Lecture 18
Satellite Communication

CS397/497 – Wireless Protocols for IoT

Branden Ghena – Spring 2024

Some slides borrowed from Ambuj Varshney (NUS)

Materials in collaboration with
Pat Pannuto (UCSD) and Brad Campbell (UVA)

Northwestern

Administrivia

- Final Design Project
  - Feel free to reach out over Piazza (or Friday office hours) if you have any questions. I’m happy to discuss
- Return hardware
  - Give it to me! (after class)

Today’s Goals

- Understand the capabilities and restrictions of satellite communication

- Explore real-world satellite communication

- Discuss directions for cellular-to-satellite communication

Outline

- **Overview**
- Satellite Communication
  - Voyager
  - Oculus-ASR
- Satellite Communications Providers
- Cellular-to-Satellite Communication

Why use satellite communication?

- True global connectivity
- Cellular is dependent on someone actually building a cell tower near the area you want to communicate in
  - Remote areas are out-of-luck (mountain, forest, ocean)
- Satellites act as moving cell towers
  - With enough of them, you could cover the globe

Satellite communication challenges

1. Distances involved
    - Path loss
    - Latency

2. Large deployment areas
    - Shared bandwidth
    - Handoffs

3. Deployment considerations
    - Cost
    - Coordination

- Ignoring the difficulty of making the satellite itself

Satellite communication challenges

1. **Distances involved**
   - **Path loss**
   - **Latency**

2. Large deployment areas
   - Shared bandwidth
   - Handoffs

3. Deployment considerations
   - Cost
   - Coordination

- Ignoring the difficulty of making the satellite itself

Satellite orbits - LEO

- Low Earth Orbit (LEO)
  - 160-2000 km
  - Includes all current human spaceflight (ISS at 400 km)
  - Roughly 90 minutes per complete orbit

- Polar orbit will eventually cover all of Earth
- Group of satellites (constellation) can cover all of earth simultaneously if using enough satellites

https://aerospace.csis.org/aerospace101/earth-orbit-101/

Satellite orbits

- Geostationary Orbit (GEO) (a.k.a. geosynchronous orbit)
  - 35768 km
  - Exactly 24 hours per complete orbit

- Result: fixed location in the sky over a position on Earth
  - Very few satellites can cover all of Earth
  - Or an operator can choose to only service a specific region

https://aerospace.csis.org/aerospace101/earth-orbit-101/

Satellite orbits

- Medium-Earth Orbit (MEO)
  - Between LEO and GEO
  - Roughly 12 hours per complete orbit

- GNSS satellites (GPS, Galileo, etc.) are here
  - Smaller constellation and longer lifetime and LEO orbit

- Radiation belts make this area more difficult to use

https://aerospace.csis.org/aerospace101/earth-orbit-101/

Path loss to orbit

- Distance contributes significantly to signal strength loss. Frequency can hurt too
  - Increased frequency leads to smaller antenna leads to less energy collected leads to weaker signal

- Being at an angle on the horizon increases the total distance and the path loss

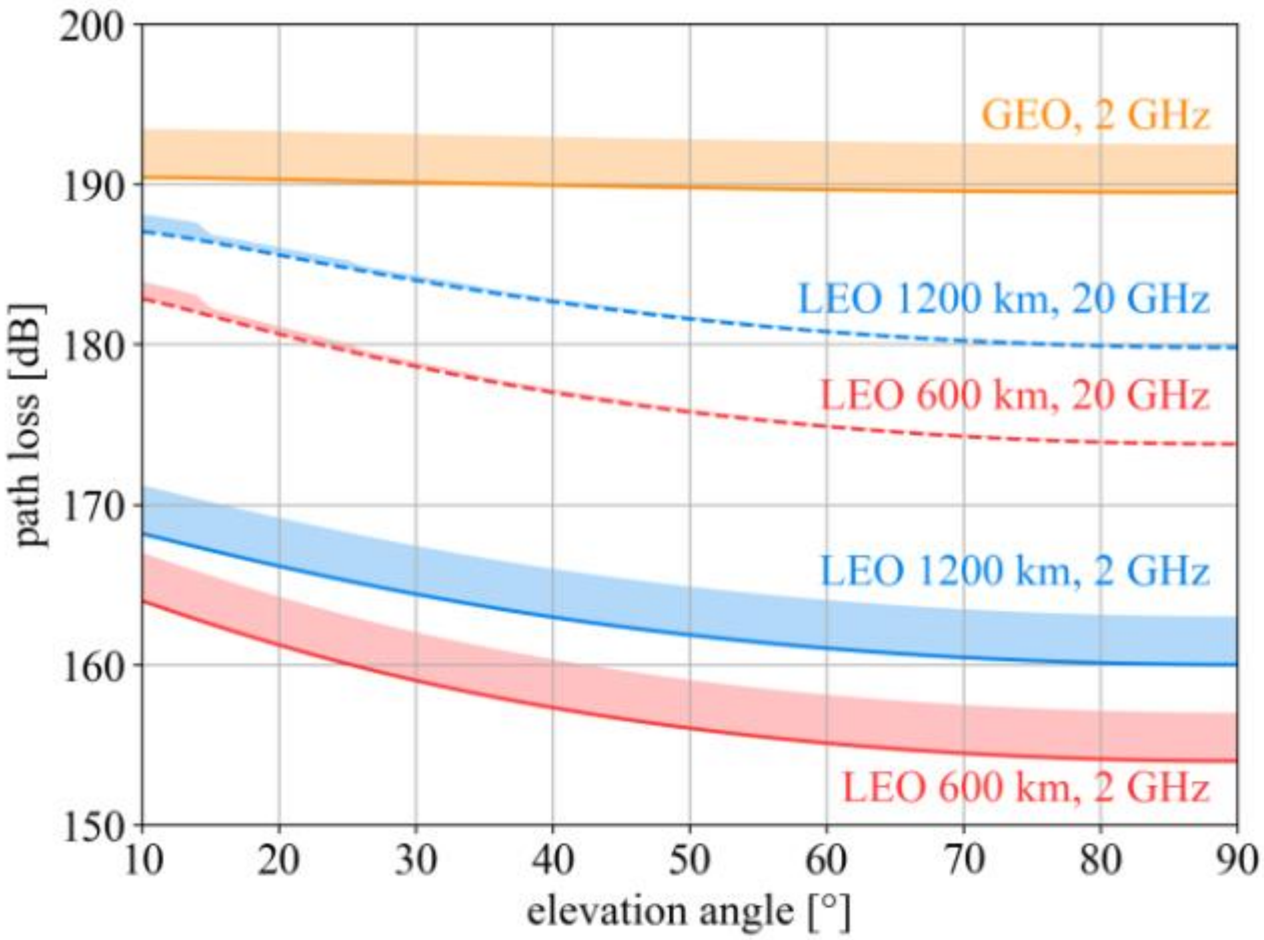


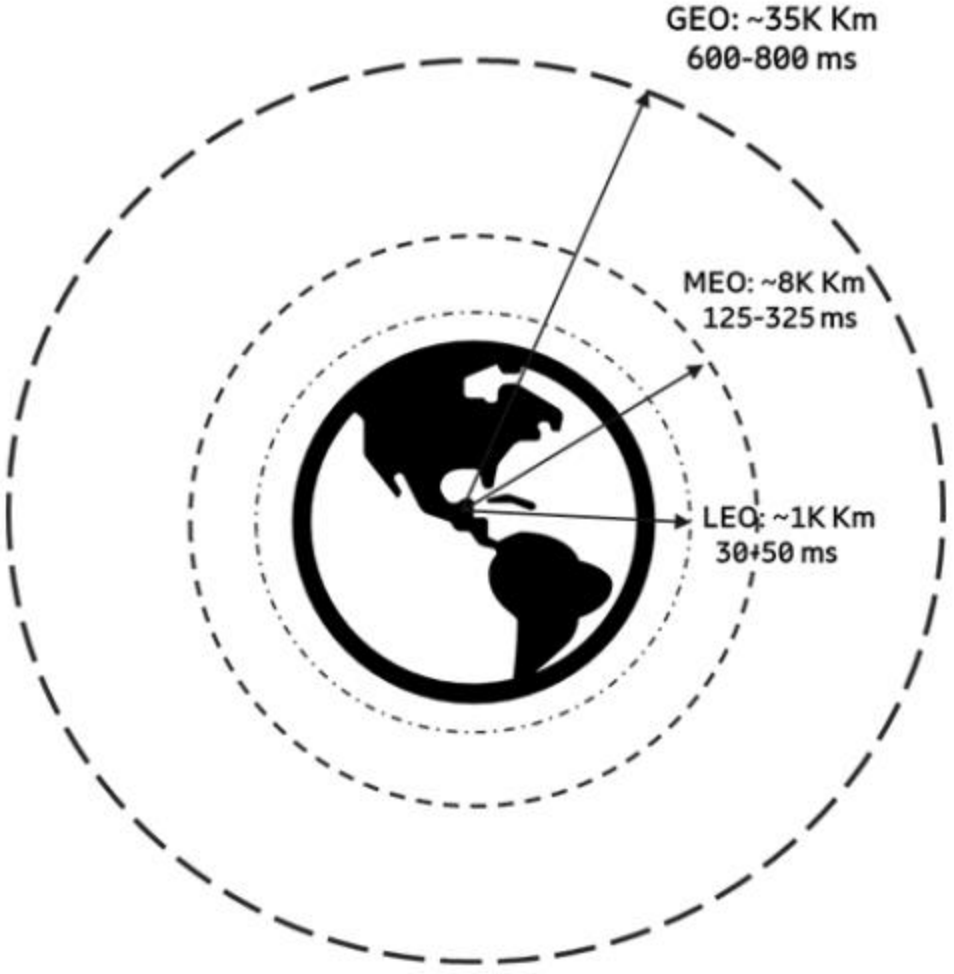
Figure 2: Path loss as a function of elevation angle

https://arxiv.org/pdf/2103.09156

Latency to orbit

- Even at speed of light, orbit distances contribute to communication delay

- 3GPP figure includes round-trip-time AND real-world delays through network



https://www.5gamericas.org/wp-content/uploads/2022/01/5G-Non-Terrestrial-Networks-2022-WP-Id.pdf

Satellite communication challenges

1. Distances involved
    - Path loss
    - Latency

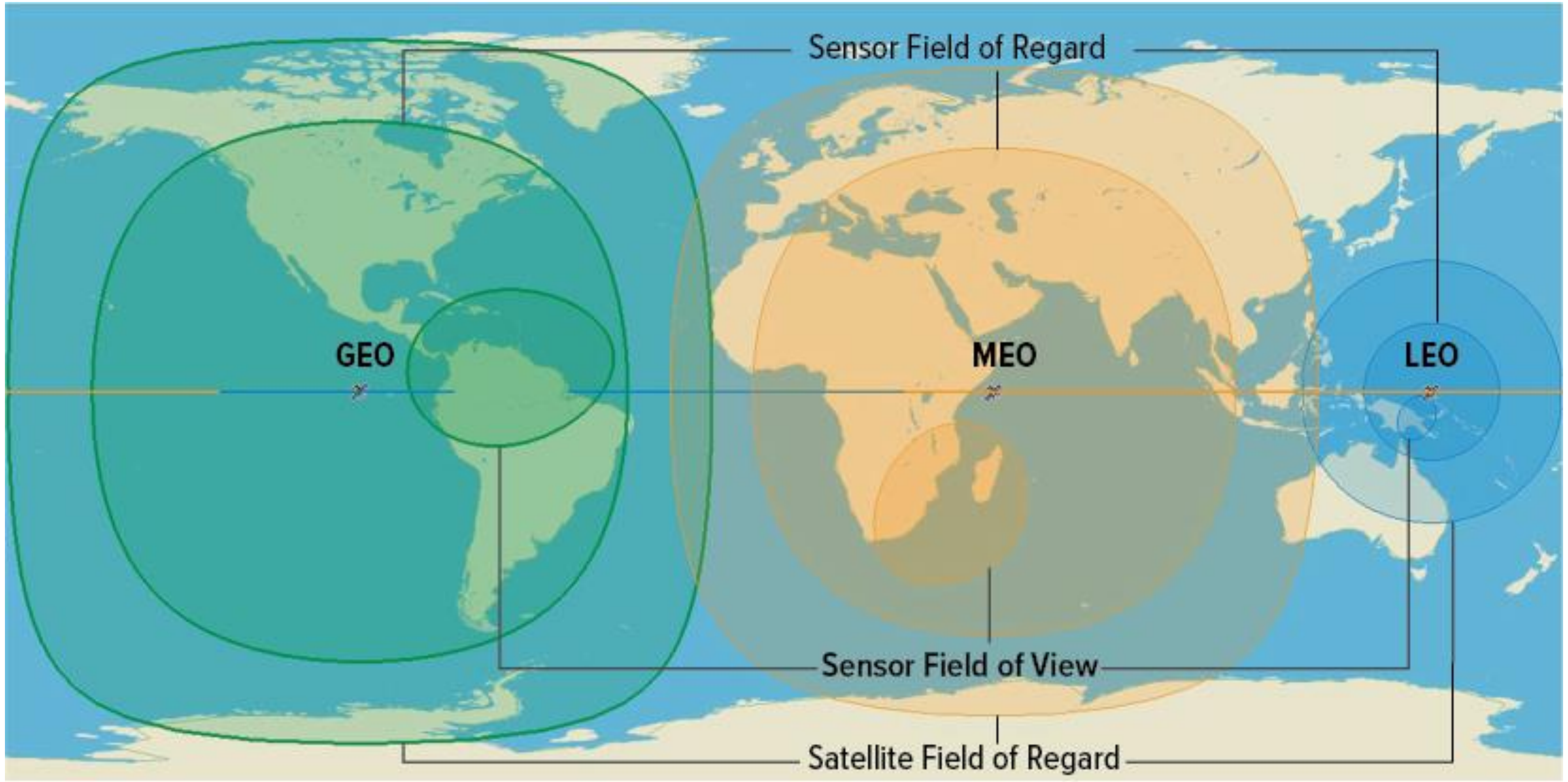
2. **Large deployment areas**
    - **Shared bandwidth**
    - **Handoffs**

3. Deployment considerations
    - Cost
    - Coordination

- Ignoring the difficulty of making the satellite itself

A single satellite provides considerable deployment area

- Coverage areas can get quite wide here
  - Biggest: all possible line-of-sight to satellite
  - Middle: limited to ≥20º above horizon
  - Smallest: example image sensing region

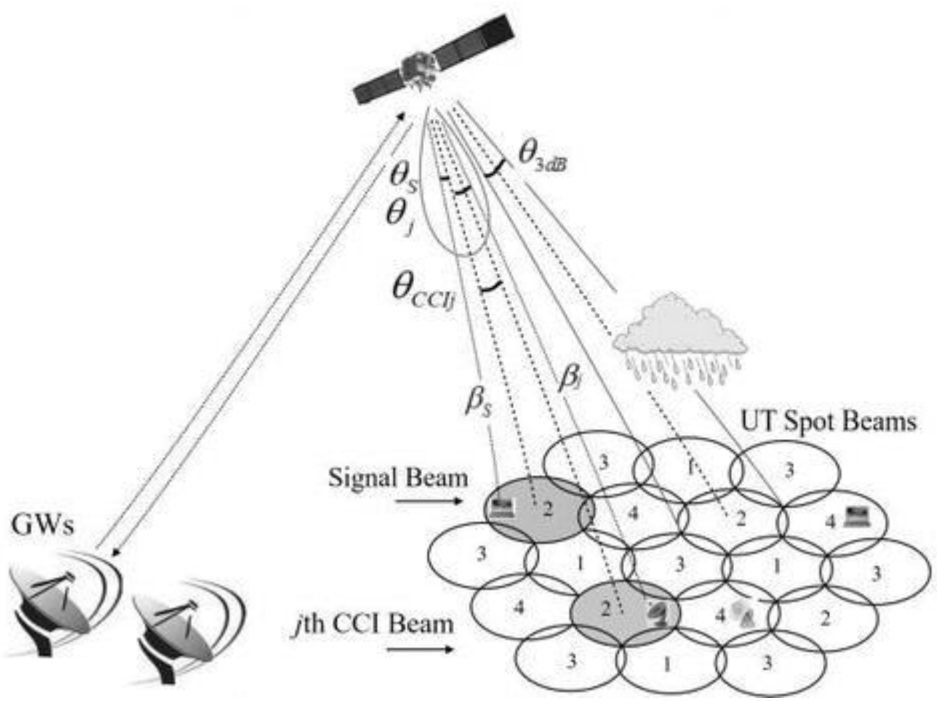


Huge coverage areas share bandwidth among many users

- Same problem as LPWANs:
  data throughput is shared across entire coverage area

- Cellular solution can apply here
  - Reduce coverage area and provide overlapping cells of coverage
  - One satellite could support many cells

- Limitation:
  - Needs many channels to support cells
  - Backhaul to downstation needs enough throughput for sum of *all* cells



Moving satellites lead to many handoffs

- In LEO, satellites are moving around 7 km/s
  - Comparatively, mobility of the user equipment is irrelevant

- Depending on cell size, the device might leave the cell within seconds
  - Smaller cells exacerbate this problem

Cell Diameter Size (km)	UE Speed (km/hr)	Satellite Speed (km/s)	Time UE remains in the cell (s)
50 (lower bound)	+500	7.56	6.49
	-500		6.74
	+1200		6.33
	- 1200		6.92
	Neglected		6.61
1000 (upper bound)	+500		129.89
	-500		134.75
	+1200		126.69
	- 1200		138.38
	Neglected		132.28

Satellite communication challenges

1. Distances involved
    - Path loss
    - Latency

2. Large deployment areas
    - Shared bandwidth
    - Handoffs

3. **Deployment considerations**
    - **Cost**
    - **Coordination**

- Ignoring the difficulty of making the satellite itself

Getting hardware in orbit isn't cheap

Launch vehicle estimated payload cost per kg

Launch Vehicle	Payload cost per kg
Vanguard	$1,000,000 [20]
Space Shuttle	$54,500 [20]
Electron	$19,039 [21][22]
Ariane 5G	$9,167 [20]
Long March 3B	$4,412 [20]
Proton	$4,320 [20]
Falcon 9	$2,720 [23]
Falcon Heavy	$1,500 [24]

- Costs have dropped significantly in recent years, but are still $1000 per kg

- Mass references:
  - Starlink v1.0: 260 kg
  - Starlink v2.0: 1250 kg
  - GPS: 1000-2000 kg

Frequency allocations often must be world-wide

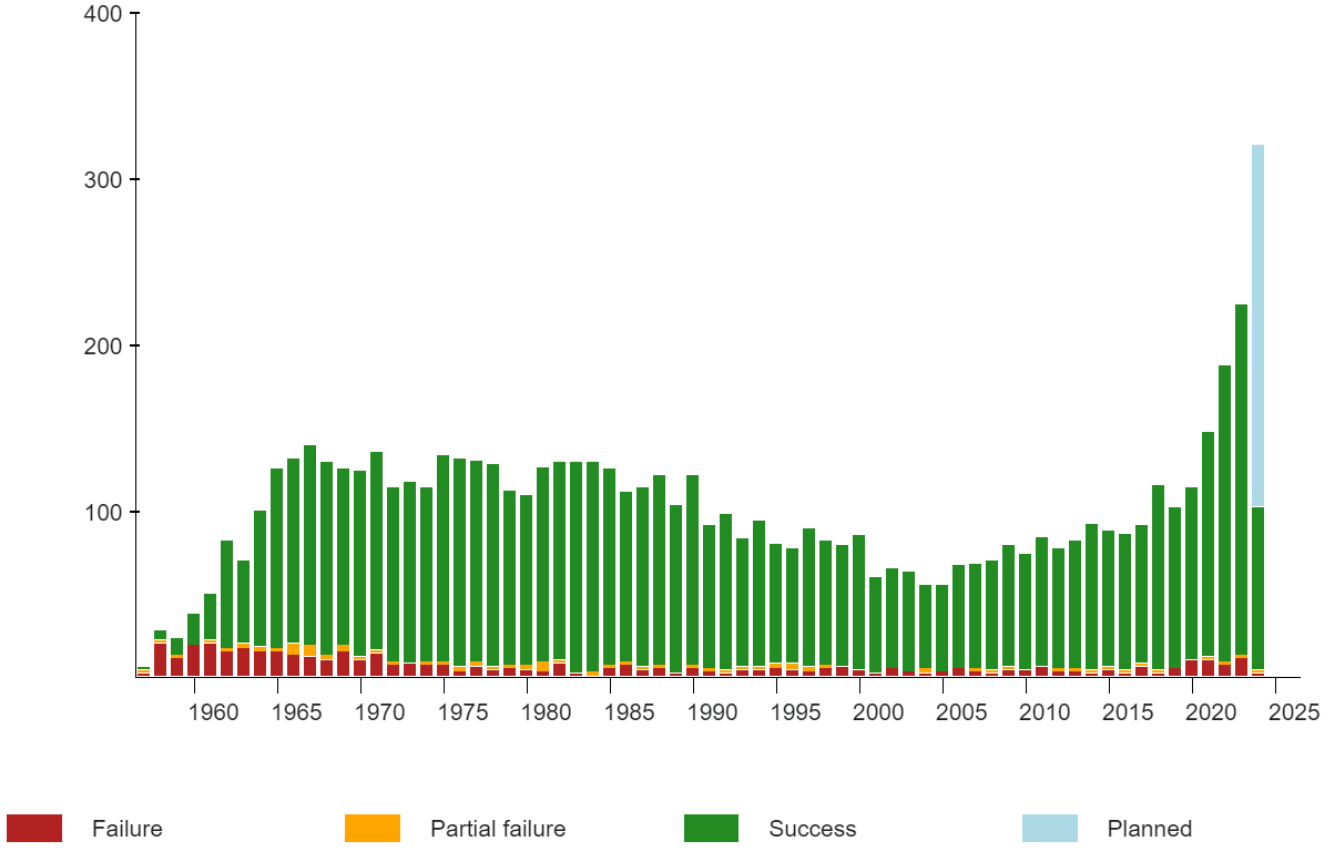
- GEO satellites can focus on a region and provide a channel for that region
- LEO constellations aiming for world-wide coverage must have a world-wide frequency allocation
- International Telecommunication Union (ITU) helps coordinate frequency allocations
  - UN agency

Actually getting a rocket to launch with has become easier

- SpaceX (and other commercial rockets) have led a recent renaissance in number of rocket launches per year

- 2019: 104 launches
- 2023: 211 launches
- 2024: 300+ planned

- This availability is generating new interest in satellite communications



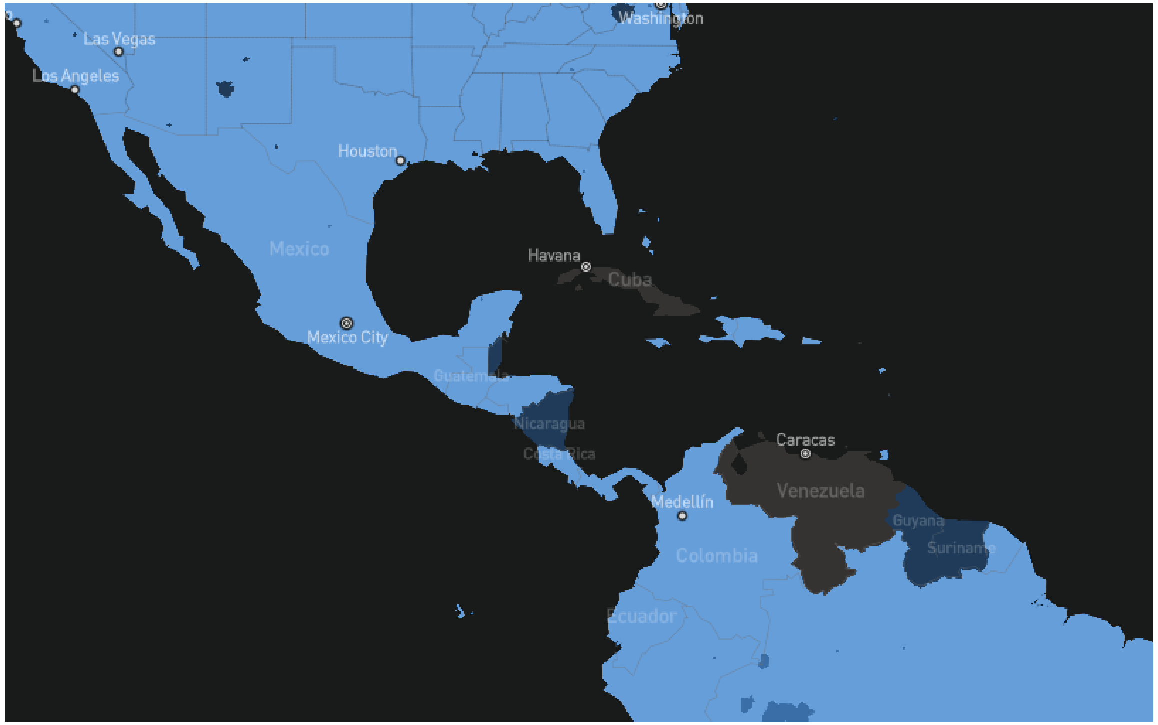
https://en.wikipedia.org/wiki/Timeline_of_spaceflight#Orbital_launches_by_year

Break + Question

- What do you do if a country *doesn't* agree to let your satellite transmit on a certain frequency?

Break + Question

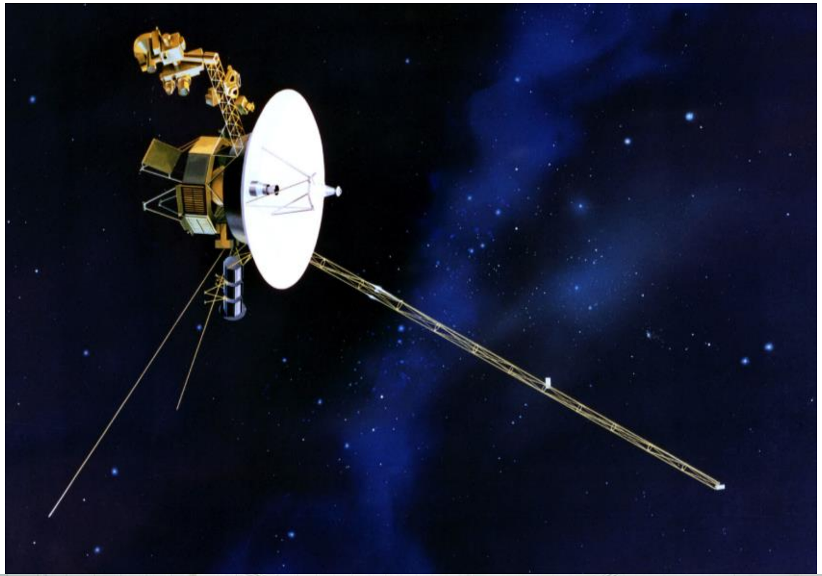
- What do you do if a country *doesn't* agree to let your satellite transmit on a certain frequency?
    - Blackout over specific regions
    - Satellites must already know their own locations to high accuracy, so this is possible

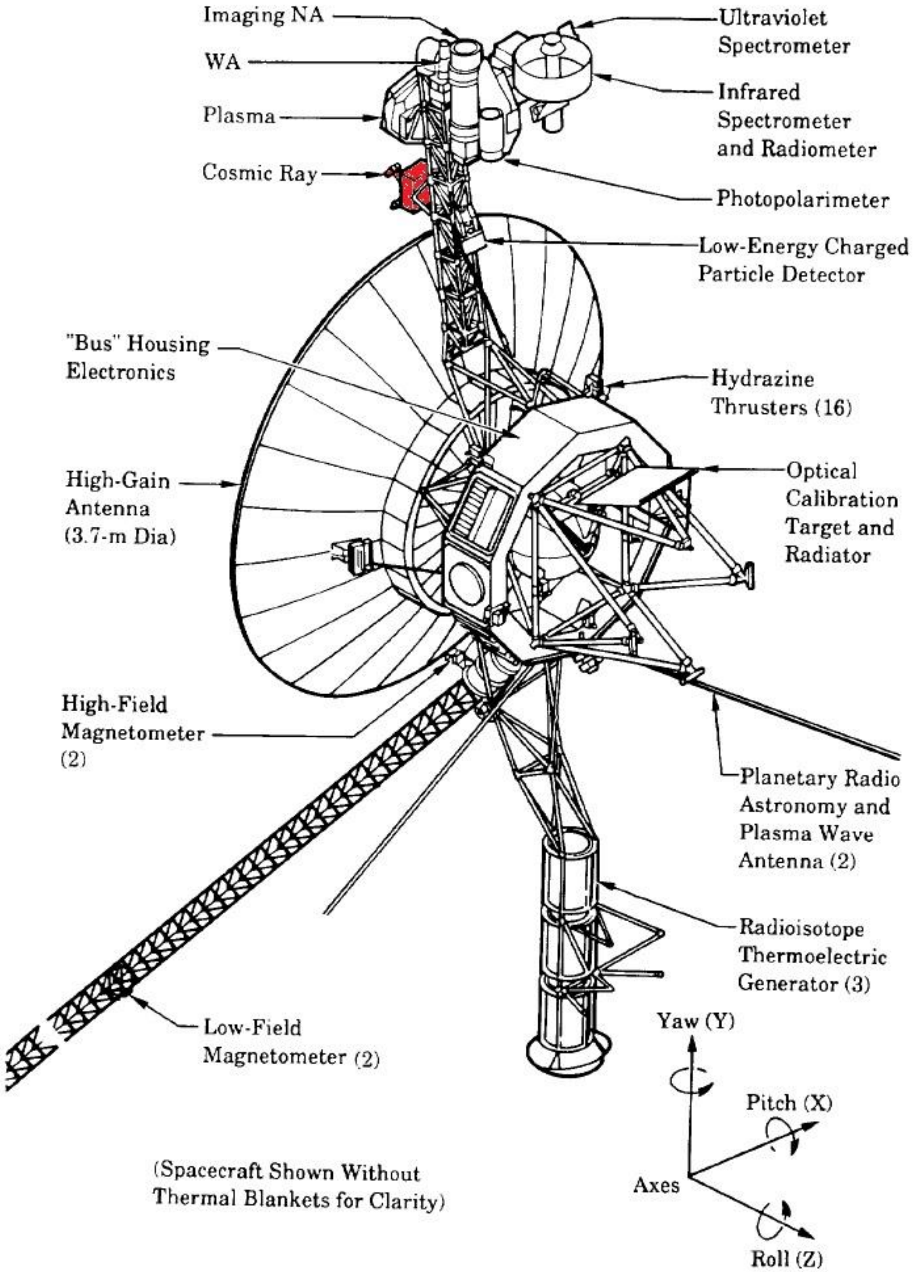


Outline

- Overview
- **Satellite Communication**
  - **Voyager**
  - Oculus-ASR
- Satellite Communications Providers
- Cellular-to-Satellite Communication

Voyager 1 and 2 (1977)



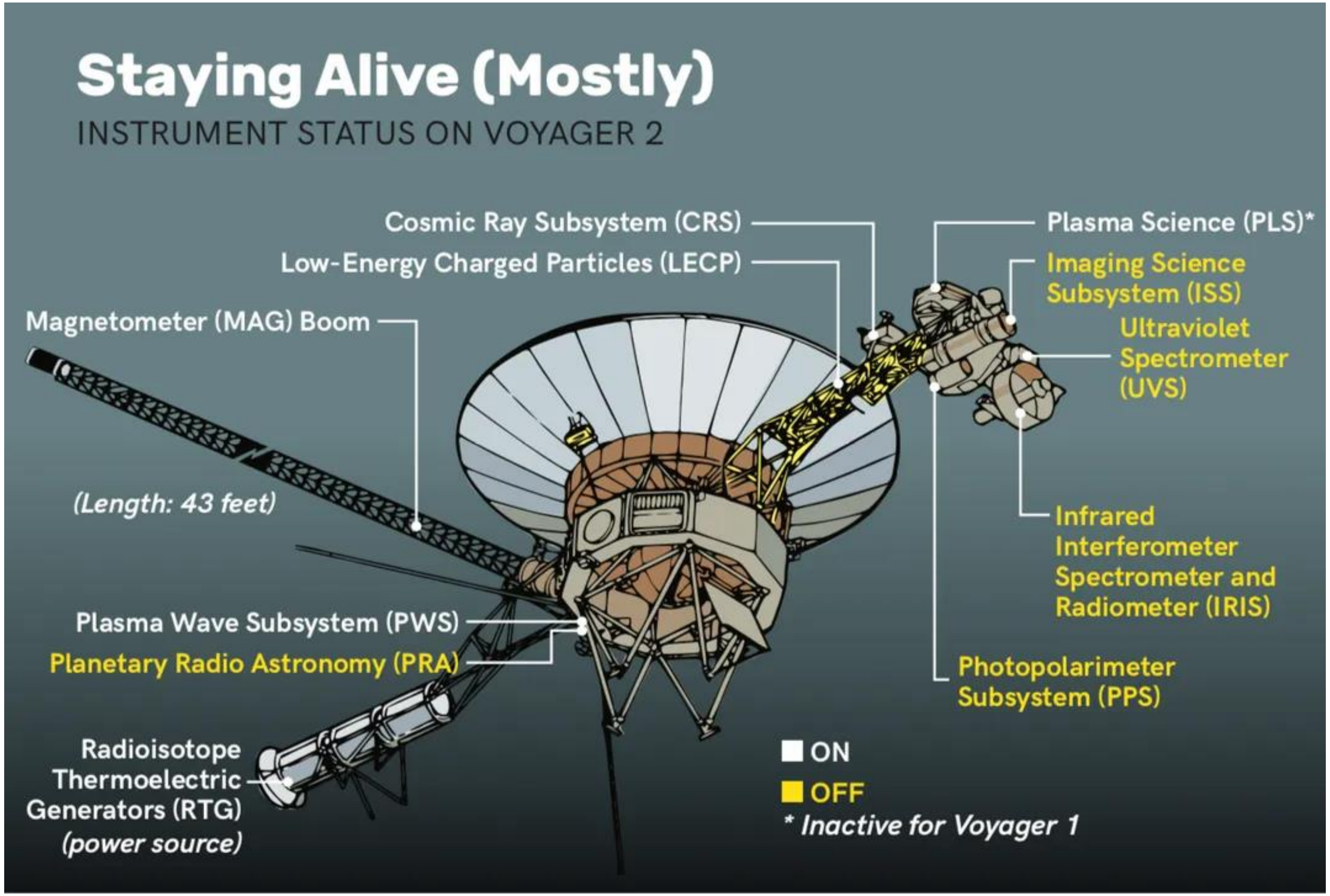


Voyager still functional

Voyager 2

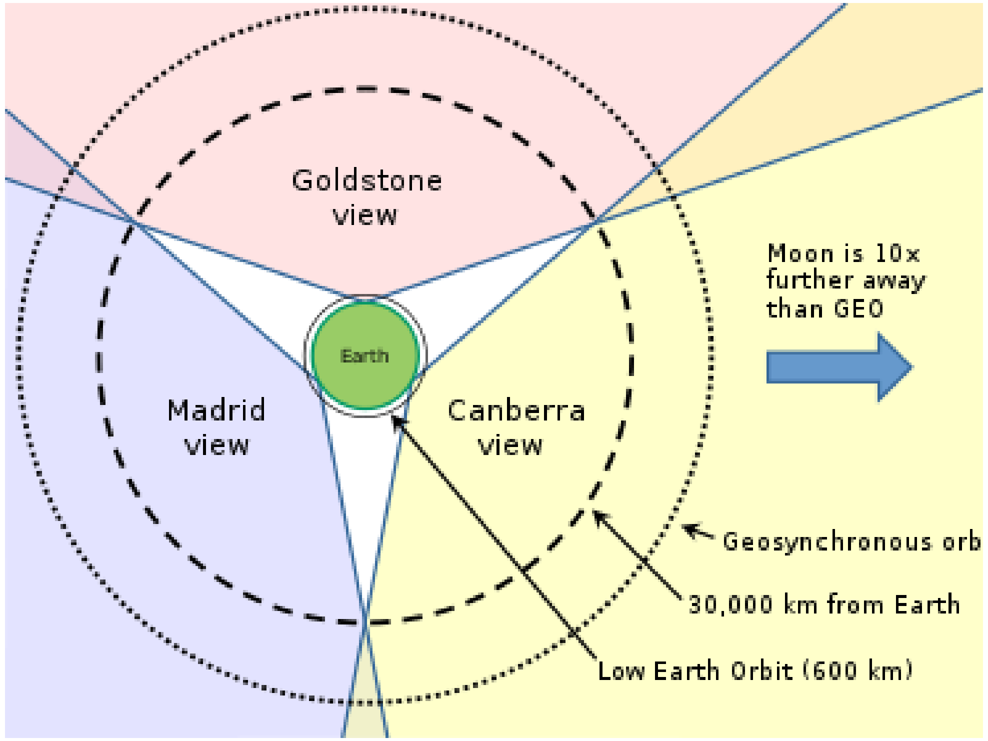
- Jupiter: 1979
- Saturn: 1981
- Uranus: 1985
- Neptune: 1989
- Edge of solar system: 2018

- Still sending data!



Deep Space Network

- Receives data from NASA deep space missions
- 70-meter antenna (60-70 dB gain)
- Array of four 34-meter antennas



Deep Space Network Canberra complex

Voyager path loss calculation

- Frequency: 8.415 GHz communication (100 kHz bandwidth)
- Distance: 24300000000 km (May 2024)

- Free Space Path Loss: 318 dB

- In 2002, FSPL was 308 dB (see source below)
  - So ~10 dB loss per 20 years

https://descanso.jpl.nasa.gov/DPSummary/Descanso4--Voyager_ed.pdf

Other factors

- Voyager Transmit:
  - Transmission power: 41 dBm (12 Watts)
  - Antenna gain: 48 dB

- DSN Receiver:
  - Antenna gain: 74 dB

- Other factors:
  - Pointing error: -0.3 dB
  - Atmospheric loss: -0.04 dB
  - Polarization loss: -0.08 dB

https://descanso.jpl.nasa.gov/DPSummary/Descanso4--Voyager_ed.pdf

Total received power from Voyager

- Received power: 41 + 48 + 74 - ~1 -318 = -156 dBm

- Compare to minimum receive sensitivity for IoT protocols:
  - -95 dBm for BLE
  - -119 dBm for LoRa
  - -141 dBm for NB-IoT

- Voyager transmits at 160 bps

https://descanso.jpl.nasa.gov/DPSummary/Descanso4--Voyager_ed.pdf

Voyager uplink math

- Biggest difference: transmission power 72.55 dBm (18 kW)

- Antennas and frequency are slightly different too
  - DSN 62 dB gain, Voyager 34.6 dB gain
  - FSPL (at 2.113 GHz): 306 dB

- Received power: 72.55 + 62 + 34.6 - ~1 -306 = -138 dBm
  - Almost 20 dB better than downlink

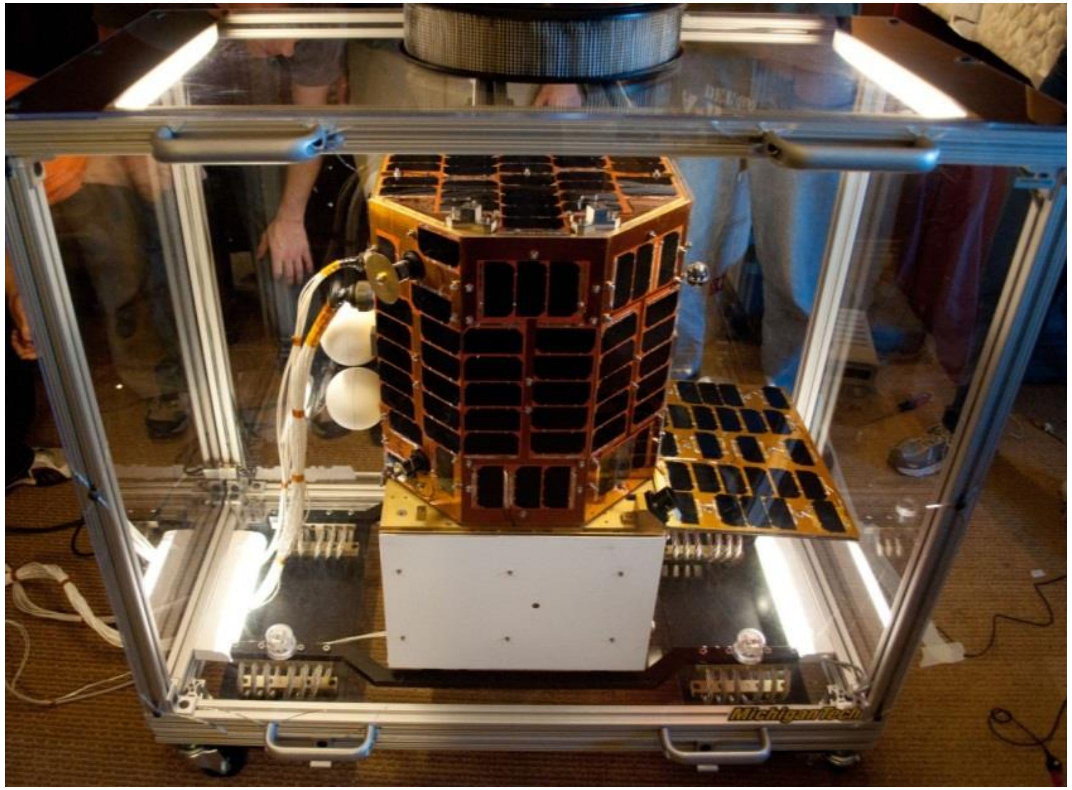
https://descanso.jpl.nasa.gov/DPSummary/Descanso4--Voyager_ed.pdf

Outline

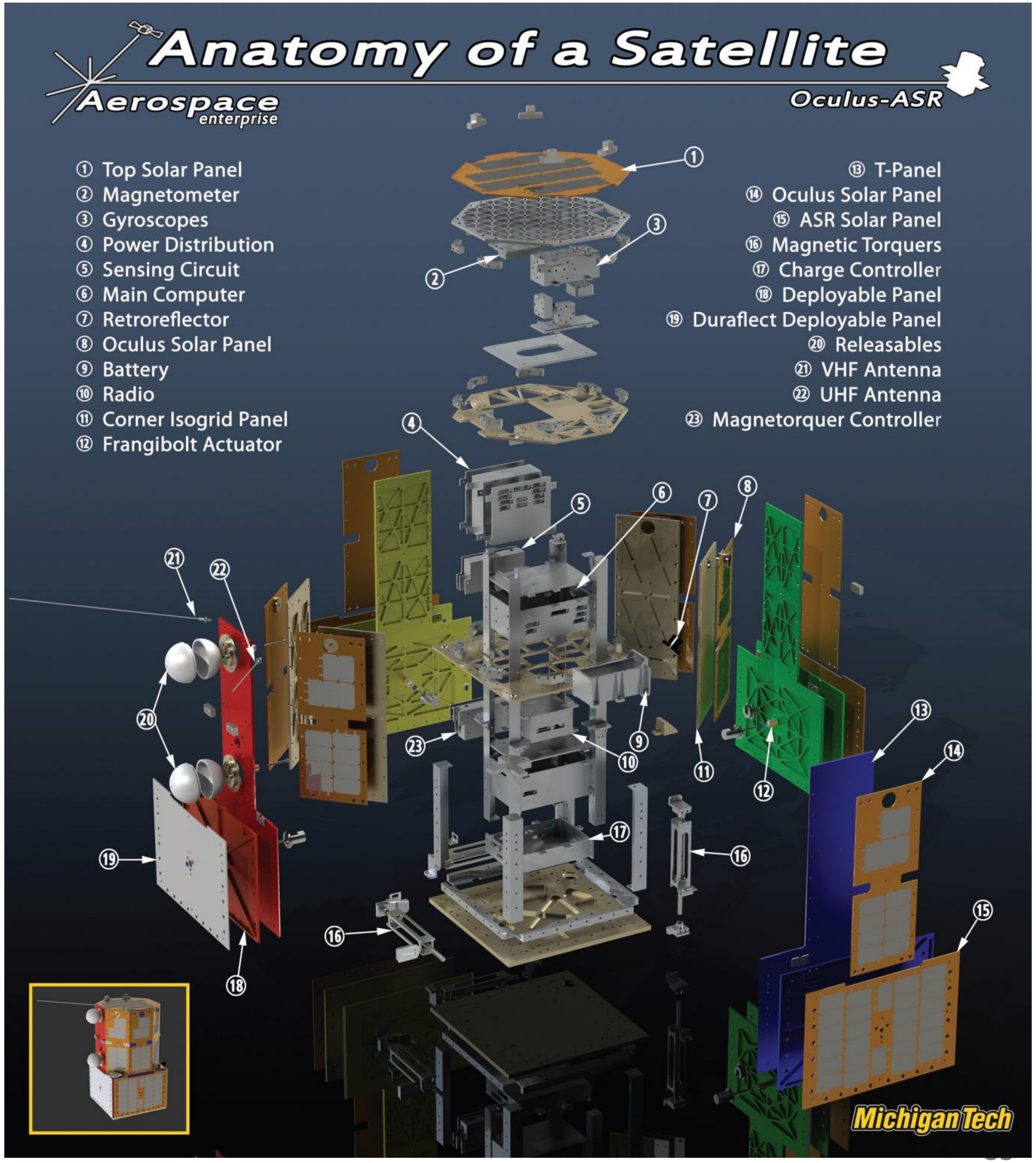
- Overview
- **Satellite Communication**
  - Voyager
  - **Oculus-ASR**
- Satellite Communications Providers
- Cellular-to-Satellite Communication

Oculus-ASR

- Satellite I worked on from 2009-2013

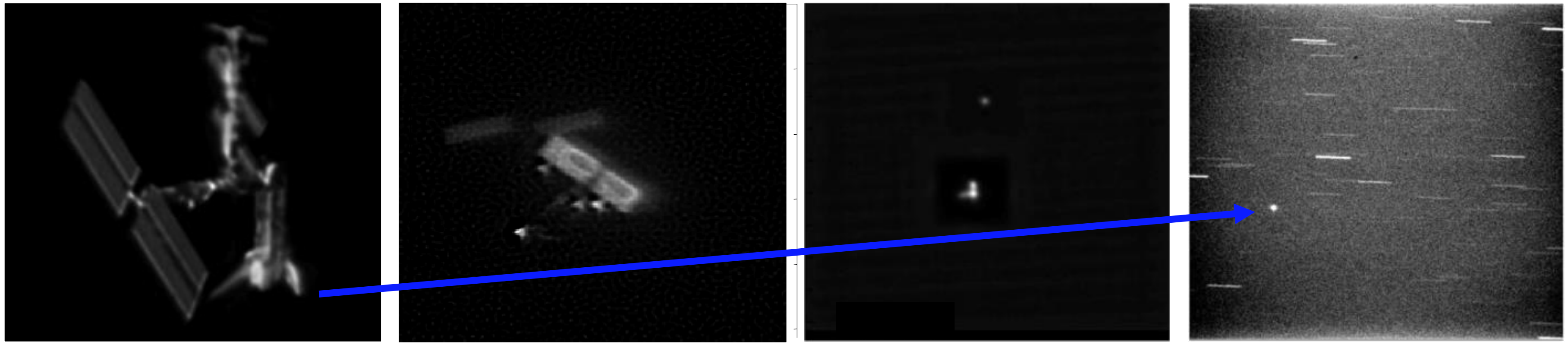


Michigan Tech
Michigan Technological University



Oculus-ASR mission

Can we determine a satellite's attitude and detect shape changes from the ground using only information gained from unresolved optical images?



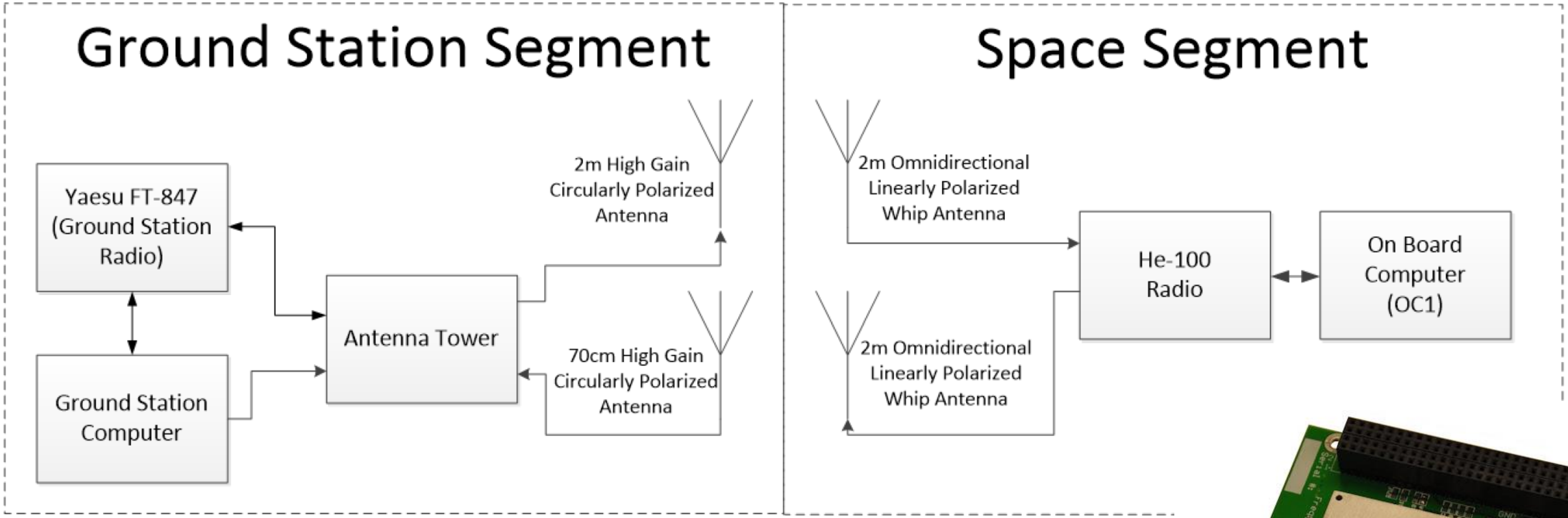
- Goal: Space Situational Awareness calibration
  - In coordination with Air Force Research Lab (AFRL) and Air Force Maui Optical and Supercomputing Observatory (AMOS)

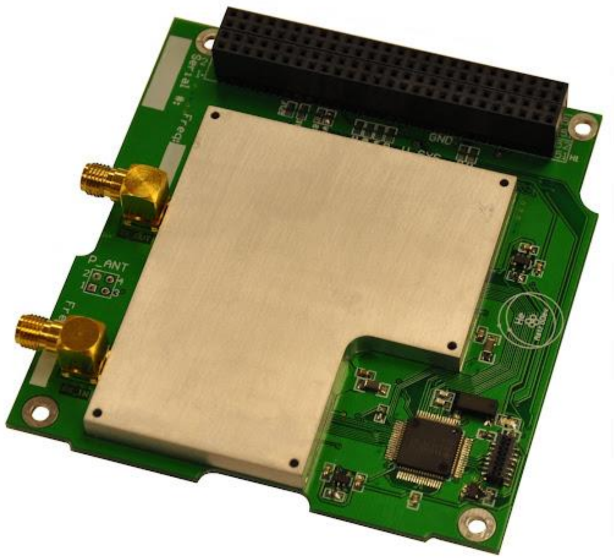
Winner of Nanosat-6: 2011

Launched in 2019

- STP-2 mission
    - Second Falcon Heavy launch

Oculus communication design





- 440 MHz downlink and 145 MHz uplink
  - Amateur bands, coordinated with IARU and AMSAT
- 9600 bps GMSK modulation
- Beacons data every 30 seconds

Oculus link budget

- Transmit power: 34 dBm (3 W)
- Path loss: 151 dB (at ~600 km)
- Receiver antenna gain: 14 dB

- Received power: -103 dB

Oculus packet data

- 108 byte beacon packets

RESPONSE PACKET STRUCTURE

	Header					
Byte Index	0	1	2	3	4-7	8-EOP
Field Name	Sync	Opcode	Payload Length	Response Type	CRC	Payload

PAYLOAD STRUCTURE

Byte Index	8-17	18-21	22-25	26	27	28-31
Field Name	Satellite Name	Uptime	Current Time	Current Mode	Current Profile	State of Charge

Byte Index	32-37	38-108
Field Name	Deployables State	Attitude Data

FIELDS

Satellite Name	The name of the Satellite in a character string (ASCII).
Uptime	The amount of time that has elapsed since the satellite was last booted.
Current Time	The current time reported by the satellite's main computer.
Current Mode	The satellite's current mode of operation.
Current Profile	The satellite's current attitude profile.
State of Charge	The satellite's current state of charge.
Deployables State	The current state of the satellite's deployables, one byte each.
Attitude Data	The satellite's current attitude data structure.

Source: Command document I wrote as a Junior in undergrad

Break + Question

- Is there a limit to how much stuff we can have in orbit? What about old, defunct satellites?

Break + Question

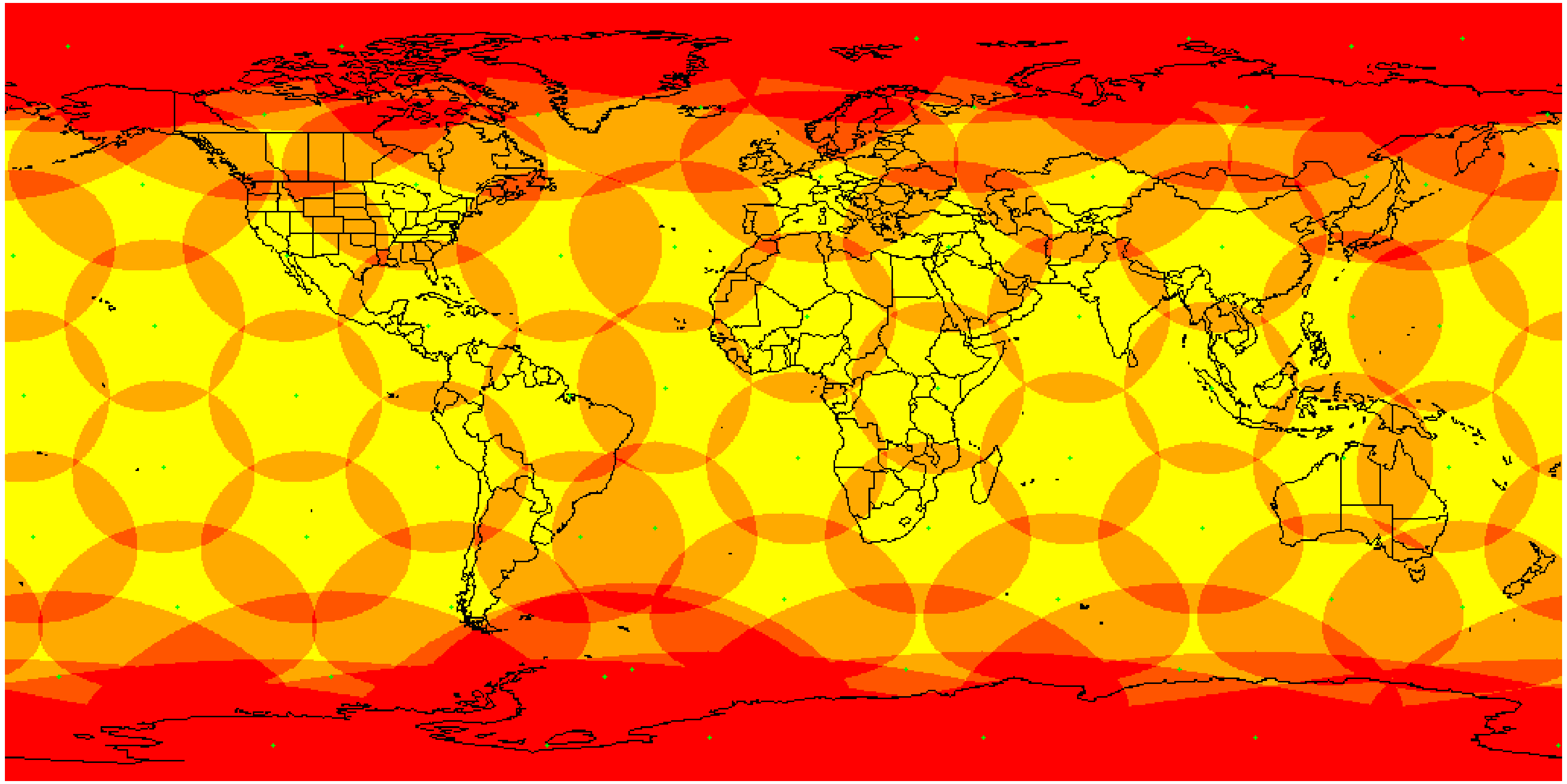
- Is there a limit to how much stuff we can have in orbit? What about old, defunct satellites?
  - Space Junk!! Major concern
  - 2022: FCC requires all satellites launched after 2024 to deorbit within five years of ending their mission
  - For GEO, graveyard orbit: location to move your satellite to that no one wants to use anyways
    - Need to move there *before* you run out of propellant

Outline

- Overview
- Satellite Communication
  - Voyager
  - Oculus-ASR
- **Satellite Communications Providers**
- Cellular-to-Satellite Communication

Iridium Constellation

- Active since 1997
- 82 active satellites in LEO for global coverage



- Each green dot is a satellite
- Yellow is coverage
- Red is overlapping coverage

Iridium satellite phones

- Initially marketed as general consumer phones
  - Total failure leading to bankruptcy
- Modern focus: highly reliable global niche
  - Journalists, explorers, military
- SMS and Voice service
  - Up to 4 hours of talk time
- Costs
  - $1800 for phone
  - Roughly $1 per minute for global voice coverage
  - $400 gets you 3000 text messages

Using Iridium from a device

- RockBLOCK radio module
  - $268
  - 5V at 500 mA (max)
    - Comparable to cellular modems

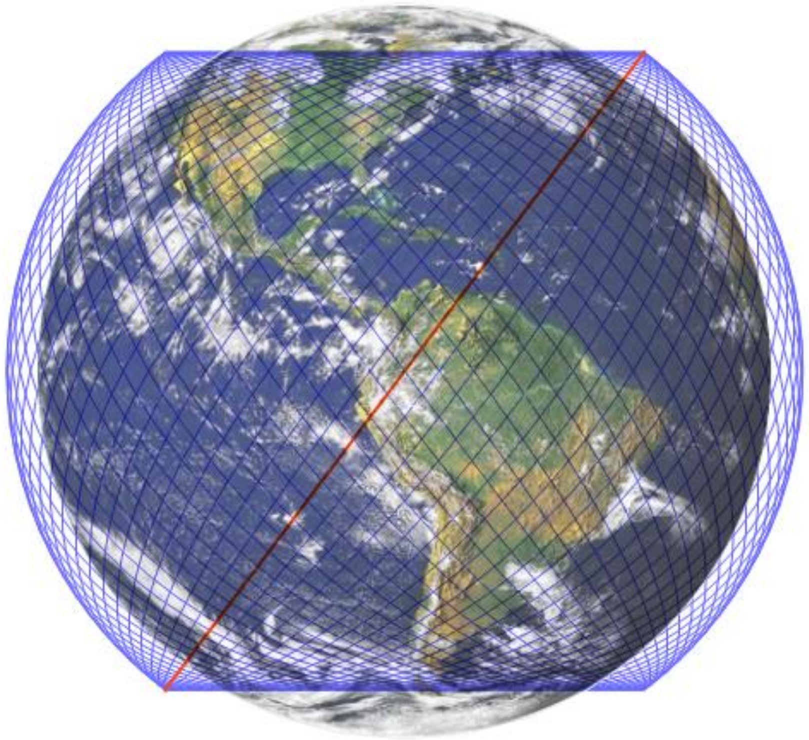
- Communication
  - 340 byte uplink packets
  - 270 byte downlink packets

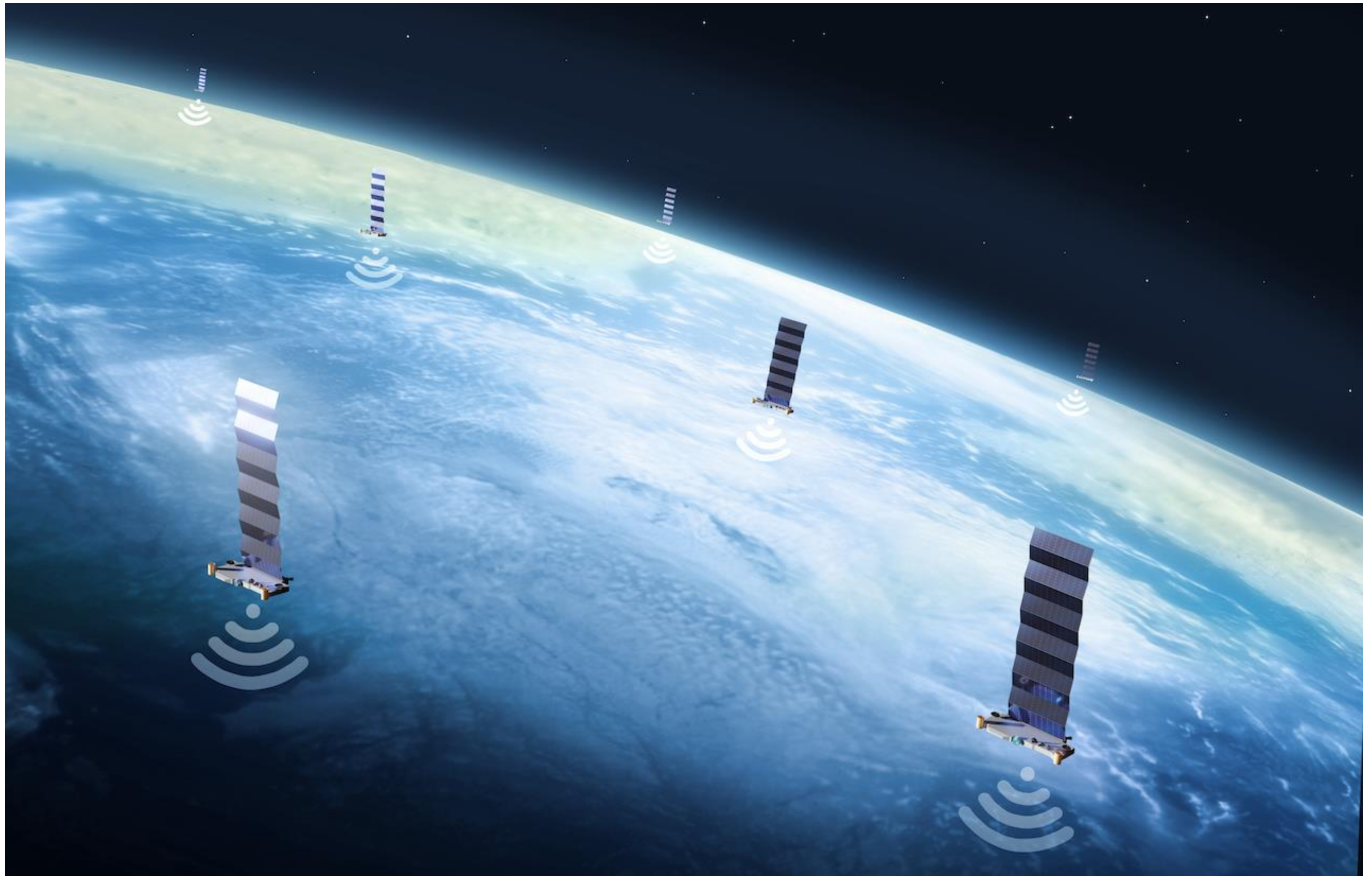
- $15 per month active
  plus ~$0.003 per byte

https://www.sparkfun.com/products/14498

Starlink constellation

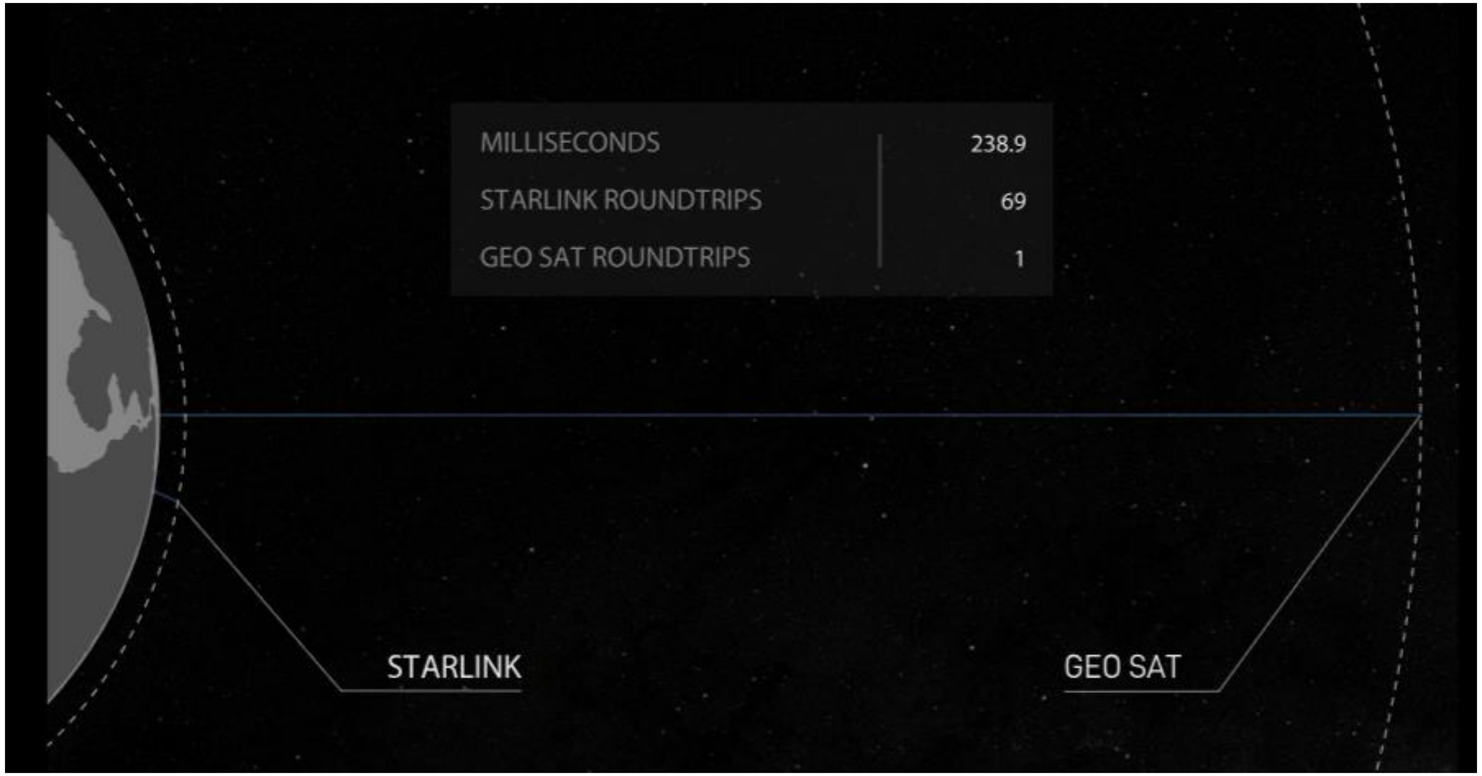
- Over 6000 satellites (as of March 2024)
  - 12000-34000 planned
- Service began in 2021





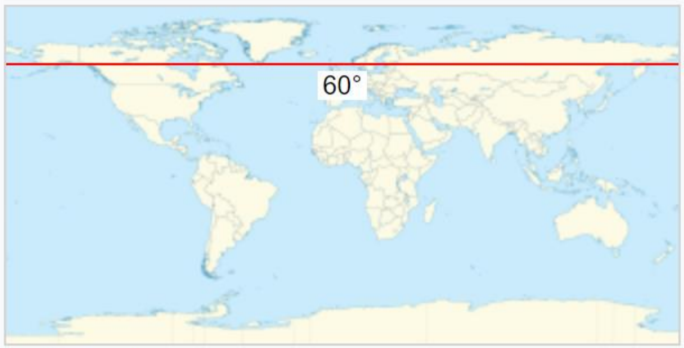
Starlink is deployed in LEO

- LEO orbit allows much lower latency for communication than GEO
  - ~60-70x faster
  - Which enables voice/video operation



Starlink targets consumer connectivity

- Broadband via satellite
  - 25-100 Mbps down, 5-10 Mbps up
  - 25-60 ms latency
- Anywhere on Earth below 60° latitude
  - But communications must be approved by individual countries (~40 so far)
- Costs
  - $600 for a hardware kit
  - $120/month for continuous service

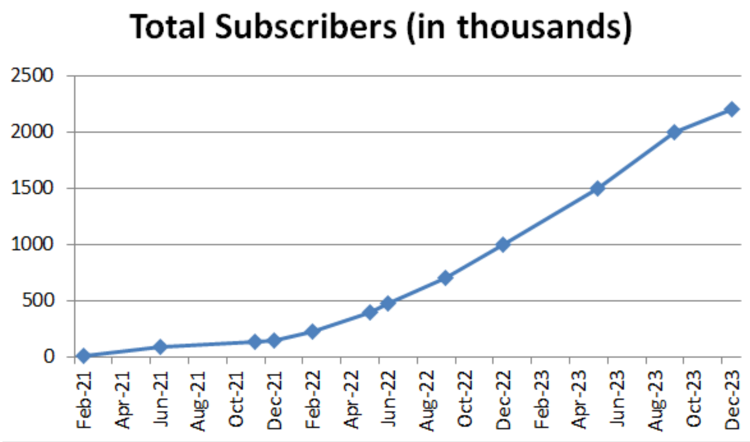


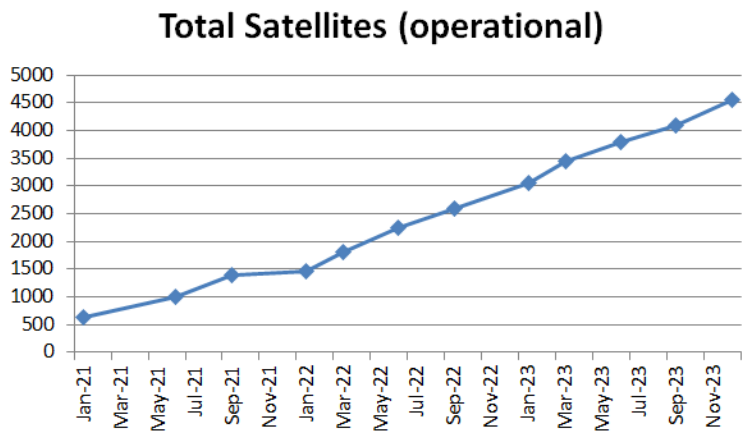
60th parallel north

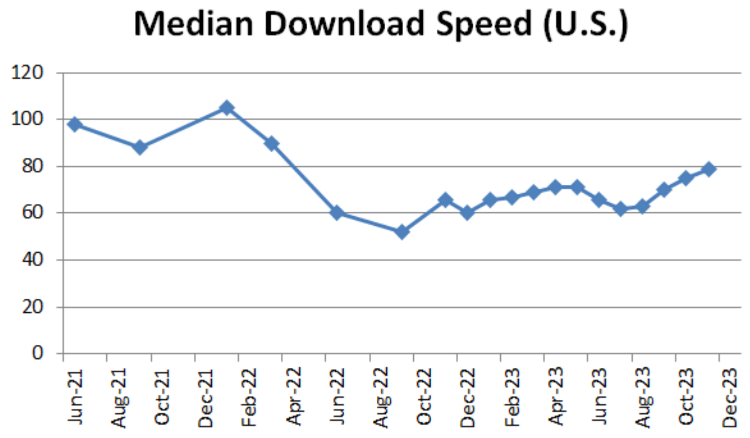
Starlink growth over two-year period

- Growth in subscribers has been sustained by growth in satellite deployments

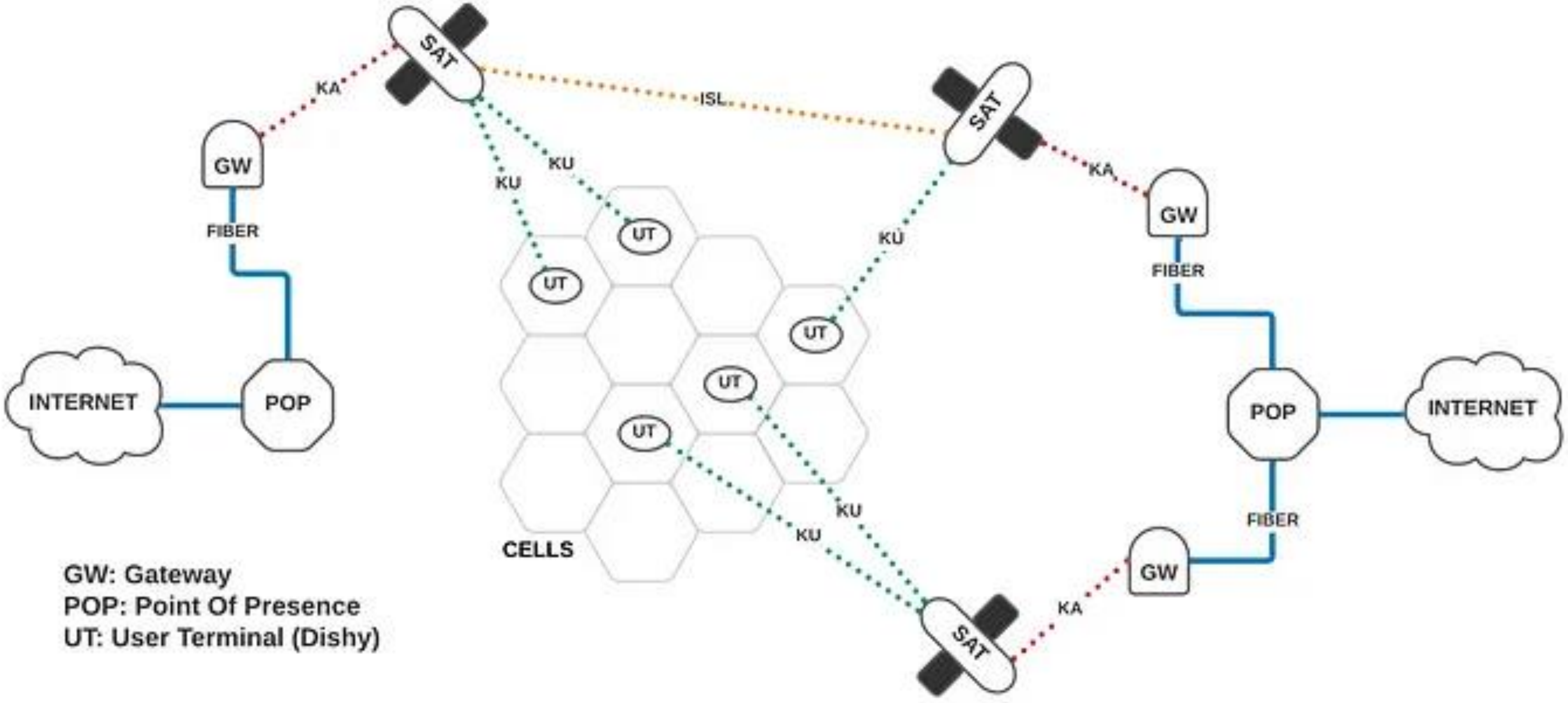
- Roughly 1 satellite per 500 users







Starlink operation model

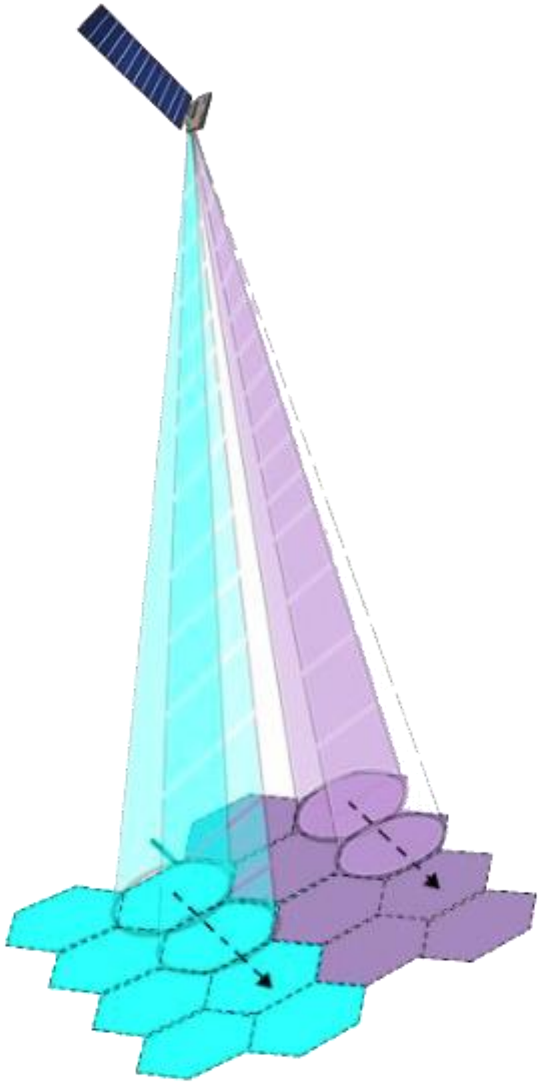


https://mikepuchol.com/modeling-starlink-capacity-843b2387f501

Starlink user communication

- Starlink cells are 15 miles in diameter

- Each satellite can communicate with 8 cells simultaneously (8 beams)
  - Cells can be directed at any location in view of the satellite
  - Can redirect cell locations quickly to time divide one beam into many cells per second



http://www.satmagazine.com/story.php?number=1026762698

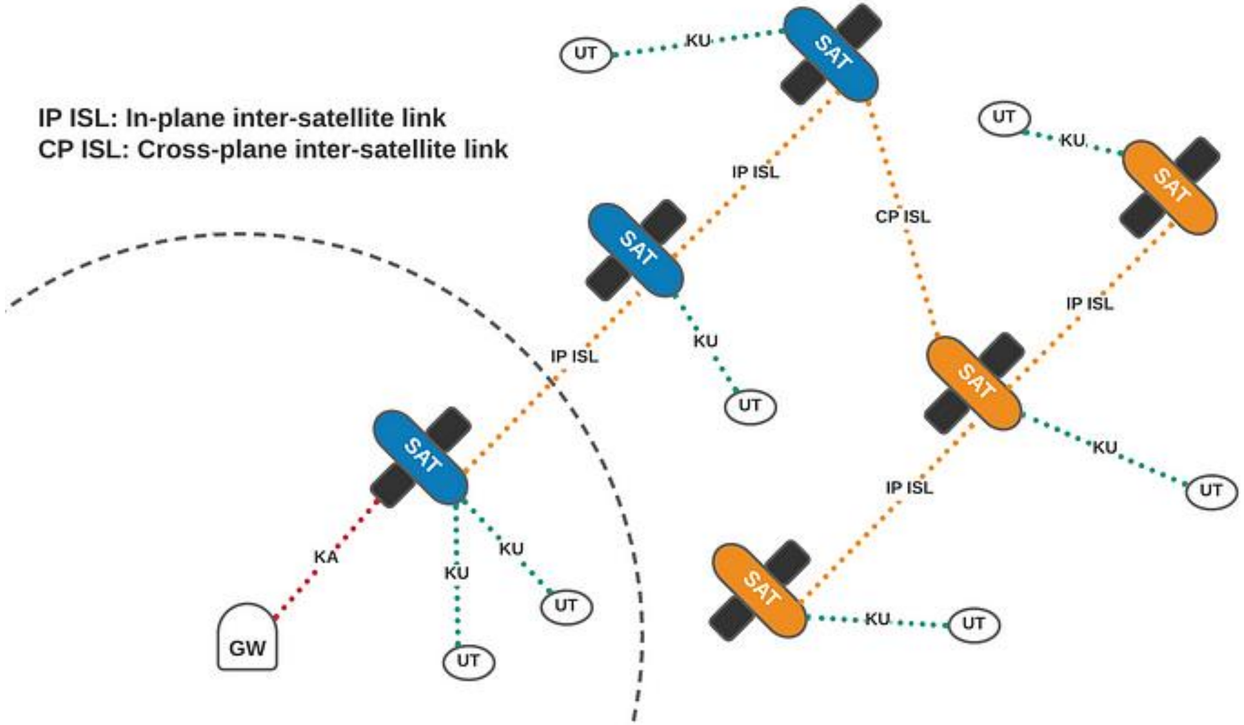
Starlink ground stations

- ~150 ground stations deployed, with ~100 in the US
- 20 Gbps throughput from satellite to ground station (shared among all its cells)
- Some regions (including eastern US) have a limitation on the band Starlink is using for downlink
  - Starlink only gets to use 50% of it

Starlink inter-satellite links

- What if a ground station isn't in view?
  - Use mesh networks!!

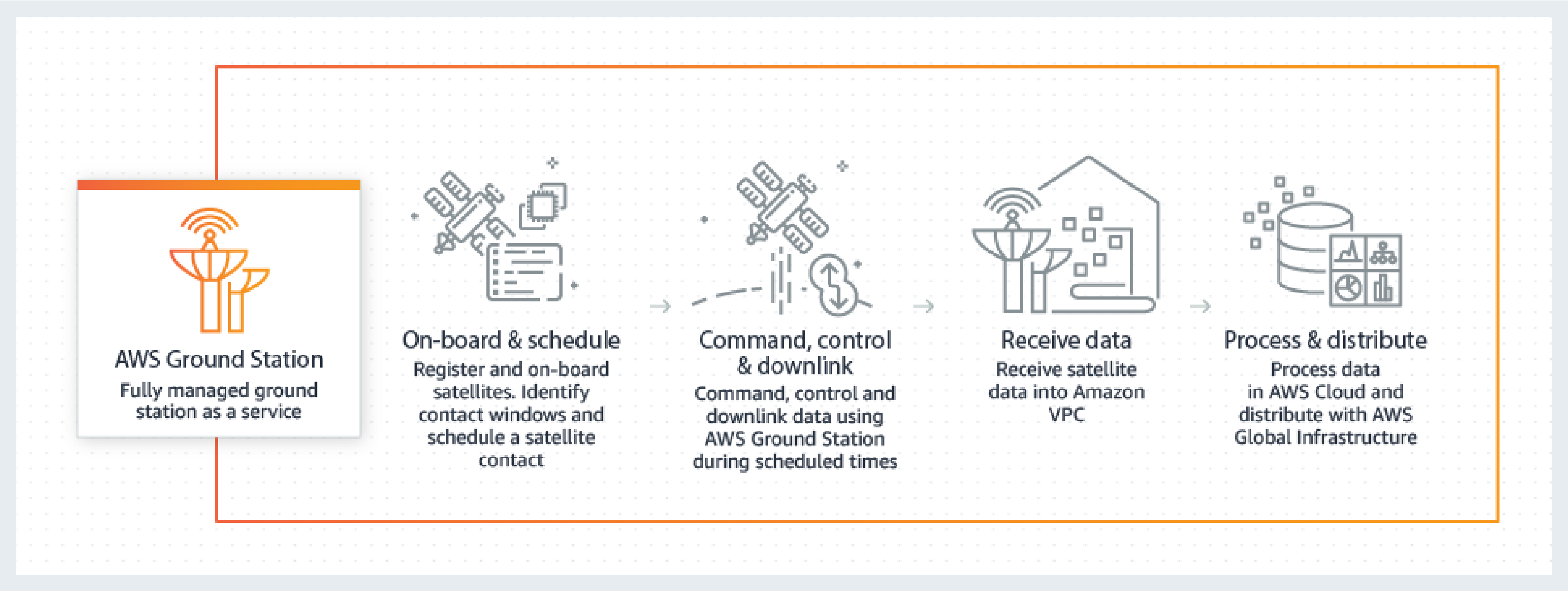
- Uses lasers to communicate with nearby satellites



Amazon's response: Project Kuiper

- First prototype satellites in 2023
- Service sometime in 2024
  - Planned constellation of 3000 satellites

- One advantage: AWS "ground station as a service" already exists



Satellite broadband providers (2023)

Operator	Satellite system (deployed)	Spectrum	Technology	Operational	Services
Space X (Starlink)	12000+ (3580)	Ku-band	Proprietary	Yes	Broadband
OneWeb	648 (542)	Ku-band	Proprietary	TBD	Broadband
Kuiper	3236 (0)	Ka band	Proprietary	Estimated 2024	Broadband
Galaxy Space	1000 (7)	Q/V spetrum	Proprietary	TBD	Broadband
Boeing	147 NGSO (1)	V band	Proprietary	TBD	TBD
Inmarsat	14 GEO (14)	TBD	Proprietary	TBD	Broadband to IoT
Telesat	188 (2)	C, Ku, Ka bands	Proprietary	TBD	Broadband
Echostar	10 GEO (10)	Ku, Ka, S bands	Proprietary	Yes	Broadband
HughesNet	3 GEO (2)	Ka band	Proprietary	Yes	Broadband
Viasat	4 GEO (4)	Ka band	Proprietary	Yes	Broadband

https://www.5gamericas.org/wp-content/uploads/2023/07/Update-on-5G-Non-terrestrial-Networks-Id.pdf

Outline

- Overview
- Satellite Communication
  - Voyager
  - Oculus-ASR
- Satellite Communications Providers
- **Cellular-to-Satellite Communication**

Goals of "Non-Terrestrial Networks"

- Support connectivity in "remote, unserved, and underserved areas"

- Target is remote regions: cities already have good cell coverage
  - Supplemental Coverage from Space (SCS)
  - Not intended to replace primary coverage

- In the US:
  - 57 million people live in "rural" areas
  - 4 million km^2 results in ~10000 15-mile-diameter (24 km) cells

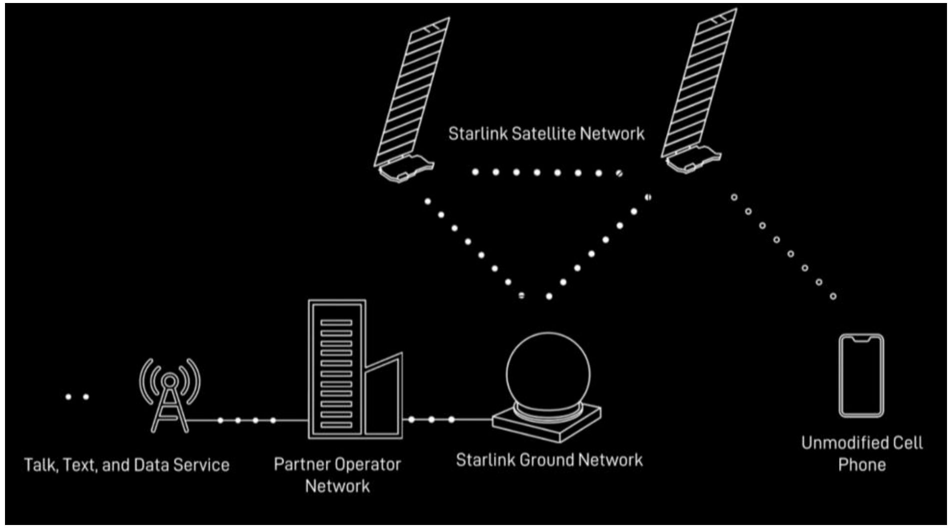
https://docs.fcc.gov/public/attachments/DOC-391794A1.pdf
http://www.satmagazine.com/story.php?number=1026762698

Apple Emergency SOS (2022)

- Allows for calling emergency services over satellite communication
  - Messages emergency contacts with your location as well
  - Possibly additional functionality: call AAA for roadside assistance
- Globalstar constellation
  - 24-satellite deployment in LEO (~1400 km)
  - Frequencies: 1.6 GHz uplink, 2.4 GHz downlink (doesn’t overlap with WiFi)
- Apple is guaranteed up to 85% of Globalstar bandwidth
- Free for first few years
  - No sense of how they’ll charge for it after that

Satellite to cellular suddenly seems viable, but nascent

- T-Mobile and SpaceX (2022)
  - Partnership in 2022
  - Direct-to-cell satellite launched in 2024
  - SpaceX says:
    - Text in 2024
    - Voice/Data and IoT in 2025



- Qualcomm and Iridium partnership (2023-2023)
  - Announced in January, ended in November
  - Qualcomm: going to focus on standards-based approaches

- Verizon and AST SpaceMobile form partnership (May 29, 2024)

- "77 publicly announced partnerships over 43 countries" (March 2024)

https://insidetowers.com/partnerships-show-potential-of-satellite-to-cell-phone-market/

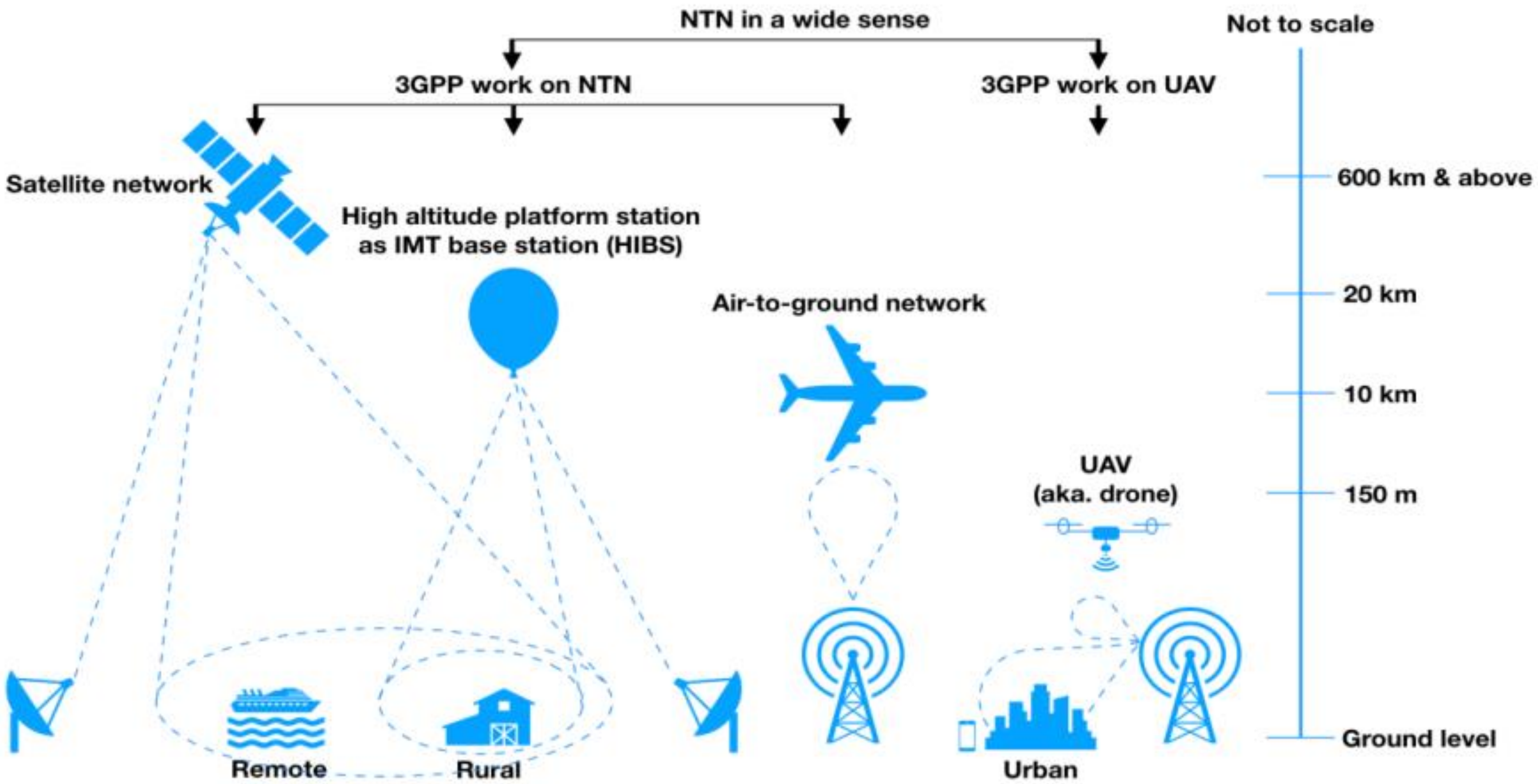
Planned and existing cellular/satellite partnerships (2023)

Operator	Satellite system (deployed)	Spectrum	Technology	Operational	Services
T-Mobile/SpaceX	2016 LEO (0)	MNO spectrum	3GPP-Rel 12	2024	Messaging, Data, Voice, Video
AT&T/AST	243 LEO (0)	MNO spectrum	3GPP-Rel 12	2024	Messagign, Data, Voice, Video
Verizon/Kuiper	3236 (0)	Ka band	Proprietary	TBD	Ground sites backhaul - LTE and 5G
Apple/Globalstar	24 LEO	L-band, S-band	Proprietary	4Q2022	Emergency Messaging
Qualcomm/ Iridium	66 LEO	L-band	Proprietary	4H2023	Messaging
Mediatek/ Skylo/Bullitt	6 GEO (Inmarsat)	L-band	3GPP-NTN	1Q2023	Messaging
Skylo/ Ligado/Viasat	1 GEO (Ligado)	L-band	3GPP-NTN	2H2023	NB-IoT, Messaging, LDR

https://www.5gamericas.org/wp-content/uploads/2023/07/Update-on-5G-Non-terrestrial-Networks-Id.pdf

3GPP non-terrestrial networks

- Satellites part of a broader Non-Terrestrial Networks (NTN) domain



3GPP 5G satellite requirements

- Release 17 (2022) included requirements for NTN. Shall support:
  - Service continuity between terrestrial and satellite networks
  - Mobility across various access network types
  - **Low power IoT type of communication**
    - LTE-M and NB-IoT are rolled into general LTE support

- Additional IoT focus
  - Network can broadcast satellite parameters so devices understand coverage and timing for communication
  - Assumes GNSS capability in IoT devices for timing and location

https://www.3gpp.org/technologies/ntn-overview
https://www.5gamericas.org/wp-content/uploads/2022/01/5G-Non-Terrestrial-Networks-2022-WP-Id.pdf

FCC gets involved (2023-2024)

- Approves regulatory framework for “Supplemental Coverage from Space” (March 2024)

- FCC attempting to fast-track new deployments
  - But also restricting them from interfering with existing stuff
  - Allocates some frequencies for SCS use, new ideas on a case-by-case basis

- Communication classes
  - Primary: existing “Mobile Satellite Services” like Globalstar and Iridium
  - Secondary: new SCS services
    - Must not disrupt existing MSS communications

https://docs.fcc.gov/public/attachments/FCC-23-22A1_Rcd.pdf
https://docs.fcc.gov/public/attachments/FCC-24-28A1.pdf
https://spacenews.com/taking-the-next-steps-for-satellite-to-smartphone-services/

Reality of satellite cellular coverage

- Low throughput communication per device
  - Needs to share bandwidth over a wide area
  - Path loss involved means reducing bitrate to keep acceptable error rate
- Targets rural areas without existing coverage
  - Somewhat mitigates need to share bandwidth
  - Some connectivity is better than none, right?
- User-focused applications: text, maybe voice, no data
  - Could get acceptable 1990s data, but the modern Internet doesn’t support that
  - Initial focus on emergency services makes sense

IoT and space coverage could be mutually beneficial

- Resulting non-terrestrial networks:
  - Global coverage (including remote regions)
  - Throughput too limited for primary human use
    - But is going to exist for backup use
    - Which means it might often go unused

- Pretty great scenario for IoT communication
  - Secondary quality-of-service (below emergency communications)
  - Infrequent data uplink of relatively small packets
  - Secondary monetary stream for service providers

Outline

- Overview
- Satellite Communication
  - Voyager
  - Oculus-ASR
- Satellite Communications Providers
- Cellular-to-Satellite Communication

Class Summary

- Network Fundamentals
- Bluetooth Low Energy
  - Advertisements, Connections
- 802.15.4
  - Thread, Zigbee, Mesh Routing
- WiFi
- Cellular
- LPWANs
  - LoRaWAN, Sigfox, Research and Challenges
- Other
  - Localization, Backscatter, Satellite Communication