The Influence of Ground Infrastructure Proximity on Starlink's Performance

A Novel Method to Unravel Starlink's Network Routing

Christiaan Baraya[1]

Supervisor(s): Nitinder Mohan[1]**, Tanya Shreedhar**[1]

[1]**EEMCS, Delft University of Technology, The Netherlands**

A Thesis Submitted to EEMCS Faculty Delft University of Technology,
In Partial Fulfilment of the Requirements
For the Bachelor of Computer Science and Engineering
June 22, 2025

Name of the student: Christiaan Baraya
Final project course: CSE3000 Research Project
Thesis committee: Nitinder Mohan, Tanya Shreedhar, Qing Wang

Abstract

Previous literature had accentuated the importance of close ground infrastructure (Ground Stations and Points of presence) on the network performance of Starlink. In order to further investigate this relation, a new method was defined, based on IPv4-traceroute, to identify the PoP associated with a Starlink user. This method has been evaluated for 95 RIPE Atlas probes connected to the Starlink network and the results have been mapped in an interactive web-tool. Using this data, a strong correlation between latency and proximity to ground infrastructure was verified.

1 Introduction

Starlink, SpaceX's satellite network, has shown tremendous growth since its launch in 2021 [28]. It currently serves more than 5 million users [30] with over 7000 satellites and it has ambitions to deploy 23,000 more [3].

Earlier research on the performance of Starlink has shown promising results [16; 34]. With multiple researchers [13; 16] also noting the importance ground infrastructure has on performance.

This paper further investigates the correlation by examining the effect that distance to the associated PoP has on the latency from a user to that PoP. To study this, a method must be used that determines the 'home' PoP that is associated with a particular user.

This has been done earlier in [37; 41] by taking the region where the user terminal is situated, and applying reverse DNS lookups over the subnet corresponding to that region in Starlink's GeoIP Feed [33]. However, this approach does not provide a singular answer, but instead provides possible PoPs for a region. Alternatively, [37] describes a method using reverse DNS lookup on the IPv6-address of users, but this method has been found to give incorrect results.

That is why this research establishes a different method, that relies on IP geolocation on traceroute results. To elaborate, when performing IPv4-traceroute measurements over the Starlink network, IP addresses belonging to the PoP will be gained. Subsequently, the city in which the PoP resides, can be acquired by issuing an IP geolocation lookup on these addresses,

Unfortunately, this procedure occasionally gives a PoP that is impossible based on the latency. To filter out these incorrect results, the results are afterwards validated by checking whether they appear in the list obtained by applying the aforementioned steps from [37] on the region that belongs the user terminal.

This method has then been developed and tested through the creation of a web-tool, which visualized the connection between Starlink RIPE Atlas probes and their associated PoPs and ground stations on a map. It also allows users to view this information at a selected time in the past and gain insight into how Starlink's routing and performance have evolved. This tool, alongside the utilized data can be found at [1].

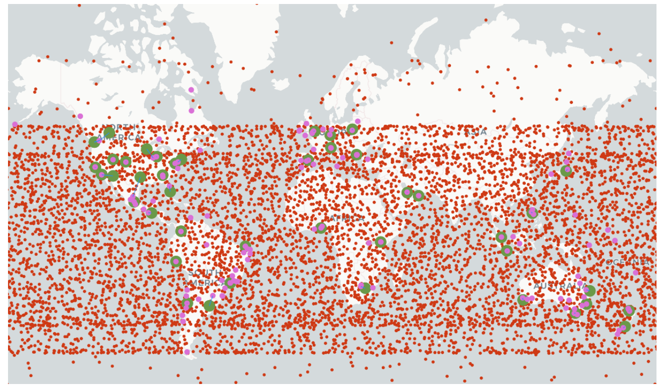


Figure 1: Each red dot is a Starlink satellite. The majority lie in the 53° orbital shell

2 Background and Related Work

2.1 Workings of Starlink

Starlink is a low Earth orbit (LEO) satellite network, operated by SpaceX [31]. Most of the satellites lie between the 53st parallel north and the 53st parallel south, which results in better satellite coverage in this part of the world [16].

To be able to use Starlink, one must directly connect their router to the Starlink user terminal (UT, also called Dishy). This is a satellite dish that, with direct sky access, sends and receives data from nearby satellites.

The field of view of a satellite is divided into hexagonal regions of 250 km² [12; 35] and one satellite is able to connect to user terminals in multiple regions simultaneously. [26].

The satellite sends the data to a ground station (GS). This can be done directly, or via a different satellite, in what is called an Inter-satellite link (ISL).

From a ground station, the data goes via high-speed cable to a Point of Presence (PoP), this PoP is called the 'home' PoP of the user terminal. A point of presence is a server that routes the packets further to the rest of the internet.

The remaining part of the forward-route is called the "terrestrial part" and goes via conventional networks. The path up to the PoP is called the ' "non-terrestrial part" and this is what sets LEO satellite networks apart from traditional ISPs.

2.2 Workings of Traceroute

Traceroute is a widely used tool for determining the path data travels over a network. It works by sending an array of packets to a destination, starting with the *time-to-live* (or *hop-limit* for IPv6) set to one and incrementing it for each packet until the destination is reached (if it is reachable).

When a network device receives an IP-datagram, it decrements the time-to-live field. If the value reaches zero, the datagram is destroyed, otherwise, the datagram is forwarded to the next router [25]. After the device destroys the packet, it must return the ICMP error message "ICMP Time exceeded" back to the source [24], together with the device's IP address. This way the source learns the addresses of the routers on the path, one hop at a time.

Traceroute also times the delay between the packet being sent and the ICMP-response being received. As a result, the

Figure 2: The result of pressing the dish at Paris on the Starlink GeoIP Map. Dishes are geoIP locations, at-signs are PoPs. The fifth line at the right goes to the PoP in Doha (dohaqat1).

round-trip time to each intermediate router on the path is also measured.

2.3 A Large-Scale IPv6-Based Measurement of the Starlink Network (Wang e.a.)

The work in [37] maps the Starlink backbone network by scanning a subset of the address space that Starlink assigns to its users. This address space can be found in Starlink's GeoIP Feed [33]. Since normal Starlink subscribers, are not assigned public IPv4 addresses, IPv6 addresses are probed instead. More specifically, for a subnet of a region, every address (with bits 57 to 127 set to 0 and bit 128 set to 1) is probed. Additionally, the paper identifies the PoP associated with a user router by performing a reverse DNS lookup on the address. A code identifying the PoP is part of the resulting DNS PTR record (e.g."sfiabgr1" is the code for the PoP in Sofia, Bulgaria). By performing this lookup over the entire user address space, 33 PoPs were discovered, alongside connections between PoPs.

This technique can also be used for a user to determine to which PoP their router is connected. The authors do remark that one limitation of this method is the untimely manner in which DNS PTR records are updated. However, this technique also has some further limitations which are explained in section 2.4.

2.4 Starlink GeoIP Map [41]

This map displays all subnets defined in Starlink's GeoIP feed [33] and links them with the PoPs possible when performing an nslookup over that subnet. The website also gives users, that are connected to Starlink, the option to retrieve their associated PoP by issuing a Cloudflare traceroute from their device.

Limitations

I believe this method is not a reliable tool for predicting which PoP a certain user is connected to. This is because of two main reasons:

Firstly, It is unknown which of the countries PoPs is taken. For countries where all data travels to the same PoP this is not an issue, but for example, France has five PoPs in figure 2. Since most Starlink users do not get a private IP-address, they can not do an nslookup themselves. This means that this user in France, could not know which of the five PoPs they use based on this method.

Secondly, nslookup does not give reliable information. France has one subnet that has "customer.dohaqat1.pop.starlinkisp.net" as its domain; this is the PoP in Doha. As of June 10th, three starlink devices with IPv6 in the southeast of France make use of this subnet (RIPE Atlas probes 1008746, 13040 and 1009894). However, the low latency makes it very unlikely that those packets from France would actually go via Qatar. Using geoIP-location on IPv4 measurements on those same probes shows that these are instead connected to the PoP in Milan, this is the closest PoP to those three probes and fits more with the measurements and expectations.

2.5 Starlink coverage tracker [27]

Another website which gives insight into Starlink's routing is Starlink.sx [27; 26]. This tool maps out PoPs, ground stations (named gateways) and satellites in real time. Using the gateway capacity (max throughput of a gateway) and the satellites in a gateway's reach, it offers a feature to stimulate which h3-cells in a region shall receive satellite coverage. It is also possible to enable or disable ground stations to evaluate the effects this could have on Starlink's coverage of a region.

This tool allows users to set a home location, to view which satellites are in the approximate field-of-regard of a user terminal, and for these satellites, which ground station they are able to connect to. However, this website only makes use of stimulation to predict possible data paths. One goal of this research is to create an application which combines routing data based on measurement with some of the features from Starlink.sx, namely, the mapping of satellites, PoPs, and ground stations.

3 Methodology

3.1 Points of presence considered

The points of presence are queried from [40]. According to [41] this dataset is composed by combining Starlink's entries in PeeringDB [23] and the PoPs in *Unofficial Starlink Global Gateways & PoPs* [36].

For this research, community gateways [29] and PoPs that are not yet operational are excluded from this list. The former since, these types of gateways are not directly connected to a PoP, but instead act like a user terminal for an entire region. To filter these entries from the list, only the elements that have their "type"-attribute set to "netfac" (network facilities) are included.

This leaves 45 PoPs as of June 10th 2025. This list can be found in appendix A (table 2).

3.2 Ground stations considered

The stations are extracted in kml-format [8] from [36]. This data-set does not have a standardised way to mark a station as operational. Therefore, any station that includes "live" or "Live" in its status-description is included in this research. This generally includes the following three categories: "Live", "Presumed Live" and "Reported live".

This resulted in 130 ground stations as of June 20th 2025. This list can be found in appendix B (table 3).

3.3 RIPE Atlas

RIPE Atlas is an internet measurement network established by RIPE NCC [21]. It works by having devices (henceforth referred to as "probes") actively perform internet measurements. All probes and measurements are stored on the RIPE Atlas platform and can be accessed by using an API.

RIPE Atlas has been chosen over other measurement platforms, such as M-lab [5; 6] and Cloudflare [2], besides these last two having a larger amount of measurements and a more diverse data-set. This is because these do not provide location data. At most the region can be inferred from the IP-address. On the contrary, for RIPE's network, each probe has its location public, obfuscated no more than one kilometre away [18].

Selected probes

Only probes which measure over IPv4 were considered. Both IPv4 and IPv6 have their advantages and disadvantages for measuring traffic. IPv6-devices all get a public address, while this is only the case for IPv4-probes with a priority Starlink plan [32].

When performing a nslookup on IPv6-address, a domain in the form of customer.*.pop.starlinkisp.net is returned with * being the name of the PoP associated with the user [37]. However, like discussed in section 2.4, this method is unreliable and does not always give the actual PoP. Instead, performing a GeoIP-lookup on the public IPv4-address by sites such as *ipinfo.io* yields much better results. This can not be done with IPv6: doing the same on the IPv6-address gives the geolocation of the user instead. Furthermore, there are more connected Starlink probes that support IPv4 than IPv6 (94 to 63) [17].

Filtering on probes that make use of Starlink was done by specifying the Autonomous System Number. All probes that have "ASN V4" set to 45700 (ASN for Indonesia) or 14593 (ASN for the rest of the world).

Applying these queries resulted in 178 probes, of which 95 were active as of June 10th, 2025.

Measurement used

There are six different types of measurements that probes support: TLS, DNS, HTTP, Ping, Trace and NTP. Of these, *trace* (traceroute) is the most applicable. This is because, in addition to giving the route, trace also allows for a way to measure the round-trip-time (RTT) up to any intermediate hop. This means that the latency of the non-terrestrial route, can be figured out, by determining the latency up to the PoP.

The measurement used was 1591146 "traceroute to 8.8.8.8" [19]. Here, 8.8.8.8 is an address that Google uses for their DNS servers [7]. This measurement is suitable because of three reasons:

1. all probes are requested to perform it, and all Starlink probes do.
2. it is running on a frequent interval of 1800 seconds. This ensures that there will be many data-points to work with in a narrow time-frame. In addition, changes to network routing will be quickly picked up and can be promptly reflected in the web-tool afterwards.
3. it has been running continuously since 2014, which is before the operations of Starlink started. As a result, latency can be analyzed over a long period of time.

Hop	Address	Median RTT (ms)	Description
1	192.168.1.1	0.856	User Terminal [22]
2	100.64.0.1	32.432	Ground Station [22; 32]
3	172.16.0.0/12	37.309	PoP [22]
4	206.224.64.0/20	37.585	Internal inside PoP [15]
5	206.224.64.0/20	32.751	Internal inside PoP [15]

Table 1: General result of IPv4 traceroute without having priority plan

3.4 Traceroute over the Starlink Network

Traceroutes over the Starlink network often return results in a general pattern. Table 1 summarizes this pattern for IPv4. The addresses are taken from [15; 22; 32], and are confirmed independently. The values in the column "median RTT (ms)" have been calculated by taking the median RTT of the latencies for all Starlink probes over a year.

The first hop is commonly from the user device to the user terminal, but it is also possible to have hops before that. Therefore, instead of using a specific hop number, the PoP is decided as the first address that belongs to the subnet 206.224.64.0/20. This subnet is announced by Starlink [15], which rules out false positives.

One thing to note is that the latency to the ground station is not much lower than the latency to the PoP ($\approx 5ms$ difference). This could indicate, that data is routed to ground stations close to the PoP.

3.5 Starlink GeoIP Feed

Starlink publishes an up-to-date GeoIP-feed [11] at [33].

For regions in which Starlink is available, a user will be provided an ip-address in the subnet of that region, if they are using IPv6 or using IPv4, with a Local or Global Priority service plan [32].

When provided an IP-address of a user, no geolocation can be inferred apart from the region in which the user terminal is located. The size of regions varies greatly: all users in India will be mapped to the same location (Mumbai), while small islands with less than a thousand inhabitants have their own GeoIP-location. This makes relying on data of this GeoIP-feed very imprecise based on region-size.

3.6 Determining PoP and GS associated with a Probe

This section describes the algorithm for identifying a PoP based on a probe. This method works for the current PoP, but can also be used to determine a previous PoP connection. These steps can also be performed on a singular traceroute, but this will result in a lower accuracy.

To determine the home PoP of a probe. All instances of measurement 1591146 over a time-span of 300 minutes are queried. This results in 10 measurements, each consisting of 3 traces. Some of these takes did not reach their target or do not go over the Starlink network, these are omitted from the results.

Based on this data, a set is created with the IP addresses of the PoPs for each traceroute result. The PoP address is the first and – in case it exists– second address that are part of the subnet 206.224.60.0/20.

Afterwards, this set is sent to IPinfo [9] for IP geolocation. This gives the name of the city in which the PoP is located based on the PoP's address. This method is not completely reliable, since the geolocation might give incorrect results. Examples of this are French probes, which were said to be connected to Chicago.

To validate the results further, connections which do not appear in the GeoIP-feed over the regions subnet, are discarded. For example, Chicago does not appear in the domain, when doing reverse DNS lookup on France (as seen in figure 2). This means that the result would be ignored if the IP geolocation placed the home PoP for a French probe in Chicago .

The possible PoPs belonging to a region are retrieved form [40]. Where the region is taken from the country code, which is part of a RIPE probe's.

To determine the ground station that belongs to a probe, the nearest ground station relative to the home PoP. This is based on the in [16]. In this paper the deduction is based on the latency difference between ground stations and PoPs being small ($\approx 5ms$). This is the same difference value that has been found in table 1.

4 Results

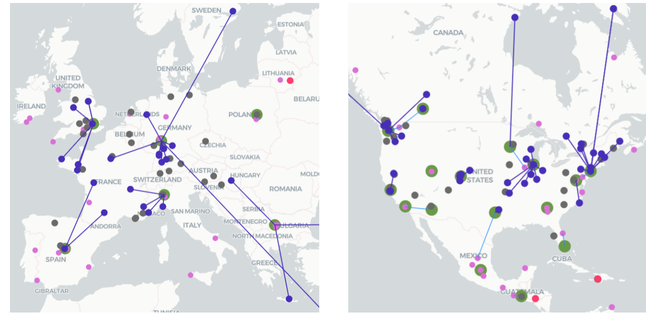
4.1 Web-tool to investigate network routing

The algorithm described in 3.6 has been incorporated into a web-tool which identifies and displays the connections to the PoPs for all probes.

The figures 3a and 3b illustrate the connections for Europe and North-America respectively. The dots in these images signify the following:

- Pink dots are ground stations,
- Green dots are points of presence,
- Light blue lines connect a PoP with its closest ground station,
- Blue dots are RIPE Atlas Probes,
- Dark blue lines connect RIPE Atlas probes with their home PoP,
- Red dots are RIPE Atlas connect RIPE Atlas probes where no PoP, connection could be identified at the selected time,
- Grey dots are RIPE Atlas Probes that are disconnected at the selected time (without measurements).

As could be expected, probes tend to be routed to the PoP that is closest to them, but there are some exceptions. A notable example is the probe 1010769 in Yemen, which is connected to the PoP in Frankfurt am Main, even though there are seven operational PoPs that are closer. Namely, Doha, Muscat, Nairobi, Sofia, Warsaw, Milan, and Johannesburg[1].



(a) Europe. (b) North-America.

Figure 3: The front-end view of the application. For each probe (blue dots), the associated PoP (green dot) is drawn with a dark blue line between them.

4.2 Comparing Distance to Ground Infrastructure with Latency

Adding a new PoP seems to greatly improve performance in some places (see section 4.3). This suggest that there is a strong correlation between distance to a PoP and latency. Having the PoPs belonging to probes identified, this relation can further be analyzed.

Figure 4a shows the latencies of the RIPE Atlas probes compared to the geodesic distance to the home PoP. The y-axis shows the median RTT of the non-terrestrial path between 1 and 7 June 2025, this time-span gives 84 measurements per probe. Probes with a RTT over 40 ms or a distance above 1000 km, have the id written at the data-point.

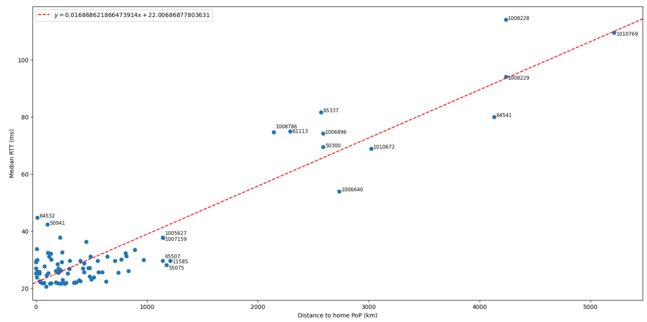
The graph demonstrates that a farther distance to a home PoP does lead to worse latencies on average, but there are some outliers.

One such outlier, that lies on the left side of the graph, is probe 50941. This probe is located at a distance of roughly 100 km to the PoP in Dallas. Despite this proximity, the latency is circa 18.54 ms higher compared to estimated point on the regression surface. One observation which might explain this, is made when looking at the infrastructure map (figure 5). Unlike most PoPs, which have a ground station in the same city, the closest ground station to Dallas is in Mexico. This indicates the importance of ground stations as well.

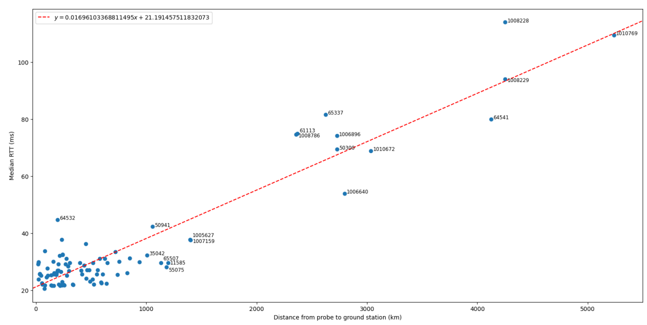
Figure 4b takes this variable into consideration, by instead plotting the distance from the the probe to the closest ground station to the probe's home PoP. The plot in figure 4c additionally adds the distance from the ground station the PoP as well.

The linear regression in both of these figures is a closer fit, than in our original plot, with figure 4c being slightly better. The latency of probe 50941 is also better predicted when accounting for ground station distance, with the corresponding data point being 4.88 ms above the fit in figure 4b and 12.33 ms below it in figure 4c.

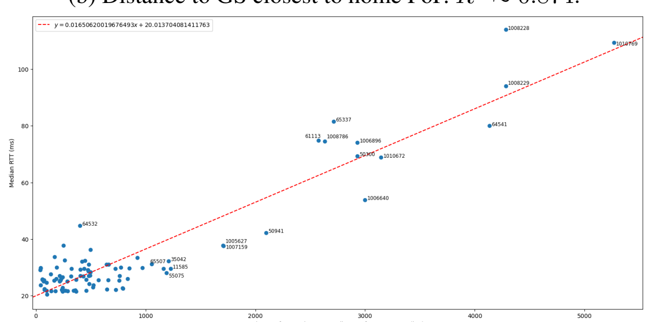
[1] Operational according to [40; 36]. All have been verified using methods from section 3.6, except Doha and Muscat. Nonetheless, these cities appearing in IP geolocation tables [?], gives evidence for these PoPs being live.



(a) Distance to the home PoP. $R^2 \approx 0.852$.



(b) Distance to GS closest to home PoP. $R^2 \approx 0.874$.



(c) Distance from Probe to GS + from GS to PoP. $R^2 \approx 0.868$.

Figure 4: Latency of the non-terrestrial path plotted against distance for each Atlas probes. Points with high latency or distance are annotated with probe ids. Red lines denote linear regression fits.

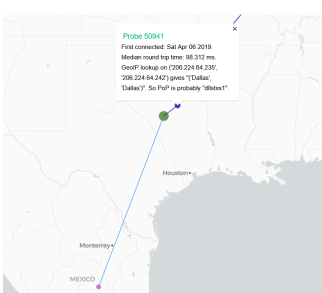


Figure 5: Probe 50941 (blue dot) in Texas, USA. The closest ground station (pink dot) to the PoP (green dot) is in central Mexico

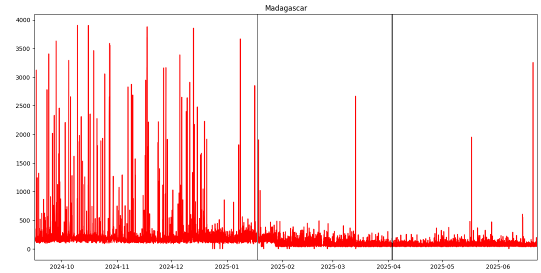


Figure 6: Round trip time in ms of probe 1008786 in Antananarivo between 2024-08-23 and 6-6-2025.

4.3 Case study: new PoPs in Africa

Background

Southern and East Africa were regions where Starlink had particular poor performances in the past. This is because all of Africa only had a single PoP (in Lagos) to connect to.

By contrast, recent reports and research have announced significantly higher performances, attributing this improvement to the addition of a new PoP in Nairobi in January of 2025 [10; 38].

RIPE Atlas probes in Africa

There are very few RIPE Atlas probes in Africa that use Starlink.

- One in Benin next to Lagos that measures over IPv4 (id=60812),
- One in Burundi that measures over IPv6 (id=16780).
- One in Madagascars capital Antananarivo that measures over IPv4 and IPv6 (id=1008786).

The probe in Burundi is not representative to the average of Africa because of the closeness to Lagos, so this one will not be used. After experimentation a GeoIP-lookup on an IPv4-addresses, gave much better results than a lookup on an IPv6-address. This is why this case study was based on the network probe in Madagascar.

Performance of Probe 1008786 over time

The probe has been active on the Starlink network since 2024-08-23. In the 240 days since then, the probe has an uptime-percentage of 83.28% [20]. Figure 6 shows the round trip time to the first PoP of the probe. The grey and black vertical line are when respectively the PoP in Nairobi and Johannesburg were first connected to.

When looking at the graph, it seems like at the end of January 2025, the latency improved considerably and became much more stable. This corresponds exactly with the PoP in Nairobi becoming operational. Such a drastic improvement was also reported in [10]. This also confirms, that a change in PoP is quickly reflected when using the algorithm in 3.6.

5 Responsible Research

5.1 Ethical Considerations

This research adheres to the principles set out in *ACM Code of Ethics and Professional Conduct* [4]. Examples of these principles include “1.7 Honor confidentiality” and “1.5 Respect the work required to produce new ideas, inventions, creative works, and computing artifacts”. These principles have been respected throughout the research: all data that has been used is publicly available. SpaceX does not object to their satellites being tracked, since they work together with Celestrack to distributes Starlink satellites TLEs [14]. Furthermore, all (data) sources used has been credited in this paper as well as on the web-tool.

Care has also been put into conserving the resources of these data sources by minimizing the amount of requests sent and not requesting more data than is being used. Additionally, to promote transparency and further research, the source code for the web-tool has been made open source and everyone is encouraged to check out or modify the project.

Privacy regarding the RIPE Atlas network

Another principle which was reflected upon is “1.6 Respect privacy”. This became relevant, when considering the privacy of the people who set up a probe for the RIPE network. The only personal information which could be gathered about the probe owner, are their IP-address (and ASN) and location (Country, latitude, and longitude).

The IP address, for Starlink specifically, expresses no information except whether a user has a priority plan.

The location is set by the user themselves [17], and is “irreversibly obfuscated up to one kilometre away” [18]. This has been done by rounded probe locations to one hundredth of a coordinate degree.

One potential privacy flaw found on the Atlas platform is that probes set to “private”, still reveal their location when using the API. This is dissimilar to the web-platform, where the location of private probes are hidden. As a result this research includes location data, which might infringe on the privacy of the owner of private probes. But, even in this case, the most that can be deduced is that some person in the range of 1 kilometre is subscribed to Starlink.

5.2 Reproducibility

All steps in section 3.6 are able to be reproduced. An implementation of this algorithm in Python can be found in the “backend”-folder of the repository at [1].

However, there are some difficulties of getting an historic result, which includes replicating my exact findings. This is because there is a lack of publicly available historic data.

For ground stations, there is no list for operational ground stations in the past. Because of this, the list of stations is included in appendix B.

A related problem with IP geolocation. The address space of the PoPs does not change, but the IP geolocation tables on IPinfo do often change. This makes historic PoP identification less accurate. Future work, could be spent on creating a public data-base, which tracks changes in these tables. For the sake of replicating this research the geolocation table at the time of writing is included in [1] as well.

For PoPs there is an available folder for historic GeoIP feeds [39]. Yet, for completeness, and in case this folder becomes unavailable, the PoPs used in this research are listed in appendix A.

6 Discussion

One difficulty, with the method to identify the associated PoP, is that its accuracy can not be assessed, since one would have to already know the actual home PoP to confirm the results.

Nevertheless, based on ample testing, I have come to believe that the method gives accurate results in most cases. Nearly all determined PoP connections, are linked to the closest PoP (figure 3), which is what I would expect. Even anomalies, like Yemen, do align with what would be expected based on the measurement data (section 4.1).

There are some probes, whose PoP is unable to be geolocated in some time-frame. These probes are marked with a red dot on the web-tool. One way to improve this would be to pick a larger time-frame, but the downside to this, is that a larger number of measurements have to be queried for each probe, which takes longer to process. It might be more efficient to request additional data for probes that could not be be appointed, but this requires making multiple HTTP-requests, which could come with considerable overhead. More research could be invested in increasing the efficiency and effectiveness of the algorithm.

One thing to consider, is that even though my conclusions are based on a large amount of measurements, they all stem from a limited number of Atlas probes. These probes are mainly located in Europe, Canada and the United States. This leaves many unrepresented areas. Further work, could integrate Atlas data with M-lab or Cloudflare Radar measurements. These data-bases do not contain precise location data, but can still offer a lot of insight, especially for smaller countries where all routing goes through the same PoP.

7 Conclusions and Future Work

In this paper a new method was presented to identify the PoP associated with a Starlink user. This method is based on IPv4-traceroute and IP geolocation, and is estimated to have a high accuracy. This method has been incorporated in a web-tool, which applies this algorithm for 95 RIPE Atlas probes. These findings confirmed a strong correlation between latency and PoP proximity, but found an even stronger relation between latency and ground station proximity. This highlights the importance of having a good coverage of both PoPs as well as ground stations.

Future work could map the network for a greater number of locations, especially in currently underrepresented regions, possibly making use of M-lab measurements.

References

[1] Christiaan Baraya, Cristian Benghe, Vlad Graure, and Janusz Urbański. Leo-viewer. https://github.com/TUD-BScResearchProject-6079/leo-viewer, 2025.

[2] Inc Cloudflare. Cloudflare radar. https://radar.cloudflare.com/. Last accessed 22 June 2025.

[3] Federal Communications Commission. Da 24-1193. https://docs.fcc.gov/public/attachments/DA-24-1193A1.pdf, November 2024.

[4] Association for Computing Machinery. Acm code of ethics and professional conduct. https://www.acm.org/code-of-ethics, 2018. Last accessed 18 June 2025.

[5] Code for Science Society. Measurement lab. https://www.measurementlab.net/#/. Last accessed 22 June 2025.

[6] Phillipa Gill, Christophe Diot, Lai Yi Ohlsen, Matt Mathis, and Stephen Soltesz. M-Lab: user initiated internet data for the research community. *ACM SIGCOMM Computer Communication Review*, 52(1):34–37, January 2022.

[7] Google. Get started — public dns. https://developers.google.com/speed/public-dns/docs/using. Last accessed 10 June 2025.

[8] Open Geospatial Consortium Inc. Ogc kml. https://portal.ogc.org/files/?artifact_id=27810, 2008. Last accessed 18 June 2025.

[9] IPinfo. ipinfo/python. https://github.com/ipinfo/python. Last accessed 22 June 2025.

[10] Michael Kan. What is a starlink pop? how ground stations improve latency, capacity. https://www.pcmag.com/news/what-is-a-starlink-pop-how-ground-stations-improve-latency-capacity, January 2025. Last accessed 22 June 2025.

[11] Erik Kline, Krzysztof Duleba, Zoltan Szamonek, Stefan Moser, and Warren Kumari. A Format for Self-Published IP Geolocation Feeds. RFC 8805, August 2020.

[12] Wei Liu. Does starlink use h3? https://github.com/uber/h3/issues/717. Last accessed 10 June 2025.

[13] Wenhao Liu, Jiazhi Wu, Quanwei Lin, Handong Luo, Qi Zhang, Kun Qiu, Zhe Chen, and Yue Gao. Efficient Satellite-Ground Interconnection Design for Low-orbit Mega-Constellation Topology, October 2024. arXiv:2410.24039 [cs].

[14] Space Exploration Holdings LLC. Application for approval of orbital deployment and operating authority for the spacex gen2 ngso satellite system. https://planet4589.org/astro/starsim/docs/SAT-LOA-20200526-00055.pdf, May 2020.

[15] ASN Lookup. Spacex-starlink. Last accessed 10 June 2025.

[16] Nitinder Mohan, Andrew E. Ferguson, Hendrik Cech, Rohan Bose, Prakita Rayyan Renatin, Mahesh K. Marina, and Jörg Ott. A multifaceted look at starlink performance. In *Proceedings of the ACM Web Conference 2024*, WWW '24, page 2723–2734, New York, NY, USA, 2024. Association for Computing Machinery.

[17] RIPE NCC. Coverage and statistics. https://atlas.ripe.net/statistics/coverage. Last accessed 10 June 2025.

[18] RIPE NCC. Faq: Security and privacy. https://atlas.ripe.net/docs/faq/security-and-privacy. Last accessed 20 June 2025.

[19] RIPE NCC. Measurement 1591146. https://atlas.ripe.net/measurements/1591146. Last accessed 10 June 2025.

[20] RIPE NCC. Probe 1008786. https://atlas.ripe.net/probes/1008786/overview. Last accessed 22 June 2025.

[21] RIPE NCC. Ripe atlas. https://www.ripe.net/analyse/internet-measurements/ripe-atlas/. Last accessed 19 June 2025.

[22] Jianping Pan, Jinwei Zhao, and Lin Cai. Measuring a Low-Earth-Orbit Satellite Network. In *2023 IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pages 1–6, Toronto, ON, Canada, September 2023. IEEE.

[23] PeeringDB. As14593 - spacex starlink, 2025. Last accessed 10 June 2025.

[24] J. Postel. Internet Control Message Protocol. RFC 792, September 1981.

[25] J. Postel. Internet Protocol. RFC 791, September 1981.

[26] Mike Puchol. Modeling starlink capacity. https://mikepuchol.com/modeling-starlink-capacity-843b2387f501, October 2022. Last accessed 20 June 2025.

[27] Mike Puchol. Starlink coverage traceker. https://starlink.sx/, 2025. Last accessed 9 June 2025.

[28] Michael Sheetz. Spacex begins accepting $99 preorders for its starlink satellite internet service as musk eyes ipo. https://www.cnbc.com/2021/02/09/spacexs-starlink-accepting-99-preorders-as-musk-considers-ipo.html, February 2021. Last accessed 22 June 2025.

[29] Starlink. Starlink community gateways. https://www.starlinkinternet.info/community-gateway. Last accessed 10 June 2025.

[30] Starlink. Starlink stories. https://stories.starlink.com/. Last accessed 6 June 2025.

[31] Starlink. Starlink.com. https://www.starlink.com/. Last accessed 6 June 2025.

[32] Starlink. What ip address does starlink provide? https://www.starlink.com/gb/support/article/1192f3ef-2a17-31d9-261a-a59d215629f4. Last accessed 10 June 2025.

[33] Starlink. Starlink geoip feed. https://geoip.starlinkisp.net/, 2025. Last accessed 9 June 2025.

[34] Hammas Bin Tanveer, Mike Puchol, Rachee Singh, Antonio Bianchi, and Rishab Nithyanand. Making Sense of Constellations: Methodologies for Understanding Starlink's Scheduling Algorithms. In *Companion of the 19th International Conference on emerging Networking EXperiments and Technologies*, pages 37–43, Paris France, dec 2023. ACM.

[35] Uber Technologies. Acm code of ethics and professional conduct. https://h3geo.org/. Last accessed 18 June 2025.

[36] Unknown. Unofficial starlink global gateways pops, 2025. Last accessed 10 June 2025.

[37] Bingsen Wang, Xiaohui Zhang, Shuai Wang, Li Chen, Jinwei Zhao, Jianping Pan, Dan Li, and Yong Jiang. A Large-Scale IPv6-Based Measurement of the Starlink Network, December 2024. arXiv:2412.18243 [cs].

[38] Karim Yaici. Connecting africa: The performance and impact of starlink's satellite internet. https://www.ookla.com/articles/starlink-ssa-q1-2025, May 2025. Last accessed 22 June 2025.

[39] Jinwei Zhao. starlink-geoip/geoip. hhttps://github.com/clarkzjw/starlink-geoip-data/tree/master/geoip, 2025. Last accessed 22 June 2025.

[40] Jinwei Zhao. starlink-geoip/pop.json. https://github.com/clarkzjw/starlink-geoip/blob/master/map/data/pop.json, 2025. Last accessed 19 June 2025.

[41] Jinwei Zhao. Unofficial starlink geoip map. pan.uvic.ca/~clarkzjw/starlink/, 2025. Last accessed 9 June 2025.

A List of Points of Presence

PoP-code	city	latitude	longitude
dnvrcox1	Denver	39.7456	-104.9956
frntdeu1	Frankfurt	50.1197	8.7346
mlbeaus1	Melbourne	-37.8217	144.9155
jtnaidn2	Jakarta	-6.2380	106.8235
sttlwax9	Seattle	47.6143	-122.3389
chrhnzl1	Christchurch	-43.5290	172.5963
clgycan1	Calgary	51.0275	-114.0719
lgosnga1	Lagos	6.4496	3.5883
mplsmnx1	Minneapolis	44.9714	-93.2545
ashnvax2	Ashburn	39.0164	-77.4590
sfiabgr1	Sofia	42.7027	23.3063
frtabra1	Fortaleza	-3.7348	-38.4580
mmmiflx1	Miami	25.7826	-80.1932
msctomn1	Muscat	23.7268	57.7942
qrtomex1	Querétaro	20.5679	-100.2541
gtmygtm1	Guatemala City	14.6537	-90.5492
sttlwax1	Seattle	47.6143	-122.3389
bgtacol1	Bogotá	4.6714	-74.1560
sydyaus1	Sydney	-33.7853	151.1315
jtnaidn1	Jakarta	-6.2380	106.8235
snjecax1	San Jose	37.2418	-121.7830
mnlaphl1	Manila	14.5645	121.0224
dohaqat1	Doha	25.2930	51.5070
mlnnita1	Milan	45.4780	9.1018
atlagax1	Atlanta	33.7586	-84.3879
tmpeazx1	Tempe	33.3955	-111.9701
sngesgp1	Singapore	1.2952	103.7898
tkyojpn1	Tokyo	35.6864	139.7648
dllstxx1	Dallas	32.8007	-96.8194
nwyynyx1	New York	40.7200	-74.0046
chcoilx1	Chicago	41.8762	-87.6315
acklnzl1	Auckland	-36.8493	174.7654
bnssarg1	Buenos Aires	-34.5902	-58.4672
wrswpol1	Warsaw	52.2274	21.0034
sntochl1	Santiago	-33.3580	-70.6763
brseaus1	Brisbane	-27.4654	153.0274
mdrdesp1	Madrid	40.4339	-3.6241
nrbiken1	Nairobi	-1.3501	36.7492
limaper1	Lima	-12.0948	-76.9735
lndngbr1	London	51.5115	-0.0029
sltyutx1	Salt Lake City	40.7209	-111.9849
lsancax1	Los Angeles	34.0479	-118.2556
prthaus1	Perth	-31.8644	115.8959
splobra1	São Paulo	-23.4976	-46.8146
jhngzaf1	Johannesburg	-26.1380	28.1975

Table 2: Points of presence used in this research. Generated on 20 June 2025.

B List of Ground Stations

Location	Country	Latitude	Longitude	Location	Country	Latitude	Longitude
Falda del Carmen (Cordoba)	Argentina	-31.5225	-64.4610	Ballinspittle	Ireland	51.6450	-8.5881
Anakie	Australia	-37.9532	144.3282	Elfordstown	Ireland	51.9532	-8.1742
Boorowa	Australia	-34.4621	148.7056	Foggia	Italy	41.4328	15.6586
Broken Hill	Australia	-31.9983	141.4411	Marsala	Italy	37.7943	12.4931
Bulla Bulling	Australia	-31.0298	120.8196	Milan	Italy	45.4750	9.0387
Cataby	Australia	-30.8483	115.6193	Milano	Italy	45.3185	9.1873
Ki Ki	Australia	-35.5717	139.8174	Akita	Japan	39.6383	140.0647
Koonwarra	Australia	-38.5181	145.9514	Hitachinaka	Japan	36.3867	140.6137
Macquarie Park	Australia	-33.7854	151.1318	Otaru	Japan	43.1732	141.2584
Merredin	Australia	-31.4948	118.2776	Yamaguchi	Japan	34.2171	131.5557
Pimba	Australia	-31.2507	136.8011	Nairobi	Kenya	-1.3291	36.8864
Sellheim	Australia	-19.9997	146.4217	Nairobi	Kenya	-1.3502	36.7503
Springbrook Creek	Australia	-30.4398	149.6839	Kaunas	Lithuania	54.8700	24.0100
Torrumbarry	Australia	-36.0253	144.5001	Petra Jaya	Malaysia	1.6065	110.3400
Warra	Australia	-26.9080	150.8916	Charcas	Mexico	23.2261	-100.9792
Willows. QLD	Australia	-23.6667	147.5025	Llano Grande	Mexico	19.2589	-99.5811
Oistins	Barbados	13.0628	-59.5376	Mazahua	Mexico	16.6096	-94.9642
Gaborone	Botswana	-24.5876	25.9114	Merida	Mexico	21.0074	-89.6439
Lobatse	Botswana	-25.2410	25.6700	Peñuelas	Mexico	21.7314	-102.2753
Aracaju	Brazil	-11.0812	-37.1467	Queretaro	Mexico	20.5735	-100.2740
Brewster	Brazil	48.1486	-119.7011	Tapachula	Mexico	14.7862	-92.3672
Fortaleza	Brazil	-3.7353	-38.4617	Krosrae	Micronesia	5.3302	163.0169
Itaboraí	Brazil	-22.6967	-42.8728	Matola	Mozambique	-25.9209	32.4149
João Câmara	Brazil	-5.5461	-35.8170	Nauru	Nauru	-0.5291	166.9177
Juazeiro do Norte	Brazil	-7.2151	-39.3367	Awarua	New-Zealand	-46.5305	168.3831
Luz	Brazil	-19.8033	-45.6811	Cleavdon	New-Zealand	-36.9897	175.0554
Manaus	Brazil	-2.9267	-59.9978	Cromwell	New-Zealand	-45.0611	169.1928
Montes Carlos	Brazil	-16.6837	-43.8333	Hinds	New-Zealand	-44.0074	171.5717
Mossoró	Brazil	-5.1570	-37.3537	Puwera	New-Zealand	-35.7935	174.3007
Nova Santa Rita	Brazil	-29.8429	-51.2845	Te Hana	New-Zealand	-36.2367	174.5121
Osasco	Brazil	-23.4905	-46.7750	Ikire	Nigeria	7.3875	4.2124
Porto Alegre	Brazil	-29.9842	-51.1209	Lekki	Nigeria	6.4495	3.5877
Presidente Prudente	Brazil	-22.1461	-51.4741	Blue City	Oman	23.7448	57.8093
Rio Negro	Brazil	-26.0886	-49.7929	Lihir	Papua New Guinea	-3.1060	152.6530
Rio de Janeiro	Brazil	-22.8110	-43.3512	Lima	Peru	-12.1480	-77.0420
Santana de Parnaíba	Brazil	-23.4564	-46.9423	Angeles	Philippines	15.1709	120.5057
Surubim	Brazil	-7.8539	-35.7801	Nueva Vizcaya (Province)	Philippines	16.4230	121.1140
Uruguaiana	Brazil	-29.7655	-56.5270	Quezon (province)	Philippines	13.9530	121.6990
Plana	Bulgaria	42.4829	23.4449	Wola Krobowska	Poland	51.8642	20.9211
Sofia	Bulgaria	42.6720	23.3840	Covilha	Portugal	40.2653	-7.4783
Stolnik	Bulgaria	42.7223	23.6167	Umm Qarn	Qatar	25.5518	51.4393
Fremont	California	37.4921	-121.9367	Kigali	Rwanda	-1.9380	30.0960
Iqualuit	Canada	63.7582	-68.5397	Singapore	Singapore	1.3976	103.8354
Kuujjuaq	Canada	58.1097	-68.3958	Ibi	Spain	38.6084	-0.6007
Marathon	Canada	48.7254	-86.3745	Lepe	Spain	37.2556	-7.2361
Sambro Creek	Canada	44.4645	-63.6131	Loeches (Madrid)	Spain	40.4010	-3.4059
Caldera	Chile	-27.0200	-70.7880	Santa Olalla	Spain	40.0254	-4.4677
Noviciado	Chile	-33.3927	-70.8833	Hoofddorp	The Netherlands	52.2908	4.6866
Puerto Montt	Chile	-41.4866	-73.0234	Muallim	Turkey	40.7888	29.5094
Puerto Saavedra	Chile	-38.8148	-73.3972	Chalfont Grove	United Kingdom	51.6155	-0.5758
Punta Arenas	Chile	-52.9397	-70.8504	Fawley	United Kingdom	50.8233	-1.3377
San Clemente	Chile	-35.5559	-71.3569	Goonhilly	United Kingdom	50.0496	-5.1814
Santa Elena	Chile	-29.9997	-71.2582	Isle of Man	United Kingdom	54.1391	-4.4973
Bogota	Colombia	4.5268	-74.2533	Morn Hill	United Kingdom	51.0602	-1.2639
Willemstad	Curaçao	12.0977	-68.9081	Atlanta	United States	33.7335	-84.4246
				Brucejack	United States	56.4658	-130.1867
Suva	Fiji	-18.1291	178.4677	Cape Canaveral	United States	28.5434	-80.6666
Villenave d'Ornon	France	44.7810	-0.5374	Elkton	United States	39.6309	-75.9097
Aerzen	Germany	52.0610	9.3282	Los Angeles	United States	33.9243	-118.3184
Frankfurt	Germany	50.3298	8.4708	San Jose	United States	37.3704	-121.9692
Accra	Ghana	5.8040	-0.0910	Thomaston	United States	32.9471	-84.2618
Pott's Junction	Guam	13.6164	144.8587	Unalaska	United States	53.8603	-166.5049
Cikarang Barat	Indonesia	-6.3063	107.0968	Virginia Beach	United States	36.7838	-76.0093
Palangka Raya	Indonesia	-2.2187	113.9254	West Jordan	United States	40.6197	-111.9861

Table 3: Ground stations used in this research. Generated on 20 June 2025.