Measuring Low-Earth-Orbit Satellite Networks

Jinwei Zhao
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University of Victoria, BC, Canada

2025/12/18

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PANDA
Parallel, Networking and Distributed Applications

About Me

Jinwei Zhao
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- Second year PhD student in the Department of Computer Science at UVic
- Obtained my MSc in Computer Science at UVic in December 2023
- Advised by Prof. Jianping Pan

- **Research interests**:
- Network measurement on Low-Earth-Orbit (LEO) satellite networks (Starlink/OneWeb)
- Networked multimedia systems, such as adaptive video streaming

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Satellite Internet Access and LEO Constellations

TELESAT

Viasat

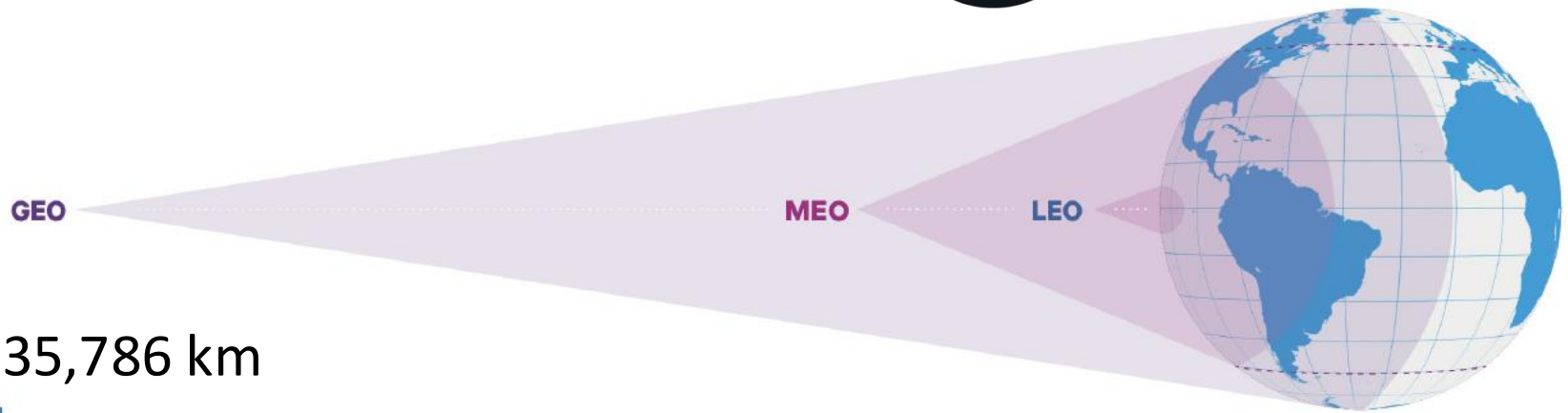
INTELSAT

STARLINK

OneWeb

O3b mPOWER

amazon LEO



35,786 km

Figure 1: Schematic of orbital altitudes and coverage areas

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TELESAT

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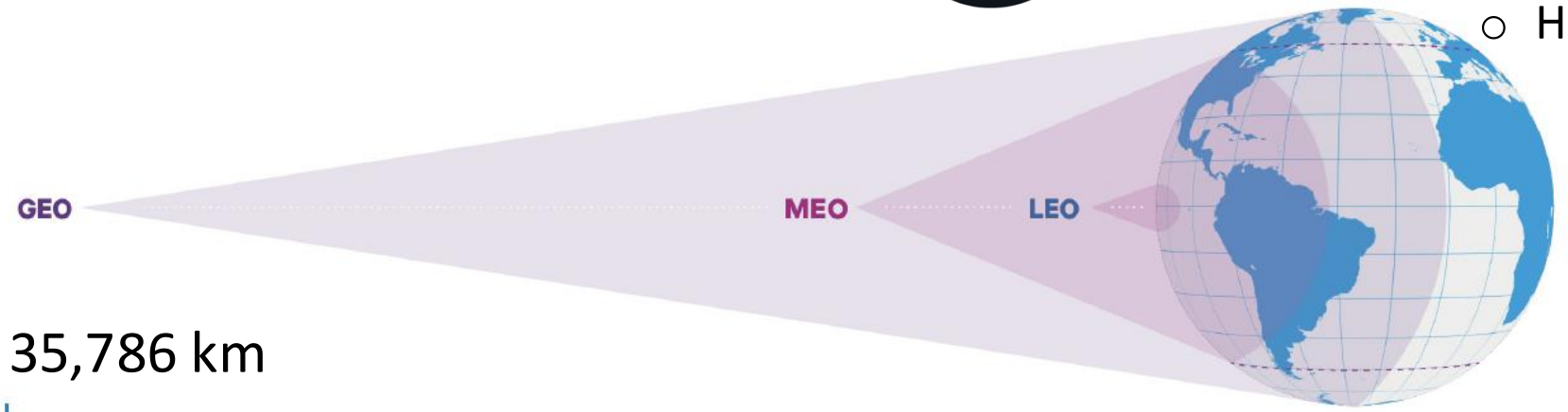

Figure 1: Schematic of orbital altitudes and coverage areas

LEO over GEO/MEO:

- Lower latency
  - GEO: 600-800 ms RTT
  - LEO: < 100 ms or even lower
- Lower launch costs
  - Expedited by reusable rockets
- Higher throughput
  - LEO operators deploy constellations of satellites, instead of a single high-throughput satellite (HTS) covering a massive service region

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LEO Satellite Network Operators

- Operated by SpaceX
- The largest LEO satellite constellation, with around 9,000 operational satellites in orbit
- Initially only targets consumer markets, now expanding to different enterprise markets
- More than 8 million users in >150 countries and regions
- Latency can be as low as 20 ms in well covered regions
- Throughput up to 400~500 Mbps downlink and ~50 Mbps uplink

- Operated by Eutelsat Group
- The second largest LEO satellite constellation, with around 650 operational satellites in orbit
- Only enterprise and government markets
- Limited ground stations
- Latency varies depending on geographic locations
- Provides guaranteed service level agreement

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LEO Satellite Network Operators

amazon LEO

- Operated by Amazon
- Previously known as Project Kuiper
- ~180 satellites as of December 2025

- Direct to AWS, private network interconnect, etc.

TELESAT LIGHTSPEED™

- By Telesat
- LEO-1 (decommissioned)
- LEO-2 (failed)
- LEO-3

- *Telesat is preparing to deploy a couple of Lightspeed pathfinders in December 2026, with 96 satellites for an initial global broadband service from low Earth orbit (LEO) set to launch the following year...*
- *https://spacenews.com/telesat-eyes-december-2026-for-lightspeed-pathfinder-debut/*

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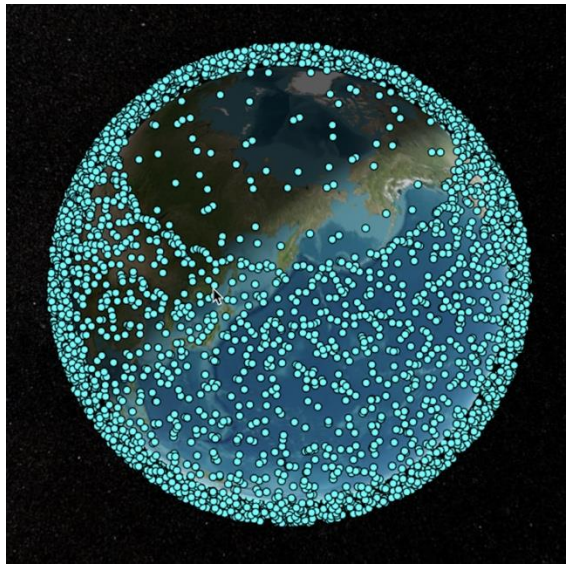
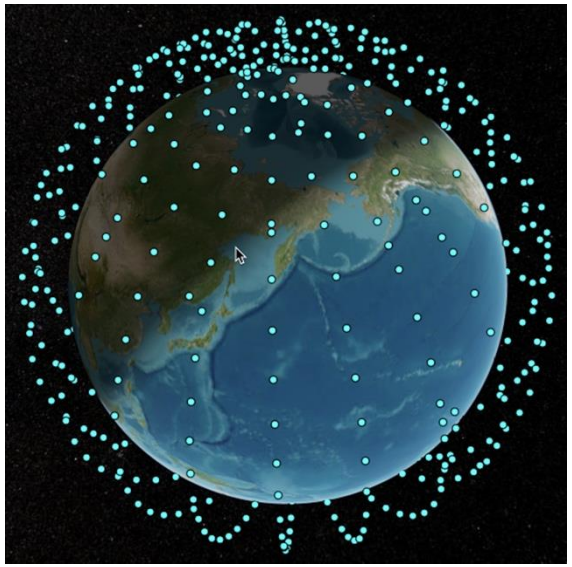
Starlink vs OneWeb Constellations





Satellites:	~9,000	~650
Altitude:	~550 km or lower	1200km
Inclination:	~53°, 70°, ~97°	~87°
ISL:	Yes	No
Infrastructure:	> 300 GS	~40 SNP

GS: Ground Station

SNP: Satellite Network Portal

Starlink

- Mostly in 53° inclination orbits at 550 km, with **i**nter-**s**atellite **l**ink (**ISL**) capabilities
- *Relatively fluctuating* RTT
  - Regular UT-Sat-GS handover every 15 seconds (12^{th}, 27^{th}, 42^{nd}, 57^{th} seconds of every minute)
  - Potential dynamic beam switching within each timeslot to avoid obstructions [1]

OneWeb

- Currently targets *enterprise and government* users
- Currently ~650 active satellites, in near polar orbits (87°) at 1200 km, no ISL capabilities
- *Relatively stable* RTT
  - No global synchronized UT-Sat-GS handover at fixed times

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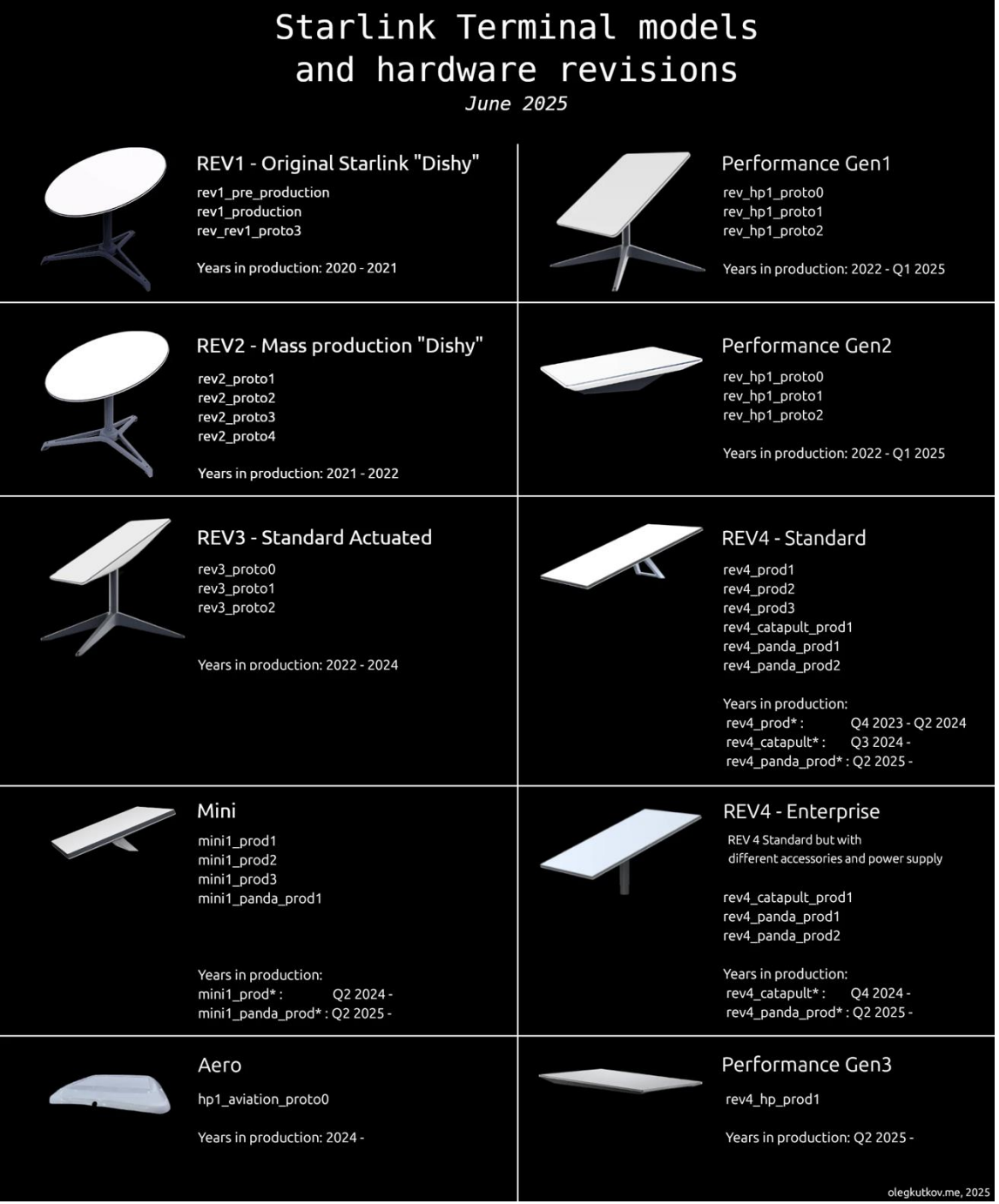
[1] https://starlink.com/updates/starlink-beam-switching



Starlink User Terminals

"In-house" production by Starlink

- Each Starlink dish exports certain limited diagnostic information via its gRPC interface at 192.168.100.1
- It does not contain connected satellite ID, antenna metrics (SNR), etc.

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[2] https://www.reddit.com/r/Starlink/comments/1l8dk5k/starlink_terminal_models_chart_june_2025_update/

OneWeb User Terminals

Hughes HL1120W

Through external collaboration with Iowa State University, we have access to an OneWeb UT in Iowa, which is Hughes HL1120W.

The Hughes OneWeb UT exposes detailed satellite tracking logs, antenna metrics, connected satellite ID, etc.

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[3] https://www.hughes.com/sites/hughes.com/files/2024-02/HL1120W_DATASHEET.pdf

OneWeb @Carleton University

Photos by Dr. Jianping Pan, 2025/09

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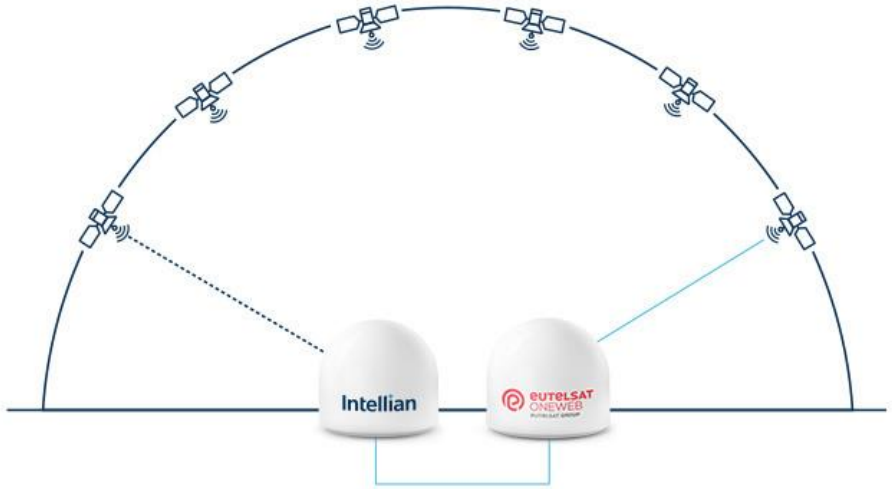
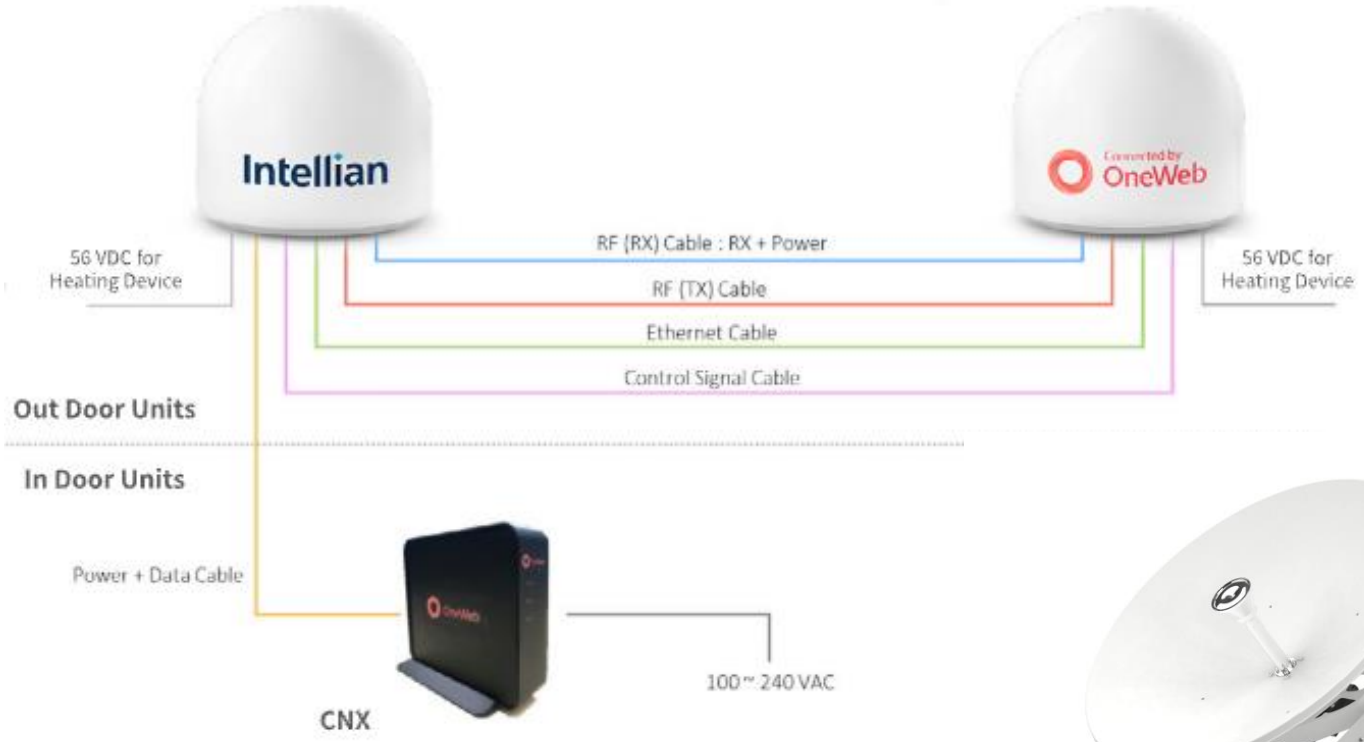
OneWeb User Terminals





Intellian OW70L

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[4] https://intelliantech.com/en/products/eutelsat-oneweb-series/ow70l

OneWeb User Terminals

Kymeta Hawk u8

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[5] https://go.kymetacorp.com/Hawk-u8-LEO-product-sheet

OneWeb User Terminals

Kymeta Hawk u8

Some vendors either encrypt satellite tracking logs, or do not export connected satellite ID directly.

Certain information, such as the azimuth and elevation of connected satellites, are still available.

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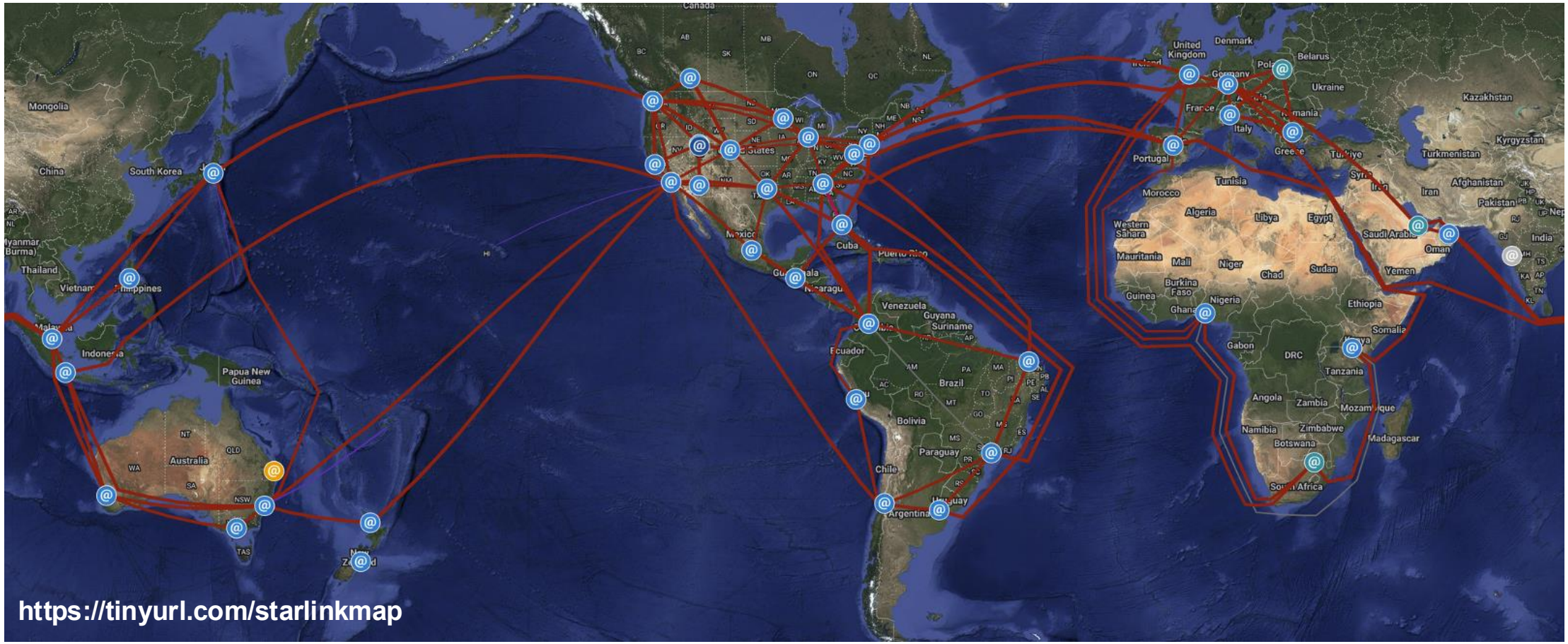
[5] https://go.kymetacorp.com/Hawk-u8-LEO-product-sheet

Identifying Starlink's Global Backbone



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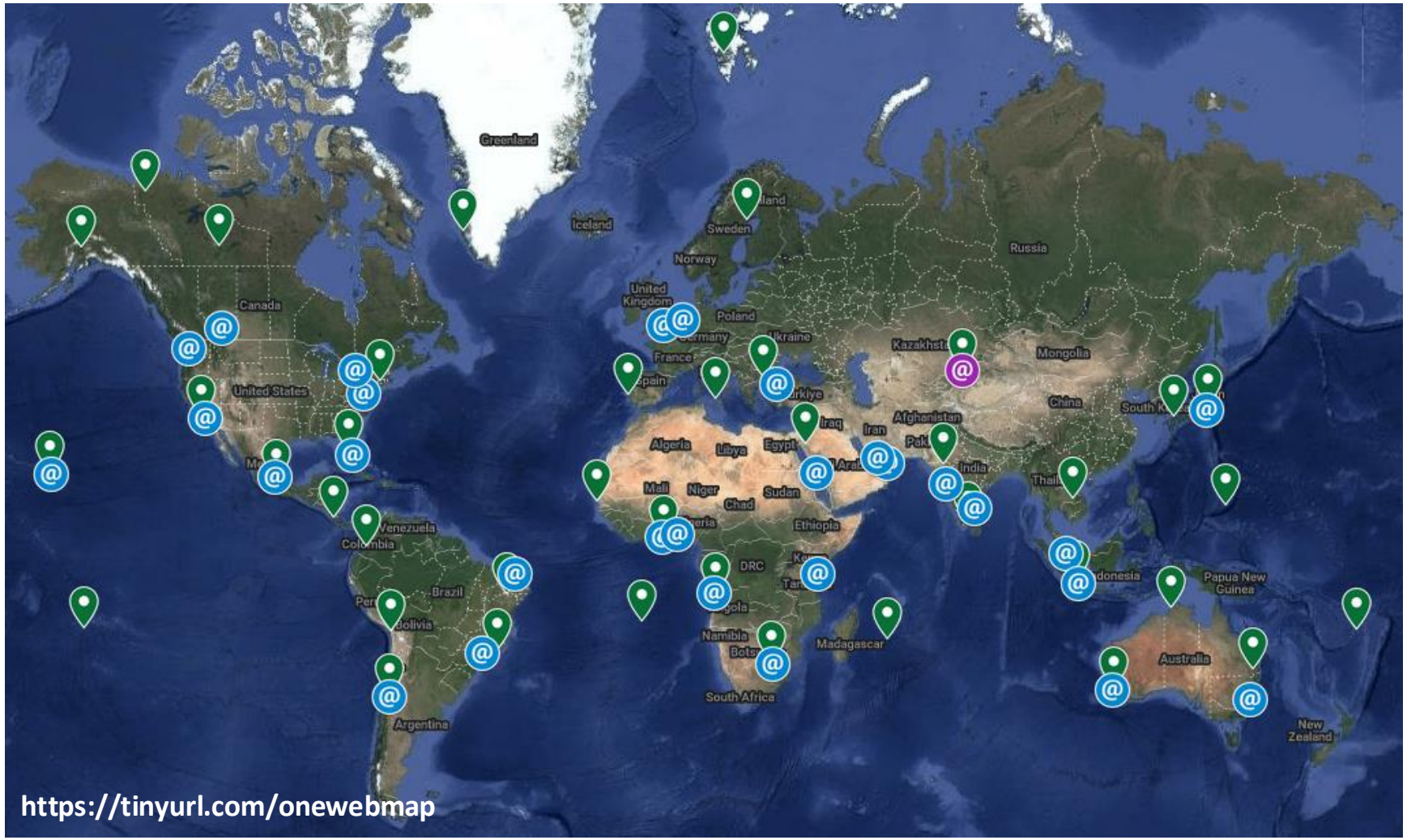
[6] Measuring a Low-Earth-Orbit Satellite Network
Jianping Pan, Jinwei Zhao, Lin Cai, (PIMRC'23), doi: 10.1109/PIMRC56721.2023.10294034

OneWeb SNPs and PoPs (May 2025)



SNPs are also known as ground stations (GSs) in Starlink's terminology

The lack of ISL capabilities on OneWeb satellites, forced them to build more SNPs in remote locations to cover more regions with the "bent-pipe" architecture.

40 SNPs and 29 PoPs worldwide as of May 2025

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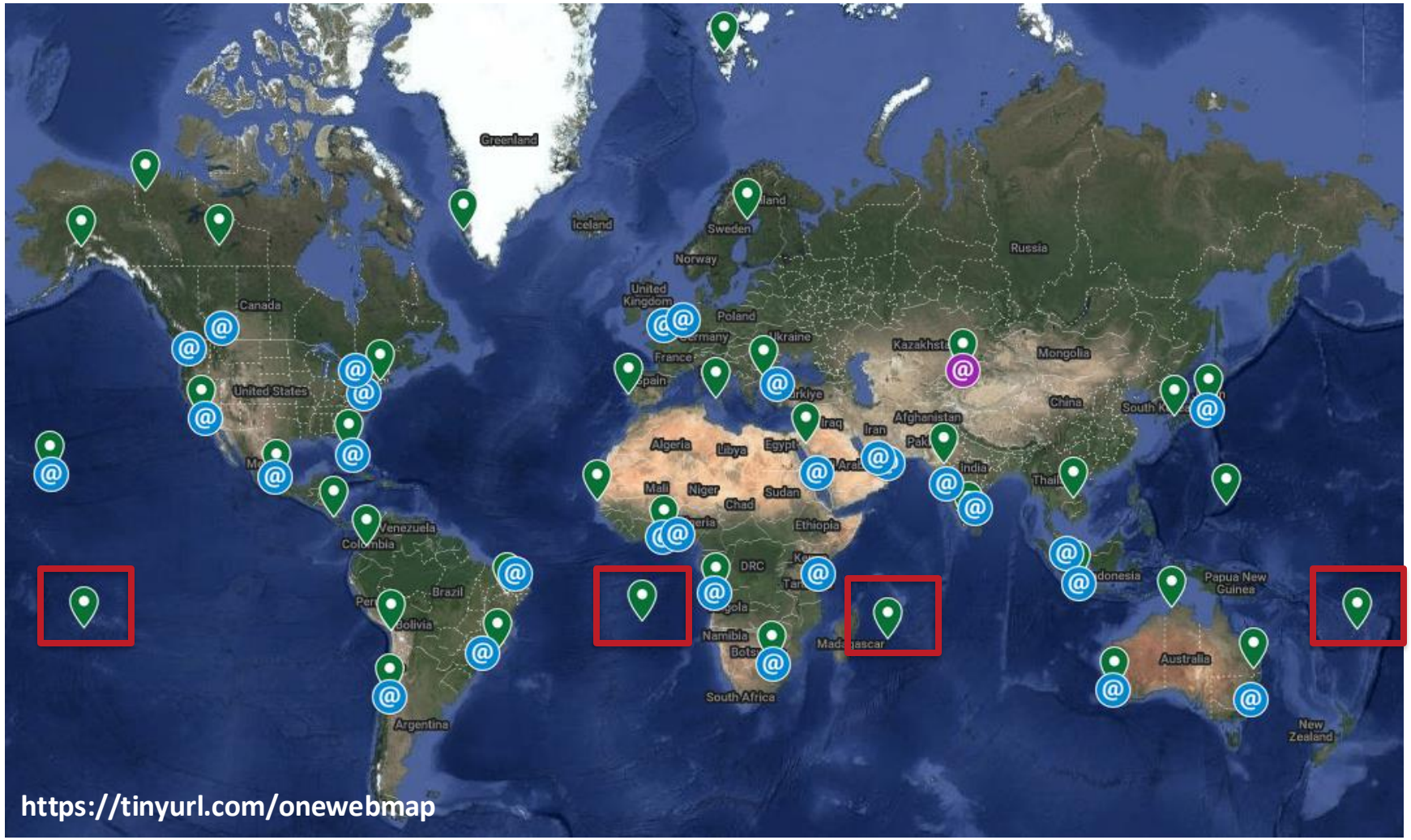
OneWeb SNPs and PoPs (May 2025)



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OneWeb SNP in Svalbard

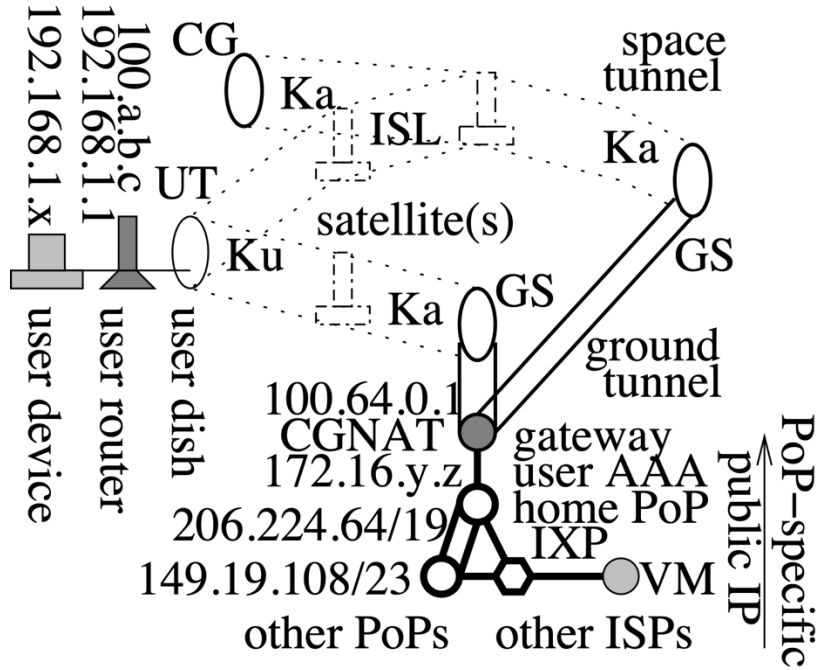
featured in the latest Mission Impossible movie

[7] https://www.linkedin.com/posts/eutelsatoneweb_did-you-spot-our-svalbard-satellite-network-activity-7320806532995047425-FZ8X

Starlink in a nutshell

- An ***outgoing*** packet's journey to the Internet (reverse for the incoming one)
  - User devices
    - 192.168.1.*x* if the default gateway is at 192.168.1.1/24
  - **User <u>router</u>** (User Terminal Router, **UTR**, provided by Starlink, can be *replaced* or *bypassed*)
    - LAN: 192.168.1.1 (by default)
    - WAN: **100.64/10** (*unique* per user dish)
  - **User dish** (Antenna, **UTA**, provided by Starlink)
    - 192.168.**100**.1 (*fixed* address as modem)
  - ***Satellite**** (inter-satellite links, **ISL**s, if possible)
  - Landing ground station (**GS**, transparent to IP)
  - **<u>CGNAT</u>** (Carrier-Grade NAT) gateway (GW)
    - **100.64.0.1** (or public IP user's gateway)
  - Home **PoP** (Point-of-Presence) entry
    - 172.16/12
  - PoP, other PoPs/ISPs, IXPs, etc: the **Internet**

1 IP hop



[8] Measuring the Satellite Links of a LEO Network, Jianping Pan, Jinwei Zhao, Lin Cai
2024 IEEE 59th International Conference on Communications (ICC'24)

Our Works

- **A Large-Scale IPv6-Based Measurement of the Starlink Network**

Accepted by IEEE INFOCOM'26

- **GeoFeed in the wild: A case study on StarlinkISP.net**

IETF IAB Workshop on IP Address Geolocation (ip-geo)

- **Measuring the OneWeb Satellite Network**

2025 Network Traffic Measurement and Analysis Conference (TMA'25)

- **Trajectory-based Serving Satellite Identification with User Terminal's Field-of-View**

2024 ACM 2nd Workshop on LEO Networking and Communication (LEO-NET'24)

- **LENS: A LEO Satellite Network Measurement Dataset**

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- **Low Latency Live Video Streaming over a Low-Earth-Orbit Satellite Network with DASH**

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https://oac.uvic.ca/leonet

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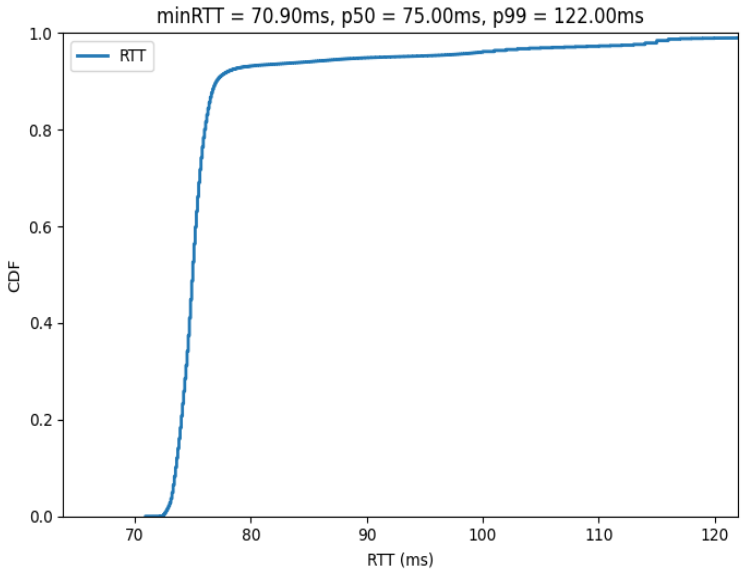
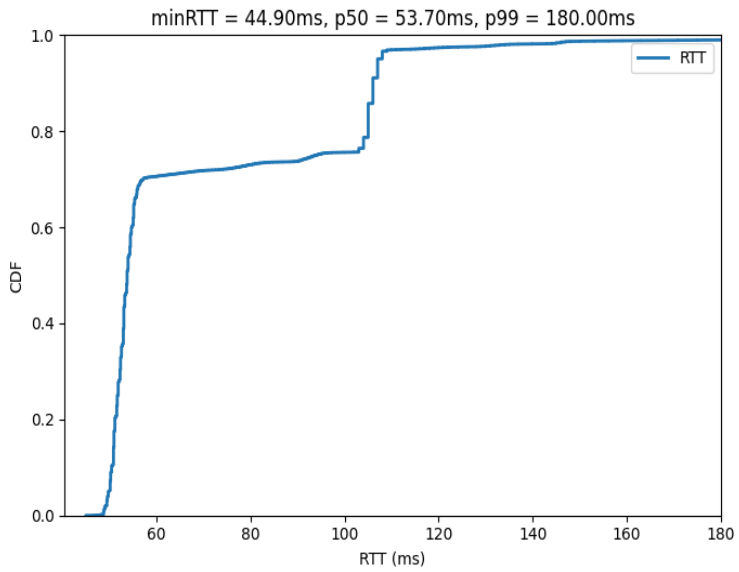
An Interesting Observation



Alaska



Iowa

We first measure the RTT from the OneWeb UT to the associated gateway at its PoP, i.e., the latency of the satellite link.

We observed an interesting bimodal pattern in the CDF of RTT from the OneWeb UT in Iowa, which is quite different from our previous observation from OneWeb UTs in Alaska.

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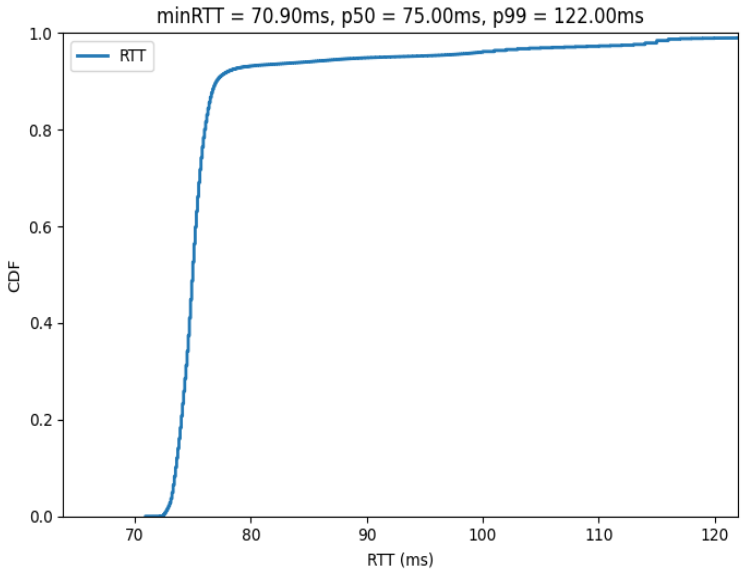
An Interesting Observation



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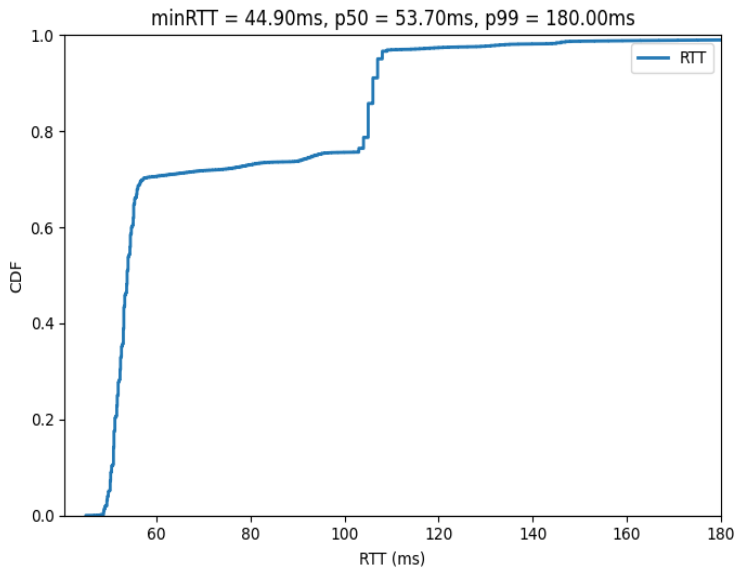

Iowa

Note:

For both OneWeb and Starlink, network packets do not exit to the Internet from landing ground stations directly.

They need to go through user's "home-PoP", for authentication, authorization and accounting (AAA) purposes. (E.g., Starlink's IPv4 CGNAT)

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We observed an interesting bimodal pattern in the CDF of RTT from the OneWeb UT in Iowa, which is quite different from our previous observation from OneWeb UTs in Alaska.

Associated PoP for both OneWeb UTs:

- Alaska UT: Seattle PoP
- Iowa UT: Ashburn PoP

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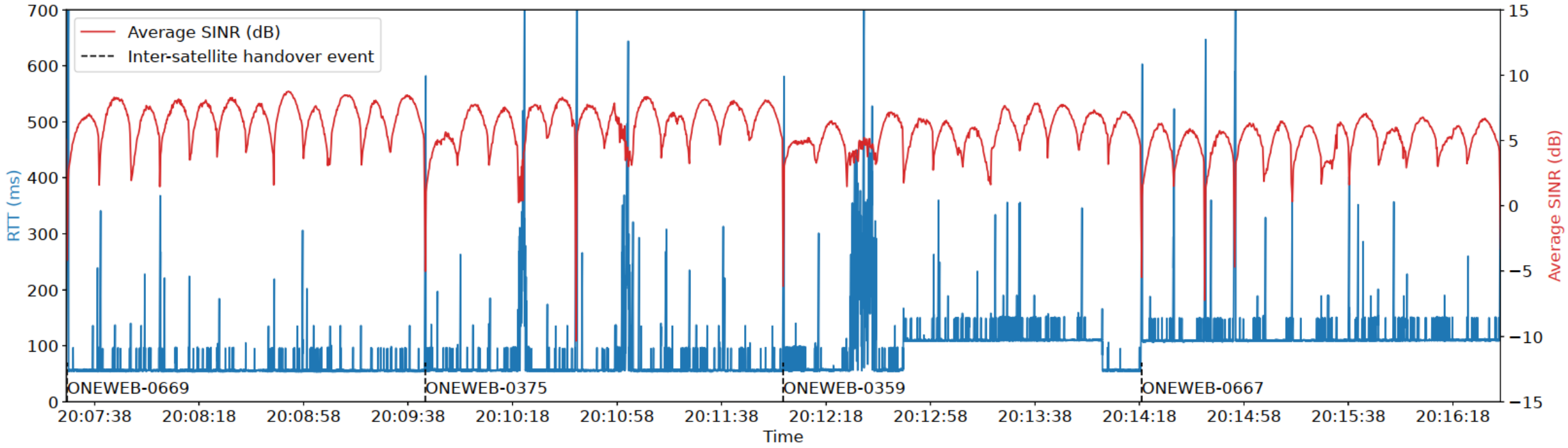
Cross-layer Measurements



1) minRTT is relatively stable across most handover events
2) Brief latency spikes occur when handover events happen
3) Deteriorated beam signal quality or anomalies affects latency performance significantly

Bimodal pattern in minRTT

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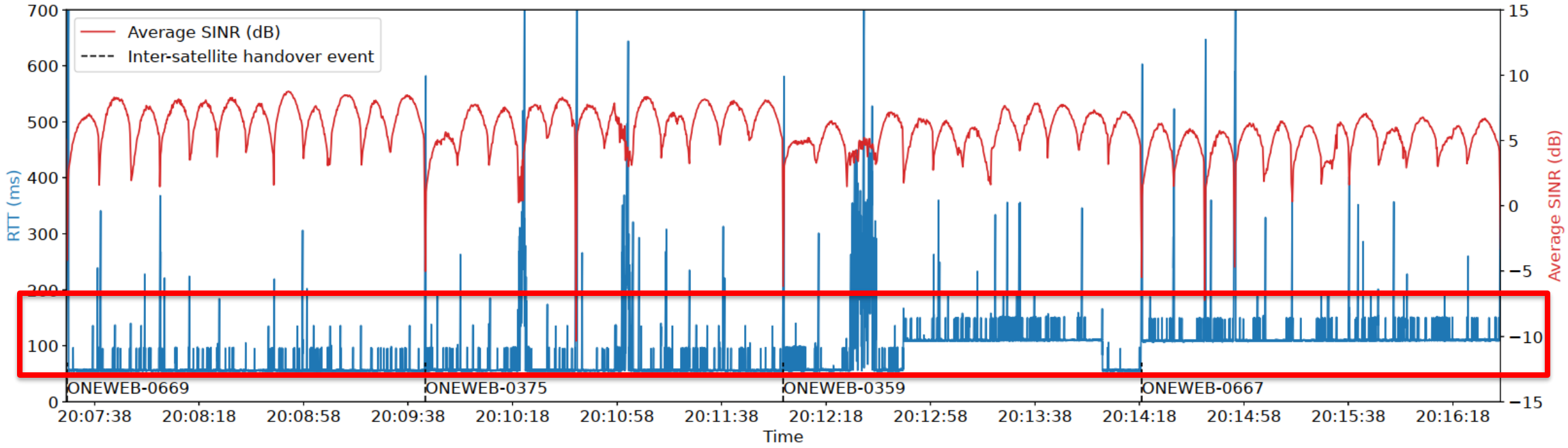
Cross-layer Measurements



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Bimodal pattern in minRTT

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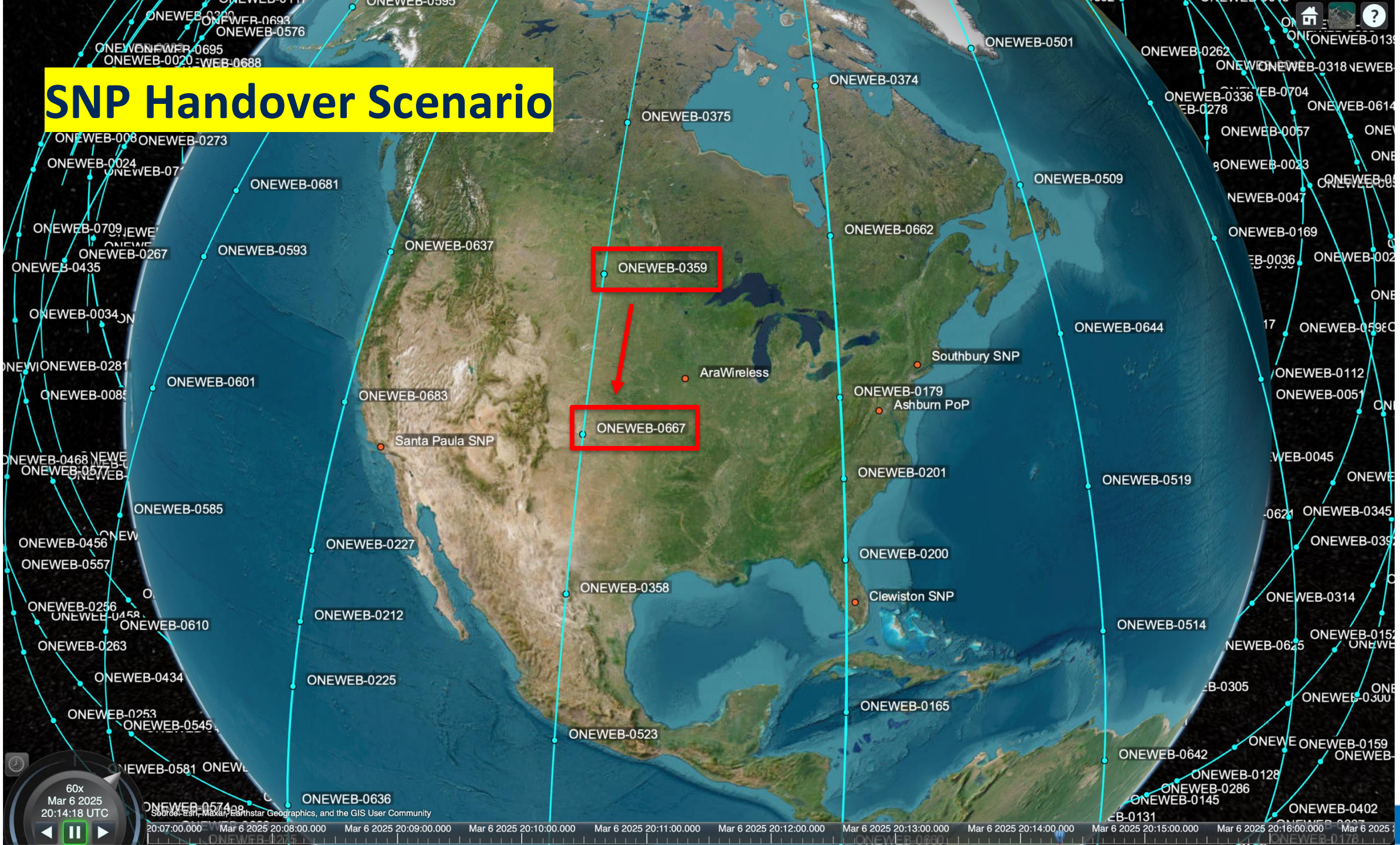
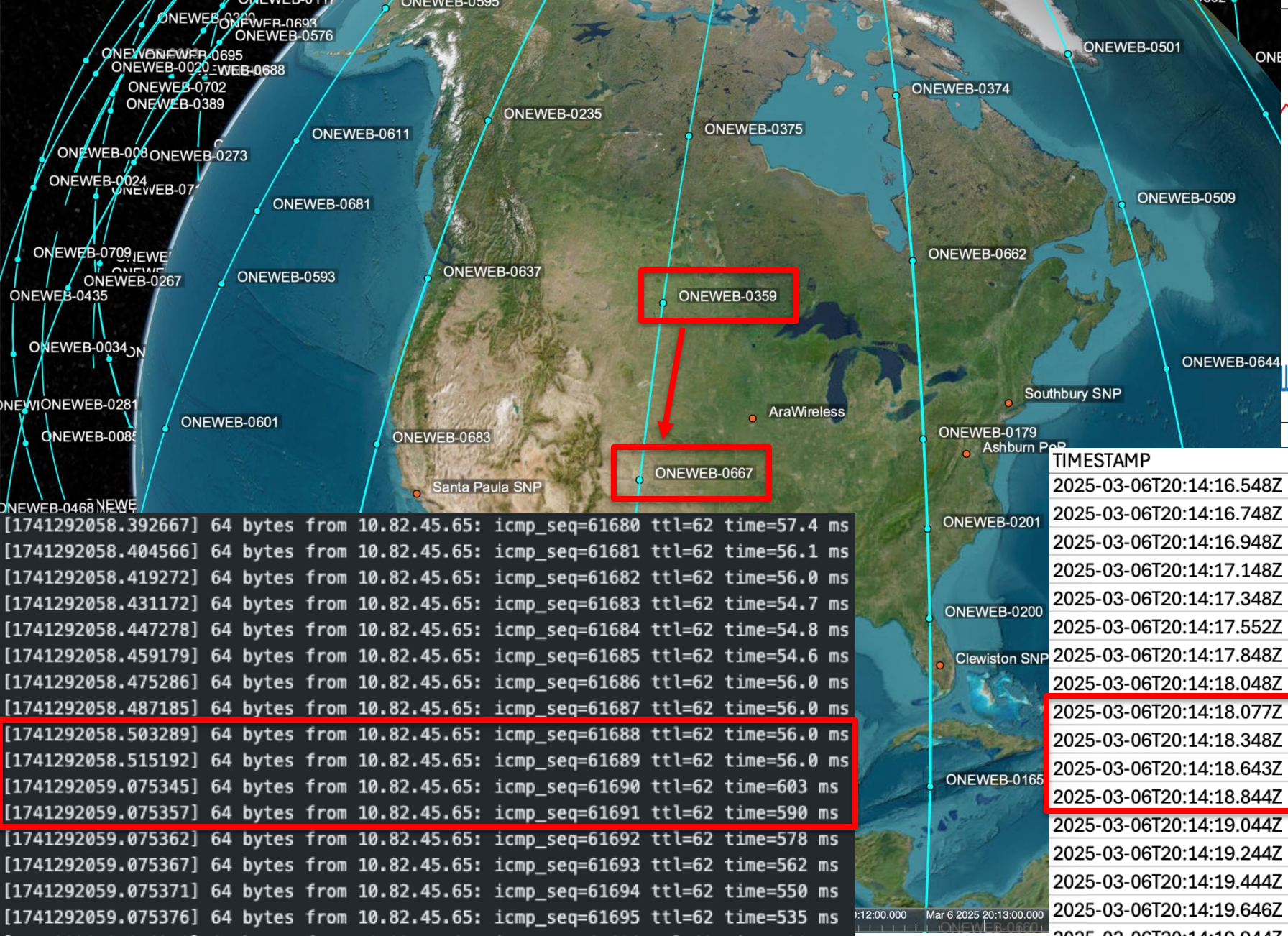
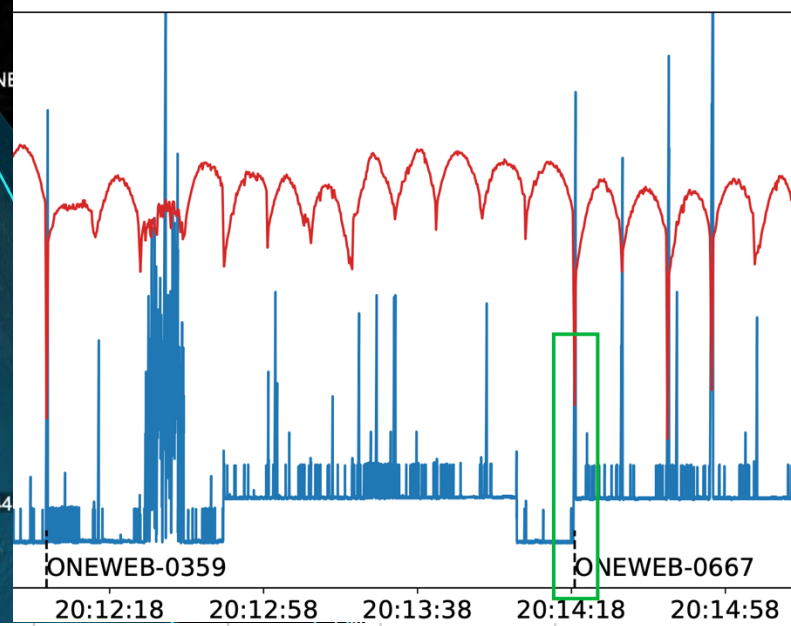

SNP Handover Scenario
ONEWEB-0359
ONEWEB-0667
Southbury SNP
AraWireless
Ashburn PoP
Santa Paula SNP
Clewiston SNP
ONEWEB-0179
ONEWEB-0683
ONEWEB-0637
ONEWEB-0593
ONEWEB-0681
ONEWEB-0601
ONEWEB-0585
ONEWEB-0227
ONEWEB-0212
ONEWEB-0225
ONEWEB-0523
ONEWEB-0636
ONEWEB-0358
ONEWEB-0200
ONEWEB-0201
ONEWEB-0165
ONEWEB-0519
ONEWEB-0514
ONEWEB-0644
ONEWEB-0662
ONEWEB-0509
ONEWEB-0501
ONEWEB-0374
ONEWEB-0375
ONEWEB-0642
60x
Mar 6 2025
20:14:18 UTC
Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community
Mar 6 2025 20:07:00.000
Mar 6 2025 20:08:00.000
Mar 6 2025 20:09:00.000
Mar 6 2025 20:10:00.000
Mar 6 2025 20:11:00.000
Mar 6 2025 20:12:00.000
Mar 6 2025 20:13:00.000
Mar 6 2025 20:14:00.000
Mar 6 2025 20:15:00.000
Mar 6 2025 20:16:00.000






```
[1741292058.392667] 64 bytes from 10.82.45.65: icmp_seq=61680 ttl=62 time=57.4 ms
[1741292058.404566] 64 bytes from 10.82.45.65: icmp_seq=61681 ttl=62 time=56.1 ms
[1741292058.419272] 64 bytes from 10.82.45.65: icmp_seq=61682 ttl=62 time=56.0 ms
[1741292058.431172] 64 bytes from 10.82.45.65: icmp_seq=61683 ttl=62 time=54.7 ms
[1741292058.447278] 64 bytes from 10.82.45.65: icmp_seq=61684 ttl=62 time=54.8 ms
[1741292058.459179] 64 bytes from 10.82.45.65: icmp_seq=61685 ttl=62 time=54.6 ms
[1741292058.475286] 64 bytes from 10.82.45.65: icmp_seq=61686 ttl=62 time=56.0 ms
[1741292058.487185] 64 bytes from 10.82.45.65: icmp_seq=61687 ttl=62 time=56.0 ms
[1741292058.503289] 64 bytes from 10.82.45.65: icmp_seq=61688 ttl=62 time=56.0 ms
[1741292058.515192] 64 bytes from 10.82.45.65: icmp_seq=61689 ttl=62 time=56.0 ms
[1741292059.075345] 64 bytes from 10.82.45.65: icmp_seq=61690 ttl=62 time=603 ms
[1741292059.075357] 64 bytes from 10.82.45.65: icmp_seq=61691 ttl=62 time=590 ms
[1741292059.075362] 64 bytes from 10.82.45.65: icmp_seq=61692 ttl=62 time=578 ms
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[1741292059.076210] 64 bytes from 10.82.45.65: icmp_seq=61696 ttl=62 time=520 ms
[1741292059.076215] 64 bytes from 10.82.45.65: icmp_seq=61697 ttl=62 time=504 ms
[1741292059.076403] 64 bytes from 10.82.45.65: icmp_seq=61698 ttl=62 time=488 ms
[1741292059.076410] 64 bytes from 10.82.45.65: icmp_seq=61699 ttl=62 time=472 ms
```
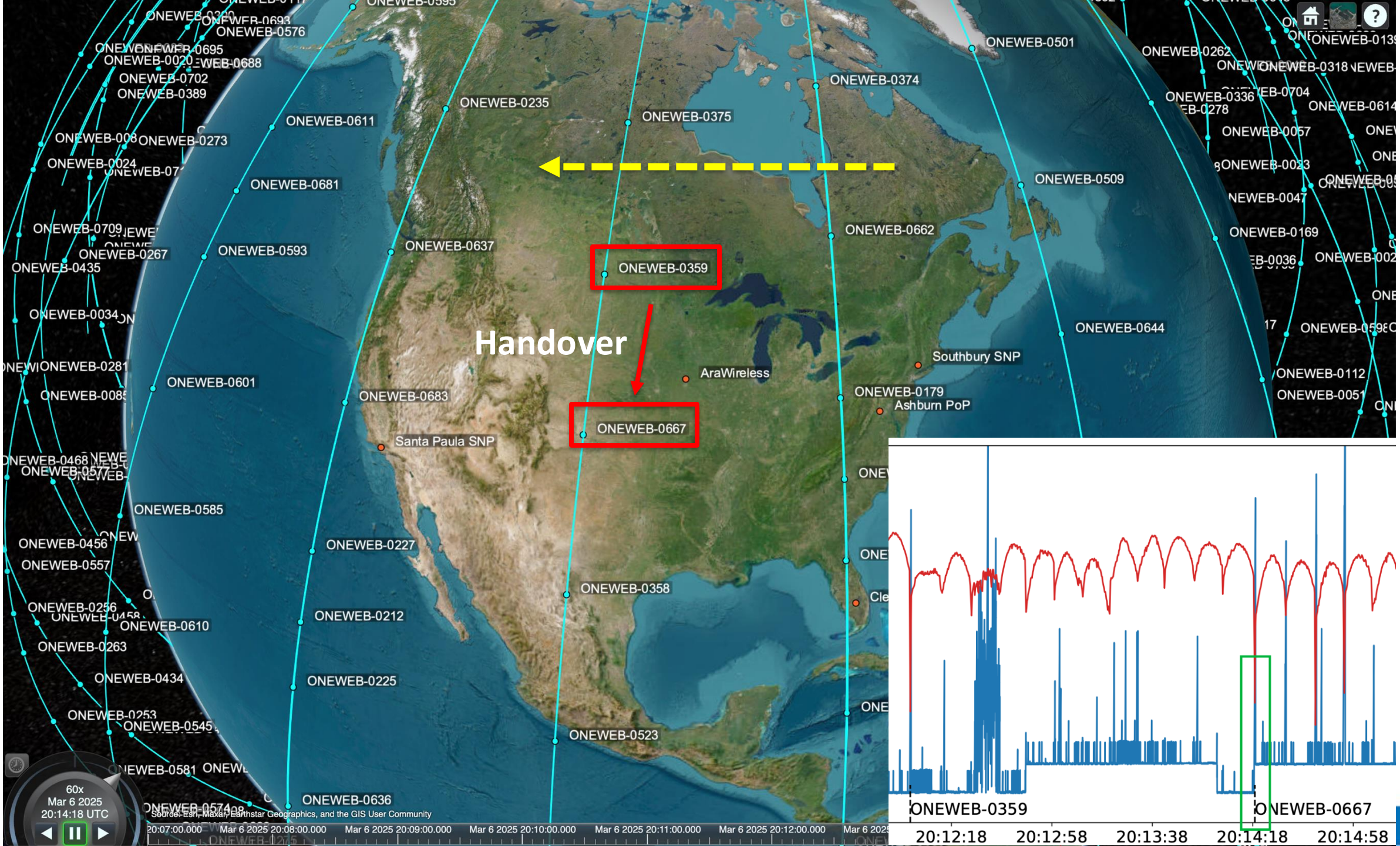
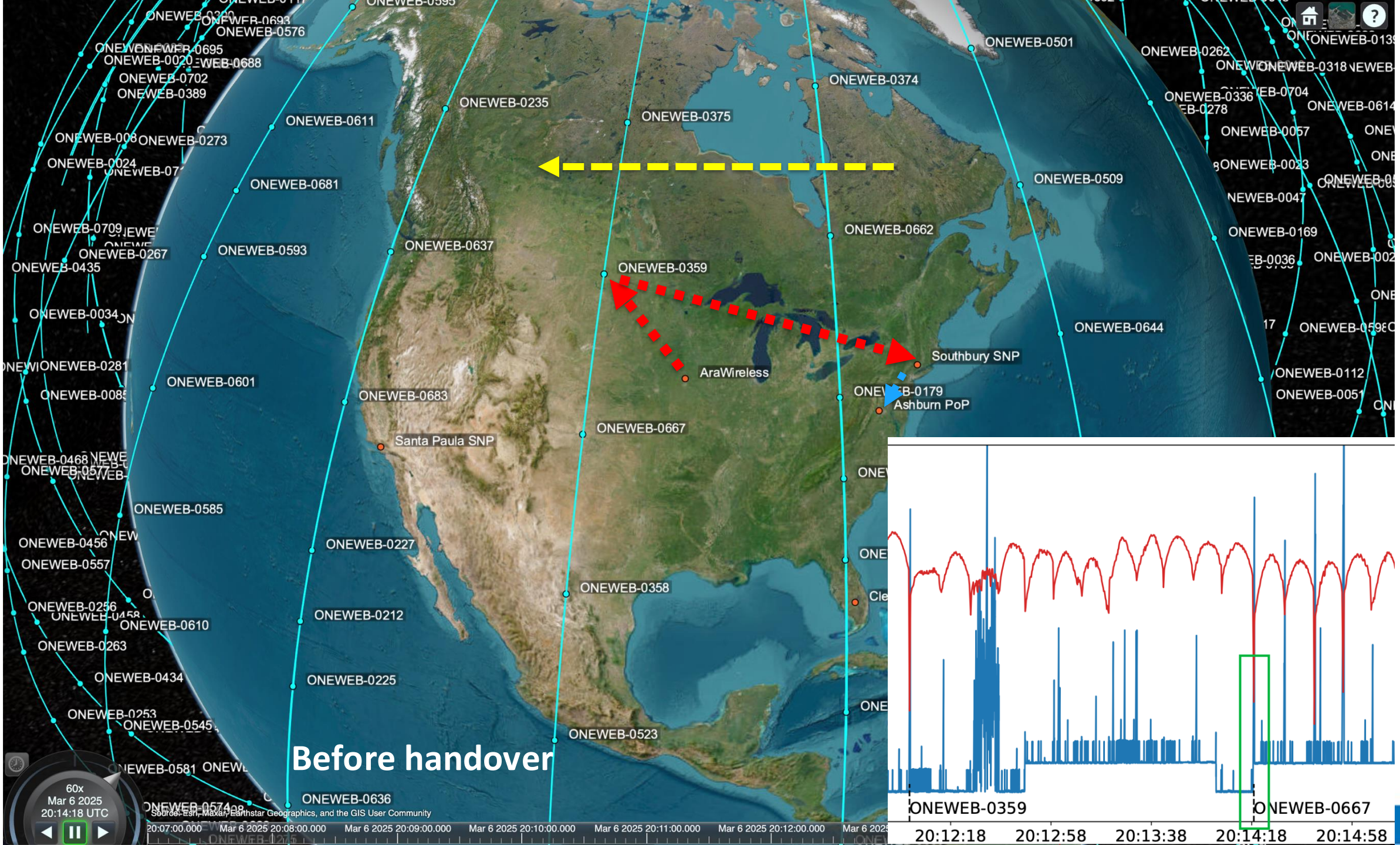
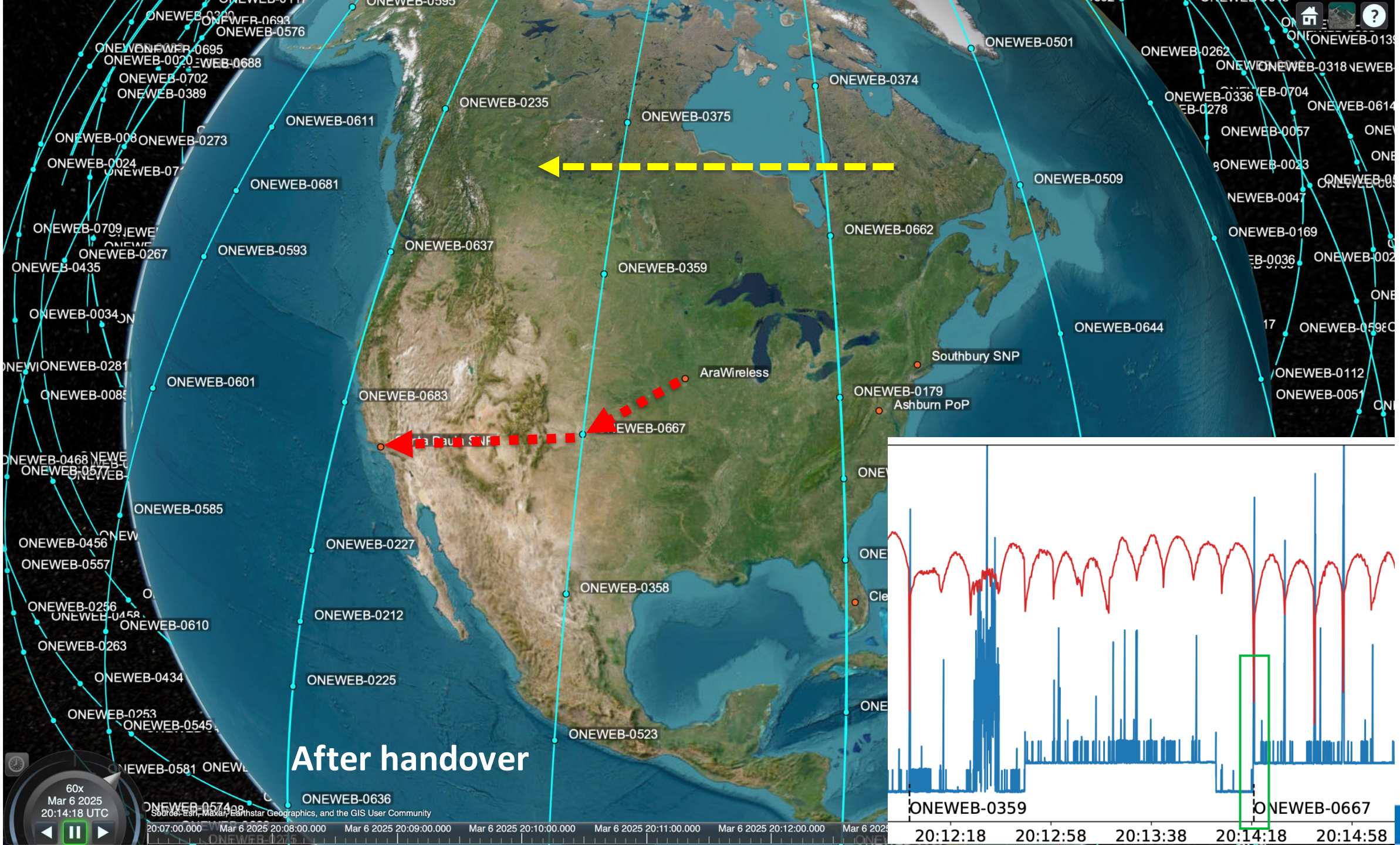

TIMESTAMP	AVERAGE_SINR	TRACK_ID	SATELLITE_ID	UT_MODEL
2025-03-06T20:14:16.548Z	5.96	390463847	359	HL1120W
2025-03-06T20:14:16.748Z	5.94	390463847	359	HL1120W
2025-03-06T20:14:16.948Z	5.79	390463847	359	HL1120W
2025-03-06T20:14:17.148Z	5.55	390463847	359	HL1120W
2025-03-06T20:14:17.348Z	5.46	390463847	359	HL1120W
2025-03-06T20:14:17.552Z	5.31	390463847	359	HL1120W
2025-03-06T20:14:17.848Z	5.15	390463847	359	HL1120W
2025-03-06T20:14:18.048Z	4.92	390463847	359	HL1120W
2025-03-06T20:14:18.077Z	4.92	390463847	359	HL1120W
2025-03-06T20:14:18.348Z	4.6	390463847	359	HL1120W
2025-03-06T20:14:18.643Z		390529691	667	HL1120W
2025-03-06T20:14:18.844Z	-5.47	390529691	667	HL1120W
2025-03-06T20:14:19.044Z	0.67	390529691	667	HL1120W
2025-03-06T20:14:19.244Z	1.6	390529691	667	HL1120W
2025-03-06T20:14:19.444Z	1.73	390529691	667	HL1120W
2025-03-06T20:14:19.646Z	2.08	390529691	667	HL1120W
2025-03-06T20:14:19.944Z	2.4	390529691	667	HL1120W
2025-03-06T20:14:20.144Z	2.69	390529691	667	HL1120W
2025-03-06T20:14:20.444Z	3.07	390529691	667	HL1120W
2025-03-06T20:14:20.644Z	3.26	390529691	667	HL1120W


ONEWEB-0359
Handover
ONEWEB-0667
ONEWEB-0501
ONEWEB-0374
ONEWEB-0235
ONEWEB-0375
ONEWEB-0611
ONEWEB-0681
ONEWEB-0509
ONEWEB-0662
ONEWEB-0637
ONEWEB-0593
ONEWEB-0644
ONEWEB-0601
ONEWEB-0683
ONEWEB-0585
ONEWEB-0227
ONEWEB-0358
ONEWEB-0212
ONEWEB-0610
ONEWEB-0225
ONEWEB-0523
ONEWEB-0636
Southbury SNP
AraWireless
ONEWEB-0179
Ashburn PoP
Santa Paula SNP
ONEWEB-0112
ONEWEB-0051
ONEWEB-0359
ONEWEB-0667
20:12:18
20:12:58
20:13:38
20:14:18
20:14:58
60x
Mar 6 2025
20:14:18 UTC
Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community
Mar 6 2025 20:08:00.000
Mar 6 2025 20:09:00.000
Mar 6 2025 20:10:00.000
Mar 6 2025 20:11:00.000
Mar 6 2025 20:12:00.000


ONEWEB-0359
Southbury SNP
AraWireless
Ashburn PoP
Santa Paula SNP
Before handover
ONEWEB-0359
ONEWEB-0667
20:12:18
20:12:58
20:13:38
20:14:18
20:14:58
60x
Mar 6 2025
20:14:18 UTC
Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community


ONEWEB-0501
ONEWEB-0374
ONEWEB-0235
ONEWEB-0375
ONEWEB-0611
ONEWEB-0273
ONEWEB-0681
ONEWEB-0509
ONEWEB-0662
ONEWEB-0637
ONEWEB-0593
ONEWEB-0359
ONEWEB-0644
Southbury SNP
AraWireless
ONEWEB-0601
ONEWEB-0683
ONEWEB-0179
Ashburn PoP
ONEWEB-0667
ONEWEB-0585
ONEWEB-0227
ONEWEB-0358
ONEWEB-0212
ONEWEB-0610
ONEWEB-0225
ONEWEB-0523
ONEWEB-0636
After handover
ONEWEB-0359
ONEWEB-0667
20:12:18
20:12:58
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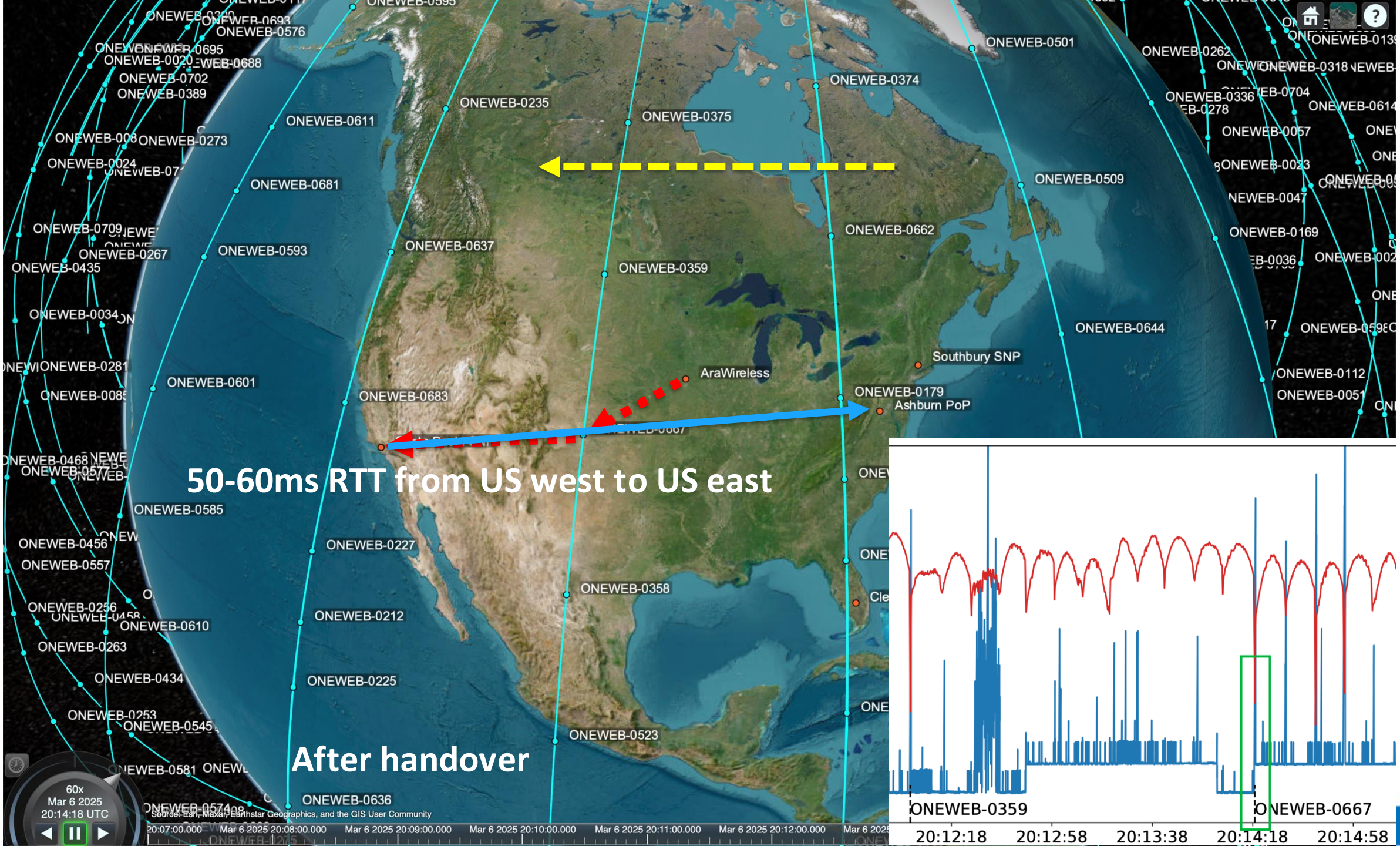
50-60ms RTT from US west to US east
After handover
AraWireless
Southbury SNP
Ashburn PoP
ONEWEB-0179
ONEWEB-0683
ONEWEB-0359
ONEWEB-0637
ONEWEB-0662
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20:14:18
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60x
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20:14:18 UTC
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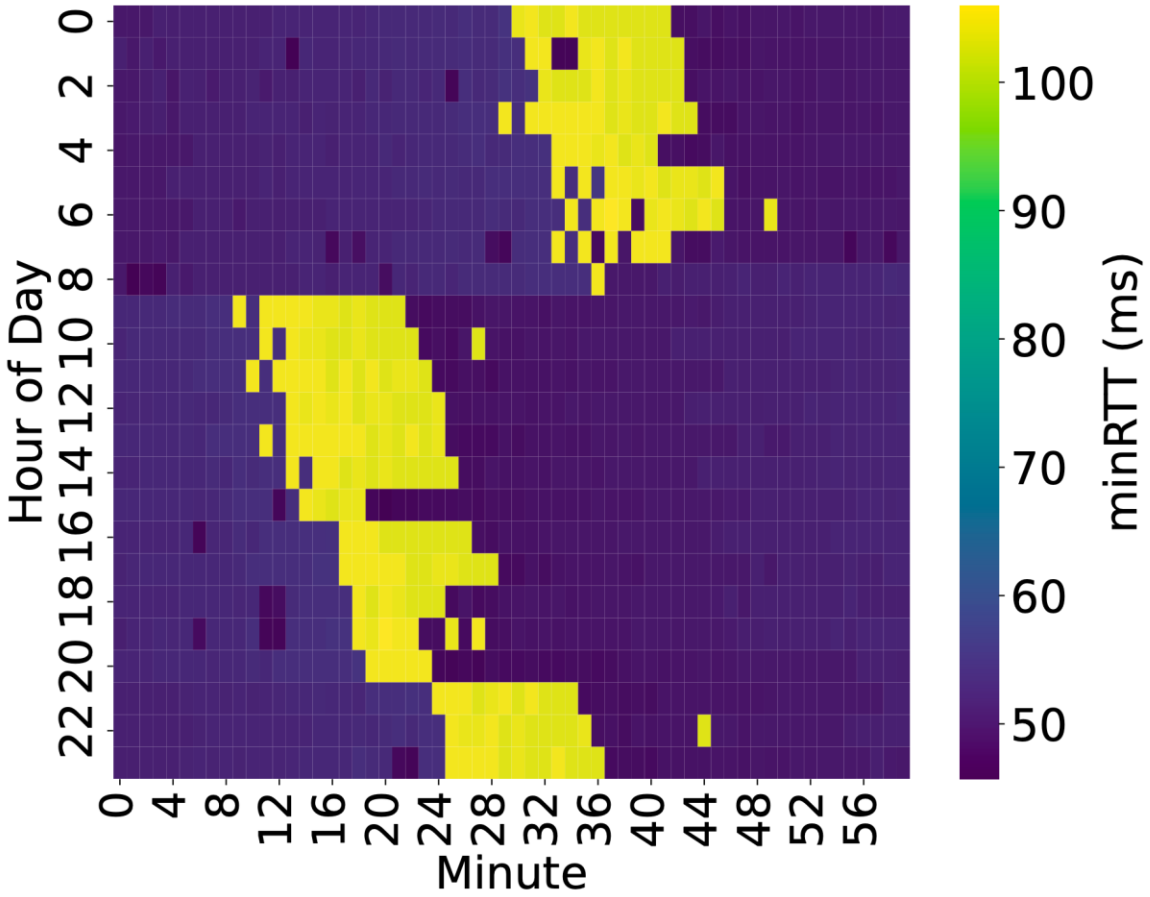
Cross-layer Measurements



Takeaways:

- SNP handovers happen due to the unique location of the dish, as well as the lack of ISLs on OneWeb satellites
- Periodic SNP handover due to regular orbital movements
- Beam/satellite handover introduces latency spikes
- Possible transport/application layer adjustment for applications with strict latency requirements
  - SD-WAN/Bonding/Multipath: Intelligent packet scheduling with LEO awareness

The heatmap shows resampled minRTT by every minute in one day

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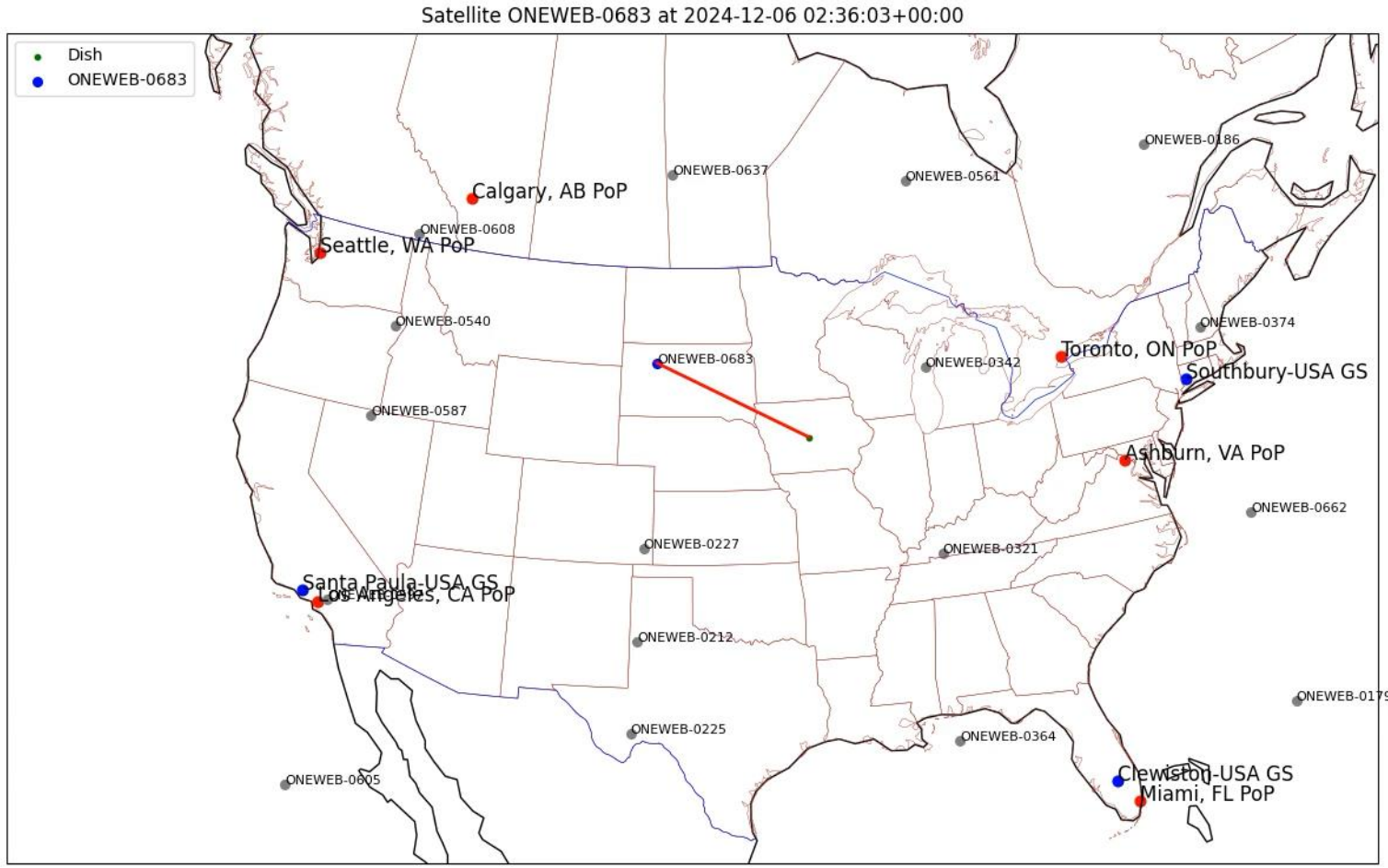
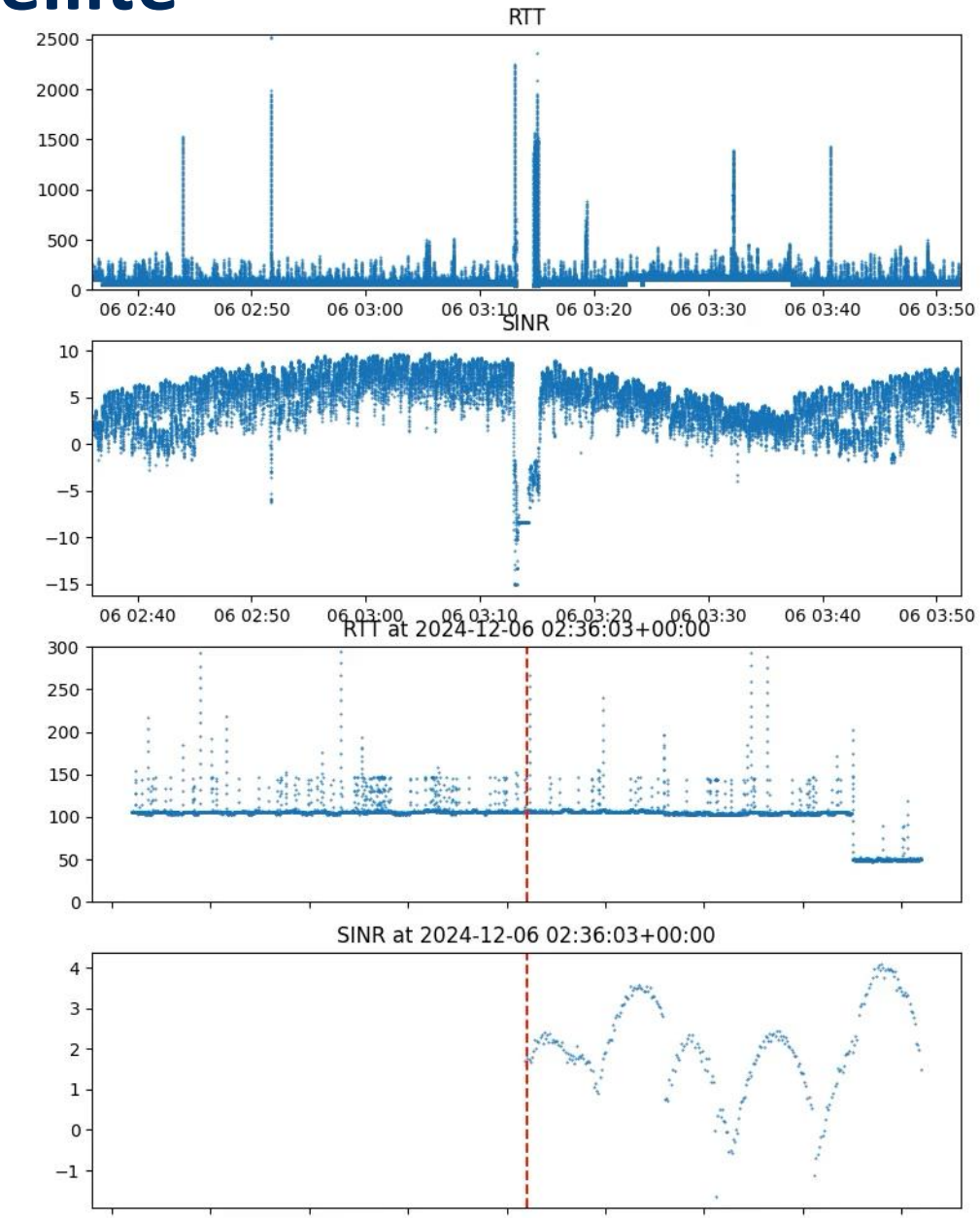
OneWeb latency, SNR, connected satellite





[Video]

Impact

- Invited to contribute guest blog posts to
  - Internet Society Pulse blog

  https://pulse.internetsociety.org/blog/measuring-the-oneweb-satellite-network
  - APNIC (Asia Pacific Network Information Centre) blog

  https://blog.apnic.net/2025/09/10/measuring-the-oneweb-satellite-network/
- Also featured in the German computer magazine c't – Magazin für Computertechnik

  https://www.heise.de/select/ct/2025/22/2527210020568160374

- Approached by some satellite network operators such as Intelsat S.A. (Now SES)

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https://oac.uvic.ca/leonet

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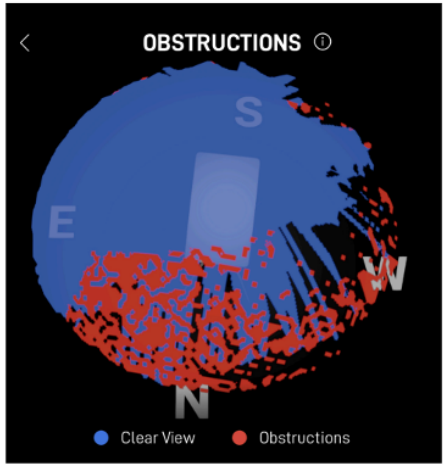
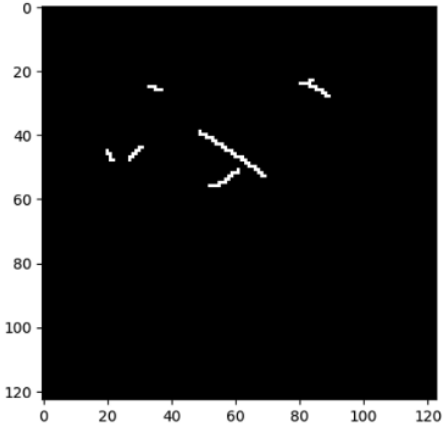
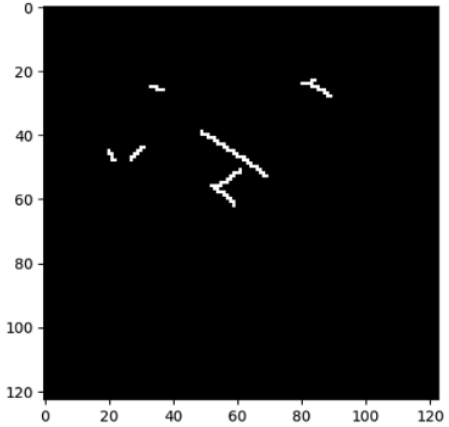
Satellite obstruction map



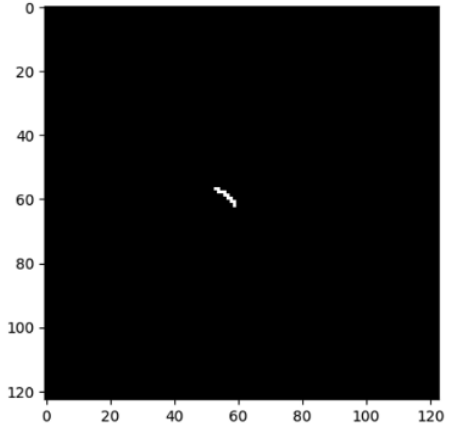
(a) Starlink app.



(b) gRPC($x-1$)



(c) gRPC(x)



(d) gRPC($x-1$) $\oplus$ gRPC(x)

Obstruction free

obstruction by trees

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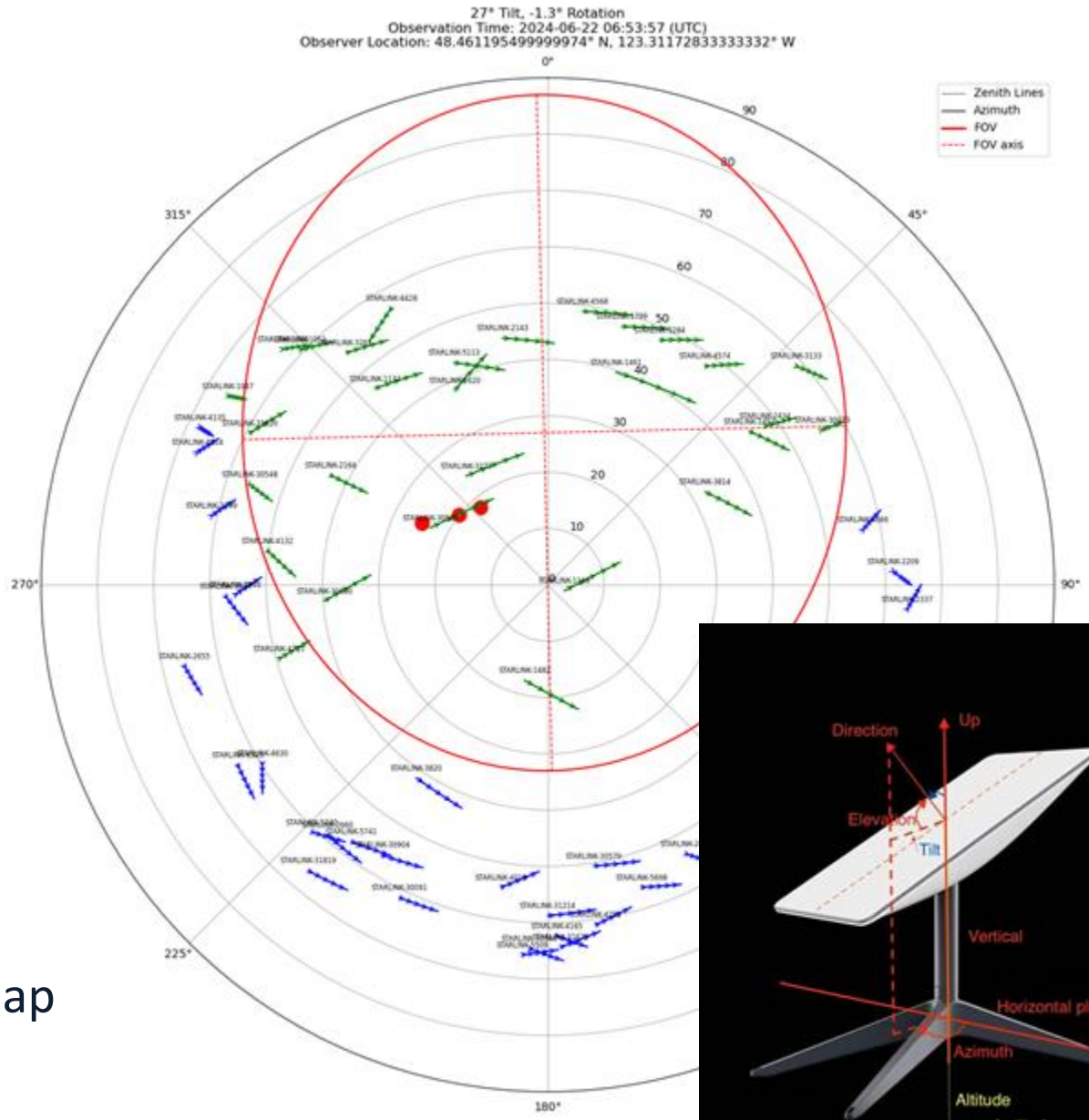
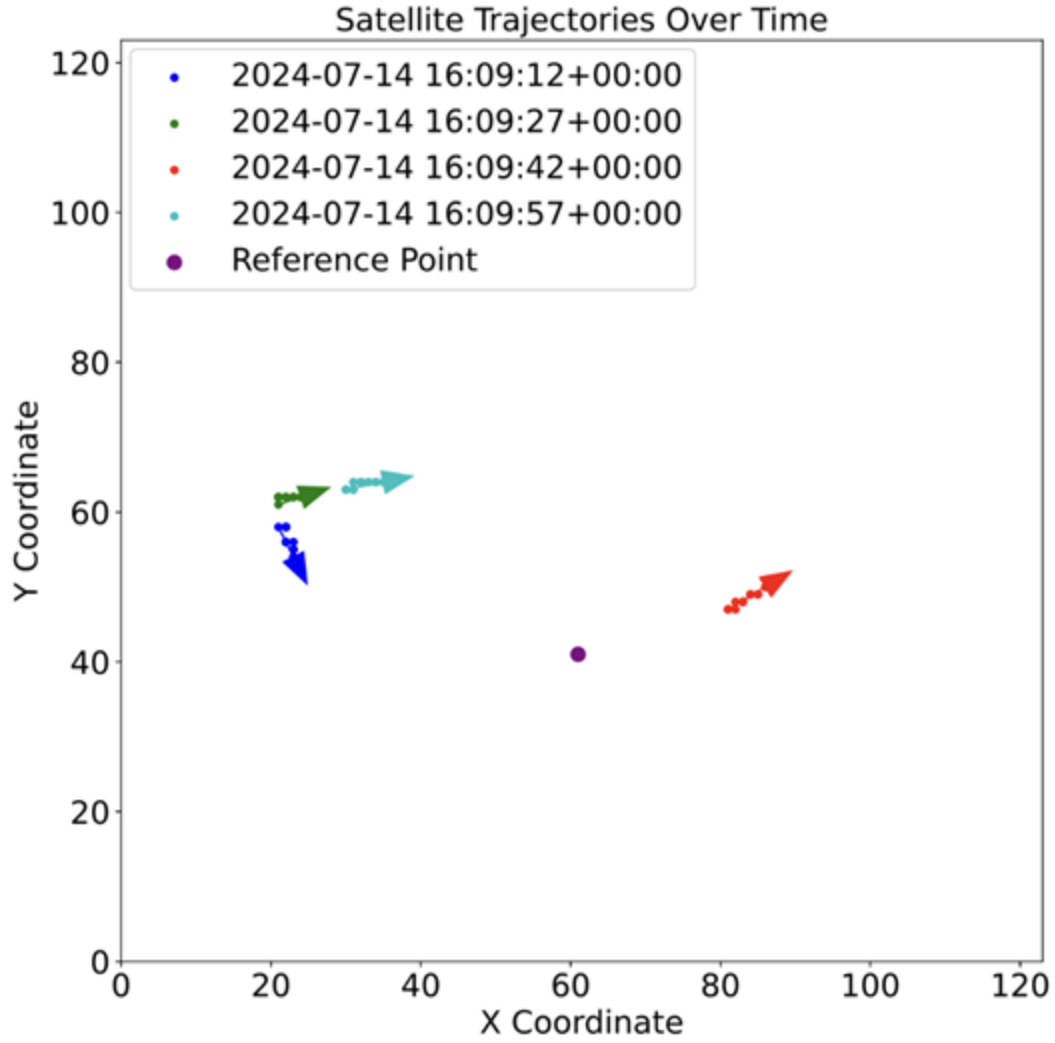
[9] https://dl.acm.org/doi/10.1145/3624354.3630586

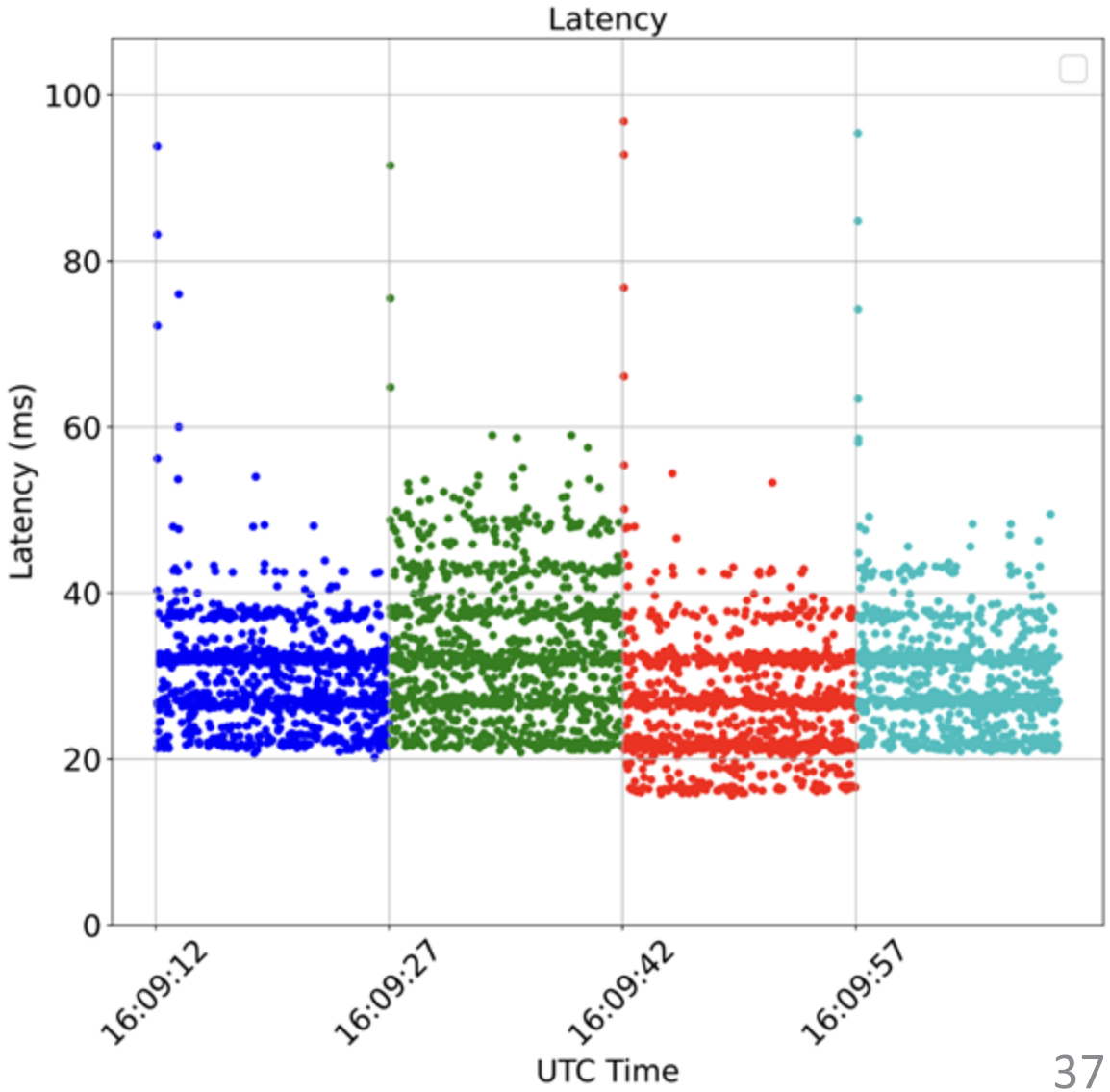
Starlink satellite identification

- **Starlink gRPC used to export**
  - Satellite ID
  - Cell ID
  - Gateway ID
- **No longer anymore**
  - For whatever reason
- **Identification is very important**
  - For research purposes
    - TLE data from CelesTrak.org
    - Dish GPS location
    - Dish orientation data
    - Dish "obstruction" map
  - Correlation between TLE data and dish map
    - With trajectory taken into account



Satellite handover and link latency performance



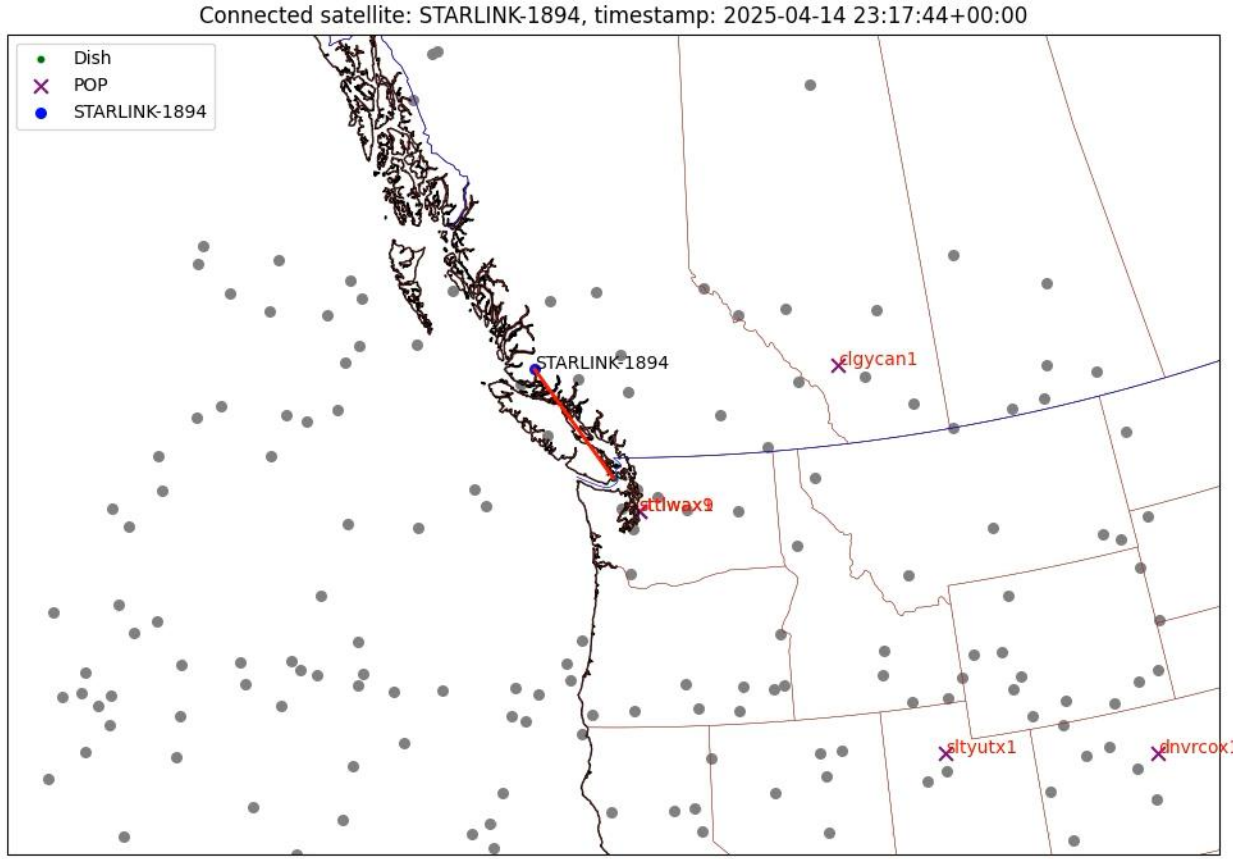


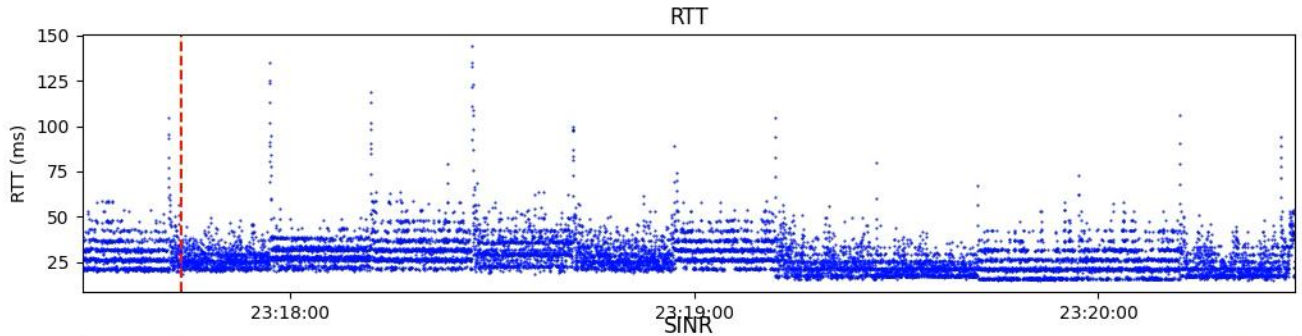
[10] https://dl.acm.org/doi/10.1145/3697253.3697266

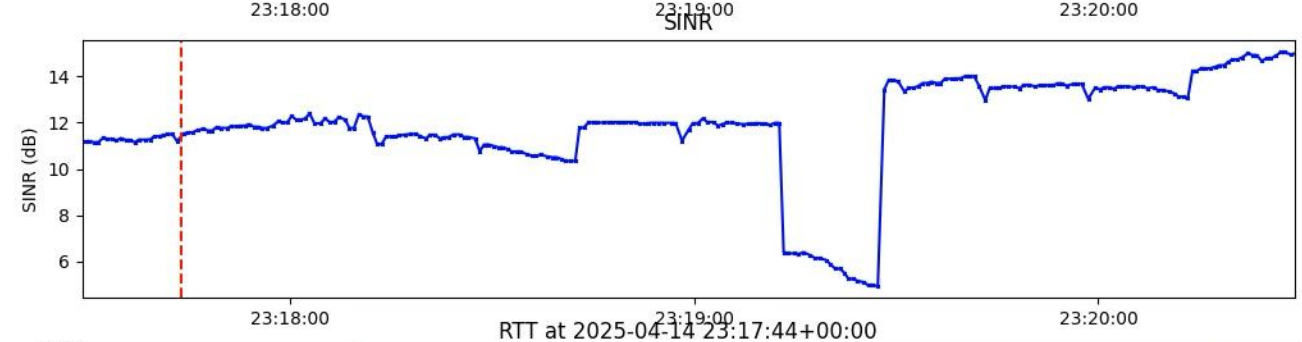
Starlink used to export SNR too

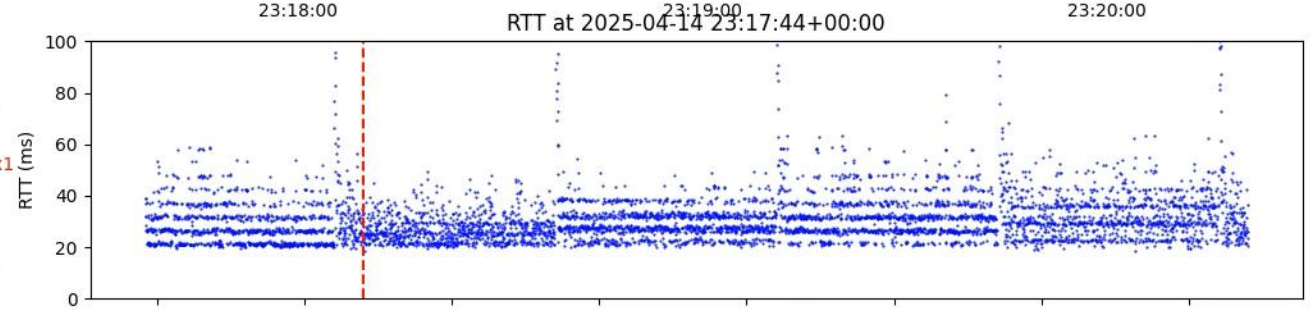
[11] https://github.com/clarkzjw/LEOViz

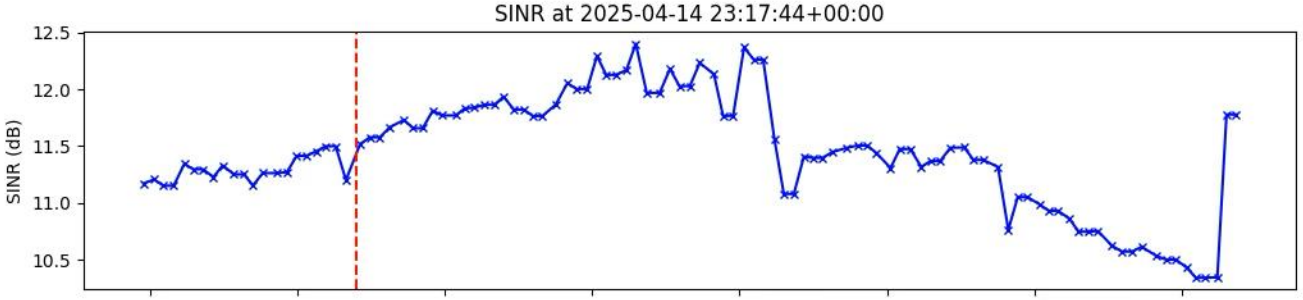
** New version that supports dish mobility to be released very soon*



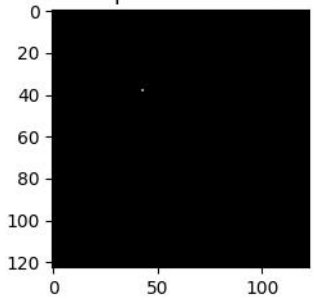








Instantaneous gRPC obstruction map in current timeslot, frame type: FRAME_EARTH



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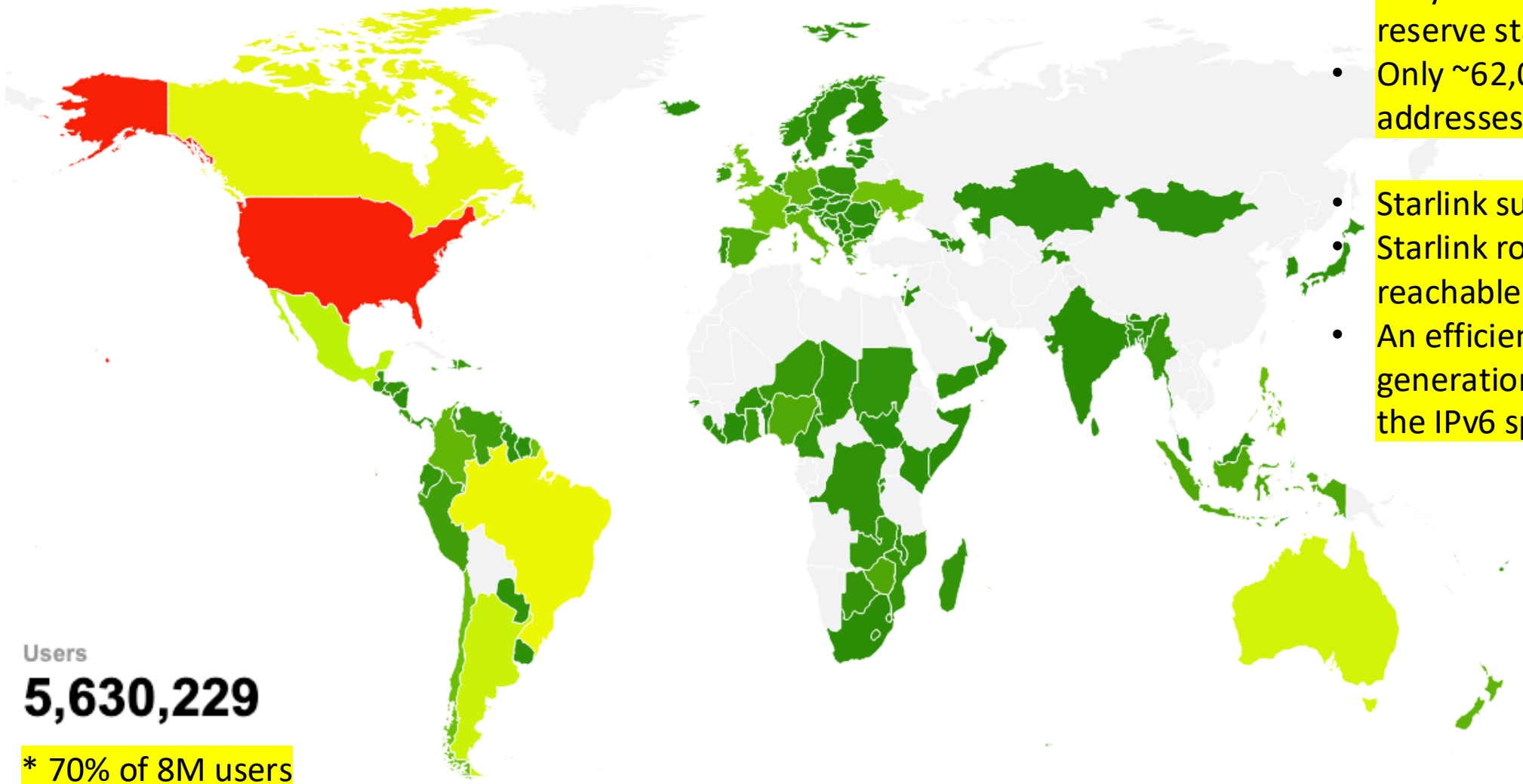
Reaching more users for "outside-in" measurement



* 70% of 8M users

- Only Starlink business users can reserve static IPv4 addresses
- Only ~62,000 reachable IPv4 addresses as of December 2025

- Starlink supports native IPv6
- Starlink router's IPv6 address is reachable from the Internet
- An efficient IPv6 target generation algorithm to scan the IPv6 space

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[12] https://arxiv.org/pdf/2412.18243 (To appear in INFOCOM'26)

Starlink on School Buses

Starlink on School Buses

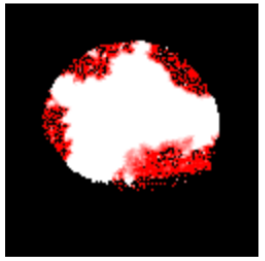
Starlink on School Buses

Coast-to-Coast-to-Coast LEO Testbed

https://oac.uvic.ca/cccleo

Our Global Starlink Dataset

https://github.com/clarkzjw/LENS

victoria_active_1	victoria_active_2	victoria_inactive
		
vancouver	seattle	seattle_hp
		
alaska	ottawa	iowa
		

denver	dallas	louvain
		
seychelles	kanazawa	brisbane
		

Continuous measurements since 2023/11 and monthly snapshots are regularly released.

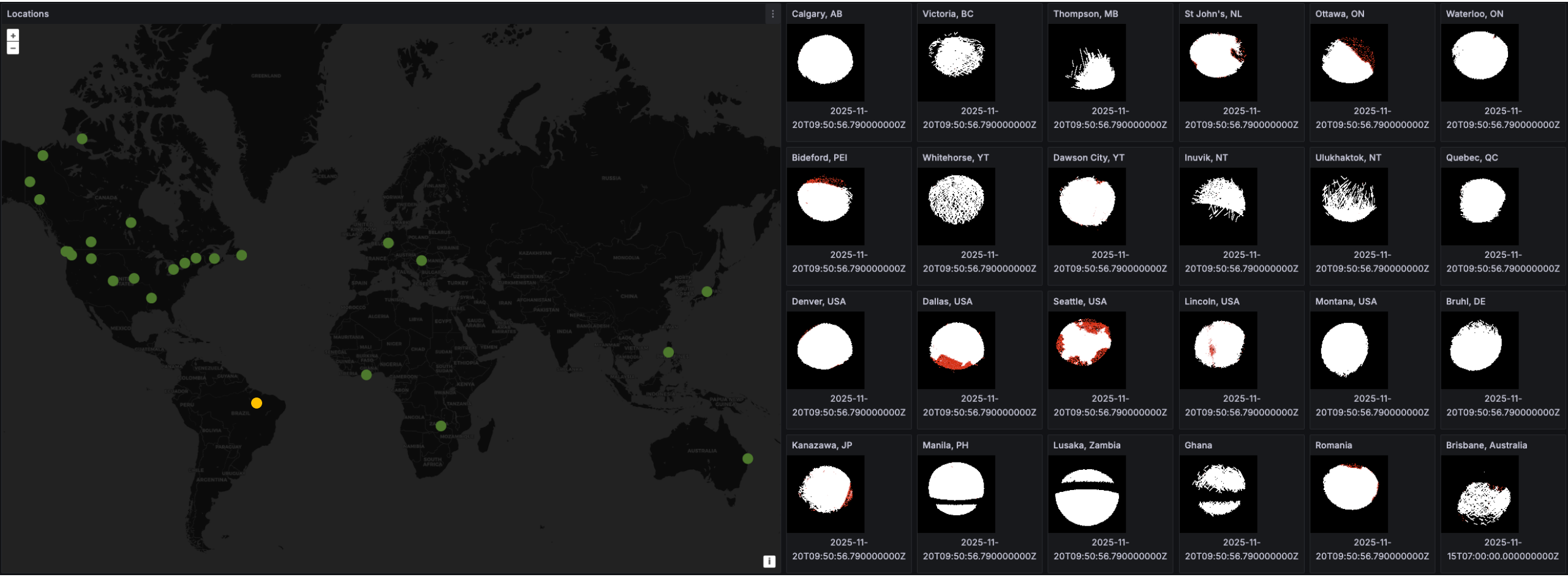
Our datasets on Zenodo.org have been downloaded over 6500 times in total, and the number continues to grow.

https://lens-starlink.jinwei.me

University of Victoria

[13] LENS: A LEO Satellite Network Measurement Dataset. Jinwei Zhao, Jianping Pan. 2024 ACM 15th Multimedia Systems Conference (MMSys'24)

Our Global Starlink Testbed



- With > 30 Starlink UTs in six continent (except Antarctica)

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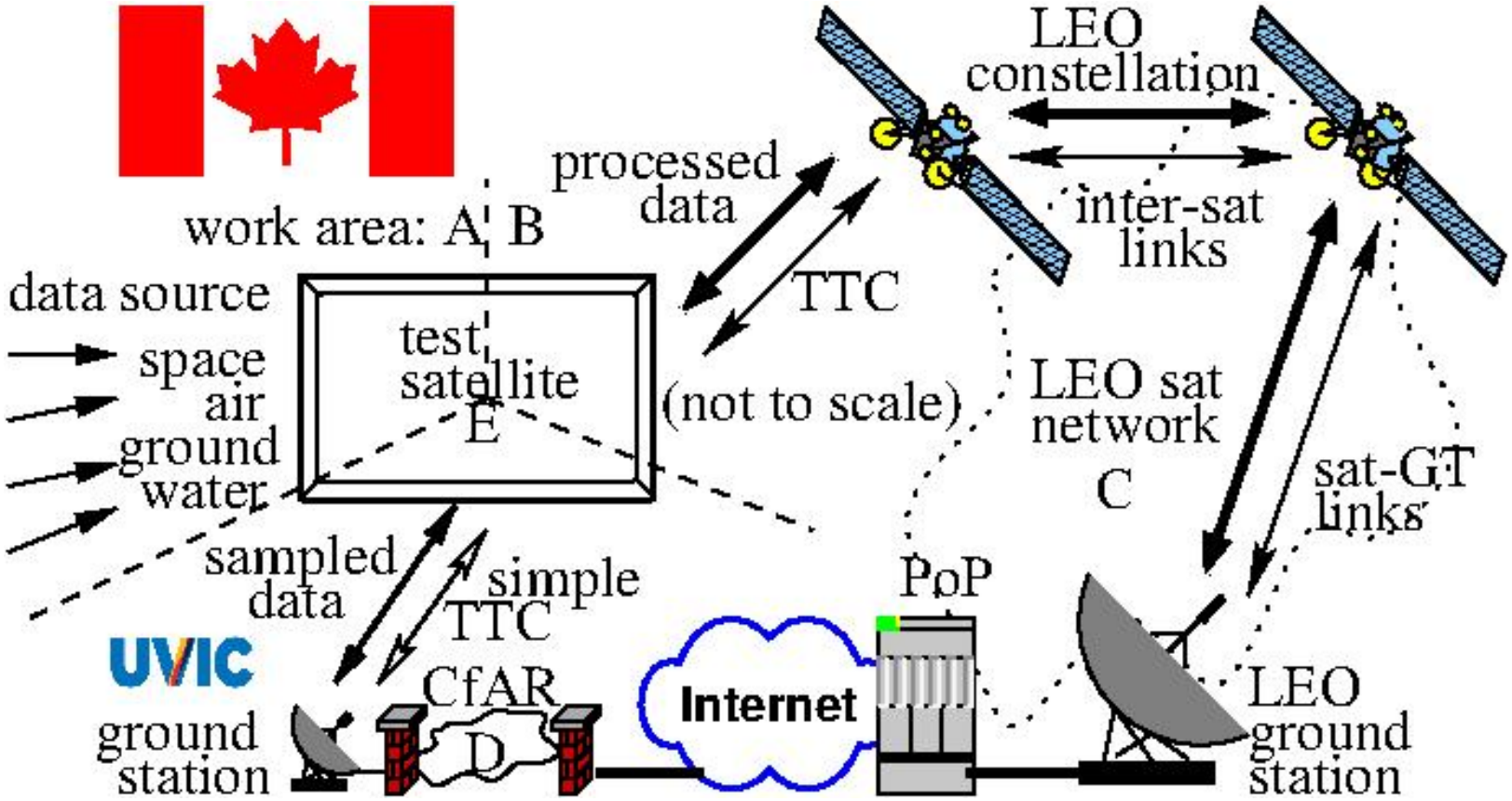
We are *no longer* just doing the groundwork …

- **PolarLink**: An Integrated, High Bandwidth, Low Latency, Vendor Neutral Space Based Communication Backbone for Canada, **funded by DRDC**



https://www.uvic.ca/ecs/news/cfar-spaceleo.php

Thanks!

Questions?

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- clarkzjw@uvic.ca
- https://pan.uvic.ca/~clarkzjw/

Dr. Jianping Pan
- pan@uvic.ca
- https://web.uvic.ca/~pan

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