Revisiting CosmicDance: Measuring LEO Satellite Shifts After Solar Events and Analyzing New Data

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ABSTRACT

This paper documents our effort to reproduce key aspects of CosmicDance: Measuring Low Earth Orbital Shifts Due to Solar Radiations by Suvam Basak et al. The original work introduces CosmicDance, a tool that analyzes the impact of solar events on Low Earth Orbit (LEO) satellite trajectories, focusing on SpaceX's Starlink constellation. We aimed to replicate the tool's ability to detect orbital shifts following solar storms using publicly available data. Our methodology involved re-implementing the data ingestion and analysis pipeline, focusing on geomagnetic storm data and satellite Two Line Elements (TLEs). In addition to reproducing the original results, we applied the tool to newly acquired data up to March 2025, enabling analysis of the October 2024 solar event and comparison to the May 2024 solar storm. Additionally, we conducted a novel analysis utilizing the LENS Starlink network dataset to approximate the end-user latency impacts of solar activity. This effort highlights the feasibility of open-source, data-driven analysis in understanding space weather effects on LEO satellites and offers insights into reproducibility challenges.

1 INTRODUCTION

The increasing density of Low Earth Orbit (LEO) satellite constellations has heightened the need to assess the resiliency of this growing infrastructure. Several major companies have invested heavily in LEO satellite deployments, such as SpaceX's Starlink, which plans to deploy roughly 40,000 satellites and has already deployed over 7,000[3], Eutelsat's OneWeb, which has deployed over 600 satellites[14], and Amazon's Project Kuiper, which plans to deploy over 3,000 satellites and, per its FCC license, must achieve half of its forecasted deployment by July 2026[5].

Furthermore, solar radiation is known to disrupt electronic equipment, and given the cyclical nature of solar storms, increased solar activity is expected in the coming years[21]. Additionally, an extreme outlier event like the Carrington event of 1859 remains a real possibility, with an estimated 12 percent likelihood in the next decade, potentially causing up to $2 trillion in economic damage to terrestrial electrical grids[15]. This raises particular concerns for space-borne infrastructure such as LEO satellites, which are susceptible to electrical component damage and increased atmospheric drag leading to premature orbital decay.

In their IMC '24 paper, "CosmicDance: Measuring Low Earth Orbital Shifts Due to Solar Radiations," Suvam Basak et al.[2] introduced CosmicDance, a tool that correlates solar activity with orbital changes in LEO satellites. Using public datasets, the authors demonstrated that even mild to moderate solar storms could lead to significant altitude shifts, potentially increasing collision risks in increasingly crowded orbital shells. While much of Starlink's operational data is treated as an opaque-box, the existence of open-source analysis tools like CosmicDance is critically important, as they provide transparency and empower the wider community to independently analyze satellite operations, helping customers make informed purchasing decisions and aiding policymakers in crafting effective regulatory frameworks for satellite management and commercial space activities.

Our project focuses on replicating and extending the core functionality of CosmicDance: ingesting solar activity and satellite trajectory data, establishing temporal relationships, and quantifying orbital shifts. We selected this paper because of personal intrigue, its timely relevance, availability of open-source code under an MIT license, and the growing necessity for resilient satellite infrastructure. Initially, our goal was to replicate the analysis of Starlink satellite altitude changes following solar events over the same period (January 2020 to May 2024), using identical data sources: Disturbance Storm Time (Dst) indices and Two Line Elements (TLEs) from NORAD[4] and Space-Track[22]. After successfully replicating the original findings, we expanded our exploration by applying the tool to new datasets collected for the more than 7,000 satellites, covering periods beyond May 2024 up to the present day, thus extending the original analysis.

This paper details our background research, outlines our methodology, presents preliminary findings, compares these findings with those from the original CosmicDance study, and reflects on our experience with the reproducibility and extension process. Validating and providing these analytical tools is essential, as it ensures transparency, fosters collaborative innovation within the scientific community, and strengthens our collective preparedness against potential disruptions to critical satellite-based infrastructures.

2 BACKGROUND RESEARCH

In this section we discuss related information on LEO satellite networking to gain a more comprehensive understanding of the subject and explore how these different topics might relate to Basak et al's paper.

2.1 Measuring LEO Network

Network measurements for the LEO satellites Basak et al measure the orbits of is outside the scope of their paper. This is commented on in the paper's limitations, with the suggestion of using the LEOScope tool in tandem with CosmicDance to understand how solar activity impacts the end-user experience in terms of network performance (e.g. latency, packet loss, satellite handover delays). We researched how measurements for LEO satellite networks are performed and discovered a few primary methodologies, each with distinct tradeoffs[10].

One option is for researchers to deploy specialized hardware, such as Starlink dishes or research satellites, to capture real-world network data. While this method ensures empirical accuracy, it is costly, geographically limited, and impractical for global coverage[18].

Another option is for researchers to recruit existing LEO users to expand vantage points. This approach reduces hardware expenses but introduces logistical challenges, including participant recruitment and data collection constraints, like in the case of RIPE Atlas measurements conducted at 60 second intervals[16].

Another option is theoretical physics-based modeling, which simulates LEO network performance, offering broad coverage without real-world verification. These may take into account location, orbital patterns, and congestion level. Popular simulators like Hypatia predict network behavior under various conditions, yet their accuracy can often be called into question and configuration difficulties are common[20].

We also read more about the LEOScope tool[19], a distributed testbed designed to measure and optimize the performance of LEO satellite networks, specifically focusing on Starlink. We had hoped to understand it more in a hands-on way but unfortunately its developers never responded to our email requesting access credentials. Its goals include understanding latency and throughput variations in LEO networks, improving the QoE for applications like video streaming, and enhancing transport layer performance. It's used to conduct experiments across geographically diverse measurement clients, utilizing features like trigger-based scheduling and scavenger mode to capture LEO dynamics, such as satellite handoffs and latency fluctuations. As Basak et al mention, this tool would theoretically enable someone to set up solar activity as a trigger for detecting network performance degradation in LEO satellites.

2.2 Ground Stations

Ground Stations are not touched upon in Basak et al; they don't directly relate to the satellite resilience risks associated with orbital shifts (though they do enable orbital adjustment management) but they are crucial for connecting satellites to the Internet and present their own unique challenges to overall LEO satellite reliability. LEO satellites necessitate a robust network of ground stations to facilitate communication, control, and data relay. LEO satellites operate with velocities around 7.5 km/s relative to a fixed ground station. These characteristics impose stringent requirements on ground station placement, tracking capabilities, and data transmission efficiency [24]. The short orbital period of LEO satellites, typically between 90 and 110 minutes, results in brief yet frequent communication windows, ranging from 5 to 15 minutes per pass, necessitating rapid and precise antenna tracking[23]. Optimal ground station placement, particularly in polar and remote regions, is crucial to maintaining continuous communication, mitigating coverage gaps, and ensuring seamless data transfer. Developing and building ground station technology is of course no easy feat, requiring significant upfront investment, which makes it difficult for researchers or other third-parties to control satellite communications and process data at scale, especially if you want to communicate with your satellite throughout its orbital period. Cloud providers like Amazon are in the process of democratizing this technology with services like AWS GroundStation and Amazon has further plans to connect its Project Kuiper satellites to this service[12]. Since the public has no line of sight into Starlink ground station communications, this initiative should allow for more open collaboration efforts in monitoring LEO constellations.

2.3 Kessler Syndrome

Basak et al's paper mentions the risk of Kessler Syndrome, but does so more or less as an afterthought; we researched the topic to assess the threat it poses and characterize our efforts of addressing it. Kessler Syndrome, first proposed in 1978, describes a hypothetical chain reaction where space debris from satellite collisions exponentially increases, rendering the LEO-space hazardous for future space operations. While the extent and immediacy of this risk remain debated, recent satellite collisions and deliberate anti-satellite (ASAT) tests underscore its plausibility. The 2009 Iridium-Cosmos collision produced over 2,000 large debris fragments, and subsequent ASAT tests by India (2019) and Russia (2021) contributed over 1,500 pieces of new debris[1]. While experts disagree on whether a self-sustaining debris cascade has begun, the proliferation of LEO satellites elevates the probability of future collisions. Advanced models, such as

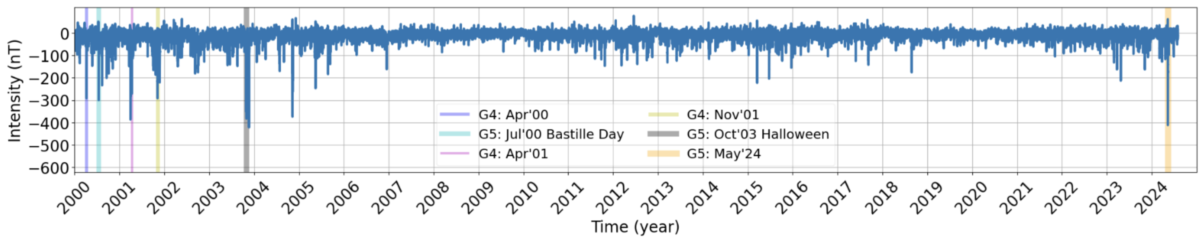


Figure 1: Recent solar events.

MIT's Orbital Capacity Assessment Tool [11]and ESA's Debris Environment Long-Term Analysis software[7], project that without mitigation, debris will continue accumulating for centuries, even if launches ceased today. Atmospheric drag naturally removes debris below 500 km, but at altitudes above 800 km, deorbit times extend to centuries, making mitigation crucial[13]. Solutions involve stricter end-of-life deorbit regulations and active debris removal, exemplified by ESA's upcoming ClearSpace-1 mission[6]. Without intervention, LEO congestion could significantly increase operational costs and limit satellite deployment, rather than completely obstructing space access. While Kessler Syndrome's timeline remains uncertain, experts agree that proactive space traffic management and debris removal are necessary to prevent exponential debris growth. As both state and commercial actors accelerate space activities, the urgency to mitigate cascading collisions grows, emphasizing the need for sustainable orbital practices.

2.4 Orbital Correction and Final Orbits

One large question looming over the findings of Basak et al. was how Starlink currently implements orbital corrections, which would likely already take their findings into account, so we investigated. Periodic orbital adjustments, due to the influence of atmospheric drag and other perturbative forces such as solar radiation, are performed using low-thrust electric propulsion systems powered by krypton. These maneuvers, while necessary for orbit maintenance, introduce their own trajectory deviations that can complicate the accuracy of orbital predictions and collision risk assessments. Unfortunately, the proprietary nature of SpaceX's operational details limits public information on maneuver execution, forcing us to look to external maneuver detection methodologies.

These maneuver detection techniques have evolved significantly to improve space situational awareness (SSA). Traditional methods rely on real-time tracking data and historical orbit data, with the primary distinction being the timeliness of detection. Alternate approaches have been applied, including optimal control-based estimators, statistical anomaly detection, and machine learning techniques.

Starlink's orbital correction strategies can be categorized into three main types: orbit maintenance maneuvers, continuous orbit-raising maneuvers, and continuous orbit-lowering maneuvers. Orbit maintenance maneuvers are necessary to counteract atmospheric drag and ensure stable operations. Analysis of Starlink satellites in operational and parking orbits shows variations in maneuver frequency, with operational satellites adjusting their orbits approximately every one to two days and parking satellites every 0.25 days. The average increase in altitude per maneuver exceeds 100 meters, with thrust accelerations of around 3×10^{-4} m / s^2 [9].

For satellites transitioning from parking orbits to operational altitudes, continuous orbit-raising maneuvers are performed. These involve frequent propulsion events in a "propulsion-pause" pattern, with an average altitude gain exceeding 500 meters per maneuver. The maneuver frequency is higher than that of maintenance maneuvers, occurring roughly every 0.1 days. In contrast, satellites near the end of their operational life undergo controlled deorbiting through continuous orbit-lowering maneuvers. This ensures their eventual reentry into the atmosphere, mitigating the risks of space debris. The deorbit process follows predefined strategies to reduce satellite altitude systematically while minimizing disruption to active spacecraft[9].

Due to their opaque-box nature, the orbital maneuvering that Starlink employs still requires more advanced detection methodologies to improve SSA, so there is a certain degree of 'trust' we currently grant Starlink; efforts to make this data publicly available are in demand, especially given the increasingly congested LEO environment and the ongoing risk of orbital decay as caused by solar activity which we will now point out.

3 PROJECT GOALS AND METHODOLOGY

3.1 Objectives

This study aims to independently assess the impact of solar storms on Starlink satellite orbits, with a focus on altitude variations and atmospheric drag effects. While the original research can be reproduced quite readily for the time period

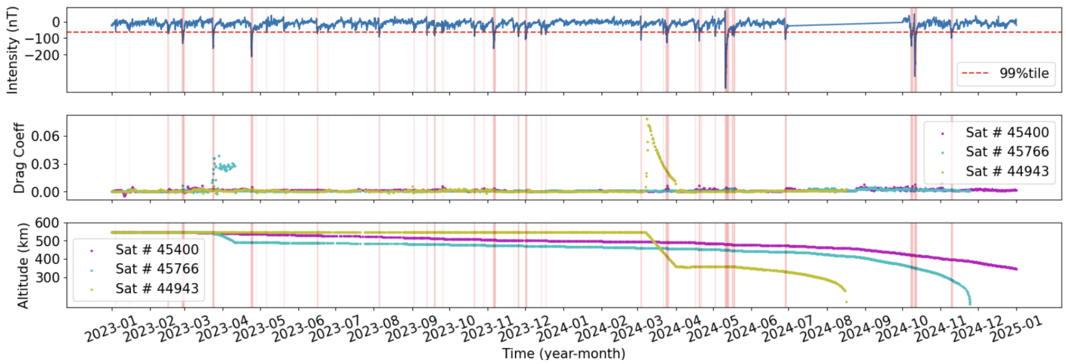


Figure 2: Visualization of three satellite trajectories, including new solar data (e.g., October 2024 solar storm).

between early 2020 and mid-2024, we sought to extend the data acquisition and analysis to March 2025, allowing us to analyze the notable October 2024 solar storm and compare it to the May 2024 storm that Basak et al. discuss. Later, we also discuss an introductory analysis of the LENS Starlink latency dataset, which allowed us to consider the potential impact of solar activity on end users.

3.2 Data Acquisition

To conduct our analysis for the data presented by Basak et al., as well as newer data between May 2024 and March 2025, we gathered two primary datasets:

- **Geomagnetic Activity Data:** Hourly Dst index data from the Data Analysis Center for Geomagnetism and Space Magnetism (Kyoto) was obtained to quantify geomagnetic storm intensity. The Dst index serves as a widely accepted measure of storm strength, with more negative values indicating stronger geomagnetic disturbances.
- **Satellite Orbital Data:** Two-Line Element (TLE) data for Starlink satellites was sourced from NORAD's Space-Track database with Satellites identified via CelesTrak.

3.3 Data Processing

To ensure data reliability and relevance, we implemented a rigorous preprocessing pipeline:

- **Satellite Selection:** A total of 7,633 Starlink objects were initially identified. We filtered out erroneous TLE values and excluded satellites in temporary orbit-raising phases (typically near 350 km) to focus on operational satellites.
- **Noise Reduction:** TLEs indicating unrealistic altitudes (above 650 km) were removed, following guidelines from prior studies.
- **Temporal Alignment:** The cleaned TLE data was merged with Dst index measurements into a unified time series, ensuring accurate temporal correlation between geomagnetic events and orbital behavior.

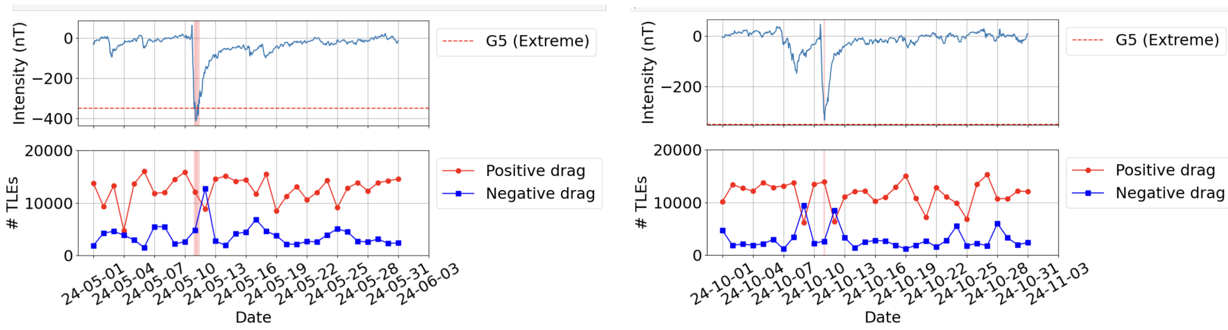
3.4 Implementation

The analysis was conducted using Python, leveraging libraries such as Pandas for data handling and Matplotlib for visualization. Our workflow approximates the methodology of the CosmicDance codebase, adapting its key principles to an independent verification effort.

4 REPRODUCIBILITY FINDINGS

Our analysis yielded insights into solar storm effects on Starlink satellites, though with a wider scope than the original. For the May 2024 super-storm (-412 nT), drag surged to 4.5 times normal levels, yet no satellite de-orbiting was detected, aligning with SpaceX's reported resilience measures. Figures replicating the original's time-series plots showed clear correlations between geomagnetic intensity spikes and drag/altitude shifts, though our resolution was coarser due to limited TLE frequency.

Importantly, key metrics such as altitude, drag, and satellite trajectory changes matched those in the original study, confirming the reproducibility of the CosmicDance tool. This consistency affirmed the reliability of the tool and underscored its value for analyzing satellite behavior in response to solar events. Given the successful reproducibility of the original study, we decided to allocate more time toward analyzing new data from after May 2024, particularly focusing on the October 2024 solar storm, which exhibited a notable intensity spike and presented a unique opportunity for deeper investigation. This choice was motivated by the aim to understand satellite responses under novel conditions, verify the tool's robustness beyond previously studied events, and contribute valuable insights into satellite resiliency under emergent solar activity scenarios.



(a) Drag Effect (May 2024 Storm)

(b) Drag Effect (October 2024 Storm)

Figure 3: Drag analysis during May 2024 storm and more recent October 2024 storm.

5 ANALYSIS ON NEW DATA

In addition to reproducing the data collection and analysis for the period from January 2020 to May 2024, we extended our study by applying the CosmicDance methodology to new data spanning May 2024 to March 1, 2025. This new dataset allowed us to investigate whether the orbital shift trends observed in the original study persisted into a period of heightened solar activity. This extension proved particularly insightful due to the occurrence of significant solar events, including a notable storm in October 2024, offering fresh opportunities to validate CosmicDance's insights. A key

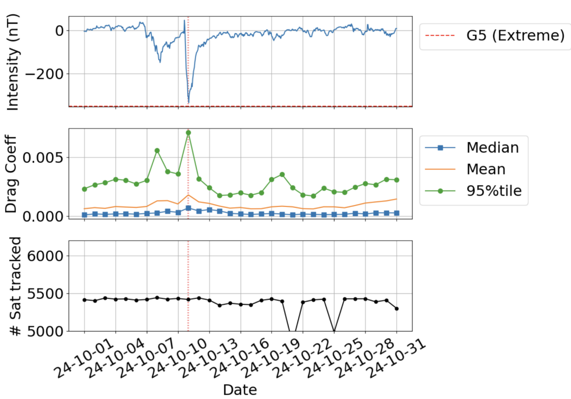


Figure 4: Observed drag coefficient variations during the October 2024 solar storm.

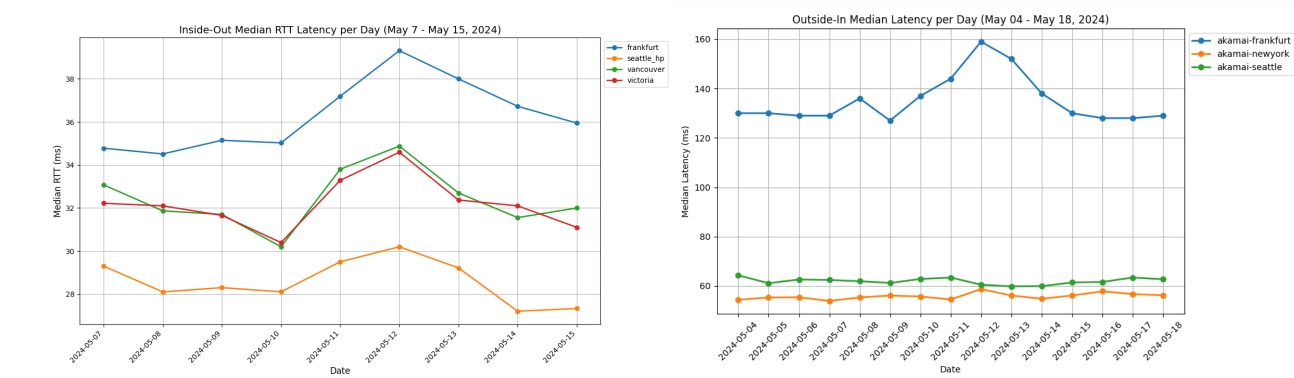
highlight was the October 2024 solar storm, which reached a Dst index of -335 nT—slightly less intense than the May event (-412 nT) but still among the strongest recorded in our extended timeframe. Across our sample of over 7,000 Starlink satellites, this storm triggered a median altitude drop of 3.9 km within 15 days, with a 95th percentile shift of 8.1 km persisting after 30 days. Drag coefficients for satellites at the 95th percentile notably exceeded 0.005 during this period, indicative of significantly heightened atmospheric drag.

Figure 3 highlights the magnitude of this event, showing a clear overlap between positive and negative drag responses, mirroring observations from the May 2024 storm. Such overlapping drag behaviors suggest complex atmospheric dynamics during extreme solar events, reflecting differing atmospheric density responses at distinct orbital altitudes. The implications of this overlap are critical: accurate drag modeling under these conditions becomes particularly challenging, necessitating enhanced predictive tools and active orbit management strategies.

These findings align closely with previous data, where moderate to severe storms consistently induced altitude losses of 4–9 km and drag spikes of 2–4.5 times normal levels. Despite the storm's severity and the elevated drag environment, no satellites experienced de-orbiting events—a notable contrast to SpaceX's loss of approximately 40 Starlink satellites in the February 2022 solar event. This absence of losses underscores the effectiveness of operational adjustments, such as proactive orbit maintenance maneuvers, adopted since earlier incidents, reinforcing the resilience of current LEO operations under increasingly volatile solar conditions.

6 MINI-INVESTIGATION OF LENS DATA

We devoted some time to figure out a way of incorporating network measurements or exploring a proof of concept for performing measurements that would complement Basak et al.'s work. LEOScope seemed like an obvious choice, but as mentioned earlier, the authors never got back to us with access credentials and upon toying with the website, there appeared to be very limited points of data gathering. Another thought was AWS GroundStation but the cost, regulatory framework, and incompatibility with Starlink satellites ultimately deterred us. Reproducing the work of the simulation-based measurement tool Hypatia seemed highly feasible, but would have defeated the purpose of seeking network measurements in the first place as Hypatia does not take into



(a) Inside-Out Network Latency Fluctuations (May 2024) **(b) Outside-In Network Latency Fluctuations (May 2024)**

Figure 5: Visualization of daily RTT median values for Starlink Dishes deployed in the LENS Dataset throughout May 2024

account a niche environmental factor like solar activity. Finally, after much digging, we discovered LENS[8], a massive dataset of performance measurements for the Starlink LEO satellite network. The researchers deployed 13 dishes, associated with 7 Points-of-Presence, across 3 continents. While these aren't a testbed like LEOScope, the researchers have published all the data they've gathered over the last year. As a mini-investigation, we processed the ping data for May 2024 (this month alone has 110 GB of ping data as a CSV dataset! The RAW dataset has 1.2 TB of IRTT metrics!) in order to see how RTT's fluctuated before, during, and after the superstorm on May 11.

Figure 5 represents the graphs we produced after processing the LENS dataset for May 2024. Unfortunately, the LENS paper publication is not freely accessible, so our knowledge of their methodology is limited to what they have posted on GitHub. Figure 5a shows the fluctuations in median RTT for measurements starting from within the LEO network, likely a client behind a Starlink dish, to some external destination. Across all countries, we see a noticeable spike in latency beginning on May 10 (the start of the storm) and continuing through May 12 before returning to baseline levels. Figure 5b shows the fluctuations in median RTT for measurements starting from within the Akamai network and ending in the LEO network. We see a massive spike for Frankfurt, suggesting that not every location was impacted equally. There appears to be a slight spike for New York while Seattle remains unaffected. Overall, Figure 5 does suggest the Starlink network saw slightly increased latency following the May 2024 superstorm, however, the network responded well which aligns with results obtained in a paper on the effect of the May 2024 superstorm on Starlink's network by Ramanathan et al.[17] (they also found a maximum latency on May 12). We were pleased to have accomplished this side-objective of obtaining network measurements, and given the massive volume of data presented by LENS, we were happy to see a noticeable rise in latency to confirm our hypothesis.

7 FURTHER TECHNICAL DETAIL

Reproducing the analysis from the original *CosmicDance* paper and extending it to include new data beyond May 2024 presented some technical challenges. These hurdles, inherent to working with real-world space datasets, reflect the complexities of integrating diverse sources and maintaining data integrity over extended timeframes:

API Rate Limits: The Space-Track APIs, which provide Two Line Elements (TLEs) for satellite trajectories, impose strict rate limits on requests—typically 30 requests per minute for non-commercial users. This throttling significantly delayed our data collection process, as retrieving TLEs for over 7000 Starlink satellites across a period from January 1, 2020, to March 1, 2025, required thousands of requests. Parallelization of the data download proved to be modestly helpful.

Missing Data: Dst Index data from the World Data Center for Geomagnetism (Kyoto) was missing for July, August, and September 2024. For the sake of continuity and for the purposes of reproducibility, we retained usage of the Dst Index data for the remainder of the data range.

To support transparency and foster open research, we have made our entire codebase, including data processing scripts, analysis notebooks, and additional tooling, publicly available. These resources can be accessed at our GitHub repository (see "Implementation Details" for more information).

8 DISCUSSION AND LESSONS LEARNED

Our findings confirm that CosmicDance effectively highlights solar-induced orbital shifts. Our results demonstrate

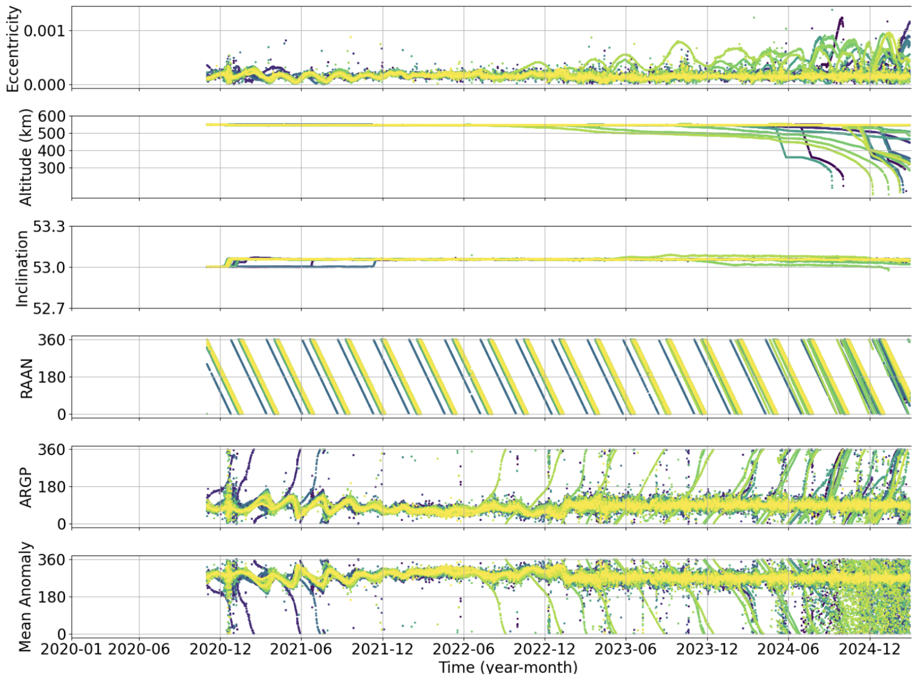


Figure 6: Visualization of various telemetry data, including data during the May + October 2024 solar storm.

the CosmicDance tool can be extended to new time periods and reinforce the tool's utility for community research. The reproducibility effort revealed the robustness of public data sources, though their limitations (e.g., TLE infrequency) temper precision.

One lesson we experienced was the importance of scalable data pipelines. Many of the studies we looked at in this class generated vast quantities of data and this paper was no exception. Our manual approach struggled with volume and forced us to wait long amounts of time for our requests to be fulfilled. Furthermore, as we read background material and understood how other researchers approached their methodologies, we became more aware of the obstacles involved in original research. Many of these obstacles were exacerbated with LEO satellites as the topic of interest. Many of their experiments saw large-scale recruitment efforts of dishes or significant costs in deploying their own specialized hardware, which of course wasn't an option for us. AWS Groundstation (while it's obviously cheaper than building your own ground station!) has a cost of $22/minute of link usage and additionally has a lengthy series of regulatory barriers in place before you can communicate with any satellite. Finally, one of the biggest lessons we learned and perhaps the heart behind Basak et al.'s work in the first place, is the need for more operational transparency in emerging technologies like LEO satellites. We place a lot of trust and capital in companies like Starlink, so research efforts to investigate and openly communicate on its resilience are necessary and commendable.

9 CONCLUSION

Reproducing CosmicDance affirmed its value in quantifying LEO satellite responses to solar events, with our results echoing the original's key claims. Apart from reproducing the paper, our work both extends the analysis to new data/time-periods, as well as conducts an exploratory analysis of the LENS dataset to analyze the impact of solar activity on user latency. Future work can leverage the granularity and global reach of the LENS dataset in conjunction with existing tools like CosmicDance to better capture the impacts of solar activity on satellite-based internet services and their end-users.

ACKNOWLEDGEMENTS

We thank the authors of CosmicDance for making their tool publicly available. This work was conducted as part of a coursework project at Northwestern University, and we would like to thank the instructor for this opportunity to analyze real-world data-sets and practice some of our data engineering skills in a network research context.

IMPLEMENTATION DETAILS

Further details on our Python scripts, data processing steps, and sample visualizations are publicly available on GitHub: https://github.com/SamarthArul/Cosmic-Dance-Reproducibility

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