To Space and Back: Integrating Next-Generation Terrestrial and Satellite Communication Networks

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RIPE Atlas Ambassador

RIPE NCC Member

Telekom Srbija



AGENDA

Motivation

So how do we actually manage to bridge this coverage gap?

Why routing behaves differently?

Why RIPE Atlas? A Global End-to-End View

From Routing Theory to Measured Reality: Measuring End-to-End Paths with RIPE Atlas

Measuremnt-Case Scenarios: Europa – Asia and Japan - Europa

NTN–TN Interoperability: Practical Necessity or Future Vision?

“The Earth is a very small stage in a vast cosmic arena...” - Carl Sagan, Pale Blue Dot: A Vision of the Human Future in Space (1994)
Yet through satellites, humanity has woven its presence into that arena.“

MOTIVATION

If we are just a tiny dot in the universe — how do we manage to connect an entire planet?



Global connectivity is not global

- ✓ Internet connectivity depends on routing decisions, not only on physical distance
- ✓ Large parts of the world still lack reliable terrestrial infrastructure
- ✓ End-to-end latency is often driven by routing policies, not geography

🗣️ Even in 2026, global connectivity is still shaped by where infrastructure exists — and where it doesn’t.

The connectivity gap is not a satellite problem

According to the GSMA (*Global System for Mobile Communications Association*) 2024 report, **more than 3.4 billion people around the world** still remain unconnected to modern internet services.

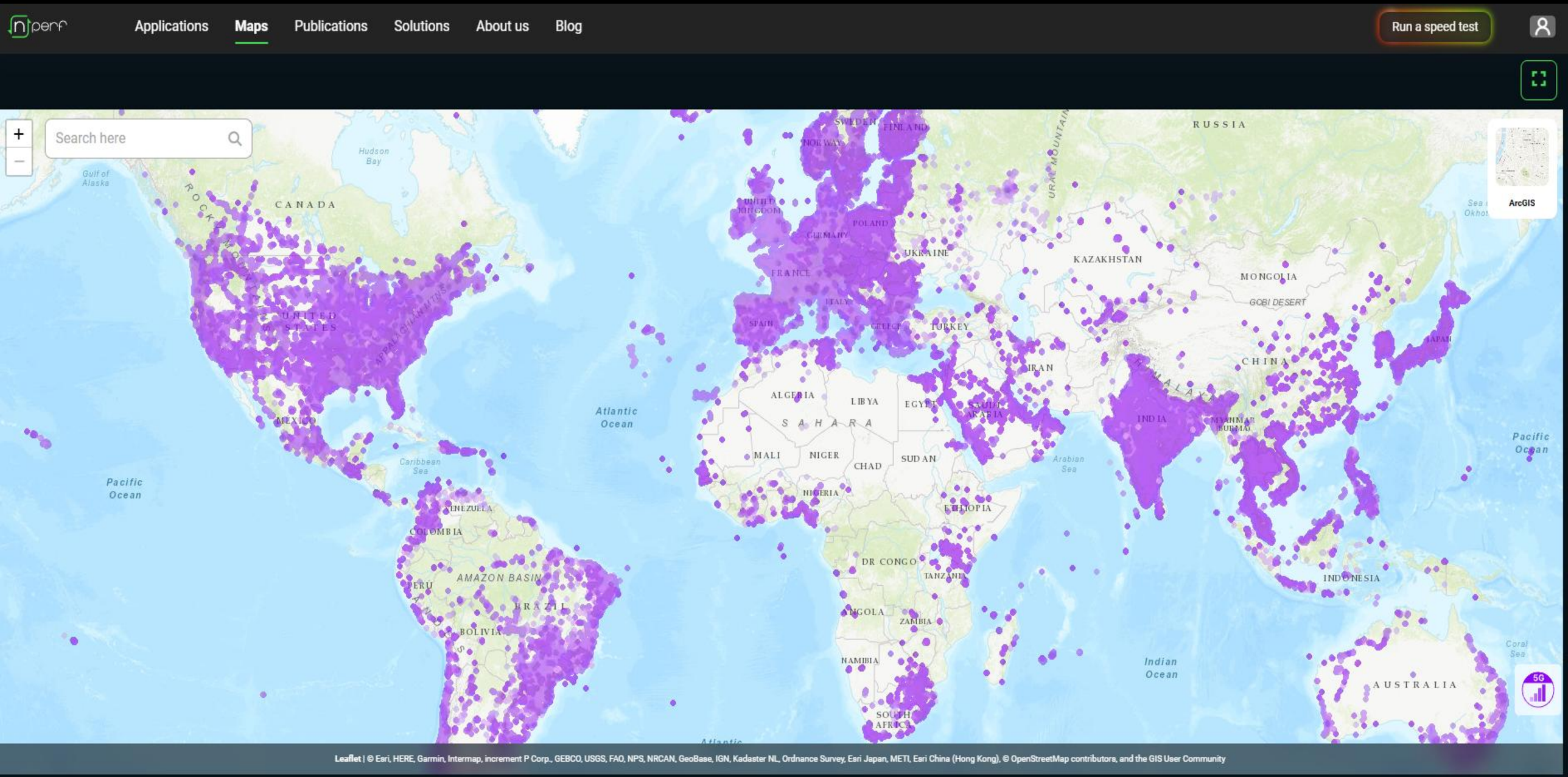
Not only lack of satellites, but limitations of terrestrial networks due to:

1. geography (highly fragmented Asia-Pacific region – Indonesia alone has ~17,500 islands, mountains, oceans...)
2. economic infeasibility of fiber deployment
3. limited peering and backbone access
4. political and regulatory constraints

🗣️ This number does not mean we lack satellites — it means terrestrial infrastructure alone is not enough.

https://www.gsma.com/r/wp-content/uploads/2024/10/The-State-of-Mobile-Internet-Connectivity-Report-2024.pdf

Blank spots – roughly 80% of Earth's surface lacks reliable terrestrial coverage



https://www.sierrawireless.com/global-coverage/

So how do we actually manage to bridge this enormous coverage gap?



Terrestrial vs LEO satellite networks — an end-to-end latency perspective

- ✓ LEO satellites introduce a new global routing layer
- ✓ Not a replacement, but an integrated network component
- ✓ Requires measurement-based evaluation, not assumptions

🗣️ The key question is not whether satellites are fast — but how they behave as part of the global Internet.


Here is why
routing behaves
differently

Architecture of LEO Satellite Systems

Satellites are no longer just signal relays — they are now an active part of the Internet.

Band	Frequencies
Ku	12-18 GHz
Ka	26,5-40 GHz



Laser Inter-Satellite Link (LISL)



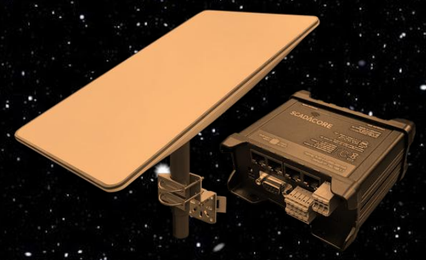
Ku/Ka band

Ku/Ka band

LAN from home PC + router



PoE cable



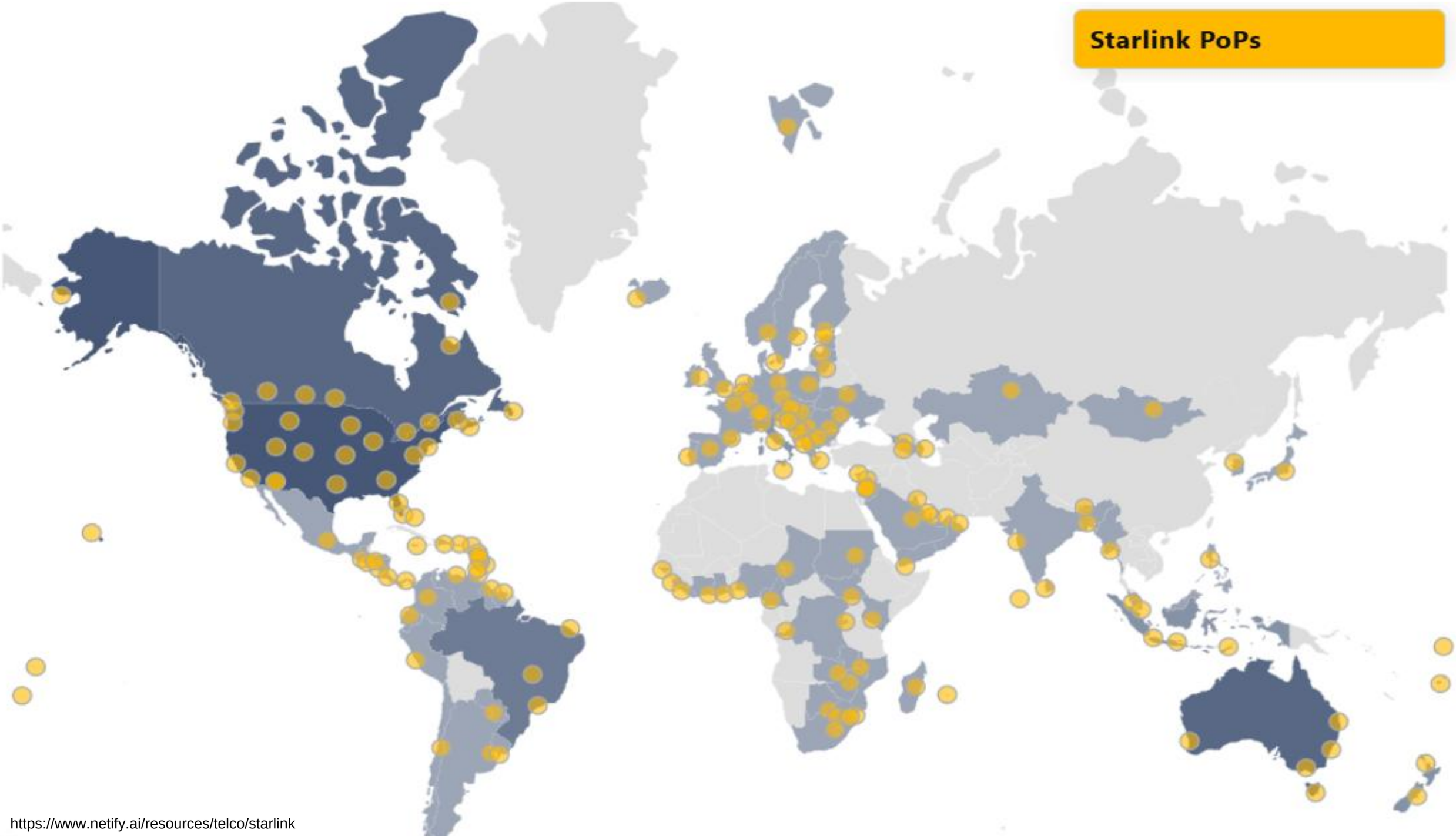
User terminal (dishy antenna)



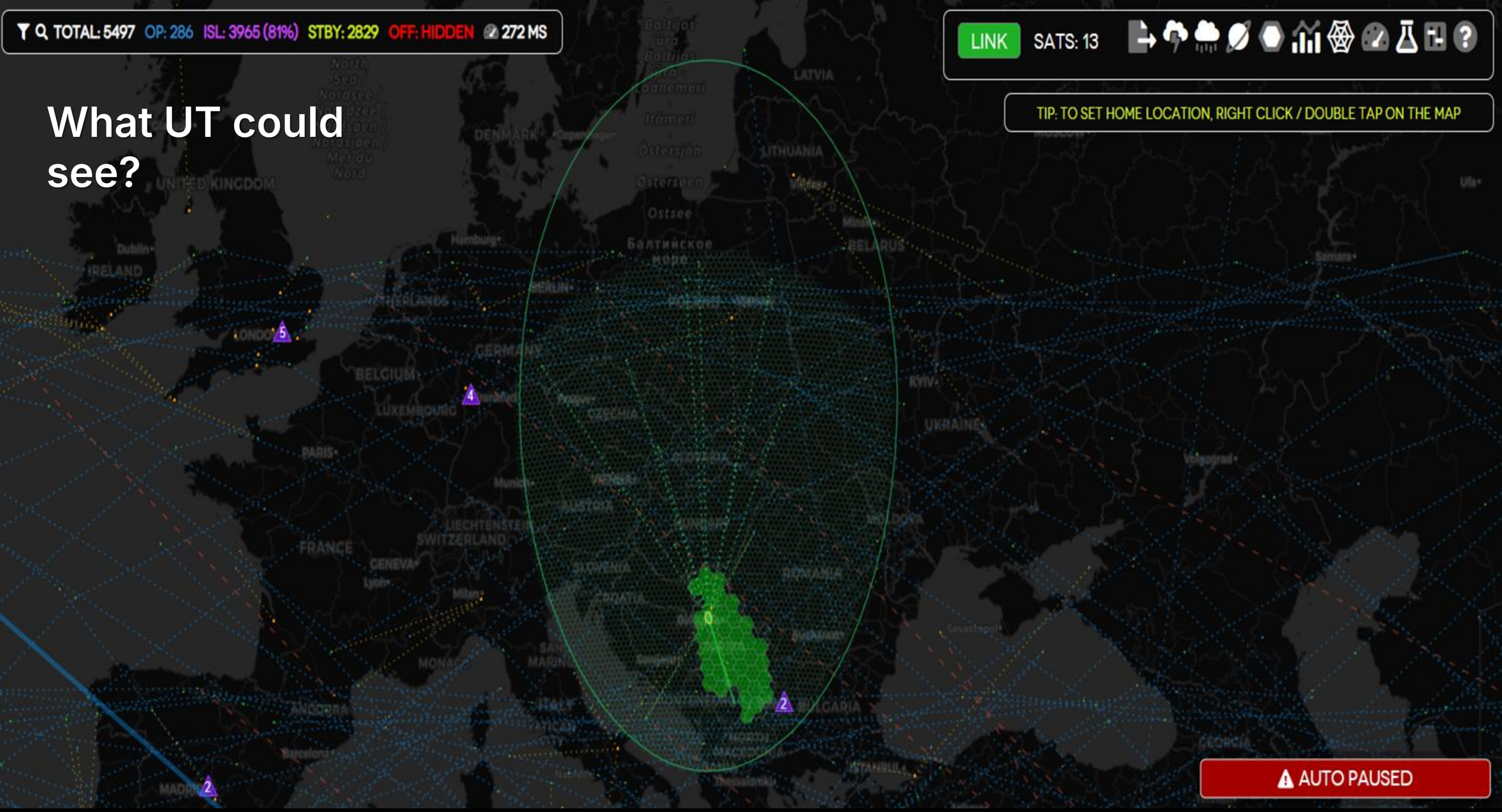
Ground Stations - PoPs

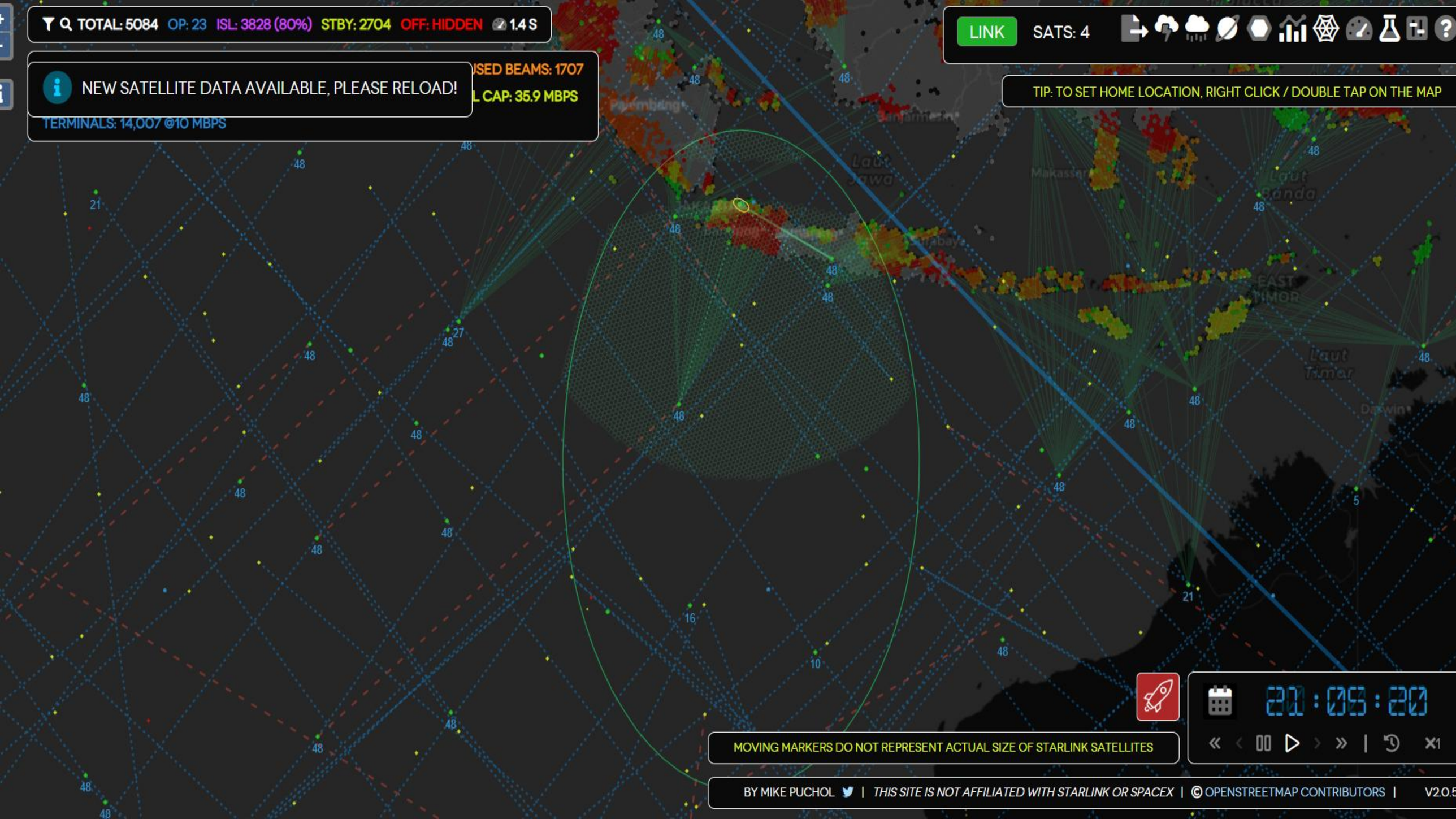
Internet



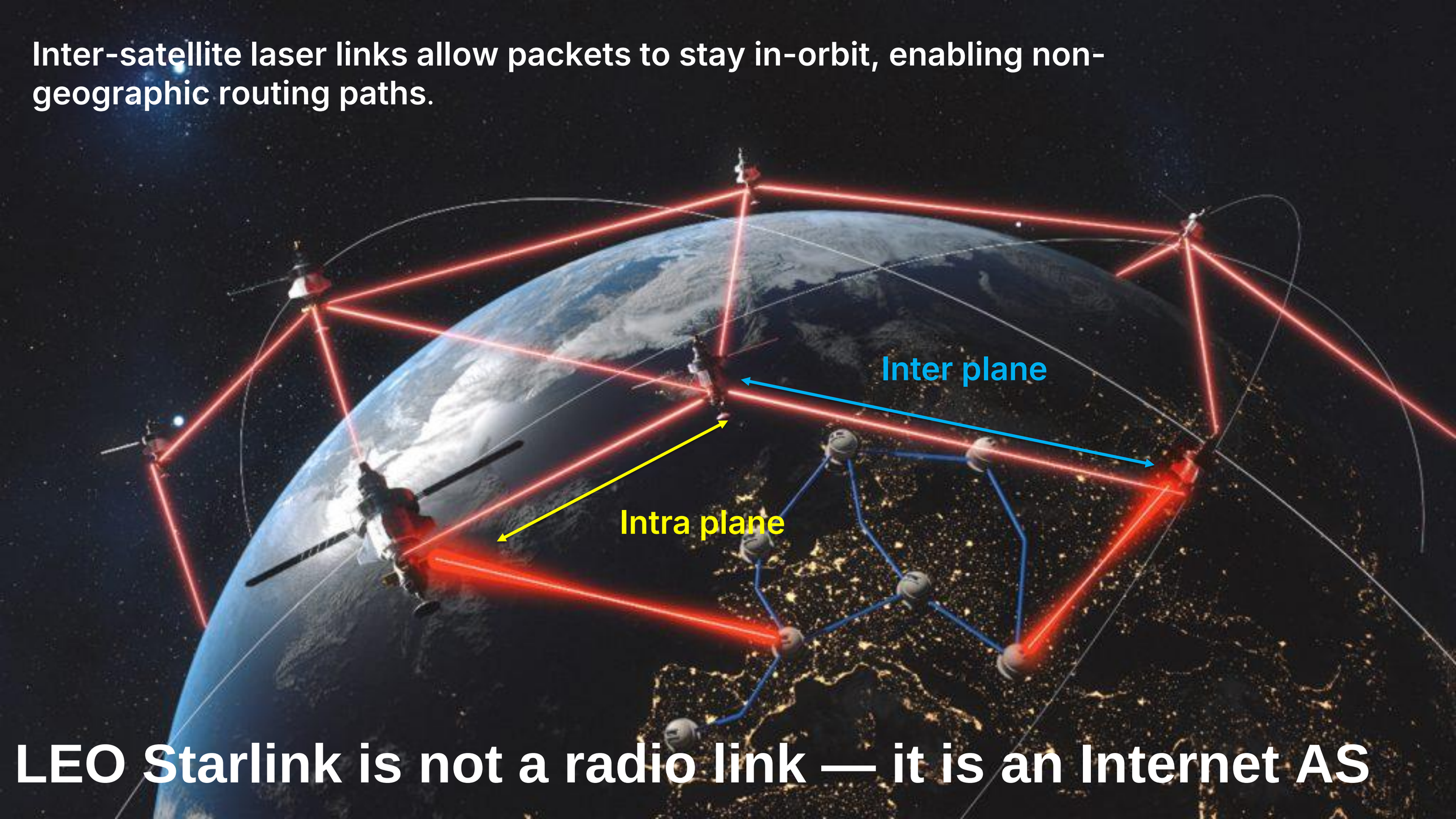


https://www.netify.ai/resources/telco/starlink


TOTAL: 5497 OP: 286 ISL: 3965 (81%) STBY: 2829 OFF: HIDDEN 272 MS
LINK SATS: 13
TIP: TO SET HOME LOCATION, RIGHT CLICK / DOUBLE TAP ON THE MAP
What UT could see?
AUTO PAUSED
https://starlink.sx

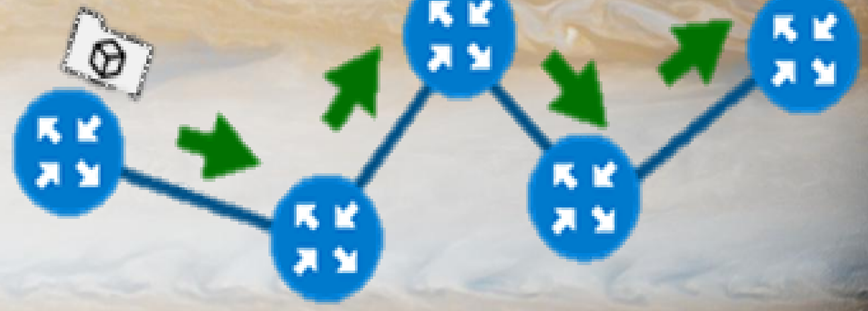

TOTAL: 5084 OP: 23 ISL: 3828 (80%) STBY: 2704 OFF: HIDDEN 1.4 S
NEW SATELLITE DATA AVAILABLE, PLEASE RELOAD!
USED BEAMS: 1707
L CAP: 35.9 MBPS
TERMINALS: 14,007 @10 MBPS
LINK
SATS: 4
TIP: TO SET HOME LOCATION, RIGHT CLICK / DOUBLE TAP ON THE MAP
MOVING MARKERS DO NOT REPRESENT ACTUAL SIZE OF STARLINK SATELLITES
BY MIKE PUCHOL | THIS SITE IS NOT AFFILIATED WITH STARLINK OR SPACEX | © OPENSTREETMAP CONTRIBUTORS | V2.0.5

Inter-satellite laser links allow packets to stay in-orbit, enabling non-geographic routing paths.

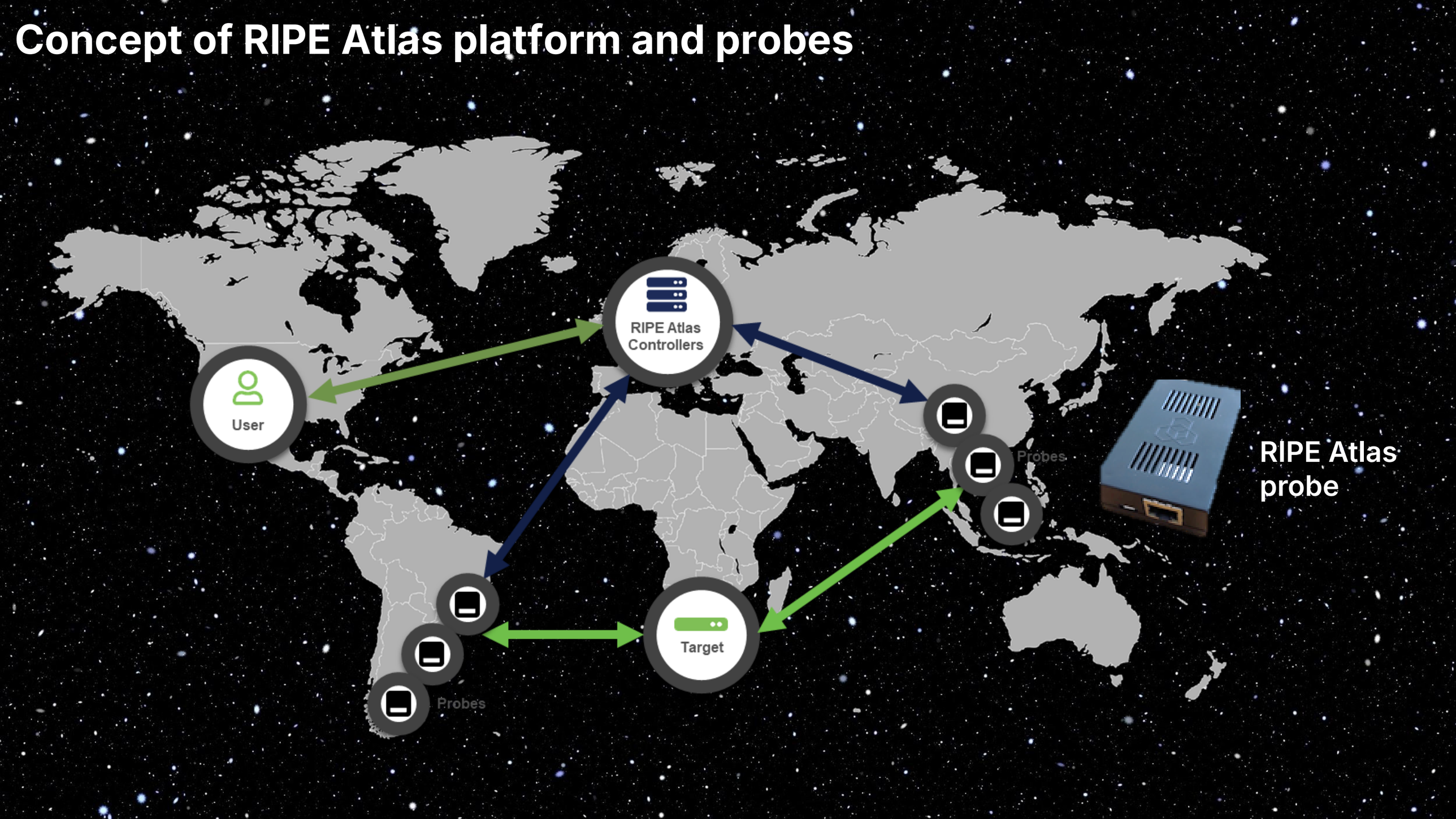


LEO Starlink is not a radio link — it is an Internet AS

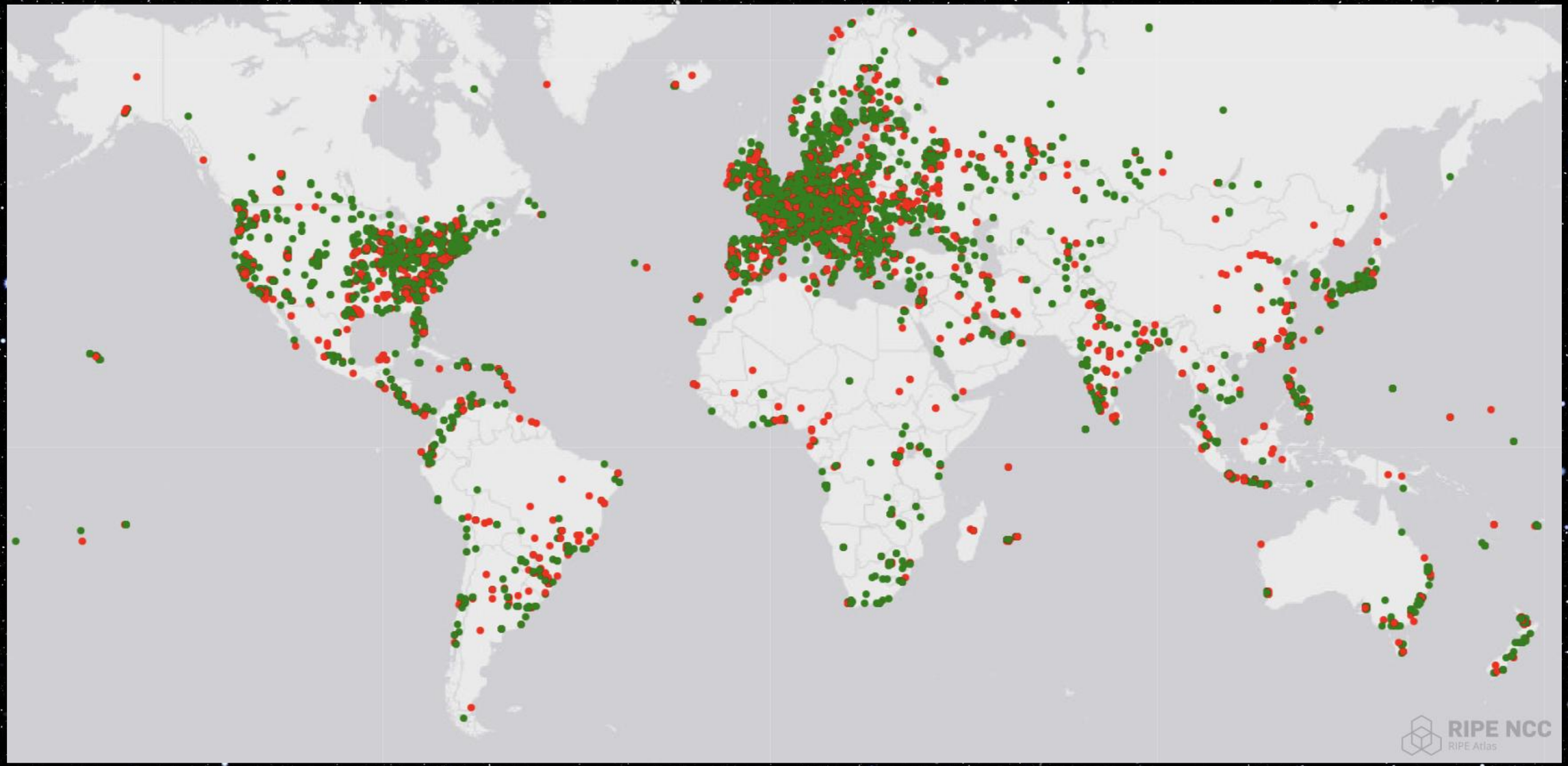
Why RIPE Atlas? A Global End-to-End View



Concept of RIPE Atlas platform and probes



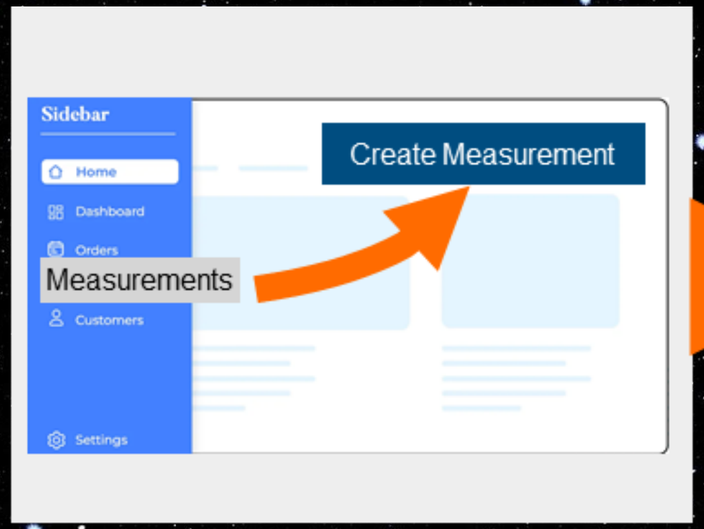
RIPE Atlas Coverage

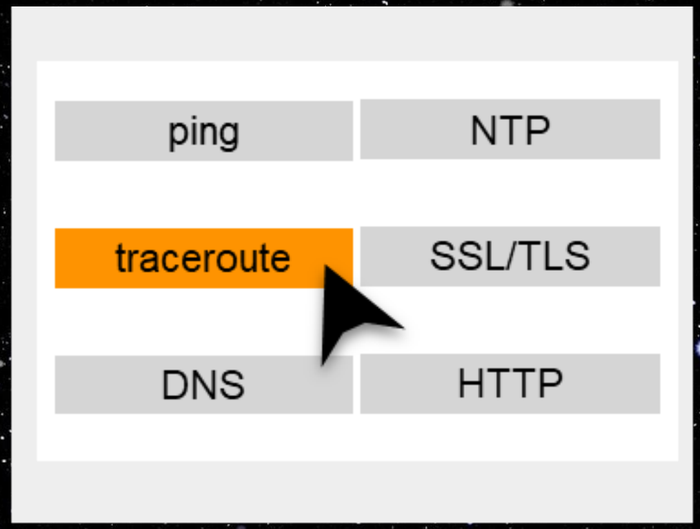


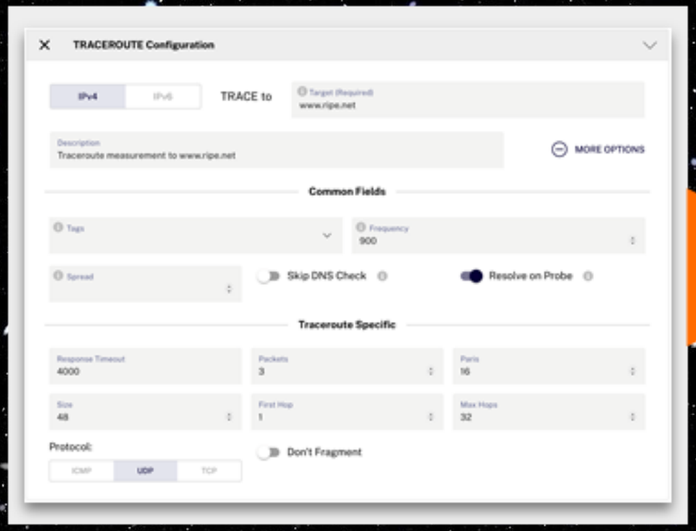
https://atlas.ripe.net/coverage/

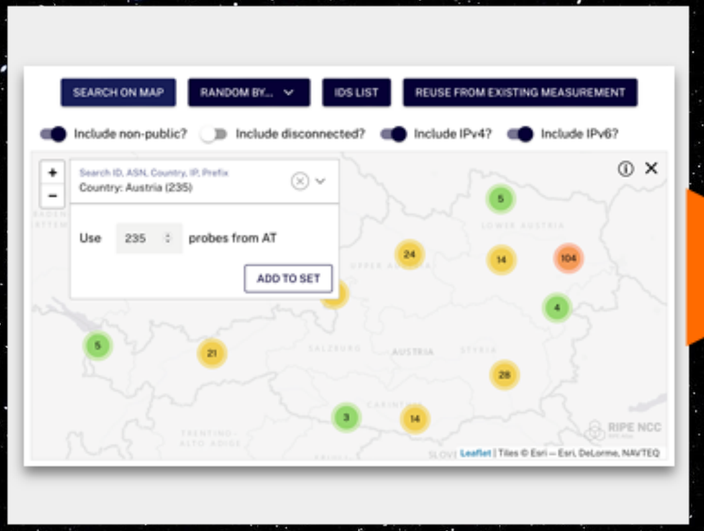
How to start measurements on the RIPE Atlas platform?

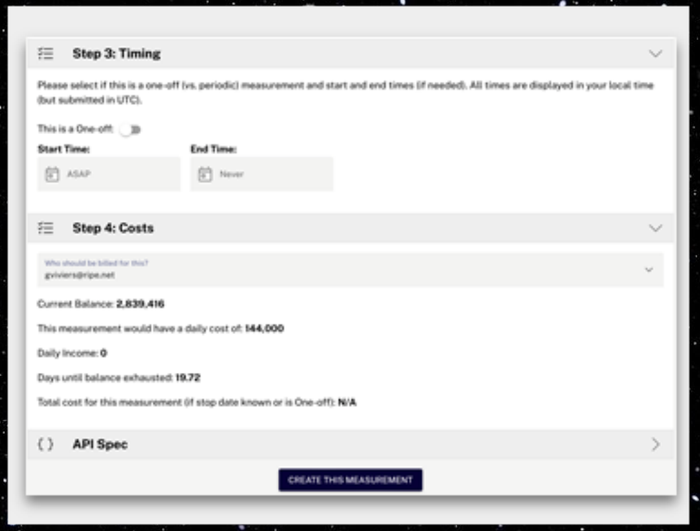












Measurement results

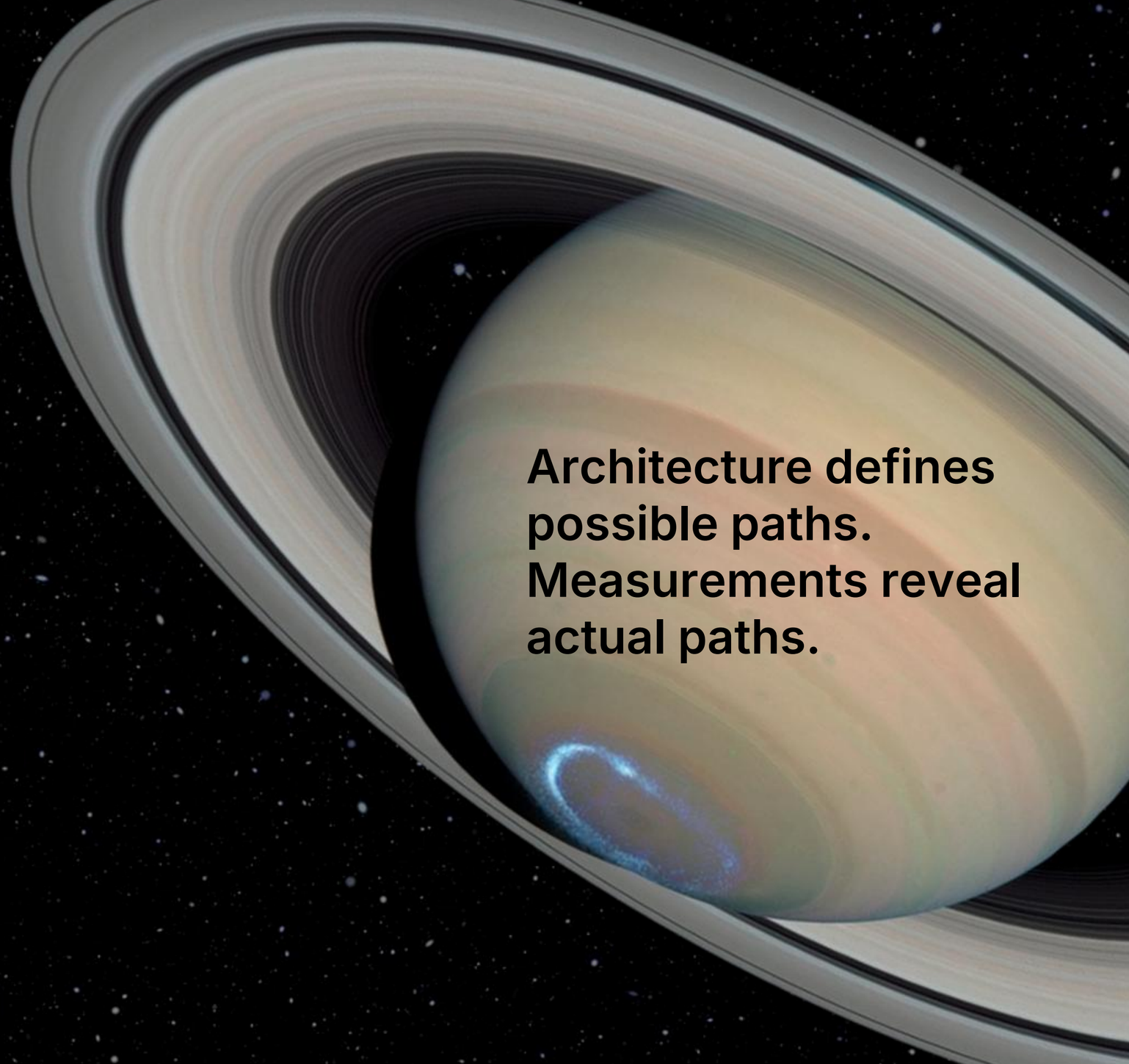
OVERVIEW | RESULTS | DETAILS

Search Results

DOWNLOAD RESULTS

Probe	ASN	Country All	Time (UTC)	Min RTT	Packet Loss
#####	#####	Where probe is located	When probe did it	RTT in milliseconds	Percent of packets lost
6025	8839	FR	2024-05-28 09:42:13	13.309 ms	0.00%
6352	13041	ES	2024-05-28 09:42:13	39.749 ms	0.00%

From Routing Theory to Measured Reality: Measuring End-to-End Paths with RIPE Atlas



Architecture defines possible paths. Measurements reveal actual paths.

Impact on latency

Satellite Communication	Mobile Communication
Architecture – UT → Satellite → ISL → Ground Station → Internet. Extra hops (space segment + PoPs) add latency. Latency depends not only on satellite altitude, but on:gateway selection, Point-of-Presence (PoP) location, inter-domain routing decisions	**Architecture** – UE → eNodeB/gNodeB → Backhaul → Core → Internet. Multiple layers (RAN + Core) introduce processing and tunneling delays.
Handover between beams – spikes (50–100 ms) when UT changes satellite beam at low elevation. Network itself is mobile (moving satellites). Frequent changes of: satellite, beam, gateway. Gateway switch-over can change Internet egress point and routing path.	**Cell handover** – spikes during RSRP/RSRQ-triggered HO, but in FWA very rare. User is mostly static → network path is mostly stable
Propagation effects – weather (rain, clouds, fog, vapor) + solar/magnetic radiation affect signal.	**Radio interface** – fading, interference, decoding errors, MIMO/beamforming fluctuations increase latency.
Congestion per beam/gateway or ISL – more UTs on one satellite beam → queuing delay, throughput drops.	**Congestion per cell/RAN/core/backhaul**– more UEs per cell → scheduling, buffering, queuing delay.
Extra hops (ISL / ground PoPs) – inter-satellite links and routing add RTT.	**Core network & routing** – EPC/5GC + peering/geography add processing and path delay.
Retransmissions (TCP/UDP) – due to jitter or packet loss in long satellite path.	**Protocols (TCP, QUIC, HTTPS)** – retransmissions, encryption overhead, session setup delays.

Setup: Fair Comparison Between FWA and LEO

- ✓ Goal: End-to-end comparison of terrestrial mobile and LEO satellite networks
- ✓ Perspective: End-host Internet performance (network-layer view, independent of application protocols)
- ✓ Measurement platform: RIPE Atlas Platform
- ✓ Comparable probe setup: RIPE Atlas probes connected via different access networks
- ✓ Probes were chosen from overlapping countries, ensuring identical geographic source regions and eliminating location-dependent latency effects.
- ✓ Same measurement tasks and timing

🗣️ The goal was not to optimize either network, but to observe how Internet routing behaves when only the access technology changes. Everything else is kept identical.

Access Scenarios: FWA vs Starlink

- ✓ Terrestrial Mobile (FWA)
- ✓ RIPE Atlas probe → LAN → 4G/5G router
- ✓ Stationary user (*Fixed Wireless Access*)
- ✓ Stable radio conditions
- ✓ Focus on core network & inter-domain routing



- ✓ LEO Satellite (Starlink)
- ✓ RIPE Atlas probe → LAN → Starlink router
- ✓ Dynamic space segment
- ✓ Alternative non-terrestrial routing paths



Selected Measurement Cases — Overview

Scenario	Region	Why this case?	What it reveals
Clean Overlap	**Japan → Europe**	Same source country and same destination anchor.	Access technology as the dominant variable (Mobile FWA vs Starlink)
Long-Haul Paths	**Europe → Asia**	Intercontinental routing with Tier-1 transit dominance.	Policy-driven detours and path inflation



Europe → Asia (Singapore): A Stress Test for Global Routing and Japan → Europe: The Clean Overlap Case

Europe → Asia (Singapore)

- ✓ One of the longest intercontinental Internet paths
- ✓ Strong dependence on Tier-1 transit and routing policies
- ✓ Ideal for exposing path inflation and routing detours
- ✓ Same destination, same measurement tasks

🗣️ If routing decisions matter anywhere, it’s on Europe–Asia paths. This scenario amplifies every architectural weakness.

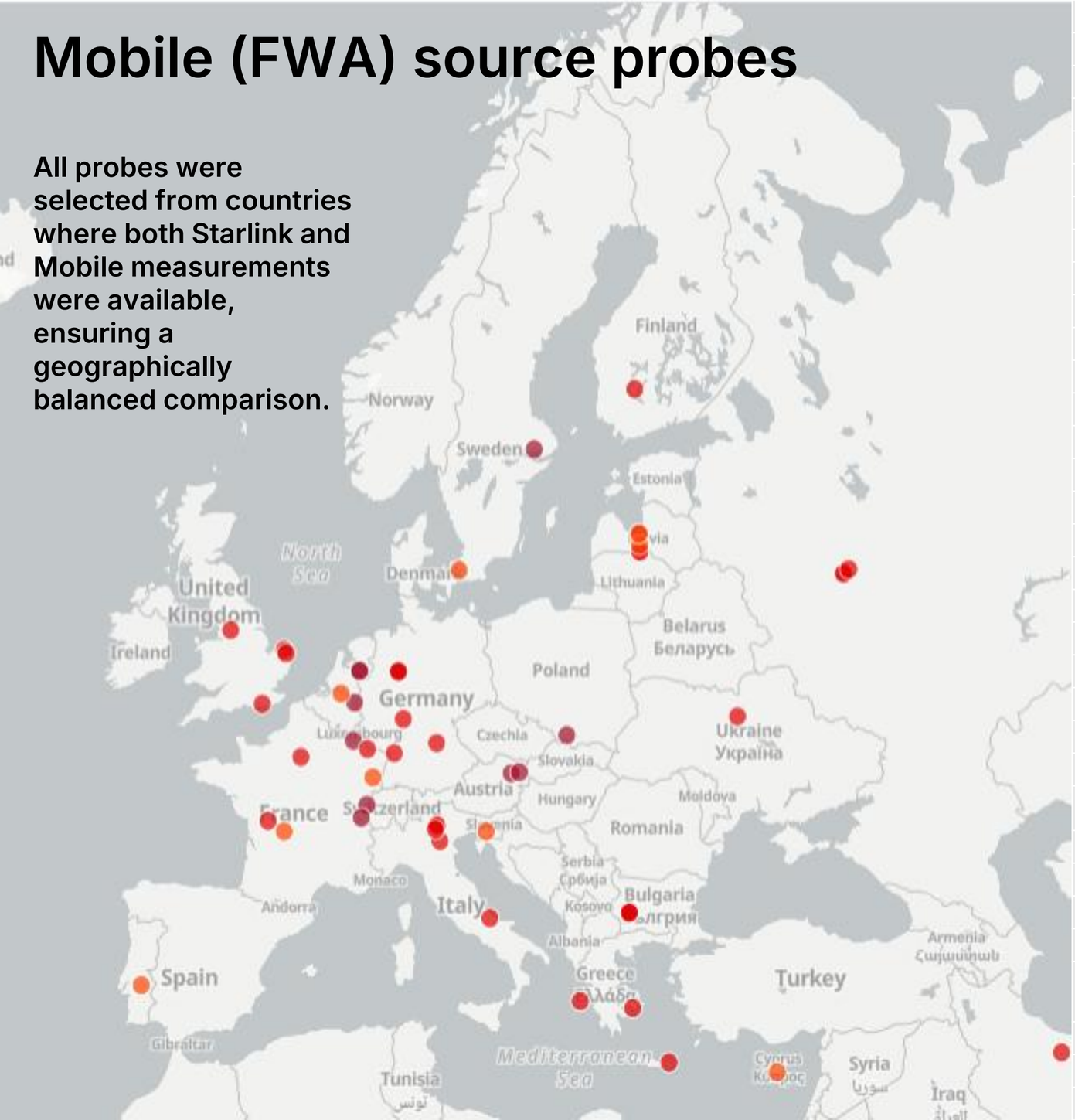
Why Singapore (SIN1) as Target

- ✓ Major Asia-Pacific Internet hub
- ✓ Dense Tier-1 and CDN presence
- ✓ Stable, globally reachable destination
- ✓ Minimizes target-side variability

🗣️ Ensures routing effects are observed on the path — not at the destination.

Mobile (FWA) source probes

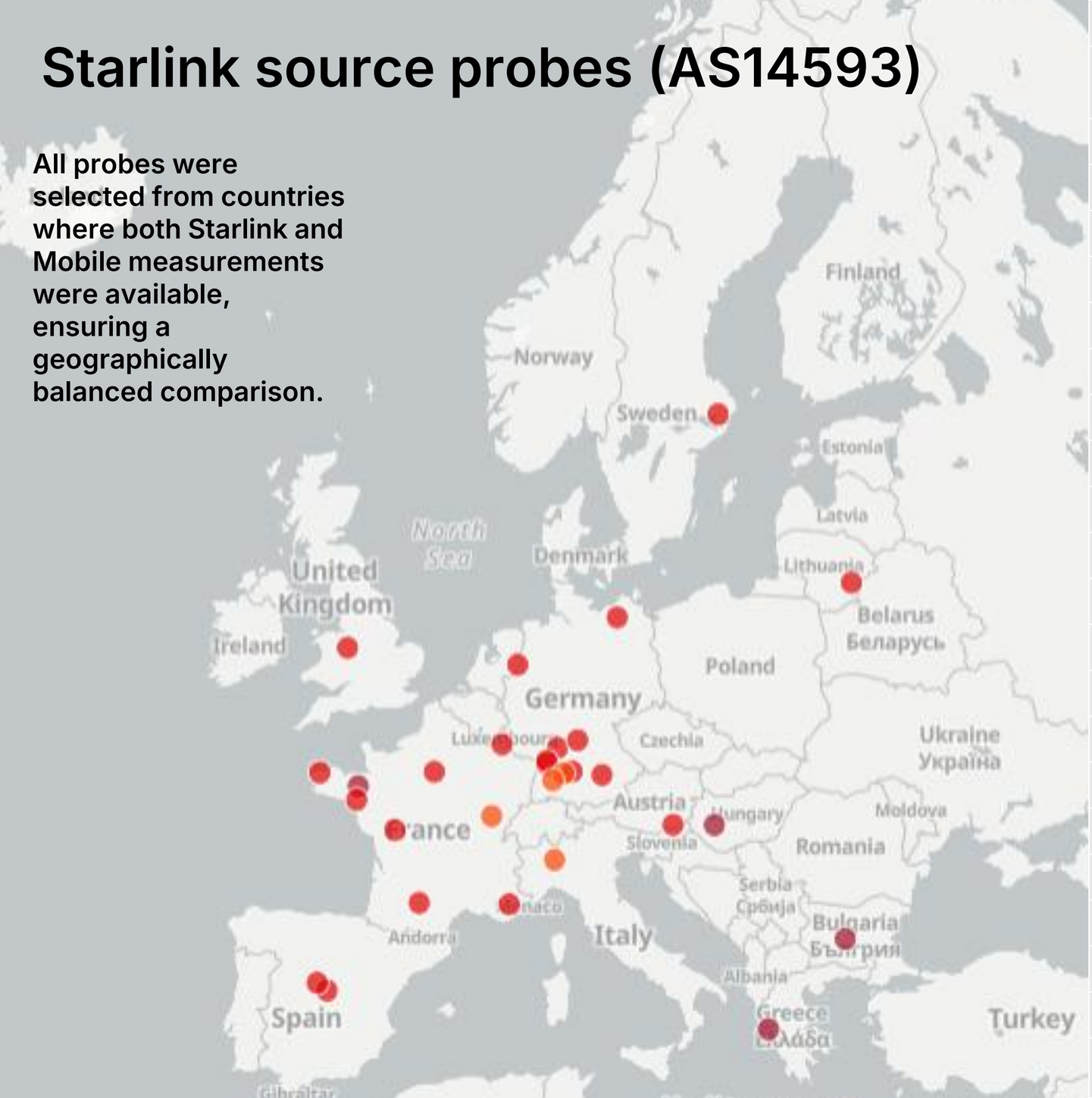
All probes were selected from countries where both Starlink and Mobile measurements were available, ensuring a geographically balanced comparison.



Country	Probe ID	ASN	Operator
Austria	21782	8447	A1 Telekom Austria
	22394	25255	Hutchison Drei Austria
Bulgaria	28126	12716	Mobiltel / A1 BG
	16377	8866	Vivacom
	64493	8866	Vivacom
France	60730	15557	SFR
	50288	15557	SFR
	17151	12322	Free SAS
	63046	51207	Zayo France
	53760	51207	Zayo France
	53064	51207	Zayo France
Germany	50081	3209	Vodafone DE
	34009	3320	Deutsche Telekom
	50532	3320	Deutsche Telekom
	52740	3320	Deutsche Telekom
	1004854	6805	Telefonica / O2 DE
Greece	55704	29247	Cosmote
	54804	29247	Cosmote
	1008005	29247	Cosmote
Italy	22074	30722	Vodafone IT
	21286	24608	WindTre
	50719	1267	Telecom Italia (TIM)
	21204	30722	Vodafone IT
	1003519	3269	Telecom Italia (TI Sparkle)
Netherlands	61071	33915	KPN
	1009782	33915	KPN
	13308	33915	KPN
Sweden	32463	3301	Telia Sweden
United Kingdom	1002421	51809	BRSK / Vodafone 4G (Mobile)
	14934	56478	Sky Broadband
	1006693	2856	BT
	53842	203649	Quickline / UK ISP

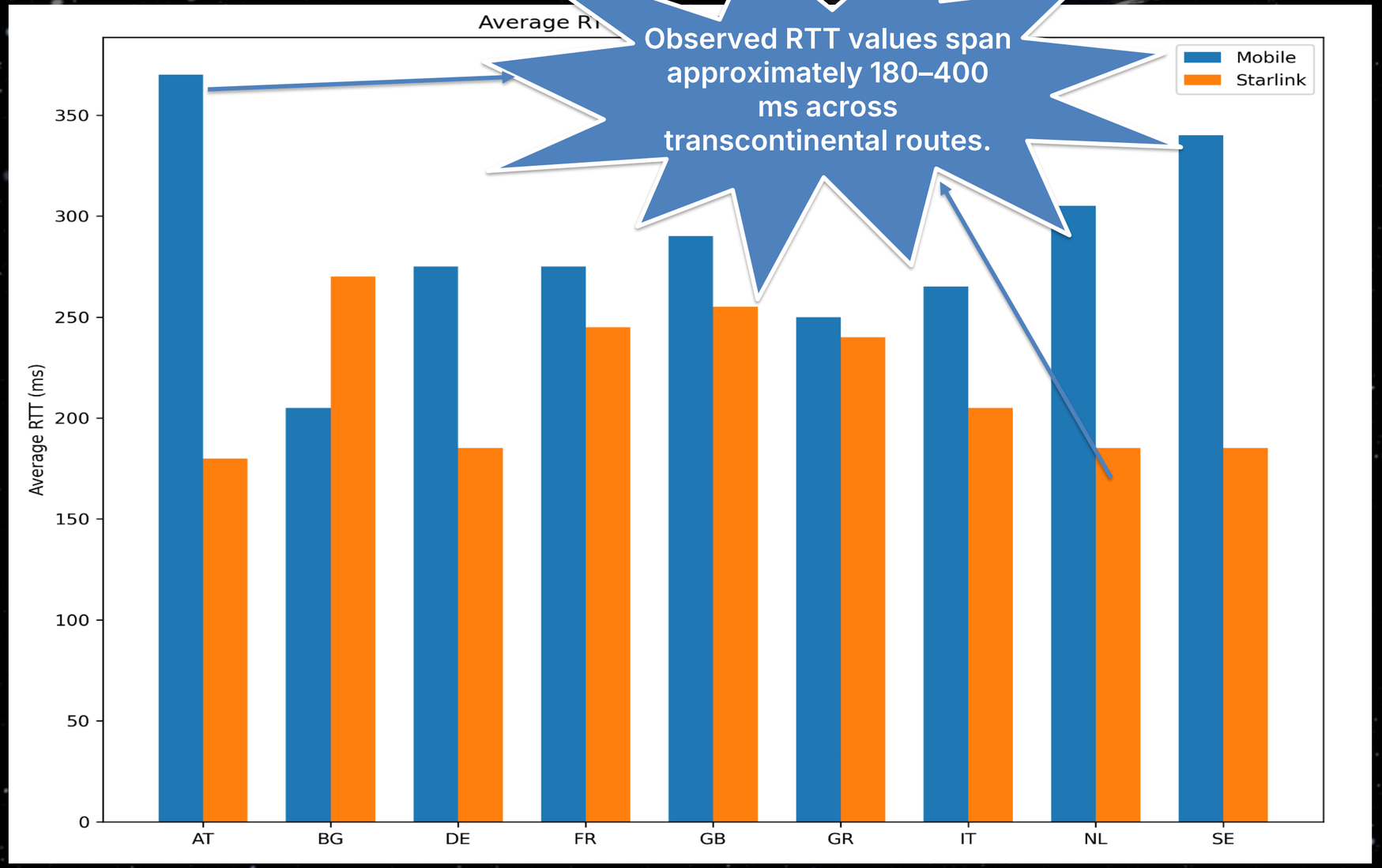
Starlink source probes (AS14593)

All probes were selected from countries where both Starlink and Mobile measurements were available, ensuring a geographically balanced comparison.



Country	Probe ID	ASN	Operator
Austria	619	14593	Starlink
Bulgaria	28911	14593	Starlink
France	32686	14593	Starlink
	1009802	14593	Starlink
	1010332	14593	Starlink
	51071	14593	Starlink
	62843	14593	Starlink
	26380	14593	Starlink
	16869	14593	Starlink
	53776	14593	Starlink
Germany	1000295	14593	Starlink
	65155	14593	Starlink
	1002750	14593	Starlink
	1006857	14593	Starlink
	60323	14593	Starlink
	1009091	14593	Starlink
	62514	14593	Starlink
Greece	60549	14593	Starlink
Italy	1006191	14593	Starlink
Netherlands	1004353	14593	Starlink
Sweden	11585	14593	Starlink
United Kingdom	51136	14593	Starlink

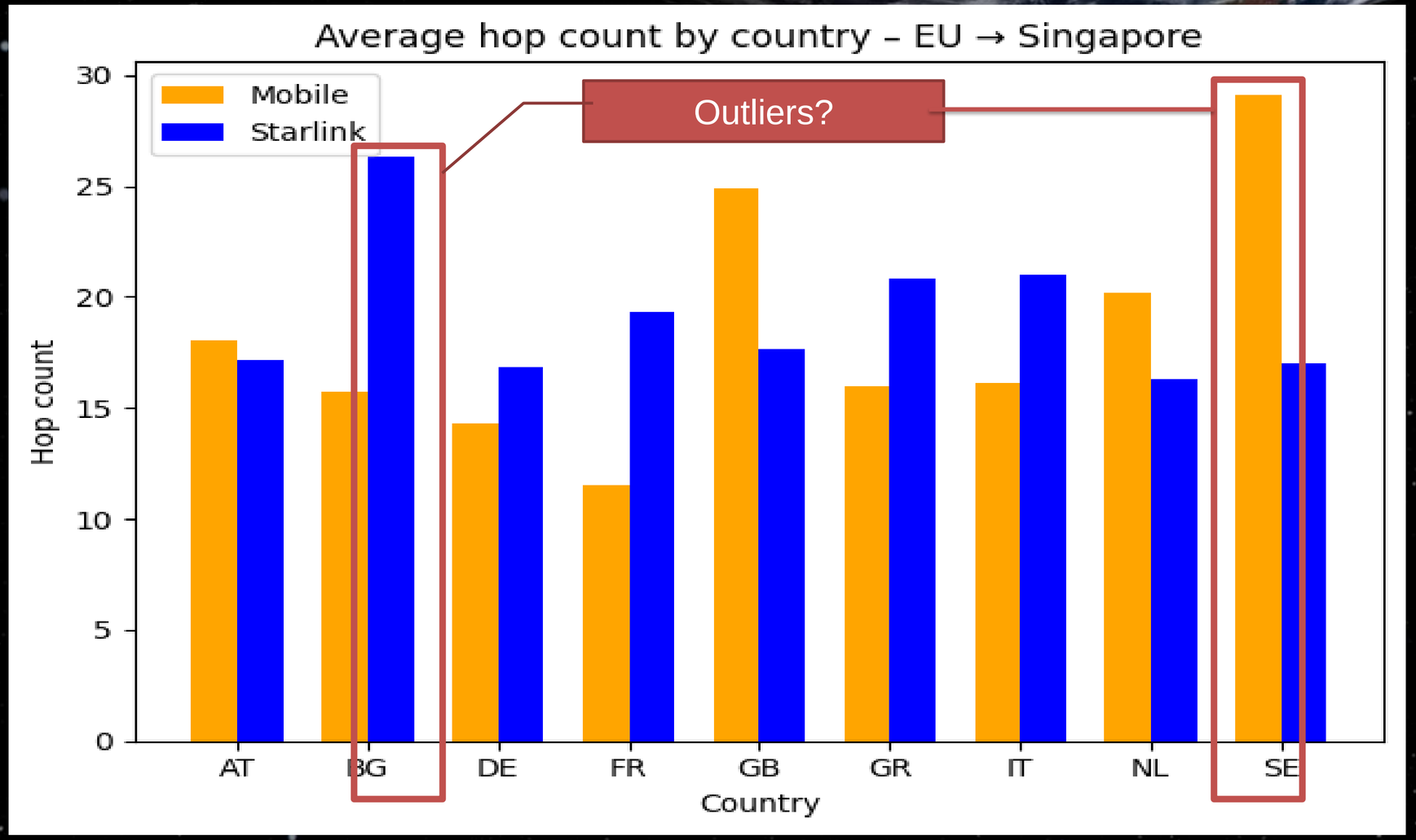
RTT Distribution (Europe → Singapore)



Mobile:
Wide spread
High jitter
Extreme outliers (>600 ms)

Starlink:
Lower median RTT
Narrow distribution
More stable

Hop Count ≠ End-to-End Latency



Bulgaria: inflated hop count + inflated RTT (routing outlier: EU → US → Asia)
Sweden: high hop count with high RTT
Starlink: often higher hop count, but lower end-to-end RTT

Backbone efficiency dominates hop count

Hop count is a poor predictor of latency when routing policies dominate.

Traceroute Breakdown using Khipu – Probe 1000295 DE (Starlink → Singapore Linode)

customer.frntdeu1.pop.starlinkisp.net

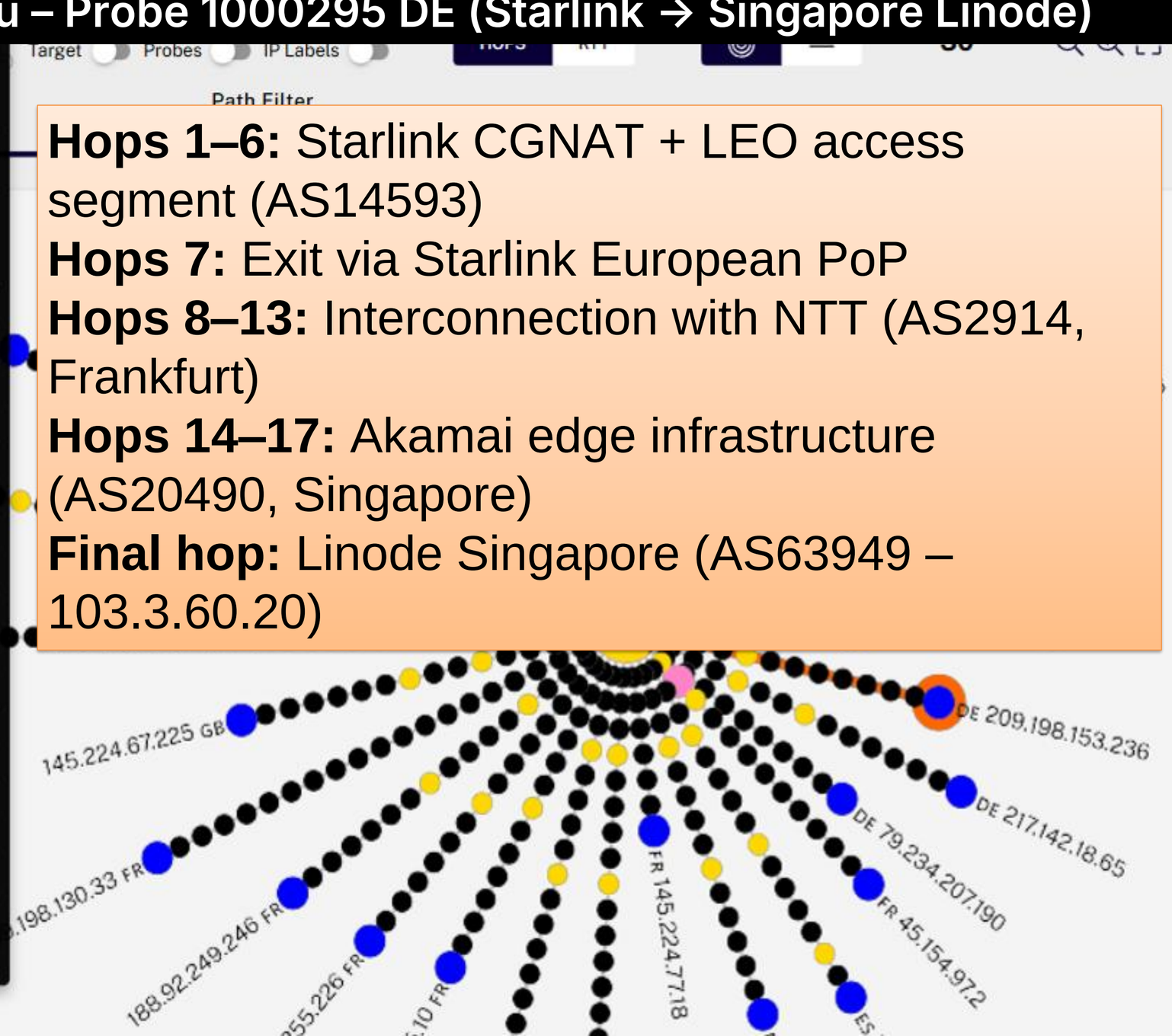
DE Germany

US AS14593 (United States-registered)

Complete Traceroute:

Hop	IP Address	Hostname	ASN	RTT (ms)
1	172.17.0.1			0.36/0.33/0.18
2	192.168.138.5			0.55/0.41/0.44
3	100.64.0.1			18.58/27.81/21.84
4	172.16.252.56			27.72/17.82/23.97
5	206.224.68.194	undefined.hostname.localhost	14593	19.29/19.9/23.86
6	206.224.65.190	undefined.hostname.localhost	14593	31.82/26.49/21.99
7	213.198.72.18	ae-26.a03.frnkge13.de.bb.gin.ntt.net	2914	18/21.75/15.88
8	*	*	2914(?)	*
9	*	*	2914(?)	*
10	*	*	2914(?)	*
11	*	*	2914(?)	*
12	129.250.2.217	ae-0.a01.sngpsi08.sg.bb.gin.ntt.net	2914	202.97/202.83/213.59
13	116.51.27.218	ae-1.akamai.sngpsi08.sg.bb.gin.ntt.net	2914	291.86/205.57/210.93
14	23.56.139.29	ae23.gw1.sin1.netarch.akamai.com	20940	207.37/201.75/202.25
15	*	*	*	*
16	*	*	*	*
17	*	*	*	*
18	103.3.60.20	resolver-3.sin1.sg.prod.linode.com	63949	204.26/196.21/206.49

Hops 1–6: Starlink CGNAT + LEO access segment (AS14593)
Hops 7: Exit via Starlink European PoP
Hops 8–13: Interconnection with NTT (AS2914, Frankfurt)
Hops 14–17: Akamai edge infrastructure (AS20490, Singapore)
Final hop: Linode Singapore (AS63949 – 103.3.60.20)



Traceroute Breakdown using Khipu – Probe 50081 DE (Mobile LTE → Singapore Linode)

DE Germany

Probe: 50081

Status: All traces successful

Complete Traceroute:

Hop	IP Address	Hostname	ASN	RTT (ms)	Country
1	192.168.102.1			1.29/0.95/0.88	-
2	*	*	*	*	*
3	*	*	*	*	*
4	*	*	*	*	*
5	*	*	*	*	*
6	92.214.120.30	ipservice-092-214-120-030.092.214.poo...	3209	31.31/38.32/37.44	DE Germany HIGH
7	145.254.2.199		3209	33.75/19.77/29.67	DE Germany MEDIUM
8	195.2.18.189	ae38-100-xcr1.dus.cw.net	1273	29.83/29.58/29.7	GB United Kingdom MEDIUM
9	195.2.2.142	ae12-xcr2.fri.cw.net	1273	234.83/234.86/255.96	EU EU MEDIUM
10	195.2.8.37	ae33-xcr1.hkg.cw.net	1273	209.31/211.13/216.17	EU EU MEDIUM
11	195.2.24.86	ae21-xcr2.sgs.cw.net	1273	244.33/229.91/219.06	EU EU MEDIUM
12	195.2.19.246	as20940-gw-xcr2.sgs.cw.net	1273	232.02/226.91/220.13	EU EU MEDIUM
13	23.56.139.29	ae23.gw1.sin1.netarch.akamai.com	20940	231.77/230.84/229.93	SG Singapore HIGH
14	*	*	*	*	*
15	*	*	*	*	*
16	*	*	*	*	*
17	103.3.60.20	resolver-3.sin1.sg.prod.linode.com	63949	237.59/229.67/229.48	SG Singapore HIGH

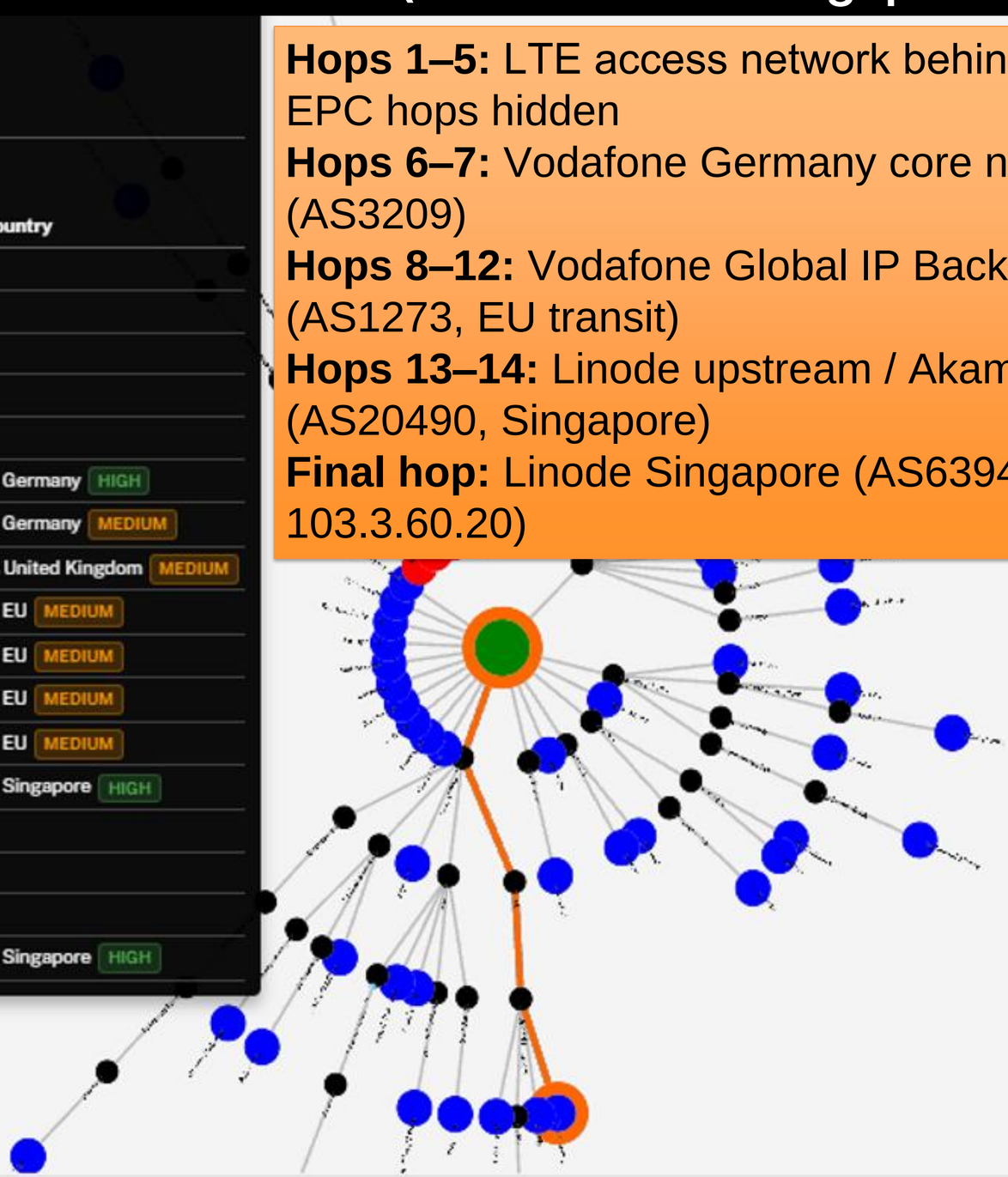
Hops 1–5: LTE access network behind CGNAT → EPC hops hidden

Hops 6–7: Vodafone Germany core network (AS3209)

Hops 8–12: Vodafone Global IP Backbone (AS1273, EU transit)

Hops 13–14: Linode upstream / Akamai transit (AS20490, Singapore)

Final hop: Linode Singapore (AS63949 – 103.3.60.20)



Hop	IP Address	Hostname	ASN	RTT (ms)
1	192.168.100.1			0.52/0.57/0.63
2	*	*	*	*
3	10.131.198.81			23.41/17.95/19.78
4	81.228.75.206	hy-c1-link.se.telia.net	3301	18.79/20.66/18.64
5	81.228.91.79	hy-peer1-link.se.telia.net	3301	18.62
6	62.115.123.170	sto-b2-link.ip.twelve99.net	1299	18.27/27.86/21.37
7	62.115.140.216	sto-bb2-link.ip.twelve99.net	1299	20.52/18.17/15.13
8	62.115.139.173	kbn-bb6-link.ip.twelve99.net	1299	26.25/25.18/24.76
9	80.91.254.91	ewr-bb2-link.ip.twelve99.net	1299	102.66/104.77/114.72
10	62.115.132.135	chi-bb2-link.ip.twelve99.net	1299	167.54/164.26/164.78
11	62.115.136.103	kanc-bb2-link.ip.twelve99.net	1299	182.69/184.2/190.2
12	62.115.140.185	den-bb2-link.ip.twelve99.net	1299	141.59/140.58/137.32
13	62.115.139.112	palo-bb2-link.ip.twelve99.net	1299	190.73/168.72/191.33
14	*	*	*	*
15	62.115.180.214	kddiamericainc-ic-350222.ip.twelve99-cust.net	1299	173.6/167.53/171.69
16	111.87.3.233		2516	185.53/184.62/189.46
17	106.187.13.41		2516	280.69/279.73/281.19
18	27.85.227.125		2516	300.76/294.38/296.81
19	27.85.227.125		2516	306.06/304.69/304.7
20	27.86.32.2	oteJIN301.int-gw.kddi.ne.jp	2516	299.73/291.05/289.95
21	111.237.74.186		2516	284.64/282.1/282.64
22	23.56.142.44	ae2.r02.tyo03.icn.netarch.akamai.com	20940	299.43/292.56/294.76
23	23.215.54.46	ae10.r02.sin02.icn.netarch.akamai.com	20940	344.23/343.96/345.01
24	23.56.139.43	ae8.r02.sin02.ien.netarch.akamai.com	20940	341.62/345.28/338.84
25	23.56.139.19	ae23.gw2.sin1.netarch.akamai.com	20940	347.67/341.83/343.7
26	*	*	*	*
27	*	*	*	*
28	*	*	*	*
29	103.3.60.20	resolver-3.sin1.sg.prod.linode.com	63949	352.45/350.14/344.76

Sweden → Singapore: Tier-1 Detour Case

- ✓ Early entry into Tier-1 (AS1299 / Arelion)
- ✓ Traffic routed via North America
- ✓ Stable but extremely high RTT
- ✓ Caused by BGP policy, not geography

Contrast:
Starlink avoids detour
→ ~2× lower RTT

Hop	IP Address	Hostname	ASN	RTT (ms)
1	192.168.178.1			1.18/0.96/0.97
2	*	*	*	*
3	172.18.25.44			6.24/6.32/6.36
4	172.18.25.212			7.46/6.95/7.49
5	172.19.184.22			8.11/8.23/8.29
6	172.19.177.68			11.88/12.04/11.7
7	172.19.177.8			19.78/20.01/20.11
8	195.22.192.144		6762	20.59/20.77/41.69
9	93.186.133.95		6762	172.04/171.65/185.14
10	93.186.133.87		6762	273.39/273.15/273.42
11	23.56.138.53	ae22.gw2.sin1.netarch.akamai.com	20940	270.59/267.88/268.07
12	*	*	*	*
13	*	*	*	*
14	*	*	*	*
15	103.3.60.20	resolver-3.sin1.sg.prod.linode.com	63949	262.56/262.14/262.54

Italy → Singapore: When Routing Is Reasonable

- ✓ Mobile uses geographically sensible route
- ✓ No intercontinental detours
- ✓ RTT comparable to Starlink

Japan → Europe: The Clean Overlap Case

- ✓ Asian country with both Mobile and Starlink RIPE Atlas probes
- ✓ Identical source geography (Japan)
- ✓ Identical destination anchor (Amsterdam, AS3333)
- ✓ Mobile (FWA) vs LEO satellite (Starlink)
- ✓ Geographic bias fully eliminated
- ✓ Major Asia-Pacific Internet hub

🗣️ Japan is the only case where geography, destination, and topology are controlled — leaving routing behavior as the dominant variable.

Egress Point Behavior: Mobile vs Starlink (Japan → Europe)

Mobile (FWA):
- ✓ Observed behavior
- ✓ Single, fixed egress point across all traceroutes
- ✓ Stable ASN sequence over time
- ✓ No dynamic path adaptation

Starlink (LEO)
- ✓ Observed behavior
- ✓ Multiple egress points observed across traceroutes
- ✓ Dynamic selection between Tier-1 providers (e.g., NTT, Tata)
- ✓ ASN path changes without service disruption

🗣️ Mobile networks rely on a single fixed egress path, while Starlink dynamically selects its egress into the global backbone — enabling more stable long-haul performance.

Structural Comparison (Japan → Europe)

Segment	Mobile (FWA)	Starlink (LEO)
Access / Local	AS138384 (Mobile operator, JP) • CGNAT + mobile core introduce early RTT variability • Initial latency fluctuations propagate end-to-end	AS14593 (Starlink) • Short, controlled access segment • Low jitter at access despite satellite hop
Regional transit	AS2516 (KDDI, Tier-2) • Stable ASN sequence • RTT variability persists even with fixed topology	AS2516 (KDDI, Tier-2) • Early handoff to backbone • More consistent RTT behavior
Global backbone	AS2914 (NTT, Tier-1) • Fixed backbone entry • Congestion effects visible without route change	AS2914 (NTT) / AS6453 (Tata) / AS6830 (Arelion) • Multiple backbone options • Dynamic selection based on performance
Hop count behavior	• Mostly constant (18 → 19 hops) • Hop count stability does **not** imply RTT stability	• Initial adjustment (21 → 19 hops) • Hop count may be equal or higher, yet RTT is lower
RTT over time	• Higher median RTT • Wide interquartile range • Pronounced daily oscillations	• Lower median RTT • Narrow distribution • High temporal stability
Egress behavior	Single, fixed egress point • No observable rerouting during congestion	Multiple, dynamic egress points • Route adaptation improves latency stability
Destination	AS3333 (RIPE NCC, Amsterdam)	AS3333 (RIPE NCC, Amsterdam)

Key Insights on Long-Haul Routing: Starlink vs. Terrestrial Mobile

- ✓ Hop count is not a reliable latency indicator
- ✓ Tier-1 presence does not guarantee optimal paths
- ✓ Mobile networks suffer from: Core congestion and Policy-driven detours
- ✓ Starlink benefits from: Early backbone entry and more flexible routing
- ✓ **Final message :Routing architecture dominates access technology**
- ✓ The future of transcontinental routing hinges on broader ISL integration and stronger PoP presence in Asia



NTN–TN Interoperability: Practical Necessity or Future Vision?



Starlink enables connectivity where terrestrial networks fail

Remote and rural communities



Remote and rural communities



Islands and maritime environments



Remote and rural communities



Research, education and healthcare access



Emergency and disaster response



Future research

- ✓ Beyond ICMP: Measure end-to-end application latency (TLS setup, full session bootstrapping).
- ✓ Global Starlink Coverage: Use all Starlink-enabled probes for multi-continent comparisons.
- ✓ Mobile vs. Satellite: Compare 4G/5G core latency and dual-stack (IPv4/IPv6) routing behavior.
- ✓ Routing Intelligence: Detect anomalies (loops, asymmetries, policy detours) and evaluate ISL impact on long-haul efficiency.

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Space may be dark...
But the future of satellite communication is bright -
where connectivity will meet interoperability,
day and night!




Thank you for your attention!
Q&A?

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