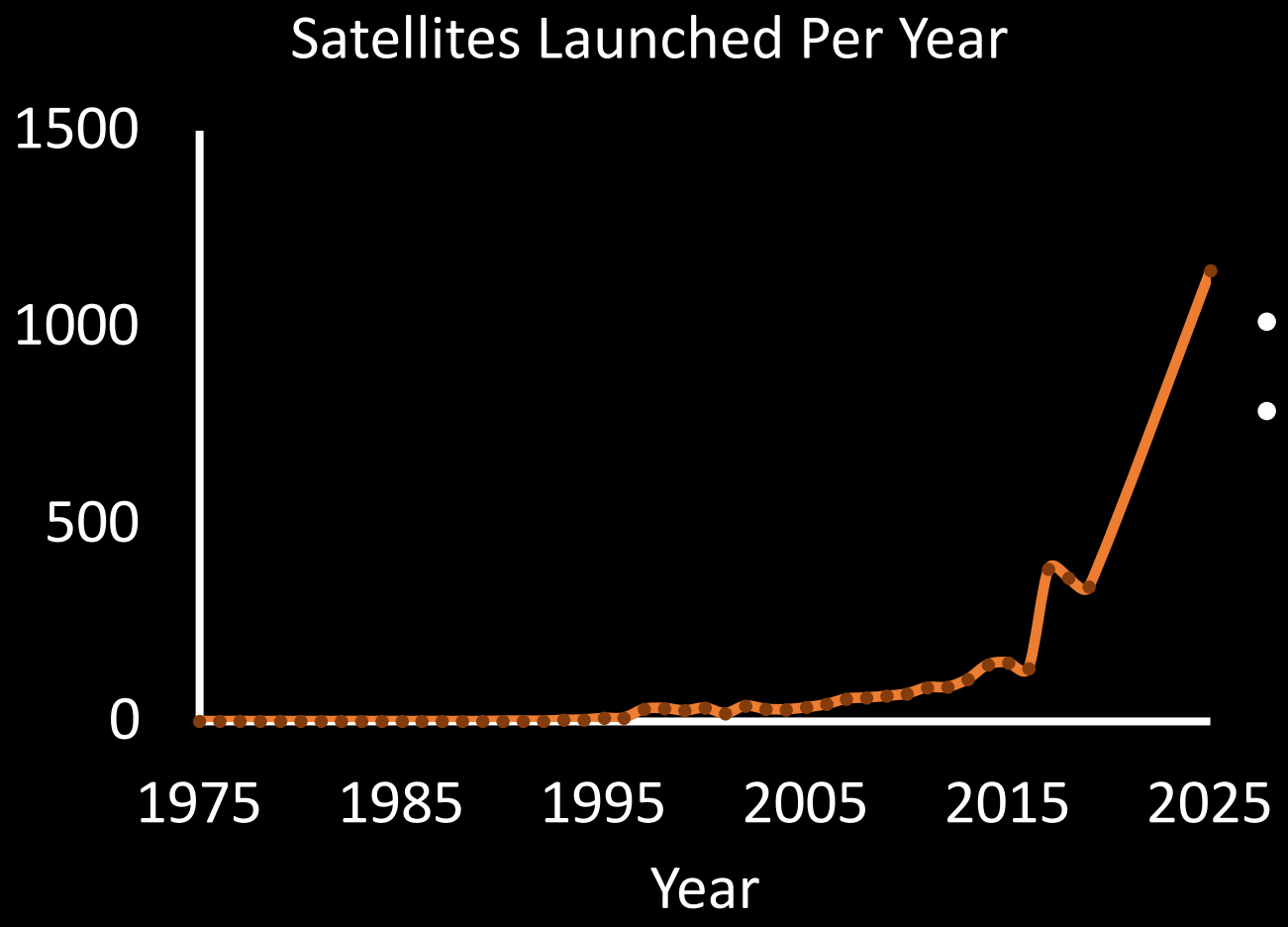
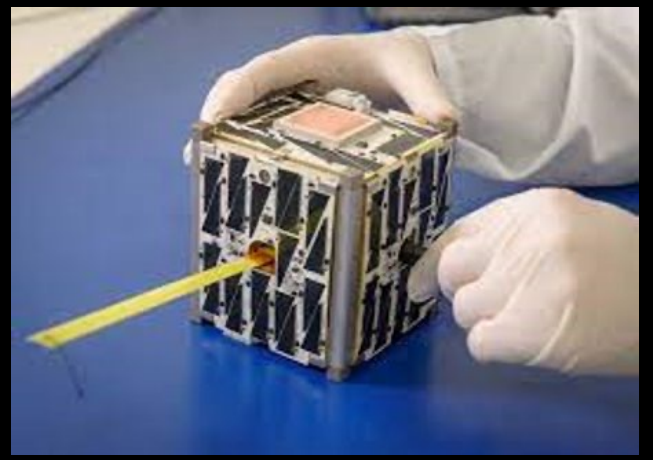
Low Earth Orbit Satellites for Communication and Earth Observation

Deepak Vasisht

UNIVERSITY OF
ILLINOIS
URBANA-CHAMPAIGN



- Low-cost Cubesats
- Rideshare agreements for launch

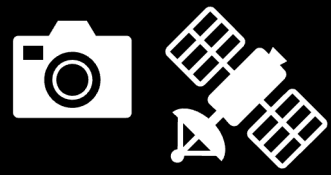


Source: UCS Satellite Database

Communication

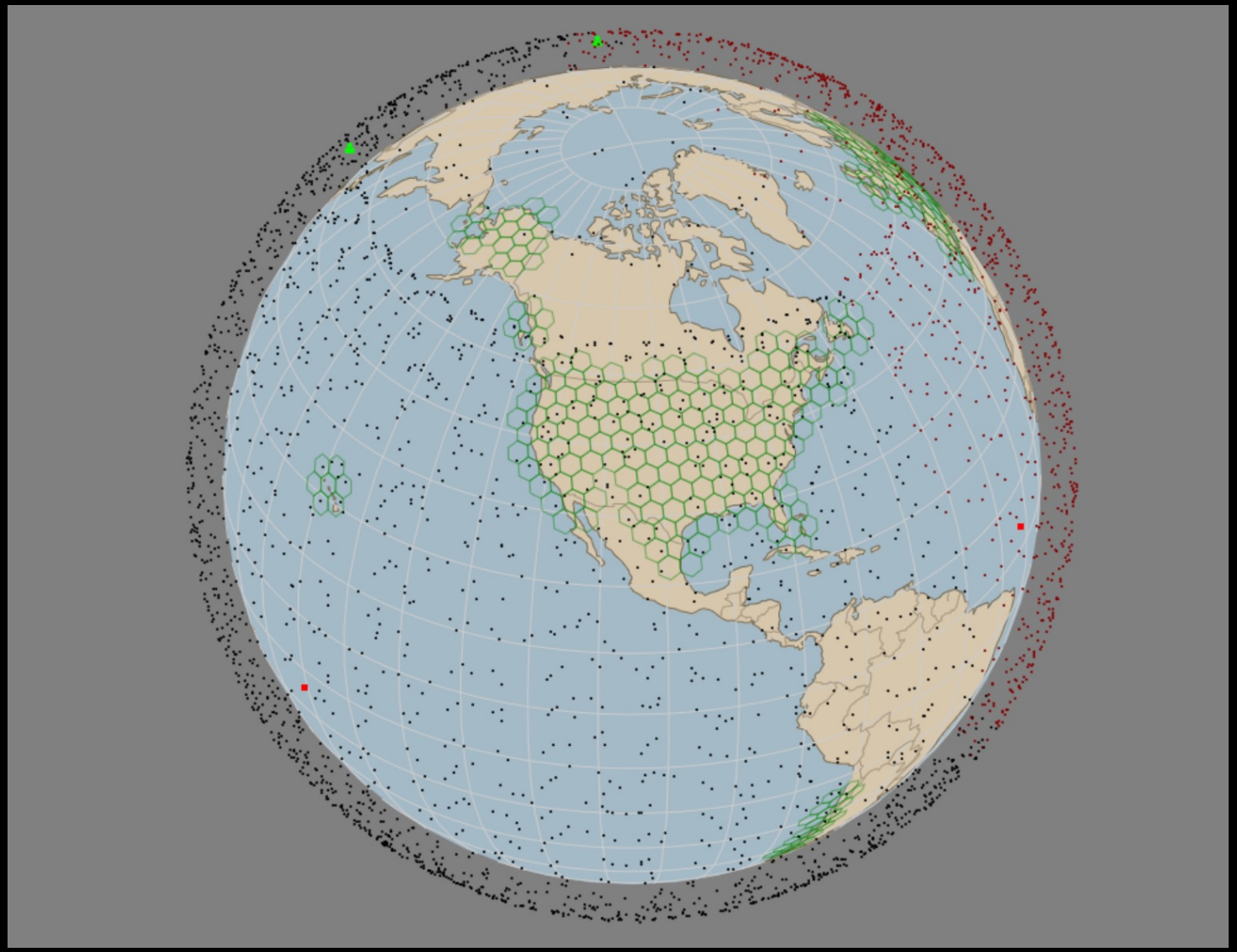
Global Internet Connectivity

Earth Observation



Sensing from Space

Communication Satellites

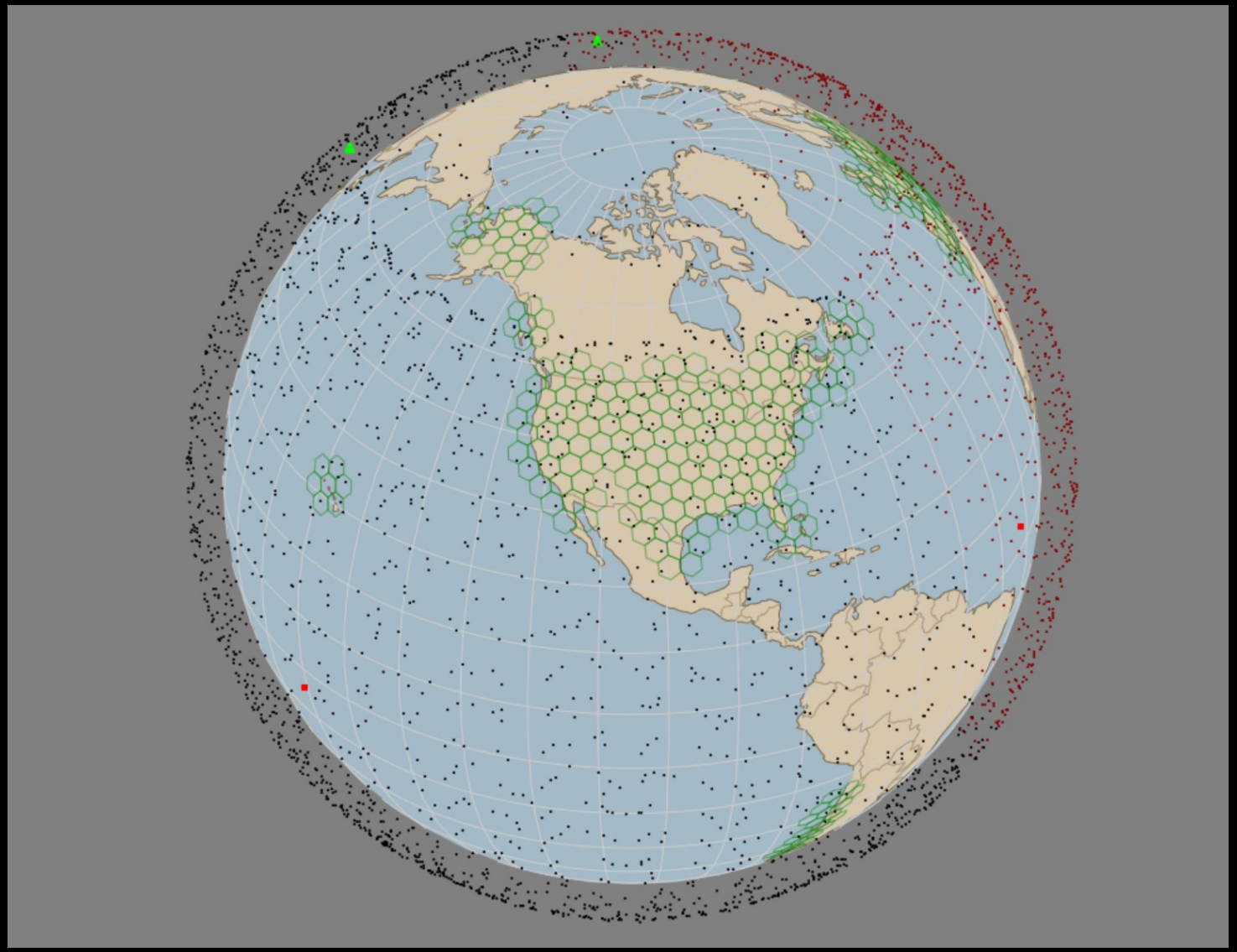


Starlink

Nearly 5000 satellites in orbit

42000 planned

Communication Satellites

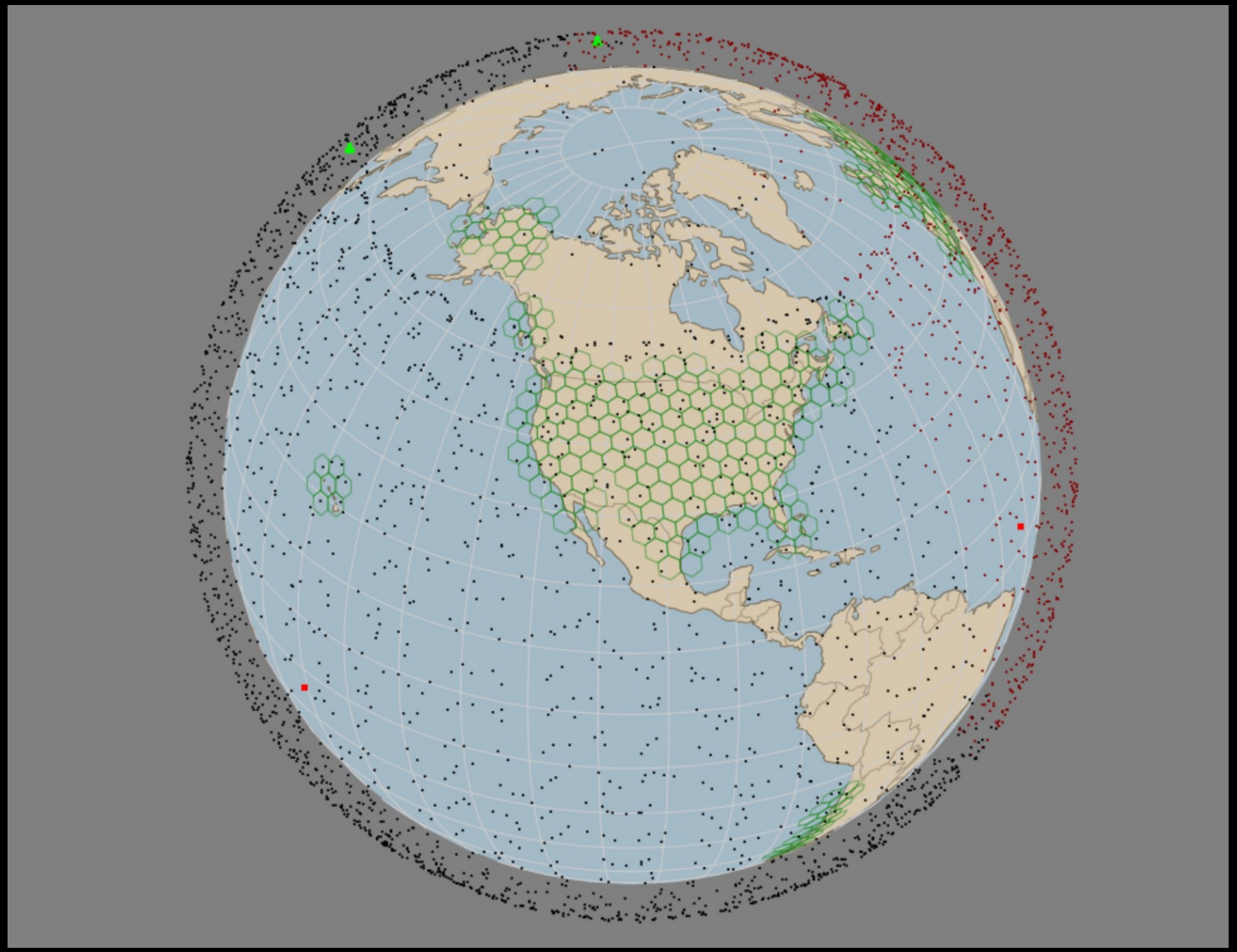


Amazon Kuiper

Launched first set of satellites in 2023

3300 planned

Communication Satellites



Other Companies

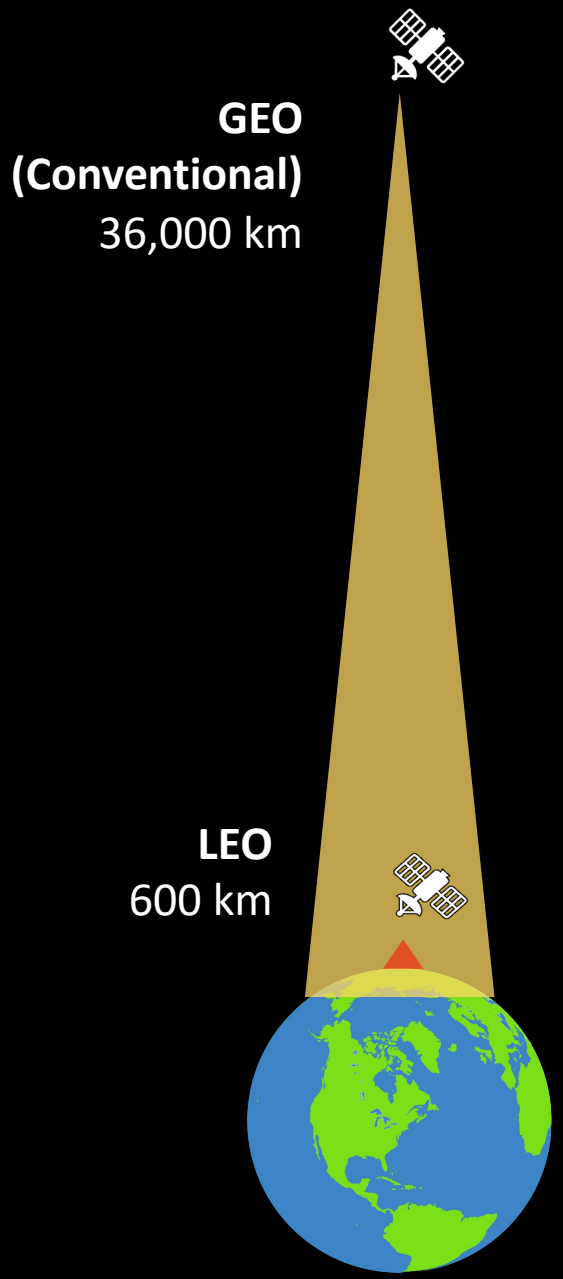
ViaSat, HughesNet, OneWeb, Telesat, Echostar

Why Satellite Internet?

- Coverage
  - Rural connectivity
  - Farms and forests
- Speed of light over air is faster than speed of light over fiber (by 50%)
  - Lower latency

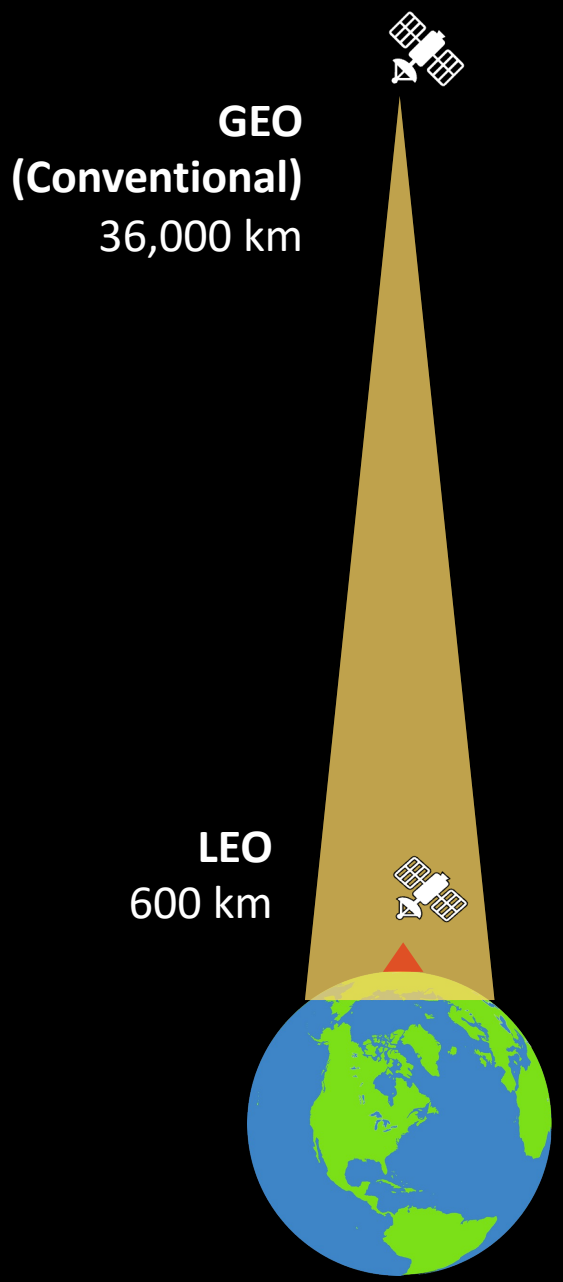
Why Satellite Internet?

Satellite Orbits



Which orbit leads to better coverage?

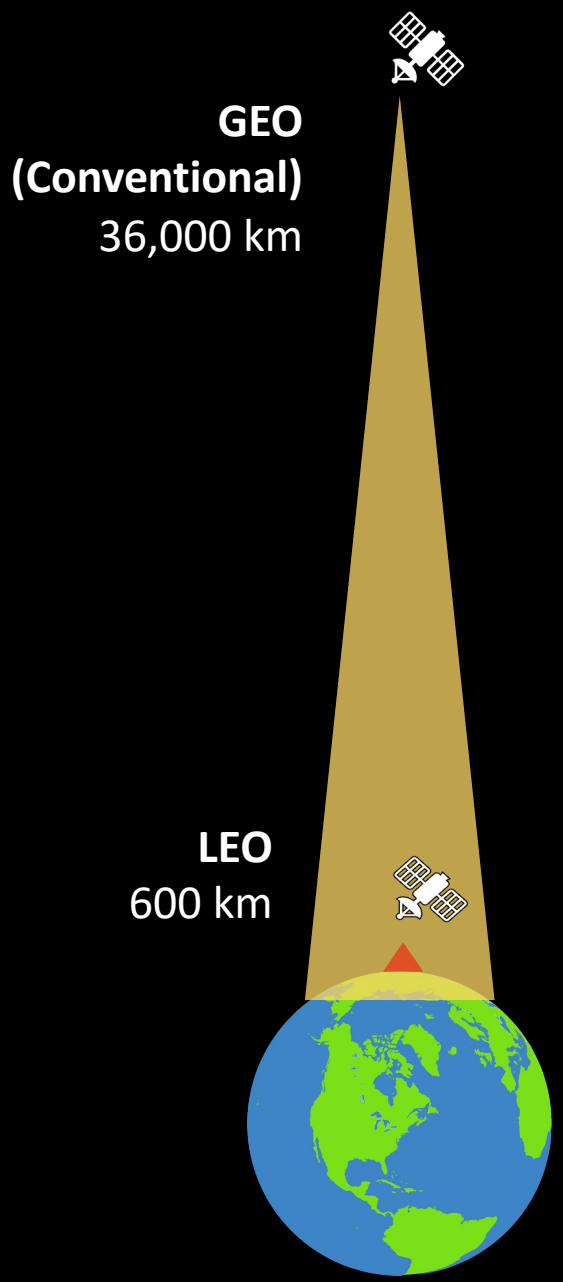
Satellite Orbits



Which satellite moves more?

Starlink satellites move few Kms per second

Satellite Orbits



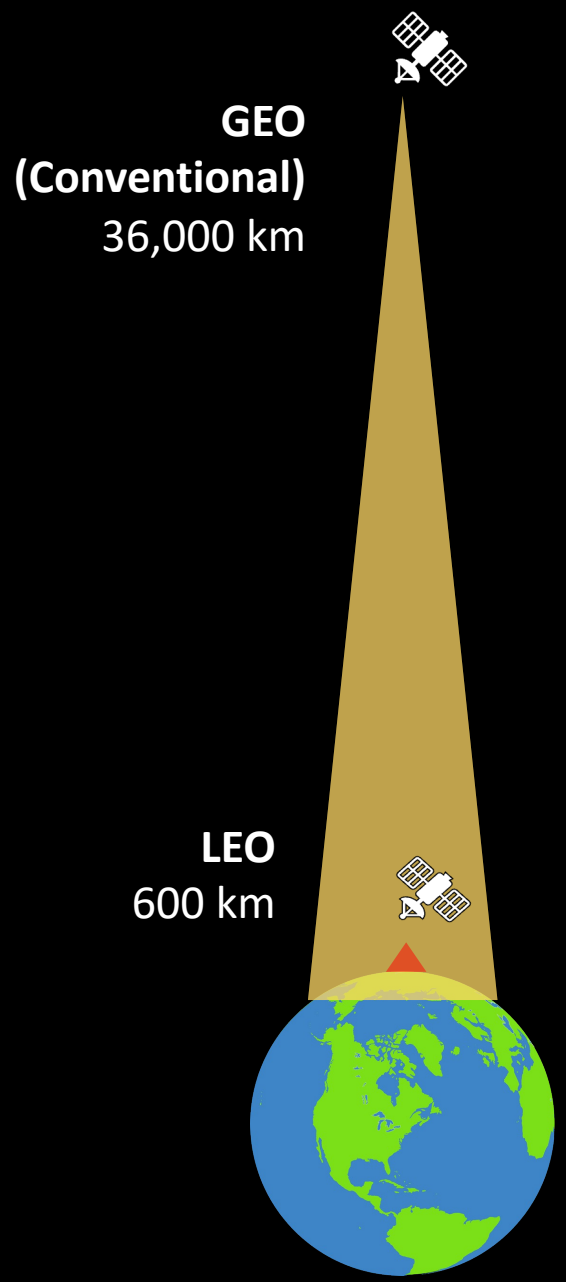
Which satellite gets stronger signals?

Power decays as d^{-2}

60X more distance

35 dB extra loss

Satellite Orbits

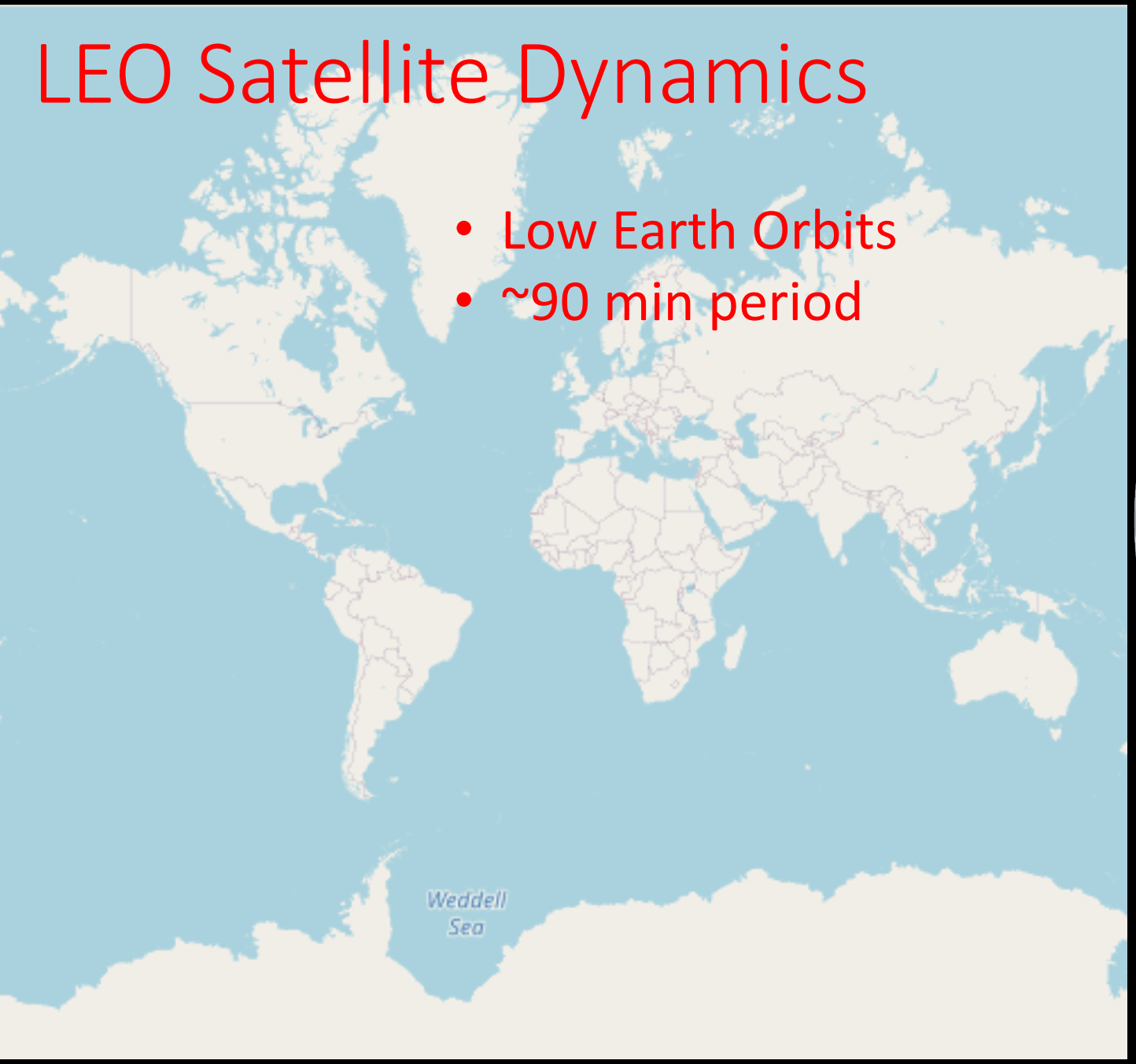


What about delays?

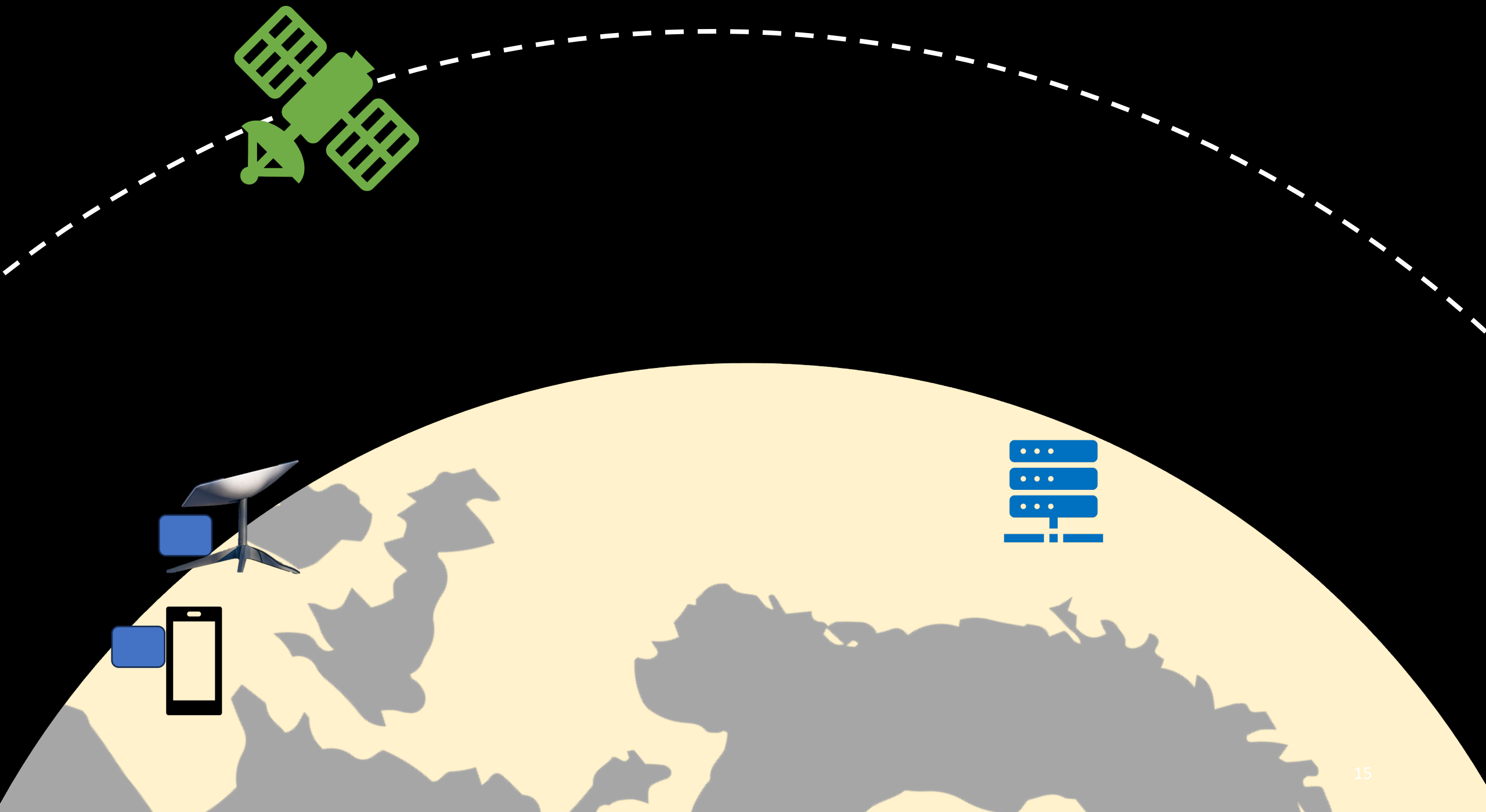
Speed of light delay:
GEO: >240 ms
LEO: >4 ms

LEO Satellite Dynamics

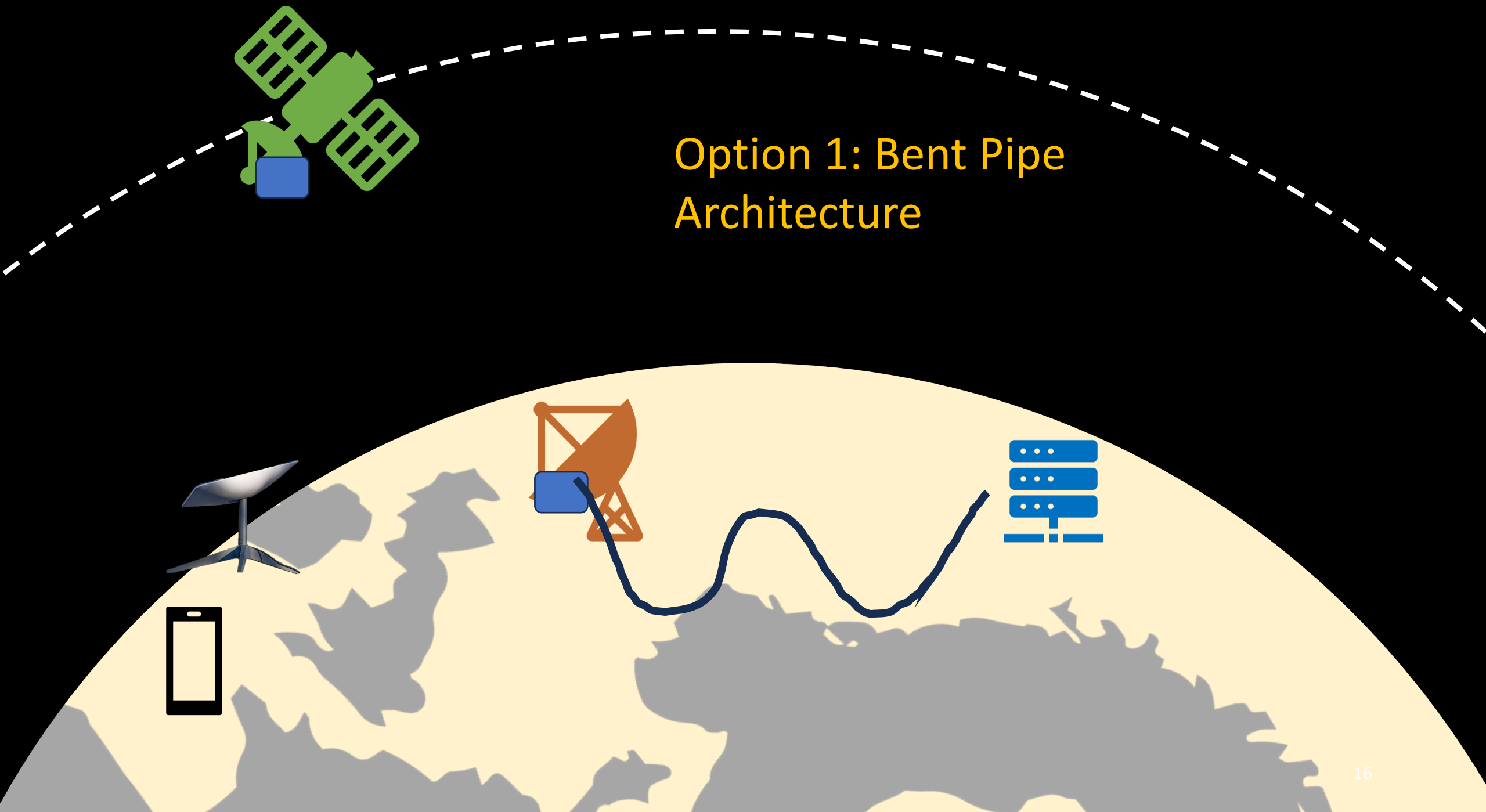
- Low Earth Orbits
- ~90 min period



How does Satellite Internet Works?

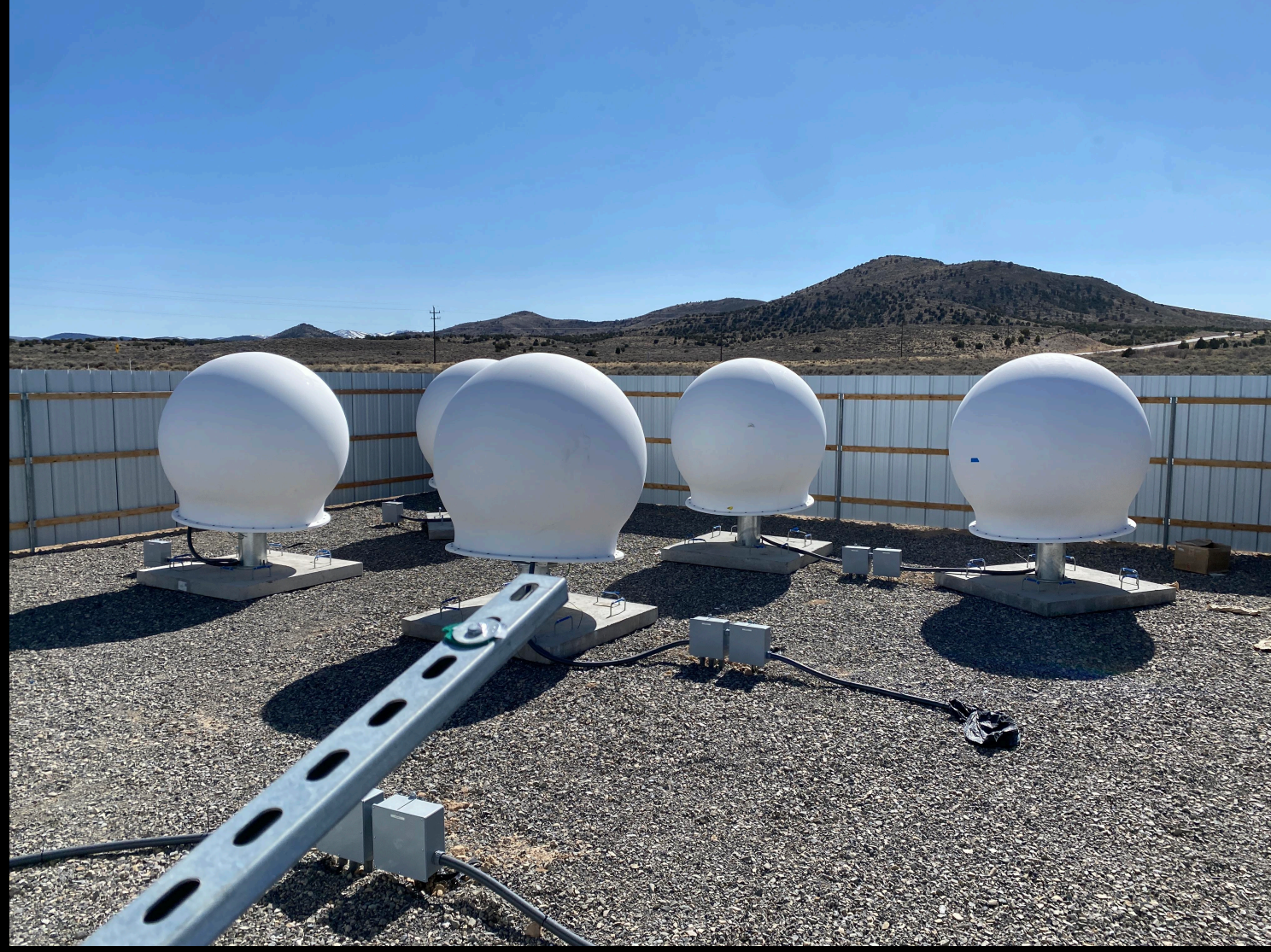


Option 1: Bent Pipe Architecture



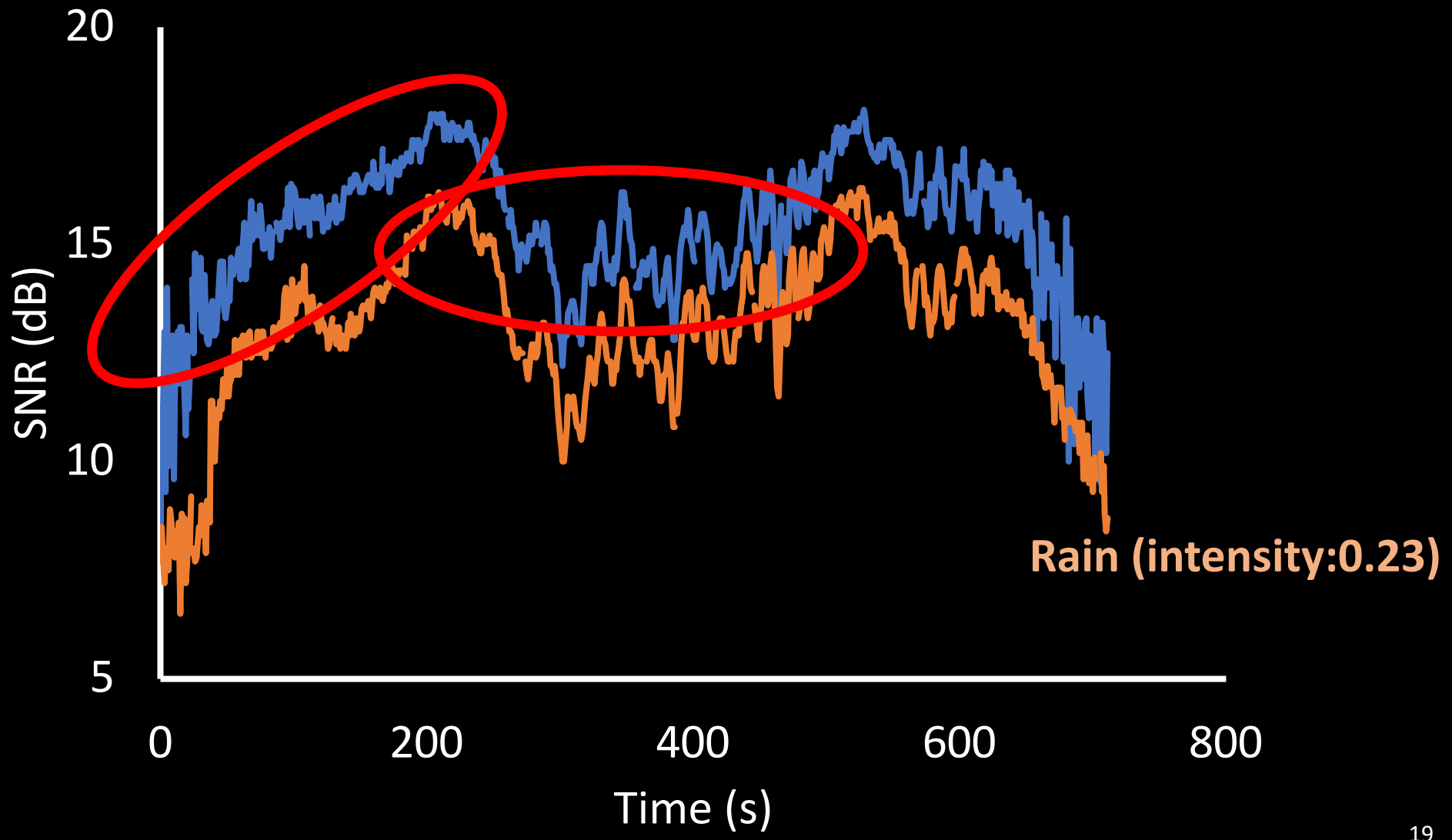
Bent-Pipe Architecture

- Needs MANY ground stations
- Starlink has nearly 100 ground stations in US

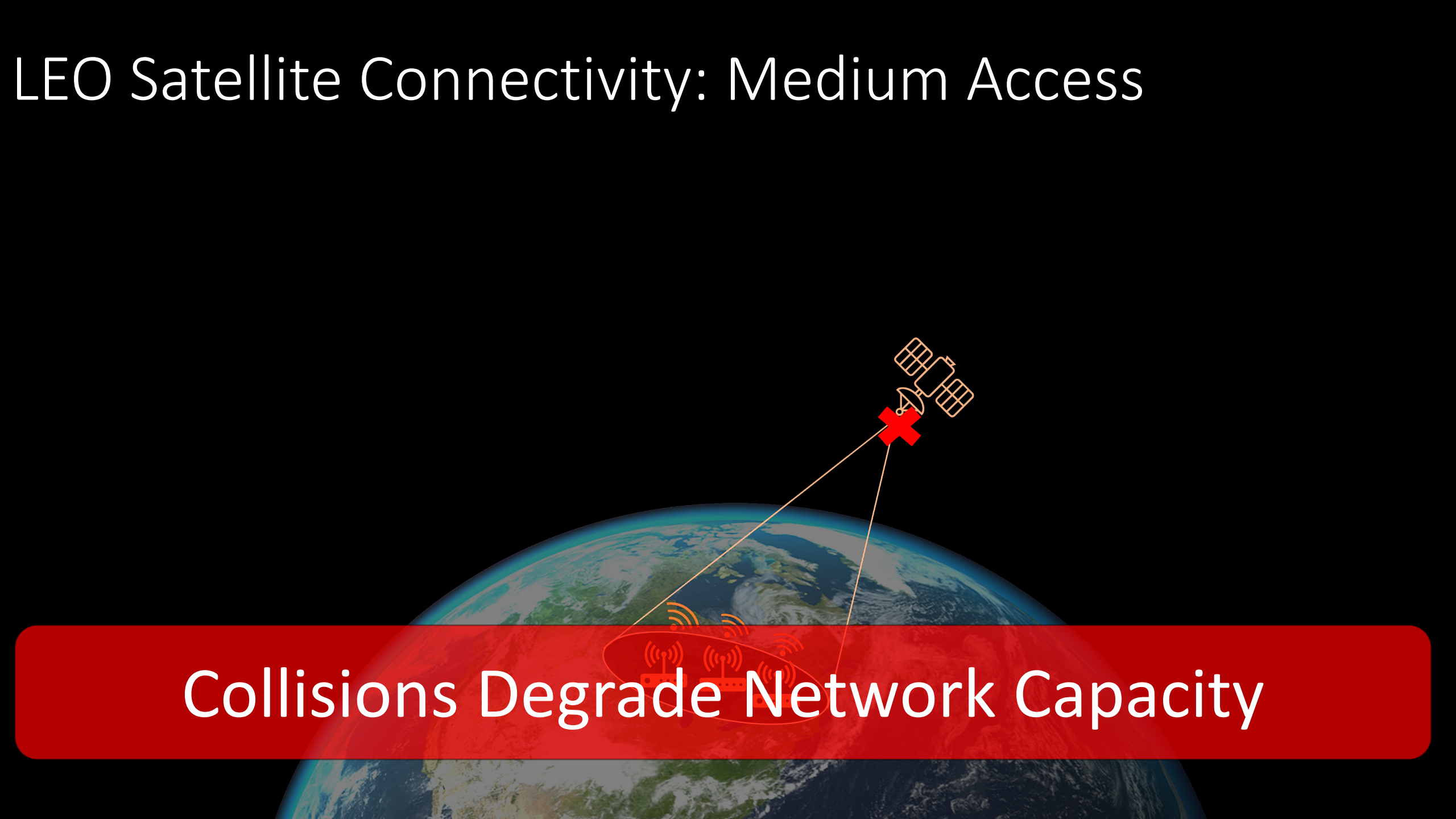


Option 2: Inter Satellite Links

LEO Satellite Connectivity: Link Variation

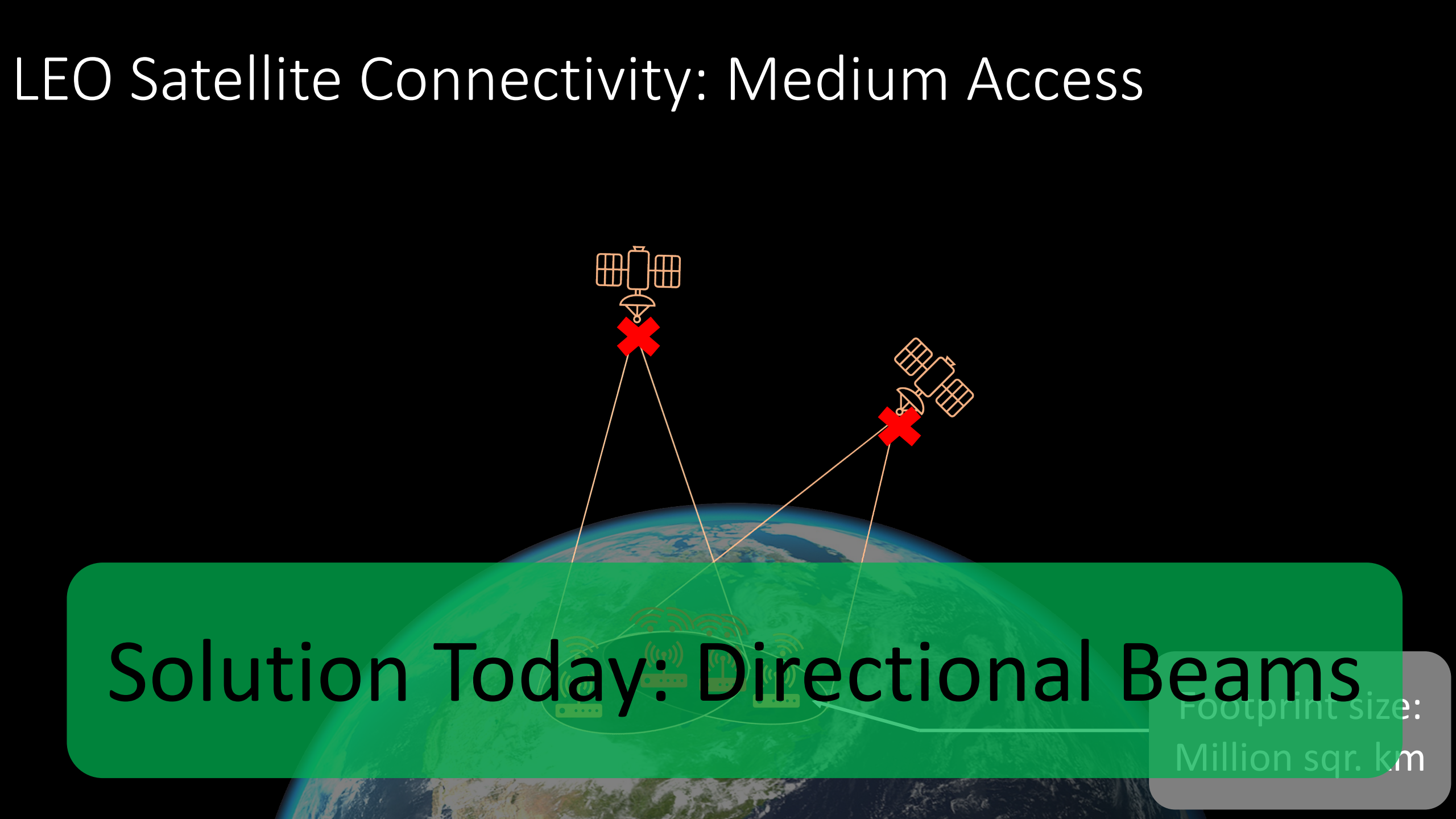


LEO Satellite Connectivity: Medium Access



Collisions Degrade Network Capacity

LEO Satellite Connectivity: Medium Access



Solution Today: Directional Beams

Footprint size:
Million sqr. km

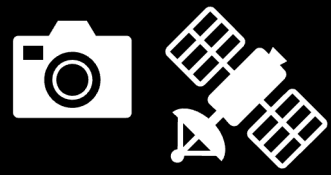
LEO Status Today

- Starlink has 5000 satellites in orbit
- >2 million subscribers
- >100Mbps downlink
- Amazon Kuiper launched their first satellites
- OneWeb has 650 satellites in orbit

Communication

Global Internet Connectivity

Earth Observation



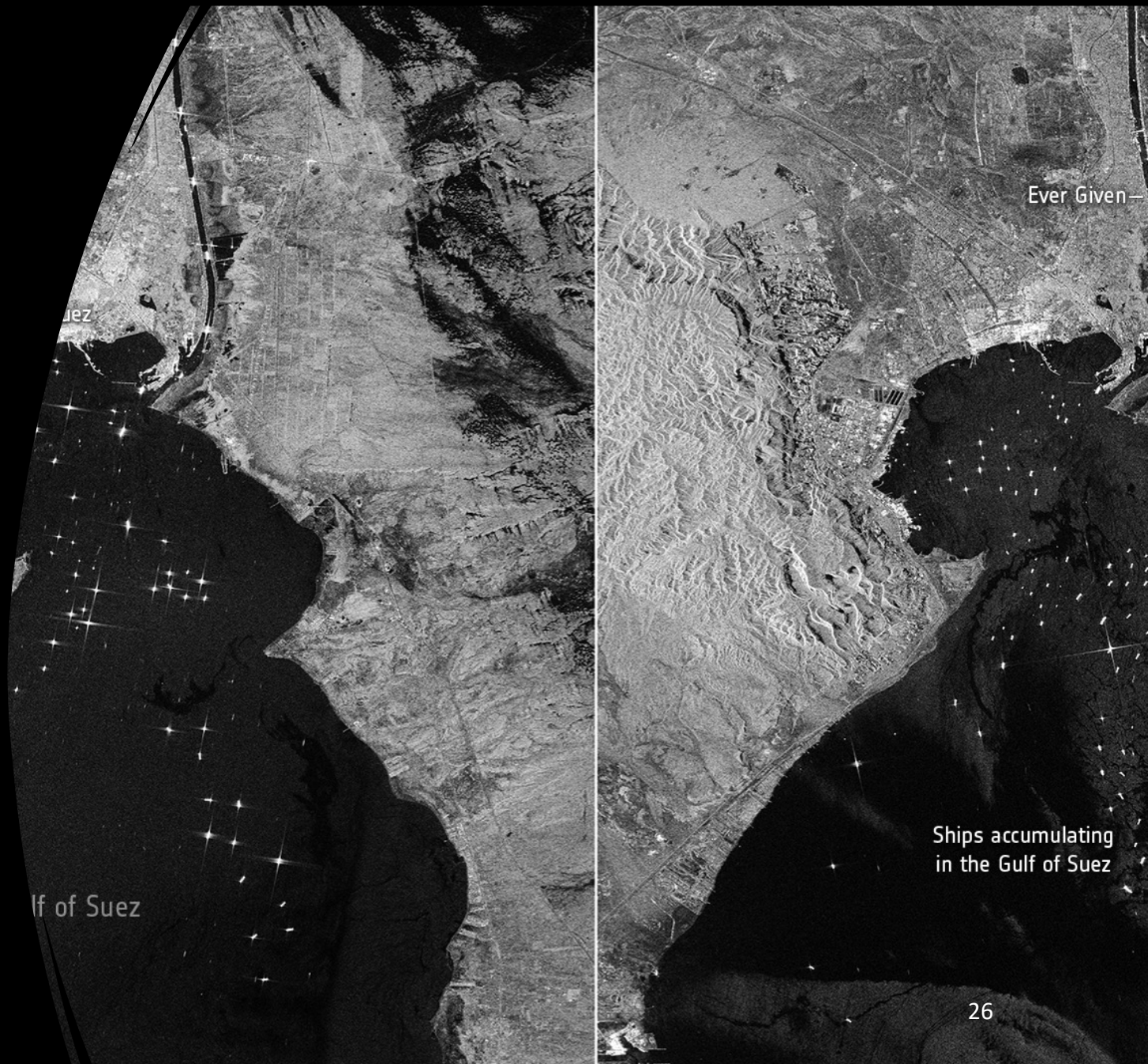
Sensing from Space

Earth Observation Applications: Agriculture

- Precision Agriculture
- Monitoring events like floods

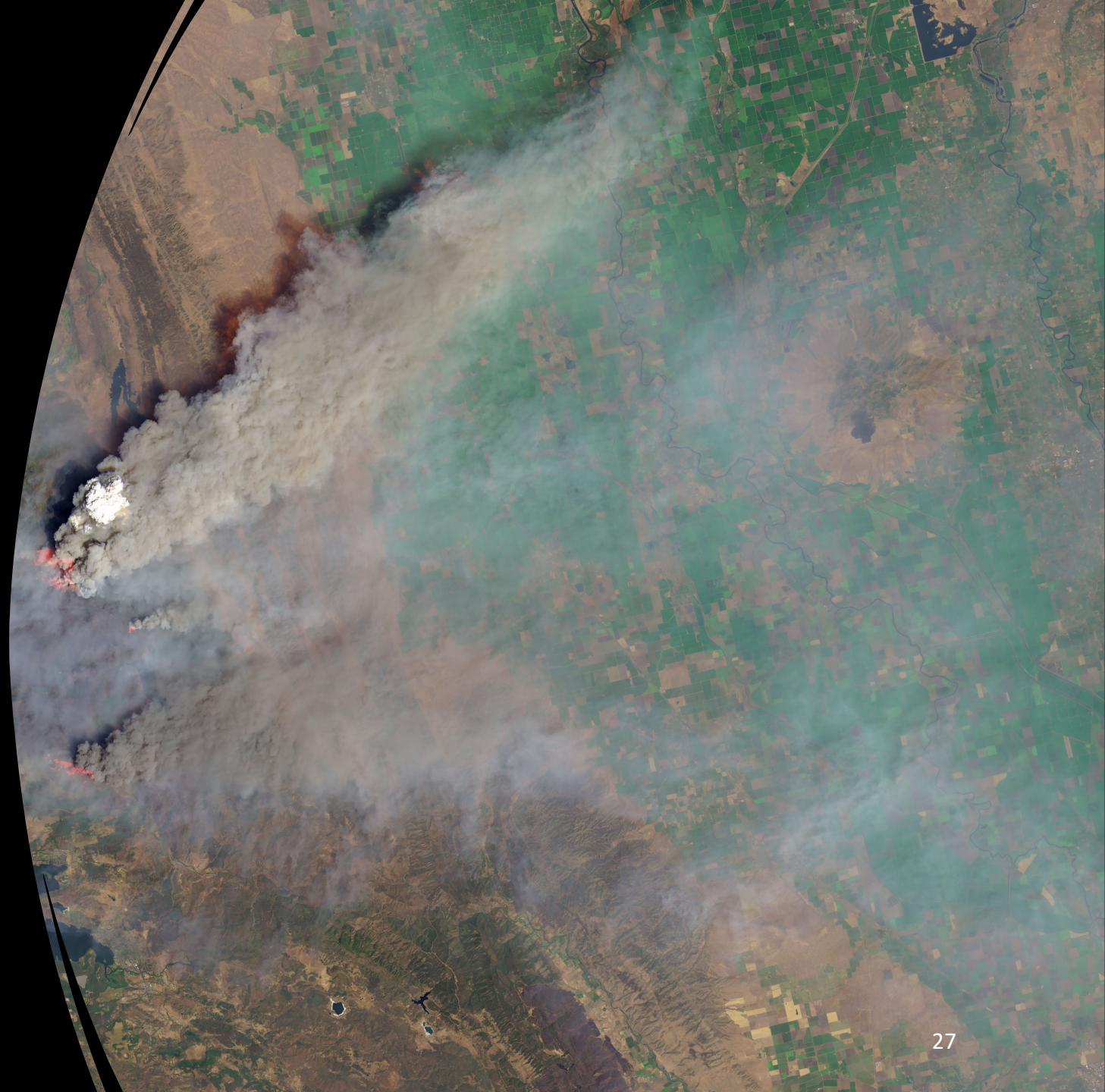
Earth Observation Applications: Maritime Tracking

- Track illegal smuggling
- Monitor ship traffic



Earth Observation Applications: Disaster Monitoring

- Early detection
- Tracking propagation



Source: NYTimes/Maxar

Capella Space

MAXAR

Earth Observation Satellites

500 km orbits

↓

High resolution

Hundreds of satellites

↓

Days to hour/minute level revisits

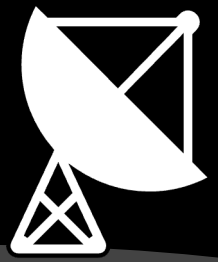
Better Hardware

↓

Multi-spectral

Challenge: Data Downlink

- Single image of Earth is 500 terra-pixels
- 100s GB of Data per satellite per day
- Each contact lasts nearly 10 minutes



Today: Large Complex Ground Stations

- Multi-million dollar investments
- 4 to 5 massive ground stations located close to the poles

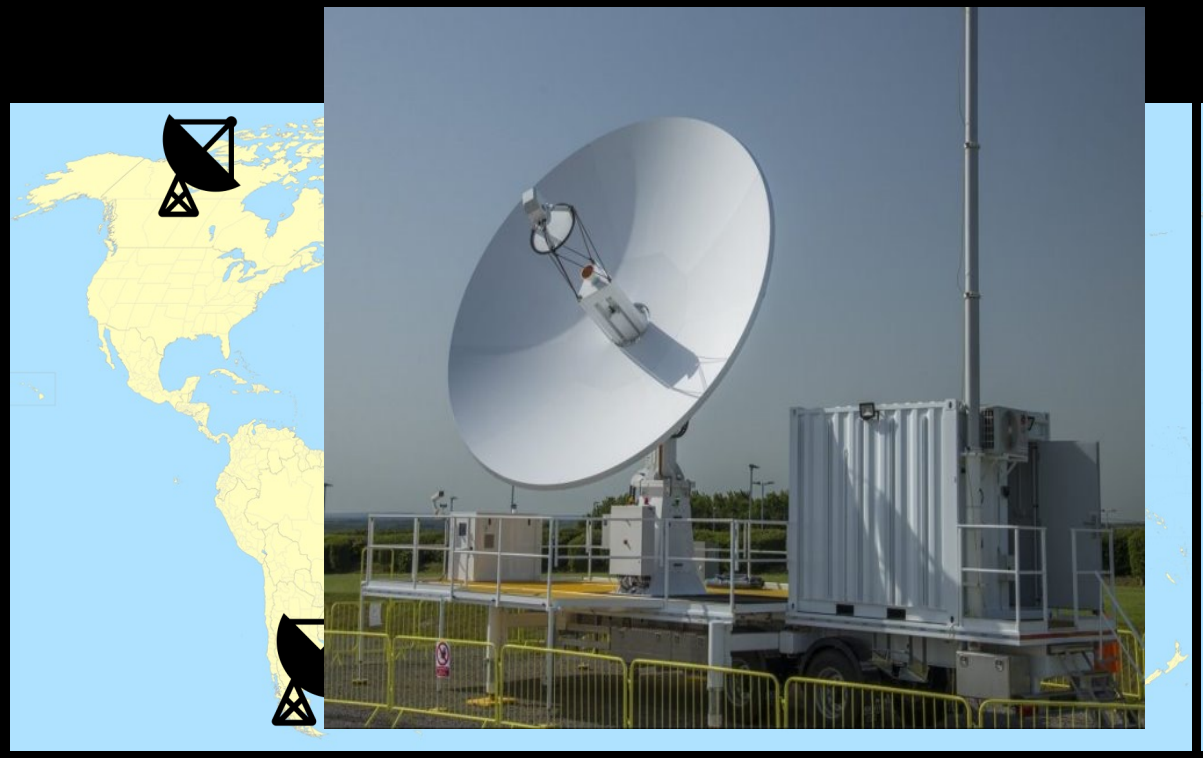
Image Source: airforce-technology.com

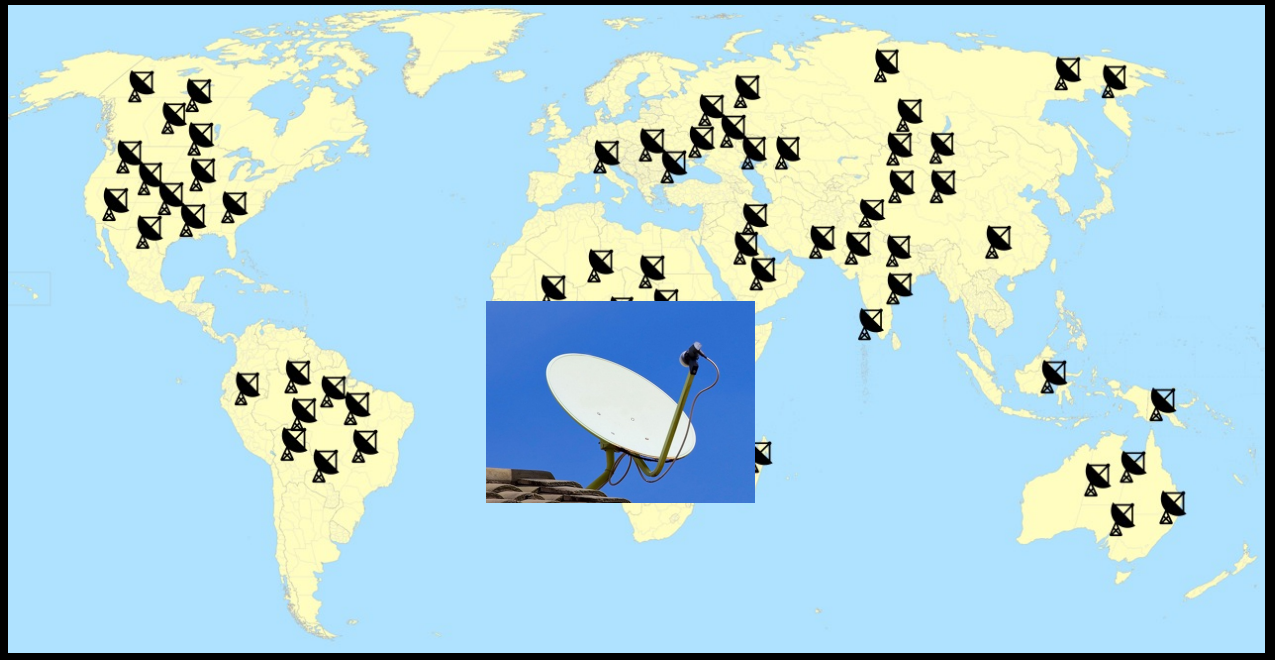
Shortcomings

- Large latency (hours)
- Scaling is capital-intensive
- Failures (e.g. weather) are disruptive

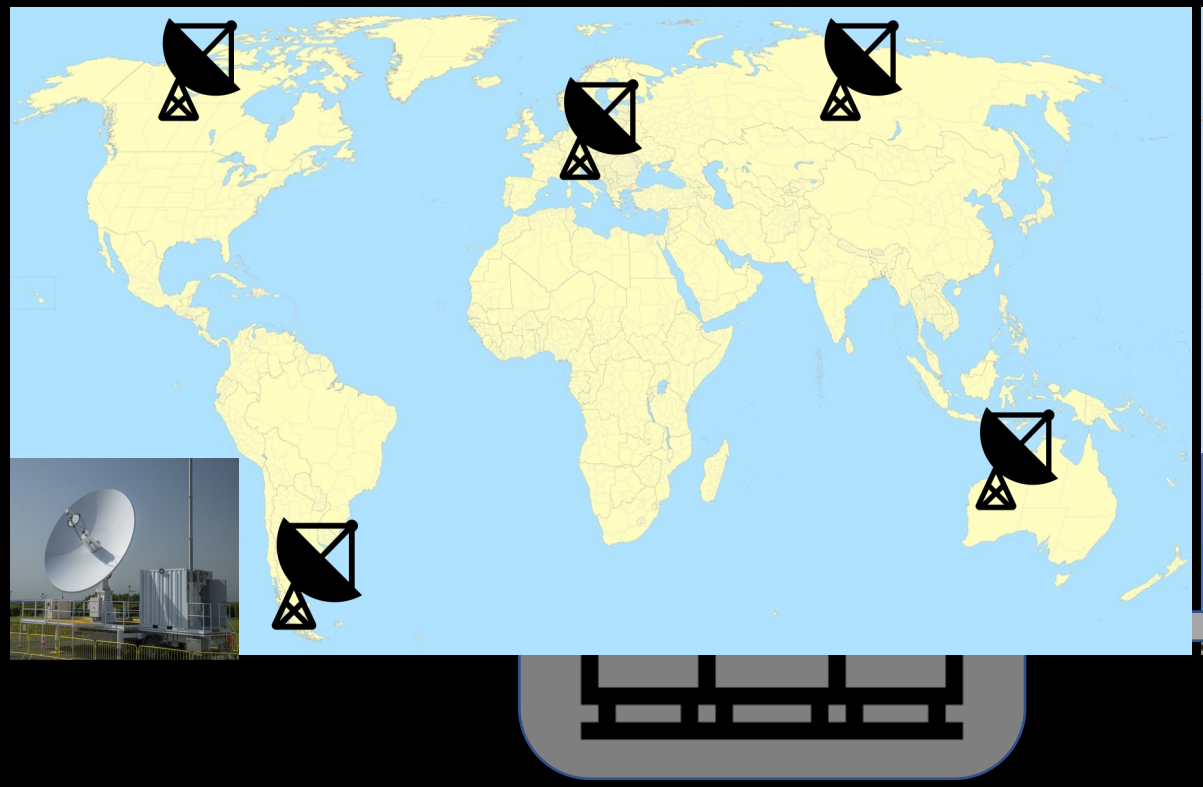
Alternative Approach: Distributed Ground Stations

Distributed Hybrid Ground Station

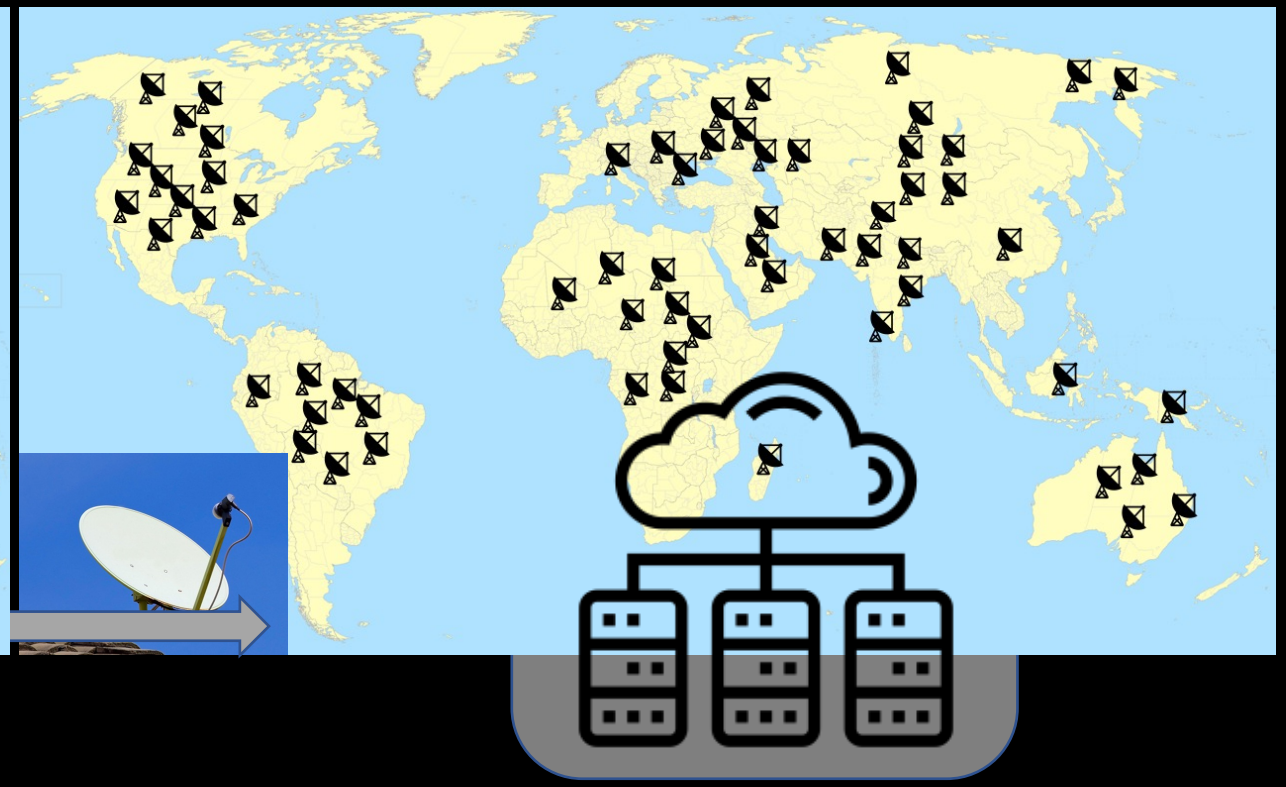




Distributed Hybrid Ground Station



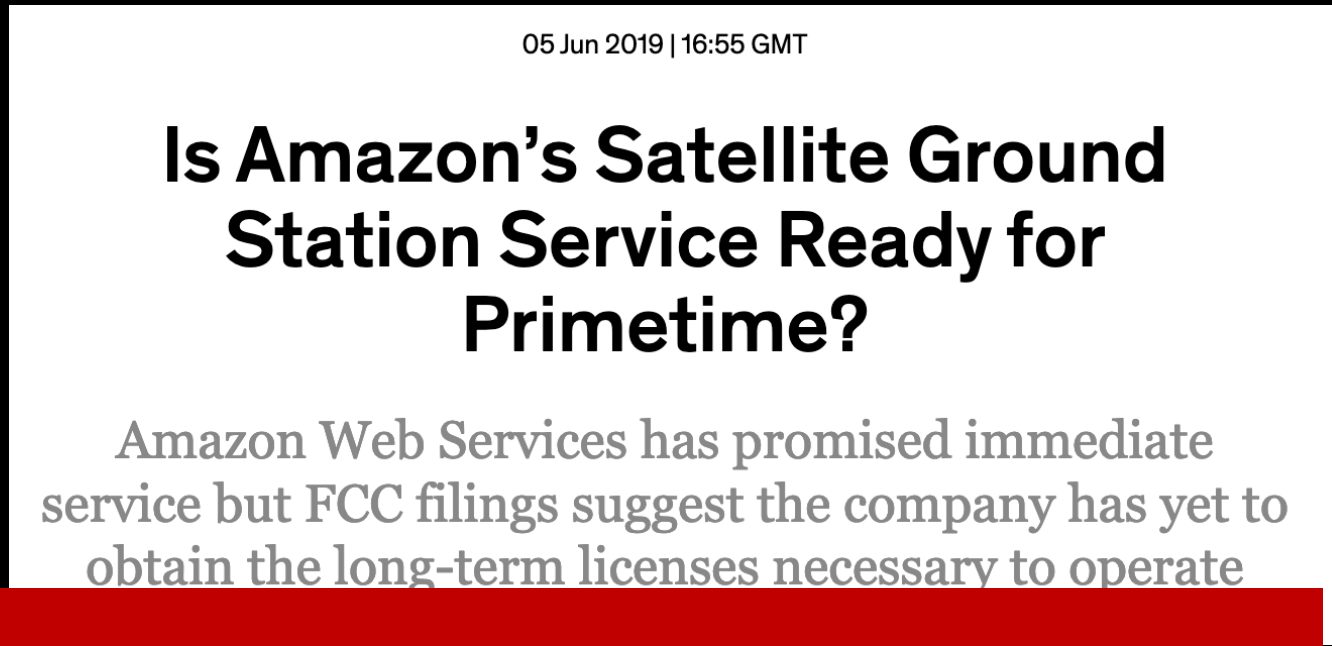
Supercomputers



Cloud Datacenters

Distributed Hybrid Ground Station

- Fault-tolerant
- Low Latency
- Receive-Only: most ground stations do not transmit



05 Jun 2019 | 16:55 GMT

Is Amazon's Satellite Ground Station Service Ready for Primetime?

Amazon Web Services has promised immediate service but FCC filings suggest the company has yet to obtain the long-term licenses necessary to operate

Can a network of tiny ground stations outperform the capital-heavy huge ground stations?

Challenges

- Rate adaptation without feedback
- Scheduling satellite-ground station links
- Lack of acknowledgements

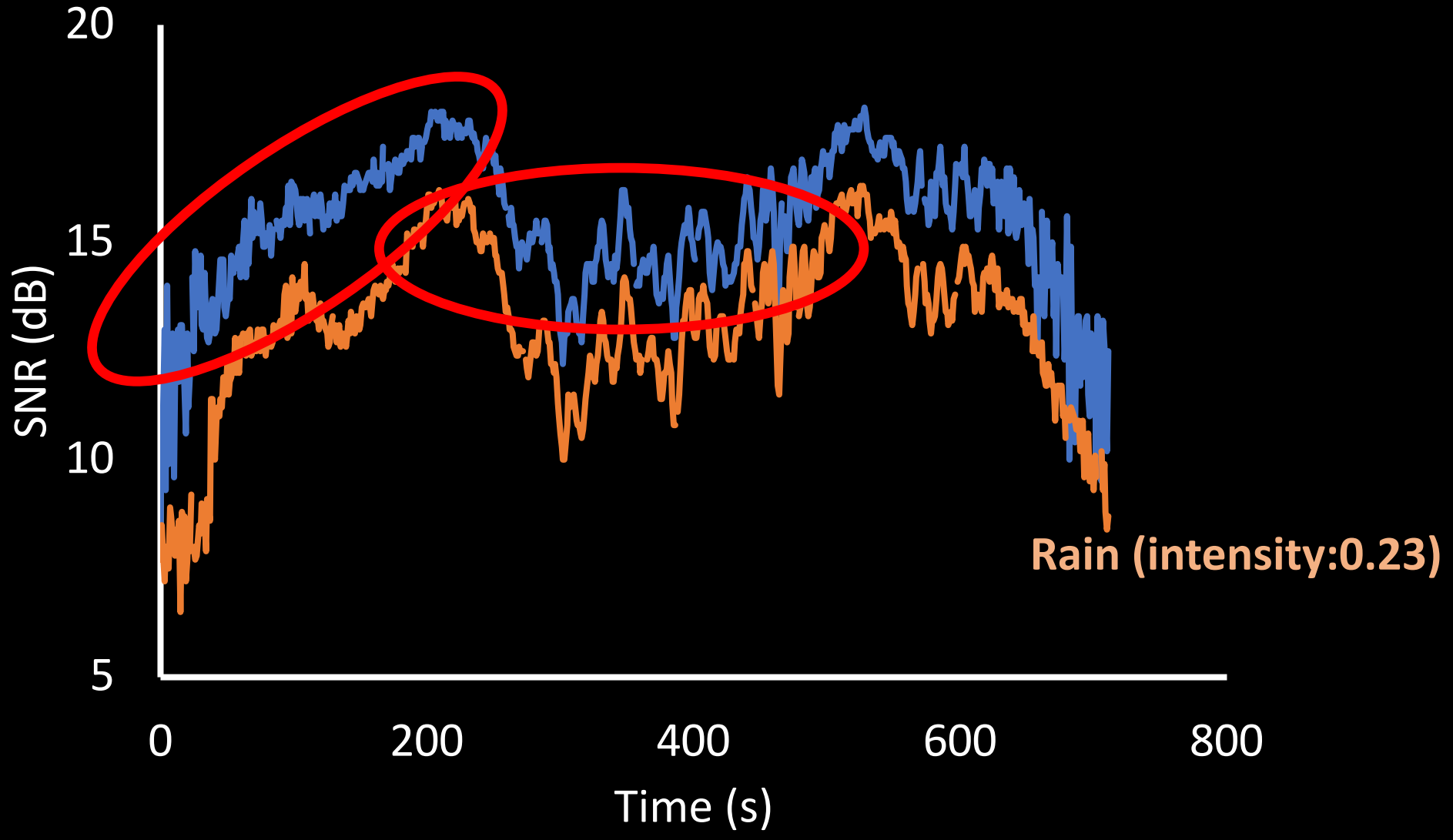
Challenge: Rate Adaptation

- Link quality varies by 10 to 20 dB
  - Depends on elevation
  - Weather (8-10 dB for X, Ku, Ka bands)
  - Equipment

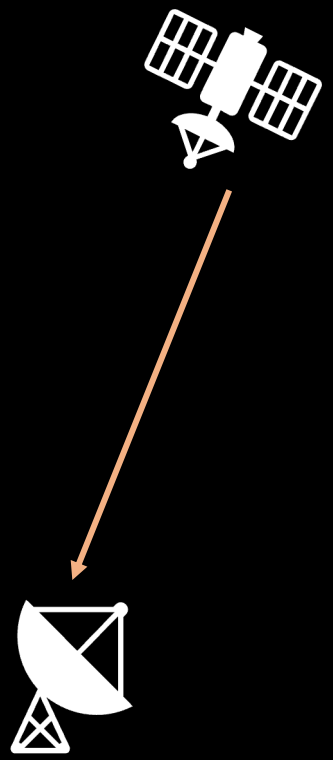
- No feedback → No rate adaptation
  - Low rate → Wasted opportunity

Need rate adaptation without feedback

Link Quality: X-band



Solution: Link Quality Estimation

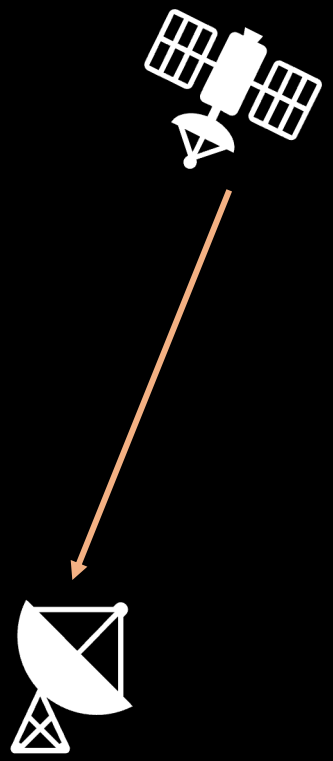


Propagation loss due to distance

Weather related loss

Device/location specific losses (multipath, etc.)

Intuition: Link Quality Estimation



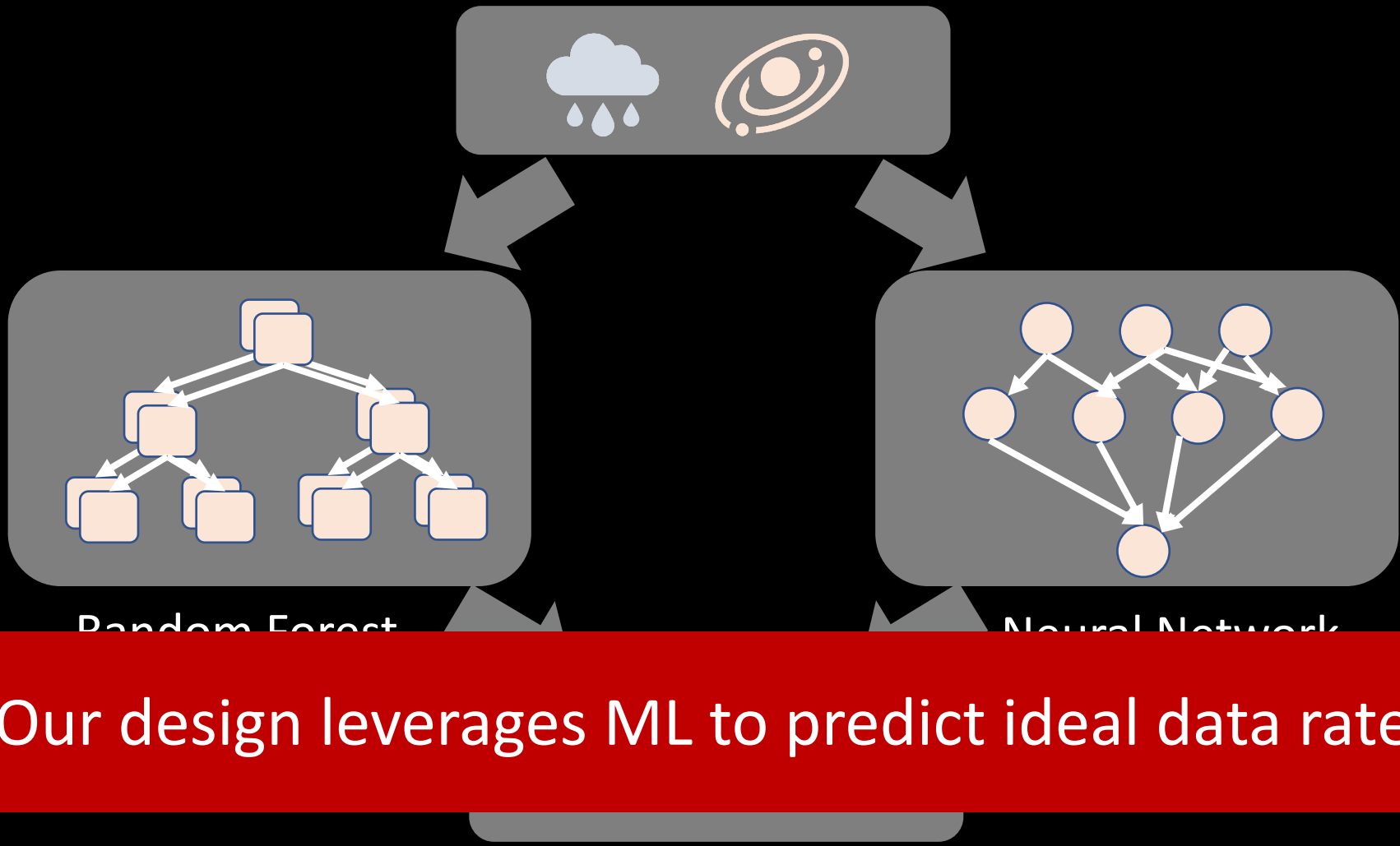
Predict distance using orbit parameters

Use weather forecasts for weather loss

Train for multipath and hardware losses

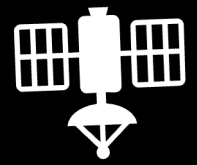
Datarate

ML Model to Predict Link Quality

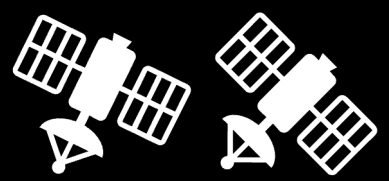


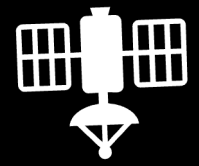
Our design leverages ML to predict ideal data rate

Challenge 2: Scheduling Satellite-GS Links

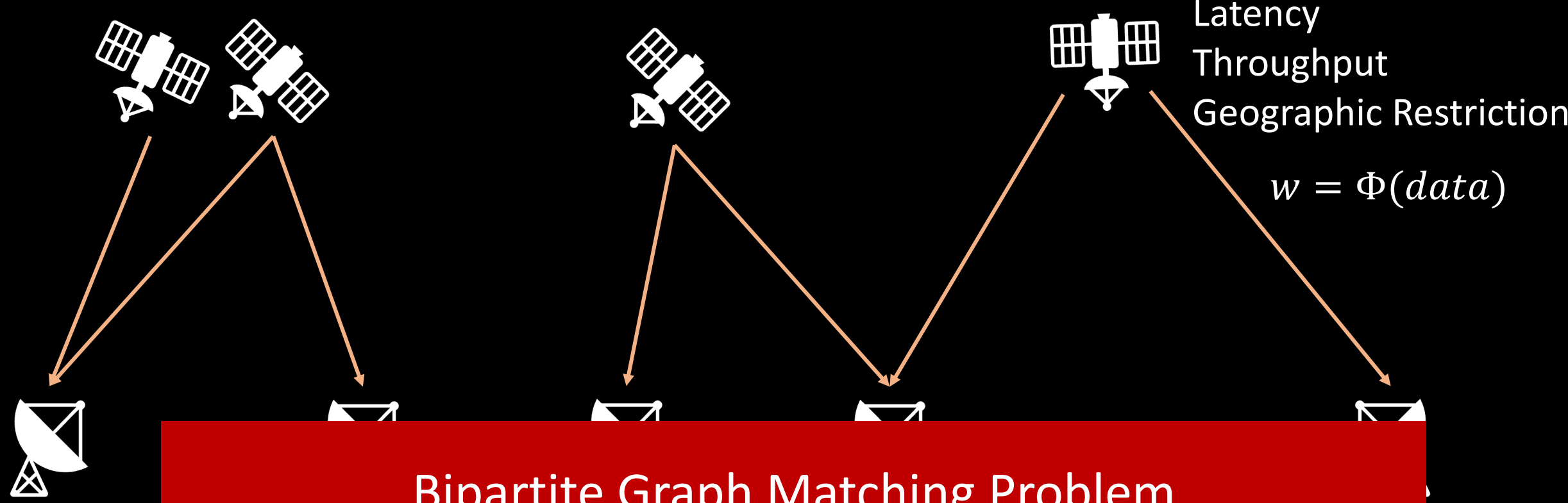


Challenge 2: Scheduling Satellite-GS Links





Challenge 2: Scheduling Satellite-GS Links

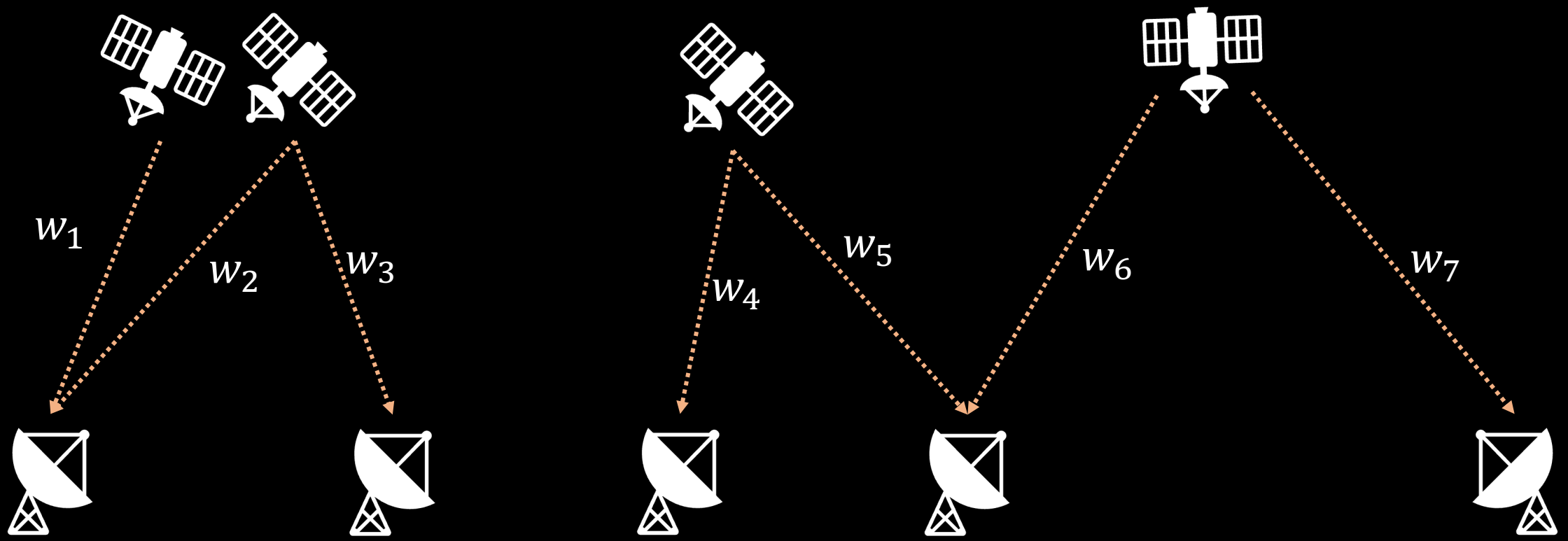


Latency
Throughput
Geographic Restriction

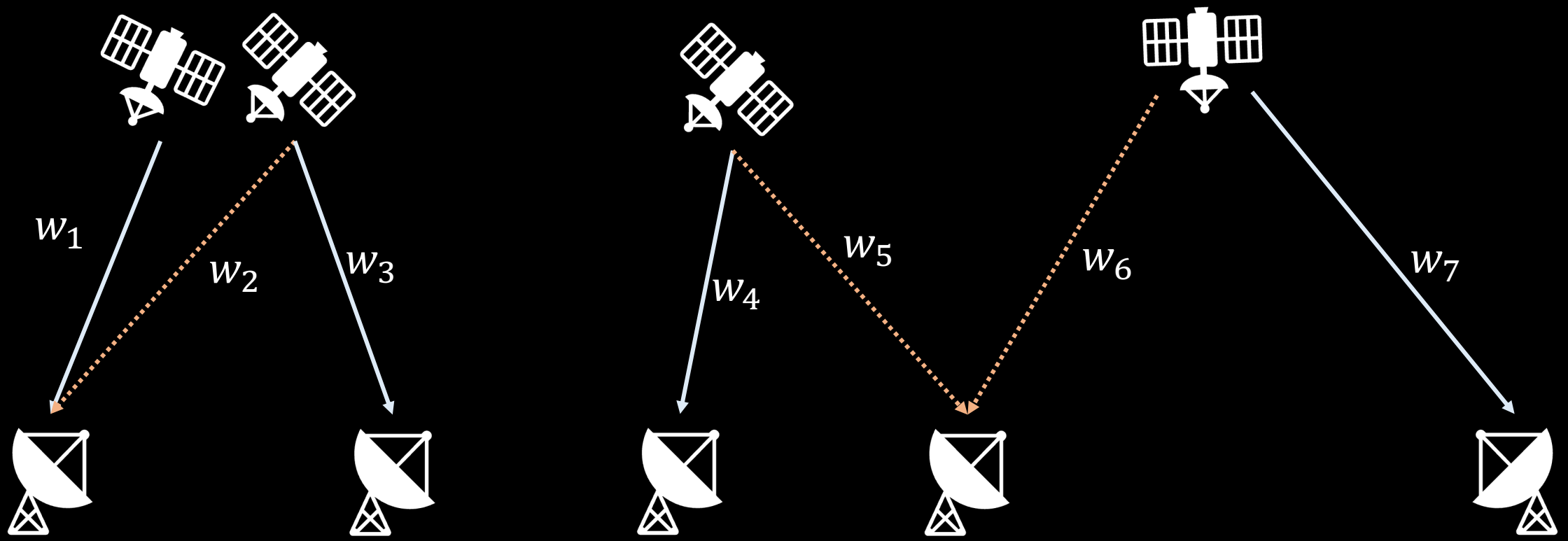
$$w = \Phi(data)$$

Bipartite Graph Matching Problem

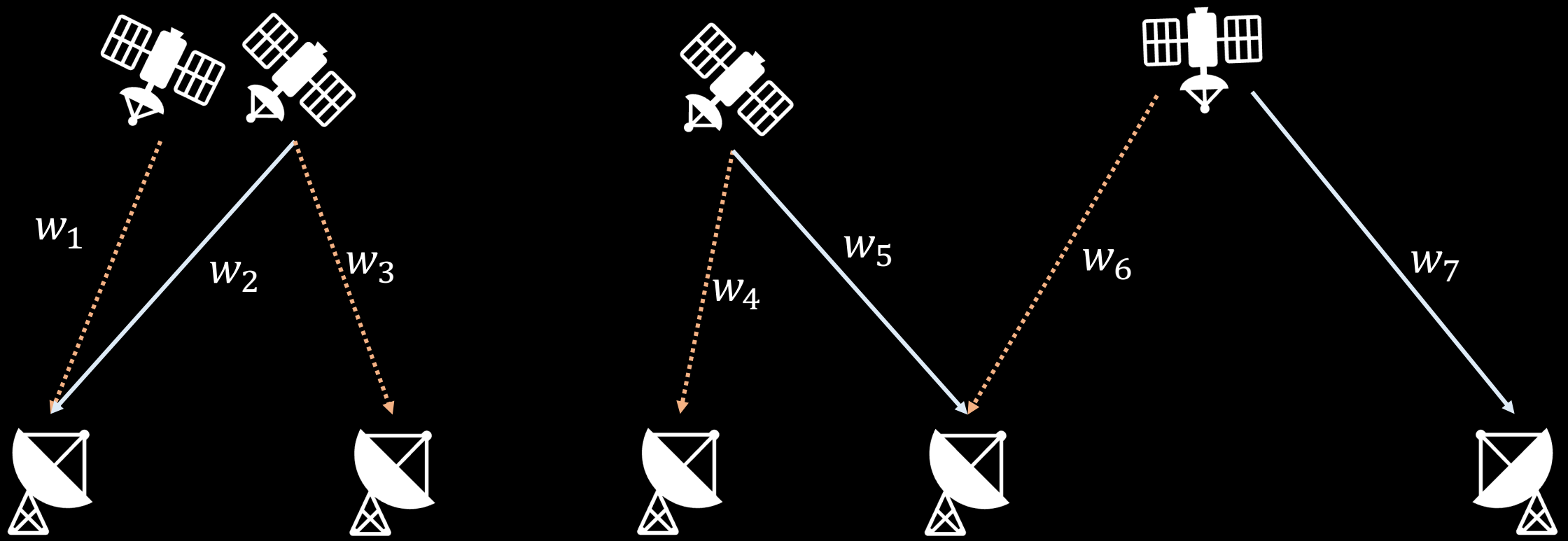
Scheduling Satellite-GS Links



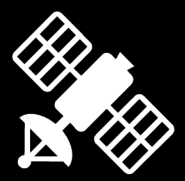
Scheduling Satellite-GS Links

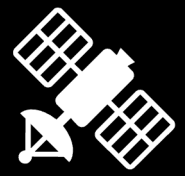


Scheduling Satellite-GS Links



Scheduling Satellite-GS Links





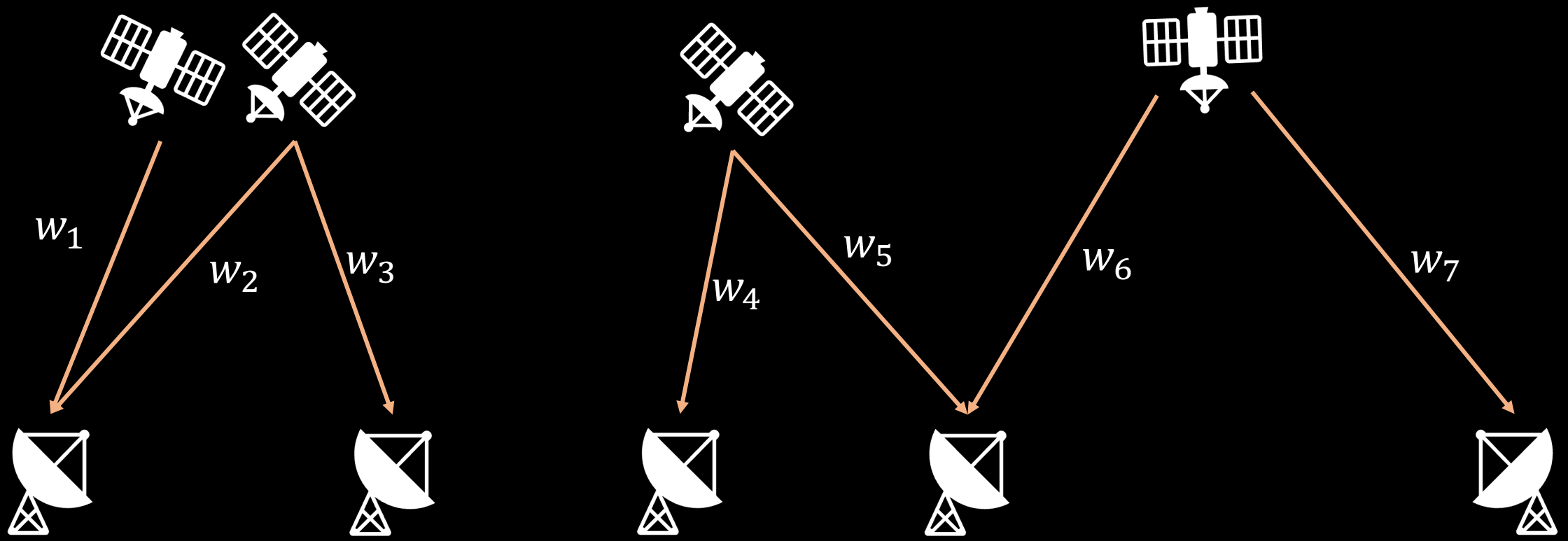
Switching links takes time

→ Matchings are not time-independent

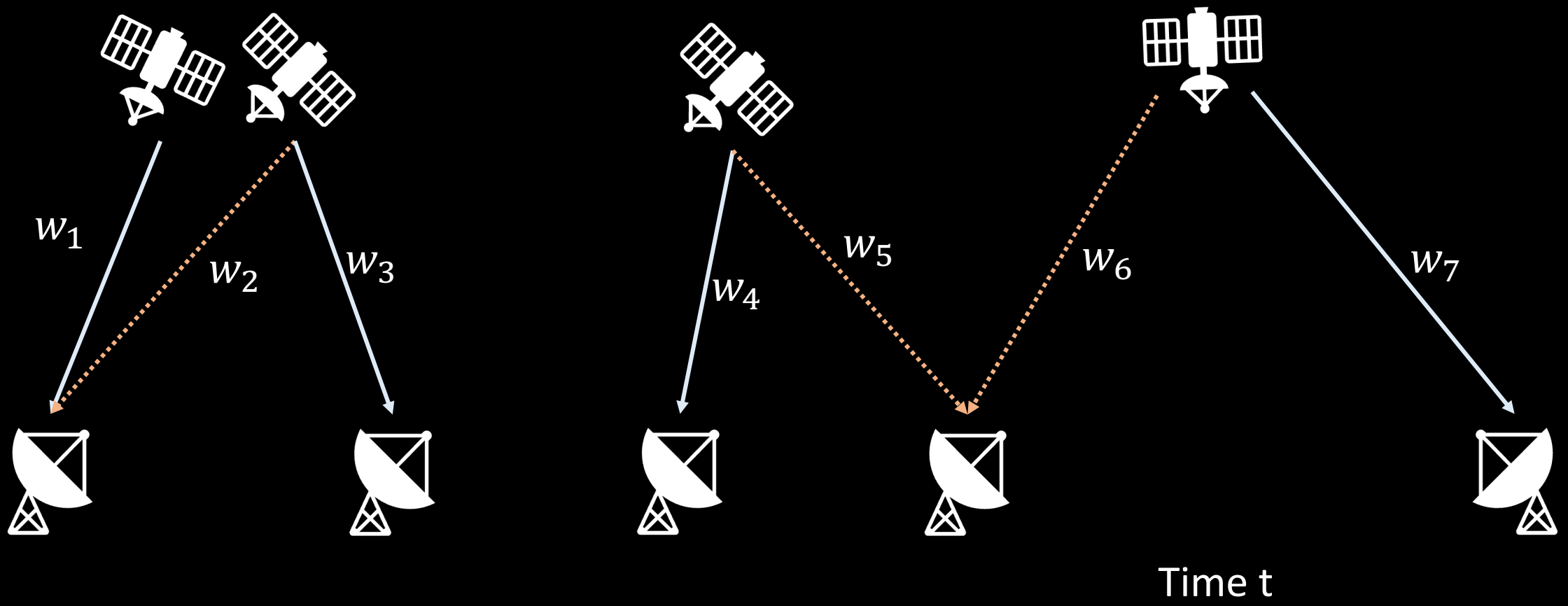
→ Need to optimize links across time

NP Hard!

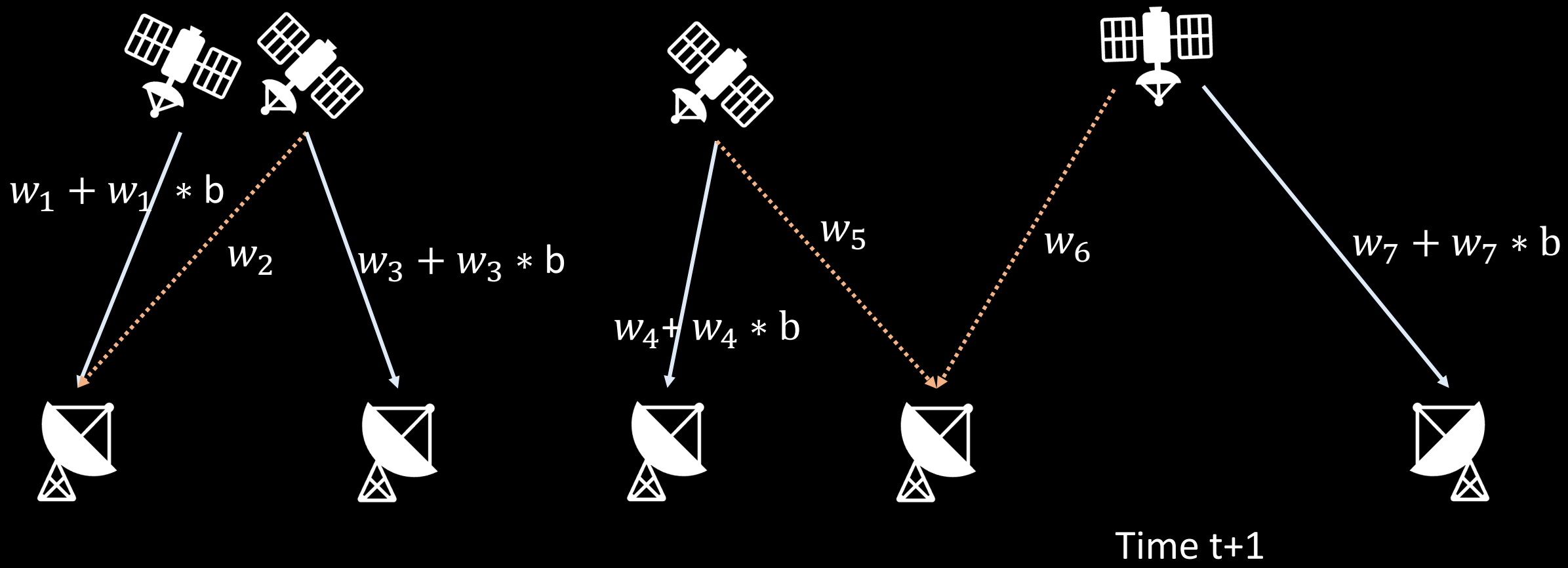
Solution: Greedy Algorithm with Sticky Links



Solution: Greedy Algorithm with Sticky Links



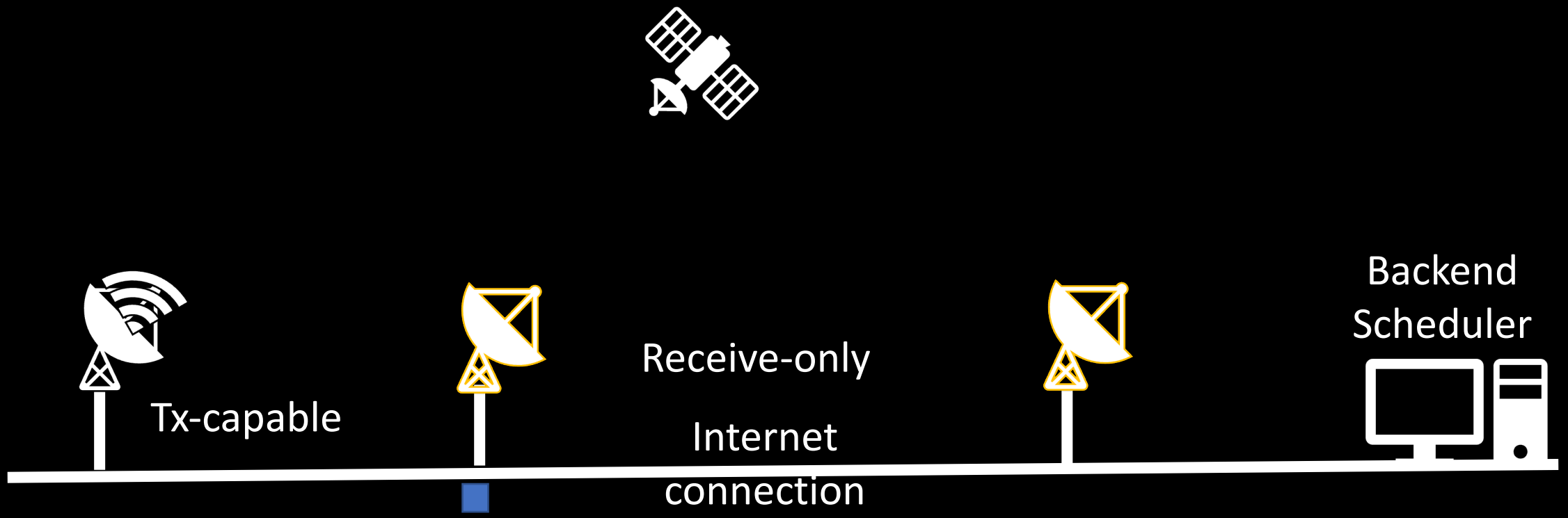
Solution: Greedy Algorithm with Sticky Links



Solution: Greedy Algorithm with Sticky Link

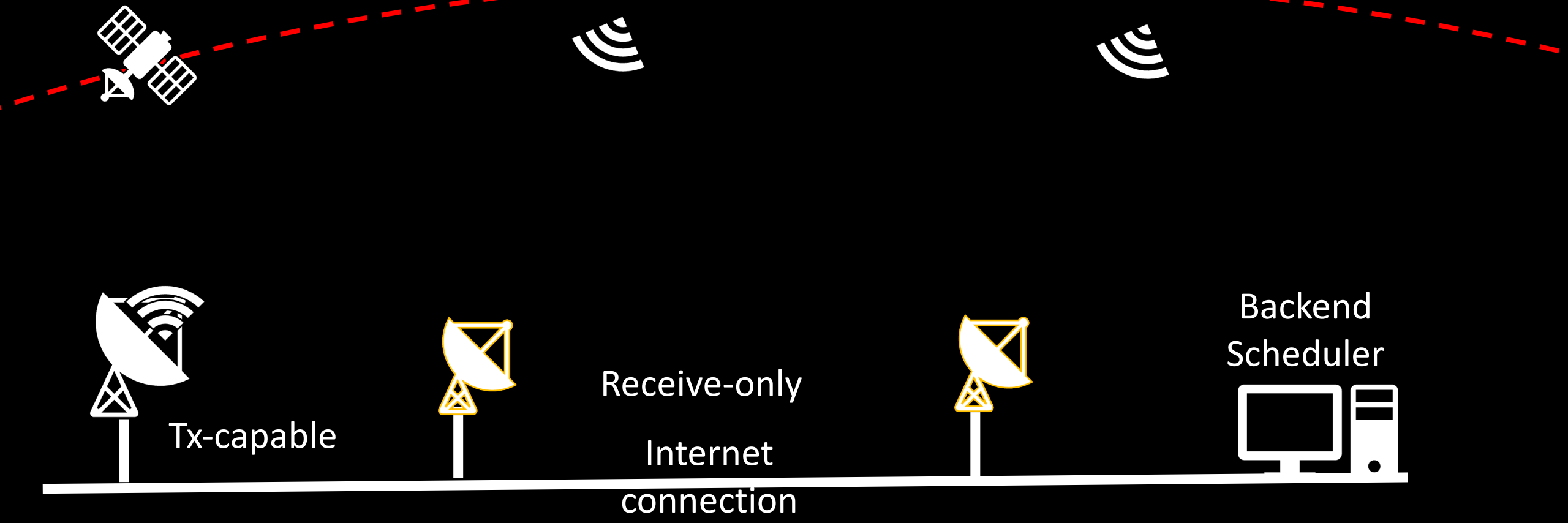
- Use Hungarian algorithm to find maximal matching
- Converges in O(K^3) where K=max(#satellite, #ground stations)
- Link estimation and schedule is computed and updated once a day

Challenge 3: No acks



Relay Acks Through Tx-Capable (With delay)

DGS: Distributed Ground Station



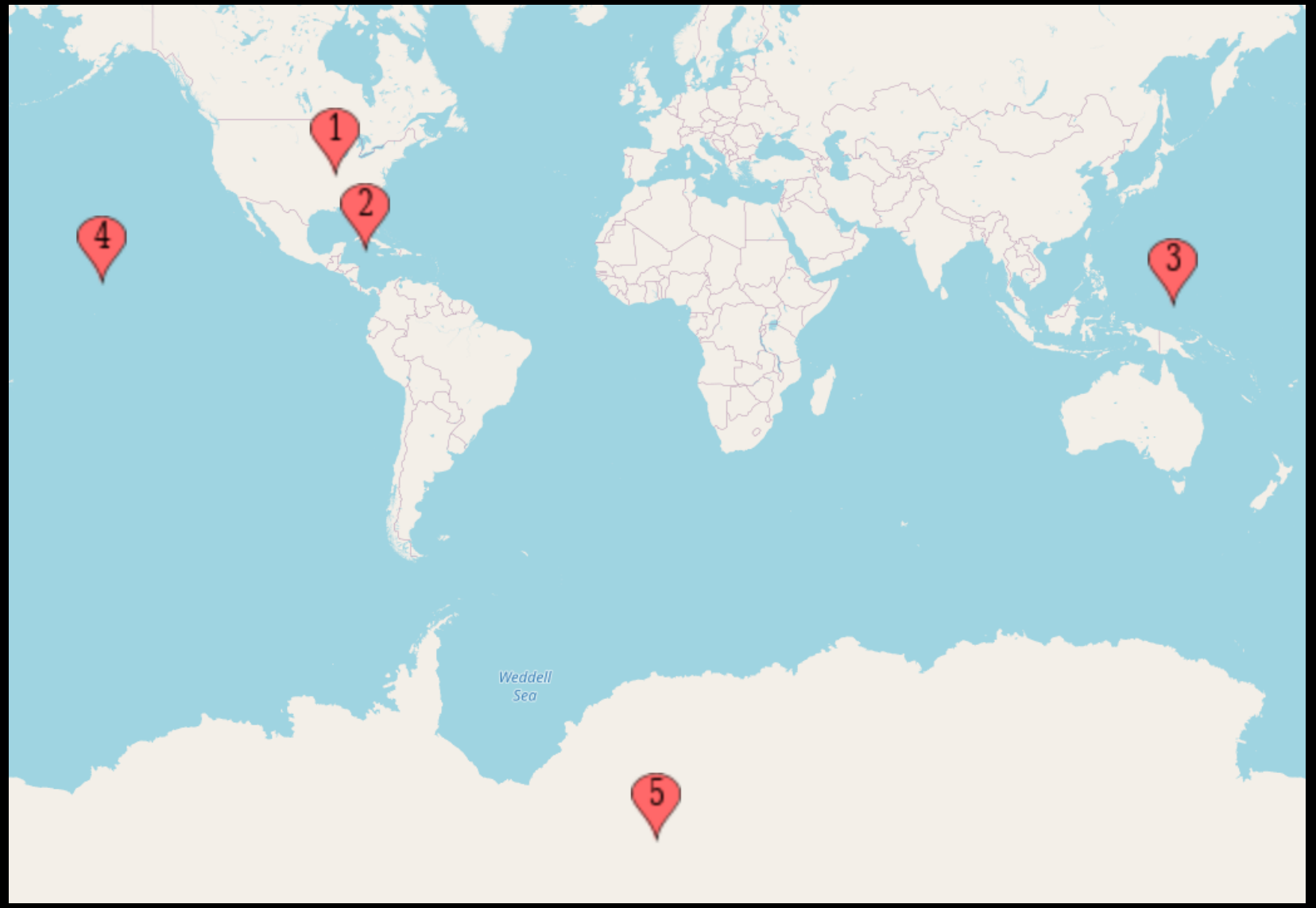
Experiments: Real-world Measurements

- 5 Ground Stations: Wisconsin, Florida, Guam, Hawaii, Antarctica

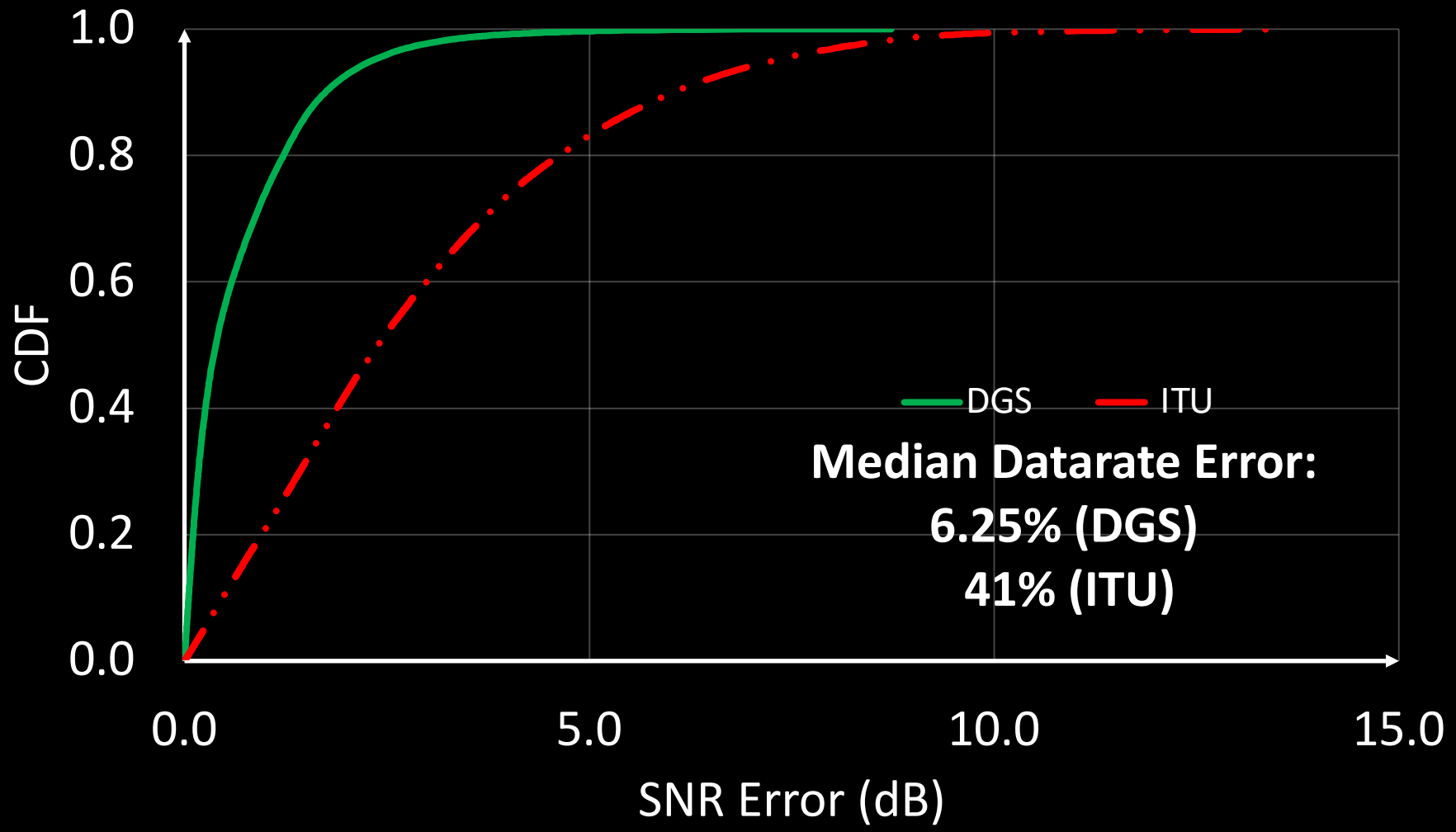
- 4 Satellites: JPSS, SNPP, Aqua, Terra
  - X-band Downlink: JPSS, SNPP, Aqua, Terra
  - Ka-band Downlink: JPSS

- Measurements across one month in 2020

Ground Station Locations



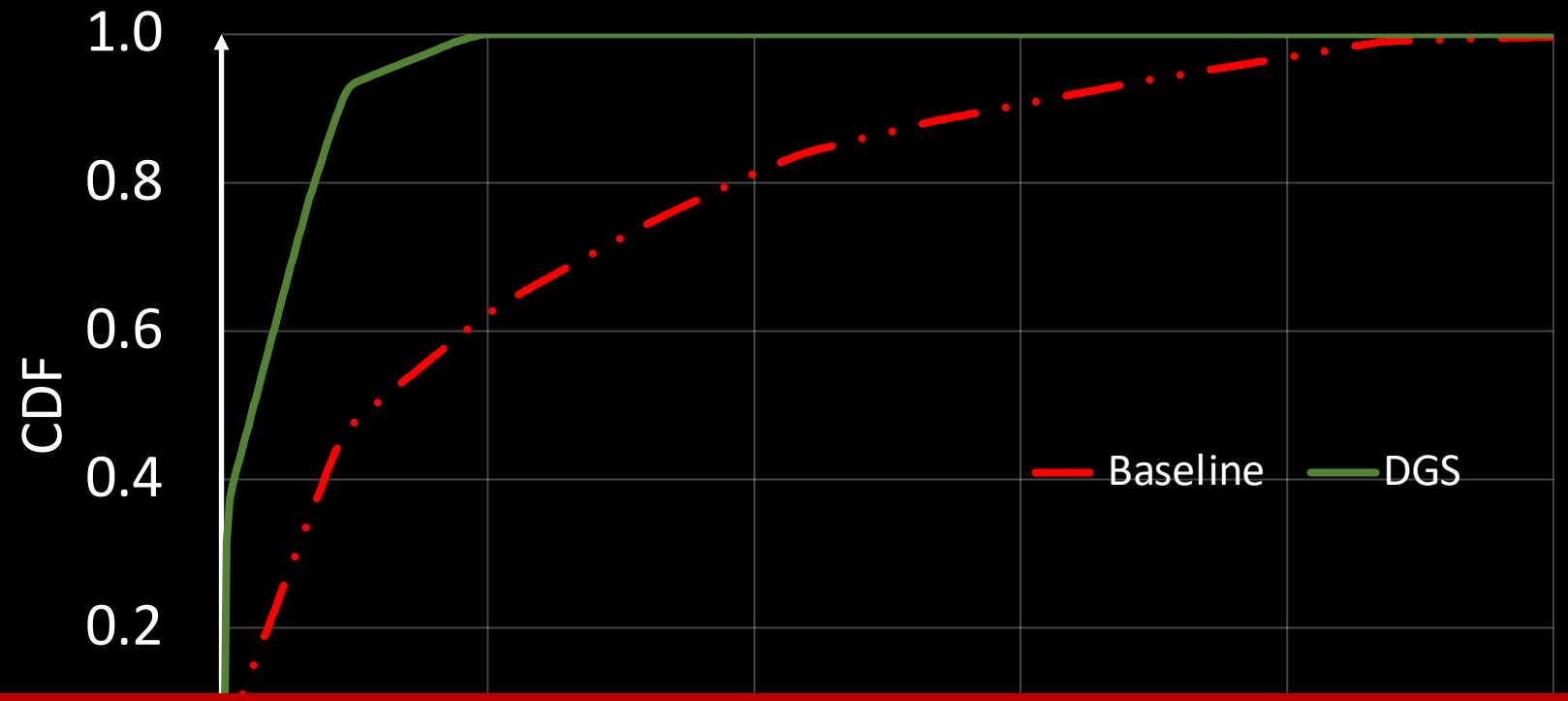
DGS ➔ Accurate Link Prediction



Large Scale Emulation

- SatNOGS: Open Source Ground Station Network
  - 259 satellites
  - 173 Ground Stations
- 100 GB data per day per satellite (26 TB total)
- Baseline: 5 Ground Stations
  - At least 10X higher median throughput

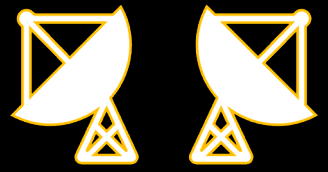
DGS ➔ Lower Latency



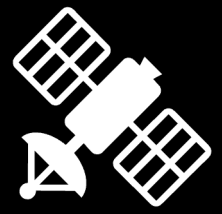
Distributed Ground Station reduces latency from hour to minutes

Open Questions/Ongoing Work

Edge Compute



Better Ground Infrastructure



Satellite Power

Economic Model