# Beyond the Radio Link: Routing Dynamics in LEO Satellite Networks

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# FROM SPACE TO THE INTERNET

## AGENDA

**01**

### WHY LEO CHANGES INTERNET ROUTING

Connectivity challenges and Internet architecture



**02**

### LEO NETWORKS AS PART OF THE INTERNET

Gateways, ISLs, PoPs and AS routing



**03**

### MEASUREMENT METHODOLOGY

RIPE Atlas and end-to-end measurements




**04**

### ROUTING DYNAMICS IN PRACTICE

Europe → Asia case study



**05**

### WHAT MEASUREMENTS REVEALED

What they tell us about routing dynamics





# THE SATELLITE ECOSYSTEM IS EVOLVING

FROM EXPLORATION TO GLOBAL CONNECTIVITY



## ARTEMIS II

PUSHING THE BOUNDARIES
OF SPACE COMMUNICATIONS

NASA

Optical communications
and deep space networks

## LEO CONSTELLATIONS

A NEW LAYER OF
GLOBAL CONNECTIVITY

STARLINK · OneWeb · amazon | project kuiper · TELESAT · iridium



Space-based networks
providing global coverage

## DIRECT-TO-CELL

SATELLITE CONNECTIVITY
TO STANDARD DEVICES

STARLINK · AST SpaceMobile · SAMSUNG



Satellite-to-smartphone
direct connectivity

## INTEGRATED NETWORKS

A SEAMLESS GLOBAL INTERNET

3GPP A GLOBAL INITIATIVE | ITU



Terrestrial + non-terrestrial
networks as one Internet



**Global connectivity** is not truly global.

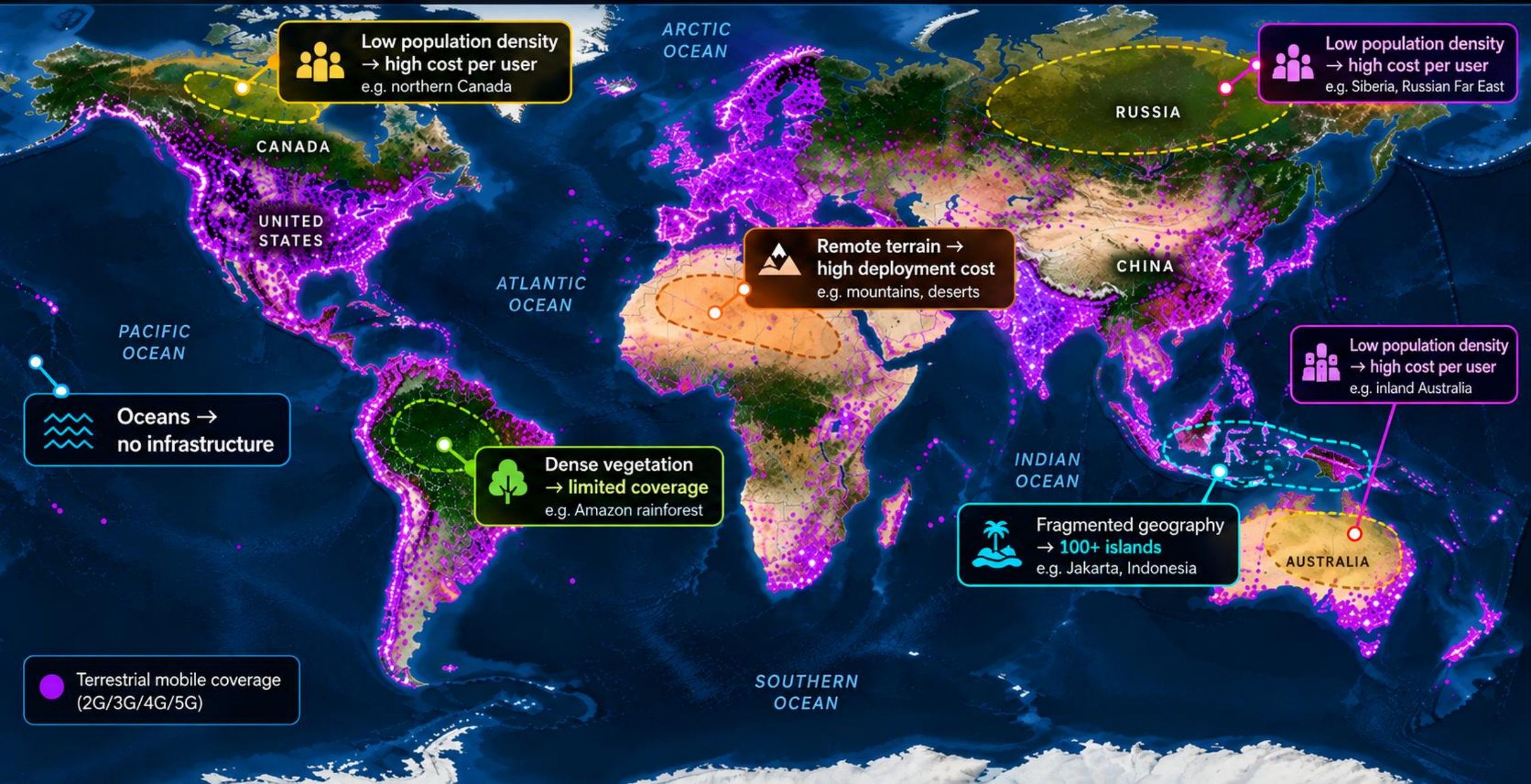
Internet performance depends on **routing decisions**,
not only on distance.

**~300M people** live outside mobile broadband coverage (GSMA).

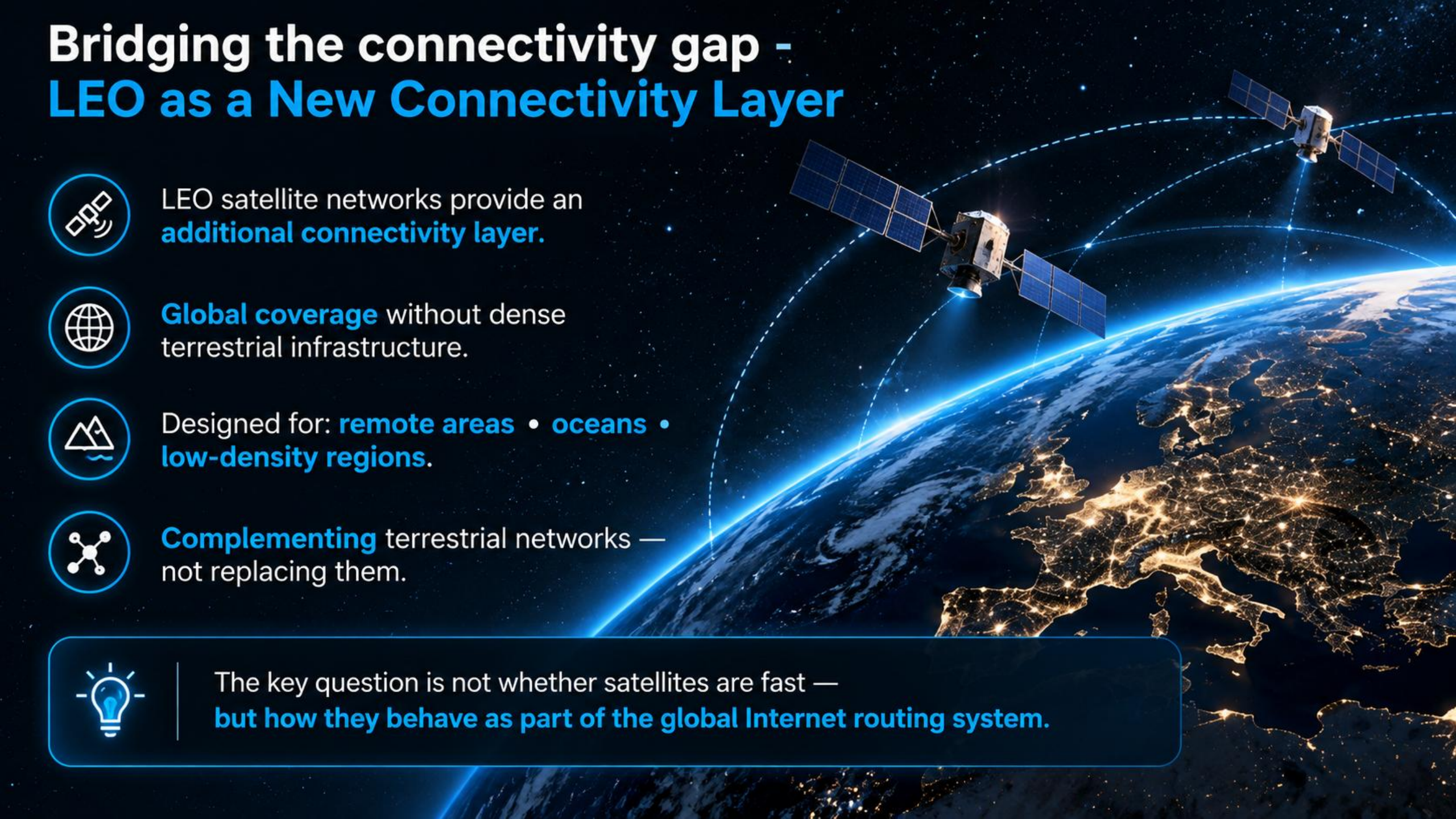
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As LEO networks become part of the Internet,
**routing behavior** becomes **as important as radio coverage**.

# Why terrestrial infrastructure cannot reach everywhere?



# Bridging the connectivity gap - LEO as a New Connectivity Layer



LEO satellite networks provide an **additional connectivity layer.**

**Global coverage** without dense terrestrial infrastructure.

Designed for: **remote areas** • **oceans** • **low-density regions**.

**Complementing** terrestrial networks — not replacing them.

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

# FROM BENT-PIPE TO SPACE-BASED NETWORKING

How LEO satellites become active network nodes.

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

On-board processing & in-space routing (enables dynamic multi-hop paths between satellites).

**Optical ISLs** (space-based backbone)

**LEO satellite (Starlink)** ~550 km

**LEO satellite (Starlink)** ~550 km

**Ku-band** (uplink) 14.0 – 14.5 GHz

**Ku-band** (downlink) 10.7 – 12.7 GHz

**Ka-band** (downlink) 17.3 – 30.0 GHz

**Ka-band** (uplink) 27.5 – 30.0 GHz

**STARLINK LINK FREQUENCIES (Ku/Ka-bands)**

| Link | Band | Frequency range |
|---|---|---|
| User ↔ Satellite (user link) | Ku-band (uplink) | 14.0 – 14.5 GHz |
| | Ku-band (downlink) | 10.7 – 12.7 GHz |
| Satellite ↔ Gateway (feeder link) | Ka-band (uplink) | 27.5 – 30.0 GHz |
| | Ka-band (downlink) | 17.3 – 30.0 GHz |

**User terminal (Starlink)**
(Dish antenna)
**Mendoza**
32.89° S, 68.84° W

Mendoza (User terminal)

**Noviciado Gateway**
(Lampa, Santiago), Chile
33.3927° S, 70.8831° W

Internet

**PoP**
(Point of Presence)
Where traffic enters the global Internet (peering & routing)

CHILE

ARGENTINA

Noviciado Gateway

**Ground gateway (Starlink)**
- Connects satellites to terrestrial fiber networks
- Forwards user traffic to the global Internet (and vice versa)
- Provides interface between space segment and terrestrial networks

Home router (Wi-Fi)

PC

**LAN** (home network)

LEO satellites connect user terminals to the global Internet via **dynamic, multi-hop paths.**

# STARLINK GLOBAL PoP LOCATIONS

## Where Starlink connects to the terrestrial Internet

STARLINK




**50+**
**global PoP locations**

Starlink uses PoPs to connect its satellite network to terrestrial Internet infra s tructure.

**Starlink AS14593 — public IXP connectivity**

| 77 | 108 | 24.9 |
|---|---|---|
| IXPs | ports | Tbps provisioned peering capacity |

IXPs enable direct interconnection (peering) with other networks and can help traffic enter the terrestrial Internet closer to users, reducing latency and improving performance.

Source: PeeringDB / current public data, Sep 2026

**Starlink PoP / interconnection facility**
(PeeringDB + Starlink information)

A PoP is a terrestrial entry point where Starlink connects its satellite network to the wider Internet infrastructure.
The home PoP for a user can change over time (e.g. due to mobility) and traffic may be routed to different PoPs to optimize performance.

# Starlink LEO Connectivity – Satellite Handover Example

Illustration of two consecutive satellites serving a user terminal in Mendoza, Argentina.









User terminal
(Starlink dish)
Mendoza, Argentina
32.89° S, 68.84° W



LEO satellite
(STARLINK, V1.5)
Altitude: ~440–550 km
(varies over time)



Ground gateway
(Starlink PoP)
Location and coordinates
(indicated on map)

User link
(Ka-band)

Satellite – gateway link
(Ka-band)

Satellite footprint
(Simulation 1)

Satellite footprint
(Simulation 2)

# Why RIPE Atlas?

## A Global End-to-End Measurement Platform

**Global coverage**
Thousands of probes in > 190 countries measure real end-to-end performance.

**Diverse measurement types**
Latency (ping), traceroute, DNS, HTTP(S), SSL/TLS, and more.

**Flexible and programmable**
User-defined measurements, scheduling and APIs.

**Ideal for terrestrial and non-terrestrial networks**
Enables comparative measurements across mobile, fixed and satellite networks.



RIPE Atlas provides a **global, open and reliable platform** for end-to-end measurements, making it ideal for studying the integration of **terrestrial and non-terrestrial networks**.

# Measurement Methodology

**Same measurement platform**
RIPE Atlas.

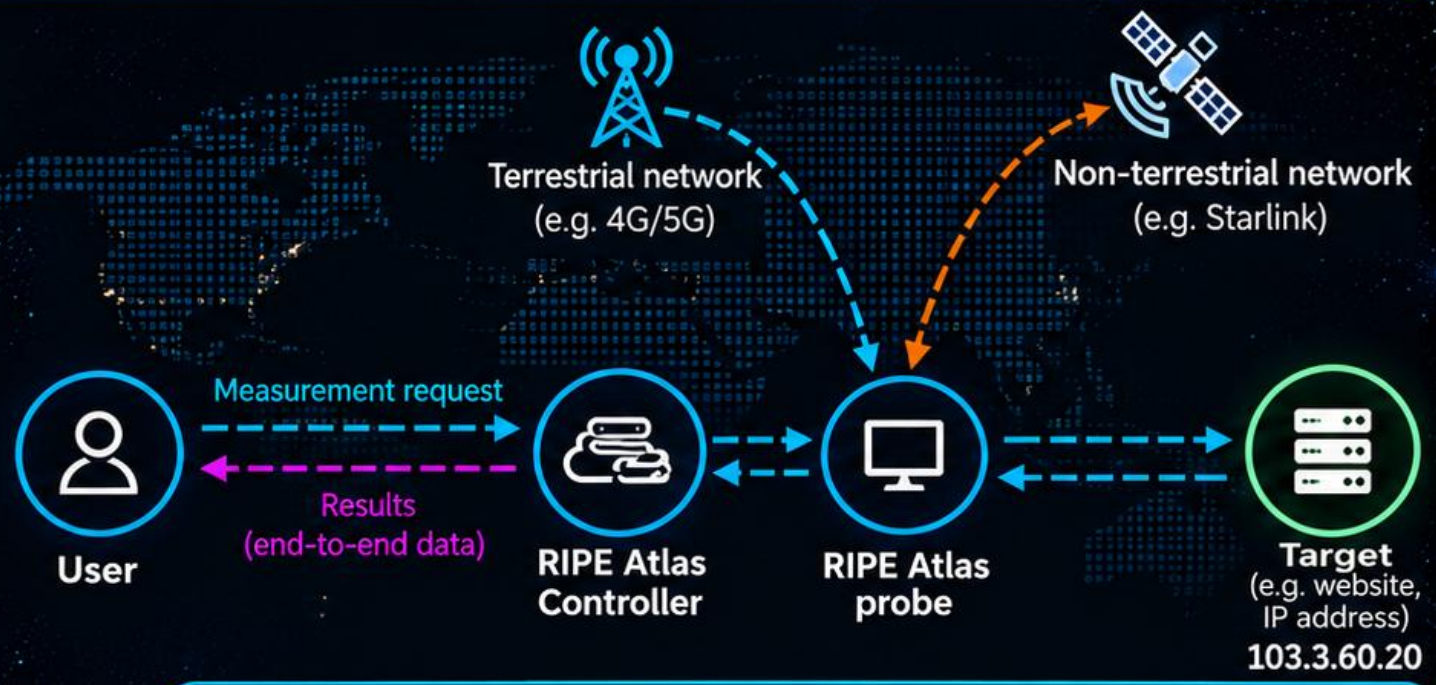
**Same countries**
Overlapping coverage
(PWA & Starlink available).

**Same measurement types**
Ping and traceroute.

**Perspective**
End-to-end performance
(TCP-based measurements).

**TCP traceroute (port 80)**
Used to avoid filtering and better reflect real Internet traffic conditions.

**~8 days / 100+** measurements per probe.




**TRACEROUTE SETTINGS (TCP)**

- Destination port: **80**
- First hop: **1**
- Max hops: **32**
- Timeout: **3 s**

Target example: **103.3.60.20**

- Port: **80**
- Protocol: **TCP**
- Response timeout: **4,000 ms**
- Size: **48 bytes**

# Source Probes – Access Comparison

## Terrestrial Mobile (FWA)

- RIPE Atlas probe → LAN → 4G/5G router
- Fixed user (FWA)
- Mostly stable radio conditions, with rare cell handovers
- Multi-ISP / multi-AS environment




**4G/5G router** with SIM card (FWA)

Different access technology

## LEO Satellite (Starlink)

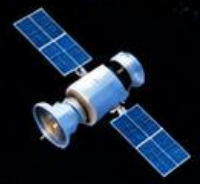
- RIPE Atlas probe → LAN → Starlink router
- Dynamic satellite topology
- Satellite handovers and gateway switching
- Single global AS (AS14593)



**Starlink** terminal and router

Unlike terrestrial FWA, Starlink operates as a **single global AS (AS14593)**, resulting in fundamentally different routing behavior.

# Impact on Latency based on Radio Access Technology



## Satellite Communication

- ✓ Dynamic satellite and gateway switching
- ✓ Satellite handovers (~15 s)
- ✓ ISL and gateway congestion
- ✓ Weather-sensitive propagation
- ✓ Dynamic Internet egress



## Terrestrial Mobile (FWA)

- ✓ Stable infrastructure
- ✓ Rare handovers
- ✓ Fixed Internet entry point
- ✓ RAN/Core congestion
- ✓ Mostly stable

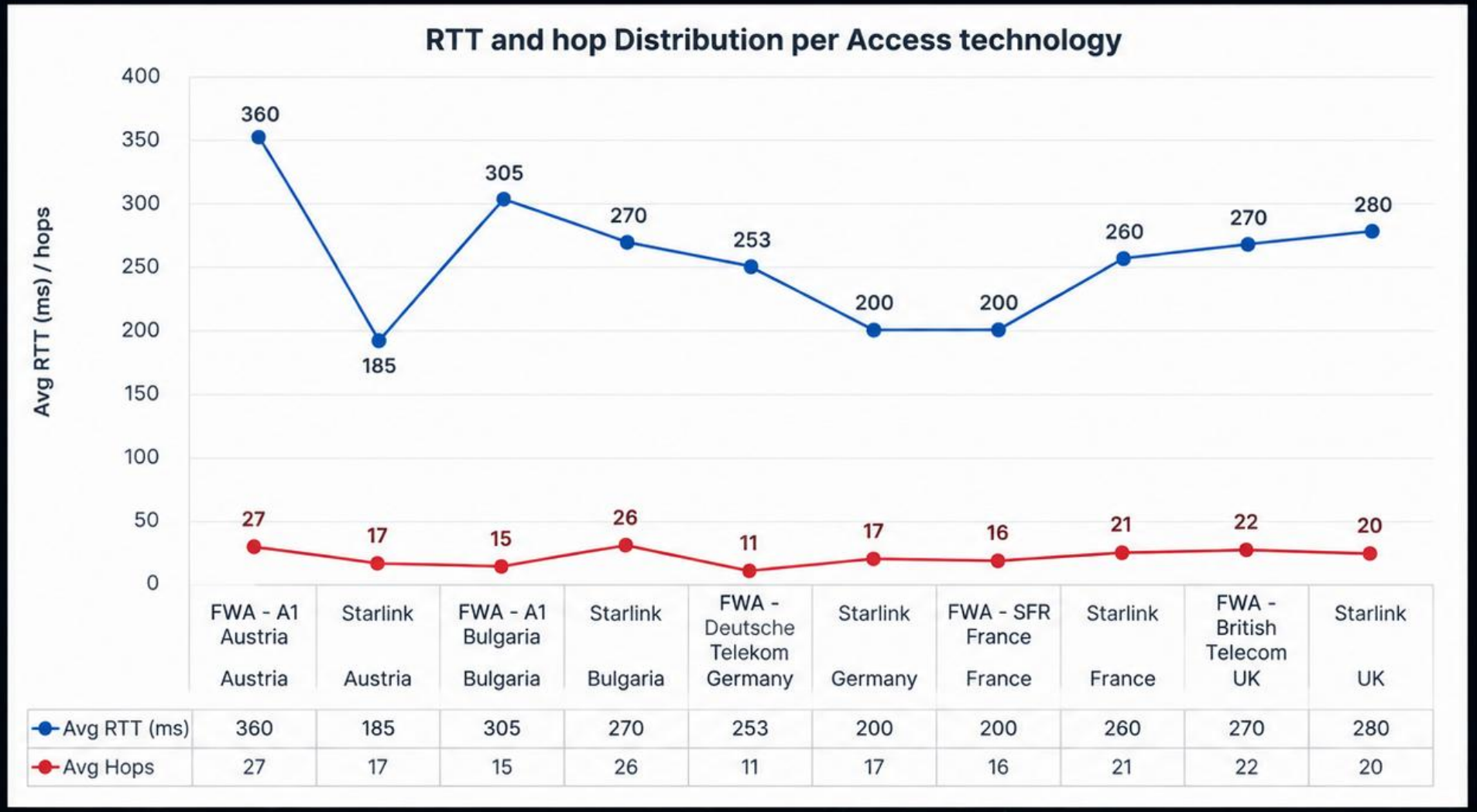
# Measurement Target: 103.3.60.20 (Singapore)

- One of the **longest intercontinental Internet paths**
- Strong dependence on **Tier-1 routing policies**
- Ideal for exposing **routing inefficiencies and detours**
- Using the same destination ensures a **fair comparison**
- Singapore is a major **Asia-Pacific Internet hub**

Long-haul measurements **amplify routing differences** between access technologies.



# Average RTT and Hop Count (Europe → Singapore)




| | FWA - A1 Austria | Starlink Austria | FWA - A1 Bulgaria | Starlink Bulgaria | FWA - Deutsche Telekom Germany | Starlink Germany | FWA - SFR France | Starlink France | FWA - British Telecom UK | Starlink UK |
|---|---|---|---|---|---|---|---|---|---|---|
| Avg RTT (ms) | 360 | 185 | 305 | 270 | 253 | 200 | 200 | 260 | 270 | 280 |
| Avg Hops | 27 | 17 | 15 | 26 | 11 | 17 | 16 | 21 | 22 | 20 |

Performance depends on **routing conditions** — not only on access technology.

# Observed Routing Paths and Latency (Bulgaria → Singapore)

| Variant | Route (regions) | Providers | Latency | Route Type |
|---|---|---|---|---|
| **Starlink** | Sofia → Vienna → Frankfurt → Paris → USA → Japan → Singapore | Telia Company → KDDI Corporation → Akamai Technologies → Linode | ~265 ms | Transatlantic + Transpacific |
| **Starlink** | Sofia → Frankfurt (IXP) → Singapore | RETN → DE-CIX → Telstra → Linode | ~207 ms | Direct (optimal) |
| **Starlink** | Sofia → USA → Japan → Singapore | GTT Communications → KDDI Corporation → Akamai Technologies → Linode | ~264 ms | Transpacific-heavy |
| **Starlink** | Sofia → Frankfurt → Singapore | Interoute Communications → DE-CIX → Telstra → Linode | **~204 ms** | Most optimal |
| **FWA (A1 Bulgaria)** | Sofia → Frankfurt → Asia → Japan → Singapore | RETN → Telstra → Akamai Technologies → Linode | ~365 ms | Static intercontinental |

We observed four distinct Internet paths within minutes for the same user and destination, confirming that Starlink **dynamically selects upstream providers and routing paths** rather than relying on a fixed Tier-1 transit.



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

- Internet **routing decisions** strongly influence end-to-end latency.
- Access technology is **one factor**; routing policies, peering, and core network design also shape end-to-end performance.
- Starlink **dynamically selects gateways and Internet paths**, while FWA terrestrial networks generally follow more stable routes.
- **IXPs and upstream routing policies** play a major role in long-haul performance.



# Measurement Evidence: Starlink In-Flight Connectivity

THE TREVOR PROJECT

SPEEDTEST

PING
115
ms

DOWNLOAD
173.9
Mbps

JITTER
27
ms

UPLOAD
23.1
Mbps

SpaceX Starlink
143.105.219.207




## Jurisdiction in motion

- On the ground → local country laws
- In the air → airline's country of registration
- Jurisdiction changes during the journey

# Open Questions and Future Perspective

If LEO networks bring the edge closer to users and create new entry points into the backbone... **are we witnessing a fundamental shift in how the Internet is structured?**

If satellite networks can route traffic through different countries before it even enters the public Internet... **who really controls the Internet experience — the user's country, or the network's point of entry?**



# 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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