CosmicDance: Measuring Low Earth Orbital Shifts Due to Solar Radiations

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Abstract

Radiation shock waves from solar activities are known to be a menace to spaceborne electronic infrastructure. Recent deployments, like the SpaceX Starlink broadband mega-constellation, open up the possibility to measure such impact on Low Earth Orbit infrastructure at scale. Our tool, CosmicDance[1], enables a data-driven understanding of satellite orbital shifts due to solar radiations. CosmicDance could also signal corner cases, like premature orbital decay, that could lead to service holes in such globally spanning connectivity infrastructure. Our measurements with CosmicDance show that Starlink satellites experience both short and long-term orbital decay even after mild and moderate intensity solar events, often trespassing neighboring shells of satellites.

CCS Concepts

• **Networks** → **Network reliability**; **Network dynamics**; **Network monitoring**; **Network management**; **Mobile networks**; **Public Internet**.

Keywords

Low Earth orbit satellite, LEO, Internet broadband constellation, Starlink, Geomagnetic storm, Solar events, Solar storms

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1 Introduction

Humanity has long appreciated the aurora in the polar sky and recorded (since the 8^{th} century BC [76]) solar activities to understand the space weather better. Solar events like solar flares, Solar Proton Events (SPEs), and more rarely Coronal Mass Ejections (CMEs) [64, 100] could significantly affect the space weather near Earth (Geomagnetic Storms) leading to radiation hazards to spacecrafts, satellites, and astronauts. Such events could also reach the Earth at times, generating Geomagnetically Induced Currents (GICs) [91] and disrupting power grids [61, 79], parts of the Internet infrastructure [78], and other man-made infrastructure. The two most widely reported solar events impacting the Earth happened in 1859 (Carrington Event [62, 77]) and 1921 (New York Railroad Storm [84]) disrupting the telegraph networks, undersea telegraph cables, and electrical services of the day. At this point, note that these CME events happened way before the Internet came into existence – a recent work [78] highlights that this globally spanning network is also significantly vulnerable to such high-intensity solar events. Internet disruptions could lead to losses of billions of dollars per day for the US [28] and other countries too.

A very recent development in the global connectivity landscape is the deployment of Low-Earth Orbit (LEO) satellite mega-constellations beaming the Internet from space. SpaceX (Starlink constellation) [7, 11] plans to deploy ~40,000 low-flying satellites in the long-term. They have already deployed 6,000+ satellites [25] and have started offering services in 100+ countries [51]. Eutelsat OneWeb [17] has deployed 634 satellites too. Many other big players, like Amazon (Project Kuiper [6, 15]) and Telesat [8], have also joined this 'space race' toward hosting non-terrestrial global networks serving a large fraction [19] of the total Internet traffic. Thanks to significantly lower launch costs today, satellite providers could send thousands of lower-cost satellites to orbit that offer shorter life spans (~5 years [49]) but could be replenished in time leveraging continuous launches. These mega-constellations are often arranged as concentric envelops or shells of satellites around the globe – for SpaceX Starlink, this inter-shell gap is ~5 km as per their FCC filings [11] toward minimizing the chances of collision. The LEO satellites are also being used for other use cases like satellite telephony [3], imagery [2], and Internet of Things [69]. In short, *the LEO space is getting crowded* and at a time when the Sun is coming out of its hibernation over the last few decades [85].

Solar events and LEO constellations: High-intensity solar events could cause radiation hazards to these large fleet of LEO satellites, leading to bit-flips, temporarily lost connectivity, or permanent damage to the electrical components. Such damages coupled with the higher drag in LEO during solar storms [60, 61, 70, 72] could lead to uncontrolled orbital decay. Given (*a*), many constellations today rely on COTS (commercial-off-the-shelf) hardware instead of radiation-hardened ones (due to significant cost differences) [16], and (*b*) the community anticipates high-intensity solar activities round the corner [73, 85], it is imperative that we study the impact of solar events on LEO infrastructure at scale.

While past works [60, 72, 93] have modelled the impact of solar events on satellites and spacecrafts, and a more recent work [78] studying such impact on the terrestrial Internet did mention that LEO satellites *"are under high risk of collapse if a Carrington-scale*

[1] Also known as Tandava – a dance performed by Nataraja, a depiction of the Hindu God Shiva.

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event occurs again", the time is just ripe to perform a data-driven analysis in this context. SpaceX has been heavily deploying their Starlink satellites over the last few years, thus contributing more observable data points (flying routers) in space. While Carrington-scale events are thankfully rare, such measurements at scale could offer useful insights to better prepare for high-intensity solar events as the LEO space gets significantly crowded [10].

Our contributions: Toward this, we built `CosmicDance` – a tool that ingests solar activity time series data and satellite trajectory data from multiple sources, cleans the data, and establishes *happens closely after* relationships between a solar event A and a satellite trajectory event (change) B, i.e., B *happens closely after* A. Such individual temporally ordered relationships, once established, could generate useful insights in aggregate. Leveraging `CosmicDance`, our first-cut analyses show that solar storms of mild to moderate intensities could also result in noticeable orbital shifts of Starlink satellites. We have observed altitude changes of tens of kilometers as well as permanent orbital decay of Starlink satellites closely after solar events. Such orbital shifts (which we call cosmic dance) of LEO satellites could increase the chances of collision across different satellite shells in LEO. `CosmicDance` code is publicly available [27] for community use under an MIT license. The data that it ingests are in the public domain already [9, 13].

Outline: §2 presents our motivation for designing `CosmicDance`. §3 lists down the steps for developing `CosmicDance`. §4-5 quantify the recent solar activities and their impact on SpaceX satellites. §6 discusses future work. §7 concludes our paper.

2 Background

In this section, we broadly discuss solar phenomena in the context of LEO deployments.

Solar radiation shock waves: Solar winds (steady omni-directional streams of charged particles), solar flares (explosions on the Sun releasing bursts of energy), Solar Proton Events (storms of high energy protons), and rarer Coronal Mass Ejections (CMEs; massive directional bursts of solar material and magnetic fields) could all reach the Earth and have varying effects on its magnetic field, atmosphere, and electrical infrastructure [61, 79]. These intense solar phenomena could induce terrestrial Geomagnetically Induced Current (GIC) [91], high levels of radiation in the upper atmosphere, increased ionization in the ionosphere, and higher atmospheric drag due to the heating up and expansion of the atmosphere [60, 72].

The G-scale by the National Oceanic and Atmospheric Administration (NOAA) classifies geomagnetic storms (manifestation of solar storms) into 5 categories based on their intensities [1], as follows: (*a*) G1 (minor): −100 to −50 nanoTesla (nT), (*b*) G2 (moderate): −200 to −100 nT, (*c*) G3 (strong): ∼−200 nT, (*d*) G4 (severe): −350 to −200 nT, and (*e*) G5 (extreme): below −350 nT [88]. The recorded intensity of the Carrington event (1859) was close to −1,800 nT [29]. This massive geomagnetic storm hit the telegraph and electrical services of the day.

The Sun goes through solar cycles [63] with each cycle having peaks (solar maximum) and troughs (solar minimum) of solar activities. These are combinations of shorter 11-year cycles and much longer 88-year (Gleissberg) cycles [68, 90] with the solar maximums of shorter cycles varying in intensities over the longer ones. Based on solar activity observations and models, the Sun is currently coming out of a 3-decade long lower activity phase [73, 85] and is expected to reach solar maxima by the next year [18, 41]. Hence, it is crucial to understand and evaluate the robustness of today's communication infrastructure, which was primarily built during the dormancy of the Sun, to solar storms. While there is a body of past work [5, 61, 79] on the impact of such solar events on power grid, and a recent work evaluates the terrestrial Internet deployment in this context [78], there is no work yet on understanding the impact on LEO deployments.

LEO getting crowded: The last decade has seen significant strides in LEO deployments across use cases like satellite broadband connectivity (e.g., SpaceX, Eutelsat OneWeb, Telesat, Amazon), Earth imagery (e.g., Planet, Maxar), and IoT (e.g., Astrocast, Lacuna Space) and this trend is set to continue [14]. SpaceX Starlink [7, 11] is the largest deployment aimed at beaming Internet from space. They have already deployed 6,000+ satellites [25] in LEO orbit as multiple concentric envelopes or shells with inter-shell height differences of ∼5 km [11]. SpaceX is currently operational across 100+ countries [51]. Various other large players are deploying in LEO too. As launch costs have reduced significantly [12] over the last few decades, LEO players could afford to follow a let-die-and-replenish model – cheap satellites with COTS hardware (without radiation hardening) last for up to ∼5 years [49] and are replaced by newer ones being deployed at regular cadence. As these constellations are below the inner Van Allen radiation belt [70] (1,000 - 2,000 km), chances of radiation hazards are comparatively lower. Of course, LEO satellites need frequent orbit corrections to deal with the higher drag due to Earth's upper atmosphere [32, 60, 98].

Triggering LEO "cosmic dance": Can solar storms push satellites to change trajectories, leading to significant orbital shifts? Intense solar activities are known to result in large dips (200 km above Earth [72]) of the inner Van Allen radiation belt and expansion of the upper atmosphere [60]. While the former results in higher radiation on LEO infrastructure, the latter results in increased atmospheric drag. The cumulative effects on LEO satellites could be bit flips, software and hardware failures, temporarily/permanently lost connectivity, and temporary/permanent uncontrolled orbital decay. On 29^{th} Jan, 2022, a moderate solar storm led to uncontrolled orbital decay and re-entry of 38 SpaceX Starlink satellites from their staging orbits [60, 72].

As the SpaceX Starlink network is a massive opaque-box, it is hard to quantify such bit flips or failures. But satellite trajectory information is public data [9, 13], which could be leveraged to quantify LEO orbital changes 'after' solar activities in the last few years (post Starlink's massive deployment onset). Note that no solar event in our dataset that spans the last 4+ years (99^{th}-ptile [2] intensity: −63 nT) was even close to the Carrington scale event (−1,800 nT). Very recently (on 11^{th} May, 2024), an intense solar storm (intensity up to −412 nT [54]) was recorded; however, its intensity was still well below the Carrington scale event.

For the interested reader, there are more discussions on solar storms and their impact on satellite systems in Appendix A.1.

[2] We use percentile and ptile interchangeably.

Why this study? The previous research in this field has primarily concentrated on the orbital lifetime of satellites [98], the effects of orbital drag during geomagnetic storms [87], and the investigation of the Starlink incident on 3^{rd} Feb, 2022 [59, 60]. Interestingly, all of them used empirical and data-driven magnetohydrodynamic (MHD) modeling [59, 60, 87, 98] in their studies to simulate these events. In addition, authors in [86] highlighted how space weather can cause satellite anomalies and listed all satellites that lost onboard instruments in the past for the same. However, with the ongoing extensive deployment of satellites in LEO and the increasing solar activity, it is now possible to study the orbital changes using real-world datasets too. Since these LEO satellite networks are likely to become integral parts of the future Internet, data-driven tools are crucial in understanding the orbital shifts due to solar events. This could also aid the design and deployment of more resilient constellations over time and prevent triggering of the Kessler Syndrome [81].

3 Building `CosmicDance`

As part of this work, we built the `CosmicDance` tool, which ingests solar activity data and satellite trajectory data from multiple sources, orders them in time, cleans the data, and draws conclusions on the impact of solar events on LEO satellite trajectories. While in this work, we focus on SpaceX Starlink, which is currently the largest LEO constellation, `CosmicDance` can be used for any orbit (LEO/MEO/GEO) or satellite constellation without any major code changes. We published `CosmicDance` code for community usage [27].

Ingesting solar activity data: Solar activities hitting the Earth or its atmosphere change its magnetic field. The hourly intensity (in nanoTesla or nT) of this geomagnetic field is recorded in the Disturbence storm time (Dst) index [57]. `CosmicDance` fetches these hourly records and align them against satellite trajectory data. Our first-cut analyses cover a 4+ year period between Jan'2020 and 1^{st} week of May 2024. We separately (falls outside our initial measurement window) discuss the early impact of the May 2024 super-storm in §5.

Ingesting satellite trajectory data: The US Space Force's Combined Space Operations Center (CSpOC) [4] tracks and logs all objects (larger than a bullet; including debris) flying around the Earth as Two Line Elements (TLEs) [74]. Most current TLEs for satellites are logged in CelesTrak's NORAD [9, 43] – these trajectory information need to be refreshed often to reflect changes due to the uncertainties of space that could change trajectories over time. `CosmicDance` fetches the current TLEs of SpaceX Starlink satellites from NORAD, extracts catalog numbers (satellite ID), and fetches the historical TLE information using Space-Track APIs [13] for specific dates and/or incrementally depending on the use case. `CosmicDance` minimizes API calls by fetching/extracting satellite catalog numbers only once and fetching historical information as and when needed incrementally.

Ordering in time: Both geomagnetic field data (hourly) and satellite trajectory data (refresh time ranges between <1 and 154 hours; on average 12 hours) carry a notion of time. `CosmicDance` merges these multi-modal data into a single time-series representation toward establishing temporal relationships – as discussed already, we

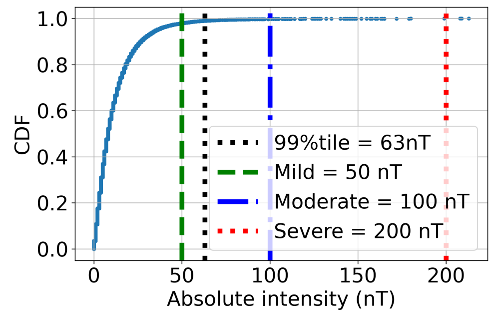


Fig. 1: Storm intensities in our dataset between Jan'20 and 1^{st} week, May'24.

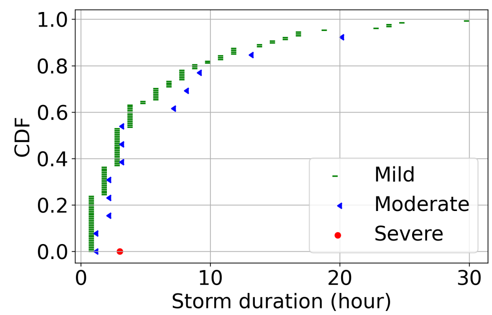


Fig. 2: Distribution of storm duration.

are interested in identifying trajectory change events that *happens closely after* high-intensity solar events.

Cleaning the data: SpaceX, while deploying a new batch of Starlink satellites, first launches them to a lower staging orbit (~350 km) [72]. In a few months, once testing is over, they attain their long-term LEO orbit. During this orbit raising satellite trajectories change rapidly irrespective of the physical conditions. Hence, `CosmicDance` filters out the initial orbit-raising windows of individual satellites. Also, `CosmicDance` filters out noisy TLE data having satellite orbital elements grossly different than values reported in FCC filings (§A.2). Finally, `CosmicDance` filters out the natural orbital decay of the satellites to restrict the analyses to only satellites affected closely *after* high-intensity solar events. If the difference between a satellite's altitude immediately before a solar event and its median long-term altitude is more than 5 km (empirically set; configurable), the satellite is considered to have started decaying already and hence eliminated from our analyses. Further details about our datasets and data processing steps are included in Appendix A.2.

Limitations: Note that satellite trajectories may also change to avoid collisions in space. `CosmicDance` stick to *happens closely after* events to minimize false positives.

4 Quantifying Solar Activities

In this study, `CosmicDance` has fetched the geomagnetic intensity data between January, 2020 and 1^{st} week of May, 2024 at a 1-hour granularity. Note that Starlink's first launch, L1, of 60 'operational' satellites happened on 11^{th} November, 2019 followed by testing at a staging altitude and orbit-raising [72].

Fig. 1 shows the distribution of observed geomagnetic intensities (a reflection of solar activity intensity) over the entire dataset. We

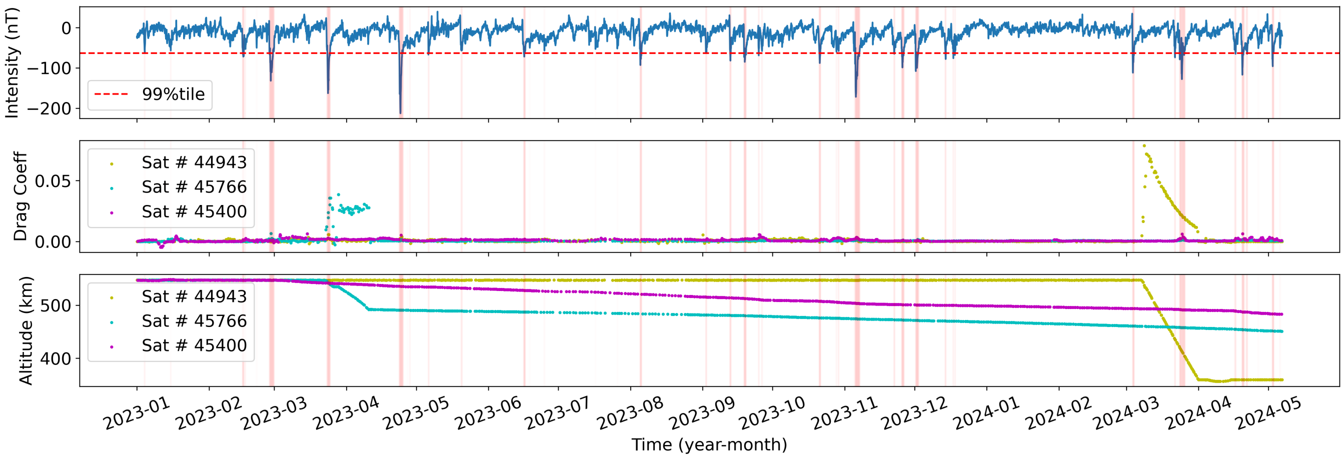


Fig. 3: Time series plot of geomagnetic intensities and the atmospheric drag and altitudes of 3 Starlink satellites. The red dashed horizontal line denotes the 99^{th}-ptile (i.e. −63 nT) across all observed geomagnetic field intensities over the last 4+ years. The light red vertical lines represent high intensity (99^{th}-ptile) zones.

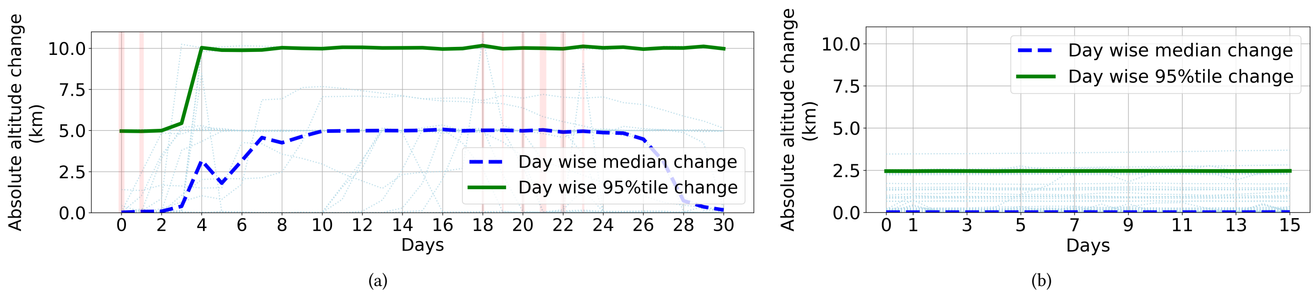


Fig. 4: (a) Altitude variations of the affected satellites after a solar storm (excluding permanent decay cases). (b) Variation of satellite altitudes when no major storm is observed.

observe that over the last 4+ years the 95^{th}-ptile recorded intensity is lower than that of minor storms. Interestingly, we do find a few high-intensity periods of mild (720 hours in total) and moderate (74 hours in total) storms. Only 3 data points (hours) had severe geomagnetic storms recorded with intensities −209, −213, and −208 nT (3 hours on 24^{th} April, 2023). Hence, most of the interesting solar events in our dataset resulted in only mild and moderate geomagnetic storms. So, essentially this study is a *soft* lower-bound on the impact of solar activites on LEO satellite systems.

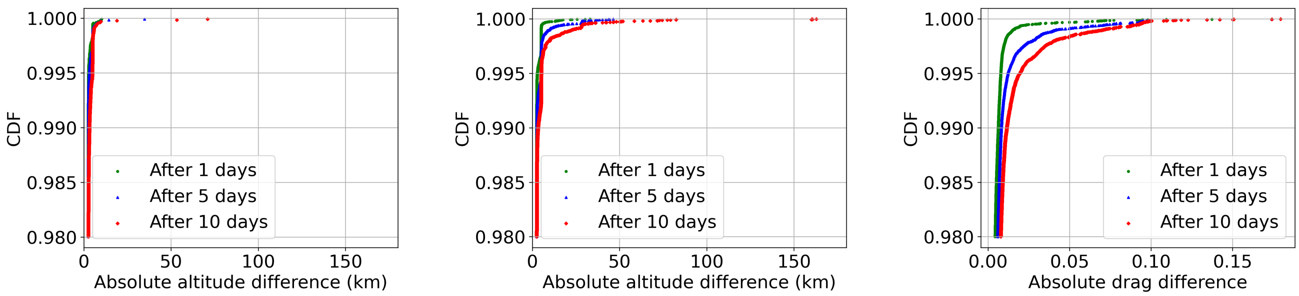
It is also imperative to understand the duration of such elevated solar activities. Long-lasting solar storms could mean longer disconnections with satellites and higher time-to-repair. Fig. 2 shows the distribution of storm duration of different categories in our dataset. We observe that the severe storm of 24^{th} April, 2023 lasted for 3 contiguous hours. For moderate (likewise, mild) storms, the median, 95^{th}-ptile, 99^{th}-ptile, and maximum storm duration are ~3, 15.8, 19.1, and 19 (likewise, ~3, 17, 24.7, and 29) hours respectively.

5 Quantifying the Orbital Shifts

We now leverage `CosmicDance` to perform a thorough time-series analyses of the impact of solar storms on Starlink satellites over the last 4+ years. As discussed already, `CosmicDance` orders in time both solar events and satellite position/trajectory information, thus implicitly establishing *happens after* relationship in the data. As satellite TLEs are not regularly updated, and solar storms could last for different duration, we resort to using a *happens closely after* relationship towards establishing causality. As there are many unknowns in all space-based systems, `CosmicDance` leverages *circumstantial evidence* [39] in connecting solar events to abrupt satellite trajectory events happening closely after. Only additional first-party information from Starlink could corroborate our findings.

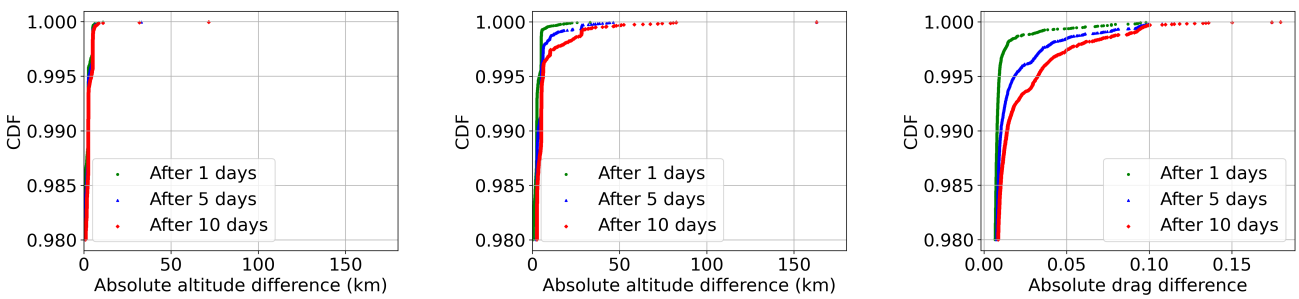
Time-series analysis: While `CosmicDance` extracts all orbital elements [33] defining satellite trajectories from the collected TLEs, we could only find changes in the atmospheric drag and altitude (derived from the mean motion orbital element) of Starlink satellites in response to solar activities. We did not find any observable change in satellite inclination due to solar storms. Fig. 3 plots the geomagnetic field intensity (nT) time series starting January, 2023 along with the atmospheric drag and altitude (km) of 3 Starlink satellites [3] cherry-picked to demonstrate the observed interesting trajectory changes. We could observe from the figure that often higher geomagnetic intensities lead to higher atmospheric drag that could, in turn, trigger orbital decay, leading to observable change in altitude. For example, a moderate scale solar event on 24^{th} March, 2023 resulted in significantly higher atmospheric drag for satellite

[3]Satellite numbers are used as-is from NORAD database



(a) (b) (c)

Fig. 5: CDFs of Starlink satellite altitude change with storm intensity (a) below 80^{th}-ptile and (b) above 95^{th}-ptile. (c) Distribution of drag coefficient changes with storm intensity above 95^{th}-ptile.



(a) (b) (c)

Fig. 6: CDFs of Starlink satellite altitude change with storm intensity above 99^{th}-ptile and storm duration (a) less than and (b) longer than 9 hours. (c) Distribution of drag coefficient changes for the longer storms.

catalog #45,766 (as per NORAD). Closely after the geomagnetic storm, we also observe the onset of orbital decay for this satellite as well as another one (#45,400). For the latter though, the change in drag was not too significant – remember that both radiation (due to lowering of the Van Allen radiation belt) and increased drag due to expansion of the upper atmosphere could affect satellite systems in LEO. Also, another moderate storm on 3^{rd} March, 2024, as seen on the plot, was closely followed by a significant increase in atmospheric drag for satellite #44,943 followed by a sharp drop in satellite altitude (∼150 km) over the next few weeks.

Comparison of storm vs. no-storm cases: To illustrate the orbital shifts after a solar event, we picked at random a high-intensity solar event (intensity: −112 nT) and plotted satellite altitude variations over the next 30 days in Fig. 4(a) for only those satellites which have not started decaying already during the solar event and for which the median altitude difference (from the long-term median altitude of the satellite) in a 30-day window, is higher than both the altitude differences immediately after the event and at the end of the 30-day period. Notice that means we also excluded satellites which started decaying permanently closely after the event, if any. In this figure, the light dotted lines represent the altitude change of individual satellites after the event, and the vertical red lines represent the high-intensity (≥95^{th}-ptile) solar events – the higher the thickness, the higher the storm intensity is with respect to the first day (i.e. the 0^{th} day). The blue (dotted) and green (solid) lines show the median and the 95^{th}-ptile of the altitude variations across all the affected satellites. We observe that the median altitude variation goes up to 5 km within 10-15 days after the event. Interestingly, the 95^{th}-ptile values remains at ∼10 km even after a month hinting long-term orbital shifts.

In contrast, on a relatively quiet day (when the geomagnetic intensity is <80^{th}-ptile), we do not observe noticeable altitude/orbital shifts, as shown in Fig. 4(b). Notice that in our dataset the storm intensity seldom remains below 80^{th}-ptile consistently for a month; we therefore kept our observation window limited to 15 days in Fig. 4(b).

Influence of storm intensity: Fig. 5 shows the changes in satellite altitude and atmospheric drag for different geomagnetic field intensities. Fig. 5(a) and 5(b) show the altitude variations for intensities lower than 80^{th}-ptile and higher than 95^{th}-ptile respectively. We observe that during periods of low solar activity (epoch set with no storms around) the extent of these variations remains below 10 km most of the time, while after mild and moderate storms, few (at most 1%) satellites experience significantly larger (10s of kilometers; up to ∼163 km) altitude variations. Such large orbital shifts translate to satellites trespassing multiple adjacent shells. Intense solar storms also result in larger drag, as observed in Fig. 5(c). It is hard to establish causality between drag and altitude change, as a change along one dimension could trigger a change along the other. Hence, we report the impact of solar storms on both these orbital parameters separately.

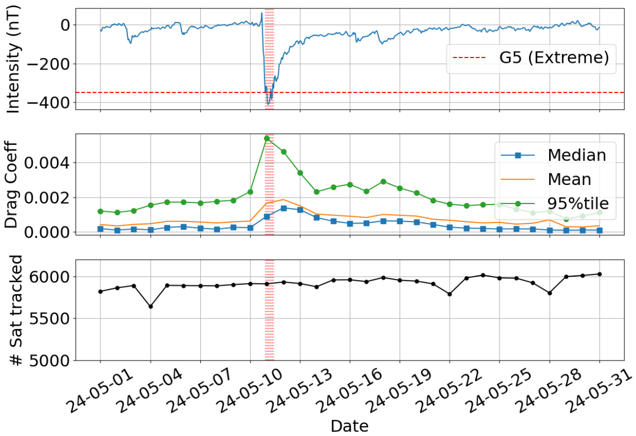


Fig. 7: Effect of the May, 2024 super-storm. Satellites experienced 5× drag than usual days, no loss of satellites is observed.

Influence of storm duration: We now discuss the impact of solar storm duration on the orbital parameters. To do this, we divide the storm duration above the 99^{th}-ptile mark (i.e., −63 nT) into two categories: (*a*) storms lasting <9 hours (the median storm duration), and (*b*) the longer ones lasting ≥9 hours. Fig. 6(a) and 6(b) show the distribution of altitude variations for storms of different duration. As expected, storms with longer duration result in larger altitude change. In fact, the tail of Fig. 6(b) is significantly longer and denser than that of Fig. 6(a). We can also observe large increase in drag in Fig. 6(c) due to longer storms.

Effect of May 2024 super-storm: On 10^{th} and 11^{th} May, 2024 the Earth was hit by a massive solar super-storm – the maximum observed intensity was −412 nT (most intense since 2003 Halloween solar storms [35, 55]) and the intensity was below −200 nT for 23 hours [54]. This was widely reported in the media [37, 39, 42, 47, 52, 56] and northern lights were observed from as far south as Ladakh [46]. Some users have also reported a short service outage and latency inflation during the solar event [50]. Our post-analysis of the event with `CosmicDance` is shown in Fig. 7. From Fig. 7, we can observe that after the storm, the atmospheric drag on the satellites increased up to five times, whereas the number of tracked satellites remains almost the same. At the same time, `CosmicDance` has not indicated any drastic altitude change. In response to the FCC public notice [30], Starlink has also confirmed the high drag experience and short outage on the 11^{th} May [26], which is consistent with the outcome of Fig. 7. They have also mentioned that there was no satellite loss, attributing the resilience to a reduction in a frontal cross-section, a capable propulsion system, and an attentive operational response against the drag in real time [26]. This demonstrates how proactive measures could significantly reduce the impact of such high intensity solar events on satellite systems.

6 Discussions & Future Work

`CosmicDance` is the first step towards building a data-driven tool for understanding satellite orbital shifts due to solar storms. In future, we want to extend our `CosmicDance` framework to incorporate the following points.

Active network measurements at scale? An even deeper analysis of the impact of solar storms on satellite connectivity needs to leverage active network measurements run at scale during such events to reveal the end-user experience. This could be achieved by using `LEOScope` [97] in tandem with `CosmicDance`. `LEOScope` is a LEO network testbed [94] that allows the orchestration of network measurement clients behind Starlink user terminals to measure the performance across measurement servers hosted in geo-distributed public cloud instances (or VMs). `LEOScope` supports trigger-based scheduling of network experiments and could consume solar event signals from `CosmicDance` as triggers. In addition to network measurements, end-users behaviors and their sentiments on social media posts/discussions also provide a strong indication about users' perceived experience with ISPs [96], which can also be integrated to `CosmicDance`. `CosmicDance` opens up the opportunity to enable such interesting integrated Internet measurements in the future.

Finer granularity: `CosmicDance` could do all the analyses at a finer spatio-temporal granularity if more frequent TLEs, carrying trajectory change information, are made available. Such analyses could pin-point when and where satellites get affected during solar events. For example, it is well-known that higher latitudes are more prone to these storms. Keeping in mind that Starlink satellites at ~550 km altitude take roughly 100 min to complete an entire revolution, such a latitude-band wise study would need latest TLEs every 10s of minutes.

Kessler's Syndrome analysis: Kessler syndrome [81] is a scenario where space debris triggers further collisions that generate more debris thus keeping space unusable for years until the junk reenters the Earth's atmosphere. As more satellites and junk are added to LEO, the probability of a Kessler syndrome increases. In our work, we did not evaluate how the LEO cosmic dance during solar events could increase this probability. We keep this for future work.

7 Conclusion

In this paper, we present `CosmicDance`, a tool for understanding the LEO satellite orbital shifts due to solar storms. Using this tool, we analyze the impacts of solar activities in LEO satellites from real-world satellite tracking and the magnetic intensity measurement dataset of the last 4+ years and quantify the deviation of satellites during and after relatively high geomagnetic disturbance. Our work not only provides useful insights about the *happens closely after* relationship between the solar events and the satellite trajectory changes, but also provides a useful tool for the community towards designing resilient constellations.

Ethics

This work does not raise any ethical issues.

Acknowledgments

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A Appendix

In this section, we add more background to describe further the details of solar storms along with the datasets used in our analysis to aid the networking community.

A.1 Solar storms and their impact on satellites

Space weather near Earth: The weather in space near Earth is primarily influenced by the Sun. The Sun continuously emits a stream of charged particles in space known as the Solar Wind [40, 48], which can vary widely in velocity and density and carry the Sun's magnetic field. A sudden massive explosion on the Sun, such as a solar flare [67, 95] or a Coronal Mass Ejection (CME) [64, 100], releases high-velocity radiation consisting of a strong electromagnetic field outward into space. If correctly aligned on the path of the radiation, these bursts of charged particles can sweep through the Earth, interfering with the Earth's magnetosphere and creating disturbances in the Earth's magnetic field, a phenomenon known as a Geomagnetic Storm [71, 82]. The charged particles can enter the polar cusp (near the north and south magnetic poles) and become trapped in the Van Allen radiation belt [65, 75, 83] before entering the Earth's atmosphere. The interaction of these charged particles with the thermosphere creates an eye-catching aurora in

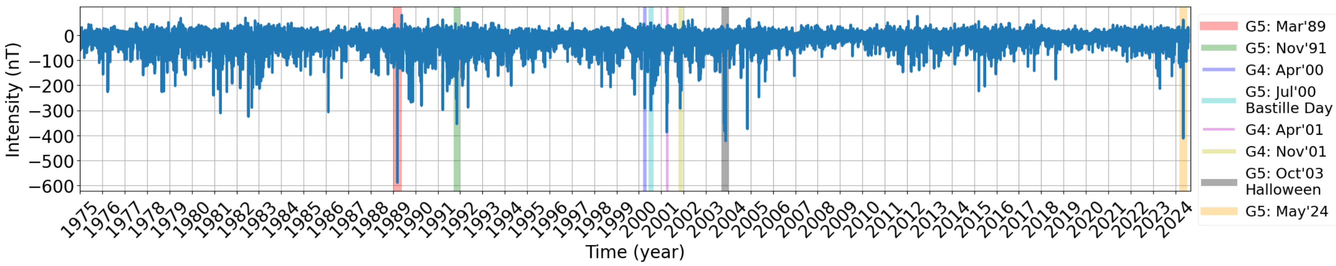


Fig. 8: Variation of Dst indices over last ~ 50 years highlighting some well-known Geomagnetic storms.

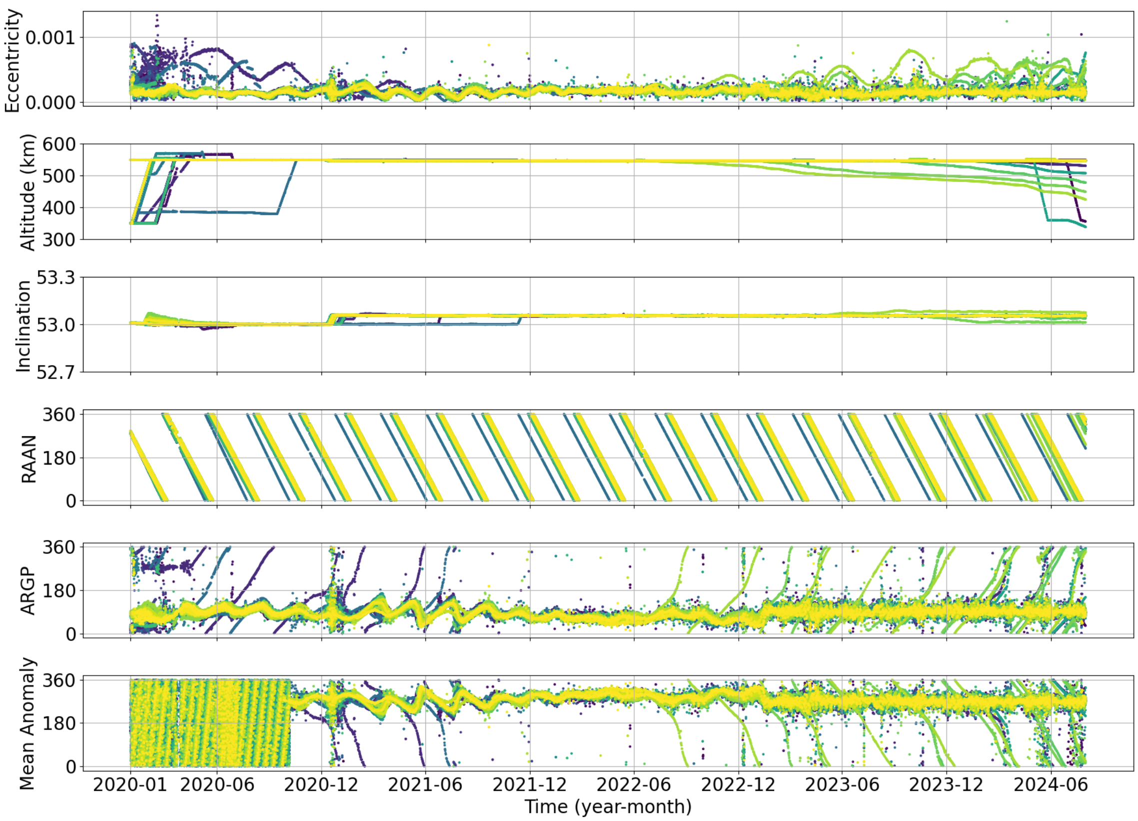


Fig. 9: Time series of orbital elements of 43 Starlink satellites from the first launch on 11^{th} November, 2019.

the sky [101]. It also heats the upper atmospheric layer, causing it to expand up to hundreds of kilometers [101].

Impact on satellites: Although humans on Earth are shielded by the dense atmosphere, man-made infrastructure in space and on the ground is still vulnerable to high-intensity solar events [78]. Satellites in space, particularly at higher altitudes such as MEO, GEO [53], and HEO [31], face the effect of solar radiation, which can lead to various satellite anomalies, such as Electrostatic Discharge (ESD), Surface Charging, Internal Charging, and Single Event Effects (SEEs), all of which can cause temporary outages or even complete mission failure due to radiation damage to critical components on board [61, 70]. However, LEO satellites operate below 2,000 km under the Earth's inner Van Allen radiation belt [83]. Although LEO satellites face limited radiation exposure, they may still encounter it at the South Atlantic Anomaly [99] and polar regions (if deployed in higher inclination, i.e., polar orbits). However, satellites in LEO are closer to Earth and must deal with upper atmospheric drag, which requires regular orbit corrections to maintain the correct trajectory. Strong solar events, such as Solar Superstorms, can significantly increase drag force due to atmospheric expansion, leading to uncontrolled satellite reentry into Earth's atmosphere. For instance, 38 out of 49 satellites re-entered the atmosphere from the staging orbit due to a moderate Geomagnetic storm caused by a solar eruption on 29^{th} January, 2022 [60, 72]. Apart from this incident, there are a few publicly reported failures of LEO operations in the past. For example, the Earth observation satellite ADEOS-II (Advanced Earth Observing Satellite-II), also known as Midori-II [21], experienced solar panel damage resulting from a severe power failure on 24^{th} October, 2003. Another LEO satellite, ASCA (Advanced Satellite for Cosmology and Astronomy) or Astro-D [23], lost altitude control instruments on 15^{th} July, 2000, causing the solar array to lose its lock on the sun and start free spinning, eventually leading to reentry into the atmosphere on 2^{nd} March, 2001. Apart from LEO satellites, various malfunctioning of higher orbit satellites due to solar events are reported in [61, 86].

A.2 Datasets used for measurement

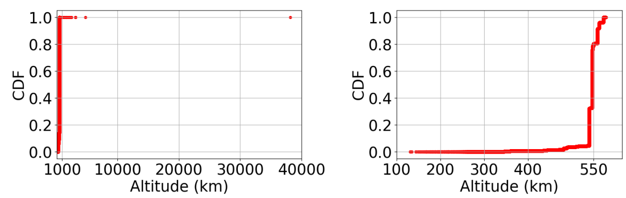
To study the after-effects of the discussed solar events on the trajectory of LEO satellites, we use two datasets: Dst Index (space weather near Earth) and TLEs (satellite trajectory information). Further details on these two datasets are given below.

Disturbance Storm Time (Dst) Index: The decrease in Earth's magnetic field's horizontal component at the geomagnetic equator (i.e. the magnetospheric ring current [102]) is measured to determine the intensity of solar activity [22]. The Data Analysis Center for Geomagnetism and Space Magnetism, located in Kyoto, Japan, publishes hourly data on the temporal and spatial mean from four observatories located at Kakioka, Honolulu, San Juan, and Hermanus, near the Earth's equator [58]. The intensity and duration of geomagnetic storms are monitored by spacecraft and power grid operators using the Dst index. Geomagnetic activity is considered high when the Dst index values drop below −50 nanoTesla (nT) [22].

The time series in Fig. 8 shows the recorded Dst indices over the last ∼ 50 years. The highlighted vertical bars (width represent the relative peak intensity observed) are well-known geomagnetic storms from the past, i.e., (i) 9^{th} March, 1989 (−589 nT) [36], (ii) 9^{th} November, 1991 (−354 nT) [66], (iii) 6^{th} April, 2000 (−288 nT) [80], (iv) 15^{th} July, 2000 (−301 nT), also known as "Bastille Day solar storm" [24], (v) 11^{th} April, 2001 (−271 nT) [80], (vi) 5^{th} November, 2001 (−292 nT) [92], (vii) 30^{th} October, 2003 (−383 nT) also known as "Halloween solar storm" [20], and $(viii)$ 10^{th} May, 2024 (−412 nT) [38, 89]. Such intensive solar storms not only impact the spacecrafts, but also damage the ground-based systems (i.e., radars, power grids, transforms, etc.) [61, 86].

Two Line Elements (TLEs): The trajectory of any Earth-orbiting object can be unambiguously described by six parameters, i.e., (i) *Eccentricity*: the shape of the orbit, which is circular for LEO Internet broadband satellites [6, 7, 11], (ii) *Mean Motion*: the number of revolutions per day, which is inversely proportional to the altitude (we drive altitude from this parameter for our analysis of decay), (iii) *Inclination*: tilt angle of the orbital plane with respect to the Earth's Equator, (iv) *Right Ascension of Ascending Node (RAAN)*: where the satellite intercepts the Earth's equator while moving northwards, (v) *Argument of Perigee (ARGP)*: where the satellite is nearest to the Earth, denoting the orientation of the orbit in the orbital plane , and (vi) *Mean Anomaly*: the precise location of the satellite in the orbit. These six attributes are known as Keplerian or orbital elements [33].

Fig. 9 shows the time series of these six parameters of 43 Starlink satellites (each color represents a unique NORAD Catalog Number, i.e., one satellite) from the batch of first launch on 11th November, 2019. Notice that the *Eccentricity* is consistently close to zero due to the circular orbit. The altitude (derived from *Mean Motion*) and *Inclination* are maintained closely at 550 km and 53° respectively, as reported in Starlink FCC filings [7]. Fig. 9 also shows that the satellites were initially stationed at ∼ 360 km, and then they were



(a) (b)

Fig. 10: CDF of altitudes in all TLEs shows (a) long tail way outside the operational altitude, indicating probable tracking errors. (b) Removing erroneous TLEs reveals the Starlink operational altitude along with some deorbiting satellites.

gradually raised to their targeted altitude. Due to the Earth's rotation, the satellites continuously drift towards the west, resulting in the continuous decrease of the RAAN. Since the orbit orientation does not change much, the ARGP remains mostly consistent. Once the satellites are deployed in the operational orbit [7], the *Mean Anomaly* also becomes consistent because the satellites arrive at the field of view of the ground tracking station when located at a particular region of their orbit. The deviations or scattering points visible in Fig. 9 could have been caused because of maneuvering or some other unknown reason, and speculating about this accurately without first-party information is challenging due to many uncertainties in space.

The US Space Force's Combined Space Operations Center (CSpOC) [4] and a few other corporations [34] use their ground-based observation stations to track any Earth-orbiting objects, including rocket bodies and space debris. Each tracked object is identified by a unique *NORAD Catalog Number*. Whenever objects pass through the field of view of radars, the observational measurements are fitted into an orbital trajectory to determine the above-mentioned orbital elements. This tracking information is shared publicly in a standardized textual data format, Two Line Elements (TLEs) [74]. Each TLE with six orbital parameters also includes NORAD Catalog Number, launch information, epoch (the particular time when tracked), drag information, and error detection code [74]. Often, satellite operators use these TLEs to analyze their satellite's trajectory to assess the collision probability in advance and, if required, maneuver fully functional satellites to avoid close conjunction [45]. Here, with `CosmicDance`, we use the same to study the orbital shift after a solar event.

Data processing: Notice that these TLEs also involve some uncertainties due to the tracking error. Even the best-case scenarios include an error of a few 10s of meters [34]. Fig. 10(a) shows the CDF of altitudes across all TLEs before cleaning up the datasets. Notice the long tail above 1,000 km went close to 40,000 km. Given the operational altitude of the Starlink constellation [7, 11], we speculate these as tracking errors. Therefore, we clean up these by removing the TLEs with altitudes that are way outside the operational ranges (> 650 km). In addition to that, we also remove the altitudes during orbit raising. After cleanup, the CDF of the altitudes in Fig. 10(b) shows that the majority of the operational satellites are at close to 550 km of altitude, and a few of the satellites started de-orbiting (< 500 km) due to the decommissioning (or potential onboard software/hardware malfunctioning) [44].