LEO Mega-Constellations

Where the challenges lie

Ulrich Speidel, School of Computer Science, The University of Auckland

Image credit: Tim Johnson

Spotted at Auckland International Airport on 20 October 2022 enroute to this talk.

Clearly, almost all challenges I was going to talk about today have already been solved.

My apologies for wasting your time this morning.

Challenges I'll talk about today

- Constellation design & coverage
  - Tropics vs. polar regions
  - GSO protection
- Inter-satellite routing
  - Building a mesh
  - Finding a route
- Local and total system capacity
- LEO networks vs. CDNs
- If we have time: Security

Basics first - orbits

- An object *orbits* if it's falling back down to Earth but is too fast so keeps missing.
- Circular (elliptic) orbit sits in an *orbital plane*
  - The orbital plane also includes the centre of the Earth
- *Orbital height* is the height of the orbit above the surface of the Earth
  - Orbital height determines how quickly a satellite completes its *orbital period*
    - Spoiler: The lower the quicker.
  - LEO orbits have an orbital height of typically < 2000 km (Starlink: around 550 km)
  - MEO orbits: around 8000 km (O3b mPower)
  - GEO orbits: 35,786 km (most conventional comms sats)
- The angle between the Equator and the orbit (projected onto the surface of the Earth) is the orbit's *inclination*.
  - Orbital plane is defined by inclination and the longitude at which it intersects with the Equator at a defined point in time.

Orbital height matters!

- All else being equal, received power in a free-space wireless communication system is proportional to one over signal path distance squared
  - GEO signal path: around 36,000 km plus a bit
  - LEO signal path: say around 1000 km?

- => LEO received power is larger than GEO by a factor of ≈ 36^2 ≈ 1,300.

- Shannon-Hartley capacity theorem gives:
  - $\log_2(1{,}300) \approx 10.34$ bits per symbol extra theoretical capacity
  - …but in practice, “all else being equal” doesn’t necessarily apply!

But wait, there's more…

- GEO and MEO orbital height put much of the globe in view
  - Bad for frequency re-use!

- LEO satellites only see a small part of the Earth's surface.
  - Good for frequency re-use!

The downside of LEO orbits

- A LEO sat rises, passes over a ground station and sets on the horizon within minutes
  - Usually won't return for many hours to same location
  - Need **many** satellites for 24/7 coverage

- MEO: overhead for hours

- GEO: always there

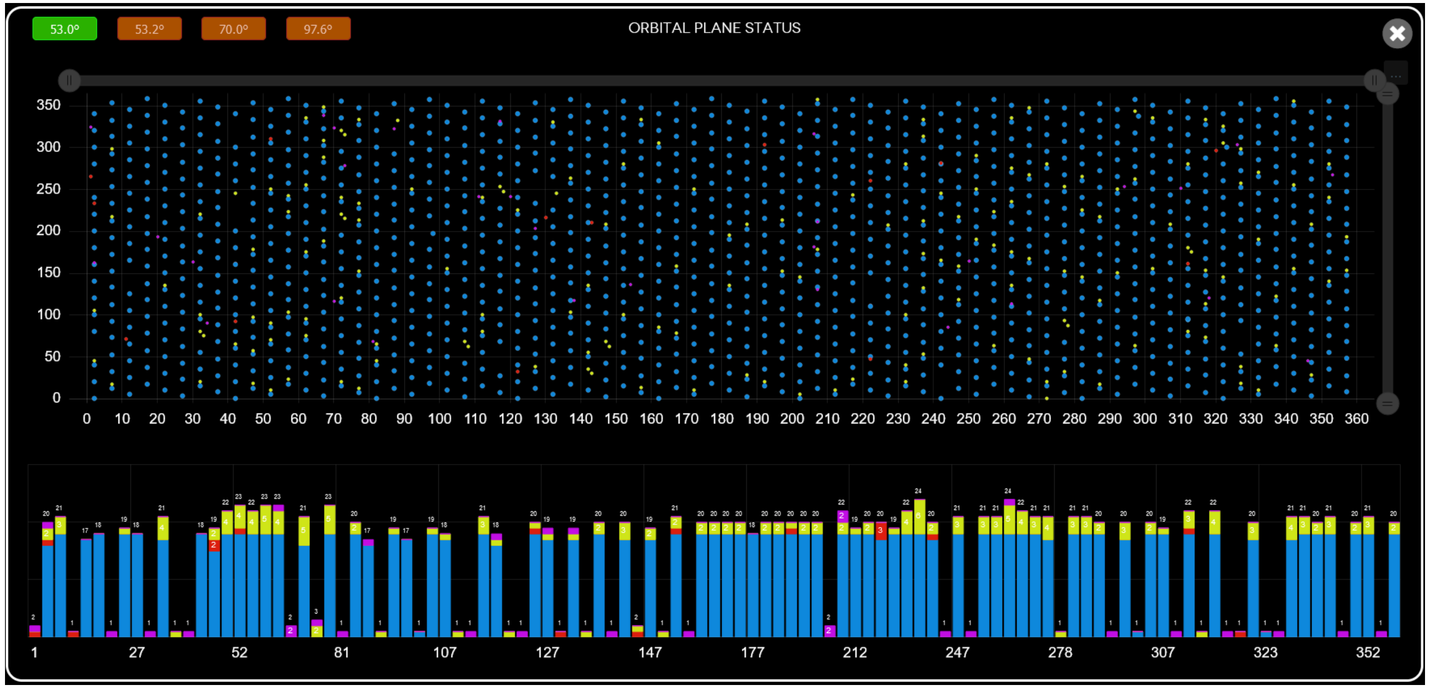
The implications of inclinations in LEO

- GEO orbits have an inclination of 0 degrees – they sit above the Equator
- Current MEO comms sats (O3b) do the same

- LEO orbits are typically inclined at >> 0 degrees

- Inclination angle also corresponds to the highest & lowest geographical latitudes that the satellites fly over.
  - No coverage significantly to the north / south of these latitudes.

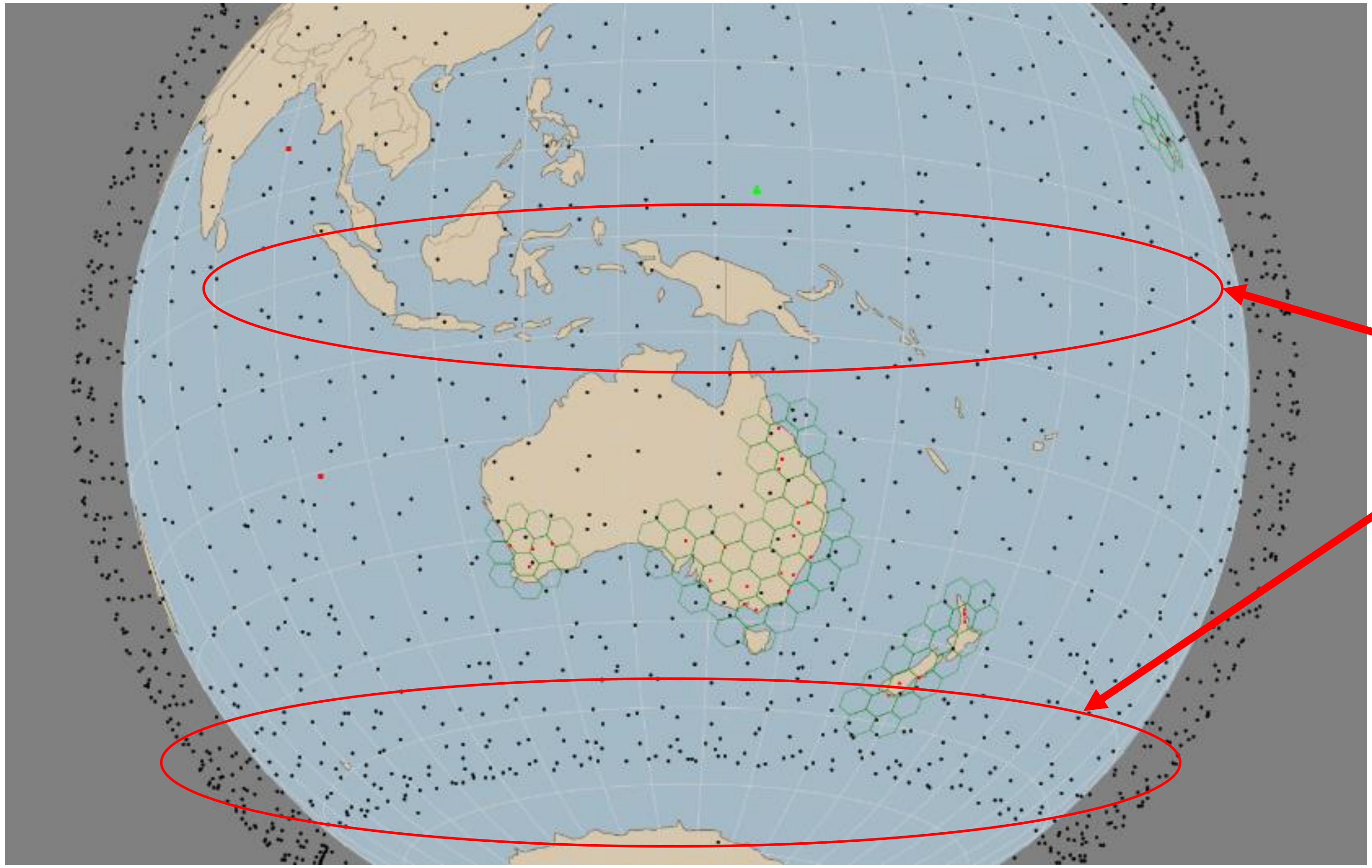
LEO constellations



Screenshot: Starlink orbital chart from Mike Puchol's starlink.sx

- Multiple satellites per orbit / orbital plane
  - E.g., Starlink: around 20-36 per plane
- Multiple orbital planes
  - E.g., Starlink: 72 planes @ 53° inclination
  - More at other inclination angles
- Shells: use of different orbital heights

The implications of inclinations in LEO



Screenshot: satellitemap.space

- Most current Starlink satellites orbit at or near 53° inclination

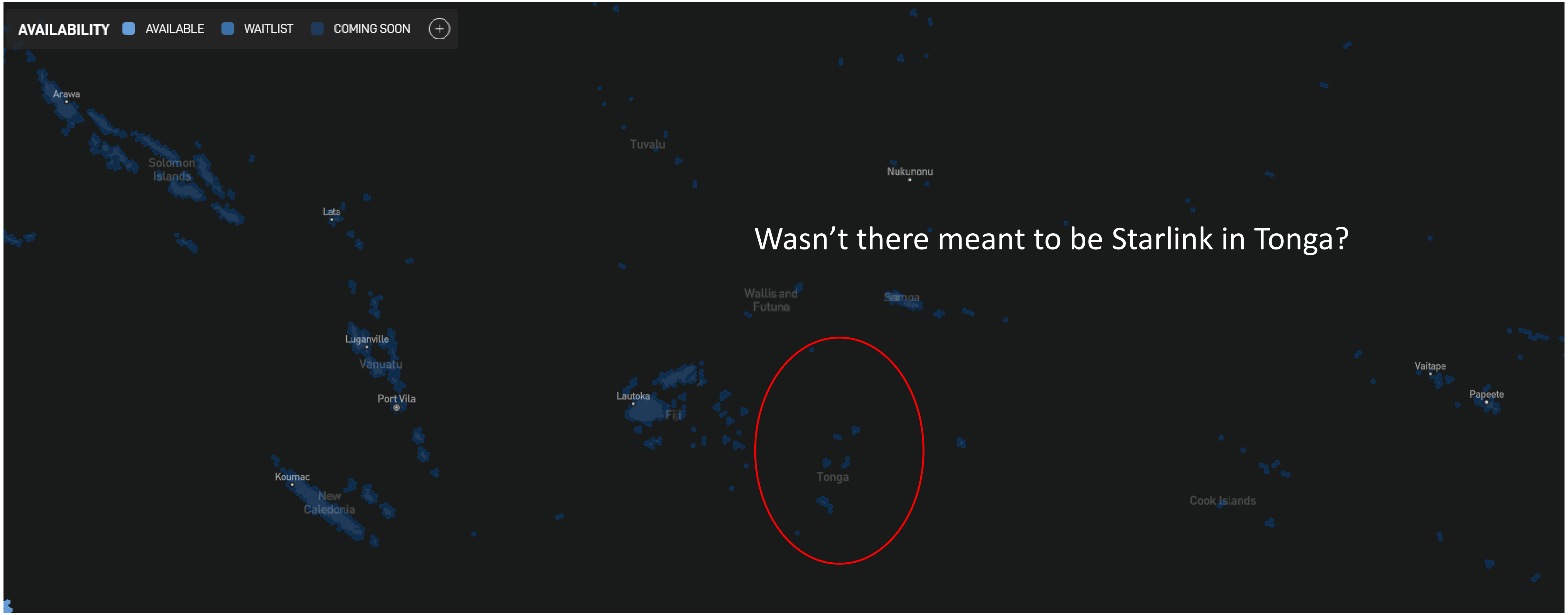
- Consequence:

Low satellite density in Tropics

High satellite density near inclination latitudes

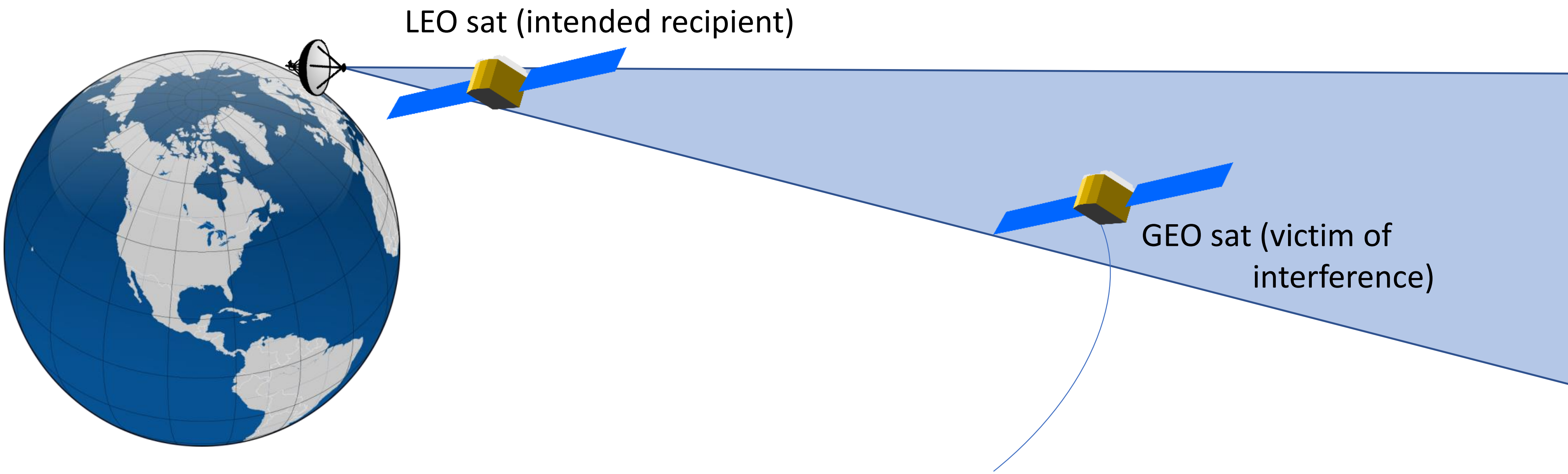
The implications of inclinations in LEO

The implications of inclinations in LEO



Regulatory: Geostationary arc protection (GSO protection)

- Ground stations must not transmit to a LEO satellite if within 18° of the geostationary arc.

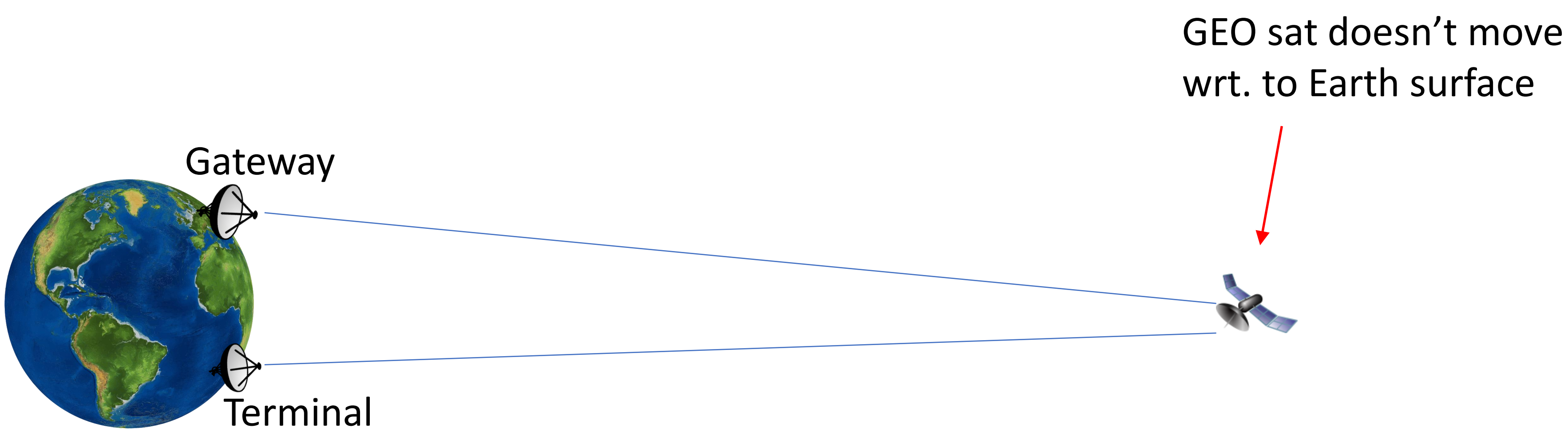


- Reason: LEO ground stations can interfere with GEO sats located “behind” target LEO sat.
- Mostly a problem in tropical regions (large “prohibited” region of sky)
  - Also a problem for northern Starlink users looking south to 53° and 53.2° inclination constellations

Forwarding and routing

- Bent pipe model: Internet<->gateway<->satellite<->terminal
  - Standard model in GEO and MEO
  - Requires:
    - Satellite must be in view of both gateway and terminal
      - …subject to GSO protection rules, too!
    - Gateway needs to know that terminal can be reached via this satellite
    - BGP route to terminal via gateway (or somesuch)

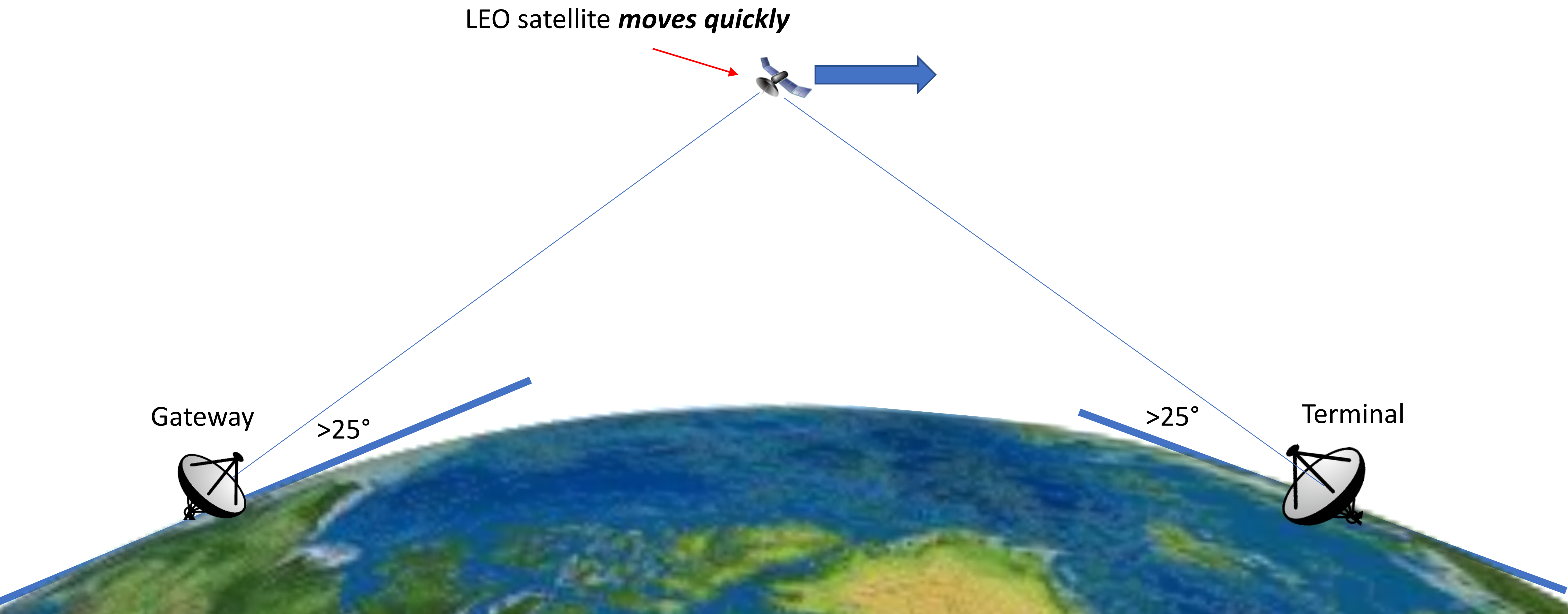
Bent pipe in GEO



Nothing moves. Boring!

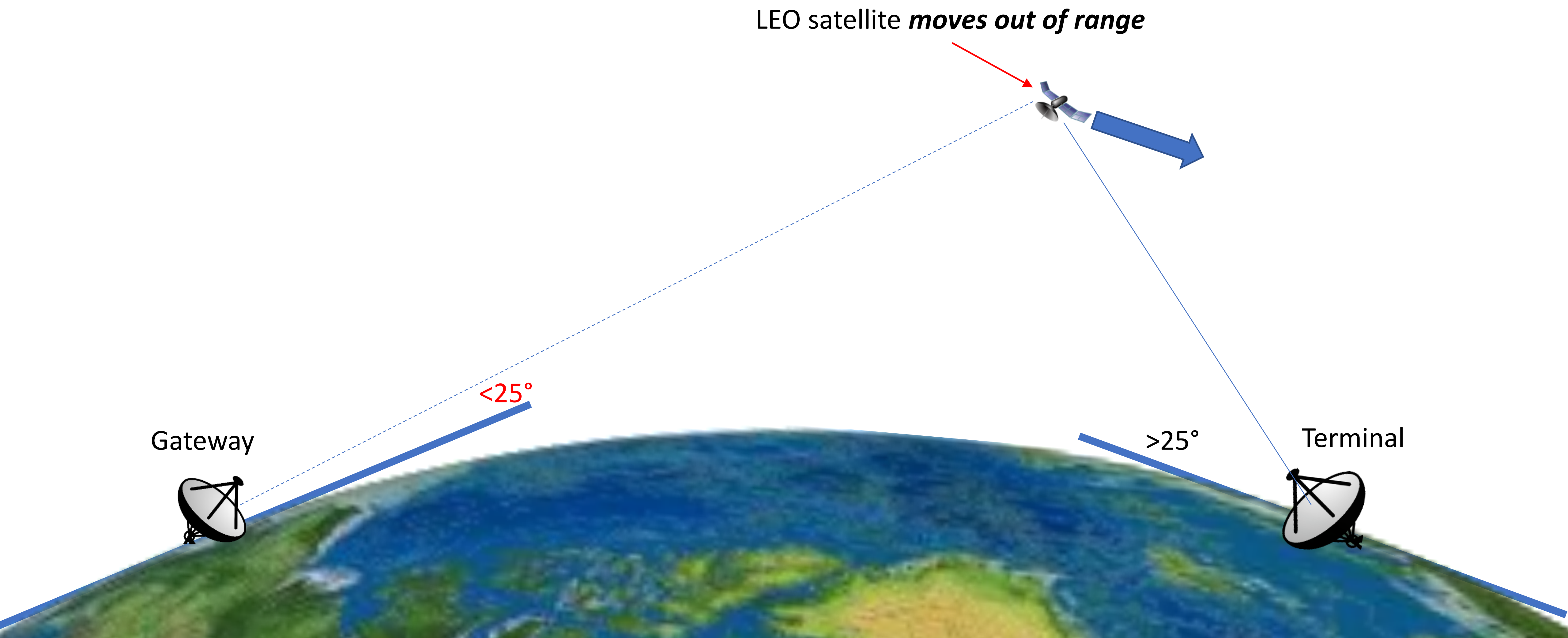
Bent pipe in LEO

LEOs such as Starlink can only bridge between two ground stations for a short time



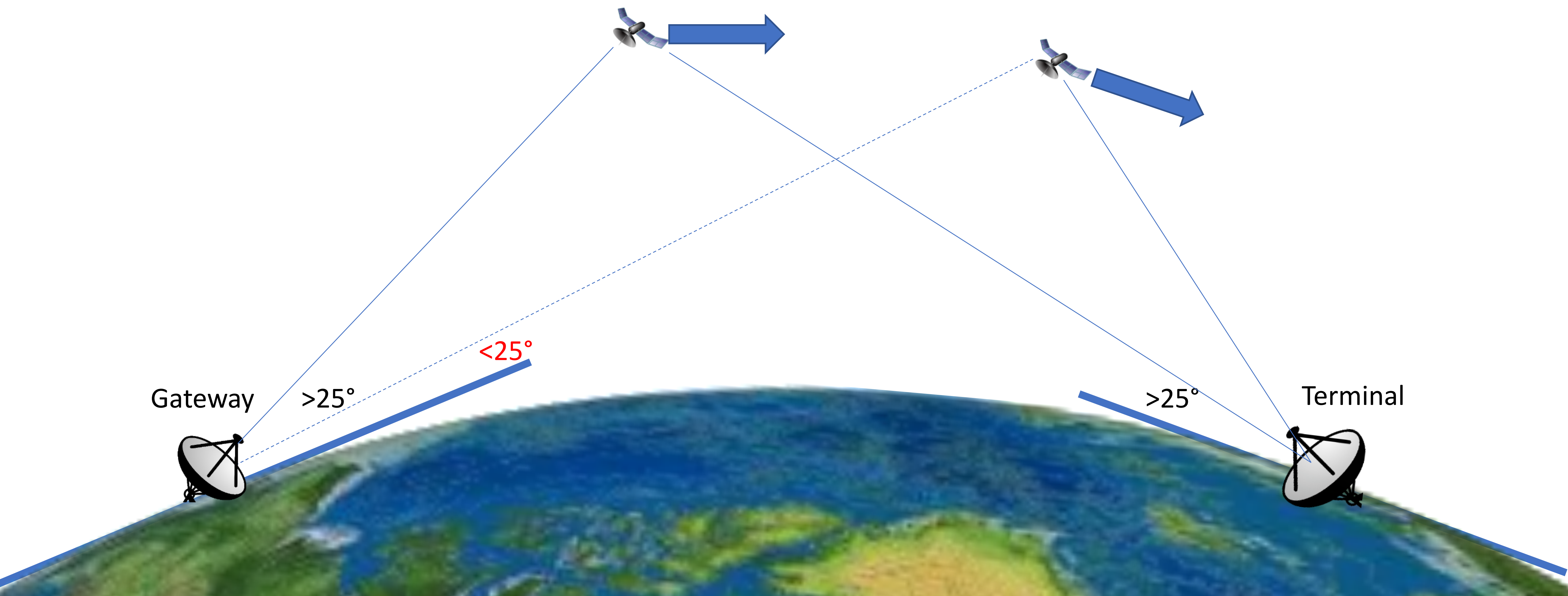
Bent pipe in LEO

LEOs such as Starlink can only bridge between two ground stations for a short time



Bent pipe in LEO

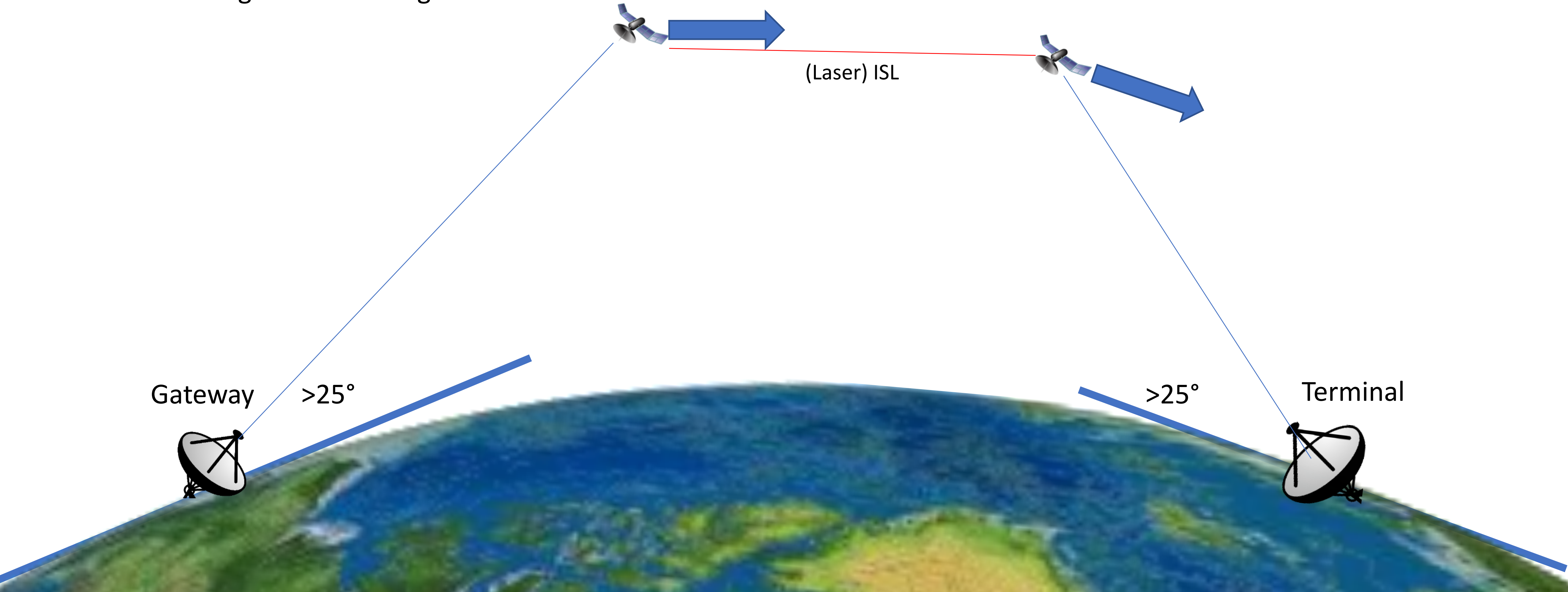
Need handovers!



Beyond bent pipe: inter-satellite links (ISLs)

Challenges:

- Establishing a mesh
- Finding a route through it



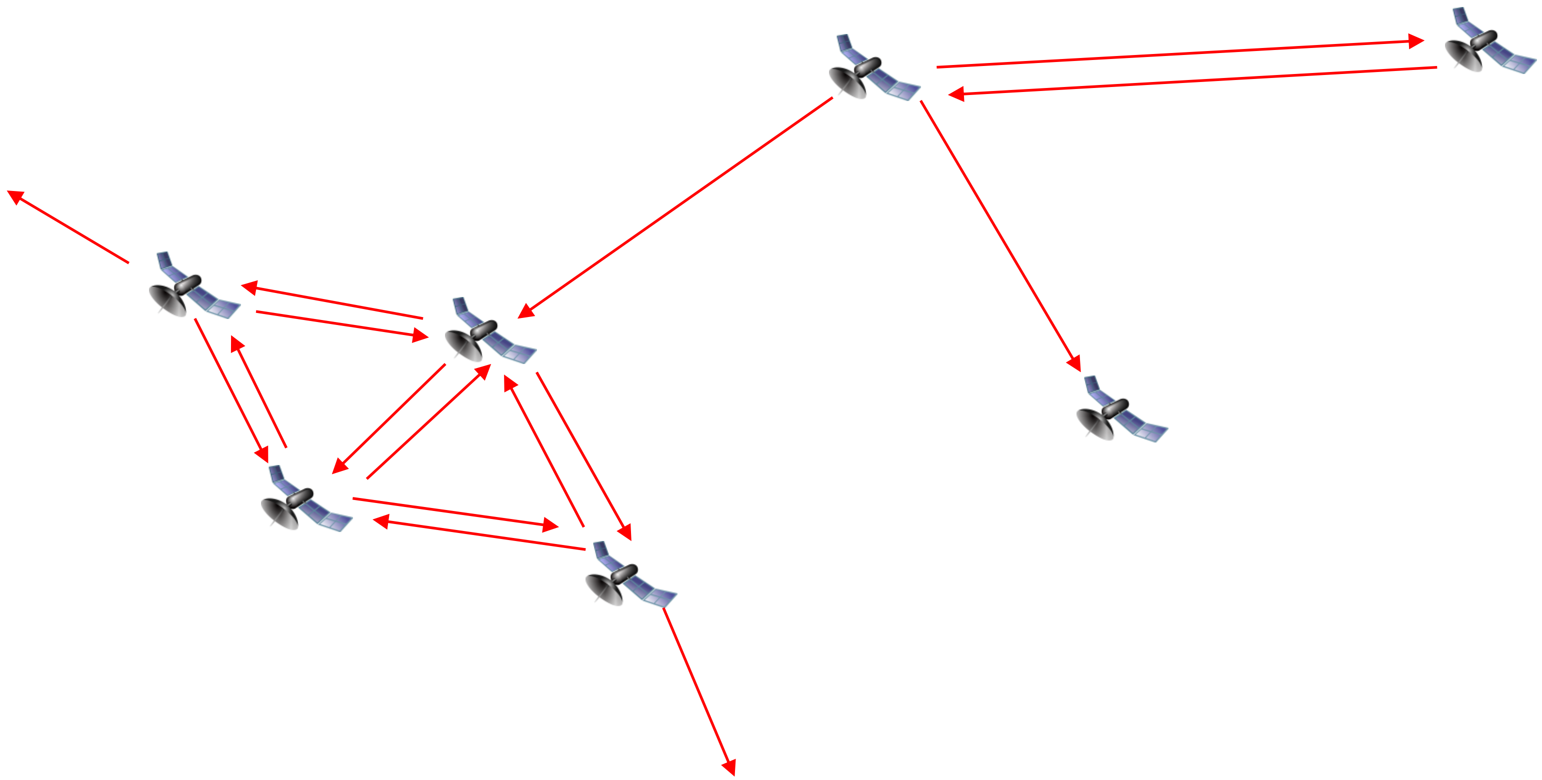
Building a mesh: Conceivable types of ISLs

- RF-based ISLs: too unfocused for mega-constellations

- Laser ISL options:
    - One-way: Transmitter points at wide angle receiver
        - Less complex on the receiver side, but translates as low gain in link budget: lower data rates
        - May not need to be bi-directional
    - Two-way: Transmitter and receiver focus on each other
        - Advantage: Good link budget / higher data rates
        - May need to split colours by direction ("blue" vs. "red" transmitters)

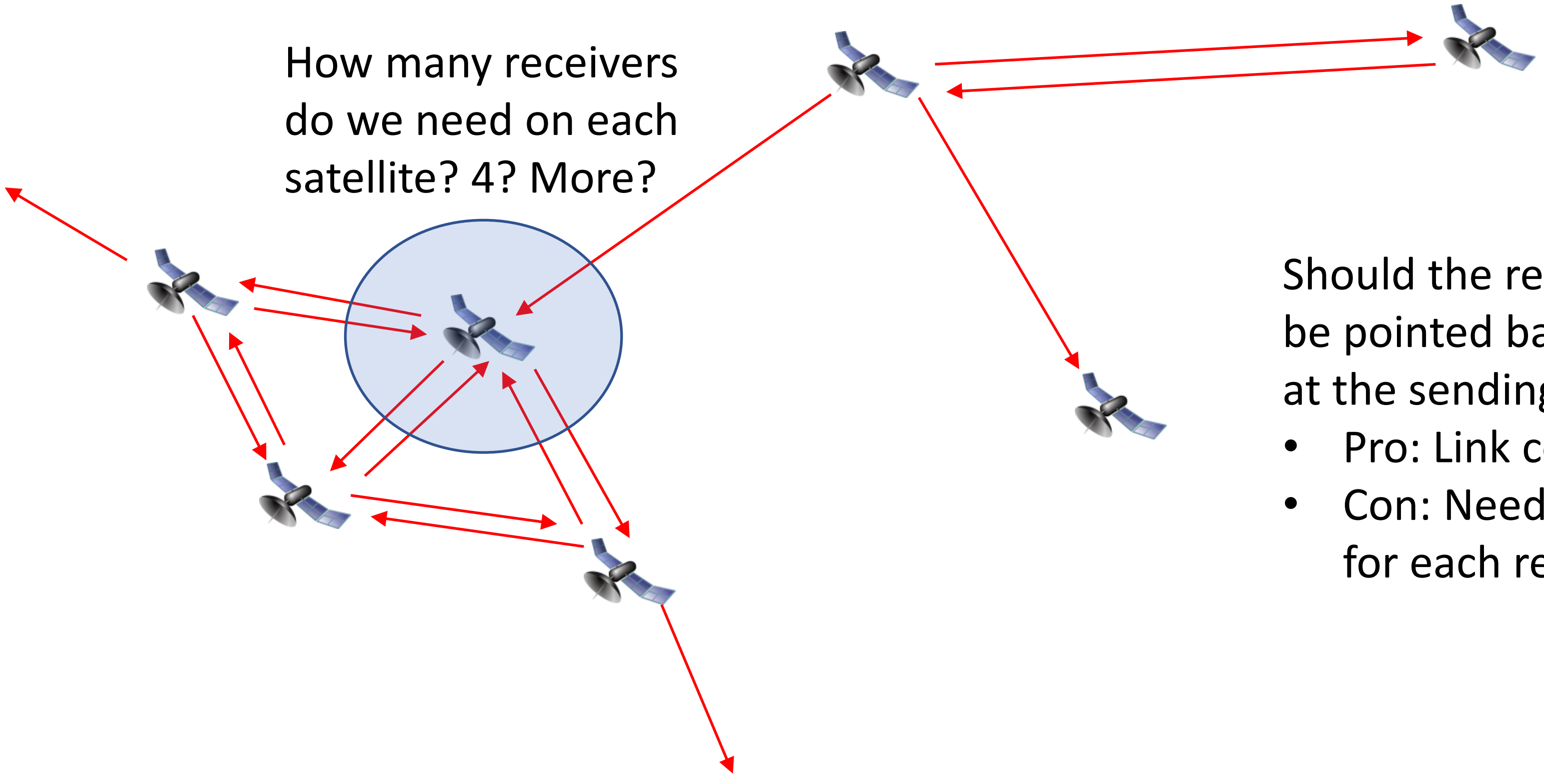
Space lasers, right?

- How many lasers does a satellite need? Say 3, one-way, pointing at the closest neighbours:



Space lasers, right?

- How many lasers does a satellite need? Say 3, one-way, pointing at the closest neighbours:



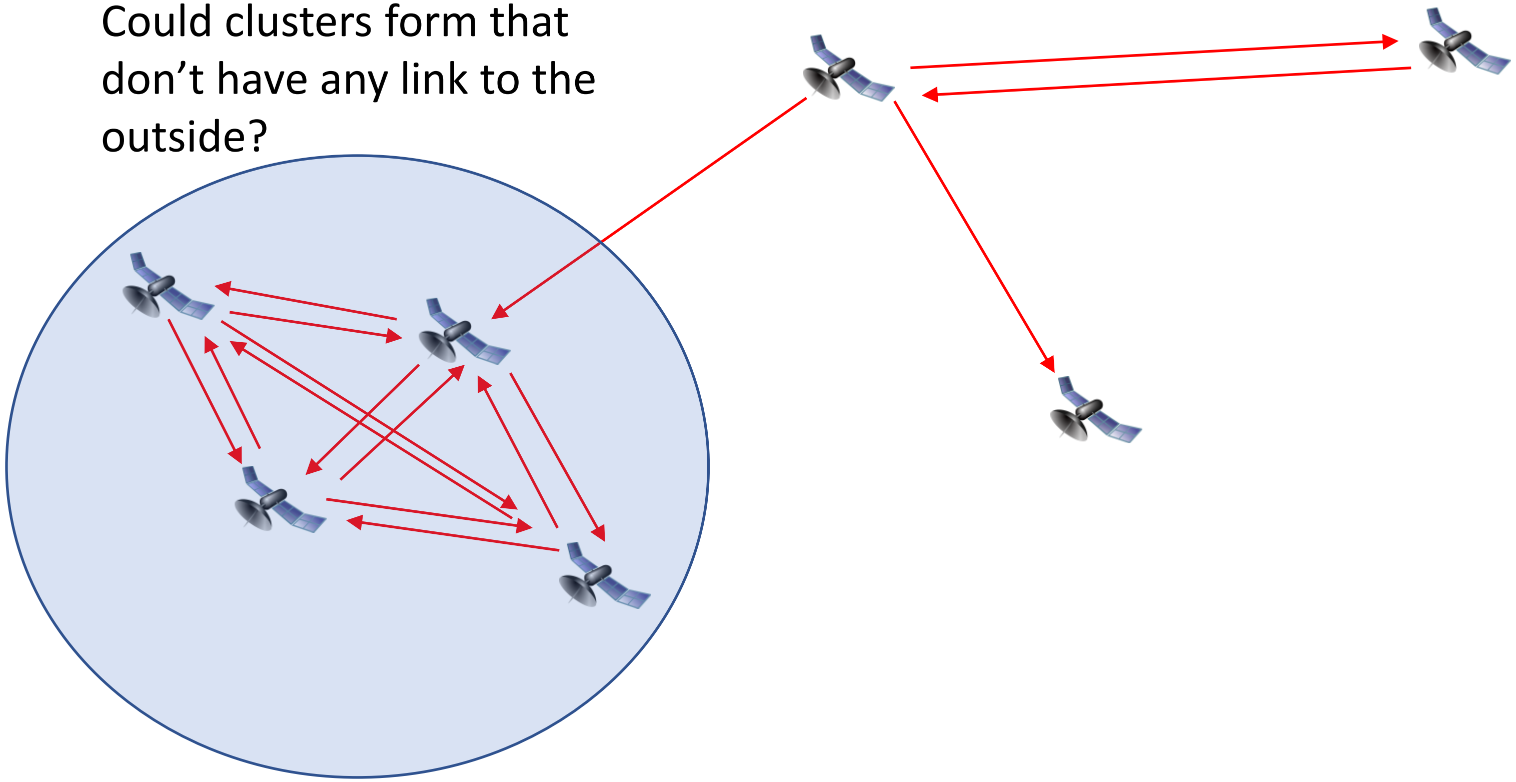
Should the receiver
be pointed back
at the sending satellite?

- Pro: Link could run at higher bit rate.
- Con: Need a separate gimbal
  for each receiver (moving part).

Space lasers, right?

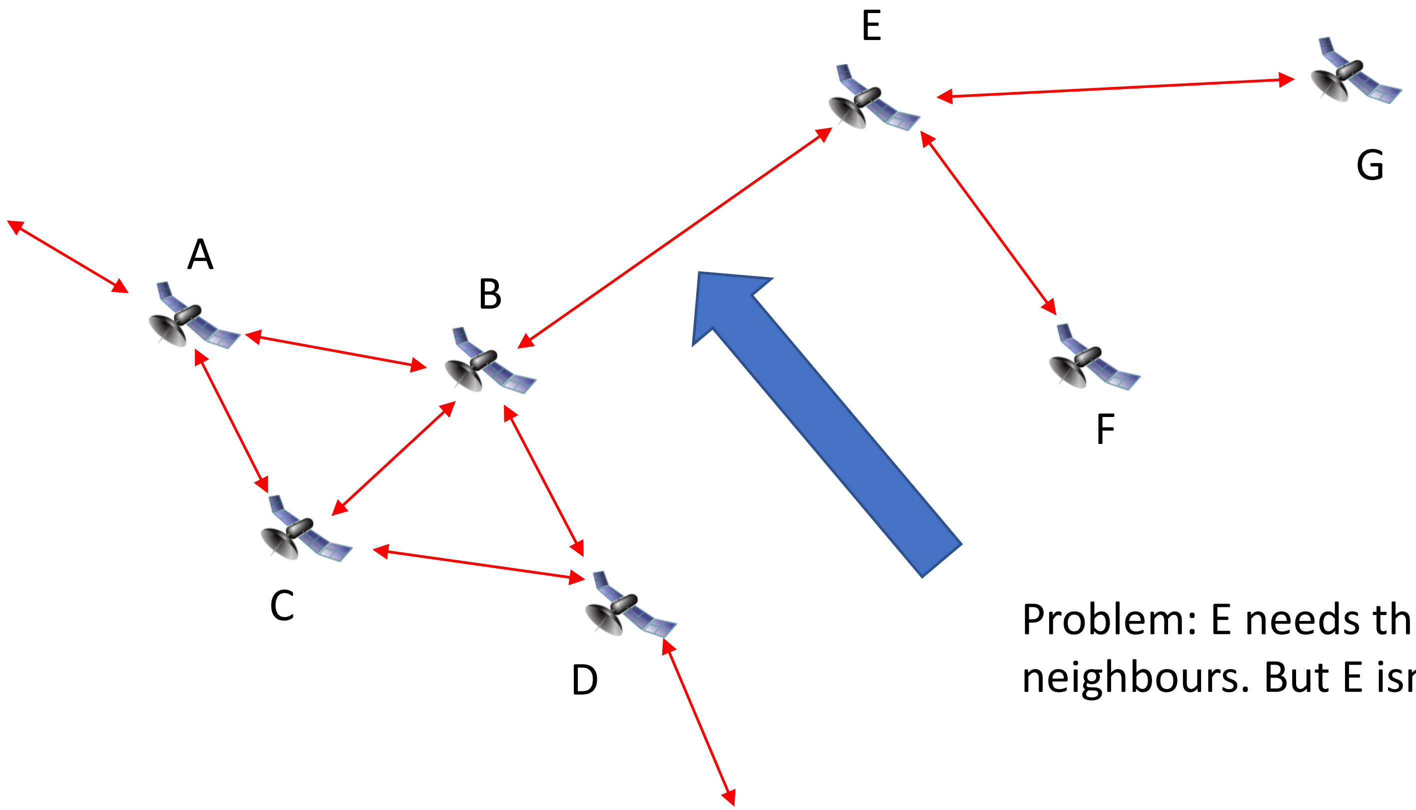
- How many lasers does a satellite need? Say 3, one-way, pointing at the closest neighbours:

Could clusters form that don't have any link to the outside?



Space lasers, right?

- Is two-way better? Assume 3 two-way links, pointing at the 3 closest neighbours:

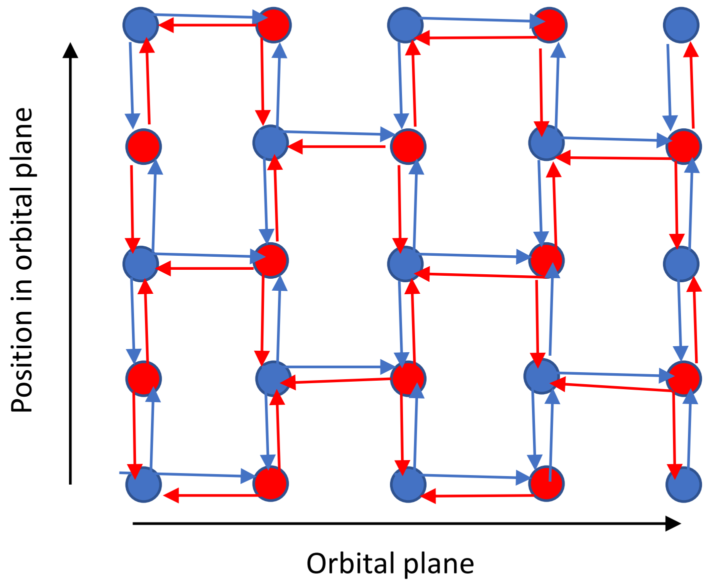


Problem: E needs this link as B is one of its 3 closest neighbours. But E isn't one of B's 3 closest neighbours!

How Starlink may do it

A nod to Mike Puchol for alerting me to this option!

- Within a constellation: 3 bi-directional ISLs per satellite, colour-separated laser optical heads
  - One ISL goes to the next satellite flying *ahead* in the same orbit.
  - One ISL goes to the next satellite flying *behind* in the same orbit.
  - Satellites along the same orbit alternate between “red” and “blue”:
    - 3rd ISL on “red” satellite goes to a “blue” satellite in the next orbital plane further west
    - 3rd ISL on “blue” satellite goes to a “red” satellite in the next orbital plane further east



“Blue” satellite transmits using shorter wavelength laser light than “red” satellite.

Challenges:

- East and west get reversed twice per orbital period
- What happens if a satellite fails?
- How does a satellite know which way a packet has to go?

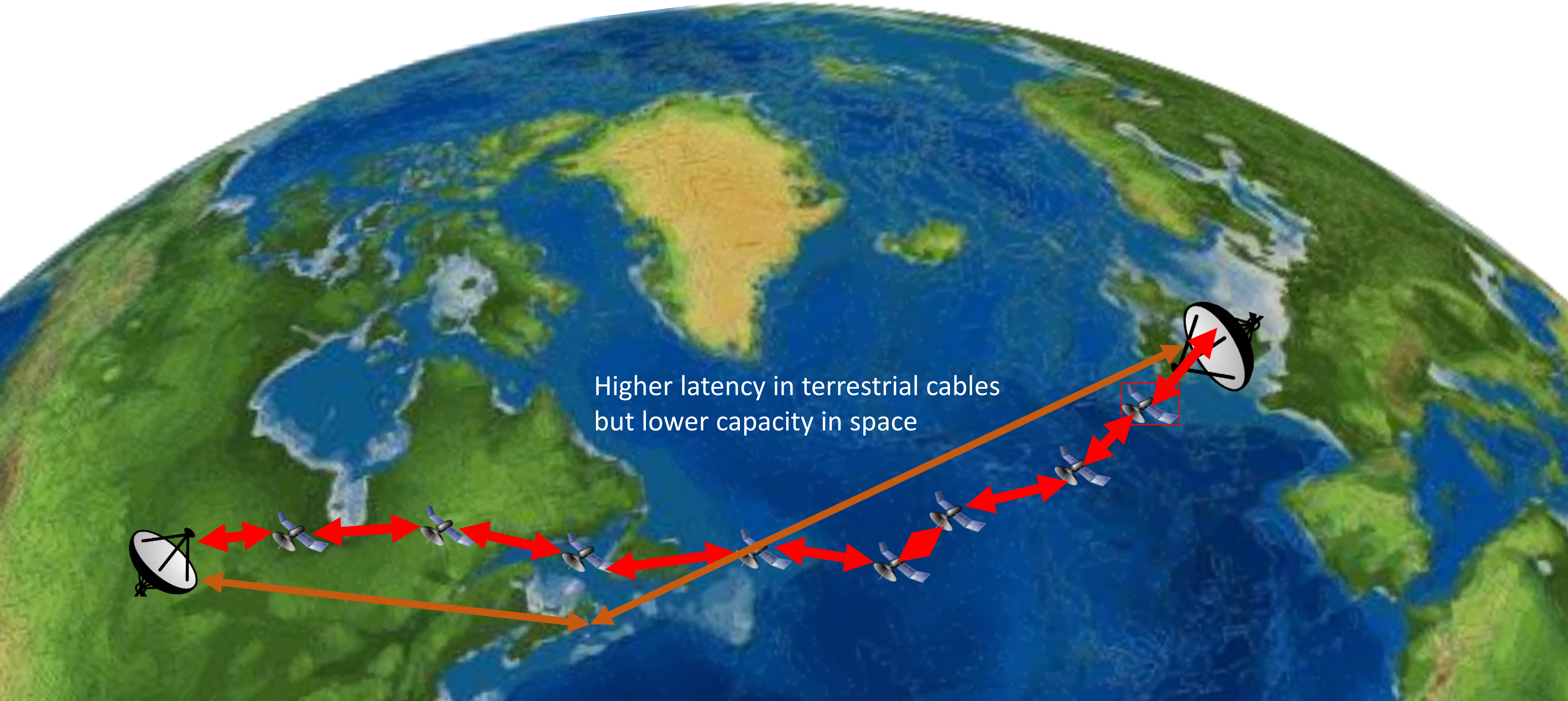
Where is my terminal?

- So we have a packet heading to a terminal of our LEO network. It arrives at the gateway to the LEO network. What next?
  - Gateway needs to find satellite capable of downlinking to terminal …
  - …or at least a good satellite to forward to.
  - Physical location of terminal is dominating factor in whatever we do next.
- Could IPv6 be the answer?
  - IPv6 addresses: 128 bits long
  - Let’s do a back-of-the-envelope calculation…

Latitude and longitude in bits

- What precision do we need / want? Is +/- 2 km enough?
- Degrees, minutes and seconds (DMS): one minute of longitude at the Equator is 1,852 m – within tolerance
  - Takes $\log_2(360 * 60) = \log_2(21,600) <= 15$ bits to encode
  - Can do latitude in 14 bits
  - Total number of bits required to encode terminal location: 29 bits
- Easy to encode as part of an IPv6 hostid!

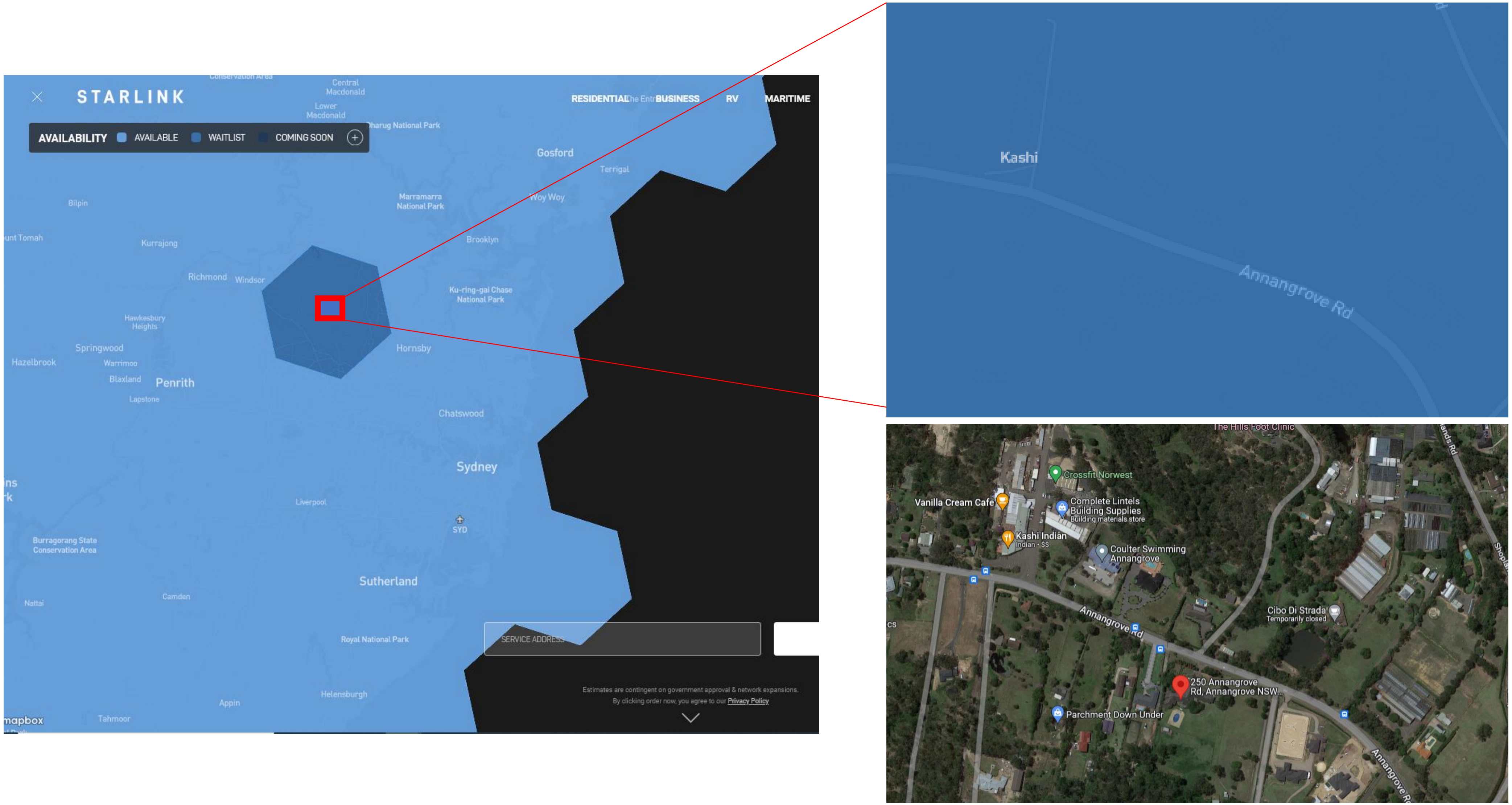
Space or ground?



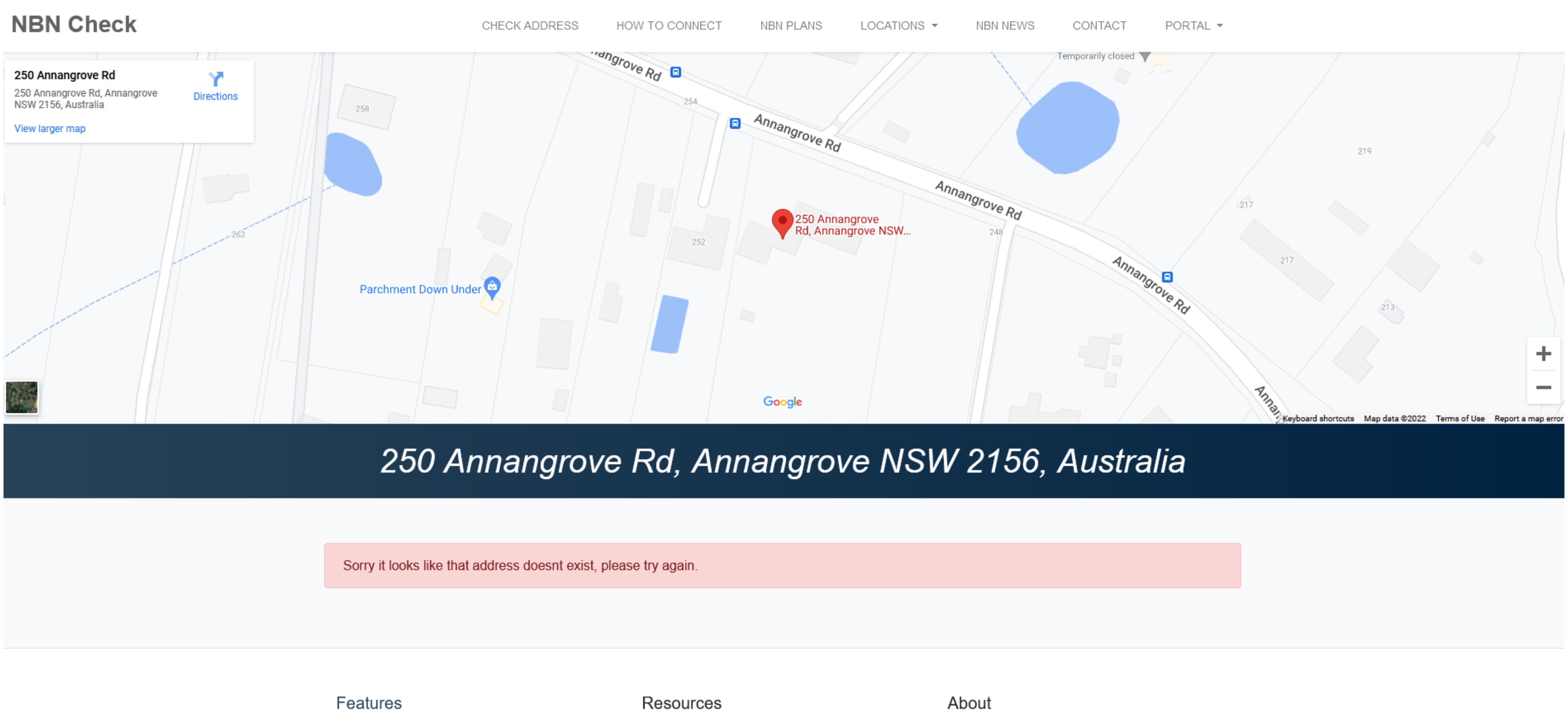
Great circle path routing?

- Demo time!

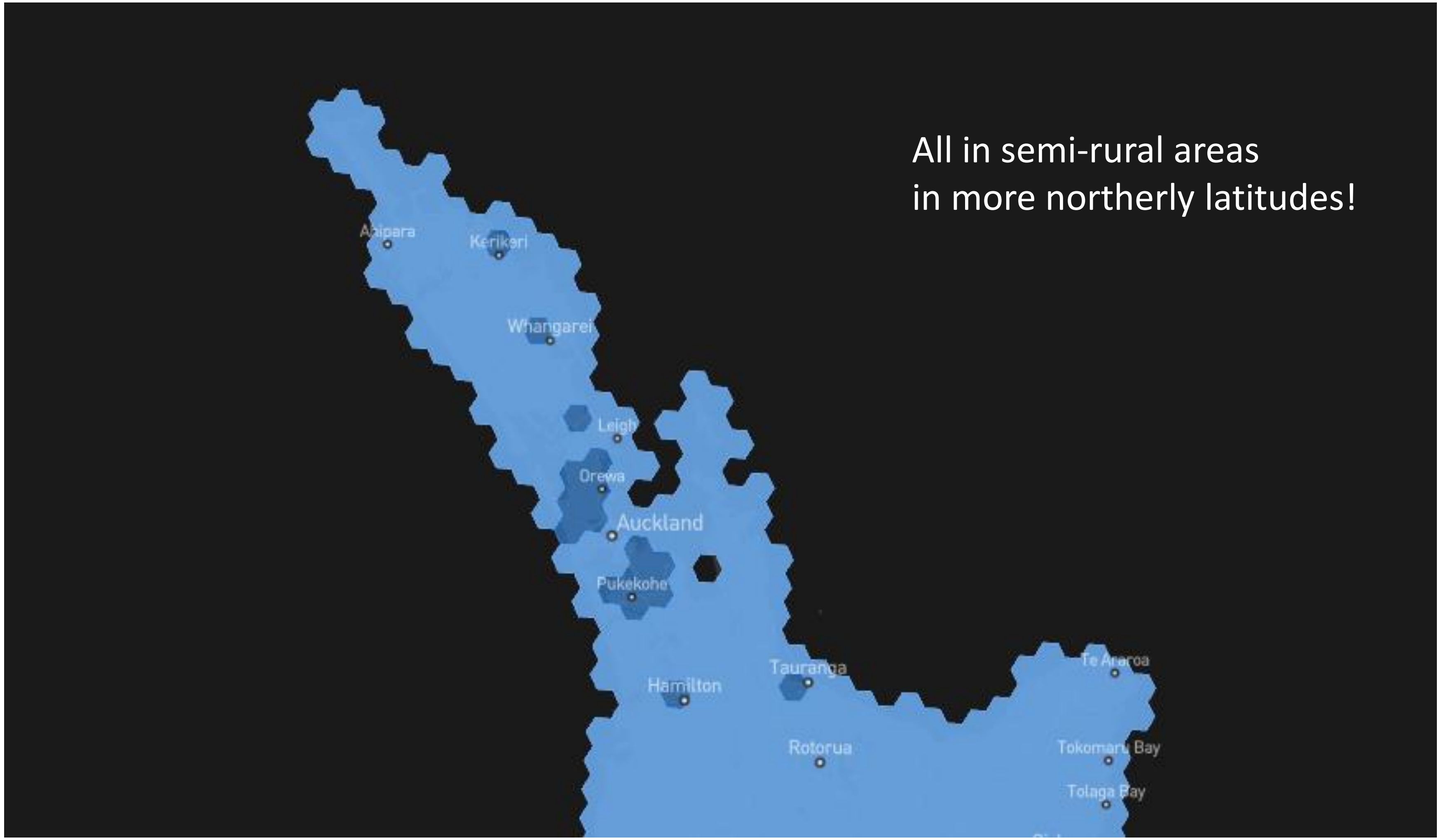
System capacity: Who's waitlisted on Starlink?



Do they have NBN? Nah!



Starlink weak spots around NZ



This week, from a mailing list about Starlink

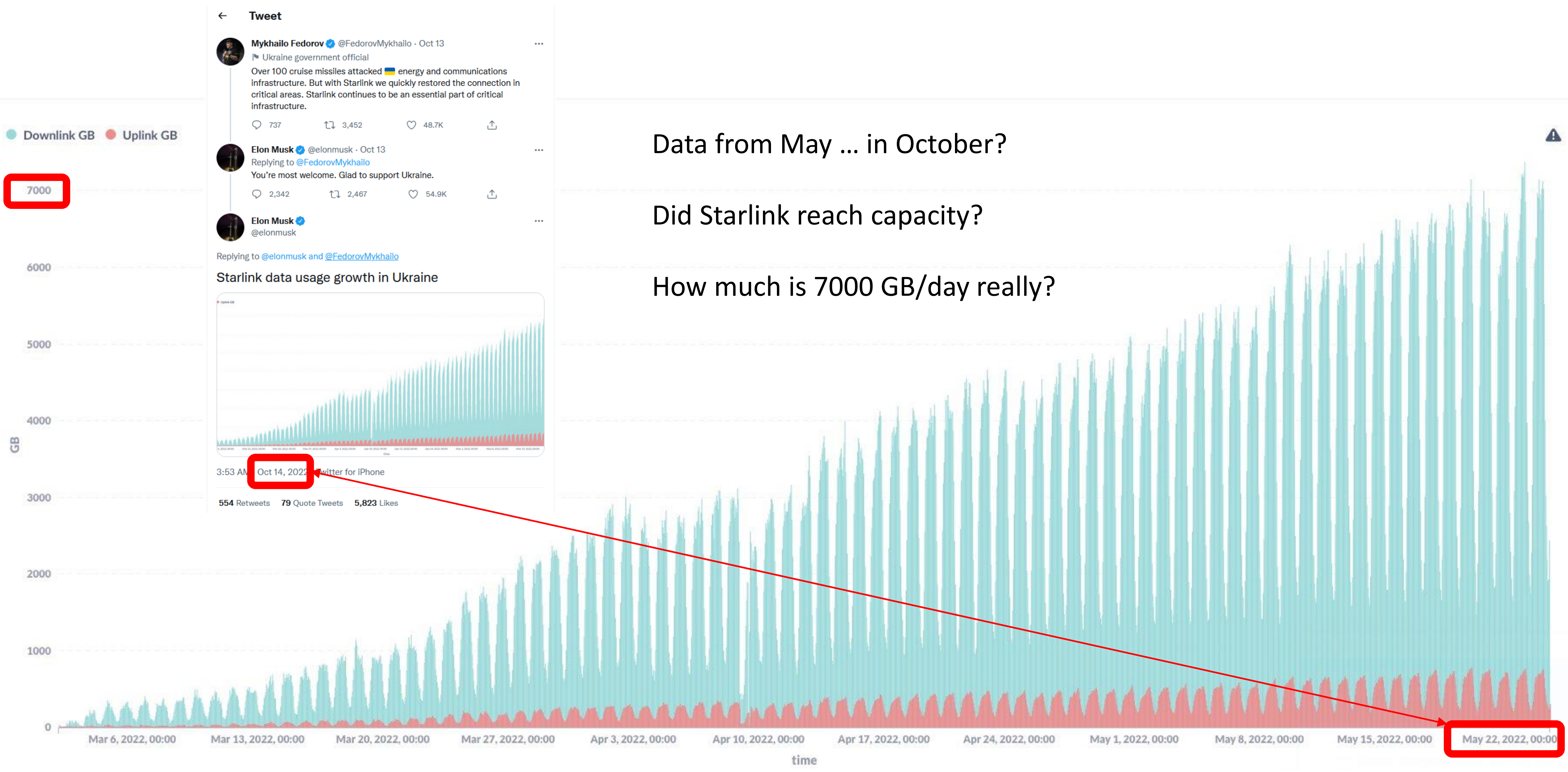
- “I’m speculating, but given that **Starlink is THE communications infrastructure for much of Ukraine**, then the scaling of the ground stations to provide that level of service must be a significant expense. To provide that much bandwidth would require deploying a lot of ground stations, each with expensive hardware, power infrastructure (including backup), fiber backhaul, skilled labor, and no small amount of fiber bandwidth that SpaceX has to pay SOMEONE to provide.”

- Wow! Now for a reality check…

Data from May … in October?

Did Starlink reach capacity?

How much is 7000 GB/day really?



Another back-of-the-envelope calculation

https://www.statista.com/statistics/267194/forecast-of-internet-traffic-by-subsegment/

https://www.broadbandsearch.net/blog/internet-statistics

~5 billion users worldwide

Total amount of Internet traffic per month in 2022: just under 300 million TB (300 EB)

Note: **predicted before Covid / Zoom!**

Ukraine:

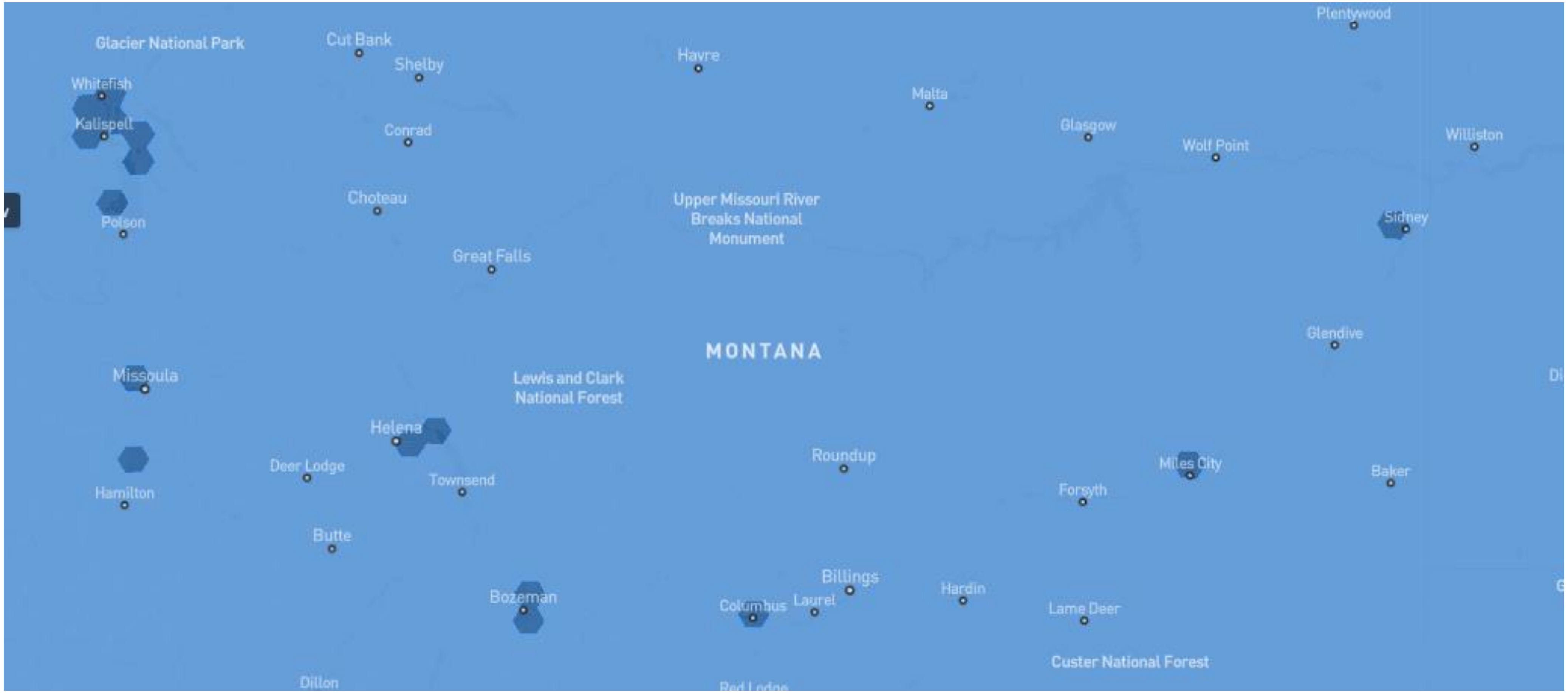
7000 GB/day
* 8 bits/byte /
(24 * 3600 * 186000 b/s)
= **3,484 users**

300 million TB * 8 bits/byte / (5 billion users * 30 days * 24 h * 3600 s) = 3 * 10^{20} * 8 / (5 * 10^{9} * 30 * 24 * 3600) = 10^{8} / (15 * 36) = **186 kb/s per user**

Population of Ukraine: around 43 million….

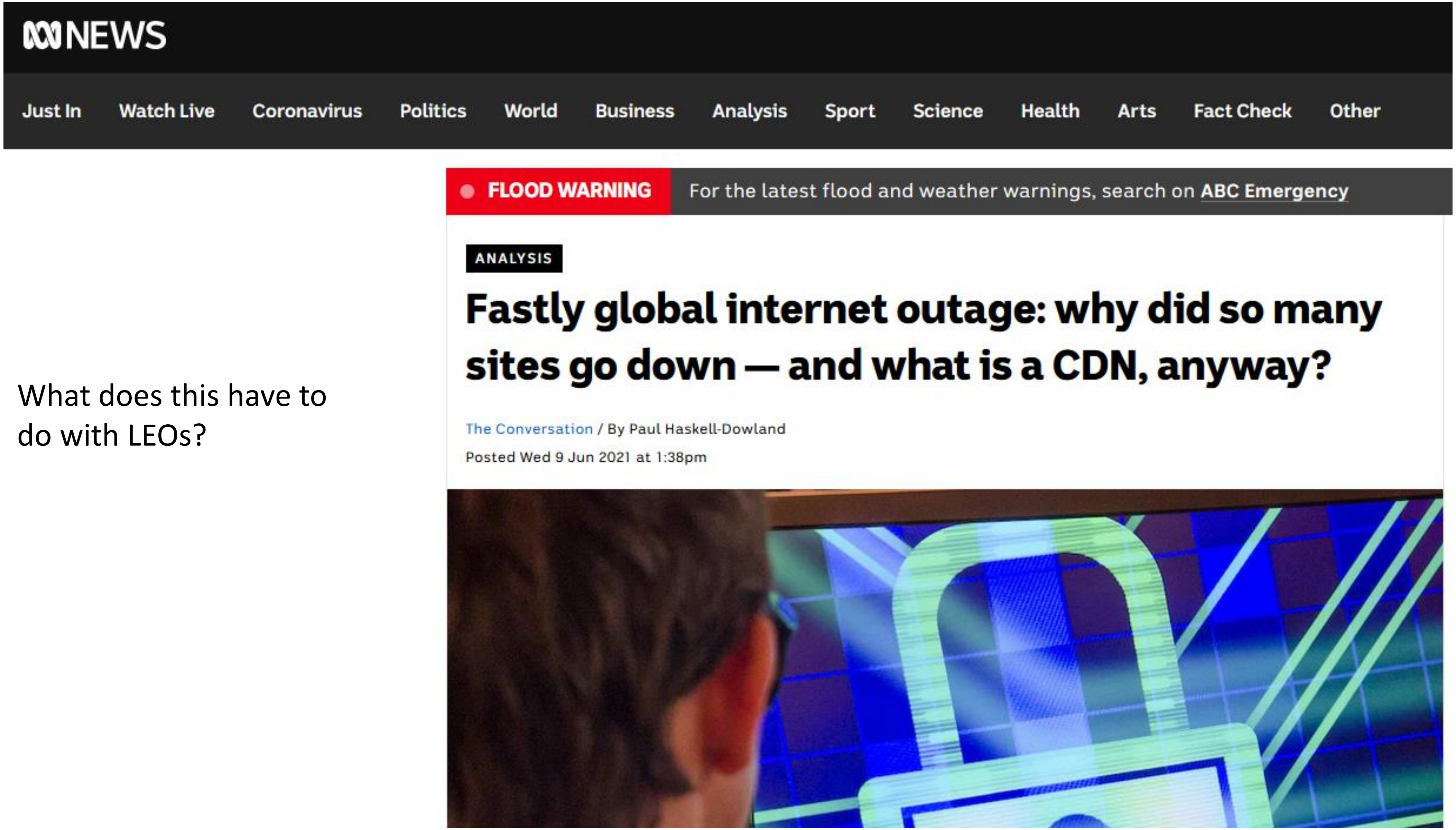
Now for something a little easier: Montana

Population: Just over 1 million, large, mostly rural, several gateways, near ideal latitude just short of 53°



What contributes to lack of capacity?

- Not enough satellites?
- Too few gateways / limited gateway ground bandwidth?
- Limited RF spectrum / blocked capacity
- RF beam width preventing frequency re-use
- Satellite power budget
- Satellite processing power / forwarding bottlenecks



ABC NEWS

Just In | Watch Live | Coronavirus | Politics | World | Business | Analysis | Sport | Science | Health | Arts | Fact Check | Other

FLOOD WARNING For the latest flood and weather warnings, search on ABC Emergency

ANALYSIS

Fastly global internet outage: why did so many sites go down — and what is a CDN, anyway?

The Conversation / By Paul Haskell-Dowland

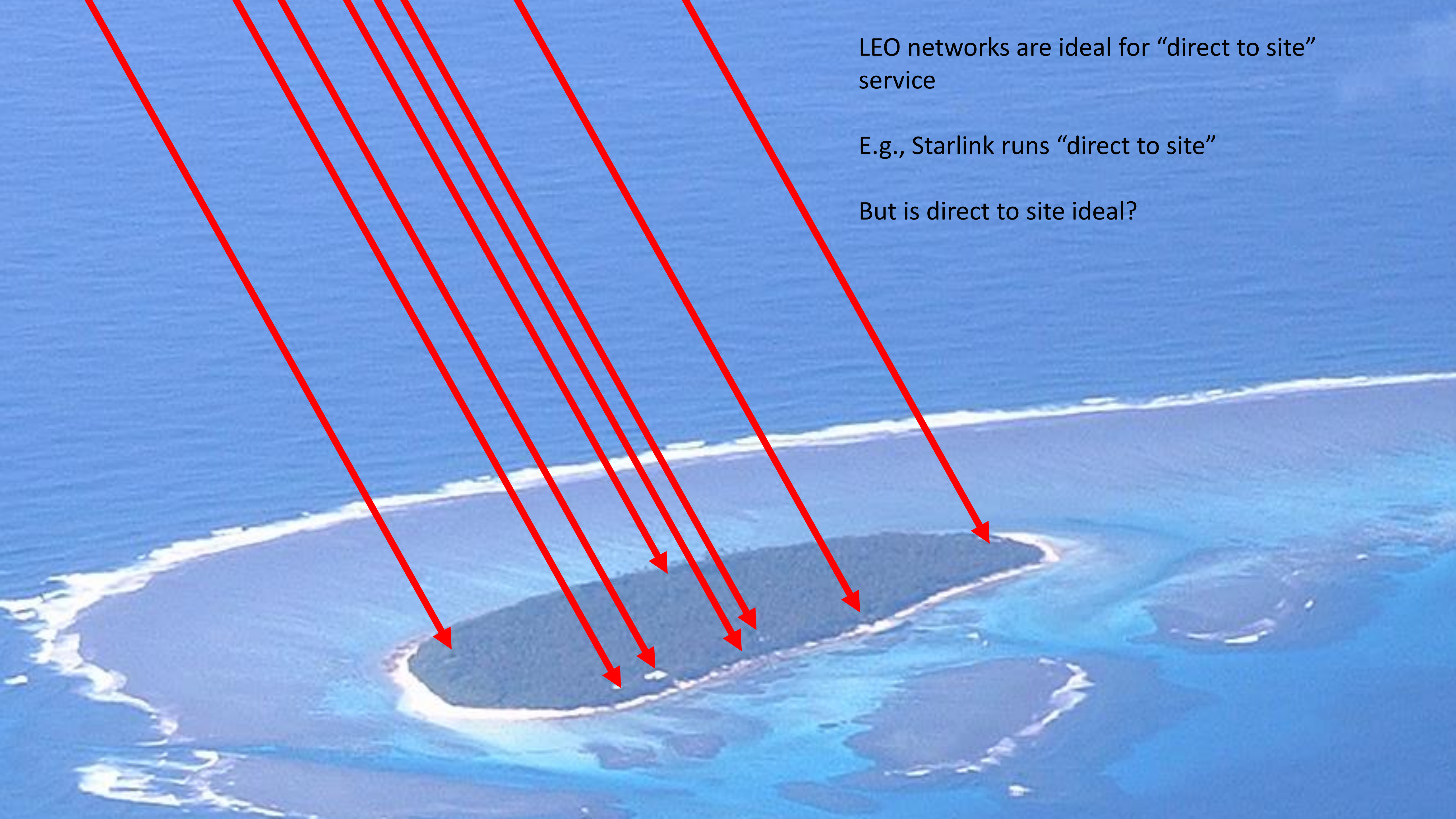
Posted Wed 9 Jun 2021 at 1:38pm

What does this have to do with LEOs?

LEO networks are ideal for “direct to site” service

E.g., Starlink runs “direct to site”

But is direct to site ideal?

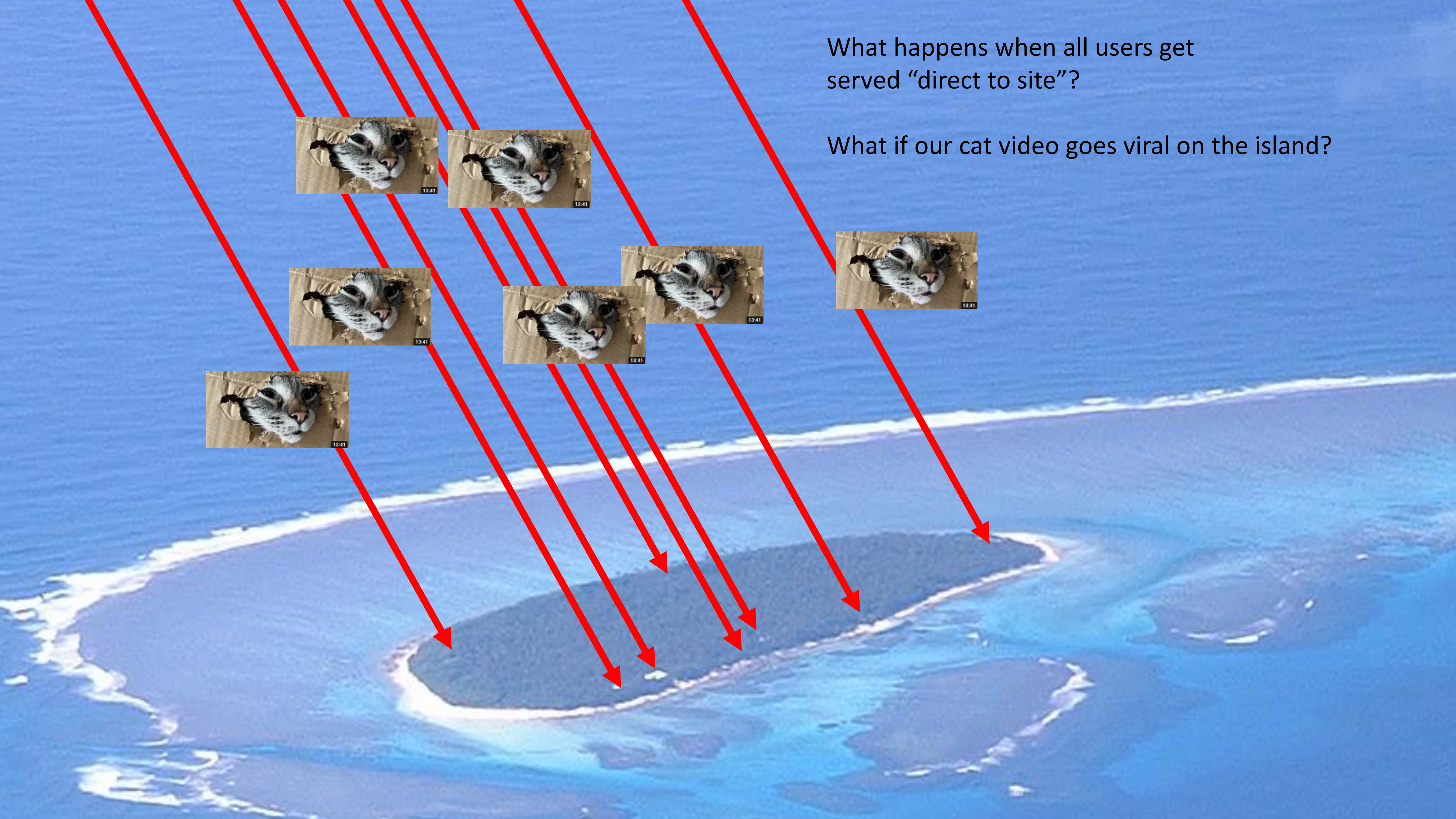



13:41
13:41


13:41
13:41
13:41
13:41


13:41
13:41
13:41
CDN
server

What happens when all users get served “direct to site”?

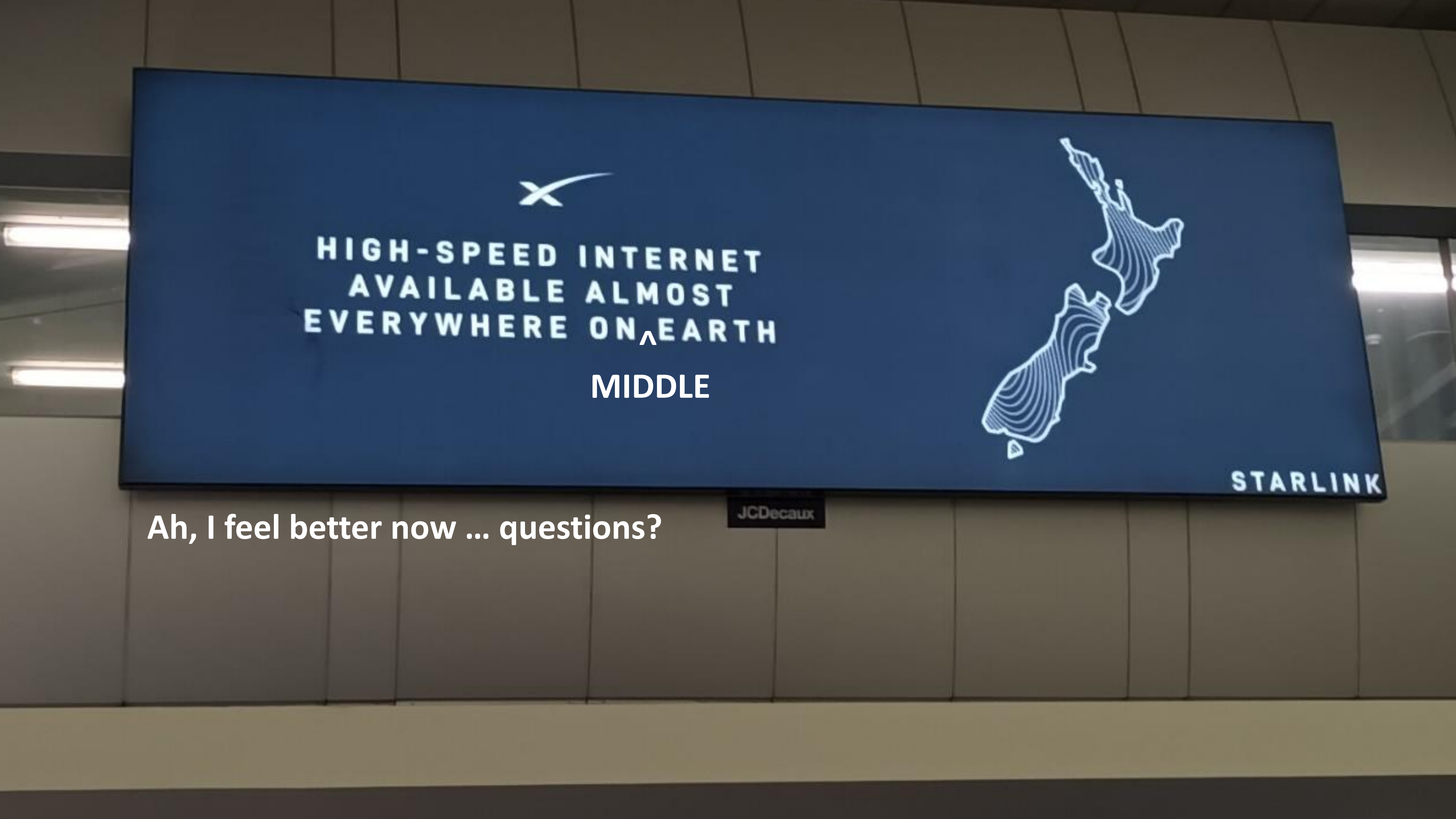

What happens when all users get served “direct to site”?
What if our cat video goes viral on the island?
13:41

LEO security challenges

- Harder to jam than GEO sats (ask the Russians!)
- But: Large number of satellites / gateways means large number of network entry points
- Complexity of network / routing is a risk and potential target
  - Need for widespread over-the-air updates
- Direct-to-site services make DDoS an attractive attack vector

Conclusion

- LEO mega-constellations need multiple shells with a wide range of constellations to give truly global coverage
  - What is the optimal shell design?
- Routing in mega-constellations is possible but not trivial
  - IPv6 has potential, as has distributed routing
  - How much sense does it make to exploit orbital geometry?
- Capacity is a huge challenge
  - Is it best to stick to ground transit as much as possible?
- How do we make LEOs fit around content delivery?



Ah, I feel better now … questions?