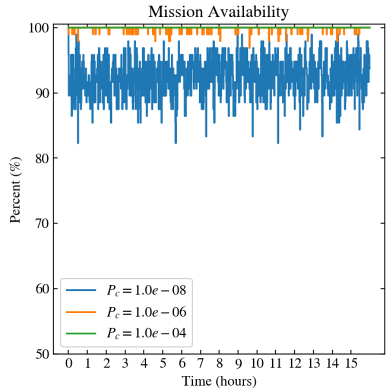

Fig. 1: A_o for the Flock constellation for 18 hours in the existing debris environment.

With the baseline, existing debris environment established, we introduce additional debris by simulating several collision events between satellites in the NOAA constellation and notional debris objects. We simulate the same debris-generating events using three values of η_v: 0, 0.15, and 0.3. For each η_v, we measure A_o for the Flock constellation using three risk tolerance thresholds: 10^{-8}, 10^{-6}, and 10^{-4}. The $\eta_v = 0$ case, plotted in Fig. 2a, is a perfectly deterministic simulation that applies the SPHC results exactly as they are to each of the NOAA satellite breakups. Compared with the results from the existing debris environment, the notional debris-generating event further reduces A_o. For the 10^{-4} risk tolerance threshold, the Flock constellation went from 100% A_o during the entire 18-hour simulation for the existing debris environment to as low as 95% availability during the first 18-hours after the notional debris generating event. This result is amplified if operators' base maneuvers on lower risk tolerance thresholds. The Flock constellation, using the 10^{-8} risk tolerance threshold, experience a ~40% reduction in A_o within the first 3 hours for the same debris-generating event. A_o gradually increases as time advances due to the debris clouds becoming more dispersed and some objects de-orbiting. The simulation duration does not allow for an evaluation of the new steady-state debris environment after the notional debris generating event. However, we expect A_o to be lower than prior to the event due to some debris remaining in stable orbits.

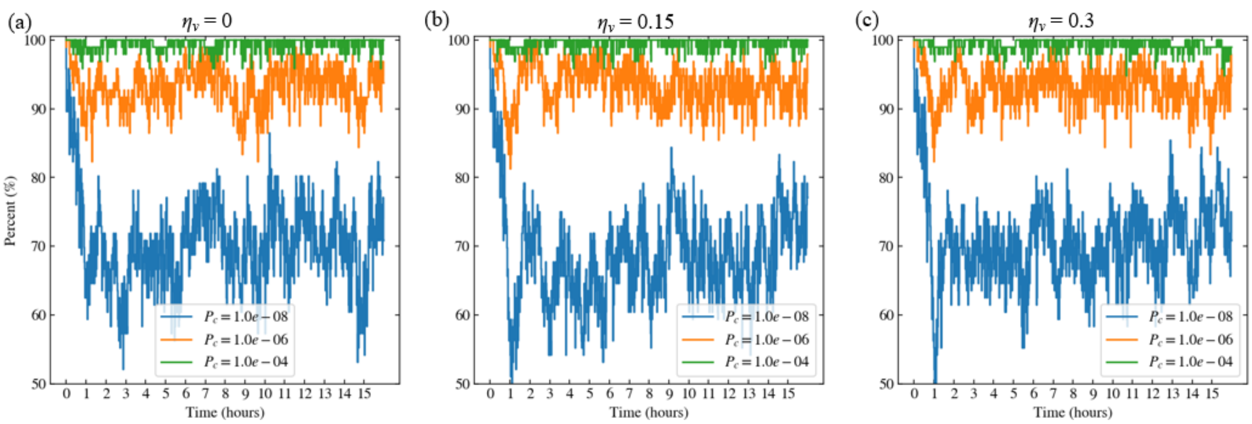

Fig. 2. A_o of the Flock constellation after the NOAA constellation notionally collides with debris, generating more debris. (a) Debris generation with no variation from notional SPHC results of a similar collision. (b) Same collision scenario in (a) but debris is generated with at most 15% variation from the initial velocity vectors calculated by SPHC for each debris object. (c) Same collision scenario in (a) but debris is generated with at most 30% variation from the initial velocity vectors calculated by SPHC for each debris object.

The $\eta_v = 0.15$ and 0.3 cases are stochastic due to the random sampling of the initial velocity of debris particles. The results for these cases, shown in Fig. 2b and c are single randomized instances of these stochastic simulations. A_o for the different risk tolerance thresholds in both stochastic simulations follow the same trends as the deterministic case.

Since the SPHC simulated breakups are notional, the three results in Fig. 2 can be treated as possible initial conditions for the debris clouds formed from the notional NOAA collisions. Although the individual peaks and valleys of A_o are different in the time series (due to the difference of the initial debris velocities via η_v), one can conclude the *average* degrades are similar in magnitude. For a more direct comparison of the variance, we compare these three possible instances of initial conditions in Fig. 3 as percent difference from the deterministic $\eta_v = 0$ case. We observe that A_o can vary up to 15%, 10%, and 5% depending on risk tolerance thresholds of 10^{-8}, 10^{-6}, and 10^{-4}, respectively, due to variations in the initial debris cloud conditions. However, we do not observe that the magnitude of variation of the initial conditions introduced by the $\eta_v = 0.15$ and 0.3 cases had any substantial effect on the variation of A_o. Our results suggest that risk tolerance threshold impacts an operator's ability to predict A_o for their constellation more than the uncertainty in the initial conditions of the velocity of debris following orbital collisions.

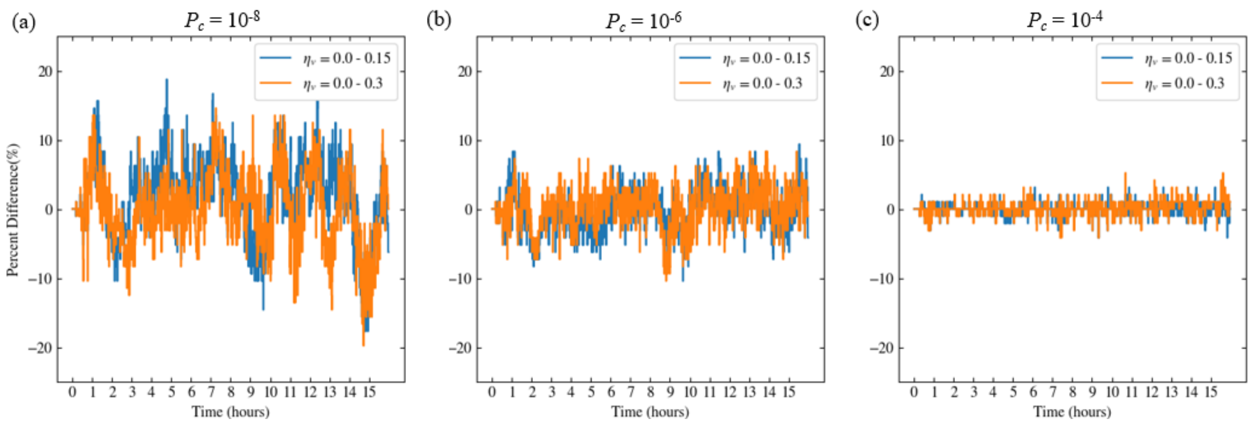

Fig. 3. Percent difference[2] of A_o for the Flock constellation of the two uncertainty values from the $\eta_v = 0\%$ deterministic case because of the notional debris generation. Three different risk tolerance thresholds are evaluated for each possible future: P_c = (a) 10^{-8}, (b) 10^{-6}, and (c) 10^{-4}.

Satellite operators select risk tolerance thresholds based on mission criticality, operational costs, and programmatic risk tolerance. The risk tolerance threshold for a constellation is often fixed as part of mission planning and execution. The number of conjunctions that have P_c greater than any risk tolerance threshold is dependent on the number and quality of debris tracks provided by space situational awareness (SSA) assets. More orbital debris will inherently cause more conjunctions to be identified. Reducing the amount of orbital debris is essential to keeping A_o as high as possible. Additionally, improving SSA capabilities will reduce uncertainty of tracked object's orbits. If there is less uncertainty that potential conjunctions will result in a collision, P_c will be lower for all conjunctions and keep A_o high for operators regardless of risk tolerance threshold.

It is important to interpret these results in the context of the methodology and assumptions made. The artificial debris scenarios were initialized at a single epoch; variations in the starting positions of the Flock and NOAA constellations may lead to different results. The covariances used for each object in our simulations were identical and time-independent; true covariances periodically update and evolve with time. We modeled each collision using the same notional SPHC result; each collision should be modeled in detail to better understand initial debris cloud conditions. Finally, the debris used to represent the debris-related risk to satellites in this study is only *tracked* debris objects that are larger than 10 cm. Untracked debris < 10 cm represent the majority of debris on orbit and pose a substantial risk that has only been quantified statistically [1, 3].

4. CONCLUSIONS

The risk of orbital collisions between operational satellites and debris has been well characterized. However, the threat of orbital debris extends beyond catastrophic failure and includes temporary mission-unavailability of the satellite

[2] Percent difference is calculated by: $\frac{(\#\ satellites\ available\ in\ deterministic\ case) - (\#\ satellites\ available\ in\ stochastic\ case)}{\#\ satellites\ in\ constellation}$

when it maneuvers to avoid a potential collision. In the present study, we quantify this risk as mission availability (A_o) on a satellite-by-satellite basis for the Flock constellation. We first represent the risk due to debris as the existing debris on orbit. As expected, the Flock constellation has lower A_o for lower risk tolerance thresholds; satellites encounter more conjunctions with lower P_c and are forced to maneuver if they operate with a low risk tolerance threshold. We then introduce additional orbital debris by notionally causing the satellites in the NOAA constellation to simultaneously collide with debris objects and investigate the impacts to A_o for the Flock constellation. We found that the notional debris generating event causes A_o to drop by up to 40% within 3-hours of the notional collisions if the constellation is operating with a 10^{-8} risk tolerance threshold. A_o drops less if the constellation operates with a higher risk tolerance threshold. We also investigated the impact of degree of uncertainty in the initial conditions of the generated debris but found that this did not have a short-term impact on the average A_o, regardless of risk tolerance threshold. In summary, we quantify the transient risk to particular satellites immediately following a notional debris-generating event. Our results should motivate mission planners and satellite operators to conduct similar debris-risk analyses for their own constellations to better understand, mitigate risk, and increase satellites mission availability in their debris environments.

5. REFERENCES

[1] C. Liang, P. Fanto and A. Signoracci, "On the Risk of Kessler Syndrome: A Statistical Modeling Framework for Orbital Debris Growth," *The Journal of the Astronautical Sciences,* vol. 71, no. 45, p. 22, 2024.

[2] J. Liou, D. Hall, P. Krisko and J. Opiela, "LEGEND - a three dimensional LEO-to-GEO debris evolutionary model," *Advances in Space Research,* vol. 34, no. 5, pp. 981-986, 2004.

[3] D. J. Kessler and B. G. Cour-Palais, "Collision frequency of artificial satellites: The creation of a debris belt," *JGR Space Physics,* vol. 83, no. A6, pp. 2637-2646, 1978.

[4] A. D'Ambrosio and R. Linares, "Carrying Capacity of Low Earth Orbit Computed Using Source-Sink Models," *JSR,* vol. 61, no. 6, 2024.

[5] SpaceTrack, "SpaceTrack API," 30 January 2025. [Online]. Available: https://www.space-track.org/. [Accessed 30 January 2025].

[6] 18th & 19th Space Defense Squadron, "SPACEFLIGHT SAFETY HANDBOOK FOR SATELLITE OPERATORS," Combined Force Space Component Command, Vandenberg Space Force Base, 2023.

[7] P. B. Selding, "SpaceX's Semi-Annual Update on Starlink Network Health, Failure Rate, Collision Risk: Why Don't All Constellations Provide This Data?," Constellations, 15 January 2025. [Online]. Available: https://www.kratosdefense.com/constellations/articles/spacex-semi-annual-update-on-starlink-network-health-failure-rate-collision-risk. [Accessed 26 July 2025].

[8] T. Pultarova, "SpaceX Starlink satellites had to make 25,000 collision-avoidance maneuvers in just 6 months — and it will only get worse," Space.com, 6 July 2023. [Online]. Available: https://www.space.com/starlink-satellite-conjunction-increase-threatens-space-sustainability. [Accessed 26 July 2025].

[9] H. Yi, J. Williamsen, R. Stellingwerf and D. Pechkis, "Creation of Lethal Debris from Meteoroid and Orbital Debris Impacts on LEO Solar Array Materials," in *17th Hypervelocity Impact Symposium*, Tuskuba, 2024.

[10] B. Corbett, J. Williamsen, R. Stellingwerf and M. Squire, "Smooth Particle Hydrodynamic Code Predictions for Meteoroid Damage to Thermal Protection Systems Shielded by Composite Structures," in *17th Hypervelocy Impact Symposium*, Tsukuba, 2024.

[11] Celestrak, "Celestrak," 30 July 2025. [Online]. Available: https://celestrak.org/. [Accessed 30 July 2025].

[12] Hapsira, "Hapsira - Astrodynamics in Python," Read the Docs, 2023. [Online]. Available: https://hapsira.readthedocs.io/en/stable/. [Accessed 26 July 2025].

[13] National Aeronautics and Space Administration, "NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook," NASA, Washington, DC, 2020.

[14] Y. Zhang, B. Li, H. Liu and J. Sang, "An analysis of close approaches and probability of collisions between LEO resident space objects and mega constellations," *Geo-spatial Information Science,* vol. 25, pp. 104 - 120, 2022.

[15] X.-Z. Bai and L. Chen, "An algorithm of space debris collision probability based on space compression infinite series," *Acta Mathematicae Applicatae Sinica,* vol. 32, no. 2, pp. 336 - 352, 2009.

[16] S. Hesar, "Coordinate Frame, Ephemeric & Covariance File Formats," in *SSA Operators' Workshop*, Maui, 2018.

[17] J. H. J. Frisbee, "An Upper Bound on High Speed Satellite Collision Probability When Only One Object has Position Uncertainty Information," in *AAS/AIAA Astrodynamics Specialist Conference*, Vail, 2015.

[18] Space-Track, "Public Conjunctions," Space-Track.org, 31 January 2025. [Online]. Available: https://www.space-track.org/conjunctions. [Accessed 31 January 2025].

[19] C. Duster, "The International Space Station adjusts its orbit to avoid space debris," NPR, 20 November 2024. [Online]. Available: https://www.npr.org/2024/11/20/nx-s1-5196986. [Accessed 5 August 2025].