A Networking Perspective on Starlink's Self-Driving LEO Mega-Constellation

Yuanjie Li[1,2], Hewu Li[1,2], Wei Liu[1], Lixin Liu[1], Wei Zhao[1], Yimei Chen[1], Jianping Wu[1,2], Qian Wu[1,2], Jun Liu[1,2], Zeqi Lai[1,2], Han Qiu[1,2]
[1]Tsinghua University, [2]Zhongguancun Laboratory

ABSTRACT

Low-earth-orbit (LEO) satellite mega-constellations, such as SpaceX Starlink, are under rocket-fast deployments and promise broadband Internet to remote areas that terrestrial networks cannot reach. For mission safety and sustainable uses of space, Starlink has adopted a proprietary onboard *autonomous driving* system for its extremely mobile LEO satellites. This paper demystifies and diagnoses its impacts on the LEO mega-constellation and satellite networks. We design a domain-specific method to characterize key components in Starlink's autonomous driving from various public space situational awareness datasets, including continuous orbit maintenance, collision avoidance, and maneuvers between orbital shells. Our analysis shows that, these operations have *mixed impacts* on the stability and performance of the entire mega-constellation, inter-satellite links, topology, and upper-layer network functions. To this end, we investigate and empirically assess the potential of networking-autonomous driving co-designs for the upcoming satellite networks.

CCS CONCEPTS

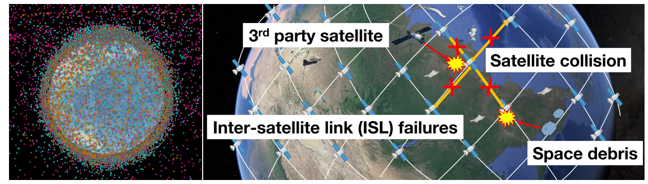
• **Networks** → **Mobile networks**; **Network protocols**.

KEYWORDS

Satellite network; autonomous orbital maneuvers; Starlink.

1 INTRODUCTION

The Internet is taking a giant technical leap from Earth to space. SpaceX's Starlink [1], the largest low-earth-orbit (LEO) satellite mega-constellation in operation, has deployed 1,000s satellites in orbit and planned 10,000s satellites in the near term. It expands broadband Internet services to remote areas that terrestrial networks can't reach, and yields a tens-of-billions-of-dollar market with 3.7 billion "unconnected" users [2] in rural areas, developing countries, aircraft, and oceans.



(a) Congested space **(b) Safety threats for satellite networks**

Figure 1: The harsh, crowded, and extremely mobile space environment for LEO satellite networks.

LEO satellites operate in *harsh, crowded, and extremely mobile* space environments (Figure 1). They are constantly surrounded by dense, fast-moving space debris and 3rd-party satellites. The deployments of 1,000s-10,000s LEO satellites from mega-constellations will further congest the orbits. Hence, LEO satellites are at high risk of physical collisions and potential cascade catastrophes [3]. To combat them, operators must sense space situations, calibrate their satellite orbits, and avoid collisions via *orbital maneuvers* if necessary.

The orbital maneuver has been a long-standing, yet still challenging topic from the aerospace community. To date, most maneuvers between operational satellites are *manual and ad-hoc*, thus not responsive, accurate, or scalable for LEO mega-constellations (§2). To this end, Starlink has developed a proprietary onboard *autonomous driving* system in its LEO mega-constellation for automatic orbital maneuvers [4, 5].

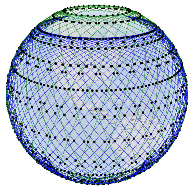
Autonomous driving in LEO mega-constellations differs from well-known ones in terrestrial vehicles/UAVs due to its sizeable spatiotemporal scale, extreme mobility, and orbital movements. It also departs from classical orbital maneuvers as it should concern not only each individual satellite, but also the *entire mega-constellation and inter-satellite networking* (analogous to fleet management). Starlink is expected to strive for mission safety, preserve the *global* orbital properties of its constellation, facilitate its inter-satellite networking, and enhance the networking's resiliency to failures from orbital drags and physical collisions. However, it is unclear if Starlink's maneuver system has met these expectations. Its proprietary nature prohibits the community from evaluating its effectiveness and hence raises concerns by major space powers [6], regulators [7], and other satellite operators [8].

This paper conducts, to our best knowledge, a previously unexplored study on Starlink's orbital maneuvers and their impacts on satellite networking. Our core idea is that, while

Corresponding author: Hewu Li (lihewu@cernet.edu.cn).

ACM Mobicom '23, October 2–6, 2023, Madrid, Spain

ACM ISBN 978-1-4503-9990-6/23/10…$15.00
https://doi.org/10.1145/3570361.3592519



Num. satellites	Num. orbits	Altitude H (km)	Inclination angle ϕ
1584	72	550	53
1584	72	540	53.2
720	36	570	70
348	6	560	97.6
172	4	560	97.6

(a) Multi-layer orbits (b) Orbital shell design filling to FCC [9].

Figure 2: Starlink's LEO satellite mega-constellation.

Starlink's maneuver strategy is proprietary, its maneuvers will result in observable changes in its satellites' orbital parameters that differ from expected orbit propagations *without* maneuvers. By collecting various space situational awareness datasets, predicting upcoming orbital parameters with these datasets, and comparing predicted parameters with real ones, we can detect orbital maneuvers, correlate them with multi-sourced side-channel information, reason about their root causes, and assess their impacts on networking.

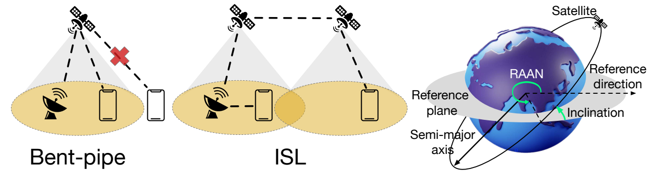
We apply this method to characterize three categories of Starlink's orbital maneuvers: *continuous orbit maintenance, collision avoidance, and maneuvers between orbital shells.* We evaluate each category from the view of each satellite, the mega-constellation, and the networking. Our key finding is that, *despite achieving excellent mission safety in most cases, Starlink's orbital maneuvers yield mixed impacts on its network topology and inter-satellite links (ISLs).* While feasible for each individual satellite and the current bent-pipe communication, it still has room to strive for the stability and performance of the upcoming inter-satellite networks. Specifically,

- Unlike most LEO satellites, Starlink continuously conducts maneuvers to compensate for orbit decays. This practice helps stabilize the satellite mega-constellation topology to facilitate usable inter-satellite routing (§5);
- While excellent for mission safety, a viable amount of Starlink's collision avoidance maneuvers turns more than necessary and unexpectedly interrupts ISLs due to their bursty nature. Moreover, some proactive maneuvers even raise the collision risks with nearby space objects (§6);
- Starlink forms heterogeneous orbit shells and maneuvers its satellites between them. Such maneuvers are protracted (up to days) and yield extreme relative motions between satellites. They accumulate ISL delays, cause frequent ISL failures, and challenge the stability and performance of topology and upper-layer network functions (§7).

Based on these lessons, we explore and assess the potential of networking-orbital maneuver co-designs in §8.

In summary, this paper makes three contributions:

(1) We design a data-driven method to demystify LEO maneuvers and diagnose their impacts on networking;
(2) We apply this method to unveil Starlink's orbit maintenance, collision avoidance, inter-orbital-shell maneuvers, and their mixed impacts on satellite networking;
(3) We explore and empirically validate the potential of networking-orbital maneuver co-designs for Starlink.



(a) Bent-pipe and ISL modes (b) Orbital elements

Figure 3: Networking and orbits in Starlink.

While this work focuses on Starlink, we believe our method and lessons are generalizable to other LEO networks.

Artifacts: The dataset and analysis code are released at [10].

2 AUTONOMOUS DRIVING IN SPACE

We introduce Starlink's LEO satellite mega-constellation (§2.1), its surrounding harsh, crowded outer space (§2.2), and explain why and how it should be self-driving (§2.3).

2.1 The Starlink LEO Mega-Constellation

Starlink adopts low-earth orbits (LEO) satellites with Ku/Ka high-frequency radio bands to offer low-latency, high-speed data access. As shown in Figure 2, each LEO satellite has limited coverage of Earth due to its low altitude. So Starlink has formed a satellite mega-constellation for global coverage. As of January 2023, Starlink has launched over 3,300 small satellites and planned 42,000 satellites to deploy. This mega-constellation comprises multiple orbital shells at different altitudes to optimize its coverage.

To offer Internet services, the current Starlink satellites work as standalone "mirrors" to reflect signals between terminals and ground stations (Figure 3a). This mode's network coverage is constrained by the geographic ground station distributions, since both the ground station and terminal should reside within each satellite's coverage [11, 12]. So Starlink is progressively adopting optical inter-satellite links (ISLs) [13, 14] to form a networked LEO mega-constellation.

2.2 The Harsh, Crowded Outer Space

LEO satellites operate in a harsh, crowded, and extremely mobile space environment. Today, there are already about 8,300 satellites in space [15]. The recent adoption of LEO mega-constellations further congests orbits. These satellites constantly experience atmospheric orbit drags, multi-body orbit perturbations, solar/lunar activities, thermal fluctuations, and space radiations. Moreover, they are surrounded by numerous 3rd-party satellites and space debris. As shown in Figure 4 from our dataset in §4, LEOs are particularly congested, with ≥27,000 pieces of space debris at ≈15,700 mph and ≥10cm in diameter [16]. Space debris can arise from launch missions, space collisions [17, 18], disintegration [19, 20], and anti-satellite weapons [21–23].

The dense LEO satellite mega-constellation deployments and space debris have raised space safety threats. Every satellite is at high risk of high-speed physical collisions by debris

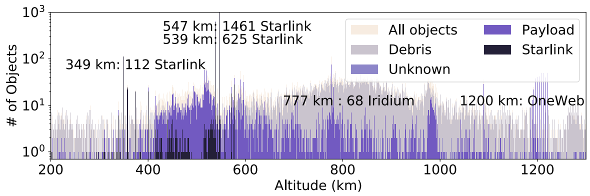


Figure 4: Distribution of space objects by altitudes.

or 3rd-party satellites. Once collided, the satellite may break up into 10s–1,000s more debris pieces, thus causing cascade collisions known as Kessler syndrome [3]. In reality, cascading collisions have occurred in the past decade [17, 24]. With more LEO satellites launched recently, inter-space-object conjunctions (thus potential collisions) surge to 3,500–60,000 events per month [25, 26]. Thus, it is crucial for satellites to calibrate their orbits and avoid collisions.

2.3 The Self-Driving LEO Satellites

For mission integrity and safety, operators rely on space situational awareness services to track satellites and run orbital maneuvers. We next introduce its high-level workflow.

Space situational awareness (SSA): This is the first step to assessing the satellite status and collision risks. It refers to the ability to track, understand and predict the physical location of satellites and space debris [27]. Ideally, satellites and debris follow Kepler's laws to orbit elliptically around Earth. But in reality, these orbits are not as regular as expected due to chaotic orbit drags (§5). Satellite operators should timely track orbital perturbations to calibrate the satellite trajectory.

SSA can be performed by satellites' onboard sensors or terrestrial nodes. Modern LEO satellites have onboard GPS to track their locations and report them to ground stations [4, 28]. For debris and satellites without GPS, their locations can be tracked by terrestrial radars, telescopes, or surveillance satellites [29–32]. The U.S. Space Surveillance Network (SSN) has publicized most SSA data to operators (§4).

With SSA data, operators can next forecast the collision risks between space objects. Given two space objects, NASA suggests two metrics to quantify collision risks [33–35]: (1) the *miss distance* between the two objects as they orbit. A miss distance smaller than the sum of both objects' radius indicates a potential collision; (2) the *collision probability* P_c between two objects given their positions, velocities, and uncertainties of these observations. NASA suggests the satellite should maneuver if $P_c \geq 10^{-4}$ [33], while Starlink adopts a stricter threshold $P_c \geq 10^{-5}$ [4] for a larger safety margin due to its mega-constellation scale and high capital expenditure.

Orbital maneuvers: To avoid potential collisions, operators can instruct their satellites to run orbital maneuvers. Maneuvers use the satellite's propulsion system to raise/lower its altitude, change its speed, or adjust its orbital inclination angles. Besides collision avoidance, maneuvers are also used to calibrate orbits and conduct mission-oriented orbit

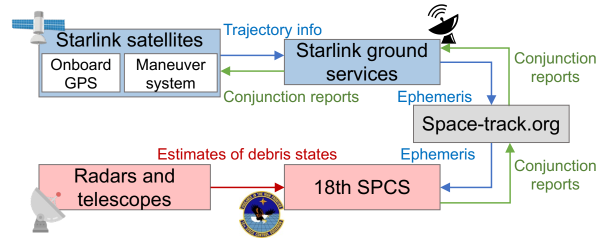


Figure 5: Starlink's automatic collision avoidance [5].

changes. Planning maneuvers is inherently a *multi-objective optimization* and should balance the following goals:

(1) Reduce the collision risks between space objects;
(2) Avoid that collision avoidance increases the collision risks with other space objects;
(3) Save the satellite's fuels with fewer maneuvers; and
(4) Minimize impacts on missions (e.g., earth observation for surveillance satellites and networking for Starlink).

The tradeoff between these goals yields diverse maneuver policies by heterogeneous satellites and operators.

From manual to autonomous maneuvers: Traditional satellite operators plan orbital maneuvers in a *manual, ad-hoc* fashion. They receive the SSA data, manually schedule maneuvers in the upcoming days/weeks, and instruct maneuver commands to each satellite via ground stations. While feasible for a few satellites, manual maneuvers are *not scalable* to the mega-constellations, *not responsive* due to the LEO satellite's high mobility, and *error prone* due to human mistakes (e.g., in the Iridium-Cosmos collision in 2009 [18]).

To this end, Starlink has installed a proprietary onboard self-driving system in its LEO satellites [4, 5], as shown in Figure 5. Each satellite estimates its runtime trajectory via onboard GPS and reports it to the ground station. Together with satellite/debris observations from SSN, Starlink and SSN use these data to estimate potential collisions and upload the collision risk information to each satellite, which then automatically schedules its orbital maneuvers.

3 MOTIVATION AND OVERVIEW

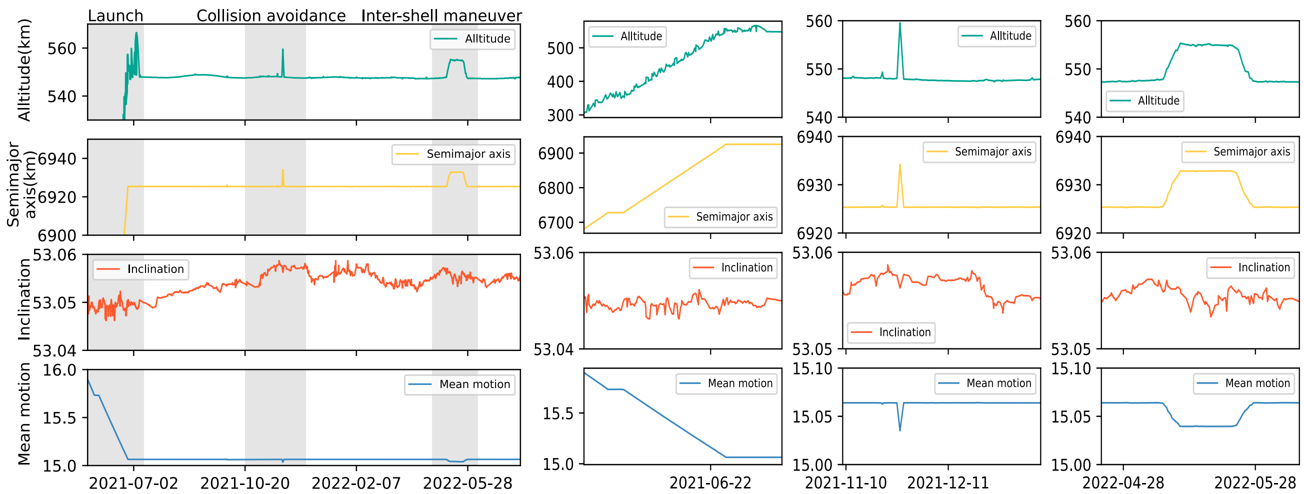
As a proprietary system, Starlink's autonomous driving largely remains under-explored by the open community. We seek to characterize it and understand three fundamental issues:

Q1: From the *individual satellite* view, can Starlink's autonomous driving ensure mission integrity and safety?

Q2: From the *mega-constellation* view, can Starlink manage its satellite distributions well with autonomous driving?

Q3: From the *networking* view, can autonomous driving facilitate stable, scalable, and performant satellite networks?

We start with the observation that Starlink's autonomous driving exhibits signs to ensure mission safety and integrity for the inter-satellite networking. Figure 6 exemplifies an operational Starlink satellite's trajectory from 2021/05 to 2022/07 based on its public space situational awareness dataset (detailed in §4). On the one hand, Starlink's satellites exhibit



(a) An example of Starlink maneuver **(b) Satellite launch** **(c) Collision Avoidance** **(d) Inter-shell maneuvers**

Figure 6: An example of Starlink satellite's maneuver behaviors.

stable and predictable trajectories in most cases. This helps stabilize satellite topology and various networking functions under high satellite mobility. On the other hand, Starlink's satellites conduct various orbital maneuvers for collision avoidance, migration between orbit shells, and launching/de-orbiting. These orbital maneuvers can *accumulate* dynamics of inter-satellite networking, as we will see below.

To better understand how autonomous driving impacts satellite networking, we examine five myths:

M1: Are satellite orbits stable and predictable *for granted*?

M2: Can Starlink's proper constellation design avoid all potential collisions between its satellites?

M3: Are all collision avoidance maneuvers necessary?

M4: Except for satellite launching/de-orbiting, are most orbital maneuvers transient and negligible in nature?

M5: Are orbital maneuvers' impacts on inter-satellite links, topology, and upper-layer network functions negligible?

Surprisingly, our study shows negative answers for all these myths about Starlink's autonomous driving. Due to various orbit drags and perturbations, an LEO satellite constantly experiences chaotic orbit decays and fluctuations, hence invalidating M1. Fortunately, unlike most operational satellites, Starlink continuously conducts orbit adjustment maneuvers to compensate for orbit decays, which strives for predictable satellite trajectories to facilitate networking (§5).

Despite so, Starlink's current autonomous driving is mostly *networking-agnostic* as its multi-hop satellite networks are still under deployments. While feasible for current bent-pipe communications, it could incur *accumulative* link/topology fluctuations, performance degradation, and failures for its upcoming inter-satellite networking. Specifically, we classify Starlink's remaining maneuvers by their purpose and duration, and evaluate their impacts on networking:

• **Collision avoidance (§6):** Starlink congests orbits and raises collision risks. Even with a proper constellation design, its own satellites can still collide and must cooperate at runtime to avoid collisions (thus invalidating M2). To this end, Starlink adopts an aggressive collision avoidance strategy with *transient, bursty* maneuvers. However, some maneuvers are unnecessary or even raise collision risks, both of which challenge the stability of satellite networks (invalidating M3).

• **Maneuvers between shells (§7):** Starlink adopts heterogeneous orbit shells (§2.1) and maneuvers of satellites between them. These maneuvers are *protracted* (lasting up to 10s days, invalidating M4) and accumulate extreme mobility between neighboring satellites. They result in frequent inter-satellite link breakups, prolonged link delays, topology updates, and networking instability (invalidating M5).

Dataset type	TLE ephemerides	Conjunction reports
Dataset source	space-track.org	celestrak.org
Time range	2019/05–2022/07	2022/04–2022/08
Num. entries	41,188,538	9,350,134
Entry intervals	3.0–34.7 hrs	8 hrs
Num. space objects	24,237	21,743
Orbit altitudes	162–575,074 km	239–91,314 km
Orbit inclinations	0°–145°	0°–145°

Table 1: Our space situational awareness datasets.

4 METHODOLOGY

We develop a three-step method to characterize Starlink's proprietary autonomous driving. First, we extract its observable orbital trajectories and collision forecasts from the public space situational awareness dataset (§4.1). Second, we unveil its core components using runtime orbital trajectories, Starlink's high-level specifications, the domain knowledge of maneuvers, and the celestial orbit propagators (§4.2). Last, we empirically evaluate how the inferred autonomous driving behaviors affect Starlink's networking (§4.3).

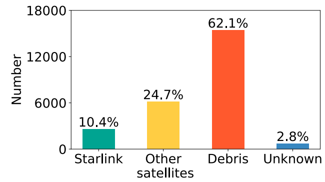
	Object ID and Classification	Year and Order of launch	Epoch	1st derivative of Mean Motion	2nd derivative of Mean Motion	Drag Term	Type and Set Number	Checksum
1	47150U	20088AE	22151.00102699	-.00001063	00000-0	-52481-4	0999	9
	Object ID	**Inclination**	**Right ascension of the ascending node**	**Eccentricity**	**Argument of perigee**	**Mean anomaly**	**Mean motion**	**Revolution number at epoch**	**Checksum**
2	47150	53.0559	0.7866	0001588	67.5938	292.5219	15.06390011	8418	0

(a) Two-line element set (TLE)

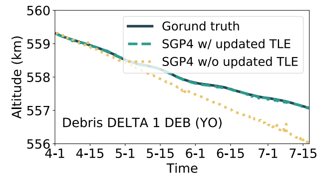
Object1 ID	Object1 Name	Days Since Epoch	Max Probability	Dilution Threshold (km)	Min Range (km)	Relative Velocity (km/sec)
46121	STARLINK -1602	6.294	5.436E-04	0.021	0.087	
Object2 ID	**Object2 Name**	**Days Since Epoch**	**Start (UTC)**	**TCA**	**Stop (UTC)**	11.951
20673	COSMOS 886 DEB	6.678	2022 Aug 14 23:19:48.698	2022 Aug 14 23:19:49.116	2022 Aug 14 23:19:49.535	

(b) Conjunction report

Figure 7: Message formats of space situational awareness datasets.



(a) Space objects in our dataset



(b) SGP4 accuracy *w/o* maneuvers.

Figure 8: Our TLE dataset & its SGP4 orbit propagator.

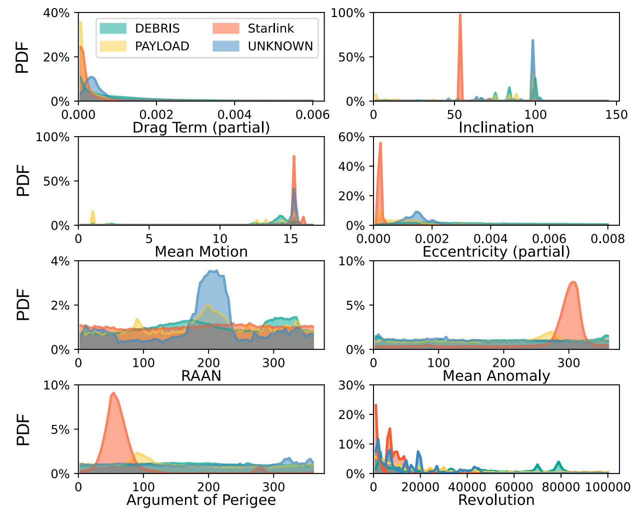


Figure 9: Orbital parameter distributions in dataset.

4.1 Datasets

We collect two datasets on space situational awareness, as summarized in Table 1 and Figure 7. Figure 8a, Figure 9, and Figure 10 show the distribution of the space objects, orbital parameters, and conjunction reports from these dataset.

• **Two-line element sets (TLEs):** TLEs are NASA's standard format of encoding space objects' trajectories. As shown in Figure 7a, each TLE entry encodes a space object's orbital elements in Figure 3b for a given point in time (the epoch). It is observed by ground-based radars, telescopes, or satellites' onboard sensors. Given this TLE, one could predict its upcoming position and velocity using *orbit propagators* such as SGP4 [36] *if no orbital maneuvers were conducted*. As shown in Table 1, we collect all 41,188,538 TLEs in 2019/05–2022/07 from space-track.org, resulting in a dataset of 8,487 satellites, 15,061 pieces of debris, and 689 other space objects.

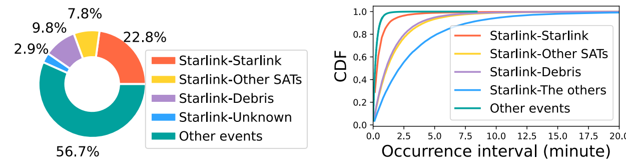
• **Conjunction reports:** They are standardized messages [37] to describe the upcoming conjunction events between space objects. As shown in Figure 7b, each conjunction report encodes a pair of space objects' types, operators, positions, velocities, their uncertainties (covariances), miss distance, and collision probability at the time of closest approach (TCA). With conjunction reports, satellite operators can assess the collision risks and coordinate orbital maneuvers. As shown in Table 1, we collect conjunction reports in 2022/04–2022/08 from celestrak.org, forming a dataset of 9,350,134 reports between 21,743 pairs of space objects.

4.2 Dissecting Autonomous Driving

With the space situational awareness datasets in Table 1, we next detect and analyze Starlink's self-driving behaviors. Our core insight is that, although Starlink's orbital maneuver strategy is proprietary, its maneuvers will cause observable changes in its satellites' orbital parameters that differ from expected orbit propagations *without* maneuvers. We thus devise a three-step method to detect and analyze maneuvers:

Step 1: orbital prediction without maneuvers. Given a time series of a satellite's observed real orbital parameters $\{\mathsf{TLE}_1, \mathsf{TLE}_2, ..., \mathsf{TLE}_n, ...\}$ from our dataset, we predict the upcoming orbital parameter $\hat{\mathsf{TLE}}_{n+1}$ based on previous observation TLE_n. Without maneuvers between TLE_n and TLE_{n+1}, the orbital parameter changes are mainly attributed to Kepler planetary motions and orbital drags. We can predict such changes with the standard SGP4 orbit propagator [36] that was designed jointly with TLEs by NASA. Figure 8b shows that, if no maneuvers are performed, SGP4 is sufficiently accurate for our study due to our near-term predictions.

Step 2: orbital maneuver detection. To detect orbital maneuvers, we next compare the predicted orbital parameter $\hat{\mathsf{TLE}}_{n+1}$ with the real observation TLE_{n+1}. A significant deviation of $\hat{\mathsf{TLE}}_{n+1}$ from TLE_{n+1} implies orbital maneuvers between time slot n and $n+1$. Our experiments show that a straightforward comparison between $\hat{\mathsf{TLE}}_{n+1}$ and TLE_{n+1} is erroneous due to inaccuracies of runtime orbital parameter observations and orbital propagators (detailed in §5). To tolerate these noises, we maintain a sliding window of 5 consecutive TLEs, predict the next TLE, and compare it with the average of TLEs within this window. If their difference of the orbit's semi-major axis is greater than 1 km (consistent with



(a) Distribution of event types **(b) Occurrence interval**

Figure 10: Statistics of conjunction events.

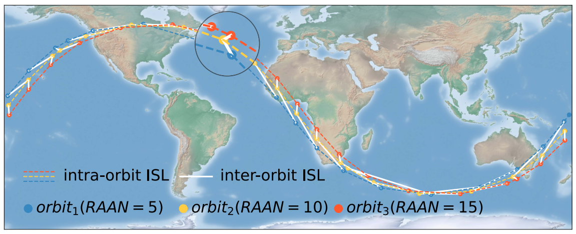


Figure 11: Inferring satellite neighborship by RAAN.

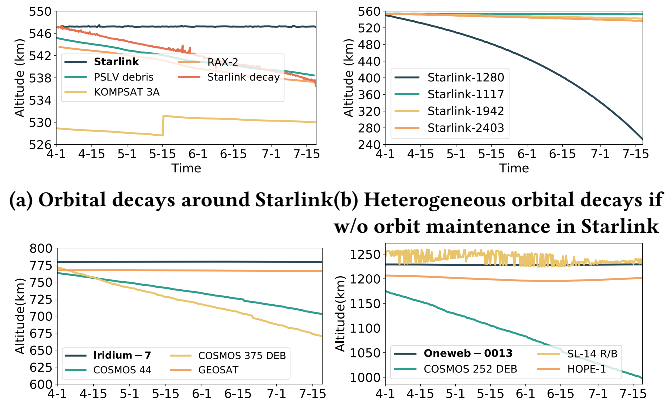
the public report on Starlink-OneWeb collision avoidance [38] in Figure 18b), we label it as a maneuver.

Step 3: root cause analysis. Upon detecting an orbital maneuver, we seek to analyze its root causes. Since we have no access to Starlink's internal maneuver logic, we correlate each maneuver event with multi-sourced side-channel information to reason about it. Specifically, Starlink discloses that it initiates a maneuver if the collision probability $P_c \geq 10^{-5}$ [4], and conducts maneuvers through a single in-track burn approximately 12 hours before the predicted closest approach of satellites [38]. So we align each detected maneuver with conjunction reports for the same satellite in a 12-hour time window and check these conjunction reports' collision probabilities, miss distances, and target satellites' surrounding environments. Moreover, whenever possible, we seek to attribute detected maneuvers to publicly reported conjunction events [6, 8, 39] to understand their causes better.

We point out that the above root cause analysis still has room to improve and deserves future research. First, not all detected maneuvers can be correlated to multi-sourced side-channel information. For instance, a collision avoidance maneuver that cannot be correlated with conjunction events or public reports may be indistinguishable from orbital maneuvers for other missions. Second, minor orbital maneuvers with < 1km semi-major axis changes cannot be detected or distinguished from natural orbital fluctuations. Third, transient orbital maneuvers whose durations are less than the interval between TLEs may not be detected.

4.3 Assessing Impacts on Networking

Beyond maneuvers from a single satellite, we step further to assess their impacts on inter-satellite networking. Although Starlink currently only offers bent-pipe communications, it is actively testing and deploying ISLs for networking (§2.1). We thus take a forward-looking perspective to study how its current autonomous driving should be adapted to manage inter-satellite links, topology, and network functions.



(a) Orbital decays around Starlink **(b) Heterogeneous orbital decays if w/o orbit maintenance in Starlink**

(c) Orbital decays around Iridium **(d) Orbital decays around OneWeb**

Figure 12: The necessity of orbit maintenance.

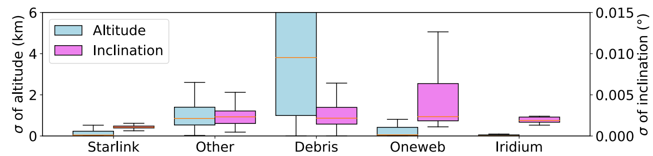


Figure 13: Deviations of LEO orbital parameters.

Specifically, we follow recent studies and operational practice [40–44] to consider the grid network satellite topology in Starlink. Each satellite connects to its nearest intra/inter-orbit neighbors (thus 4 ISLs). We construct this topology from real orbital trajectories by grouping Starlink satellites and inferring their neighboring relations, as shown in Figure 11. Satellites are grouped by their orbital inclination, semi-major axis, and right ascension of the ascending node (RAAN). To establish intra-orbit/inter-orbit ISLs, we find each satellite's intra-orbit/inter-orbit neighboring satellites by calculating their distances. After setting up the topology, we track its evolution with orbital parameter changes and maneuvers to analyze networking behaviors.

5 CONTINUOUS ORBIT MAINTENANCE

We first discover that, without proper maintenance, LEO satellites' orbits would not be as stable as expected (M1). Compared to traditional geostationary communication satellites, LEO satellites at lower altitudes suffer from more chaotic orbit drags and decays. Orbit decays could disrupt the LEO constellation's uniformity, incur fluctuations of ISLs, and challenge the stability of satellite network topology. To combat them, we reveal that Starlink runs continuous maneuvers to compensate for its orbits (§5.1), retain the uniformity of its constellation (§5.2), and strive for stable networking (§5.3).

5.1 The Individual Satellite View

We start from a single satellite's view to demystify its orbit maintenance. Ideally, space objects should follow Kepler's laws to orbit elliptically around Earth. But in reality, their orbits decay due to atmospheric drag, tidal effects, gravitational

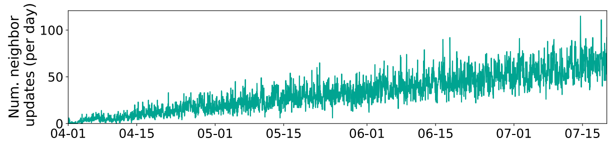


Figure 14: Neighborship updates w/o maintenance.

radiation, and electromagnetic drag [45]. Orbital decays are particularly obvious in LEOs as satellites are closer to the atmosphere. They continuously lower LEO satellite's orbits to eventually enter the atmosphere and burn up in the fall.

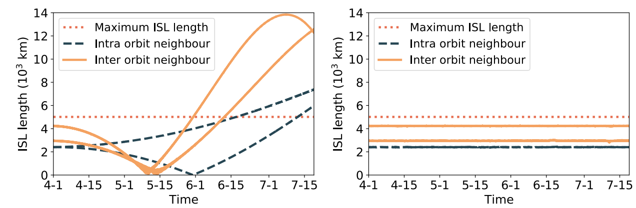
Figure 12 compares Starlink's orbits with other space objects' at similar altitudes (550 ± 30km). For comparison, we also project Starlink's orbits without maneuvers using the SGP4 propagator. We make three observations. First, without orbital maintenance, space objects experience continuous orbit decays due to drags. Second, due to a lack of maneuver capabilities, the orbits of debris (PSLV DEB) are less stable than satellites'. Third, if Starlink did not adjust its orbits, its satellites would decay similarly to others.

To combat orbit decays, Starlink constantly compensates for its orbital parameters via maneuvers. As shown in Figure 12, Starlink satellites' real orbits approximate an ideal Kepler orbit. This differs from most satellites that either decay (e.g., RAX-2) or occasionally adjust orbits (e.g., KOMPSAT 3A). In our dataset, except Starlink, only 6% of satellites at the 550 ± 30km altitude regularly adjust orbits. Besides Starlink, we also note that other LEO satellites for communication/networking like Iridium and OneWeb tend to conduct more frequent orbit maintenance than others, thus having stabler orbits as shown in Figure 12c–12d and Figure 13.

5.2 The Mega-Constellation View

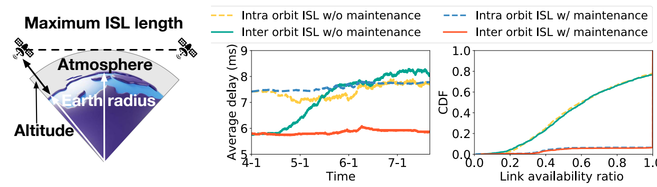
From the perspective of satellite mega-constellation, orbital maintenance is crucial to retain Starlink's stable neighbor relationship and uniform constellation. As introduced in §2.1, Starlink's constellation is uniform by design to simplify deployments and streamline networking. At the first glimpse, orbital decays occur for all Starlink satellites and hence would not affect satellites' neighboring relations.

However, we find Starlink satellites would exhibit *heterogeneous* orbital decays if no orbit maintenance was conducted, as shown in Figure 12b. Such diverse orbital decay patterns arise from satellites' different temporal-spatial states (position, velocity, etc.) that experience heterogeneous atmospheric drags, solar/lunar activities, Earth's oblateness, and others. As a result, Starlink's satellites would no longer maintain stable neighbor relationships due to relative motions, complicating satellite networking. As shown in Figure 14, without orbit maintenance, each satellite's nearest neighbor would fluctuate due to satellites' time-varying distances from heterogeneous orbital decays. As every Starlink satellite's orbital decay accumulated, each satellite's nearest neighbor would update more frequently, from 10s/day in 2022.04 to 100s/day in 2022.07. This orbital propagation experiment confirms that, Starlink's continuous orbit maintenance is valuable to retain the uniformity of the LEO mega-constellation.



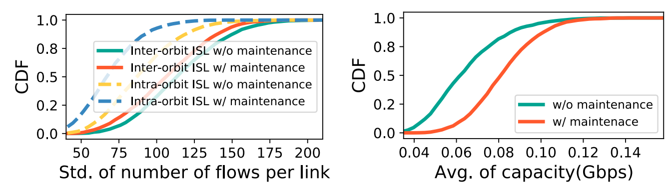
(a) Without orbit maintenance. **(b) With orbit maintenance.**

Figure 15: Orbit maintenance's impacts on ISLs.



(a) Maximum ISL **(b) ISL stability and delay**

Figure 16: Orbital maintenance facilitates ISL stability.



(a) Imbalanced flow distributions **(b) Average per-flow throughput**

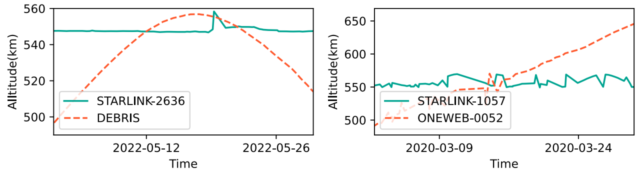
Figure 17: Orbital decay's impacts on 1,000 randomly distributed inter-satellite network traffic flows.

5.3 The Networking View

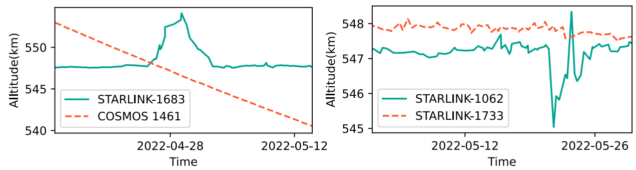
From the networking perspective, Starlink's orbital maintenance helps stabilize inter-satellite links, topology, and thus upper-layer network functions. Heterogeneous satellite decays in §5.2 magnify the relative motions between neighboring satellites and thus cause fluctuating inter-satellite link delays, link availability (if exceeding the maximum visibility distance), and thus inter-satellite topology updates.

To validate this issue, we first compare Starlink's ISLs and topology with/without orbital maintenance using the SGP4 orbit propagator. Figure 15 shows that, without maintenance, the orbit decay will cause the time-varying distance between the satellite and its neighbors, eventually exceeding the maximum distance to establish an ISL and thus disconnecting the ISL. It is thus necessary for Starlink to maintain its orbital parameters to strive for stable ISLs and topology.

Figure 16b quantifies how Starlink's orbit maintenance helps stabilize satellite links and delays. We make three observations. First, Starlink's orbit maintenance helps stabilize ISLs. About 90% of the ISLs stay connected within three months. Instead, without orbit maintenance, most ISLs would eventually be disrupted and reconfigured when a satellite's



(a) Starlink-on-debris **(b) Starlink-on-3rd party satellite (OneWeb, maneuverable [8])**



(c) Starlink-on-3rd party satellite (Cosmos, not maneuverable) **(d) Starlink-on-Starlink**

Figure 18: Classification of collision avoidance in Starlink's autonomous driving (the solid green line).

neighbor is out of its visibility due to accumulative orbital decay. Even if still connected, the remaining intra(inter)-orbit ISLs would still increase their average propagation delays by 2ms (3ms). Second, inter-orbit and intra-orbit ISLs show similar characteristics. Third, even with orbit maintenance, 10% of Starlink's ISLs are disrupted. As we will see, they are from deficient collision avoidance and inter-shell maneuvers.

Beyond link stability, orbit maintenance also helps balance the satellite network traffic load for less congestion. We randomly generate 1,000 source-destination pairs between satellites, run shortest-path between them, count the number of flows on each ISL, and compute each flow's average bandwidth assuming 10-Gbps ISLs. As shown in Figure 17a, orbital decay would disrupt more ISLs, force more traffic flows to traverse the same links, and result in highly imbalanced traffic flow distributions and smaller per-flow capacity. Instead, orbit maintenance stabilizes the satellite topology with more ISLs, thus resulting in 1.2× per-flow throughput improvement and more balanced flow distributions.

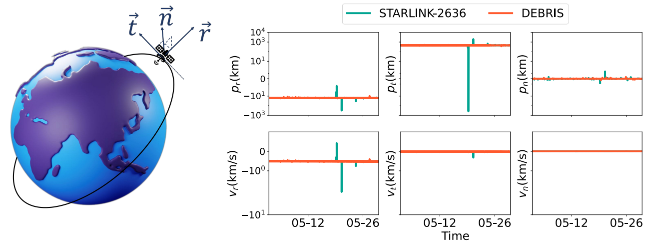
6 COLLISION AVOIDANCE

For mission safety, Starlink's autonomous driving conducts *transient, bursty* maneuvers for collision avoidance. We first classify them and characterize their key properties (§6.1). Then we unveil Starlink's cooperative collision avoidance in its LEO mega-constellation (§6.2, invalidating M2). We last show that some maneuvers are unnecessary or risky, which could interrupt satellite networks (§6.2, invalidating M3).

6.1 The Individual Satellite View

We first classify and characterize a single Starlink satellite's maneuvers for collision avoidance.

Classification of collision avoidance: A Starlink satellite faces collisions with three types of space objects [5]: space debris, 3rd-party satellites/spaceflights, and other Starlink satellites. By analyzing the TLEs and conjunction reports in



(a) RTN Coordinates **(b) Starlink's position and velocity in RTN**

Figure 19: A 3D view of Starlink's collision avoidance maneuver in Figure 18a in the RTN coordinate system.

Distribution	Maneuver duration (hour)	Maneuver extent (km)
min	12.73	1.49
25%	92.74	3.05
50%	120.50	4.99
75%	181.62	6.61
max	369.42	21.19

Table 2: Duration and extent of collision avoidances.

Table 1, we have observed collision avoidances for all these scenarios, as shown in Figure 18–20 and Table 2.

∘ *Starlink-on-Debris* (Figure 18a): Since debris is not maneuverable, the Starlink satellite should take the full responsibility for collision avoidance.

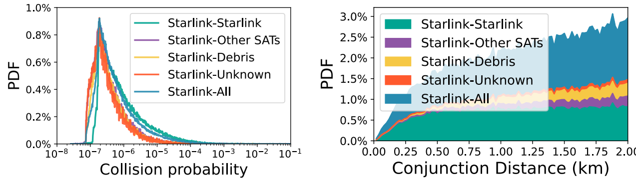
∘ *Starlink-on-3rd-party satellite* (Figure 18b–18c): The 3rd-party satellite or spaceflight can be maneuverable (e.g., the U.K.'s OneWeb in Figure 18b) or non-maneuverable (e.g., Russia's Cosmos in Figure 18c). For the former case, Starlink can *manually* coordinate with other operators to schedule maneuvers [8, 39]. For the latter case, Starlink takes full responsibility for collision avoidance maneuvers.

∘ *Starlink-on-Starlink* (Figure 18d): Both satellites belong to Starlink and hence can *automatically* cooperate for optimal maneuvers. We detail such cooperative behaviors in §6.2.

A 3D view of collision avoidance: Figure 19 exemplifies the Starlink satellite's 3D location and velocity dynamics during the maneuver in Figure 18a in the Radial, Tangential, Normal (RTN) coordinate[1]. To conduct maneuvers, the Starlink satellite's propulsion system accelerates in the R and T axis to raise orbits' altitudes in both directions. The location and velocity changes in the N direction are negligible.

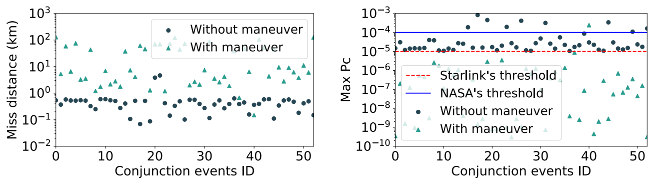
Effectiveness on collision avoidance: We further confirm that Starlink's autonomous driving excels in lowering the collision risks. We follow §4.2 to correlate each collision avoidance maneuver event with conjunction reports, and evaluate the collision risks with/without this maneuver. As shown in Figure 21, most Starlink's maneuvers increase the miss distances between two space objects by 28.4 km on average and lower the collision probability below Starlink's collision threshold ($P_c \leq 10^{-5}$) by 1–3 orders of magnitude.

[1]As shown in Figure 19a, the RTN coordinate system's origin is the center of the satellite. The T axis points to the direction of the satellite's movement. The N axis points to the normal direction of the orbital plane. The R axis points to the direction that forms a right-handed system with T and N axis.



(a) Collision probability (b) Miss distance

Figure 20: Collision risks between space objects.



(a) Miss distance (b) Collision probability $P_c^{\max}$

Figure 21: Effectiveness of collision avoidance.

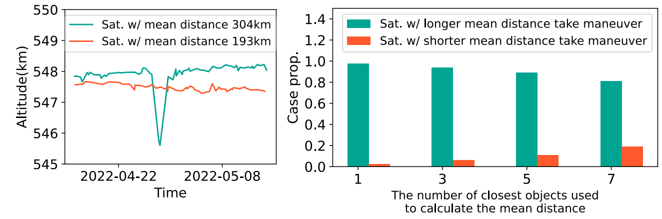
6.2 The Mega-Constellation View

We next switch to the mega-constellation view and focus on collision avoidance between Starlink satellites. At first glimpse, collisions between Starlink satellites can be avoided by properly separating them during the constellation design (M4, also claimed by Starlink in [5]). In reality, we find that such passive deconflicts do not suffice to avoid all collisions. Instead, we observe that Starlink satellites indeed *cooperate* at runtime to prevent collisions. We study the key factors that influence this cooperation.

Are "passive deconflicts" sufficient? By design, Starlink's LEO satellites are distributed distantly from each other. But this is insufficient to de-risk all collisions: Starlink's *mega-constellation* nature congests orbits and unavoidably raises collision risks inside the constellation. Figure 10 shows the conjunction events from our dataset. 22.8% of conjunction events with the collision probability $P_c \geq 10^{-5}$ come from conjunctions between Starlink satellites. 90% of Starlink-on-Starlink conjunction events occur in less than 2.5 minutes.

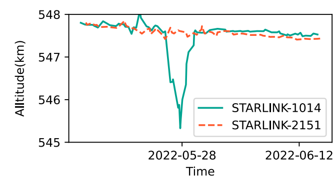
Cooperative collision avoidance: In principle, each Starlink satellite can adopt the same collision avoidance strategies for other Starlink satellites, debris and 3rd-party satellites. However, this approach is sub-optimal for Starlink-on-Starlink collision, in which satellites can cooperate to save fuels and lower collision risks after maneuvers (§2.3).

We find Starlink satellites indeed cooperate for collision avoidance by comparing their surrounding environments. Figure 22a exemplifies collision avoidance between two Starlink satellites on 05/21/22 from our dataset. The Starlink satellite whose neighboring space objects are farther conducts the maneuver. This allows the satellite to safely maneuver without colliding nearby space objects. Figure 22b confirms that this cooperation strategy is ubiquitous in Starlink. For all Starlink-on-Starlink collision avoidances in our datasets, more than 98% of cases conduct maneuvers at the Starlink satellite with longer distance to nearby space objects.



(a) A showcase trace (b) Statistical results

Figure 22: Cooperative Starlink-Starlink maneuver.



	Unnecessary maneuver	Necessary maneuver
Average P_c	2.77e-06	1.17e-04
Average extent	2.842 km	4.369 km
Percentile	56.8%	43.2%

(a) A showcase at $P_c = 6.17 \times 10^{-7}$ (b) Statistical characteristics

Figure 23: Unnecessary collision avoidances.

6.3 The Networking and Safety View

While Starlink mostly excels in collision avoidance, it may unnecessarily interrupt ISLs and network topology. We found that some collision avoidance maneuvers are unnecessary, and may even raise higher collision risks with other space objects (thus invalidating M5). They may misalign laser ISLs (thus failures) and cause more topology updates (§7.3).

Unnecessary collision avoidances: We define unnecessary maneuvers as those that significantly raise/lower semi-major axis (>1 km) at a low collision probability ($P_c < 10^{-5}$). We analyze how these maneuvers affect the satellite network by leveraging the methods in §7.

Figure 23a exemplifies an unnecessary collision avoidance. The Starlink-1171 satellite raised its altitude about 4 kilometers but the probability of collision between it and another satellite was 5.138e-07 that did not exceed the threshold.

Figure 23b shows that such unnecessary maneuvers are not uncommon. In our dataset, 56.8% of maneuvers have low collision probability (2.77×10^{-6} on average) by raising/lowering orbit altitudes by 2.842 km. These maneuvers were conducted when their collision probabilities were even *below* Starlink's stringent threshold (10^{-5}), thus deemed unnecessary according to Starlink's safety criteria. A major cause of these maneuvers is operators' over-estimated collision probability due to time-varying uncertainties (covariances) of satellites' positions and velocities [4, 8, 33, 34]. Due to the radar/telescope's limited observation capacity, it is difficult for them to accurately track all LEO satellites simultaneously. To this end, we gauge that Starlink tends to adopt a conservative probability prediction. The over-conservative avoidance strategy with inaccurate orbital information employed by Starlink results in a high level of unnecessary avoidance. These unnecessary maneuvers will waste Starlink satellites' fuels and shorten their lifetime. Moreover, as shown in §7.3, they can unnecessarily interrupt ISLs and

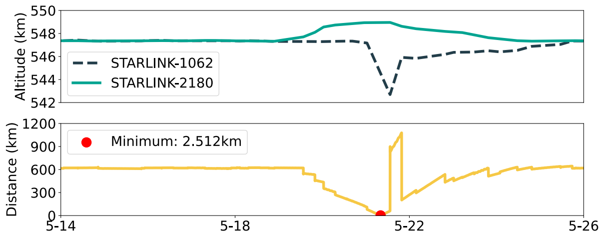
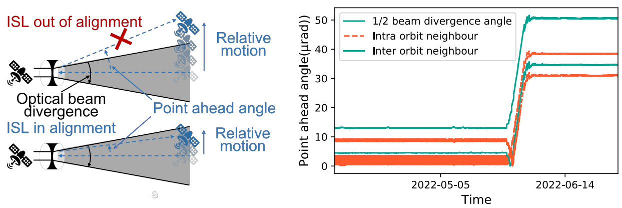


Figure 24: Starlink's high-risk orbital maneuver.



(a) ISL's Out-of-alignment (b) A showcase from our dataset

Figure 25: ISL's out-of-alignment by maneuvers.

cause more topology updates. Since their collision probabilities are below Starlink's safety threshold, they could be mitigated to achieve lower network delays and failures *without* compromising mission safety.

High-risk collision avoidance: Although ≥98% of maneuvers avoid collisions with surrounding objects (§6.2), we find that a small portion of maneuvers can still raise collision risks. Figure 24 showcases it from our dataset. After the collision avoidance with a 3rd-party satellite, the STARLINK-2180 satellite almost hits another nearby Starlink satellite (< 3 km distance). Such maneuvers may cause network node/link failures. The reason for running these maneuvers deserves further exploration. Even if they intended to avoid smaller unaccounted objects like debris, they raised collision risks and offset their intentions. They could be optimized by maneuvering earlier with smaller altitude changes [46, 47].

Impacts on ISLs: The above maneuvers can cause unnecessary link failures due to ISL out-of-alignment. Due to relative motion between satellites, the optical signals between satellites should be calibrated by a *point ahead angle* for successful transmission. Once the point ahead angle exceeds 1/2 beam divergence angle of the transmitting satellite, the ISL may be disrupted [48–53] (Figure 25a). Figure 25 showcases this issue between two Starlink satellites with an unnecessary maneuver from our dataset (assuming the 70 μrad beam divergence angle in the commodity ISL [49]). Their point ahead angle has exceeded 1/2 of beam divergence angle, which may lead to the ISL out-of-alignment and even failures.

7 MANEUVERS BETWEEN SHELLS

We find that, Starlink runs *protracted* orbital maneuvers for some satellites (mostly between its orbital shells) by up to 43.97 days (thus invalidating M4). Such maneuvers differ from continuous orbit maintenance in §5, transient collision avoidances in §6, and launching/de-orbiting in Figure 6. While they marginally impact each individual satellite (§7.1), their long-lasting nature incurs significant relative motions between neighboring satellites (§7.2), *accumulates* network link delay fluctuations and topology updates, and affects upper-layer network functions (§7.3, violating M5).

7.1 The Individual Satellite View

As shown in §2.1, Starlink adopts multiple orbital shells to optimize its coverage. Figure 26a shows the statistics of these shells in operation from our dataset. As of July 2022, 83.57% of satellites reside at the 550 km altitude with 53°inclination (primarily covering North America), 14.29% of satellites reside at the 540 km altitude with 53.2°inclination, and 2.14% of satellites reside at the 570 km altitude with 70°inclination (for networking at high-latitude locations).

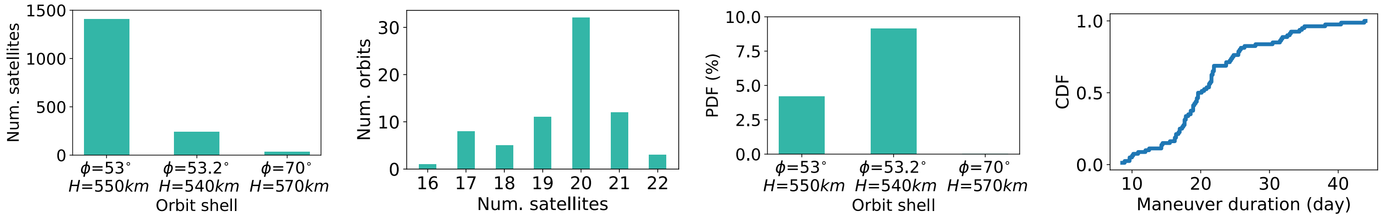
We find that, Starlink migrates its satellites between shells via protracted maneuvers. Figure 27 showcases how it works. A satellite originally stayed in the shell at the 550 km altitude. From 05/12 to 05/17, it slowly raised its orbit's semi-major axis by 6 km to migrate to another shell at the 560 km altitude. After staying in the new shell for about 10 days, it lowered its orbit to return to the original shell. Such maneuver differs from continuous orbit maintenance in §5, transient collision avoidances in §6, and launching/de-orbiting in Figure 6.

We further show that such protracted maneuvers are not uncommon in Starlink. Figure 26c-26d shows the statistics of such protracted maneuvers from 2022/04 to 2022/07 whose semi-major axis increased by ≥1 km and last for 5 consecutive TLEs (≈ 31 hours). It shows that, 81 satellites from 46 orbits conducted protracted maneuvers between shells in 2022/04–2022/07. 4.19% satellites in the first shell and 9.13% satellites in the second shell conduct maneuver, and no satellite conduct maneuver in the third shell. More than 99.95% of the maneuver durations are more than 10 days, and the longest can last 43.97 days. As shown in Figure 28, most of these maneuvers took place in May and June 2022. While seemingly fine for each satellite, such maneuvers challenge the stability of constellation and network as shown next.

7.2 The Mega-Constellation View

From the mega-constellation perspective, the protracted maneuvers above challenge the stability of the neighborship between satellites. According to Kepler's laws[2], satellites at higher altitudes move slower. As shown in Figure 29, if a satellite raises its orbit, it will incur high relative motions to its neighbors at lower altitudes, thus prolonging their distances and link delays. The longer this maneuver lasts, the more distant these two satellites become. When the distance

[2] $v_{\text{mean}} = \sqrt{\frac{\mu}{a^3}}$, where v_{mean} is the average angular velocity, μ is standard gravitational parameters and a is the length of semi-major axis.



(a) Multiple orbital shells **(b) Satellites at $\phi = 53°$, $H = 550km$** **(c) Distribution by source shells** **(d) Maneuver duration**

Figure 26: Starlink's maneuvers between multiple orbital shells.

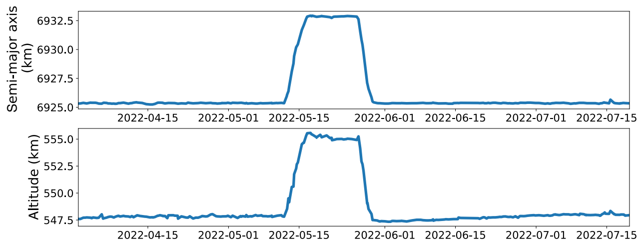


Figure 27: A showcase of inter-orbit-shell maneuver.

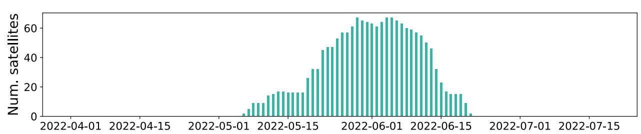


Figure 28: The number of satellites conducting inter-orbit-shell maneuvers per day.

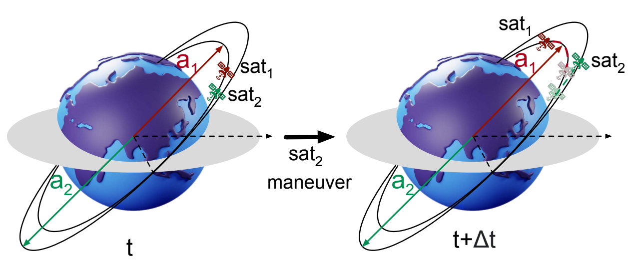


Figure 29: Maneuvers between orbital shells prolong neighboring satellites' distance accumulatively.

exceeds the maximum visible distance (≈4,782 km in Starlink, Figure 16a), the neighboring satellite no longer becomes visible. Moreover, such high relative motions between neighboring satellites complicate the alignment of laser ISLs and may result in link failures due to out-of-alignment (§6.3).

Figure 30 shows the frequency of Starlink's satellite neighborship updates. The number of neighborship updates increased in 2022/05 and 2022/06 when some satellites conducted long-term orbit maneuvers. Therefore, the inter-orbit shell maneuvers cause dramatic neighborship changes.

7.3 The Networking View

The dramatic satellite neighborship updates by protracted maneuvers threaten the stability and performance of satellite networking. The severity of such impacts depends on how

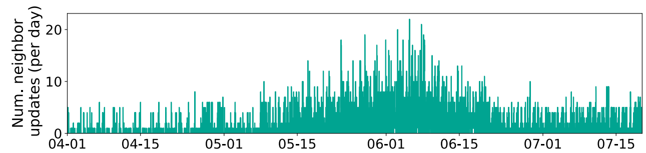


Figure 30: Satellite neighborship updates per day.

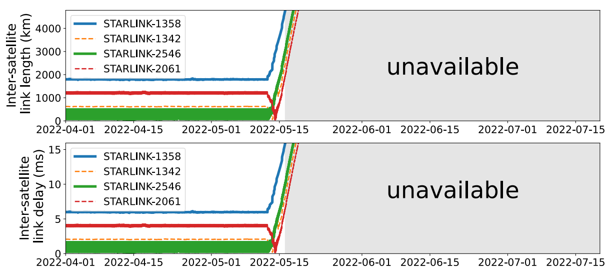
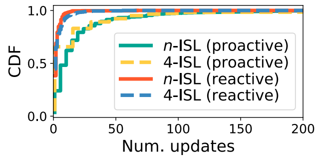


Figure 31: ISL's length and delay under maneuvers.

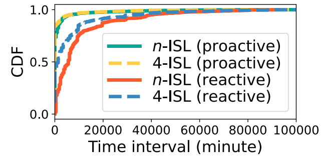
Starlink will inter-connect its satellites. Since Starlink is still testing its ISLs and has not specified its networking schemes, we study various networking schemes and evaluate their dynamics due to Starlink's protracted maneuvers.

We consider two variants of the classic Grid topology in satellite networks [41–44]: (1) 4-**ISLs**: Each satellite connects to its four nearest intra/inter-orbit neighbors (thus ≤4 ISLs per satellite, which is consistent with most Starlink satellites today). (2) n-**ISLs**: Each satellite connects to its two nearest intra-orbit neighbors and multiple nearest inter-orbit neighbors, which reduces the inter-orbit ISL length and tolerate maneuvers. For each variant, upon the change of its nearest neighbors, we consider two strategies for reconfiguring ISLs and topology: (a) **proactive** strategy, in which each satellite updates its ISL as soon as its nearest neighboring satellite changes; (b) **reactive** strategy, in which each satellite updates its ISL until its neighbor is no longer visible. Note that both strategies update the network ISL/topology without affecting collision avoidances in §6.

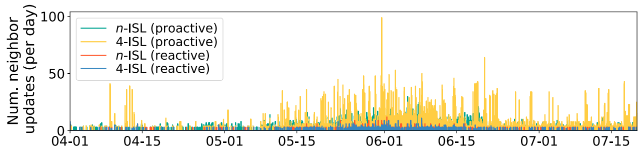
Impacts on ISLs: We consider all satellites in the first shell at the 550 km altitude with 53° inclination (1,441 satellites in total, accounting for 83.57% of operational Starlink satellites in orbit). Figure 31 showcases that Starlink's inter-orbit-shell maneuvers prolong the length (propagation delay) of the ISL and even cause link failure. Figure 32 shows the frequency of ISL updates in the first shell. We make four observations. First, 91.98% and 89.21% of Starlink satellites suffer from ISL



(a) ISL updates per satellite



(b) Interval between updates

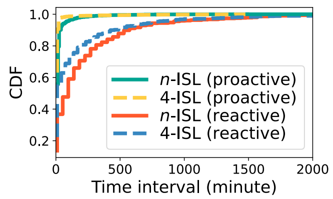


(c) ISL updates of different topologies

Figure 32: ISL updates in various networking schemes.

Networking scheme	Avg. num. snapshots/day
4-ISL (proactive)	64.13
n-ISL (proactive)	51.29
4-ISL (reactive)	8.16
n-ISL (reactive)	5.92

(a) Num. snapshots per day



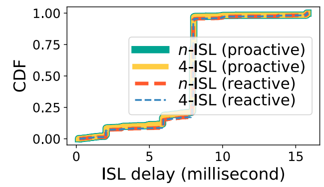
(b) Time interval between snapshots

Figure 33: Topology updates in various schemes.

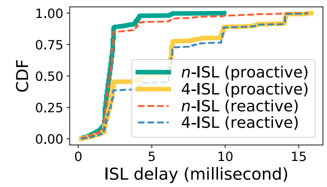
changes under *n-ISL (proactive)* and 4*-ISL (proactive)* strategies, respectively. Instead, the reactive strategy decreases the number of satellites whose ISLs changed to 54.15% and 47.48%, respectively. Second, reactive strategies can increase the interval between ISL updates. Third, Figure 34 shows that *n-ISL* has a lower inter-orbit ISL delay. Fourth, proactive strategy saves link propagation delays at the cost of more frequent link/topology updates.

Impacts on network topology: As the inter-satellite distance accumulates in the inter-orbit-shell maneuver, two neighboring satellites can eventually become invisible to each other. Their ISL will break and cause frequent satellite network topology updates. Table 33a, Figure 33b, Figure 34, and 35 show the topology update frequency ("snapshots"), interval, ISL delay, and failure in 2022/04–2022/07, respectively. For today's 4-ISL Starlink satellites, we find that the reactive strategy surprisingly outperforms the proactive strategy in the topology updates (6.85× reduction) and link failures (1.69×) with marginal ISL delay increment (≈0.34 ms on average). This is because the 4-ISL constraint limits the proactive strategy's freedom of choosing closer satellites (thus less delays and failures). Instead, if the 4-ISL constraint is removed, the proactive strategy will achieve lower ISL failures and delays at the cost of more topology updates (7.66×, which is acceptable for today's SDN).

Impacts on upper-layer network functions: Upon ISL failures or topology updates, the satellite network should re-compute the data path for traffic delivery via layer-2 switching or layer-3 routing. The protracted maneuvers impact traffic delivery with frequent topology changes, prolonged link delays, and potential link failures. For example, suppose



(a) Intra-orbit ISL



(b) Inter-orbit ISL

Figure 34: ISL delay in various networking schemes.

software-defined networking (SDN) or L2 tunneling is used to pre-compute each satellite's data path (like Google Loon [54, 55]). In that case, protracted maneuvers will yield more topology snapshots and thus more frequent pre-computations and routing updates. If distributed routing (e.g., OSPF/BGP) is used by satellites, frequent topology updates will cause global routing re-convergence, before which the traffic cannot be delivered (thus lowering network availability [11]).

8 SUGGESTIONS AND VALIDATIONS

As shown in §5–7, our answer to if Starlink's autonomous driving works coherently with satellite networking is mixed. On the one hand, it can stabilize its satellites' orbits and avoid collisions in most cases for network stability and reliability. On the other hand, it can also unnecessarily accumulate satellite network dynamics to offset the above merits. The root cause is that, satellite autonomous driving and networks are independently designed by different domain experts with limited mutual awareness and coordination.

To this end, we explore and quantify the potential of *networking-autonomous driving co-designs* for LEO mega-constellations. Our goal is two-fold (ordered by importance): (1) guarantee mission safety and sustainable use of space; and (2) strive for stable, reliable, and performant inter-satellite networking. Even though our discussion below focuses on Starlink, we believe our co-design principle should generalize to other LEO constellations for networking as well.

Autonomous driving-aware satellite network: Safety is the first priority and prerequisite for functional LEO networking. Due to Starlink's mega-constellation scale and high capital expenditure, We suggest it should retain its stricter collision avoidance threshold for a larger safety margin. Given unavoidable maneuvers, it is necessary for satellite networks to tolerate orbital dynamics and strive for stable, reliable, and performant networking. The key is that, the satellite operators are aware of the forthcoming orbital maneuvers and can reactively rearrange their networking to mitigate disruptions and performance penalties.

Specifically, for today's 4-ISL Starlink satellites in operation, we suggest the operator adopt the *reactive* ISL update strategy in §7.3 to stabilize network topology and mitigate link failures. Figure 33-35 validate that this strategy can stabilize satellite network topology/link, reduce link failures and mask their impacts on upper-layer network functions

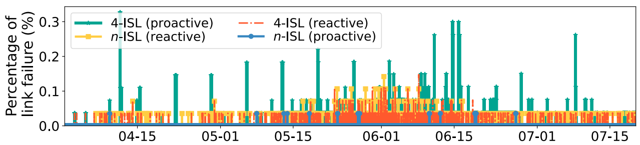


Figure 35: ISL failures in various networking schemes.

at a negligible ISL delay increment (≈0.34 ms). If future Starlink satellites can equip more ISLs, the *proactive* ISL strategy would have the potential of more stable ISLs at an acceptable cost of topology updates. In both cases, Figure 36 shows that the reactive and proactive ISL update strategies exhibit minor differences in their traffic flow distributions and per-flow throughputs, thus achieving similar load balancing levels. Beyond ISL updates, upper-layer network functions can also mask delays by predicting the upcoming ISL churn and pre-fetching data. Moreover, to avoid link failures due to collision avoidance (Figure 25), each LEO satellite planning maneuvers can jointly schedule its link realignments to its upcoming nearest neighbors. This can be implemented by adopting software-defined networking at ground stations to track and control satellite networks (similar to Loon [55]).

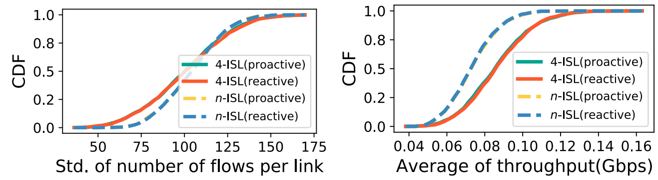
Satellite network-aware autonomous driving: Starlink is primarily designed for networking. While its safety is the top priority for autonomous driving, it should avoid being over-cautious to unnecessarily interrupt its satellite links (thus more delays/failures). For this issue, our analysis in §6–7 suggests two remedies for Starlink's autonomous driving:

◦ *Mitigate unnecessary collision avoidances:* As evidenced in Figure 21, unnecessary maneuvers indeed exist in Starlink, partially due to its over-cautious triggering condition for collision avoidance maneuvers ($P_c \geq 10^{-5}$, 10× smaller than NASA's, as discussed in §2.3) and inaccurate collision risk estimations. As shown in §6.3, there exists room to reduce these maneuvers *without* risking collisions based on Starlink's strict criteria, thus safely improving network stability and performance. Moreover, the launch and de-orbit of satellites can also interfere with other functioning satellites with more collisions (Figure 18b–18c). These events can be rescheduled to prevent conjunctions and maneuvers.

◦ *Optimize unavoidable maneuvers:* Some maneuvers can be refined to mitigate their impacts on networking. For example, inter-shell maneuvers in §7 can be grouped to reduce topology updates, similar to the strategy in scheduling space-terrestrial link updates [56]. The high-risk maneuvers in Figure 24 should also be avoided to incur network failures.

9 RELATED WORK

Autonomous driving of terrestrial cars, UAVs, and airplanes have been extensively studied with numerous work on vehicle positioning [57], environment perception [58–60], maneuvers [61], intersection management [62], collision avoidance [63, 64], to name a few. Instead, autonomous driving



(a) Traffic flow distributions **(b) Average per-flow throughput**

Figure 36: Traffic performance in various schemes.

in space gains less attention. Google Loon [55, 65], a mesh network in the Stratosphere, adopts automated fleet management for self-driving loons and network optimization. For satellites, extensive efforts have been made in space situational awareness [66, 67], orbital maneuvers [33, 34, 46, 47], and collision avoidance [33, 34] with privacy preservation [68, 69]. But these efforts from the aerospace community are network-agonistic and mostly manual. Self-driving satellites are made possible until recently by Starlink [4, 5]. We take an early step to characterize it from the networking perspective.

LEO satellite networks originated from Iridium in the 2000s [40] and now regain public attention due to Starlink's rapid deployments. Various design aspects of LEO networks have been investigated, such as optical inter-satellite communication [48, 70, 71], topology [41], addressing [11], routing [42–44, 72], state management [12], software-defined networking [54, 73], delay-tolerant networking [74], ground station networking [75, 76], navigation [77, 78], in-orbit computing [79, 80], security [81, 82], and many more. These efforts implicitly assume ideal LEO networks without maneuvers. Our work complements them by studying how actual orbital maneuvers impact inter-satellite networking.

10 CONCLUSION

This paper characterizes SpaceX Starlink's proprietary autonomous driving for its LEO satellites, and evaluate their impacts on the mega-constellation and satellite networks. We develop a domain-specific method to demystify its core components such as orbit maintenance, collision avoidance, and maneuvers between orbital shells. We find that while effective for mission safety, these maneuvers are mostly networking-agnostic and yield mixed impacts on satellite networks. Resolving these issues calls for inter-disciplinary collaboration between the networking and aerospace community. We hope our lessons can call for both communities' attention to demystify real "black-box" satellites and strive for a stable, safe, and performant "Internet from space."

Acknowledgment: We sincerely thank our anonymous shepherd and reviewers for their valuable feedback. This work is partially supported by the National Key Research and Development Plan of China (2022YFB3105201), the National Natural Science Foundation of China (62202261), the key fund of National Natural Science Foundation of China (62132009), and Tsinghua University-China Mobile Communications Group Co., Ltd. Joint Institute.

REFERENCES

[1] SpaceX Starlink. https://www.starlink.com/, 2022.
[2] ITU Publications. Measuring Digital Development: Facts and Figures 2021. https://www.itu.int/en/ITU-D/Statistics/Documents/facts/FactsFigures2021.pdf, 2021.
[3] Donald J Kessler, Nicholas L Johnson, JC Liou, and Mark Matney. The Kessler Syndrome: Implications to Future Space Operations. *Advances in the Astronautical Sciences*, 137(8):2010, 2010.
[4] SpaceX's Approach to Space Sustainability and Safety. https://www.spacex.com/updates/index.html, Feb 2022.
[5] SpaceX Starlink Orbital Space Safety. https://forum.nasaspaceflight.com/index.php?PHPSESSID=tu14od0adpt8lrslne9nr33tug&action=dlattach;topic=48297.0;attach=2054365;sess=0, Aug 2021.
[6] TheVerge. China complains to UN after maneuvering its space station away from SpaceX Starlink satellites. https://tinyurl.com/ycyhr2ja, Dec 2021.
[7] NTIA, NASA, NSF Letter To FCC Regarding Starlink Gen 2. https://www.scribd.com/document/557924666/NTIA-NASA-NSF-letter-to-FCC-regarding-Starlink-Gen-2, Feb 2022.
[8] Paul M. Sutter. Starlink and OneWeb have their first avoidance maneuver with each other's constellations. https://phys.org/news/2021-05-starlink-oneweb-maneuver-constellations.html, 2021.
[9] Application for Fixed Satellite Service by Space Exploration Holdings, LLC. https://fcc.report/IBFS/SAT-MOD-20200417-00037/2274316/, 2020.
[10] https://github.com/self-driving-satellite-network/starlink-autonomous-driving.
[11] Yuanjie Li and Hewu Li and Lixin Liu and Wei Liu and Jiayi Liu and Jianping Wu and Qian Wu and Jun Liu and Zeqi Lai. "Internet in Space" for Terrestrial Users via Cyber-Physical Convergence. In *Twentieth ACM Workshop on Hot Topics in Networks (HotNets)*. ACM, 2021.
[12] Yuanjie Li, Hewu Li, Wei Liu, Lixin Liu, Yimei Chen, Jianping Wu, Qian Wu, Jun Liu, and Zeqi Lai. A Case for Stateless Mobile Core Network Functions in Space. In *Proceedings of the ACM Special Interest Group on Data Communication (SIGCOMM)*. ACM, 2022.
[13] Wccftech. SpaceX Successfully Tests Inter-Satellite Starlink Connectivity via Lasers. https://wccftech.com/spacex-starlink-satellite-laser-test/, Sep 2020.
[14] TheVerge. With latest Starlink launch, SpaceX touts 100 Mbps download speeds and "space lasers" (though the system still has a ways to go). https://tinyurl.com/hj8juyun, 2020.
[15] ESA. Space debris by the numbers. https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers, April 2022.
[16] NASA. Space Debris and Human Spacecraft. https://www.nasa.gov/mission_pages/station/news/orbital_debris.html, 2021.
[17] Chinese Satellite Got Whacked by Hunk of Russian Rocket in March. https://www.space.com/space-junk-collision-chinese-satellite-yunhai-1-02, 2021.
[18] Iridium 33 and Russian Military Cosmos 2251 Collision. https://en.wikipedia.org/wiki/2009_satellite_collision.
[19] Ker Than. Rocket Explodes Over Australia, Showers Space with Debris. https://www.space.com/3493-rocket-explodes-australia-showers-space-debris.html, 2007.
[20] SpaceRef. Debris from Explosion of Chinese Rocket Detected by University of Chicago Satellite Instrument. http://www.spaceref.com/news/viewpr.html?pid=2464, 2000.
[21] BBC. Russian anti-satellite missile test draws condemnation. https://www.bbc.com/news/science-environment-59299101, 2021.
[22] India anti-satellite weapon test: Mission Shakti . https://en.wikipedia.org/wiki/Mission_Shakti, 2019.
[23] 2007 Chinese anti-satellite missile test. https://en.wikipedia.org/wiki/2007_Chinese_anti-satellite_missile_test, 2007.
[24] Russian Satellite Hit by Debris from Chinese Anti-Satellite Test. https://www.space.com/20138-russian-satellite-chinese-space-junk.html, 2013.
[25] Tereza Pultarova. SpaceX Starlink Satellites Responsible for Over Half of Close Encounters in Orbit. https://www.space.com/spacex-starlink-satellite-collision-alerts-on-the-rise, 2022.
[26] Average monthly conjunction rates surge from 2017 to 2020. https://spacenews.com/space-traffic-management-idling-in-first-gear/, 2020.
[27] John A Kennewell and Ba-Ngu Vo. An overview of space situational awareness. In *Proceedings of the 16th International Conference on Information Fusion*, pages 1029–1036, 2013.
[28] SpaceQuest - Model GNSS-701/702 - Satellite GNSS Receiver. https://www.environmental-expert.com/products/spacequest-model-gnss-701-702-satellite-gnss-receiver-735275.
[29] Jayant Sharma. Space-based visible space surveillance performance. *Journal of Guidance, Control, and Dynamics*, 23(1):153–158, 2000.
[30] J Utzmann, A Wagner, Jiri Silha, Thomas Schildknecht, P Willemsen, F Teston, and T Flohrer. Space-based space surveillance and tracking demonstrator: mission and system design. 2014.
[31] Space-Based Surveillance System. https://eoportal.org/web/eoportal/satellite-missions/content/-/article/sbss.
[32] Paul Maskell and Lorne Oram. Sapphire: Canada's answer to space-based surveillance of orbital objects. In *Advanced Maui Optical and Space Surveillance Conference*, 2008.
[33] Frederic Joshua Krage. NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook. Technical report, https://nodis3.gsfc.nasa.gov/OCE_docs/OCE_50.pdf, 2020.
[34] 18th Space Control Squadron. USSPACECOM Spaceflight Safety Handbook for Satellite Operator. Technical report, https://www.space-track.org/documents/Spaceflight_Safety_Handbook_for_Operators.pdf, 2020.
[35] Salvatore Alfano. A numerical implementation of spherical object collision probability. *The Journal of the Astronautical Sciences*, 53(1):103–109, 2005.
[36] Hoots, Felix R and Roehrich, Ronald L. Models for Propagation of NORAD Element Sets. Technical report, Aerospace Defense Command Peterson AFB CO Office of Astrodynamics, 1980.
[37] CCSDS Recommendation for Space Data System Standards (508.0-B-1): Conjunction Data Messages. https://public.ccsds.org/Pubs/508x0b1e2c2.pdf, 2013.
[38] SpaceX. Fact Sheet: Operator to Operator Physical Coordination: SpaceX-OneWeb. https://cdn.arstechnica.net/wp-content/uploads/2021/04/SpaceX-OW-Ex-Parte.pdf, 2021.
[39] The European Space Agency (ESA). Predicted near miss between Aeolus and Starlink 44. https://www.esa.int/ESA_Multimedia/Images/2019/09/Predicted_near_miss_between_Aeolus_and_Starlink_44, 2019.
[40] Sydney Finkelstein and Shade H Sanford. Learning from corporate mistakes: The rise and fall of iridium. *Organizational Dynamics*, 29(2):138–148, 2000.
[41] Debopam Bhattacherjee and Ankit Singla. Network Topology Design at 27,000 km/hour. In *ACM CoNEXT*, 2019.
[42] Handley, Mark. Delay is Not an Option: Low Latency Routing in Space. In *Proceedings of the 17th ACM Workshop on Hot Topics in Networks (HotNet)*, pages 85–91. ACM, 2018.
[43] Debopam Bhattacherjee, Waqar Aqeel, Ilker Nadi Bozkurt, Anthony Aguirre, Balakrishnan Chandrasekaran, P Brighten Godfrey, Gregory Laughlin, Bruce Maggs, and Ankit Singla. Gearing up for the 21st century space race. In *Proceedings of the 17th ACM Workshop on Hot Topics in Networks*, pages 113–119, 2018.

[44] Tobias Klenze, Giacomo Giuliari, Christos Pappas, Adrian Perrig, and David Basin. Networking in heaven as on earth. In *Proceedings of the 17th ACM Workshop on Hot Topics in Networks*, pages 22–28, 2018.

[45] Orbit decay. https://en.wikipedia.org/wiki/Orbital_decay.

[46] Morselli, Alessandro and Armellin, Roberto and Di Lizia, Pierluigi and Bernelli-Zazzera, Franco. Collision Avoidance Maneuver Design Based on Multi-objective Optimization. *Advances in the Astronautical Sciences*, 152(4):1819–1838, 2014.

[47] Claudio Bombardelli, Javier Hernando-Ayuso, and Ricardo García-Pelayo. Collision avoidance maneuver optimization. *Advances in the Astronautical Sciences*, 152(7402):1857–1870, 2014.

[48] Wu Feng, Yu Siyuan, JIE ZHOU, MA JING, and TAN LIYING. Analysis of the Stability of Bidirectional Beam Tracking in Inter-Satellite Optical Communication. *Chinese Journal of Lasers*, 40(11), 2013.

[49] Kerri Cahoy, Peter Grenfell, Angela Crews, Michael Long, Paul Serra, Anh Nguyen, Riley Fitzgerald, Christian Haughwout, Rodrigo Diez, Alexa Aguilar, et al. The CubeSat Laser Infrared CrosslinK Mission (CLICK). In *International Conference on Space Optics—ICSO 2018*, volume 11180, pages 358–369. SPIE, 2019.

[50] Marco A Fernandes, Bruno T Brandão, Petia Georgieva, Paulo P Monteiro, and Fernando P Guiomar. Adaptive Optical Beam Alignment and Link Protection Switching for 5G-over-FSO. *Optics Express*, 29(13), 2021.

[51] Aiyan Guo, Wenjun Gao, Aosong Zhou, Jingshuang Cheng, and Shanbao He. Beaconless Acquisition Tracking and Pointing of Inter-Satellite Optical Communication. *Infrared and Laser Engineering*, 46(10), 2017.

[52] Tianyu Song, Qian Wang, Ming-Wei Wu, and Pooi-Yuen Kam. Performance of Laser Inter-Satellite Links with Dynamic Beam Waist Adjustment. *Optics express*, 24(11):11950–11960, 2016.

[53] Qiang Wang, Liying Tan, Jing Ma, Siyuan Yu, and Yijun Jiang. A Novel Approach for Simulating the Optical Misalignment Caused by Satellite Platform Vibration in the Ground Test of Satellite Optical Communication Systems. *Optics Express*, 20(2), 2012.

[54] Brian Barritt and Vint Cerf. Loon SDN: Applicability to NASA's next-generation space communications architecture. In *2018 IEEE Aerospace Conference*, pages 1–9. IEEE, 2018.

[55] Frank Uyeda, Marc Alvidrez, Erik Kline, Bryce Petrini, Brian Barritt, David Mandle, and Chandy Aswin Alexander. Sdn in the stratosphere: Loon's aerospace mesh network. In *Proceedings of the ACM Special Interest Group on Data Communication (SIGCOMM)*. ACM, 2022.

[56] Jihao Li, Hewu Li, Jun Liu, Zeqi Lai, Qian Wu, and Xiaomo Wang. A timeslot division strategy for availability in integrated satellite and terrestrial network. In *2021 IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1–7. IEEE, 2021.

[57] Chia-Cheng Wang, Jyh-Cheng Chen, Yi Chen, Rui-Heng Tu, Jia-Jiun Lee, Yu-Xin Xiao, and Shan-Yu Cai. MVP: Magnetic Vehicular Positioning System for GNSS-denied Environments. In *Proceedings of the 27th Annual International Conference on Mobile Computing and Networking (MobiCom)*, pages 531–544, 2021.

[58] Xumiao Zhang, Anlan Zhang, Jiachen Sun, Xiao Zhu, Y Ethan Guo, Feng Qian, and Z Morley Mao. EMP: Edge-Assisted Multi-vehicle Perception. In *Proceedings of the 27th Annual International Conference on Mobile Computing and Networking (MobiCom)*, 2021.

[59] Yulong Cao, Chaowei Xiao, Benjamin Cyr, Yimeng Zhou, Won Park, Sara Rampazzi, Qi Alfred Chen, Kevin Fu, and Z Morley Mao. Adversarial Sensor Attack on Lidar-based Perception in Autonomous Driving. In *Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security (CCS)*, pages 2267–2281, 2019.

[60] Jiachen Sun, Yulong Cao, Qi Alfred Chen, and Z Morley Mao. Towards Robust LiDAR-based Perception in Autonomous Driving: General Black-Box Adversarial Sensor Attack and Countermeasures. In *29th USENIX Security Symposium (USENIX Security 20)*, pages 877–894, 2020.

[61] Feng You, Ronghui Zhang, Guo Lie, Haiwei Wang, Huiyin Wen, and Jianmin Xu. Trajectory Planning and Tracking Control for Autonomous Lane Change Maneuver based on the Cooperative Vehicle Infrastructure System. *Expert Systems with Applications*, 42(14):5932–5946, 2015.

[62] Kurt Dresner and Peter Stone. A multiagent approach to autonomous intersection management. *Journal of artificial intelligence research*, 31:591–656, 2008.

[63] Samer Ammoun and Fawzi Nashashibi. Real time trajectory prediction for collision risk estimation between vehicles. In *2009 IEEE 5th International Conference on Intelligent Computer Communication and Processing*, pages 417–422. IEEE, 2009.

[64] Quan Tran and Jonas Firl. Online maneuver recognition and multimodal trajectory prediction for intersection assistance using non-parametric regression. In *2014 ieee intelligent vehicles symposium proceedings*, pages 918–923. IEEE, 2014.

[65] Loon LLC. The Loon Collection: Software, Wind, Navigation, Simulation, Fleet Management Technical Overview. Technical report, https://storage.googleapis.com/x-prod.appspot.com/files/Loon%20-%20Software%2C%20Wind%2C%20Navigation%2C%20Simulation%2C%20Fleet%20Management%20Technical%20Overview.pptx, 2021.

[66] Tim Chen, Sophie Deng, and Nicholas Miller. Orbital Congestion. Technical report, https://github.com/mads-hatters/SIADS-591-Orbital-Congestion, 2021.

[67] James Pavur and Ivan Martinovic. On Detecting Deception in Space Situational Awareness. In *Proceedings of the 2021 ACM Asia Conference on Computer and Communications Security (AsiaCCS)*, pages 280–291, 2021.

[68] Liina Kamm and Jan Willemson. Secure Floating Point Arithmetic and Private Satellite Collision Analysis. *International Journal of Information Security*, 14(6):531–548, 2015.

[69] Brett Hemenway, Steve Lu, Rafail Ostrovsky, and William Welser Iv. High-Precision Secure Computation of Satellite Collision Probabilities. In *International Conference on Security and Cryptography for Networks*, pages 169–187. Springer, 2016.

[70] Chaudhry, Aizaz U and Yanikomeroglu, Halim. Temporary Laser Inter-Satellite Links in Free-Space Optical Satellite Networks. *IEEE Open Journal of the Communications Society*, 3:1413–1427, 2022.

[71] Kaushal, Hemani and Jain, VK and Kar, Subrat. Acquisition, Tracking, and Pointing. In *Free Space Optical Communication*, pages 119–137. Springer, 2017.

[72] Mark Handley. Using Ground Relays for Low-Latency Wide-Area Routing in Megaconstellations. In *Proceedings of the 18th ACM Workshop on Hot Topics in Networks (HotNets)*, pages 125–132, 2019.

[73] Arled Papa, Tomaso De Cola, Petra Vizarreta, Mu He, Carmen Mas-Machuca, and Wolfgang Kellerer. Design and Evaluation of Reconfigurable SDN LEO Constellations. *IEEE Transactions on Network and Service Management*, 17(3):1432–1445, 2020.

[74] Kevin Fall. A Delay-Tolerant Network Architecture for Challenged Internets. In *Proceedings of the 2003 conference on Applications, technologies, architectures, and protocols for computer communications (SIGCOMM)*, pages 27–34, 2003.

[75] Deepak Vasisht, Jayanth Shenoy, and Ranveer Chandra. L2D2: Low Latency Distributed Downlink for LEO Satellites. In *Proceedings of the 2021 ACM SIGCOMM 2021 Conference*, pages 151–164, 2021.

[76] Vaibhav Singh, Akarsh Prabhakara, Diana Zhang, Osman Yağan, and Swarun Kumar. A Community-Driven Approach to Democratize Access to Satellite Ground Stations. In *Proceedings of the 27th Annual International Conference on Mobile Computing and Networking (MobiCom)*, pages 1–14, 2021.

[77] Narayana, Sujay and Prasad, R Venkatesha and Rao, Vijay and Mottola, Luca and Prabhakar, T Venkata. Hummingbird: Energy Efficient GPS

Receiver for Small Satellites. In *Proceedings of the 26th Annual International Conference on Mobile Computing and Networking (MobiCom)*, pages 1–13, 2020.

[78] Peter Anthony Iannucci and Todd E Humphreys. Fused Low-Earth-Orbit GNSS. *IEEE Transactions on Aerospace and Electronic Systems*, 2022.

[79] Bhattacherjee, Debopam and Kassing, Simon and Licciardello, Melissa and Singla, Ankit. In-orbit Computing: An Outlandish thought Experiment? In *Proceedings of the 19th ACM Workshop on Hot Topics in Networks (HotNets)*, pages 197–204, 2020.

[80] Bradley Denby and Brandon Lucia. Orbital Edge Computing: Nanosatellite Constellations as a New Class of Computer System. In *Proceedings of the Twenty-Fifth International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, pages 939–954, 2020.

[81] Giacomo Giuliari, Tommaso Ciussani, Adrian Perrig, Ankit Singla, and E Zurich. ICARUS: Attacking Low Earth Orbit Satellite Networks. In *USENIX Annual Technical Conference (ATC)*, pages 317–331, 2021.

[82] James Pavur, Daniel Moser, Martin Strohmeier, Vincent Lenders, and Ivan Martinovic. A Tale of Sea and Sky on the Security of Maritime VSAT Communications. In *2020 IEEE Symposium on Security and Privacy (S&P)*, pages 1384–1400. IEEE, 2020.