Understanding LEO Satellite Networks

Technology, Economics, and Future Challenges

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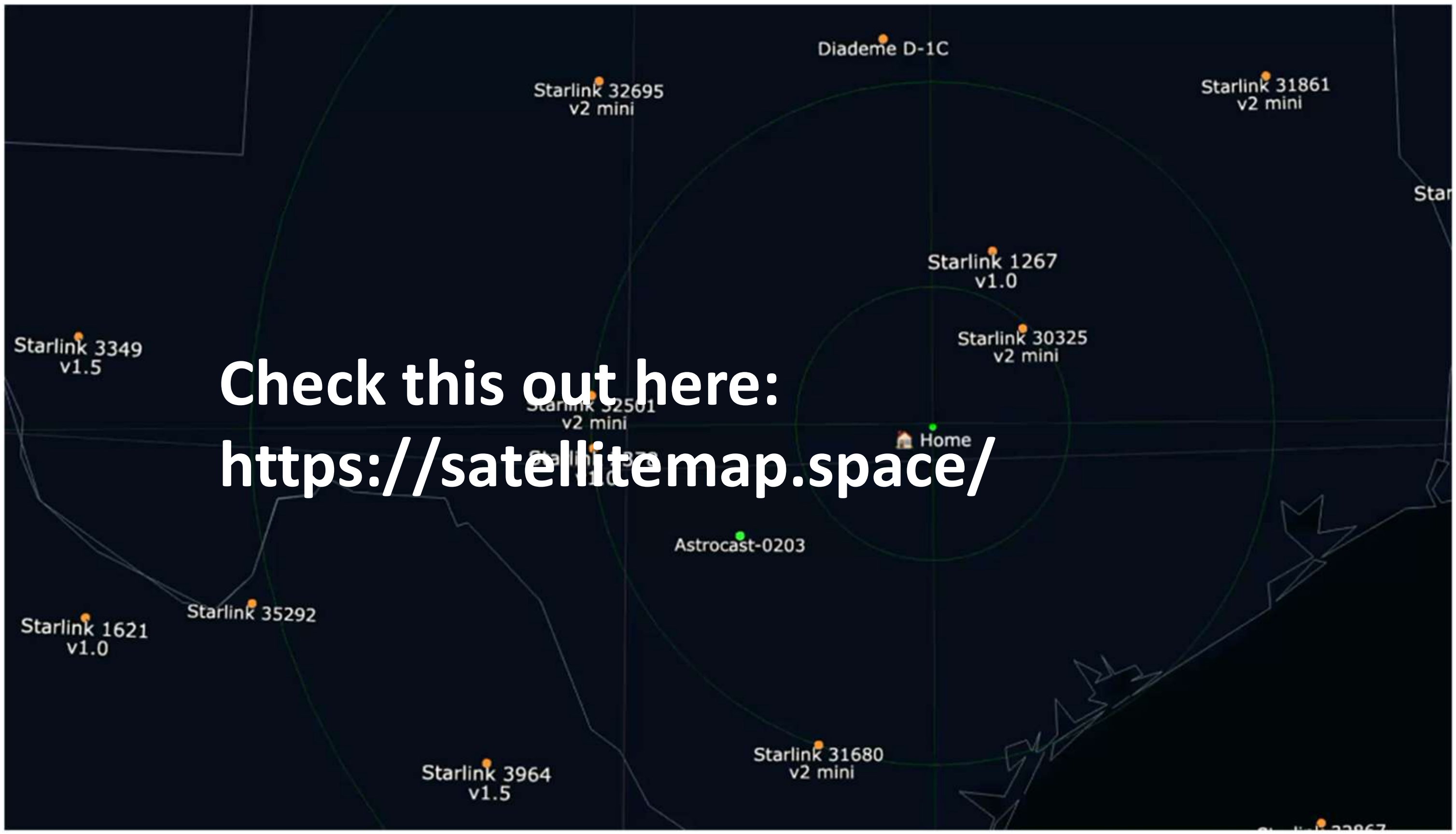
Visualizing the Mega-Constellation

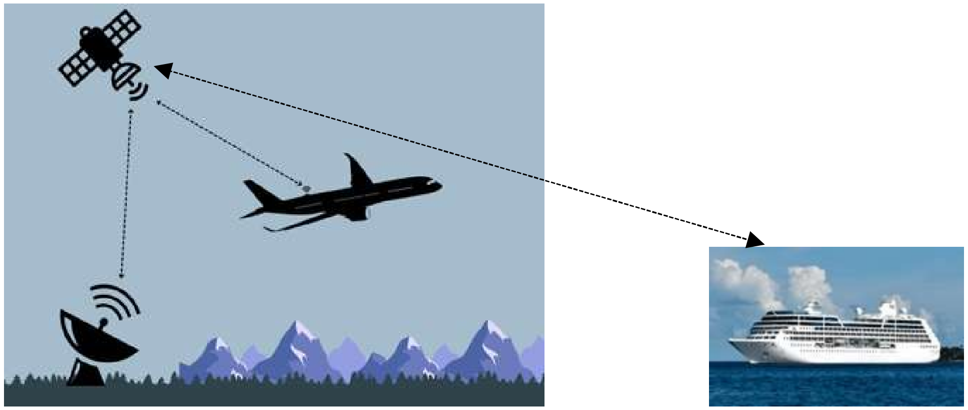


Dynamic visualization of satellite trajectories and global coverage density.

Why Satellites Are Essential

Bridging the gap for remote communication

- Critical for areas **without terrestrial infrastructure** (cellular/landlines).
- Essential for **maritime operations**, Wi-Fi in flights, and disaster recovery.
- Modern systems eliminate the need for specialized operators, enabling **direct user access**.



Evolution of LEO: From Iridium to Starlink

The Pioneer: Iridium (1990s)

- **Constellation:** 66 satellites in polar orbits.
- **Architecture:** First space-based mesh network with Inter-Satellite Links (ISL).
- **Focus:** Global voice and low-speed data (2.4 kbps).
- **Legacy:** Proved the LEO concept but struggled with high launch costs and terminal size.

The Modern Era: Starlink (Present)

- **Mega-Constellation:** 9,000+ satellites (expanding to 15,000+).
- **Enabler:** SpaceX reusable rockets dramatically reduced launch CAPEX.
- **Performance:** High-speed broadband (100+ Mbps) with low latency (~25-50ms).
- **Innovation:** Advanced phased-array antennas and optical laser links.

Orbital Classification: LEO, MEO, and GEO

LEO

Low Earth Orbit

Altitude

160 – 2,000 km

Orbital Period

90 – 120 Minutes

Primary Use

Low-latency Comms, Earth Observation

Example Systems

Starlink, Iridium

MEO

Medium Earth Orbit

Altitude

2,000 – 35,786 km

Orbital Period

2 – 24 Hours

Primary Use

Navigation (PNT), Specialized Comms

Example Systems

GPS, GLONASS, Galileo

GEO

Geostationary Orbit

Altitude

35,786 km (Fixed)

Orbital Period

23h 56m 4s (Sidereal)

Primary Use

Broadcast, Meteorology, Fixed Comms

Example Systems

Intelsat, Inmarsat, Chollian

LEO Systems: Performance vs. Constraints

Altitude: 160 – 2,000 km | **Orbital Period: 90 – 120 min** | **Propagation Delay: ~20 – 40 ms**

Technical Advantages

- **Link Budget Efficiency:** Proximity reduces path loss, allowing hand-held devices to communicate without high-power amplifiers.
- **Signal Integrity:** Highly focused beams achieve superior data rates and are less susceptible to wide-area interference.
- **Low Latency:** Propagation in vacuum is ~47% faster than in fiber-optic cables, enabling ultra-low latency paths.

Operational Challenges

- **Dynamic Topology:** Rapid orbital motion requires a large constellation for continuous global coverage.
- **Frequent Handoffs:** Short visibility windows (minutes) necessitate seamless inter-satellite or satellite-to-ground handoffs.
- **Constellation Management:** Complex coordination of thousands of satellites to maintain network availability.

Economic Transformation: The Cost of Space Access

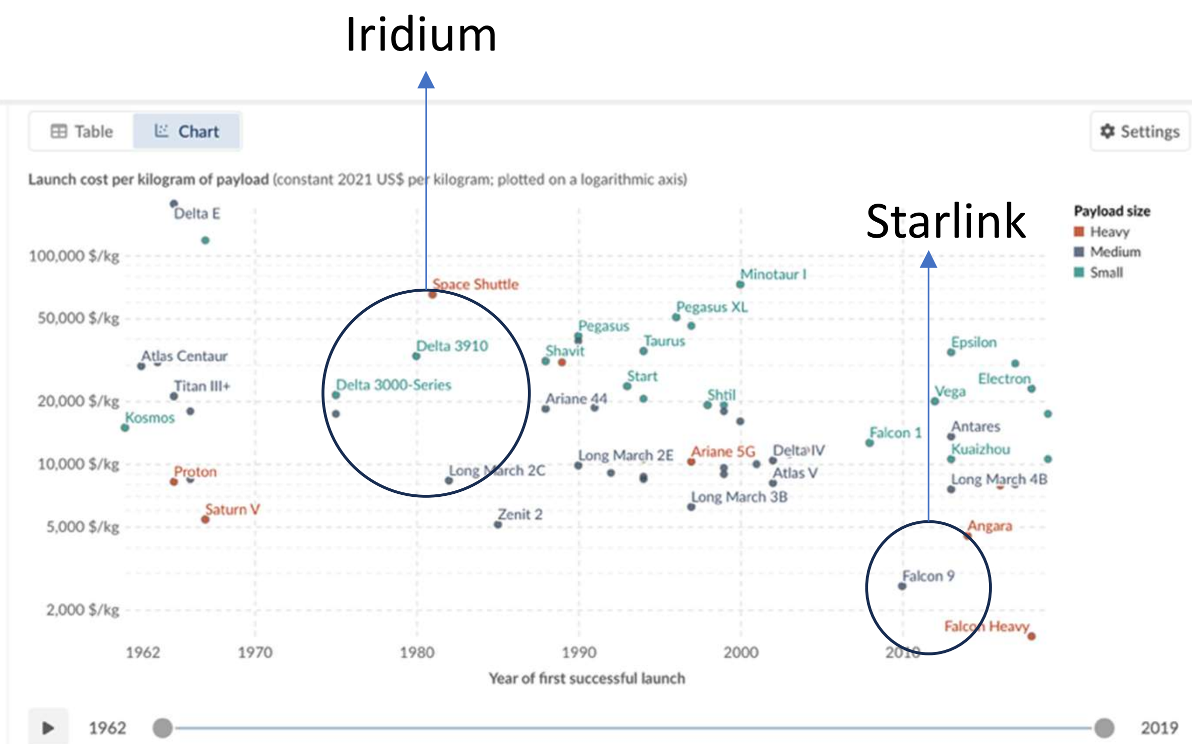


Figure 1: Historical trend of launch costs to Low Earth Orbit (USD per kg). Data source: Our World in Data / CSIS.

The Reusability Revolution

The advent of **Reusable Launch Vehicles (RLV)** has fundamentally disrupted space economics. Costs have plummeted from ~$20,000/kg (Space Shuttle) to **~$2,000/kg** (Falcon 9/Heavy).

Commercial Viability

Lower launch costs enable the deployment of **Massive Constellations**. What was once a "billion-dollar gamble" (Iridium) is now a scalable commercial infrastructure (Starlink, Kuiper).

Impact on Network Design

Reduced CAPEX allows for shorter satellite lifespans and **rapid hardware iteration**, keeping space-based networks at the cutting edge of technology.

Technical Challenges: Latency & Capacity Dynamics

Dynamic Latency Drift

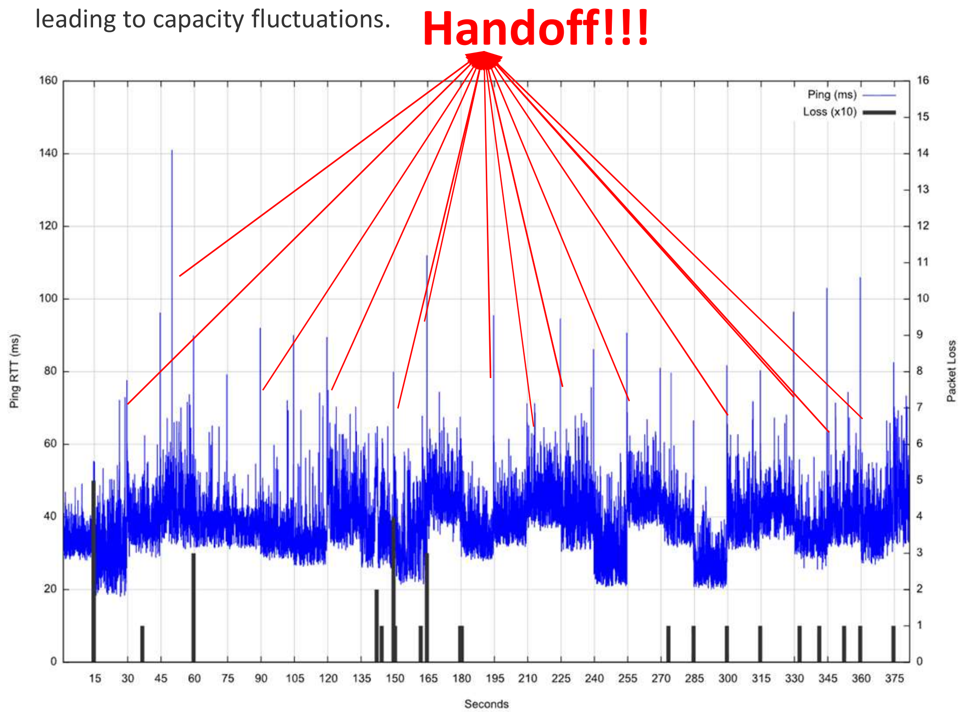
Network latency in LEO constellations is **non-stationary**, exhibiting significant drift within short intervals.

- **Handoff Impact:** Latency shifts abruptly during satellite switches (approx. every 15s).
- **Geometric Drift:** Propagation delay varies as the satellite tracks across the sky, changing the relative distance.
- **Buffer Effects:** Large modem buffers and cross-traffic introduce additional stochastic jitter.

Observation: TCP control struggles to optimize against a "shifting target" due to high-frequency RTT variations.

SNR & Capacity Instability

Varying Signal-to-Noise Ratio (SNR) forces **continual modulation refinement**, leading to capacity fluctuations.



TCP Mismatch: ACK pacing fails to adapt to capacity shifts occurring faster than multiple RTTs.

The Mismatch: Traditional TCP in LEO Networks

Traditional TCP Assumptions

- Stable and predictable **Round Trip Time (RTT)**.
- Gradual and infrequent changes in network capacity.
- Packet loss is primarily a signal of **congestion**.

VS

LEO Network Reality

- **High-frequency RTT drift** due to rapid orbital motion.
- Abrupt capacity shifts and stalls during **satellite handoffs**.
- Loss can be stochastic or link-layer related, not just congestion.

Discussion: The Handoff Challenge

How would you handle frequent handoffs?

The satellite moves at 27,000 km/h. Your connection lasts only 5-10 minutes before it disappears over the horizon.

How do we keep the internet "seamless"?

Predictive Switching

Since orbital paths are fixed, can we switch satellites *before* the signal actually drops?

Smart Buffering

Should we download more data right before a handoff to survive the "gap" in connectivity?

Protocol Design

If TCP is too slow to adapt, what kind of new rules (protocols) should we invent for space?

Any Questions?