An investigation of Starlink's performance during the May ′24 solar superstorm

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Abstract

Low Earth Orbit (LEO) satellites have revolutionized the consumer-grade Internet market. The main giant of this landscape, Starlink, is already operating the world's largest LEO satellite fleet of 8,000 satellites made of non-radiation-hardened components. The recent May 2024 solar superstorm created an opportunity to evaluate the performance and reliability of such a network under intense solar events. In this paper, we conduct a statistical study on the packet loss, latency, and orbital drag experienced by satellites from a long-term perspective. The results indicate marginal inflation in loss and latency during and immediately after the superstorm. While increasing the observation window size dilutes the inflation under regular performance fluctuations. Additionally, we list out a few roadblocks that need to be addressed to pinpoint the impact on any specific satellite, along with the end-user's network connectivity experience caused by solar radiation.

CCS Concepts

• **Networks → Network performance analysis**; **Network measurement**.

Keywords

Low Earth Orbit, LEO, Starlink, Satellite, Network Measurement, Geomagnetic Storm, Solar Superstorm, Space Weather

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1 Introduction

Space weather is a menace to space-borne electronics. Solar flares [23, 48] and Coronal Mass Ejections (CMEs) [20, 53] from the Sun's active regions can release extreme ultraviolet (EUV) radiation [14, 52], X-Rays [54], or a burst of dense, hot, high-velocity plasma into outer space. This surge of plasma consists of strong magnetic fields; hence, the interaction with the Earth's magnetic field leads to geomagnetic storms [27, 32]. Exposure to radiation from highly charged particles presents a constant risk to manmade infrastructure in space. There is a documented history of onboard instruments and even complete mission failures due to these intense space weather events [18, 25, 30, 36, 44]. However, the lack of sufficient data points has always been a challenge in studying the effects of past solar events.

The 21st century's advancements in space technology, i.e., the reduction in launch cost and production of small satellites with relatively low-cost commodity hardware [5, 19, 22], have enabled SpaceX's Starlink (and many others) to deploy a massive constellation of thousands of LEO satellites. Their success in serving worldwide 5 million customers [12] under a global ISP has now opened an opportunity to investigate the LEO operational challenge due to solar events and its implications on the Internet service experience. Many researchers have already started utilizing this opportunity to explore areas such as the failure of the 38 Starlink satellite deployment [15, 17] and the impacts on the satellite's orbital stability due to solar events [16]. However, a significant gap still exists in quantifying the effect of the degradation of satellite link quality on end-user Internet experience and pinpointing the cause-and-effect relationship from solar events to particular infrastructure.

After last year's, i.e., May 2024 solar superstorm, an effort [47] has been made to quantify the impact of such an event on Starlink's LEO network using 81 RIPE Atlas probes deployed across 18 countries. Their analysis illustrated an immediate rise in packet loss and a delayed inflation in round-trip time (RTT) after the commencement of the superstorm. While Starlink, in their response to the FCC public notice seeking comment on the impact of this G5 class storm [21], stated that the service experienced less than 1 minute of disruption and continued without degradation [26]. They praised the advanced collision avoidance and auto station-keeping system, which kicked in real-time with capable thrusters to countermeasure against $2-5\times$ orbital drag between altitudes 300 to 550 km during the event.

Given that prior work [47] has focused on the Starlink performance within a 15 day window of the superstorm, we broaden this window of analysis to draw a conclusion from a long-term perspective. A statistical analysis of Starlink performance measurements over a couple of months shows a negligible difference in performance measurements during this superstorm as compared to the long-term performance characteristics. Shortening this window close to the May 2024 geomagnetic storm does show a marginal inflation on packet loss and a barely visible increase in latency. The magnitudes of inflation are not large enough to be concerned about, as they remain within the range of regular performance fluctuations that occur over Starlink networks. Additionally, we experience and state some limitations of existing satellite link measurements to deep dive into such studies to establish a concrete causality from solar radiation to impact on LEO infrastructure, and then user-perceived Internet performance implications at the user end. Given that we have already started approaching the minima of

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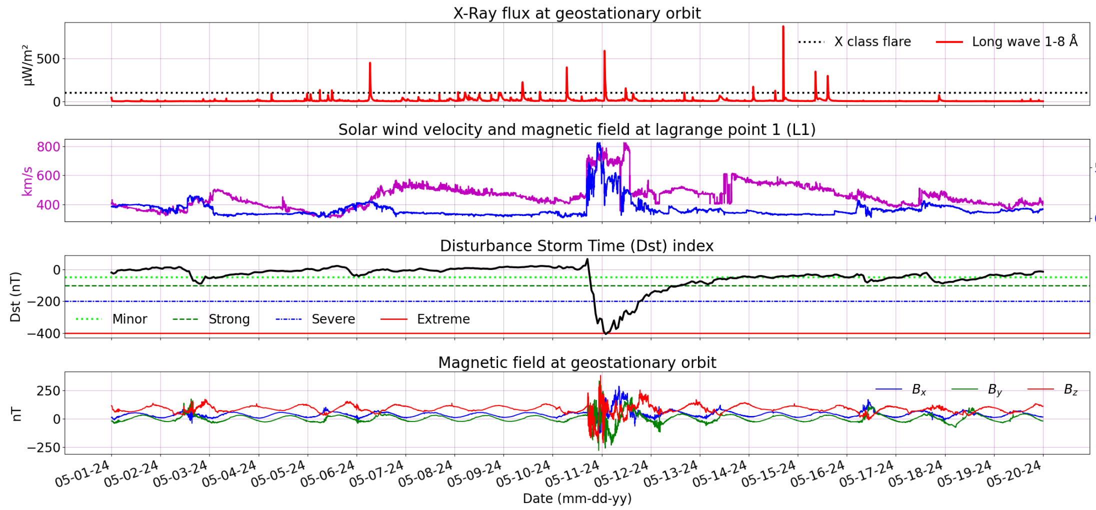
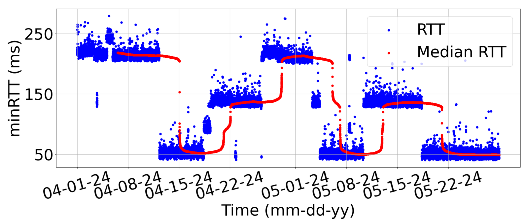
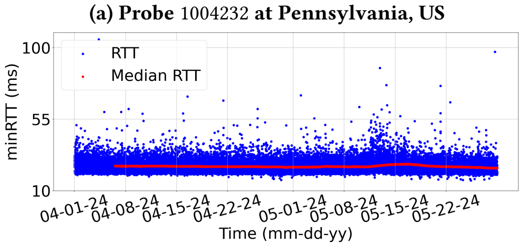


Figure 1: Studying the impact of May 2024 solar superstorm from Sun to Earth – solar flare as X-Ray radiation to shock wave of solar wind at L1, then impact piercing through Earth's magnetosphere, leading to the disturbance in magnetic fields.



(a) Probe 1004232 at Pennsylvania, US



(b) Probe 28221 at Colorado, US

Figure 2: Probe with (a) a drastic shift and (b) relatively stable RTT measurements.

the current solar cycle, we are left with a short window to address these issues in the current cycle.

The remaining paper is organized as follows – §2 discusses the background and related works. Then §3 discusses the dataset used for the analysis. In §4, we investigate the performance implications of the May '24 superstorm. Finally, the paper is concluded in §5.

2 Background and related work

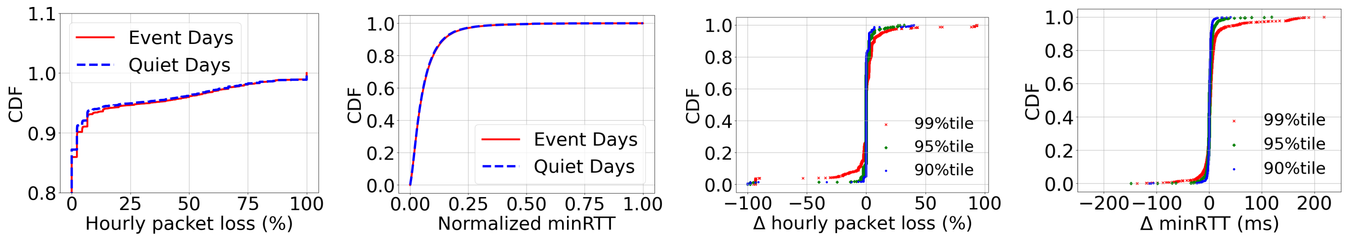
This section provides an overview of the May 2024 geomagnetic superstorm and previous research.

May 2024 solar storm: Between May 8 and 10, 2024, the Sun released six X-class solar flares, including one X3.98 class flare on May 10 from the NOAA active region (AR13664) [34]. These events are reflected as spikes in X-Ray flux captured by the NOAA GOES satellite at geostationary orbit [41], as shown in Fig. 1 (top). These back-to-back eruptions of plasma or CMEs collided and merged with each other, forming a composite solar wind consisting of a strong magnetic field while moving toward Earth [49]. The impact of this solar wind was measured by the DSCOVR satellite at L1[1] [40], showing sudden increases in the velocity of charged particles, along with varying magnetic fields after May 10, 2024, at 16:30 UTC, as shown in Fig. 1. Approximately at 17:00 UTC on May 10, this gust of solar wind collided with the Earth's magnetosphere. The effects on the magnetosphere are reflected in the Dst index, which fell to −412 nanoTesla (nT) by May 11 at 02:00 UTC. According to the NOAA space weather scale [42], this is classified as a G5 class, an extreme geomagnetic storm. This is the strongest storm recorded after two decades, since the 2003 Halloween solar storm [1, 7]. These intense space weather conditions compressed the Earth's dayside magnetosphere (magnetopause), pushing it below the geostationary orbit (35,786 km from Earth) for several hours. Thus, magnetic field disturbances during this event were observed by the NOAA GOES-18 geostationary satellite [39], as shown in Fig. 1 (bottom).

Related work: The impact of space weather or geomagnetic storms on Earth has always been an active area of research. Authors in [16, 37, 43] have explored the satellite's orbital drag, particularly in LEO during solar events. Some works [15, 17] have investigated the loss of 38 Starlink satellites in February 2022 due to a minor geomagnetic storm. More recently, following the May 2024 geomagnetic superstorm, the authors in [45] have discussed the characteristics of satellite drag and decay during the event, while in [14], the authors have studied how the preconditioning of the superstorm could have led to the early reentry of 12 decommissioned Starlink satellites. Authors in [49, 55] have unveiled the impact of the event on Earth's magnetosphere and ionosphere.

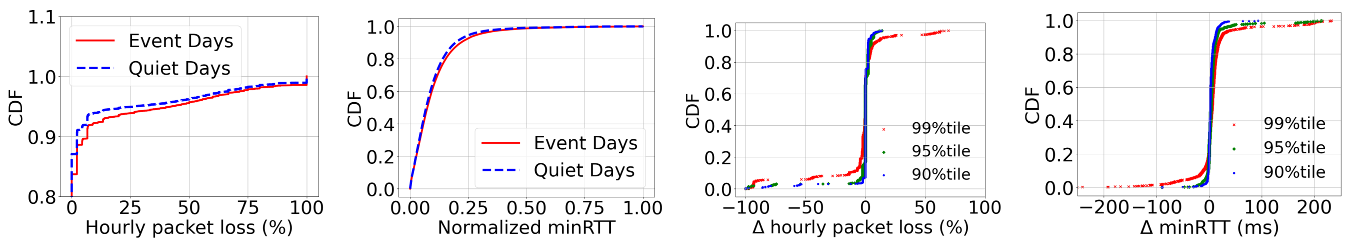
However, the majority of the works [14–17, 37, 43, 45] have studied the physical impacts of geomagnetic storms on satellites. On the other hand, the studies in [29, 31, 33, 35, 38, 46] have reported Starlink's performance measurements under regular weather conditions. Only a recent study [47] has explored Starlink's network performance during the May 2024 superstorm. Hence, the knowledge

[1]Lagrange point 1, a saddle point of gravitational force between the Sun and Earth located 1.5 million kilometres from Earth.



(a) CDF of packet loss (b) CDF of normalized RTT (c) CDF of difference in loss (d) CDF of difference in RTT

Figure 3: Long-term distribution (a)-(b) of network measurements in event time and quiet time, and (c)-(d) of difference in 90th, 95th, and 99th %-tile network measurements in event time and quiet time for each source and destination pair.



(a) CDF of packet loss (b) CDF of normalized RTT (c) CDF of difference in loss (d) CDF of difference in RTT

Figure 4: Short-term distribution (a)-(b) of network measurements in event time and quiet time, and (c)-(d) of difference in 90th, 95th, and 99th %-tile network measurements in event time and quiet time for each source and destination pair.

of how these space weather events affect the Internet connectivity of LEO satellite networks is quite limited.

Our work: While the prior work [47] zooms into a window of 15 days of May 2024 solar superstorm, in this work, we broaden this window to showcase how Starlink connectivity performance differs when compared against long-term performance characteristics.

3 Preparing the datasets

Acquiring: We use the following datasets for this analysis.
Network measurement: We rely upon RIPE Atlas probes [9] connected to Starlink. We use the RIPE Atlas REST API [10] to acquire details of all the 96 probes across 24 countries attached to Starlink's Autonomous System Number (ASN 14593 [8]). Then, we fetch 1,551 (source and destination pairs) built-in periodic ping measurements over IPv4 and IPv6 from April 1 to May 31, 2024.
Orbital drag: We use *CosmicDance* [16] to acquire drag term [28] from the publicly available TLEs of Starlink's satellites.

Cleaning: Next, to minimize the inaccuracy in the analysis, we take the following steps to clean up the acquired datasets.
Network outages: We explore the public domain reports on network issues and remove all the measurements data after May 28, 2024, since Starlink global outage is reported by CISCO ThousandEyes on May 29, 2024 [51].
Socioeconomic factor: We also remove all the probes from Ukraine, due to reports of electronic warfare and jamming [24].

Data anomalies: In the remaining datasets, we found that the RTT between many source-destination pairs is not stable and shifts at arbitrary levels for a duration of days, irrespective of the intensity of solar events, as shown in Fig. 2(a) with RTT measurements in probe 1004232. We speculate that this is because of the frequent changes in the assigned Points of Presence (PoP) [29, 38]; however, we do not find any clear evidence because we are missing the route traces. To tackle this, we adopt a simple yet effective method: calculating the median of consecutive RTT points in the timeseries window of length 2,000 (empirically decided), which is denoted with a red dot in Fig. 2. The difference between the maximum and minimum of the median values (we call this '*stability score*'), in Fig. 2(a) is 169 ms, which is much higher than the 2.57 ms in a stable RTT measurement over two months in Fig. 2(b). We use this *stability score* throughout the remaining paper to analyze the performance.

4 Analysis of performance implications

Now, we evaluate how the network performance during solar events differs over a long-term and short-term window of observations. We also point out the most impacted regions and the most impacted satellites, using probe locations and orbital drag, respectively.

4.1 Long term implications

To make a fair comparison, we split the timeseries from April 1 to May 28, 2024 of minimum RTT and hourly packet loss percentage into two sets – *Event days*, and *Quiet days*, based on the Dst index. We consider all the days where the Dst index < -50 nT (or at least G1, a minor geomagnetic storm in the NOAA space weather scale) as *Event days*, whereas all the remaining days within our dataset are in *Quiet days*, leading to 20 event days and 38 quiet days altogether.

Impact on overall loss and RTT: To evaluate if there is any change in Starlink's performance characteristics due to the solar events, in Fig. 3(a)-(b), we plot the CDF of event days and quiet days hourly packet loss (%) and normalized min RTT of all source-destination pairs having *stability score* < 50 ms. Here, we use normalized min RTT to map the min RTT measurement of each source-destination pair between 0 and 1. This makes the latency measurements comparable, regardless of the distance between source-destination pairs. From Fig. 3(a), we can observe that the

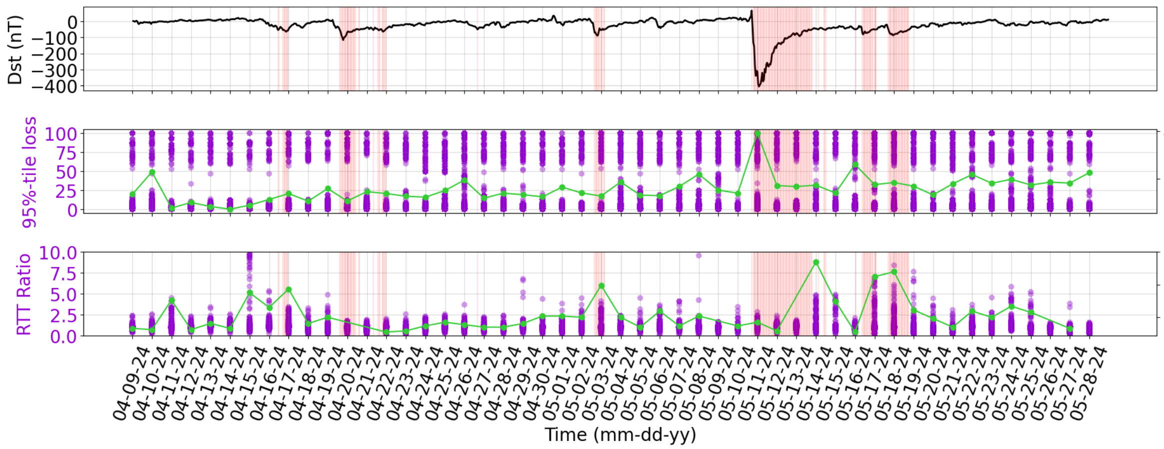


Figure 5: Measuring the changes in loss and min RTT over the window of the past seven days for each source-destination pair. The violet dots represent the 95th %-tile loss and RTT ratio for each source-destination pair, and the green line indicates the percentage of impacted source-destination pairs. The red vertical bars signify occurrences of geomagnetic storms.

hourly packet loss of the event days slightly increased by up to 2.3% between the 85 – 95 percentile (%-tile). However, in Fig. 3(b), the normalized min RTT distribution of event days and quiet days closely overlap, showing no visible changes. The characteristics of the distribution remain consistent while repeating this experiment with different *stability scores* from 10 to 100 ms; however, we do not include these results for brevity.

Inspecting the difference between event and quiet days: To understand the performance implications at the individual source-destination pair, we calculate the differences (Δ) in the 90th, 95th, and 99th %-tile of hourly loss (%) and min RTT between event days and quiet days for each source-destination pair having a *stability score* < 50 ms. Fig. 3(c)-(d) shows the CDF of these differences. From Fig. 3(c), we can observe that, for 80% of the source-destination pairs, the difference in hourly packet loss remains within ±5%. We can also observe that the density of the points between 5 to 50%, is denser than the points between −50 to −5%. This marginal increase in loss on the event day for a few source-destination pairs led to a slight increase in 85 – 95%-tile overall loss in Fig. 3(a).

From Fig. 3(d), we can observe that, for almost 99% of the source-destination pairs, the difference in min RTT remains within ±10 ms. Only the CDF of the difference in 99th %-tile of min RTT shows a tiny shift above 80 %-tile. The discrete points in the long tail beyond the min RTT difference of ±100 ms originate from the outliers of RTT measurement in both event days and quiet days. These outliers are visible in Fig 2(b) with probe 28221, where the majority of observations lie within 20 – 45 ms, and a few outliers exceed 90 ms irrespective of solar events. As a result, the overall min RTT distribution of event days and quiet days in Fig. 3(b) shows no visible difference.

Key takeaway: Over the long-term statistics of two months, 85-95 %-tile of hourly packet loss during solar events increased by ~2%, while RTT shows no visible change.

4.2 Short term implications

Since we do not see any major impact of the solar events on the Starlink network with an observation window of two months, we now reduce this window size from May 5 to 14, 2024 to focus only on the May 2024 G5 class geomagnetic storm. In the following, we discuss the results of repeating the same experiments as above, considering the first five days (May 5 – 9) as *quiet days* and the remaining five days (May 10 – 14) as *event days*.

Impact on overall loss and RTT: In Fig. 4(a)-(b), we show the CDF of event days and quiet days hourly packet loss (%) and normalized min RTT of all source-destination pairs having *stability score* < 50 ms. In Fig. 4(a), the distribution of the hourly packet loss of event days shifted up to 3% between 83 – 93%-tile, while more than 15% above 93%-tile. This is a notable increase in loss as compared to the distribution of two months in Fig. 3(a). In addition, the RTT distribution in Fig. 4(b) shows a marginal shift of up to 1% within 50 – 97%-tile.

Inspecting the difference between event and quiet days: Similarly, Fig. 4(c)-(d) illustrates the CDF of the differences in the 90th, 95th, and 99th %-tile between event days and quiet days for each source-destination pair. The only noticeable difference is a slight shift in all the CDFs near the 70%-tile for both hourly packet loss and min RTT as compared to Fig. 3(c)-(d).

Key takeaway:- In the short term, statistics of 10 day window of May 2024 superstorm, shows marginal increase in loss (95th %-tile loss increased by 15%), while RTT has minimal visible change.

4.3 Inspecting magnitude and regions

After the statistical distribution of loss and RTT, we measure the magnitude of the impact on Starlink's network performance due to solar events and then geo-locate the most impacted regions using the probe's locations. For this, in Fig. 5, the top panel, we show the solar radiation intensity using the Dst index. In the middle panel, each point denotes the 95th %-tile of the hourly packet loss (%) observed by each source-destination pair. The green line represents the percentage of source-destination pairs that experience 95th %-tile hourly packet loss of at least 5%. In the bottom panel, we show the impact on min RTT – calculated as a ratio between the 95th %-tile of min RTT of a day and 95th %-tile of min RTT of the previous 7 days. The green line represents the percentage of

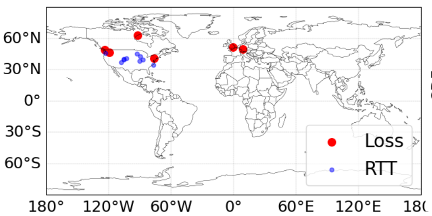
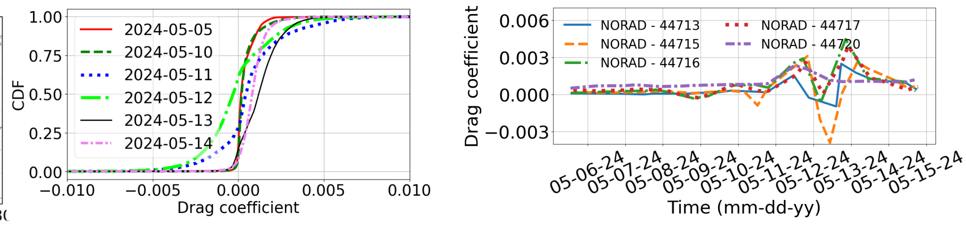


Figure 6: Locations of severely impacted probes.



(a) CDF of date-wise orbital drag.

(b) Five most impacted satellites.

Figure 7: Analyzing the drag (a) distribution of all satellites and (b) timeseries of severely impacted satellites.

source-destination pairs with a ratio of at least 2. We only consider source-destination pairs having a *stability score* < 50 ms. From Fig. 5, we can observe that the magnitude of the impact on the loss and min RTT varies drastically over this period of two months. Irrespective of the intensity of the solar radiation, many source-destination pairs encounter 95th %-tile hourly packet loss of 100%, whereas the RTT ratio reaches beyond 10 (the Y-axis is restricted to 10 for visual clarity). This indicates that the magnitude of the performance impact is not strongly correlated with the intensity of solar radiation.

However, during the May 2024 superstorm, we see a distinguishable spike in the number of source-destination pairs that experience loss. Notice that on May 11, the day of the peak intensity, 40% of the source-destination pairs experience 95th %-tile hourly packet loss of at least 5%. On May 14, three days after the peak intensity, 5% of source-destination pairs experienced 2× RTT ratio; however, this is not significant over a baseline of 2 − 3%. This indicates that the immediate response to such events is packet loss. However, our analysis does not show any significant anomalies in the RTT measurements.

In addition, we plot the probe locations in Fig. 6 that suffered the maximum increase in loss (95th %-tile hourly packet loss > 50%) on May 11, and in min RTT (ratio > 4×) on May 14, respectively. Notice that the majority of these probe locations are above the latitude 30°N in the US, Canada, and Europe.

Key takeaway:- The immediate impact of the superstorm is moderate packet loss across many probes. The impact on the RTT is negligible.

4.4 Impact on orbital drag

Finally, we explore the orbital drag experienced by the Starlink satellite fleet to understand the impact on physical LEO infrastructure [16], which could have led to the mild network performance implications discussed above. To do this, we plot the date-wise CDF of the orbital drag of Starlink satellites in Fig. 7(a) to demonstrate the changes in distribution during the May 2024 solar superstorm. First, notice the distribution of the orbital drag on May 5. Since this was a quiet day with the Dst index close to 0 nT, we consider it as a baseline to compare the event days. Now notice the commencement day of the storm on May 10, the 90%-tile of the orbital drag distribution overlaps with May 5 since the radiation shockwave collides by the end of the day at 17:00 UTC. Over the next two days, the distributions changed drastically. On May 11, the day around 02:00 UTC Dst index went below −400 nT, above 70%-tile of orbital drag shows a drastic positive increase. This is the same day where Fig. 5 shows that around 40% source-destination pairs experience 95th %-tile hourly packet loss above 5%. On May 12, the 60%-tile of orbital drag shifted towards the negative side as compared to the 25%-tile on May 11. We speculate that this negative shift is because of Starlink's station-keeping maneuvering to countermeasure the orbital decay. Starlink also mentioned in their response to the FCC that a "capable propulsion system" kicked in real time, to counter the drag [26]. Recovery begins over the next two days. On May 13, the orbital drag remains on the higher side, while from May 14, the Dst index reaches above −50 nT, and the orbital drag distribution approaches characteristics similar to May 5.

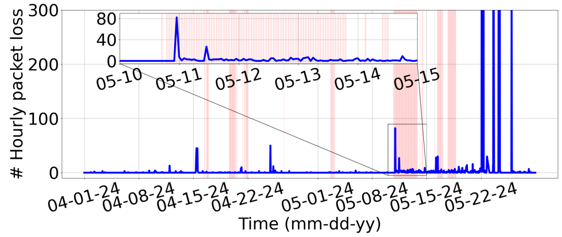
Additionally, in Fig. 7(b), we show a timeseries of the drag coefficient of the five severely impacted satellites on May 11, 2024 with their NORAD ID [11]. This figure validates Starlink's claim that their satellites indeed experienced 3 − 5× drag during the superstorm [26]. Interestingly, all five severely impacted satellites in Fig. 7(b) belong to the first generation of satellites launched on November 11, 2019 [6]. At the time of our analysis, NORAD ID – 44713 and 44715 were decommissioned on October 2, 2024 and February 21, 2025, respectively. However, NORAD ID – 44716 and 44717 is currently operational, while 44720 is nonoperational since November 9, 2024 will be decommissioned soon [6].

Key takeaway:- On the day of the peak intensity of the solar superstorm (i.e. on May 11, 2024), satellites experience the highest orbital drag, which might have caused 40% of source destination pairs to experience a higher loss than usual days.

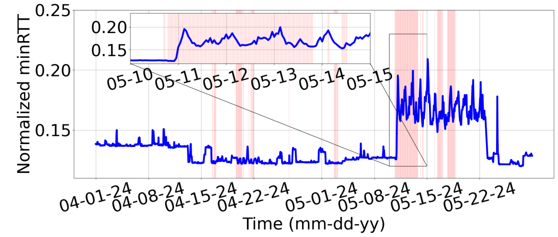
4.5 Comparison with prior work

While our analysis using RIPE Atlas probes shows almost negligible inflation in RTT and a marginal increase in loss, the prior work [47] that explored the same solar event, reported probe 1007389, located in British Columbia, Canada, was most impacted on May 11, showing (*a*) clearly distinguishable spike in the number of packet losses and (*b*) an increased RTT measurement that continued for the next few days. Unfortunately, our analysis does not reflect either observation. Therefore, we further investigate the measurements from this particular probe.

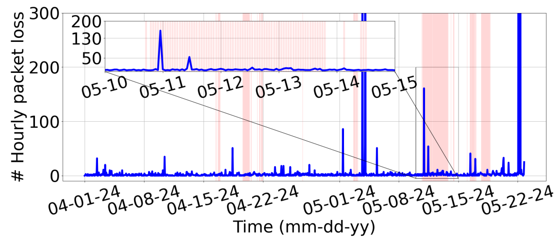
Reproducing the prior work: All RIPE Atlas probes periodically pings 19 root servers [4]. While our work treats each source-destination pair separately, the prior work [47] took a different approach. They accumulated all measurement results from a given probe and computed the hourly mean of the normalized min RTT and the number of hourly packet losses. We adopt the same approach to reproduce the RTT and packet loss figure for probe 1007389 to validate the contradictions.



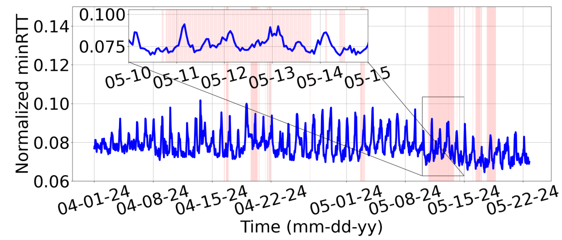
(a) Loss over IPv4



(b) RTT over IPv4



(c) Loss over IPv6



(d) RTT over IPv6

Figure 8: Measurements over (a)-(b) IPv4 and (c)-(d) IPv6 for two months while zooming into the five day window of the May 2024 solar superstorm for probe 1007389 at British Columbia, Canada.

Plausible reason of inconsistency: Among 96 probes connected to Starlink, some are connected to two different networks over IPv4 and IPv6 interfaces. The probe 1007389 [2], which is currently *written off (since December* 2024*)*, is one of such probes connected to Starlink (having ASN 14593 [8]) via IPv6, and to the University of Victoria (having ASN 16462 [3]) via IPv4. We fetch the network measurement of this probe for both IPv4 and IPv6 using the respective measurement IDs [4] to regenerate the packet loss and RTT figures of the prior work [47] in Fig. 8. We also zoom into the window of May 10 – 15 to highlight the measurements during the May 2024 solar superstorm. Notice that in Fig. 8(a)-(b), inside the zoomed window, the number of packet loss and the RTT measurement characteristics over time closely match with the prior work [47], thus indicating that the author of [47] could have overlooked that a few probes are not connected to Starlink via IPv4. Now, Fig. 8(c)-(d) shows the loss and RTT measurements over the Starlink network, respectively; these two figures reestablish our result using their approach as well. Hence, focusing only on May 10 – 15 shows two spikes in the packet loss in Fig. 8(c), whereas in the long term, there are many packet loss spikes, even sometimes larger than these, during the superstorm visible within the window of two months. Similarly, in Fig. 8(d), there is no such noticeable change in the RTT measurement, neither in the long-term nor in the short-term window, indicating no significant impact on latency.

5 Limitation and future work

In this section, we point out some roadblocks in establishing a direct cause-and-effect relationship between a solar event and its impact on a specific set of LEO satellites, connectivity issues caused by this event in specific regions, etc.

Proprietary systems: Constellation operators rely on proprietary systems, consequently restricting the knowledge of internal operational details. For instance, the invisibility of the IP layer [38] in Starlink. Despite many efforts [13, 29] to reveal the end-to-end latency in the Starlink network, we still lack the knowledge of the hop-to-hop latency between satellites to search for anomalies.

Data resolution: Our results, along with prior work [47], indicate that the northern latitudes are the most affected regions by solar storms. However, the geographical distribution of the probes is skewed toward North America and Europe. Thus, observations from other regions of the world are lacking. Additionally, Starlink reports disruptions of < 1 minute during the event [26], thus, the built-in ping interval of 4 minutes [4] is inadequate to capture subtle changes in connectivity.

Data availability: The satellite TLEs include the BSTAR drag term [28] – a composite value reflecting atmospheric drag, radiation pressure, and other forces. This does not reveal the instantaneous forces acting on satellites in arbitrary regions. The network measurements dataset includes some terrestrial segments, and the downlinks and uplinks of Starlink are prone to weather conditions [50] too. Therefore, it is crucial to record the weather status and route traces alongside network measurements to depict a complete picture.

Future work: As the Sun has already started approaching the minima of the current solar cycle, the likelihood of encountering a solar superstorm in the near future is low. This provides the scientific community with a large time window (at least till the next solar cycle) to address the current measurement limitations. In future, we will include all LEO constellation fleets (OneWeb and Kuiper) in our study, along with the Earth observation and communication satellites at higher altitudes, to conduct a comprehensive analysis to establish a direct relationship between solar events and space-borne infrastructure, along with the end-user connectivity implications.

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