Proximity Risks and Policy Gaps in the LEO Constellation Era

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Abstract

Low Earth Orbit (LEO) is becoming increasingly congested as satellite constellations expand, debris accumulates, and more spacecraft gain maneuvering capability. Using publicly available orbital data from 2020–2025, we find that debris from individual launch and fragmentation events exposes satellites to recurring close approaches for many years. Close approaches (conjunctions) between satellites have increased by over two fold. We also identify a small number of unexplained cases in which satellites operated by different countries repeatedly approach and maneuver near one another, warranting further review. Our findings highlight the importance of debris prevention, scalable conjunction-management capabilities, and greater transparency for sustained proximity operations.

1 Introduction

Low Earth orbit (LEO) satellite systems are becoming a critical component of communications, navigation, and sensing infrastructure. Today, more than 12,000 LEO satellites are already in orbit. However, to meet growing demand, filings from governments and commercial operators propose constellations that could expand this population to more than 2.3 million satellites [23]. Despite LEO's anticipated rapid growth, there is no universally accepted minimum separation distance between independently operated spacecraft in LEO. Operators must navigate an increasingly crowded environment without a common standard for how closely spacecraft may safely approach one another. These conditions reflect longstanding concerns about an orbital environment that U.S. space policy has described as "congested, contested, and competitive" [37].

Proximity in LEO creates several distinct operational and security risks. Uncontrolled debris and spent rocket bodies can remain in orbit for decades. These close approaches, commonly called conjunctions, require operators to assess potential collision risk. At the same time, the rapid growth of large constellations is increasing the frequency of close approaches between operational satellites, placing greater demands on tracking, conjunction assessment, and collision-avoidance coordination.

Satellite maneuverability further introduces a dual-use challenge. The capabilities needed for collision avoidance, station keeping, servicing, and other legitimate missions also enable rendezvous and proximity operations (RPO), including close approach, inspection, and potential interference with other spacecraft [6]. Public reports have documented several concerning proximity-operation incidents, including Chinese satellites conducting sustained coordinated maneuvers described as "satellite dogfighting" [18].

Despite growing policy concern, systematic empirical analysis of LEO proximity remains limited. Existing work largely relies on isolated incidents or strategic analysis, leaving policymakers without a clear understanding of how constellation growth is changing debris exposure, close-approach frequency, and the prevalence and detectability of persistent proximity operations.

In this work, we provide a policy-oriented empirical analysis of proximity risks in the rapidly expanding LEO environment. Using publicly available orbital and satellite catalog data from 2020–2025, we examine three forms of interaction: persistent proximity involving orbital debris, close approaches between operational satellites, and sustained inter-satellite proximity associated with rendezvous and proximity operations (RPO).

Our measurements show that constellation growth is is changing both how often close approaches occur and what kinds of objects are involved. Between 2020 and 2025, the average monthly number of satellites passing within 25 km of eachother—a threshold derived from NASA's collision-screening practices—increased 2.6-fold. Much of this growth is driven by large commercial constellations. We find that spacecraft publicly associated with RPO exhibit repeated proximity to independently operated satellites and elevated maneuver activity, demonstrating that potentially security-relevant behavior is already observable in public orbital data.

Together, our results show that proximity in LEO cuts across policy areas that are often treated separately. Debris creates long-lived burdens for operators far removed from the original event, large constellations increase the volume of routine close approaches that must be monitored, and sustained maneuvering raises transparency and attribution questions that collision-avoidance rules alone do not address.

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These findings motivate clearer responsibilities for fragmentation events, greater consideration of constellation-wide effects in licensing, and stronger disclosure and notification practices for sustained close approaches between independently operated spacecraft.

2 Background

Satellite Internet has existed for over 20 years [1]. However, early Internet-providing satellites were large, expensive, geostationary, and orbited more than 36,000 km above Earth. While this altitude provides wide coverage, it comes at the expense of latency: even today, the minimum round-trip time (RTT) through a GEO satellite is approximately 240 ms, physically bounded by propagation distance [4]. In response to demand for lower latency and reductions in satellite launch and manufacturing costs, operators increasingly turned to Low Earth Orbit (LEO) satellites.

LEO satellites often operate in networks comprising hundreds to thousands of satellites orbiting approximately 180–1,300 miles above Earth [9]. Their lower altitude reduces propagation delay relative to earlier satellite Internet systems, but each satellite covers a smaller area and moves rapidly relative to users on the ground. LEO satellites travel at roughly 8 km per second [25]. As a result, continuous service requires large constellations in which many satellites share the same broad orbital environment.

Orbital debris creates one persistent source of risk in LEO. Many LEO satellites are designed for operational lifetimes of approximately five years, after which operators may lower their orbits so that they re-enter Earth's atmosphere [16, 29]. However, satellites can lose maneuvering capability or become non-operational before disposal is complete. Spent rocket bodies and fragments from breakups can also remain in orbit for years or decades. These objects cannot reliably perform collision-avoidance maneuvers and may repeatedly pass near active satellites. Although existing guidelines address debris mitigation and post-mission disposal, they do not ensure successful removal in every case, and there is no widely adopted method for removing the large population of debris already in orbit [12, 24]. Notably, the International Space Station also operates in LEO and regularly receives visiting spacecraft through carefully coordinated docking operations. Such presence of crewed spacecrafts makes debris and collision risks in this region particularly consequential because an impact could threaten both spacecraft operations and human life.

Maneuverability creates a different form of proximity risk. Satellites maneuver for routine purposes including station keeping, collision avoidance, deployment, docking, inspection, and servicing. These activities may involve rendezvous and proximity operations (RPO), in which one spacecraft intentionally approaches or remains near another. RPO are therefore not inherently malicious. However, the same capabilities can also support shadowing, surveillance, or interference with another spacecraft [6].

For example, Chinese military satellites have reportedly conducted extended rendezvous and proximity operations in behavior described as satellite "dogfighting" [7]. Figure 1 shows the four satellites (*SJ-6 05A*, *SY-24C1–SY-24C3*) repeatedly maneuvering around one another between April 22 and April 28. The spacecraft repeatedly separate, re-establish close proximity, and exchange neighboring spacecraft over successive days while remaining within the same operational cluster. Across 2024, *SY-24C 03* spends 227.7 hours within 10 km of *SY-24C 01*, 175.5 hours within 10 km of *SJ-6 05A*, and 103.5 hours within 10 km of *SY-24C 02*. Although this mission involves satellites operated by the same country, the demonstrated maneuvering capability is equally applicable to interactions between independently operated satellites. Similar reports describe Russian *Kosmos* satellites maneuvering to match the orbital planes of, and approach, U.S. reconnaissance satellites [10, 21, 31]. Existing policy frameworks attempt to address the risks from such RPO behavior by emphasizing responsible conduct, collision avoidance, information sharing, and transparency between operators [8, 14, 35].

3 Methodology for Measuring LEO Interactions

Space objects can pose operational risks to one another, regardless of intent. In geostationary orbit (GEO), satellites occupy nearly identical orbital regimes, so proximity is largely determined by relative distance along a shared orbital path. In contrast, LEO is far more dynamic and complex: spacecraft operate across a wide range of altitudes, inclinations, and orbital planes.

Different classes of interactions therefore require different measurement criteria. Some interactions, such as conjunction monitoring and debris-field exposure, depend primarily on physical separation. Others, such as rendezvous and proximity operations (RPO), additionally require spacecraft to occupy similar orbital planes that permit repeated access. We therefore organize our analysis into three interaction categories: persistent debris-field interactions, collision monitoring, and rendezvous and proximity operations.

Dataset. We analyze interactions between space objects using publicly available Two-Line Element (TLE) orbital data and satellite catalog (SATCAT) records obtained from `space-track.org`. Our dataset spans 2020–2025 and includes all publicly tracked objects in low Earth orbit (LEO). We restrict the analysis to objects with altitudes between

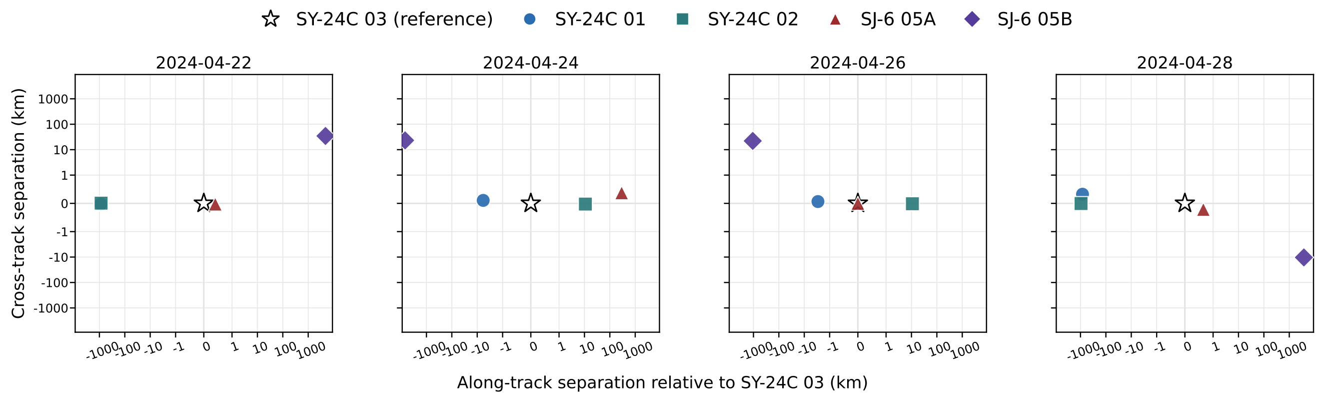

Figure 1: Chinese proximity operations—A reported mission demonstrates sustained coordinated inter-satellite maneuvering. The targeted LEO satellite is *SY-24C 03* at 0,0. The sequence shows *SJ-6 05A*, *SY-24C 01*, and *SY-24C 02* repeatedly approaching, departing, and exchanging relative positions around *SY-24C 03*, illustrating sustained coordinated proximity operations over multiple days.

160 km and 2,000 km, corresponding to the conventional definition of the LEO region [9]. We reconstruct object trajectories from TLEs using the SGP4 propagator [41]. SATCAT records provide metadata for each tracked object, including launch year, operator country, object type (e.g., payload, rocket body, or debris), and operational status. We use these attributes to characterize the objects involved in proximity events.

We identify three specific types of interactions between spacecraft that are relevant to operational safety and security, using the additional filter criteria described below.

3.1 Orbital Debris

Orbital debris presents a collision risk in LEO. Debris and spent rocket bodies are no longer actively operated by satellite owners or launch providers and generally cannot perform station-keeping or collision-avoidance maneuvers. Orbital decay, atmospheric drag, fragmentation, and other perturbations gradually alter their trajectories, making future close approaches more difficult to predict. Moreover, collisions between uncontrolled objects can generate additional debris, further increasing the long-term hazard to operational spacecraft. These persistent debris environments therefore require continued tracking and conjunction monitoring.

We distinguish two categories of close-proximity relationships. Debris–debris encounters characterize persistent debris environments created by historical fragmentation events or launch-related debris. Fragments originating from the same breakup often remain in similar orbital regimes for years, producing repeated close approaches among uncontrolled objects. Payload–debris encounters identify active spacecraft operating within these debris environments. These encounters let us measure how long-lived debris fields continue to affect active satellites.

We characterize the LEO debris field by examining the closest observable proximity between tracked orbital objects. Riesing [30] reported a third-quartile (Q3) TLE propagation error of 10.6 km for LEO satellites; we therefore use $d_{3D} \leq 10$ km to define the closest proximity regime that can be analyzed reliably using public TLE data.

3.2 Close Approaches

Close approaches between active satellites create a growing collision-monitoring burden in LEO. To define a measurable close-approach threshold, we draw on NASA's collision-avoidance procedures for the International Space Station (ISS). Mission operators continuously screen the ISS trajectory against cataloged objects and perform collision assessments when an object is predicted to enter a screening volume of approximately 25 km × 25 km × 2 km within the next 72 hours [2]. We refer to these collision-relevant close approaches as conjunctions. We use $d_{3D} \leq 25$ km as a measurable collision-monitoring threshold.

3.3 Rendezvous and Proximity Operations

Rendezvous and proximity operations (RPO) involve sustained or intentional close approaches between spacecraft. Unlike transient conjunctions, RPO require a spacecraft to actively establish and maintain proximity to another object.

NASA spacecraft used to service other spacecraft in LEO provide an example of expected RPO behavior. A common LEO servicing approach first places the servicer into an orbit with the same orientation and shape as the target spacecraft.

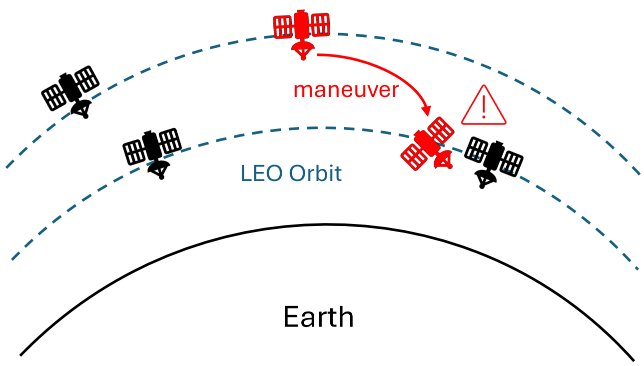

Figure 2: Satellite Proximity—In rendezvous and proximity operations (RPO), a spacecraft intentionally approaches another spacecraft. Such proximity may support coordinated benign activities, such as servicing, or uncoordinated and potentially malicious behavior, such as stalking.

The servicer then begins a co-elliptic rendezvous from several hundred kilometers behind the target [3]. Figure 2 shows a simplified example.

These rendezvous procedures illustrate three characteristics of proximity operations. First, the satellite occupies an orbital plane similar to the target, enabling repeated orbital access. Second, it reduces its separation from the target through a controlled approach. Finally, it remains in close proximity throughout the rendezvous. We therefore characterize potential RPO behavior using three related criteria for pairs of satellites: orbital-plane similarity, proximity distance, and persistence. We also characterize the maneuvering behavior of individual satellites. Frequent maneuver-like orbital changes indicate that a satellite repeatedly adjusts its trajectory. We use maneuver frequency as a supporting heuristic when evaluating candidate RPO cases.

Deriving the RPO Orbital Plane Threshold. We derive an orbital plane threshold using publicly reported military RPO cases, because public RPO guidance does not define a numerical threshold for orbital-plane similarity. Anecdotal observations reported that Kosmos 2558 was inserted into an orbital plane closely matching USA 326, with RAAN differing by approximately 0.04° shortly after launch [21]. Observers similarly reported that the orbital planes of Kosmos 2542 and USA 245 differed by approximately 0.55° while maintaining nearly identical orbital periods [27]. Reuters later reported that Cosmos 2576 was deployed into the same orbit as a U.S. government satellite [31]. These publicly reported cases consistently involve spacecraft occupying closely matched orbital planes. We therefore define spacecraft satisfying $\alpha_{\text{plane}} \leq 0.55^\circ$ as candidates for repeated co-orbital access.

To compute orbital-plane similarity, we use the mutual angle between the two orbital planes:

$$\alpha_{\text{plane}} = \cos^{-1}\left(\cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos(\Delta\Omega)\right), \quad (1)$$

where i_1 and i_2 are the orbital inclinations and $\Delta\Omega$ is the difference in right ascension of the ascending node (RAAN). We describe these parameters in more detail in Appendix A.

Deriving the RPO Distance Threshold. We derive an RPO distance threshold from two complementary sources: publicly documented coordinated rendezvous procedures and publicly reported uncoordinated RPO cases.

Publicly documented coordinated rendezvous procedures establish proximity operations at distances between approximately 23 and 39 km. The European Space Agency (ESA) describes the Automated Transfer Vehicle (ATV) rendezvous profile as reaching a point approximately 39 km behind and 5 km below the ISS before rendezvous, corresponding to a three-dimensional separation of approximately 39 km [11]. Similarly, JAXA defines an H-II Transfer Vehicle (HTV) proximity communication zone at approximately 23 km from the ISS before the final approach sequence begins [19, 20]. Publicly reported uncoordinated RPO cases exhibit similar distance scales. Open-source orbital analyses reported that Russia's Kosmos 2558 repeatedly approached the U.S. reconnaissance satellite USA 326 to approximately 50 km every seven days [21]. Other reporting similarly described repeated passes within approximately 50 km of USA 326 [5].

Together, publicly documented coordinated rendezvous procedures and reported uncoordinated RPO cases place rendezvous activities within approximately 20–50 km. We therefore use $d_{3D} \leq 50$ km for spacecraft satisfying the distance needed for orbital-access. Together, these thresholds identify satellite pairs whose proximity resembles documented rendezvous, servicing, inspection, and RPO cases.

Proximity persistence. We use proximity fraction to distinguish sustained proximity over a short interval from stable periodic conjunctions spread over a long time. Only sustained proximity is relevant to RPO behavior. For each satellite pair, we define

$$f_{\text{prox}} = \frac{T_{\text{prox}}}{t_{\text{last}} - t_{\text{first}}},$$

where T_{prox} is the total time the two satellites spend within 50 km, and t_{first} and t_{last} denote the first and last times they are observed within 50 km, respectively. Larger f_{prox} values indicate sustained close-proximity behavior, which is more relevant to identifying potential RPO activity, whereas values near zero primarily reflect periodic conjunctions. Figure 3 shows the distribution of proximity fractions across satellite encounters. For example, *YAOGAN 21–USA 320* accumulates

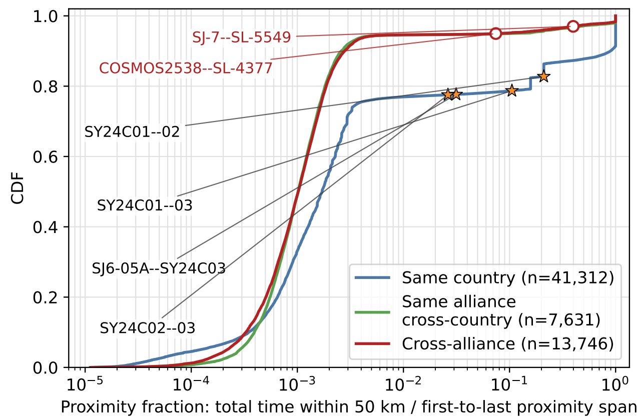

Figure 3: High proximity fraction highlights sustained RPO-like proximity—Satellite encounters with higher proximity persistence appear toward the upper right of the CDF and are more relevant to potential RPO behavior. Encounters involving a satellite with reported RPO capabilities are marked with circles, while reported Chinese "dogfighting" satellites are marked with stars.

8.1 hours of proximity over approximately 716 days, yielding a proximity fraction of only 4.7×10^{-4}, while *COSMOS 2538–STARLINK-4377* accumulates the same 8.1 hours within only 4.5 days, yielding a fraction of 0.074. We use proximity fraction as a screening metric to prioritize compact repeated encounters for subsequent orbital-history analysis.

Maneuver inference. We infer maneuver-like orbital changes from our collected TLE dataset using a simplified version of the TLE Time Series Analysis (TTSA) method proposed by Lemmens and Krag [22]. Following TTSA, we identify maneuvers as abrupt deviations from a satellite's locally expected orbital evolution using adaptive thresholds derived from its recent TLE history. For each satellite, we construct time series of the four Keplerian orbital elements defined in Appendix A.

Some Keplerian orbital elements can change gradually over time even when a satellite does not maneuver. To avoid mistaking this natural drift for a maneuver, we estimate its recent trend and subtract it from the observed values. We then analyze only the remaining deviations, which are more likely to reflect actual changes in the satellite's orbit. Thus, For each Keplerian orbital quantity, we perform the following steps:

(1) Fit a linear model using the previous $N = 15$ TLE observations.
(2) Predict the next orbital-element value.
(3) Compute the prediction error.
(4) Estimate the recent prediction variability using the interquartile range (IQR).
(5) Flag a maneuver when the prediction error exceeds both an adaptive IQR-based threshold and a minimum absolute threshold for that orbital quantity.

We identify a maneuver when at least one orbital quantity exceeds its threshold. We assign higher confidence to detections supported by multiple orbital quantities, persistent orbital changes in subsequent TLEs, and continuous TLE coverage.

Debris field	Country	Year	Fragments
COSMOS 1408 (1982-092)	CIS	1982	684
CZ-6A (2022-151)	PRC	2022	503
CZ-6A (2024-140)	PRC	2024	483
FENGYUN 1C (1999-025)	PRC	1999	450
NOAA 16 (2000-055)	US	2000	244
COSMOS 2251 (1993-036)	CIS	1993	146
RESURS O1 (1994-074)	CIS	1994	136
OPS 4682 (1965-027)	US	1965	120
DMSP 5D-2 F13 (1995-015)	US	1995	84
COSMOS 1867 (1987-060)	CIS	1987	39

Table 1: A single launch or fragmentation event can produce hundreds of tracked debris fragments. — Largest debris fields ranked by the number of tracked fragments. Debris fields are grouped by the same launch or fragmentation event. Country denotes the nation or entity responsible for the creation of each debris field.

4 Observed Proximity Risks from Debris

Debris now occupies many of the same orbital regions used by active satellites in LEO. Our results show that major launch and fragmentation events can leave debris fields that persist for decades, posing risks to operational satellites. Over time, the countries contributing most to new debris have changed. Our findings underscore the need for stronger debris-prevention practices and continued monitoring of existing debris fields.

4.1 Debris Fields

We first examine close approaches between debris and spent rocket bodies, using the methodology from Section 3.1. Between 2020 and 2025, we identify 7,422 persistent close approaches involving debris. Most—6,919 (93.2%)—occur only among debris objects and spent rocket bodies; 503 involve an active satellite.

Debris from a single satellite breakup can remain operationally relevant for decades. To identify debris fields, we group debris and rocket-body objects by launch designator, which associates fragments originating from the same launch or fragmentation event. Table 1 shows the largest 10 debris fields by number of fragments. The largest clusters correspond to the *COSMOS 1408* (1982), *CZ-6A* satellite breakup events (2022 and 2024), and *FENGYUN 1C* (1999).

Several of the largest debris fields originate from fragmentation events in the 1980s and 1990s, yet continue to persist in orbit throughout our 2020–2025 observation period.

Hundreds of debris fragments require sustained conjunction assessment, catalog maintenance, and space situational awareness over long time periods. These observations show that the operational consequences of a fragmentation event extend well beyond the original mission.

A small number of nations/entities create the most persistent debris. Three nations account for 93% of persistent debris fields. Table 2 shows that CIS (Commonwealth of Independent States; former USSR.) contributes the largest number of distinct debris fields (89, 52.0%). PRC (People's Republic of China) contributes fewer debris fields (31). However, the debris field contain the most debris objects (1,526) and cause the most persistent close approaches (4,092). Much of this comes from recent *CZ-6A* breakups, which produced hundreds of cataloged fragments. The United States contributes 39 debris fields, but they contain fewer fragments and cause fewer persistent close approaches than either CIS or PRC. These countries therefore have an outsized role in preventing new debris and responding to on-orbit breakups.

Responsibility for the debris environment has evolved over time. Figure 4 shows that CIS contributes many debris fields originating in the 1970s through the 1990s, reflecting the legacy of its historical space activities, while PRC contributes the largest number of tracked debris objects in the 2020s because the recent *CZ-6A* fragmentation events contain hundreds of cataloged fragments. These observations show that responsibility for creating the current debris environment spans both historical and recent fragmentation events. Historical debris fields continue to require long-term tracking and conjunction assessment, while countries with rapidly expanding launch activities have increasing responsibility to minimize new debris generation and promptly characterize fragmentation events. As LEO becomes more congested, both responsibilities become increasingly important for sustaining safe and sustainable spacecraft operations.

4.2 Satellite Exposure to Debris Fields

The growing number of debris fields is making spacecraft operations more challenging. Operators must track and assess an increasing number of objects for potential conjunctions.

Country	Debris Fields	Fragments
CIS	89 (52.0%)	1,206
US	39 (22.8%)	656
PRC	31(18.1%)	1,526
JPN	4 (2.3%)	24
FR	3 (1.8%)	7
IND	3 (1.8%)	5

Table 2: A few nations/entities account for the most debris fields—CIS and the US contribute near three quarters of all debris fields in LEO.

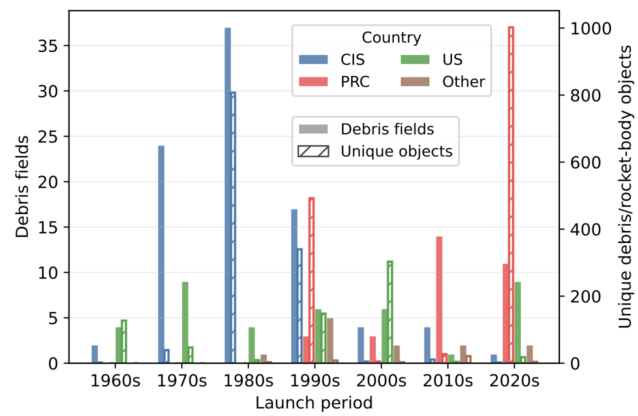

Figure 4: Debris origins shift over time—CIS dominates debris fields from the 1980s, while PRC contributes the most debris from the 2020s.

Operational satellites may encounter debris throughout multiple phases of a mission, including immediately after launch and during routine operations.

Routine launch operations create temporary proximity to debris. We identify 503 persistent encounters between active satellites and debris or rocket bodies, of which 24 are associated with a launch. Most of those 24 are directly tied to the same launch: 20 share the same launch group ID between the satellite and the debris-like object, and 22 share the same launch date. Examples include the *GEESAT 4*, *YAOGAN-31*, *LEMUR 2*, and *KINEIS* satellite constellations, whose spacecraft remain temporarily close to launch-associated objects immediately after deployment. These encounters reflect normal launch and deployment operations, during which satellites, rocket bodies, and deployment hardware separate into their operational or disposal orbits.

Rocket bodies from unrelated launches approach active satellites. We identify two cases in which an operational satellite enters persistent close proximity with a rocket body from another operator's launch. *IXPE* encounters an Electron Kick Stage rocket body from launch group 2021–120, while *STARLINK-32248* encounters a KZ-1A rocket body from launch group 2024–170. Although *STARLINK-32248* and the KZ-1A rocket body share the same cataloged launch date, they belong to different launch groups. Thus, launch activities influence the operational environment experienced by satellites from independent launch campaigns. Coordinating launch trajectories, upper-stage disposal strategies, and timely publication of orbital information can reduce the risks.

Newly launched satellites enter existing debris fields immediately after deployment. We identify two cases in which newly launched satellites immediately enter historical debris fields. First, *SDGSAT 1*, launched in 2021, encounters the *FENGYUN-1C* debris field, from 1999. Second, *BB3*, launched in 2023, encounters debris from the breakup of *COSMOS 2499* from 1982. The *FENGYUN-1C* debris field remains one of the largest persistent debris fields in LEO and continues to occupy operational orbital regimes more than a decade after the fragmentation event. Thus, satellites begin routine operations in orbital regimes already occupied by persistent debris fields generated many years earlier. Mission planning, launch scheduling, and conjunction assessment therefore benefit from accurate characterization of long-lived debris environments before spacecraft enter operational service.

Debris fields affect satellites from many operators and countries. The remaining 479 satellite–debris encounters are not associated with the launch of either object. These encounters involve 360 unique satellites and 163 debris fields during routine satellite operations. The *CZ-6A* (2022–151) debris field is encountered by 29 satellites from seven countries, while the *FENGYUN 1C* (1999–025)is encountered by 25 satellites from nine countries. *CZ-6A* (2024–140) is encountered by 17 satellites, and *NOAA 17* (2002–032) is encountered by 12 satellites from eight countries. The largest CIS-attributed example, *RESURS O1* (1994–074), is encountered by seven satellites from five countries.

A single debris field can therefore affect satellites from many countries for years after the event that created it. As the LEO environment becomes increasingly congested, preventing debris generation, maintaining accurate debris catalogs, and continuously monitoring persistent debris fields become increasingly important for supporting safe spacecraft operations.

5 Observed LEO Close Approaches

While the rapid growth of LEO debris has increased the frequency of conjunction (close approach) assessments and collision-avoidance operations, conjunction monitoring is not limited to debris. As active satellite constellations continue to expand, close approaches between operational satellites have also become increasingly common, requiring continuous tracking and collision assessment by satellite operators.

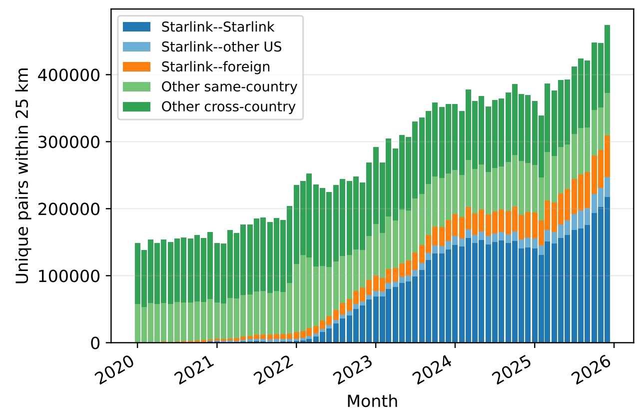

Figure 5: Starlink dominates the recent growth in LEO close-approach exposure—In 2020, 98.5% of close-approach pairs did not involve Starlink; by 2025, 59.0% did.

Starlink now drives most of the growth in LEO close approaches. Figure 5 shows the monthly number of unique satellite encounters within 25 km. The average monthly number of attributed close-approaches increases 2.6×: from 153,496 in 2020 to 406,140 in 2025. Starlink-involved pairs increase from 2,301 per month (1.5%) in 2020 to 239,790 (59.0%) in 2025. Most of the conjunction increases come from Starlink–Starlink encounters, which increase from 514 monthly pairs in 2020 to 168,165 in 2025. Starlink–foreign satellite encounters increase from 1,282 to 49,326 monthly pairs, while Starlink–other U.S. satellite encounters increase from 506 to 22,299. During the same period, non-Starlink cross-country encounters increase from 93,918 to 98,655.

Active satellites now encounter far more neighboring satellites than debris. The active LEO satellite population grows from 3,900 in 2020 to 15,151 in 2025. Much of this growth comes from the United States, which increases from 1,714 to 11,302 active satellites. Starlink alone grows from 671 satellites to 9,655, accounting for 63.7% of active LEO satellites by 2025. Figure 6 shows how this growth changes the objects that each satellite encounters within 25 km. The median number of neighboring satellites increases from 41 in 2020 to 287 in 2025. In contrast, the median number of neighboring debris and rocket bodies decreases from 47 to 34. Thus, close approaches in LEO are increasingly driven by active satellites rather than debris.

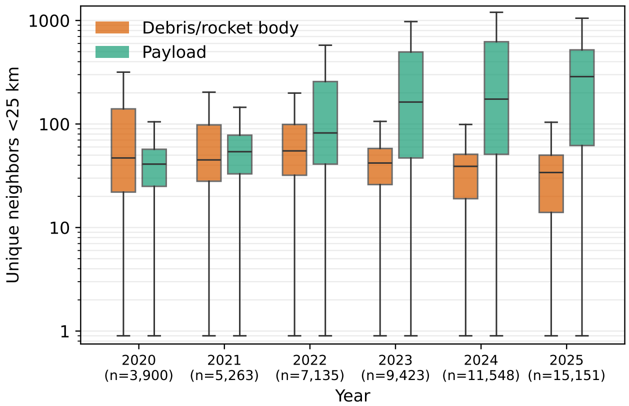

Figure 6: Active satellites now encounter far more neighboring satellites than debris— The median number of payload neighbors within 25 km rises from 41 in 2020 to 287 in 2025, while the median number of debris and rocket-body neighbors falls from 47 to 34.

The data shows that large commercial constellations are shifting conjunction exposure from debris toward interactions among active satellites. Each satellite now encounters many more neighboring spacecraft during routine operations, increasing the number of conjunction assessments operators must perform and the number of independent operators with whom they may need to coordinate collision avoidance. As LEO continues to grow, space-domain awareness systems, conjunction-screening services, and operator coordination mechanisms will need to scale accordingly.

6 Observed Persistent Inter-Satellite Proximity (RPO)

Persistent close proximity between operational satellites has become an increasingly important aspect of space operations. Inter-satellite proximity arises from many coordinated activities, including rendezvous, servicing, inspection, docking, and formation flying. It can also arise between independently operated satellites that repeatedly maneuver near one another or maintain similar orbits over extended periods.

From 2020 through 2025, we identify 23,458 cases of persistent close proximity between satellites, consistent with potential rendezvous or other sustained proximity operations A small number of independently operated satellites show repeated close proximity and warrants closer review. Although these measurements cannot determine mission objectives or adversarial intent, they provide a practical way to prioritize unusual satellite interactions for further investigation.

Case studies. *COSMOS 2538* shows one of the strongest patterns of persistent cross-alliance proximity in our data. The satellite is associated with Russia's *Nivelir* military program, which has been linked to satellite inspection and rendezvous and proximity operations (RPO) [31, 40]. *COSMOS 2538* repeatedly comes into close proximity with 76 satellites, including 75 from outside its nation's political alliance.

COSMOS 2538 encounters *STARLINK-4377* the most. The two satellites come within 25–50 km of each other 44 times over 4.54 days, spending 8.08 hours in close proximity. They reach within 32.47 km of each other . *COSMOS 2538* also repeatedly approaches *ASTROCAST-01* (1.92 hours across 8 close-approach events), *STARLINK-4359* (1.42 hours across 9 events), and *STARLINK-4358* (1.25 hours across 6 events). Together, these cases show that *COSMOS 2538* repeatedly comes near satellites operated by independent commercial operators.

SJ-7 exhibits a similar pattern of repeated proximity. SJ-7 is a Chinese technology demonstration satellite that performed a publicly reported rendezvous with another Chinese spacecraft in 2013, illustrating China's early on-orbit maneuvering capabilities. Between 2020 and 2025, *SJ-7* persistently approaches 22 unique satellites, split evenly between same-country and cross-alliance spacecraft.

SJ-7 most frequently approaches *STARLINK-5549* among its cross-alliance neighbors. The two satellites come within 10–25 km of eachother over 10 times over 0.44 days, spending 4.25 hours in close proximity. They reach within 12.75 km of each other. *SJ-7* also repeatedly approaches *STARLINK-5988*, *STARLINK-6038*, *STARLINK-5535*, and *STARLINK-5538*. Its encounters with *STARLINK-5535* and *STARLINK-5538* come even closer, reaching 6.14 km and 5.46 km, respectively.

Frequent maneuvering helps distinguish RPO. Satellites that remain near one another over time often need to adjust their orbits as those orbits naturally drift [3]. A satellite that maneuvers repeatedly is more likely to be actively maintaining its orbit relative to another spacecraft than one that simply follows its natural trajectory.

Figure 7 compares inferred maneuver counts for four groups: a random LEO baseline, operational communication satellites, the reported Chinese SJ/SY dogfighting cluster, and Russian Cosmos/Nivelir satellites. The random LEO baseline includes 94 payload satellites. These satellites have a median of 19.6 inferred maneuvers per year, with 90% below 35.5, and a maximum of 47. For comparison, the communication group includes two Starlink, two OneWeb, one Iridium, two Globalstar, and one Orbcomm satellite. These satellites routinely maneuver for orbit raising, phasing, drag compensation, and station keeping, but are not intended for proximity operations.

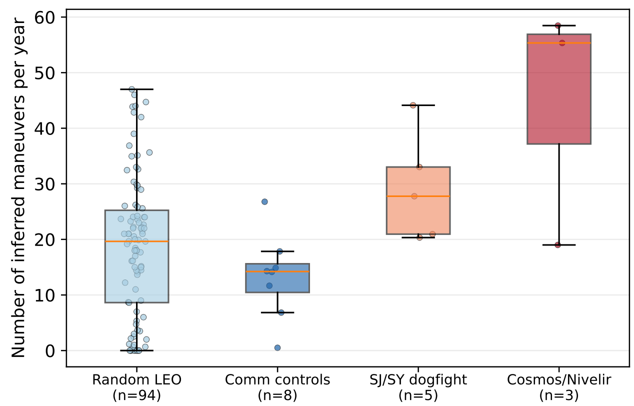

Figure 7: Known RPO LEO satellites maneuver more frequently—The reported Chinese SJ/SY cluster and Russian Cosmos/Nivelir satellites show higher maneuver rates than random LEO payloads and communication controls.

The reported Chinese SJ/SY dogfighting satellites often maneuver more than the communication-control group, consistent with their reported use in coordinated proximity operations. The Russian Cosmos/Nivelir satellites maneuver the most, especially *COSMOS 2558* and *COSMOS 2576*. While the SJ/SY satellites are reportedly only technology demonstrations, the Nivelir missions have been publicly associated with sustained monitoring of foreign spacecraft.

Overall, satellites publicly linked to RPO also repeatedly approach independently operated spacecraft in our data. Combining persistent proximity with frequent maneuvering helps narrow many close approaches to a smaller set that warrants closer review. These measurements cannot reveal intent, but they show that public orbital data can flag unusual interactions for further operational and security analysis.

7 Policy Discussion

Existing U.S. and international frameworks recognize the importance of debris mitigation, conjunction assessment, information sharing, and safe proximity operations. With millions of additional satellites planned over the coming decade, our observations show how these challenges are changing in practice. In this section, we highlight how our findings relate to ongoing efforts in debris management, scalable conjunction assessment, and transparency for proximity operations.

7.1 Persistent Debris and Shared Operational Exposure

The U.S. Orbital Debris Mitigation Standard Practices, the UN Space Debris Mitigation Guidelines, and the FCC's five-year post-mission disposal rule all emphasize preventing debris generation, minimizing collisions, and limiting the creation of long-lived debris objects [17, 34, 36]. The National Orbital Debris Implementation Plan similarly identifies debris mitigation, tracking, characterization, and remediation as complementary priorities [26].

Our analysis provides empirical evidence for the long-term operational consequences of fragmentation events. Debris fields originating decades ago continue to generate recurring close approaches, while recent fragmentation events rapidly produce debris fields encountered by operational satellites from multiple countries. These findings highlight the importance of continued debris characterization, long-term tracking, and timely information sharing throughout the lifetime of debris populations.

We also find that fragmentation events remain operationally relevant well beyond the initial breakup. Prompt disclosure of fragmentation events, updated orbital characterization, preservation of anomaly records, and continued coordination with tracking organizations can improve conjunction assessment for all operators. Existing international agreements, including the Outer Space Treaty and Liability Convention, establish state responsibility for national space activities and liability for damage caused by space objects [32, 33]. Liability for damage occurring in orbit is fault-based rather than absolute, so attributing responsibility after an in-space collision depends on technical evidence such as tracking data, fragmentation records, and operator coordination history. Our results complement these principles by quantifying the long-term operational exposure associated with persistent debris fields.

7.2 Scalable Conjunction Assessment

Space Policy Directive 3 (SPD-3) recognized that increasing satellite populations would require more interoperable data exchange, planned maneuver sharing, automation, and updated operational practices for large constellations [13]. The Department of Commerce's TraCSS program extends this direction by providing conjunction screening and civil space traffic coordination services [28]. FCC regulations similarly require applicants to describe ephemeris sharing, maneuver coordination, and aggregate collision risk across satellite systems [15]. Internationally, the UN Long-Term Sustainability (LTS) Guidelines encourage maintaining operator contact information, exchanging orbital data, and performing conjunction assessment throughout controlled flight [35].

Our results provide quantitative context for these ongoing efforts. Between 2020 and 2025, monthly close-approach pairs increased by 2.6×, the median payload encountered 7.0× more payload neighbors, and Starlink–Starlink close approaches increased by more than 300×. This growth shows how conjunction assessment increasingly reflects constellation-scale operations alongside individual spacecraft operations. The observed trends underscore the value of high-quality orbital data, scalable conjunction screening, automated coordination, and reliable communication among operators as satellite populations continue to expand.

7.3 Transparency for Persistent Proximity Operations

Existing guidance emphasizes transparency and responsible behavior during proximity operations. FCC regulations require disclosure of planned proximity operations [15]. The U.S. Department of Defense separately directs its components to avoid harmful interference, follow trajectories that allow other spacecraft to maneuver safely, and provide collision and loss-of-control notifications [38, 39]. The UN LTS Guidelines and the Outer Space Treaty also support information sharing, due regard, and consultation among operators and states [32, 35].

Public orbital data can also help identify sustained proximity that may deserve closer attention. Repeated approaches, frequent maneuvering, and long periods of close proximity provide observable signals that operators and policymakers should monitor alongside existing disclosure requirements. Our analysis also shows that public orbital data provides a consistent basis for monitoring how proximity relationships evolve over time. As maneuver-capable spacecraft become more common and satellite populations continue to increase, these measurements can help characterize persistent operational interactions while providing empirical evidence to inform ongoing discussions on proximity operations, space traffic coordination, and responsible behavior in LEO.

8 Conclusion and Discussion

LEO is undergoing rapid transformation as satellite constellations expand, debris accumulates, and maneuverable spacecraft become increasingly common. Using publicly available orbital data from 2020 through 2025, we presented a longitudinal measurement study of three complementary aspects of LEO proximity: persistent debris fields, conjunction exposure, and persistent inter-satellite proximity.

Our results show that close approaches are becoming increasingly common in LEO. The monthly number of satellites that pass within 25 km increased by 2.6×. This growth is largely driven by large commercial constellations: Starlink–Starlink close approaches increased by more than 300×. Debris also remains a long-term operational hazard. Recent fragmentation events account for nearly half of persistent debris close approaches, while debris from the 1960s still continues to approach LEO satellites. Finally, satellites publicly associated with rendezvous and proximity operations maneuver more frequently than typical LEO satellites.

Overall, these findings show that debris mitigation, conjunction management, and proximity operations are closely connected parts of managing an increasingly congested and maneuverable LEO environment. We hope this work provides empirical evidence to support evidence-based policies on debris prevention, scalable conjunction management, and transparency for proximity operations as the LEO environment continues to evolve.

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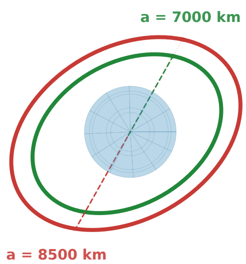
A Relevant Keplerian Orbital Elements

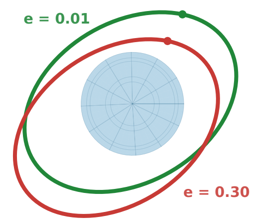
We describe each satellite orbit using standard Keplerian orbital elements. These elements provide a compact geometric description of an orbit around Earth. Figure 8 illustrates the four elements most relevant to our analysis: *semi-major axis*, *eccentricity*, *inclination*, and *right ascension of the ascending node (RAAN)*. In each subfigure, the green orbit provides the reference case and the red orbit changes only one orbital element.

Semi-major axis. Figure 8a shows the semi-major axis a, which describes the size of the orbit. For an elliptical orbit, Earth lies at one focus of the ellipse, while a is measured from the ellipse center to one end of the major axis. The red orbit has a larger semi-major axis than the green orbit, so it appears as a larger orbit with the same shape and orientation. This visual difference corresponds to changing orbital size while holding eccentricity, inclination, and RAAN fixed.

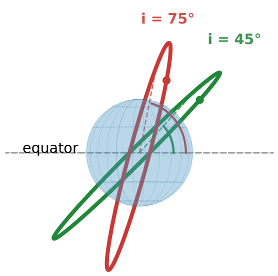
Eccentricity. Figure 8b shows eccentricity e, which describes the shape of the orbit. A circular orbit has $e = 0$, while larger values of e produce a more elongated ellipse. The red orbit has higher eccentricity than the green orbit, so it appears more stretched while keeping the same semi-major axis and orbital-plane orientation. This visual difference corresponds to changing the radial variation over an orbit while holding orbit size and orientation fixed.



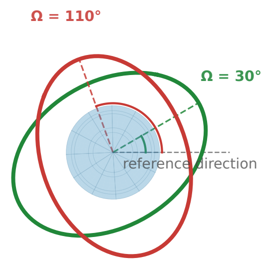
(a) Semi-major axis. Increasing a makes the orbit larger while preserving its shape and orientation.



(b) Eccentricity. Increasing e makes the orbit more elongated while preserving the same semi-major axis.



(c) Inclination. Increasing i tilts the orbital plane more steeply relative to the equator.



(d) RAAN. Changing Ω rotates the orbital plane around Earth's rotation axis.

Figure 8: Keplerian Orbital Elements— The elements describe orbit size, shape, tilt, and orientation. Each panel changes one orbital element while holding the others fixed. Green shows the reference orbit and red shows the comparison orbit.

Inclination. Figure 8c shows inclination i, which describes the tilt of the orbital plane relative to Earth's equatorial plane. The red orbit has a larger inclination than the green orbit, so it tilts more steeply relative to the equator. This visual difference corresponds to changing the north–south tilt of the orbit while holding orbit size, shape, and RAAN fixed. Inclination therefore determines the range of latitudes a satellite can reach.

Right ascension of the ascending node (RAAN). Figure 8d shows the right ascension of the ascending node Ω, or RAAN. RAAN describes the orientation of the orbital plane around Earth's rotation axis. It is measured in the equatorial plane from a fixed reference direction to the ascending node, where the satellite crosses the equatorial plane from south to north. The red and green orbits have the same semi-major axis, eccentricity, and inclination, but different RAAN values. They therefore have the same size, shape, and tilt, but their orbital planes are rotated to different orientations around Earth.