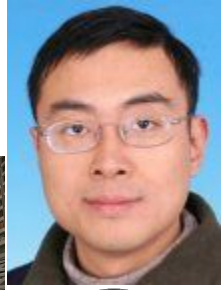
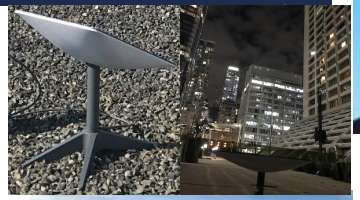


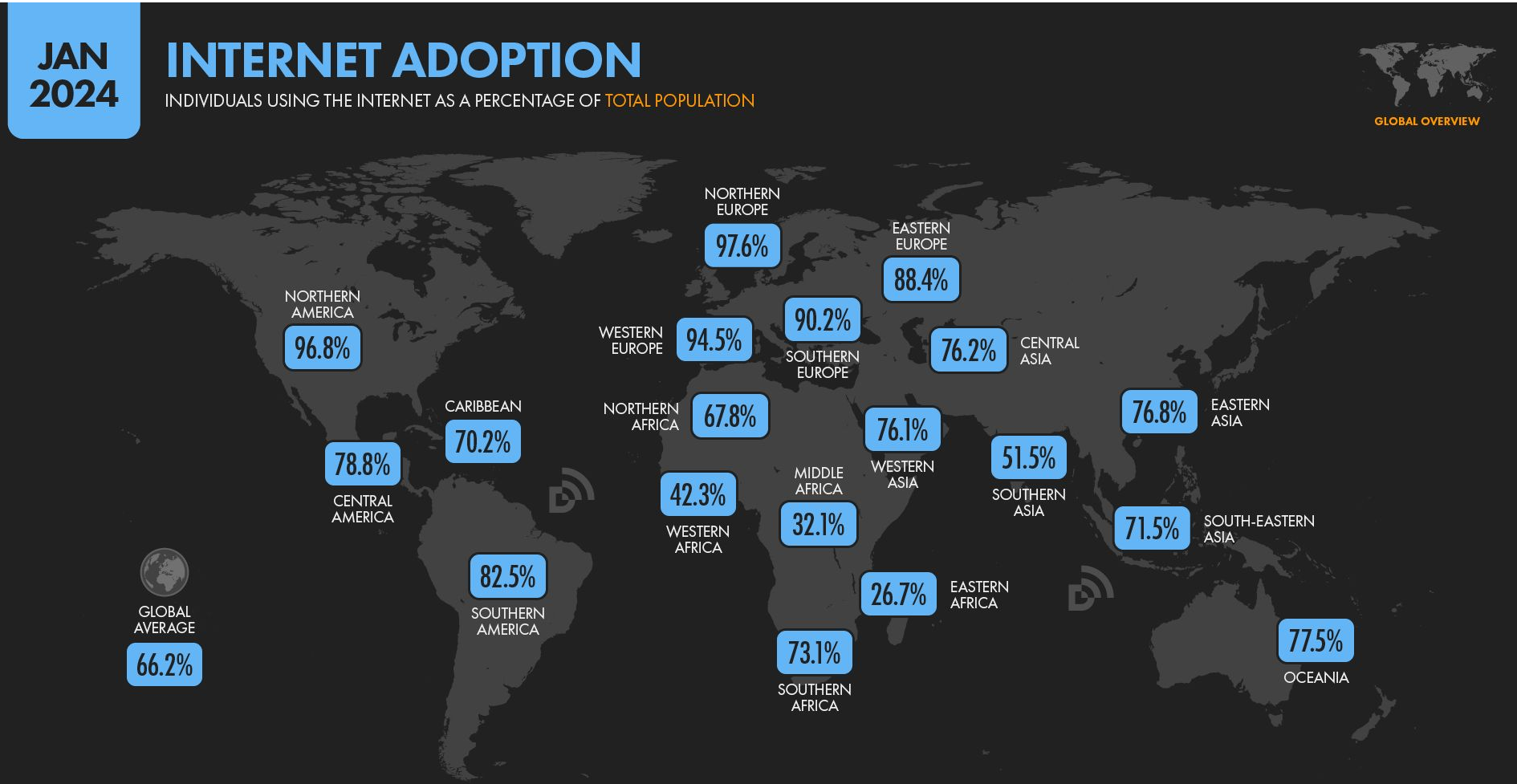
Jianping Pan



Dr Jianping Pan is a professor of computer science at the University of Victoria, British Columbia, Canada. He received his Bachelor's and PhD degrees in computer science from Southeast University, Nanjing, Jiangsu, China, and he did his postdoctoral research at the University of Waterloo, Ontario, Canada. He also worked at Fujitsu Labs and NTT Labs. His area of specialization is computer networks and distributed systems, and his current research interests include protocols for advanced networking, performance analysis of networked systems, and applied network security. He received IEICE Best Paper Award in 2009, Telecommunications Advancement Foundation's Telesys Award in 2010, WCSP 2011 Best Paper Award, IEEE Globecom 2011 Best Paper Award, JSPS Invitation Fellowship in 2012, IEEE ICC 2013 Best Paper Award, NSERC DAS Award in 2016, IEEE ICDCS 2021 Best Poster Award and DND/NSERC DGS Award in 2021, and has been serving on the technical program committees of major computer communications and networking conferences including IEEE INFOCOM, ICC, Globecom, WCNC and CCNC. He was the Ad Hoc and Sensor Networking Symposium Co-Chair of IEEE Globecom 2012 and an Associate Editor of IEEE Transactions on Vehicular Technology. He is a senior member of the ACM and a Fellow of the IEEE.

University of Victoria

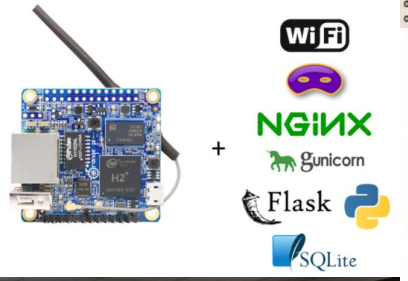
Internet access as a basic human right, not there yet



SOURCES: KEPIOS ANALYSIS; ITU; GSMA INTELLIGENCE; EUROSTAT; GOOGLE'S ADVERTISING RESOURCES; CNNIC; KANTAR & IAMAI; GOVERNMENT RESOURCES; UNITED NATIONS. **NOTE:** REGIONS BASED ON THE UNITED NATIONS GEOSCHEME. LOCAL COUNTRY VALUES HAVE BEEN CAPPED AT 99% OF THE POPULATION. **COMPARABILITY:** SOURCE AND BASE CHANGES. ALL FIGURES USE THE LATEST AVAILABLE DATA, BUT SOME SOURCES DO NOT PUBLISH REGULAR UPDATES, SO FIGURES MAY UNDER-REPRESENT ACTUAL USE. SEE NOTES ON DATA.

http://ascoderu.ca/
Email for All by Lokole

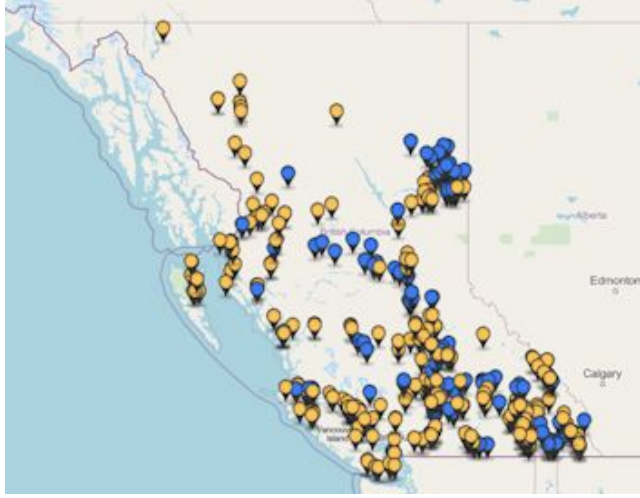
From left to right: Founder and Team Lead Nzola Swasisa, Lokole case designer Shawn Bathgate (FMF Radar shop), and Lokole case 3D printer operator Joel Pineau (FMF Machine shop).



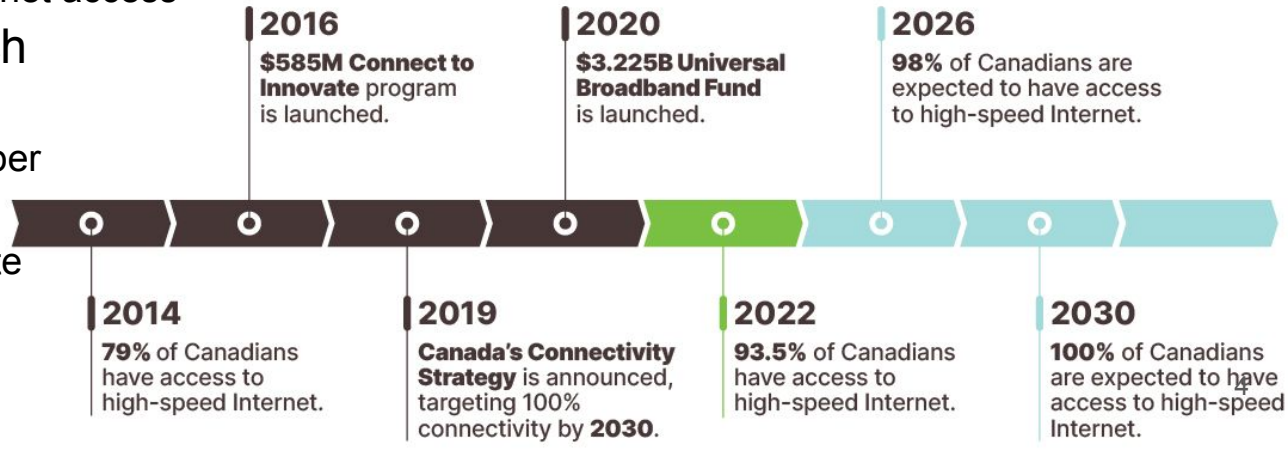
Founder and Lokole team lead Nzola Swasisa.

Left: Future Lokole users have a look at the inner working of Nzola Swasisa's invention, Lokole. Lokole operates similar to a portable router and is helping spread access to the internet to underserviced and remote regions of his former country.

Global Access to the Internet

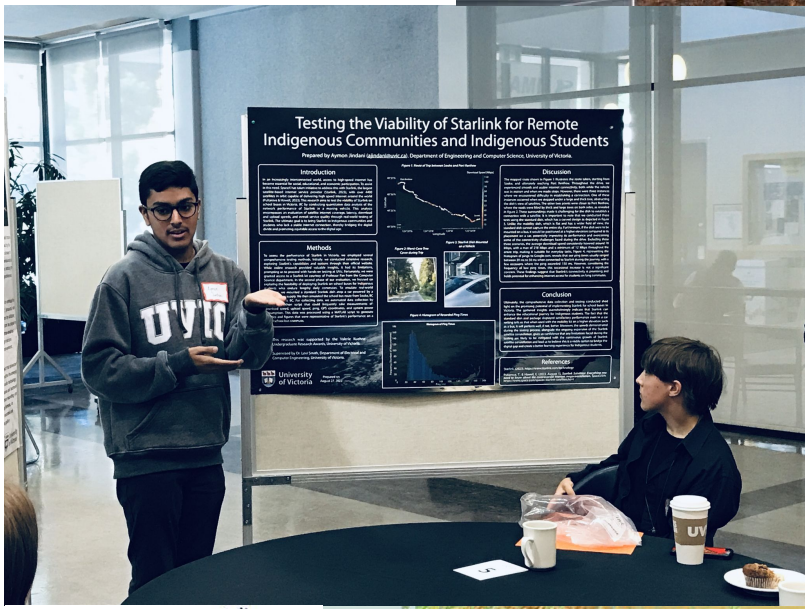


- For All
  - US: High-speed Internet for all
    - https://www.internetforall.gov/
    - A whole-of-nation approach to high-speed Internet
  - Canada: High-speed Internet for all Canadians
    - https://ised-isde.canada.ca/site/high-speed-internet-canada/
    - Goal: 98% by 2026 and 100% by 2030; Status: 93% by 2023
  - Other countries around the world
    - Also basic Internet access
- Anywhere by any-tech
  - Wireline
    - Cable, DSL, Fiber
  - Wireless
    - Cellular, Satellite



Starlink on school bus for indigenous kids

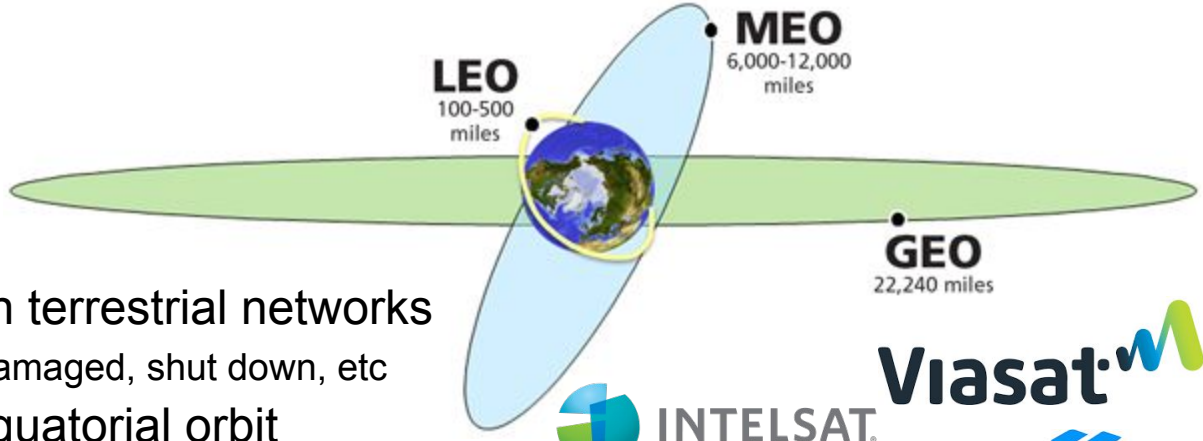
- Feasibility study
  - Sponsored by UVic VKURA
  - 2023: Sooke to Port Renfrew
- Pilot program
  - Sponsored by UVic VPRI and donors
  - 2024: Pacheedaht and Ditidaht First Nations
    - School buses to Port Renfrew and Alberni
- Regional program
  - Currently requesting funding from IEEE
  - 2024–25: for more communities
    - On the Vancouver Island not covered by CC



Global Access to the Internet for All, Anywhere

Jianping Pan
University of Victoria, BC, Canada

Why satellites?

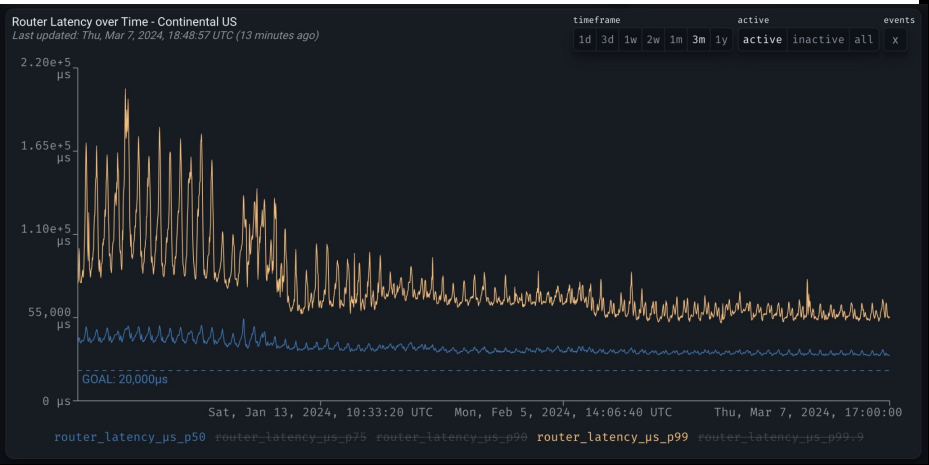


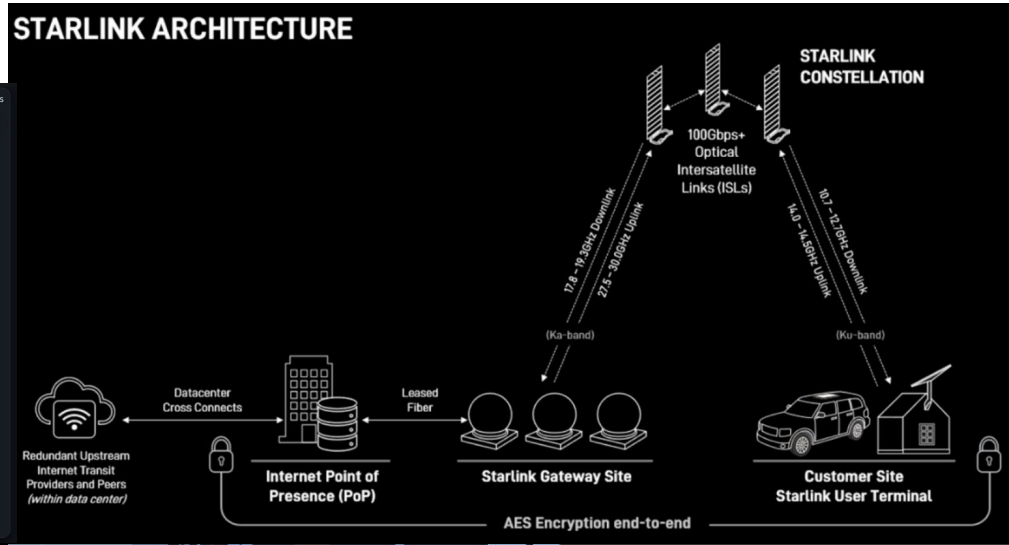
- For global coverage when terrestrial networks
  - Not available, too costly, damaged, shut down, etc
- GEO: geosynchronous equatorial orbit
  - 36 kkm above the earth, limited capacity, very large delay
  - HughesNet, Intelsat, ViaSat, etc: round-trip time (RTT) 600+ ms
- MEO: medium-earth orbit (between LEO and GEO)
  - SES O3b: 6 satellites operational now, 8 kkm, 200+ ms RTT
- LEO: low-earth orbit (below 2 kkm)
  - SpaceX's Starlink: 6k+ satellites, mostly 550 km in 53° inclination
    - 3+ million users in 70+ countries by May 2024
  - Eutelsat OneWeb: 6h+ satellites, 1 kkm altitude in polar orbits
    - mostly targeting enterprise and government customers
  - Amazon Kuiper: two prototype satellites recently tested in space
  - Telesat Lightspeed: series test satellites for space demonstration

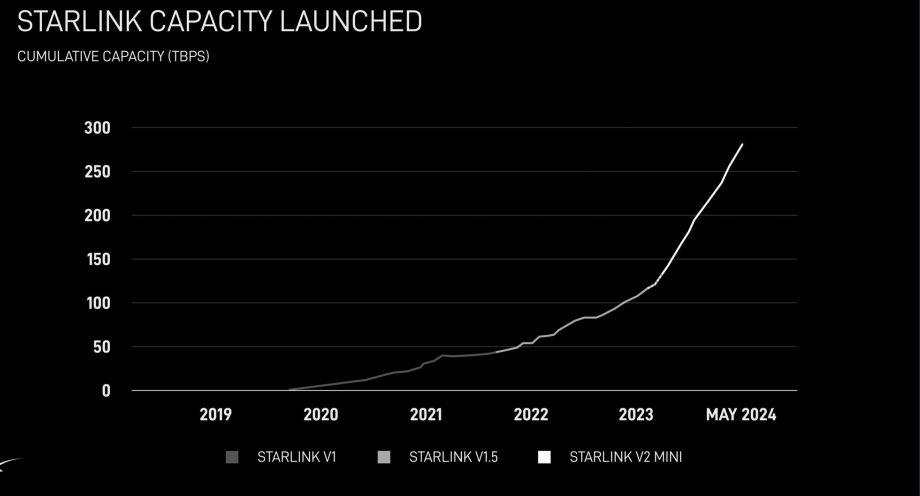
INTELSAT
Viasat
hughesnet
O3b Networks
STARLINK
OneWeb
amazon | project kuiper
TELESAT LIGHTSPEED™

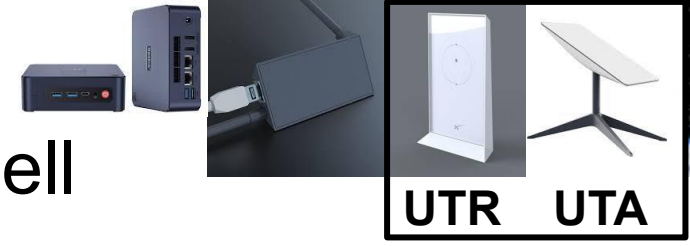
Why LEO satellites?

- Starlink as an example





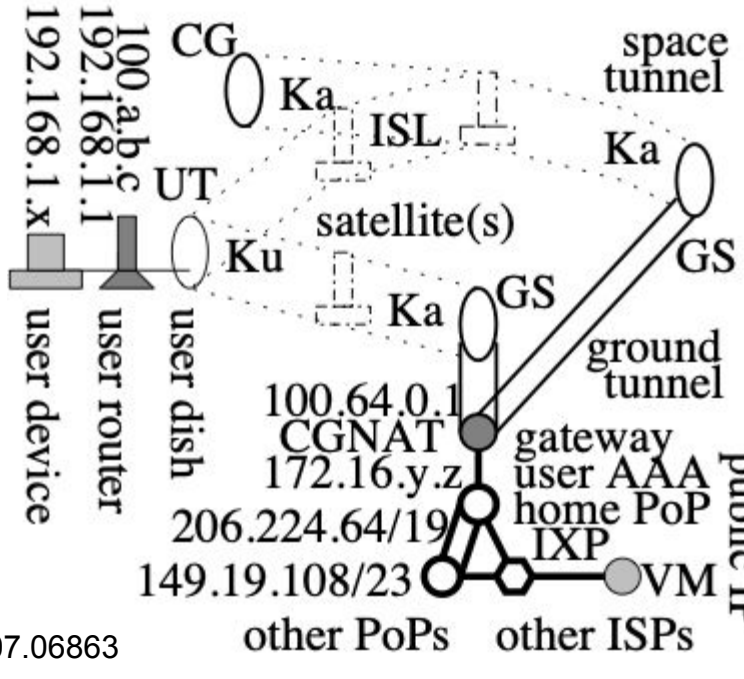




Starlink in a nutshell

- An ***outgoing*** packet's journey to the Internet (reverse for the incoming one)
  - User devices
    - 192.168.1.*x* if the default gateway 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, 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, ICPs, etc: the **Internet**

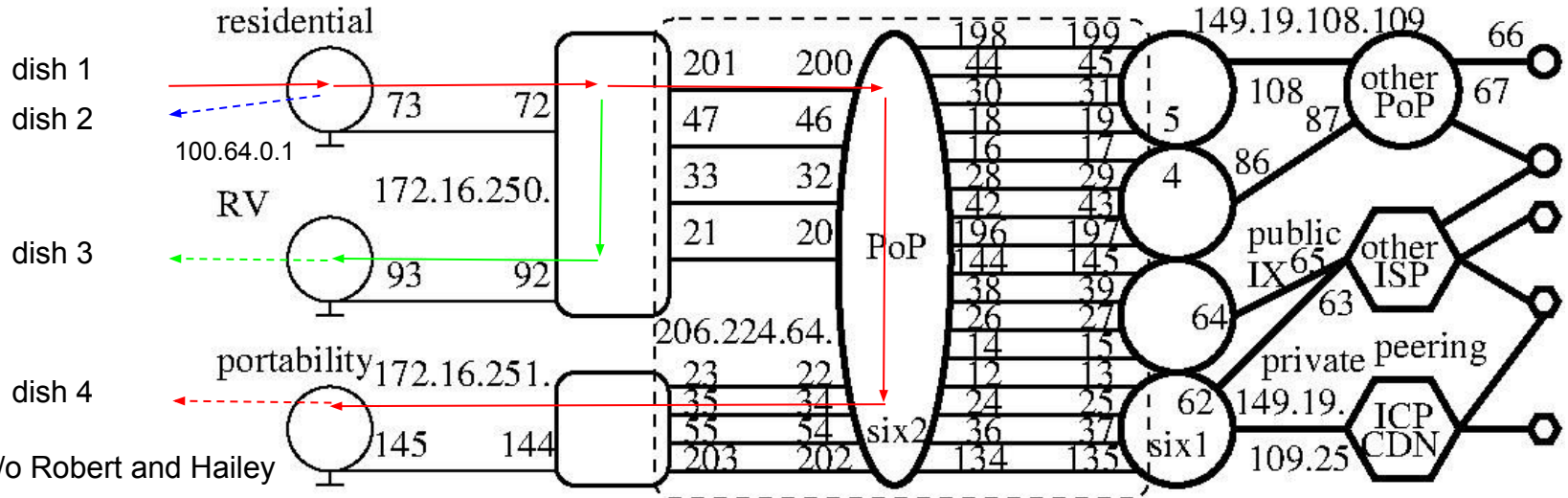
1 IP hop



* UT-(space/ground tunnel)-GW-PoP-backbone: see https://arxiv.org/pdf/2307.06863

Ground station and infrastructure

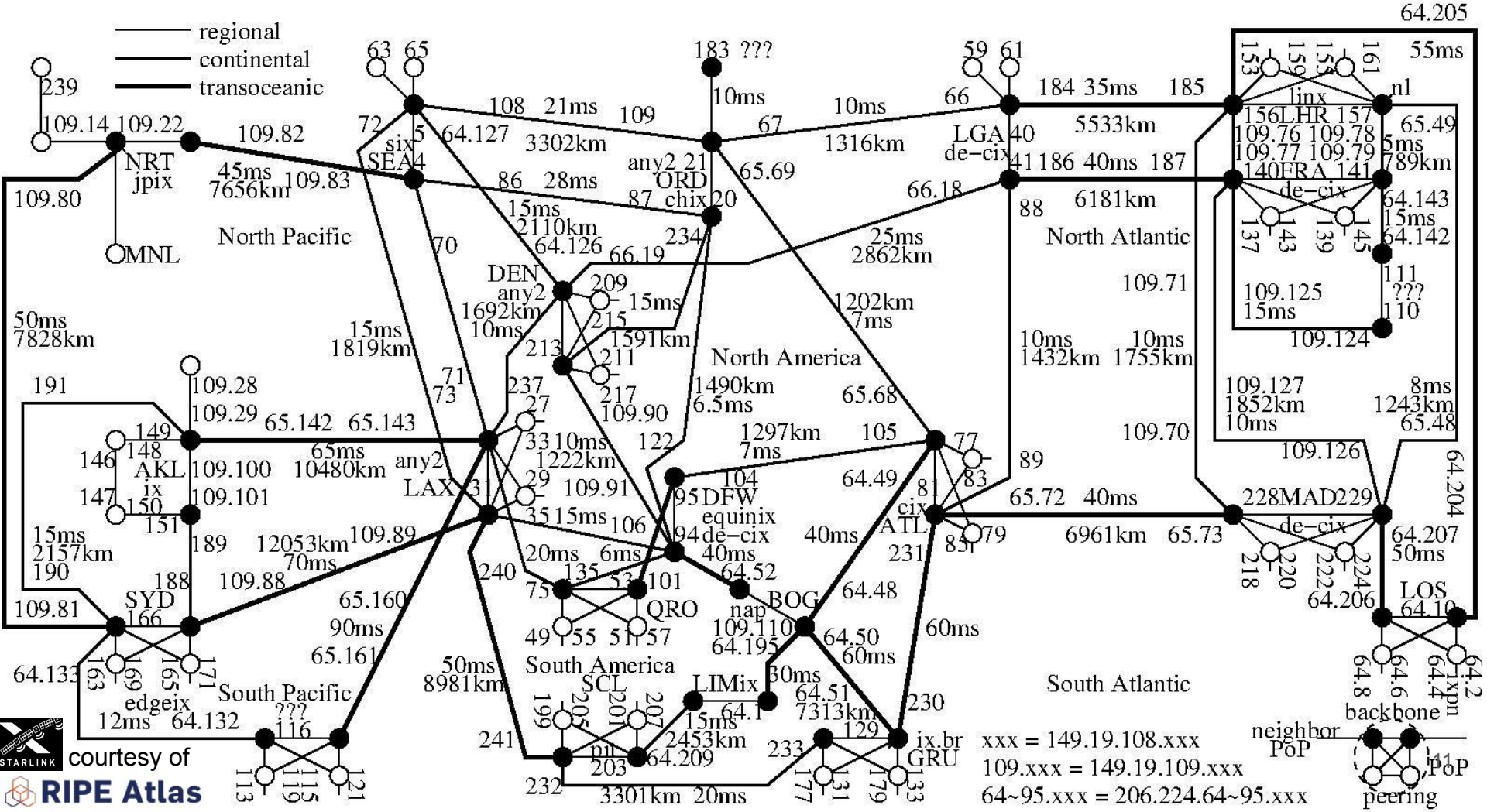
- Inside a point-of-presence (PoP, e.g., Seattle)
  - Gateway: 172.16.250/23 expanded to 172.16.252/24 (also 172.16.248/23 in other PoPs)
    - Odd ending digit: toward CGNAT
    - Even ending digit: toward the PoP
  - **Parallel** links within the PoP: 206.224.64/23 expanded to 206.224.66/24 (some inter-PoP too)
    - UDP over ECMP; ICMP unique path; TCP unique path per flow
  - Interconnection to other PoPs (mostly 149.19.108/24), ISPs and ICP/CDNs (149.19.109/24)



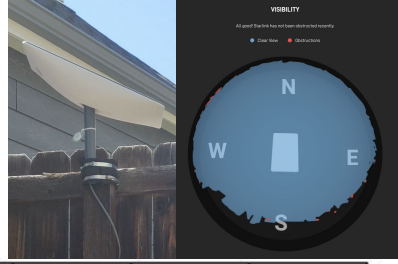
c/o Robert and Hailey

info used by http://tinyurl.com/starlinkmap

Global backbone network and growing

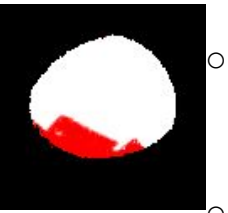


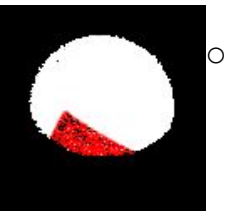
* more at http://pan.uvic.ca/webb/viewtopic.php?p=124670#p124670

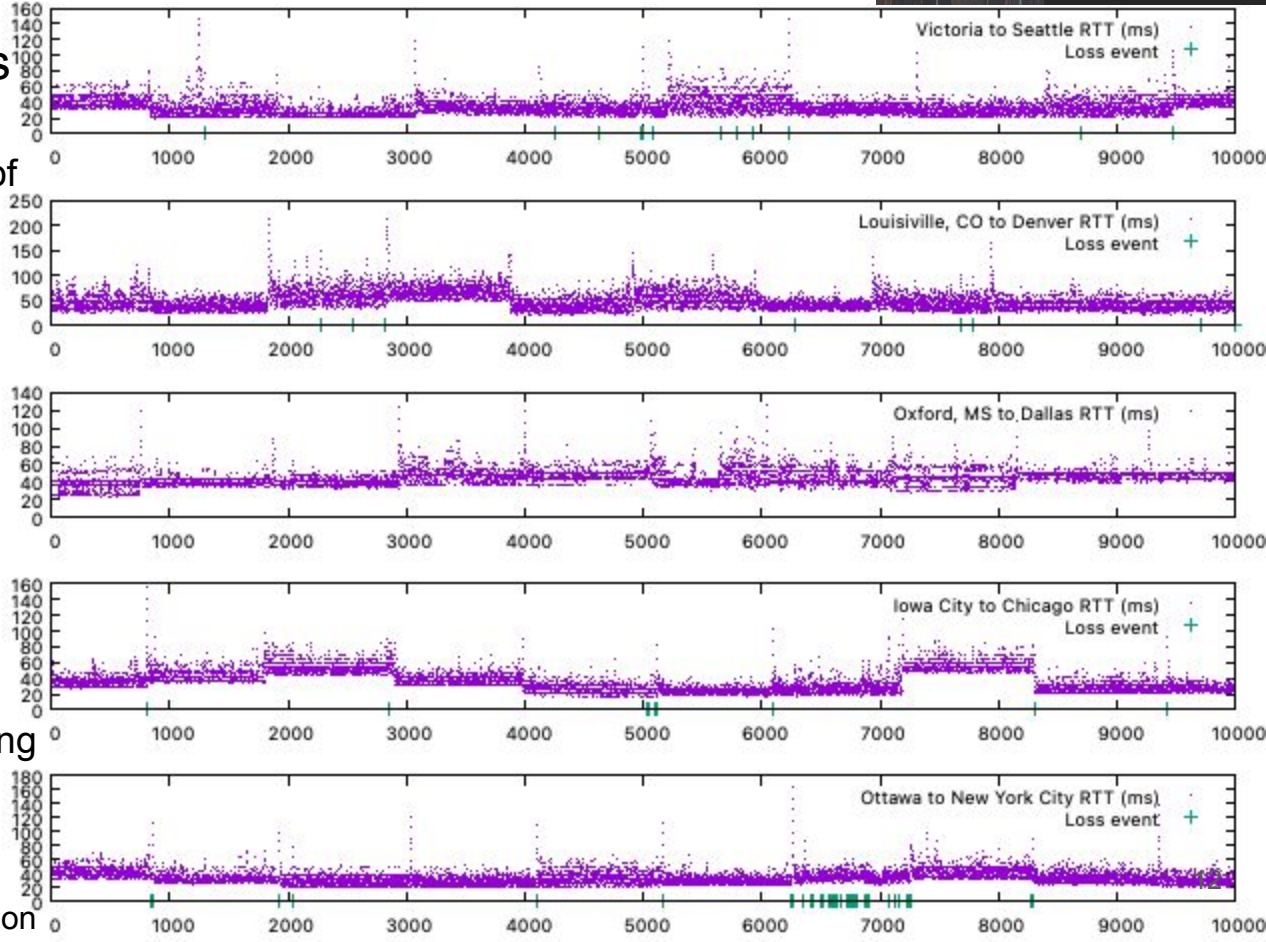


From user device to their **gateway**

- Ping in 15-ms intervals
  - Victoria to Seattle PoP
    - On UVic ECS roof
  - **Louisville**, CO^
    - Hosted by Matt
    - To **Denver** PoP
  - Oxford, MS+
    - Shared by Feng
    - To Dallas PoP
  - Iowa City, IA
    - By Hammas
    - To Chicago PoP
  - Ottawa, ON+
    - Hosted by Minming
    - To New York City

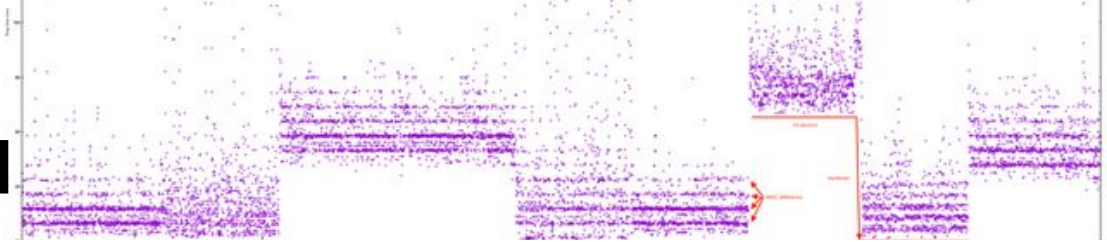




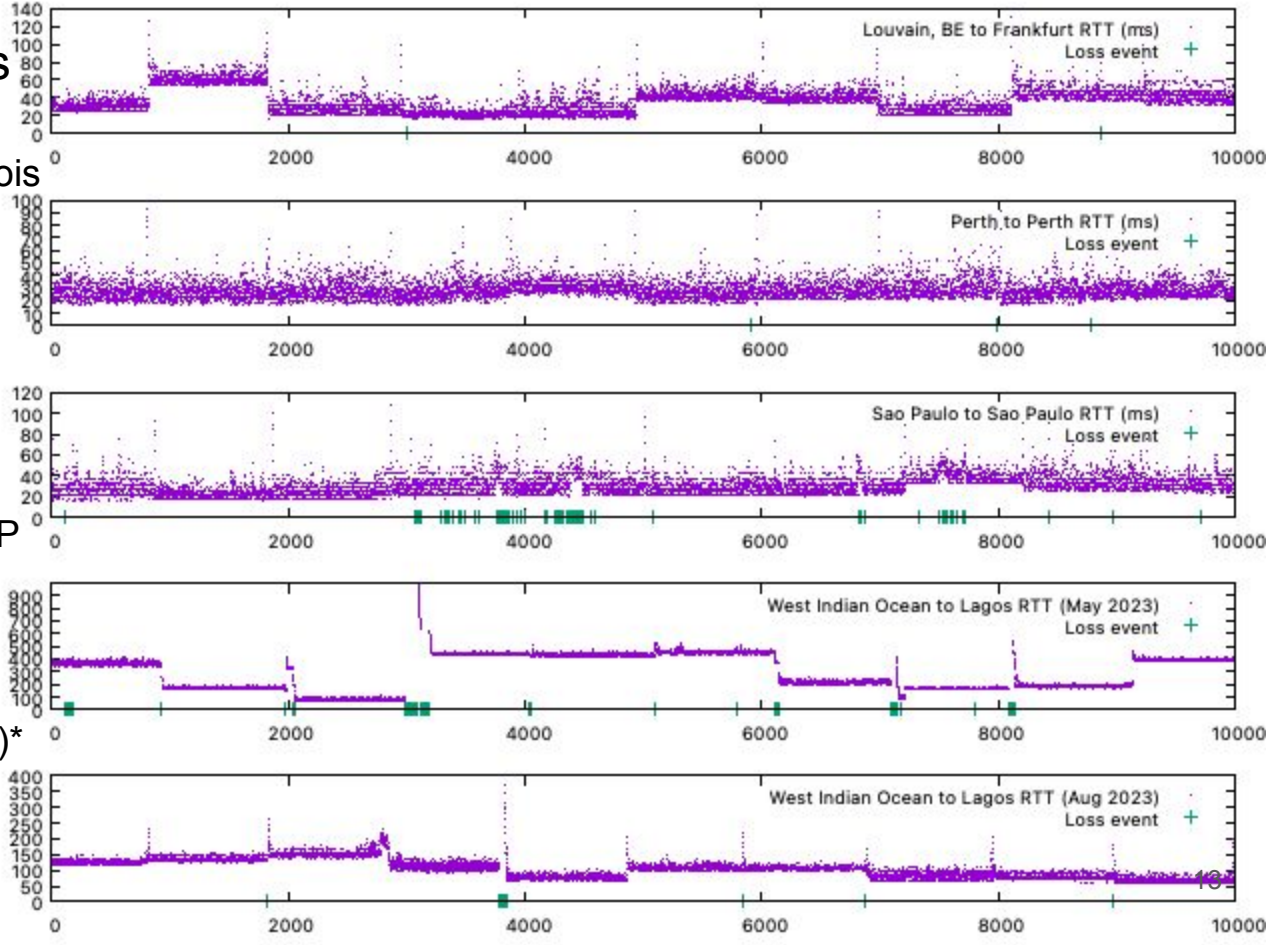


* minRTT **jumps**; ^ local WiFi; + dish obstruction

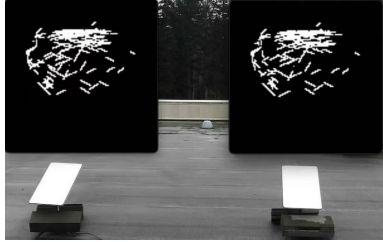
Also around the **world**



- Ping in 15-ms intervals
  - Louvain, BE
    - Shared by Francois
    - To Frankfurt PoP
  - Perth, AU^
    - By a Redditor
    - To Perth PoP
  - São Paulo, BR
    - By a Redditor
    - To São Paulo PoP
  - Seychelles (May 2023)
    - By Dominique
    - To Lagos PoP
  - **Seychelles** (Aug 2023)*
    - **ISL improved**

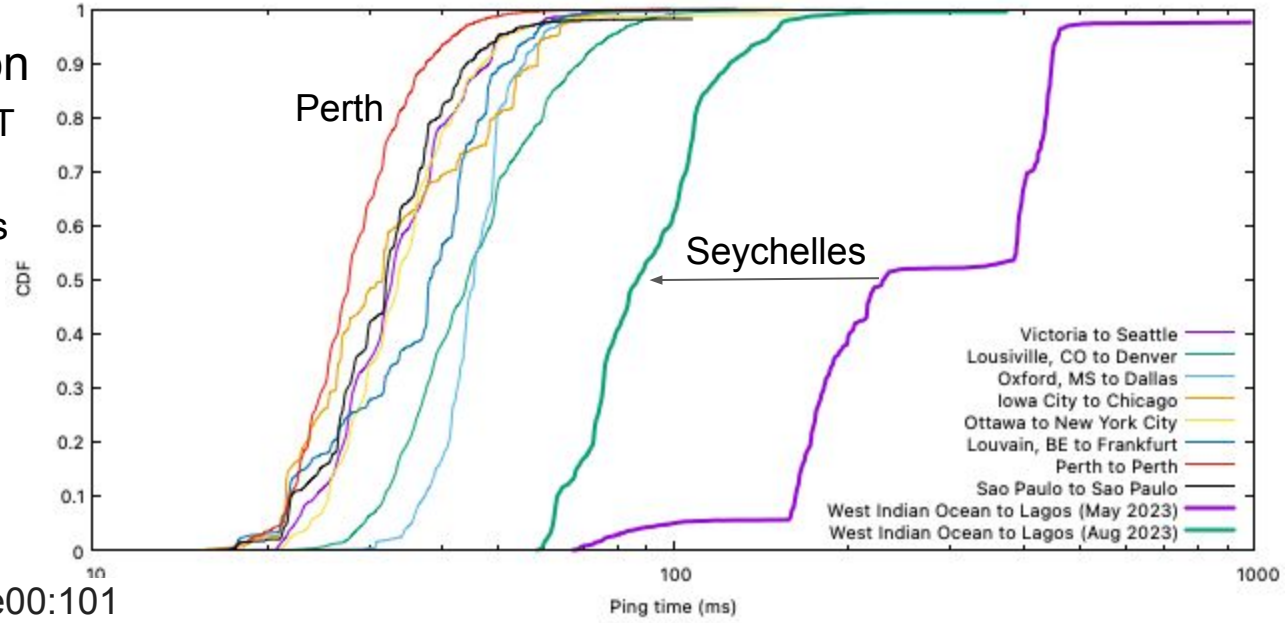


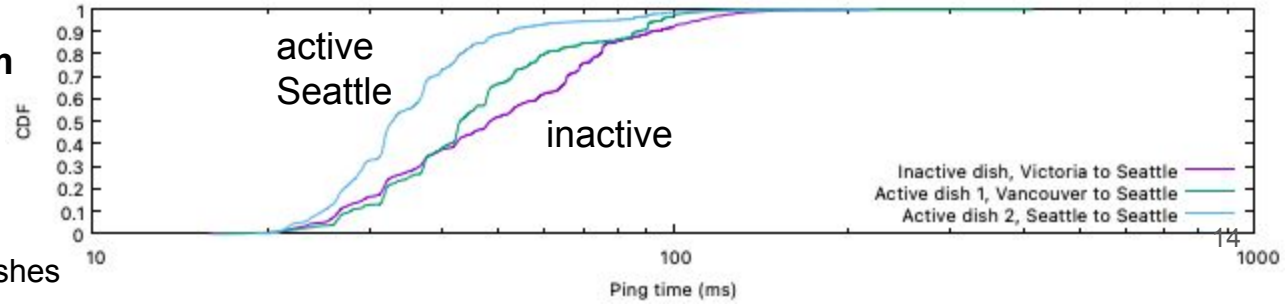
* GEO protection; ^ user population; **MAC**



From sequence to **frequency**

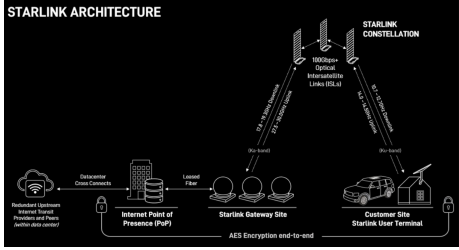
- *Cumulative* distribution
  - ISL, much **higher** RTT
  - Non-ISL
    - min RTT: ~20ms
    - Still high **jitter**
- ***Inactive*** dishes
  - IPv4 gateway
    - 100.64.0.1
    - By ARPing
  - IPv6 gateway
    - fe80::200:5eff:fe00:101
    - By Ping
  - **connect.starlink.com**
    - 34.107.166.226
    - By (HTT)Ping



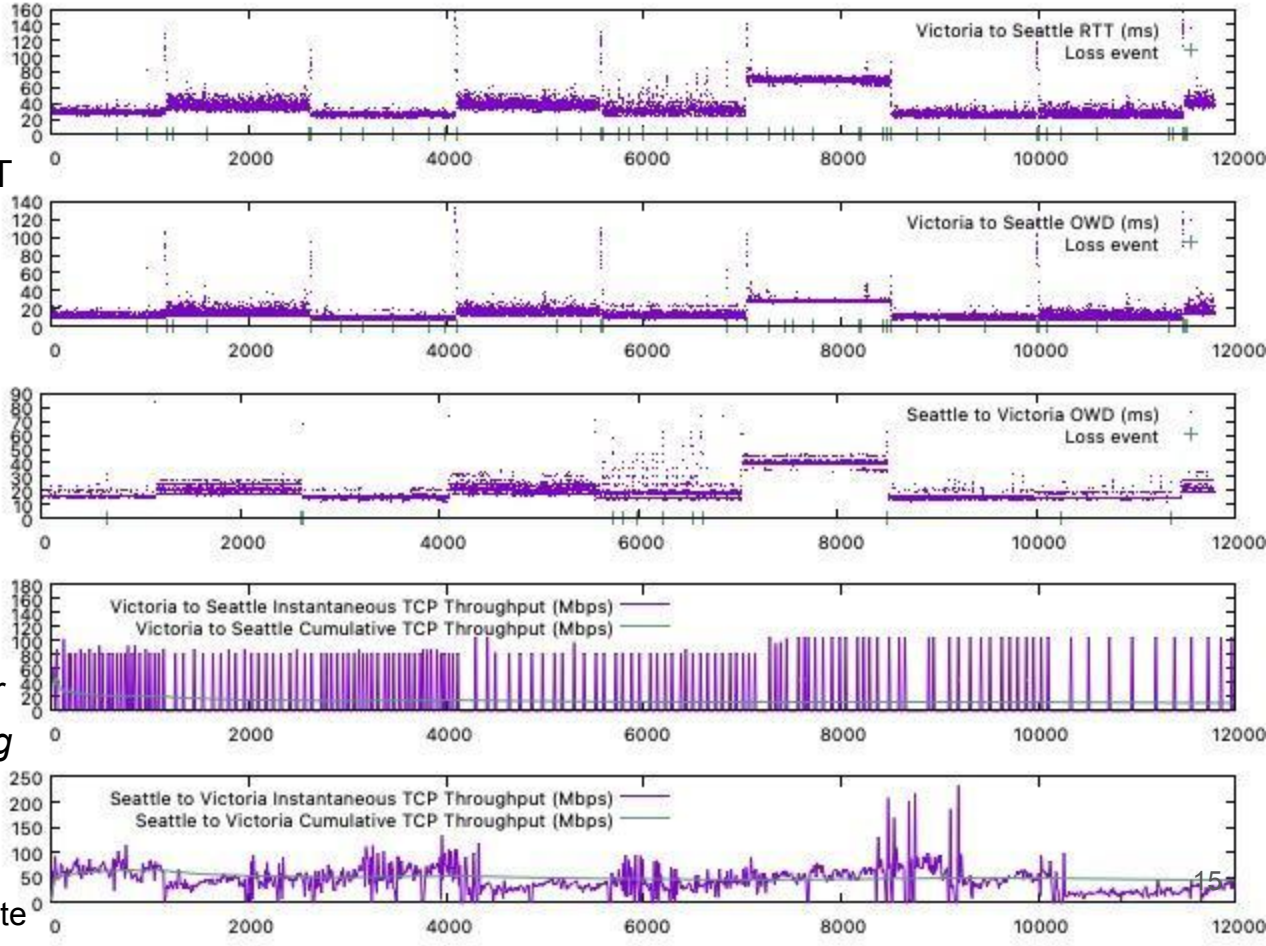


* **active** measurement on many ***inactive*** dishes

Up vs **down** link from user's viewpoint

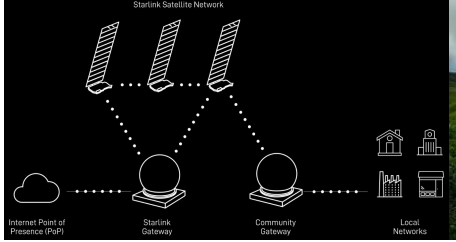


- Victoria ⇔ Seattle
  - RTT by Ping to GW
  - *One-way* delay by IRTT
    - A VM near PoP
    - Time synced
  - **Bidirectional** tunnel
    - Same satellite(s)
    - And landing GS
  - *Asymmetric* bandwidth
    - Up: contention
    - Down: allocation
  - iPerf3 TCP throughput
    - Sat-GS handover
    - Packet *reordering*
    - *Timeout*

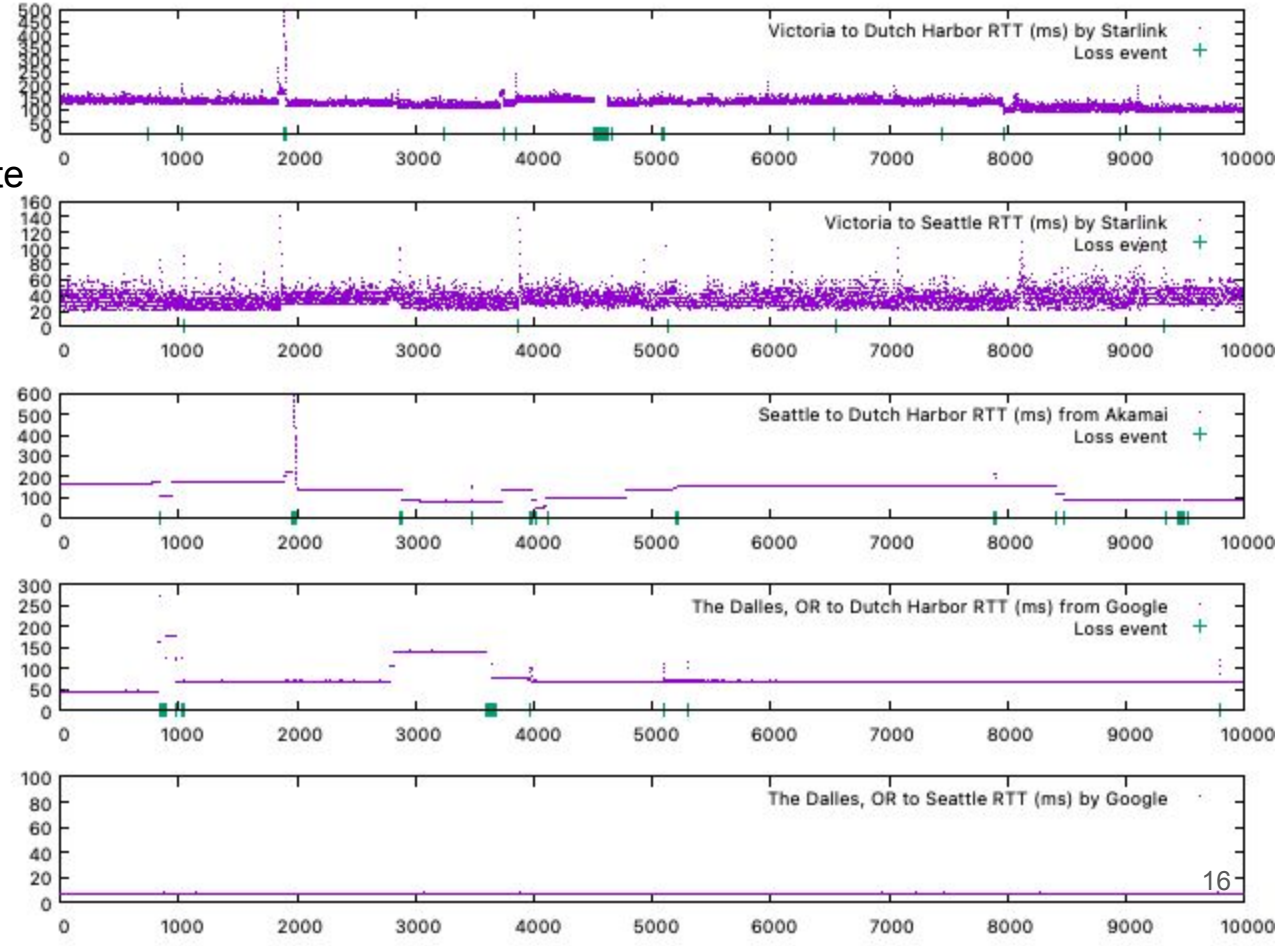


* TCP affected at 57, 12, 27 and 42 sec/minute

Community gateway



- **First** in Dutch Harbor
  - Unalaska, AK
  - A **mini** GS to aggregate
  - In **Ka** (not Ku) bands
  - 10Gbps **symmetric**
- ***Outside-in*** testing
  - From Victoria dish
    - UT-Sat-GS and
    - GS-Sat-GS
  - From Akamai VM
    - In Seattle
  - From Google VM
    - The Dalles, OR
    - Through Seattle

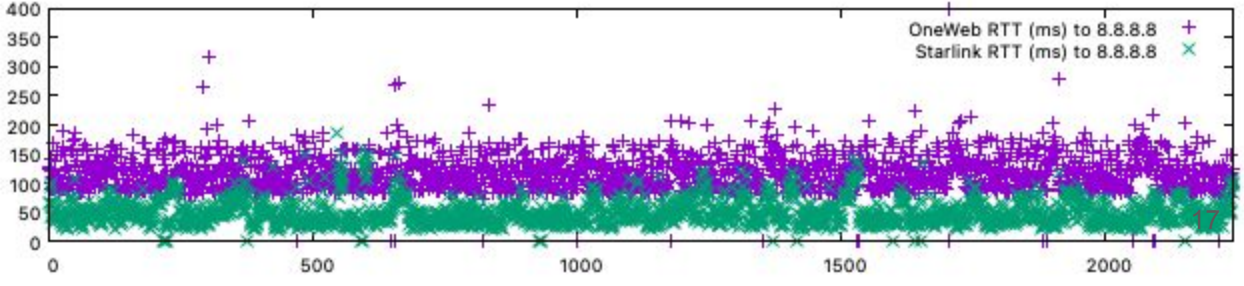


* capex: $1.25m; opex: $75k/gbps/month!

Comparing with **another** LEO network

- Starlink
  - Initially target *consumer* users
  - Mostly 53° inclination
  - Mostly 550km above the Earth
  - **Spotting** beams for individual dishes
    - Ku for UT and Ka for GS
  - Currently >6000 active satellites
    - All launched by SpaceX
  - Currently >100x ground stations
  - Many PoPs around the world
  - Lower but *relatively fluctuating* RTT
    - Due to Spotting beams
    - **UT-Sat-GS shuffling every 15 seconds**

- ***OneWeb***
  - Currently target *enterprise* users
  - Polar orbits
  - Above 1000km in altitude
  - **Sweeping** beams for community dishes
    - Similarly Ku and Ka
  - Currently ~600 active satellites
    - Limited 3rd-party launch capacity
  - Currently ~10x ground stations
  - Very few customer PoPs now
  - High but *relatively stable* RTT to PoP



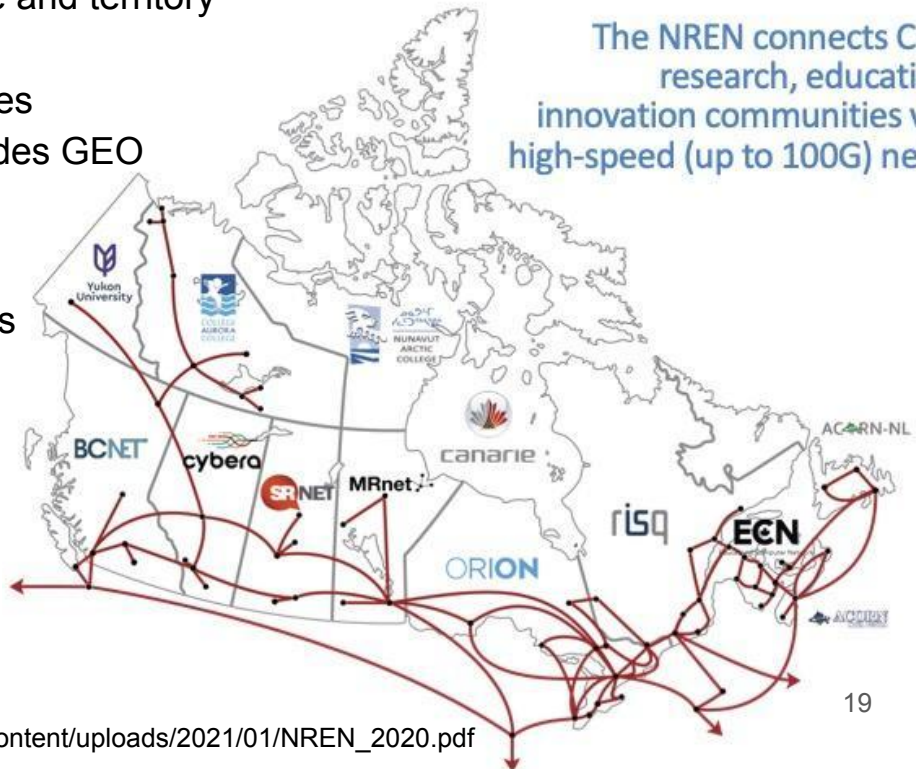
* Amazon Kuiper and Telesat Lightspeed?

Is Starlink+OneWeb+Kuiper+Lightspeed enough?

- Starlink
  - Personal: Residential, Roam, Boats
  - Business: Fixed Site, Land Mobility, Maritime, Aviation, Direct to Cell
  - Swarm: Space IoT?
- Inter-Satellite Network: An **Internet** of satellites
  - A ***testbed*** first!

Why a cross-country/continent satellite testbed?

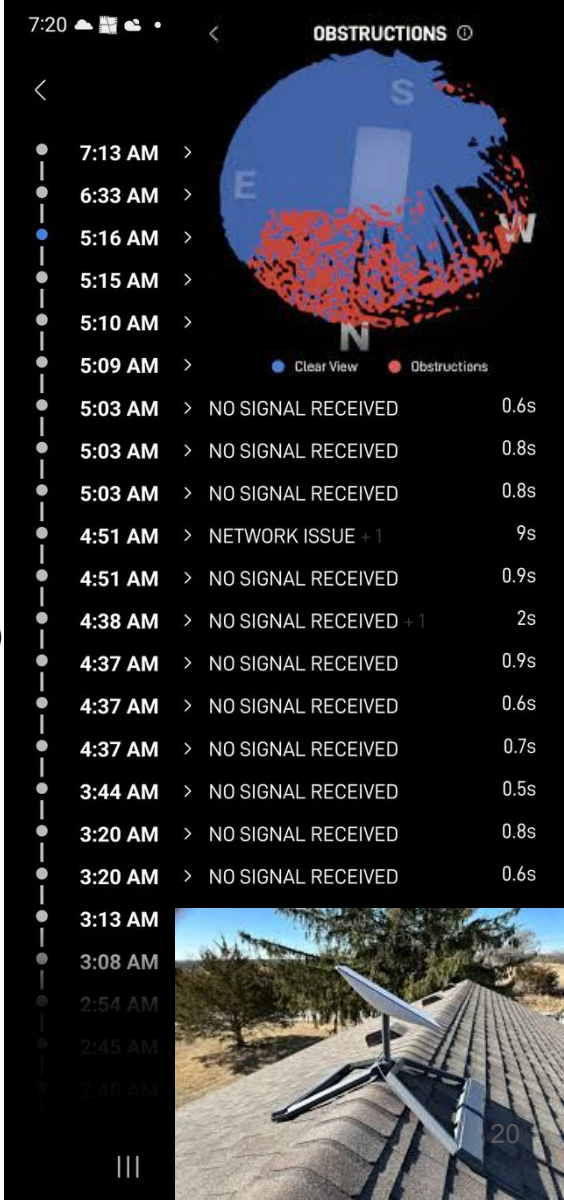
- For network researchers, leveraging CANARIE/Internet2 but on LEO satellites
  - Geo-diversity needed for satellite network research
    - At least one site in each province/state and territory
  - Much more capable than RIPE Atlas
    - Container-based measurement modules
  - Possibly different satellite technologies besides GEO
    - Starlink, OneWeb, Kuiper, Telesat, etc
- For community users
  - In remote areas and indigenous communities
    - Improved Internet access capacity
  - No security and privacy affected
    - End-to-end encryption of user traffic
  - A level playground for a fair comparison
    - For vendors, operators and regulators



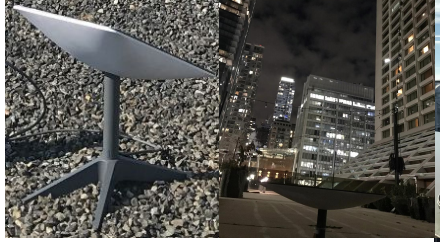
https://www.canarie.ca/wp-content/uploads/2021/01/NREN_2020.pdf

What are the challenges?

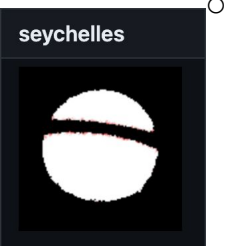
- A country/continent-wide testbed of each site including
  - Satellite dish(es): outdoor units with a clear view of the sky
    - Dish installation: roof or pole mount, cable routing, etc
    - Service cost: monthly subscription fee
  - Time-synchronized measurement nodes: indoor units
    - Mini PCs of multiple Ethernet ports, each to a different dish
    - Network adapter/switch, uninterruptible power supply (UPS)
  - Host and community access to the Internet
    - Access point for host coverage; mesh nodes for community
  - Additional equipment if needed
    - Solar panel, power generator, community cache server, etc
- Centralized control and coordination for collaboration
  - Measurement orchestration: container deployment/scheduling
  - Platform maintenance to minimize the overhead for the host



Why join us?



- Doing research in LEO Satellite Networks
  - Computing, communication and control
    - Multipath transport, congestion control, etc
  - Network security and user privacy
    - Anonymous communication
  - Network applications and improvement
    - Video streaming, online gaming, etc
- Gaining experience in various research testbeds
  - Starlink dishes in Victoria, Denver and Ottawa
    - Satellite dish, Ethernet adapter and switch, Mini PC
  - Community dishes around the world
    - Virtual machine, remote access, data collection/release
  - Outreach and broader impact
    - E.g., Starlink reddit, bug fixes adopted by Starlink, etc

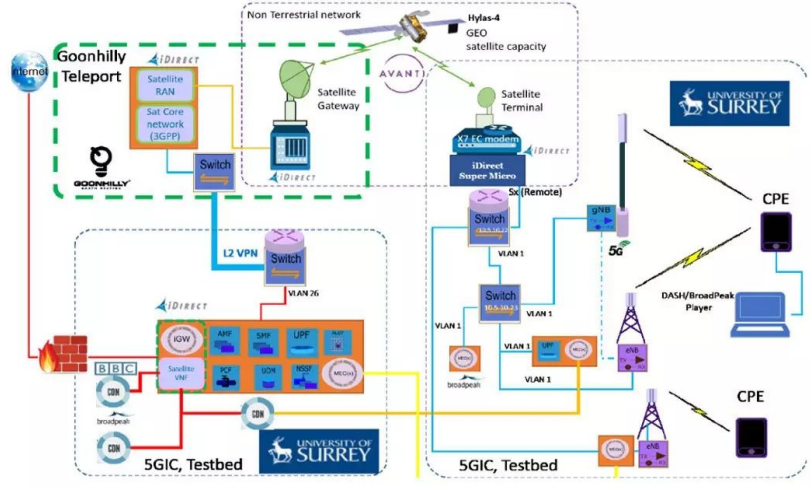


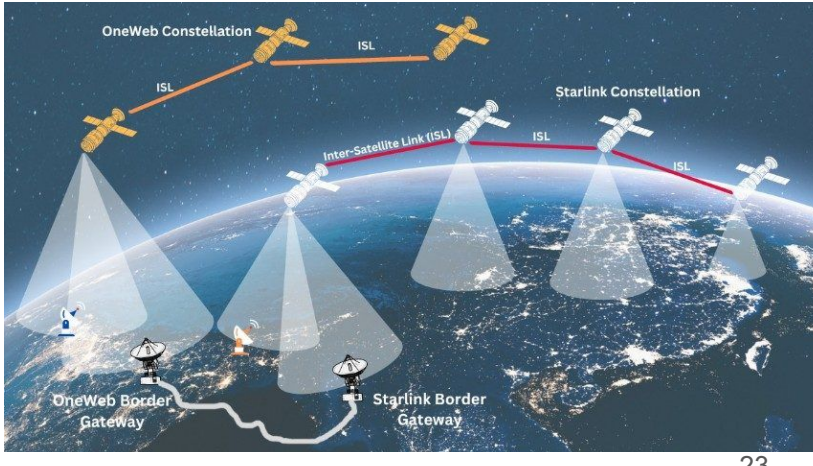
For a LEO-Sat-Net testbed!

- As a (founding) member and supporter
  - Network/fleet operators: contributing hardware and service
    - Benefit: accessing user-perceived performance and comparison
  - Funding agencies: research and equipment grants
    - Fostering across-country academia-industry collaboration
  - Government organizations: community grant and citizen service
    - Connecting research and empowering remote communities
  - Academic, industry and government researchers and students
    - Access to a coast-to-coast-to-coast testbed for research and education
- As a (pilot) host in remote areas: much improved Internet access
  - A small space and basic power supply (solar panel if needed)
  - Other Internet connectivity if available for control redundancy
    - Minimum local maintenance with mostly central control
    - Local outreach and activities with strong central support

Other efforts around the world

- With a focus on (LEO) satellites
  - University of Surrey, UK
    - Hylas-4 GEO with 5/6G integration
    - LEOScope: an emerging global testbed
  - Virginia Tech and George Mason University, USA
    - NeTSat: NSF project recently approved
    - Starlink and OneWeb mentioned
  - Carleton University, Canada
    - UAV-HAP-LEO integration with 6G O-RAN
    - Collaboration with NRC, MDA, DRDC, etc
- Unique features of us as part of LEOScope
  - Geo-distributed: coast-to-coast-to-coast
  - LEO-focused: consumers and enterprises
  - User-oriented testbed: by and for researchers





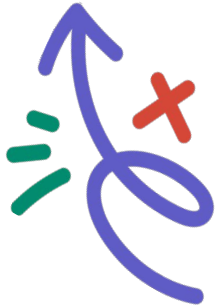
leoscope.surrey.ac.uk

LEOScope:

A GLOBAL TESTBED

for Low-Earth Orbit

Satellite Networks



Nishanth Sastry

SAEED FADAEI

MOHAMED KASSEM

Debopam Bhattacherjee

Nodes for the testbed have been donated/contributed by:

Node Contributors

University of Surrey (London, Wrexham, and Nigeria)

Edinburgh (Edinburgh Node)

Telefonica (Madrid Node)

University of Victoria

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Low Earth Network of Satellites

- **https://github.com/clarkzjw/LENS**
  - Our ***public*** datasets updated monthly

Starlink User Terminal models and hardware revisions

January 2024

REV1 - Original Starlink "Dishy"

rev1_pre_production
rev1_production
rev_rev1_proto3

Years in production: 2020 - 2021

High Performance

rev_hp1_proto0
rev_hp1_proto1

Years in production: 2022 -

REV2 - Mass production "Dishy"

rev2_proto1
rev2_proto2
rev2_proto3
rev2_proto4

Years in production: 2021 - 2022

Flat High Performance

rev_hp1_proto0
rev_hp1_proto1

Years in production: 2022 -

REV3 - Standard Actuated

rev3_proto0
rev3_proto1
rev3_proto2

Years in production: 2022 -

REV4 - Standard

rev4_proto3
rev4_proto4
rev4_prod1

Years in production: Q4 2023 -

olegkutkov.me, 2024

Thanks!

- ***Questions?***
  - Join us!

Obstruction test

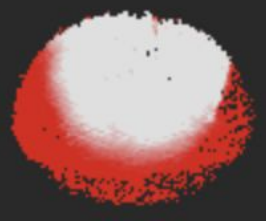
Active vs inactive vs *obstructed* dish in a cell

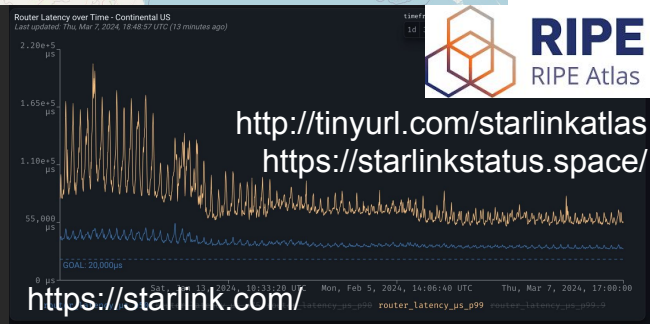
Starlink added **6** new PoPs in US in 2024

http://starlink.sx
http://tinyurl.com/starlinkmap

LEOScope

flat dish





RIPE Atlas

http://tinyurl.com/starlinkatlas
https://starlinkstatus.space/
https://starlink.com/

From Anchorage, AK to Seattle, WA: Starlink vs OneWeb vs Fiber (% Mark)
more at https://github.com/clarkzjw/LENS