Ingegneria delle Telecomunicazioni

Satellite Communications

15. SatCom Services & Constellations: High Throughput

Riccardo De Gaudenzi, ESA/ESTEC
rdegaude@gmail.it

PART 1 - THROUGHPUT GSO NETWORKS

HTS Architecture – Feeder link aspects

High Throughput Satellites (HTS) require a large feeder link bandwidth

- collection of all beams' useful bandwidth
- typically FWD throughput x 3-4 times RTN

Example: Medium HTS requiring 32 GWs

Extending user bandwidth to 1 GHz will double the # GWs required

Need to use non FSS reserved bands or to move to Q/V-band feeder link

Feeder link fading is affecting ALL user links! => ACM not a solution

How to also ensure high FL availability?

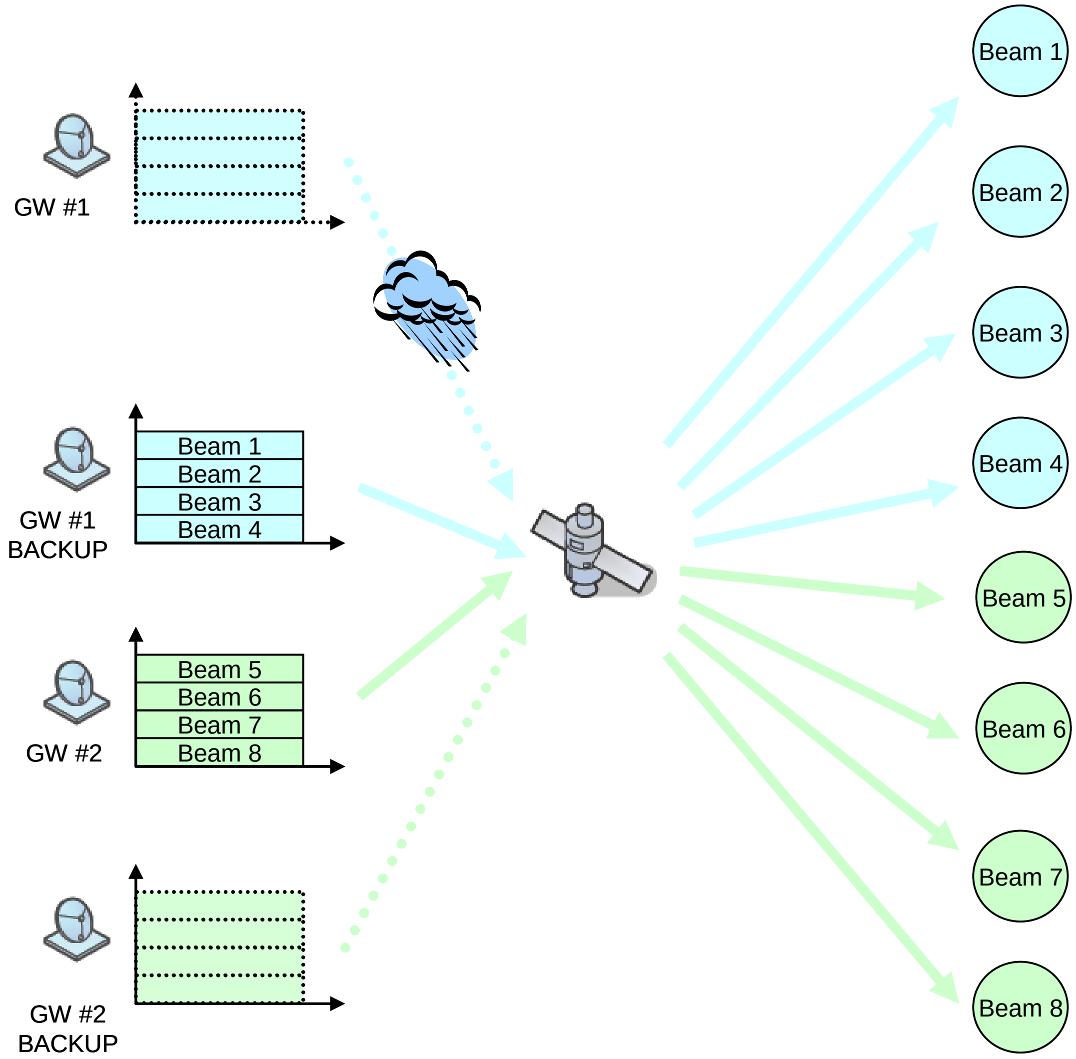
- *Step 1: uplink power control*
- *Step 2: spatial GW diversity*
- *Step 3: smart GW diversity*

	FL	RTN	TOT	
Number of beams	200	200		
Total user bandwidth/polar	500	250		
Number of polarizations	2	2		
Number of FDMs/polarization	2	2		
Number of colours	4	4		
Bandwidth/beam/polar	125	62.5		MHz
Bandwith/beam	250	125		MHz
Total user link bandwidth	50	25		GHz
Avg SE	2.5	1.25		bps/Hz
Total throughput	125	31.25	156.25	Gbps
Feeder link bandwith/pol/GW	2	2		
Number of FL polar	2	2		
Total FL bandwdith/GW	4	4		
Number of GW required	32	8	32	

HTS Architecture – Feeder link aspects

Classical GW site diversity:

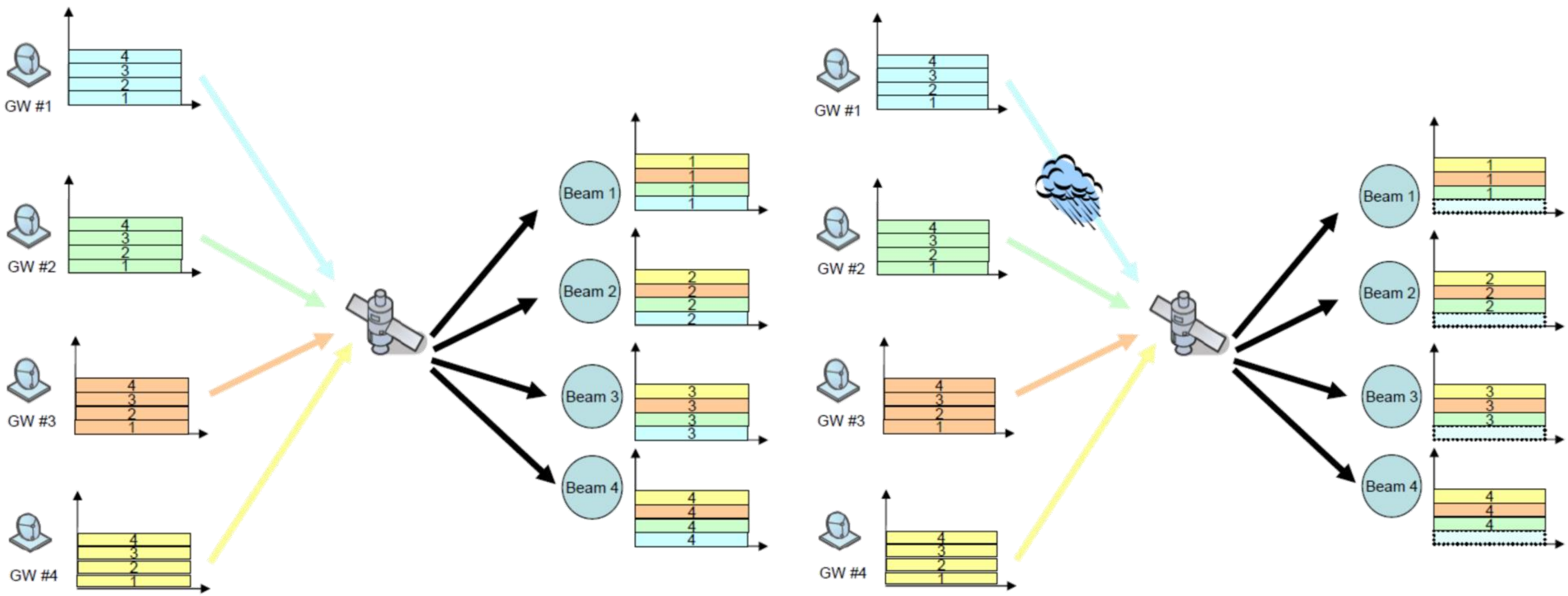
- Each GW has a backup at tenths of km of distance ready to take over in case of heavy fading
- Expensive solution in terms of ground segment
- Abandoned for HTS networks



HTS Architecture – Feeder link aspects

Smart Gateway N+0 concept: No extra GWs in diversity

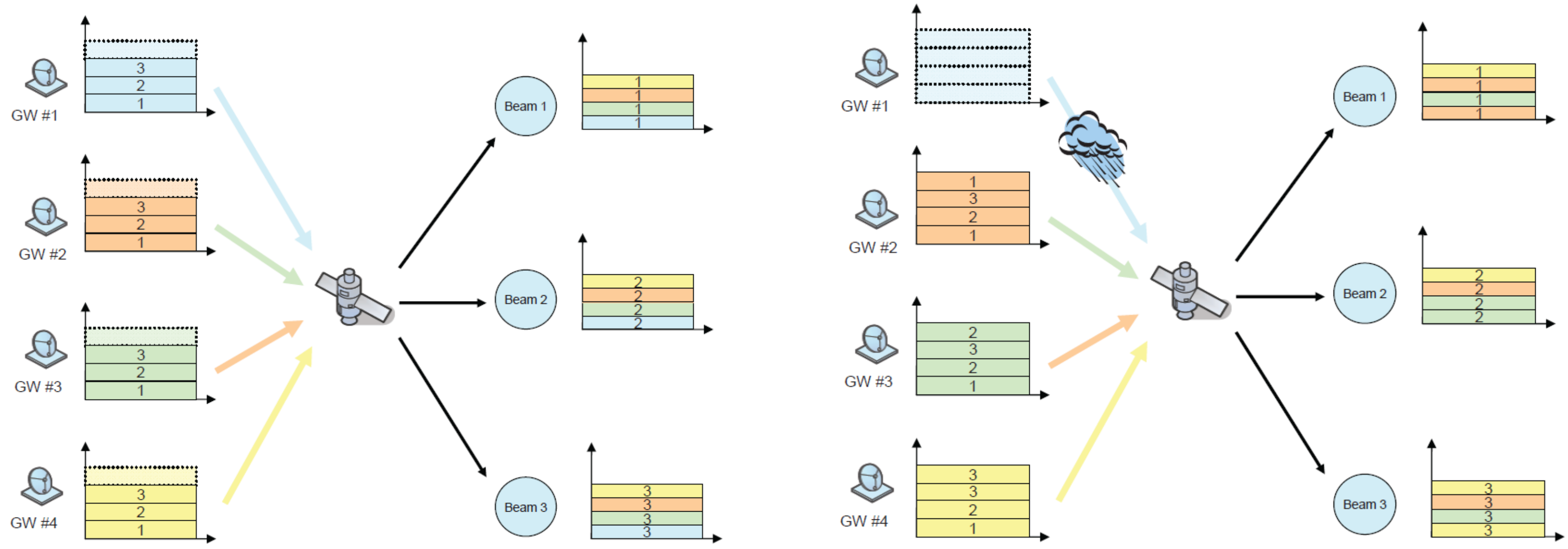
- Each user beam is served by different GWs (3-4) on different FDMs
- In case of one GW outage the other GWs take over the faded GW traffic
- Easy to implement but impact on the system (beams) throughput



HTS Architecture – Feeder link aspects

Smart Gateway N+P++ concept: P extra GWs in spatial diversity with P << N

- Each user beam is served by different GWs on different FDMs
- In case of one GW outage the other GWs take over the faded GW traffic
- Requires GWs feeder link throughput oversizing and payload flexibility to switch feeder links to beam assignment but no impact on the system throughput



Dip. Ingegneria dell'Informazione
University of Pisa, Italy
Riccardo De Gaudenzi

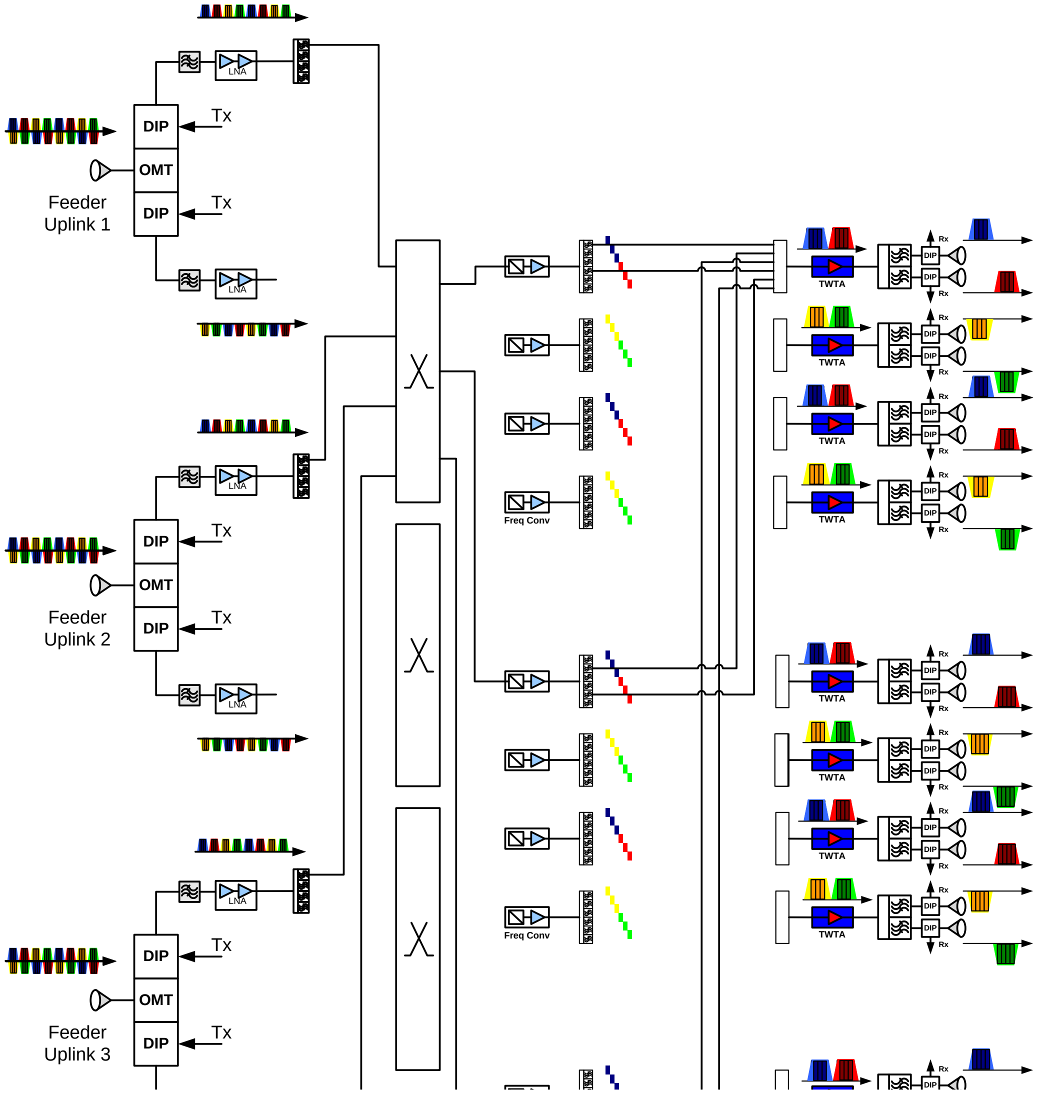
HTS Architecture – Feeder link aspects

HTS analogue payload supporting
Smart GW N+P++ solution

The use of a digital processor
is easing the implementation

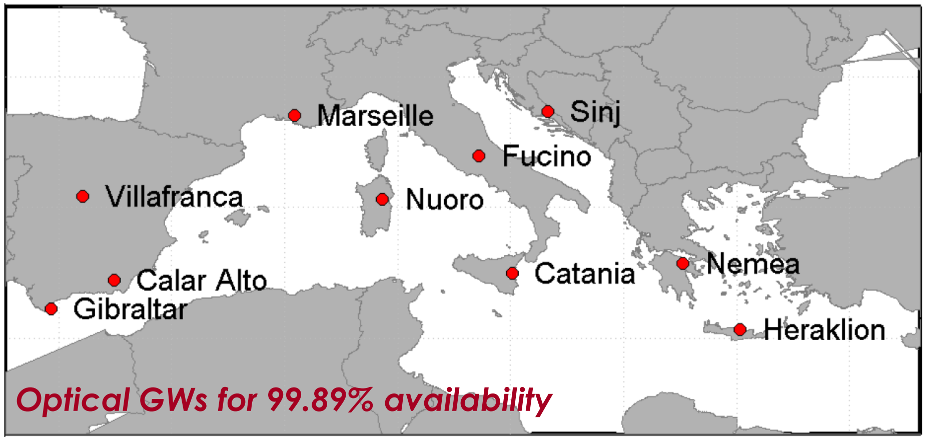
This architecture also support
Progressive gateways deployment

Increased payload complexity

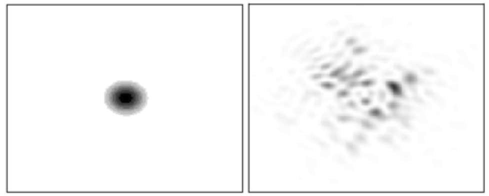


Optical Feeder Link (FL) – Myths and Realities

- **After exploitation of Q/V-band (on-going), W-band (R&D stage) optical may be the next frontier for the feeder link**
- **Pro and contra:**
  - To achieve a FL availability compared to the current RF's, several optical ground stations in special "dry" and distant locations will be required (e.g. 9-10 for Europe)
  - Each GW will have higher throughput than RF one but the backbone needs to be sized to the FL throughput (up to x Tbps)



Optical Feeder Link (FL) – Myths and Realities



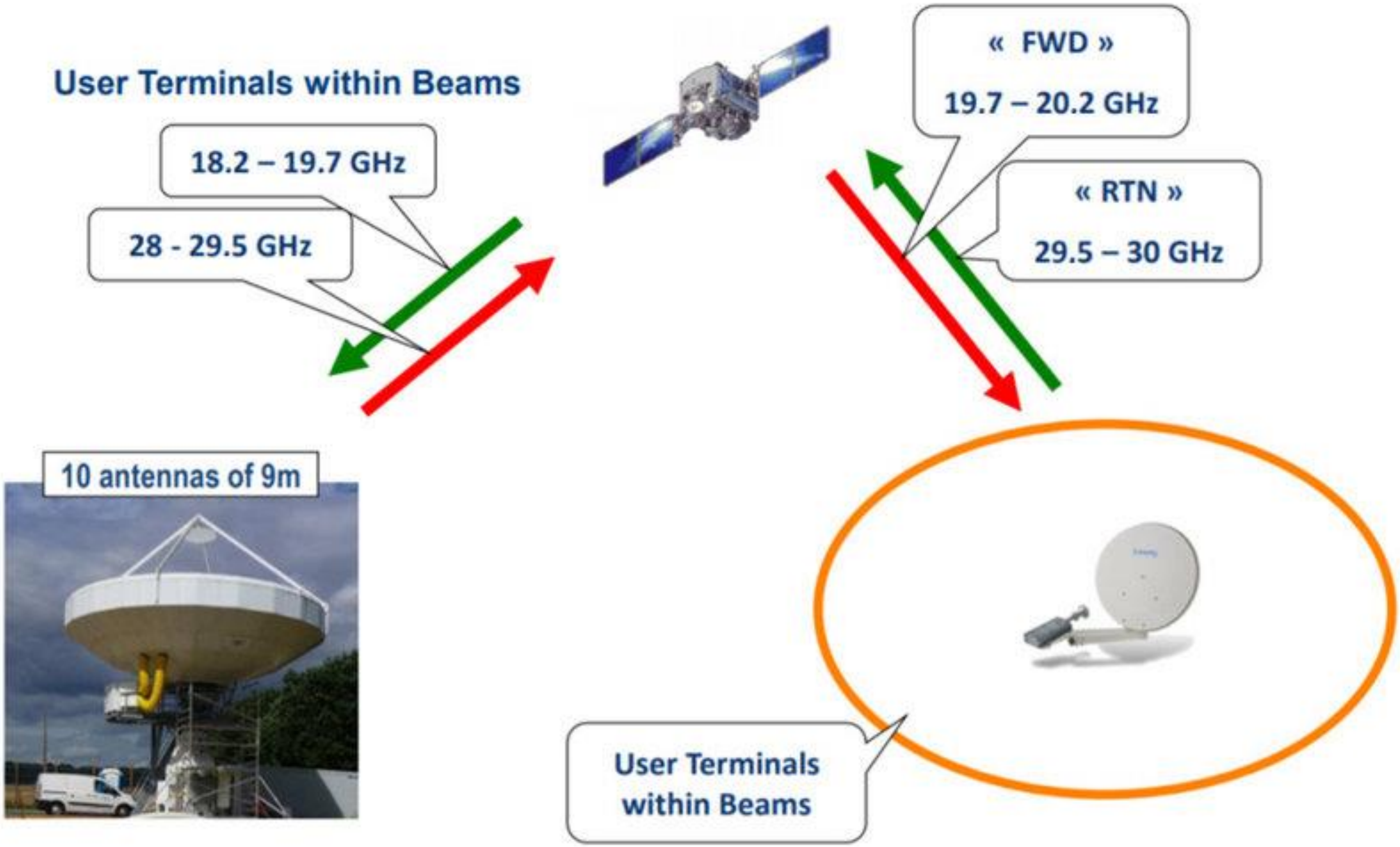
- **Atmosphere turbulence mitigation**
  - Downlink: adaptive optics
  - Uplink: multiple transmitters at distance of say 0.5 m
    more BW and power
- **Current FSO satellite links are based on digital binary modulations:**
  - To limit the FL throughput satellite payload has to be regenerative instead of transparent. This may be an issue for GEO HTS easier for LEO constellations already featuring on-board processing.
  - Digital Transparent: the analog signal is sampled / quantized with an increase by a factor ≈16 of the feeder link required throughput
- **RF-over-optical analog modulation being investigated as possible smart optical GWs approach**
  - Use of single/double-sideband modulation to limit the bandwidth occupancy and average power transmitted

High Throughout Satellite Network Example – Eutelsat Ka-sat

The Eutelsat Ka-sat HTS system [launched 2010]:

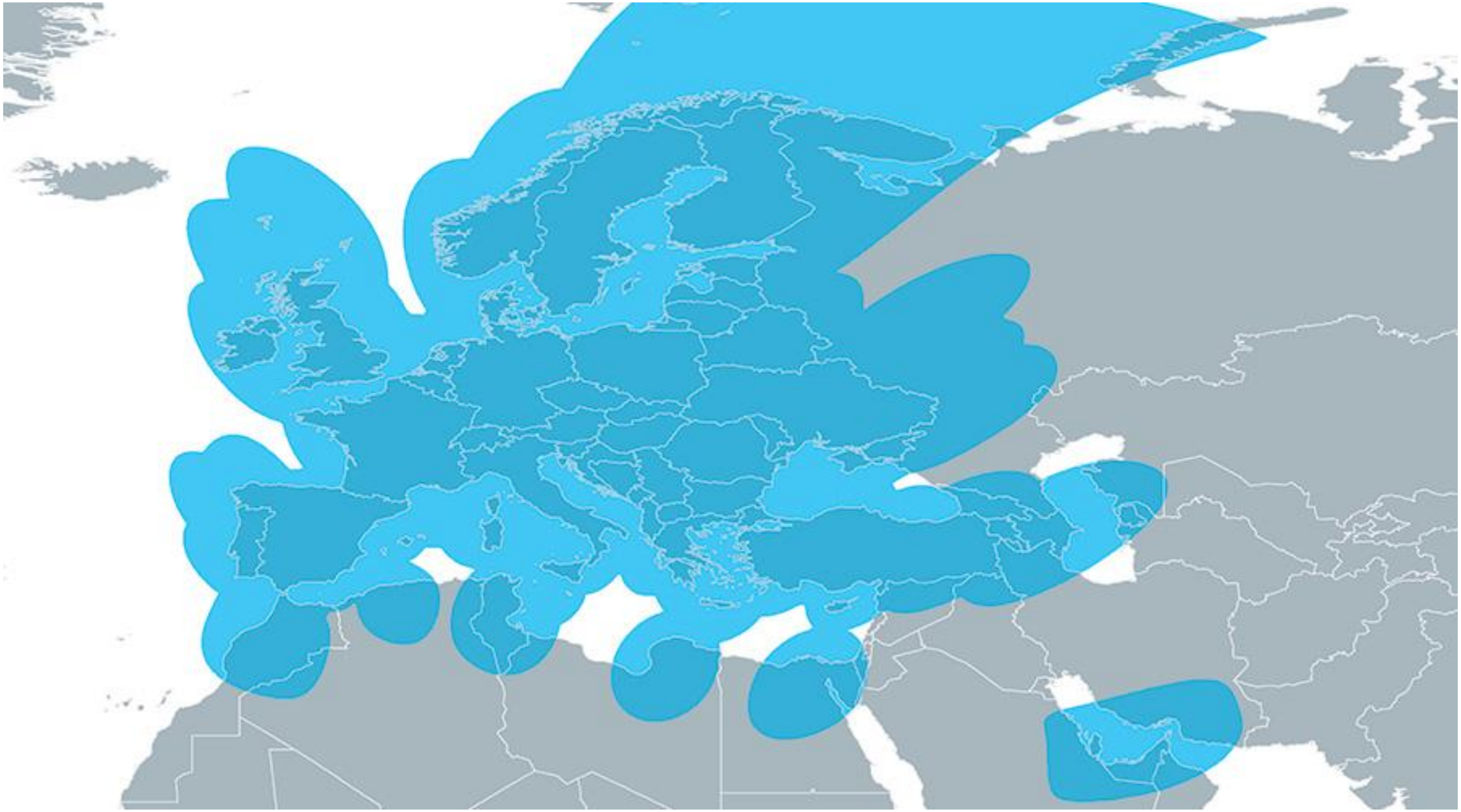
- Single Ka-band GSO covering Europe, North Africa and Middle East with 70 Gbps
- 82 beams with size of approximately 250 km
- 10 gateways interconnected with multi-protocol label switching (MPLS) high speed terrestrial network
- **Ka-sat services:**

High Throughout Satellite Network Example – Eutelsat Ka-sat



High Throughout Satellite Network Example – Eutelsat Ka-sat

Eutelsat Ka-sat coverage



High Throughout Satellite Network Example – Eutelsat Ka-sat

Eutelsat Ka-sat spacecraft

Power

- Spacecraft Power <14kW
- Payload DC power 11kW
- Solar Array Power up to 16kW

Mass

- Payload mass ~1000 kg
- Spacecraft dry mass ~3170 kg
- Satellite launch mass 5.7t -6.1t

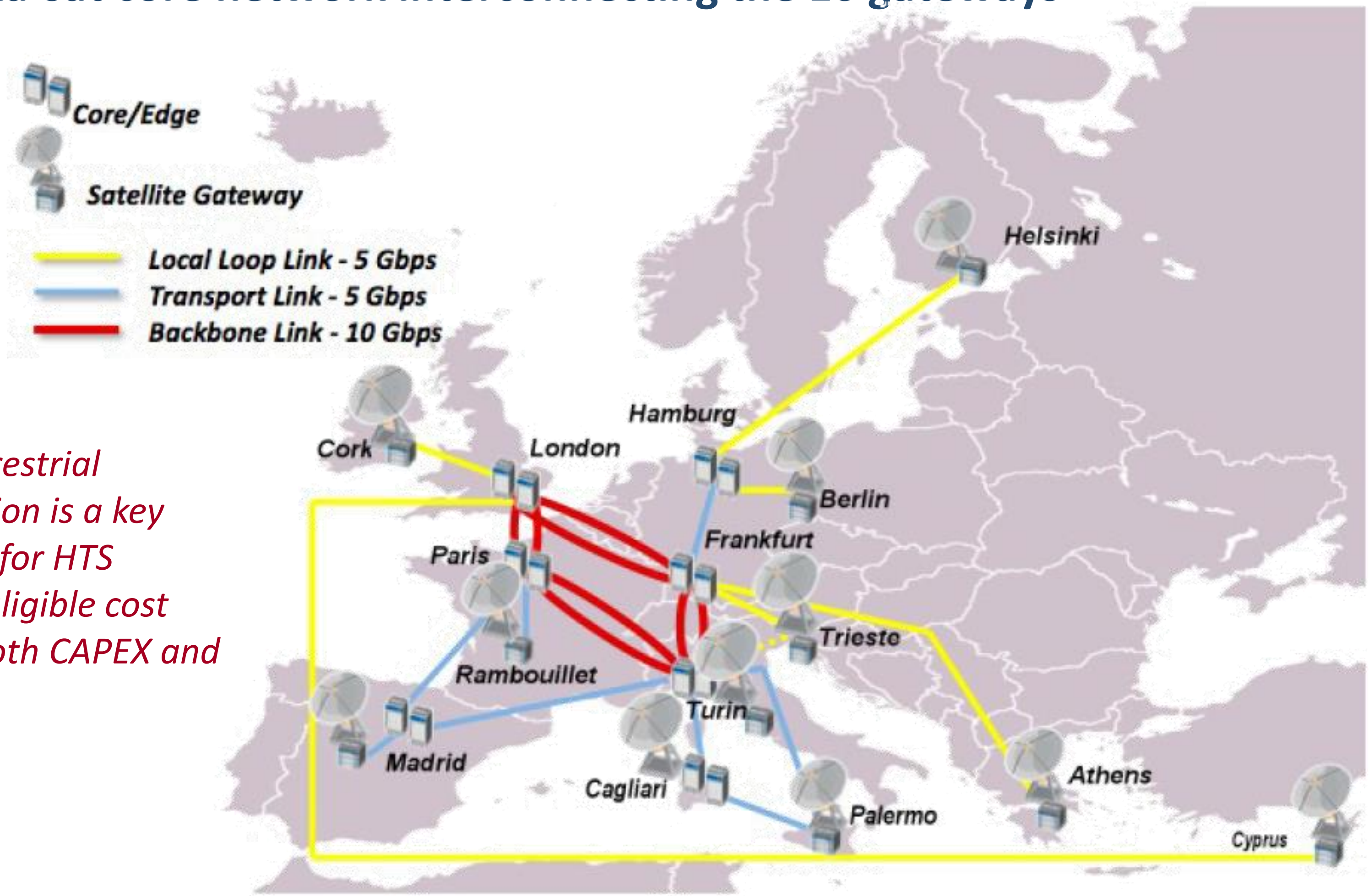
Orbital Maneuver lifetime

- 16 years

High Throughout Satellite Network Example – Eutelsat Ka-sat

Eutelsat Ka-sat core network interconnecting the 10 gateways

The GWs terrestrial interconnection is a key requirement for HTS with non negligible cost impact for both CAPEX and OPEX



High Throughout Satellite Network Example – Eutelsat Ka-sat

Ka-sat footprint

High Throughout Satellite Network Example – Eutelsat Ka-sat

Ka-sat ground segment (user terminal and gateways)

User Equipment

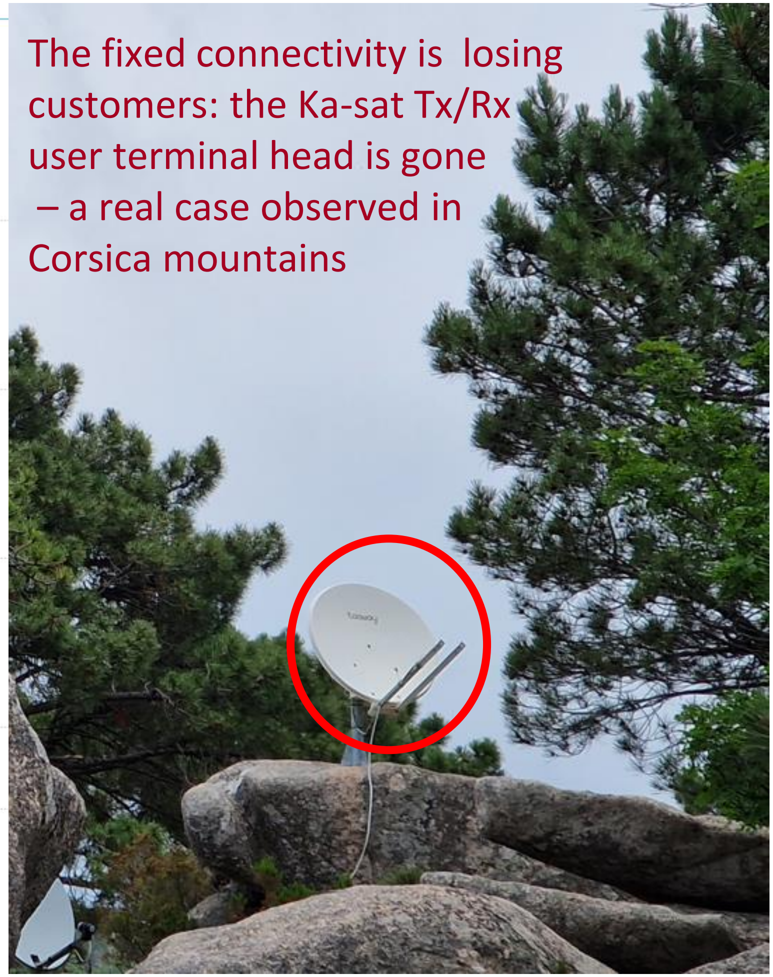
High Throughout Satellite Network Example – Eutelsat Ka-sat

FY 2022-23 REVENUES BY APPLICATION

	REVENUE CONTRIBUTION[1]	REVENUES (€m)	LIKE-FOR-LIKE[2] YOY CHANGE
VIDEO	62%	705	-8.3%
GOVERNMENT SERVICES	12%	143	-7.2%
MOBILE CONNECTIVITY	10%	110	+26.8%
FIXED CONNECTIVITY	16%	178	-2.3%
TOTAL OPERATING VERTICALS		1,136	-4.8%
OTHER REVENUES		-5	-€8m[3]

eutelsat

The fixed connectivity is losing customers: the Ka-sat Tx/Rx user terminal head is gone – a real case observed in Corsica mountains



Viasat 2

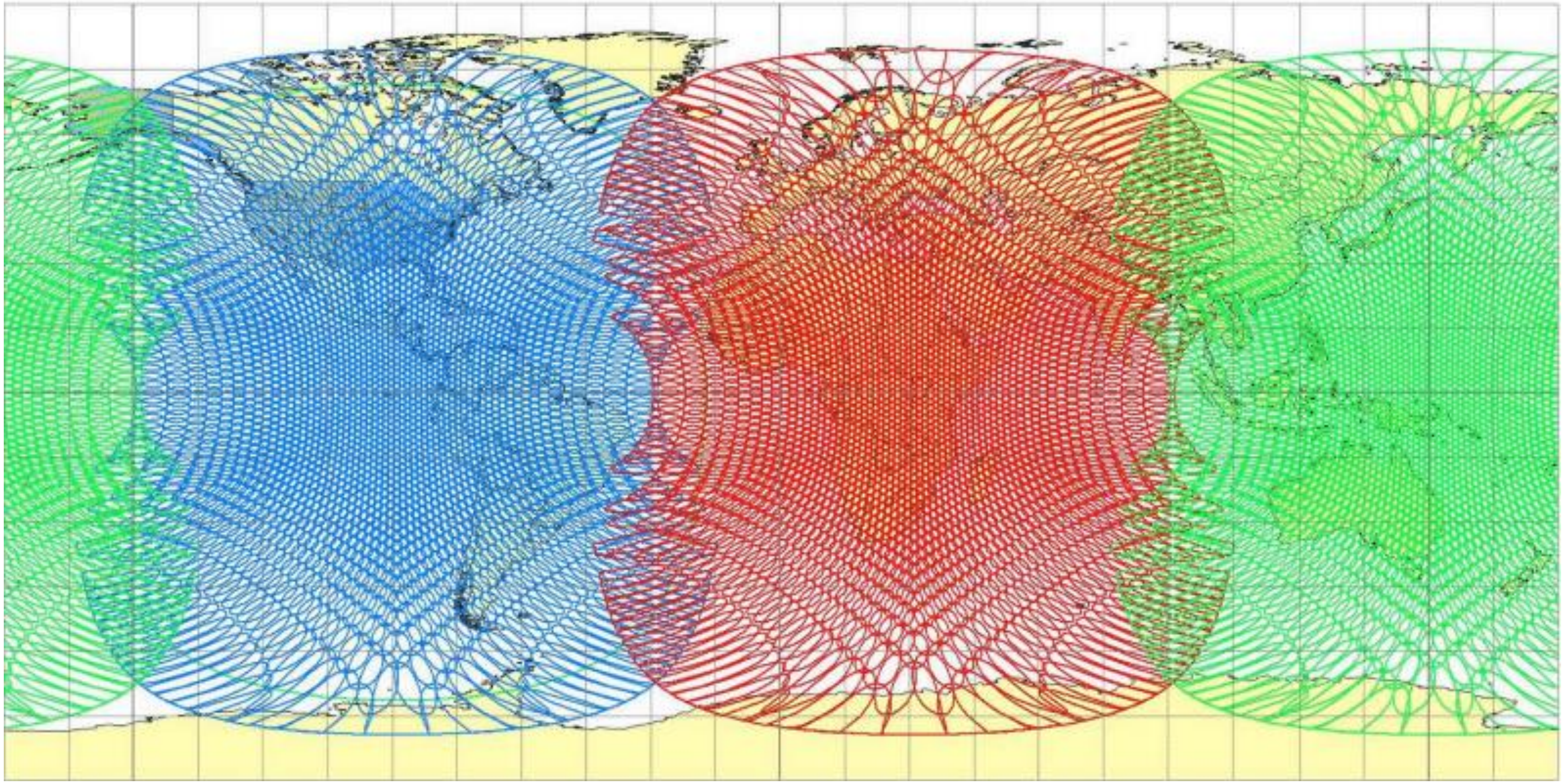
- HTS covering North-Central America and Oceanic routes to Europe
- Boeing H720P platform 6.5 tons 18 kW
- 300 Gbps throughput operating at Ka-band
- Launched mid-2017

Viasat 3: first Terabps HTS GSO system announced in 2015 has been launched in 2023 with large delay

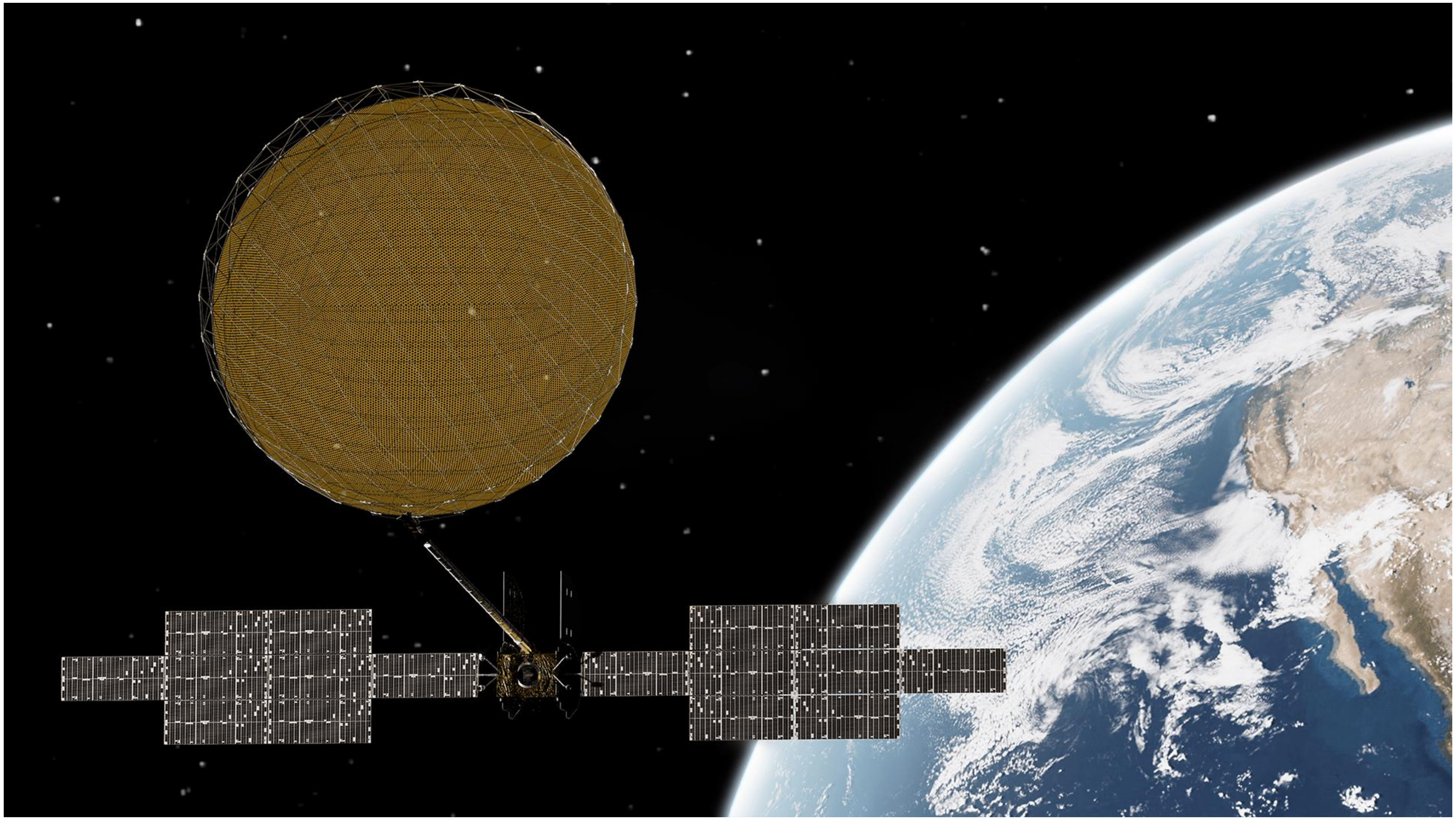
- The global ViaSat-3 constellation is expected to deliver unprecedented capacity to individuals, businesses, and governments — on the ground, in the air, at sea, and beyond.
- **Spectrum**: The ViaSat-3 constellation operates on Ka-band
- **Coverage**: The ViaSat-3 constellation is designed to cover North and South America, Europe, Africa, and Asia Pacific
- **Speed**: Each ViaSat-3 satellite is planned to have the ability to deliver download speeds of up to 100's of Mbps
- **Capacity**: Each satellite is anticipated to deliver at least 1 Terabit of data per second (1Tbps)
- **Weight**: Each satellite is expected to weigh approximately 6 metric tons
- **Payload**: Innovative payload solutions aiming at flexibility with reduced complexity

video https://www.viasat.com/space-innovation/satellite-fleet/viasat-3/

Viasat 3 planned global coverage with 3 GEOs



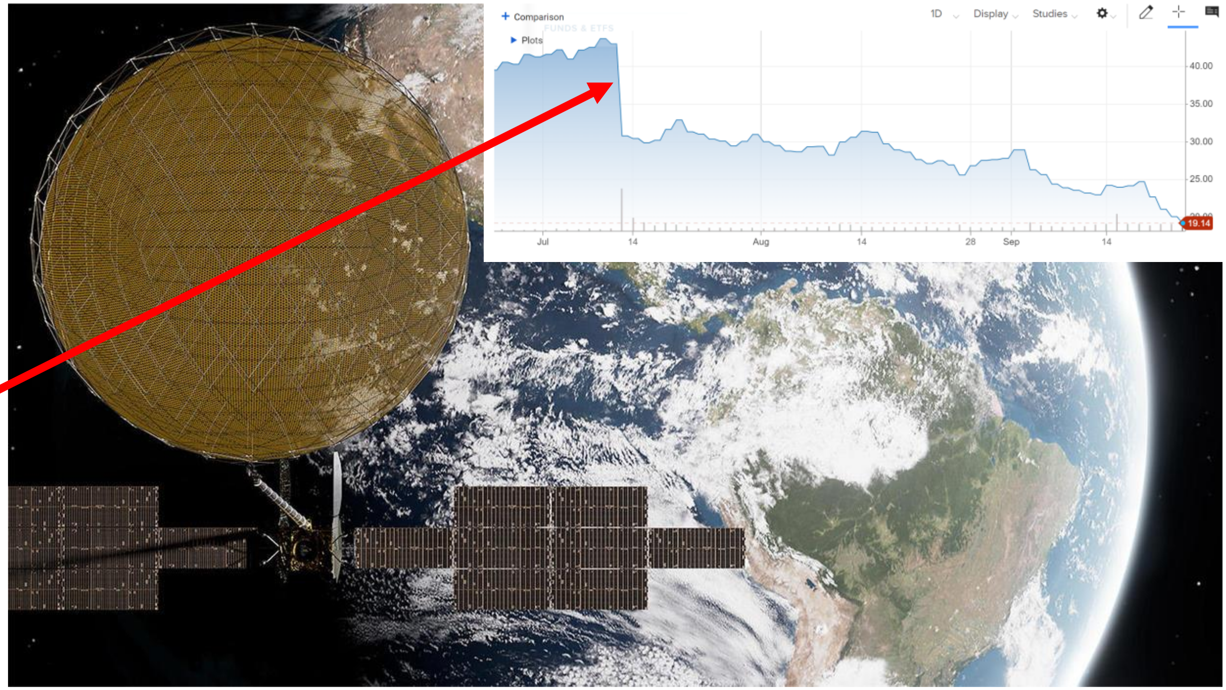
Viasat 3 satellite: very large Ka-band reflector and solar generators



Viasat 3

Risky business – It happens…

- In addition to the sizeable development delay Viasat 3 had a major issue after April 23 launch in deploying the large Ka-band reflector in July (Northrop Grumman's Astro Aerospace) probably leading to the completed satellite operational loss
- Insurance coverage expected to be 420 M US$ but not fully compensating for the mission cost > 700 M US$
- Stocks falling after July news….



Hughes Network Systems Jupiter 3 (Echostar XXIV)

- Jupiter 3 HTS made by Maxar has been launched in July 2023 is the heaviest communication satellite launched so far (9 tons vs 5.6 tons of Viasat 3 with a solar array wingspan of 39 m vs 44)
- In service in 4Q 2023, with user download speed up to 100 Mbps
- Spectrum: 18 gateways exploiting Ka-band, Q- and V-band
- Coverage: North & South America
- Speed/Throughput: Up to 100 Mbps/ More than 500 Gbps
- Total maritime mobility Spot beams: 300 - Each beam carries 500 MHz or more, providing more than 1 Gbps/beam

HTS GSO Systems Takeaways 1/2

- **GSO HTS are trying to fill the gap of the GSO broadcasting satellite decline**
  - High throughput is a must but challenging even using Ka-band high frequency reuse (hence small beams)
  - ACM is a key technique for the efficient exploitation of Ka-band
  - Smart gateway diversity to mitigate the number of ground stations required
  - Q/V-band starts to be adopted for the feeder link
  - User terminal like TVRO equipment, no tracking antenna
  - Long satellite lifetime

HTS GSO Systems Takeaways 2/2

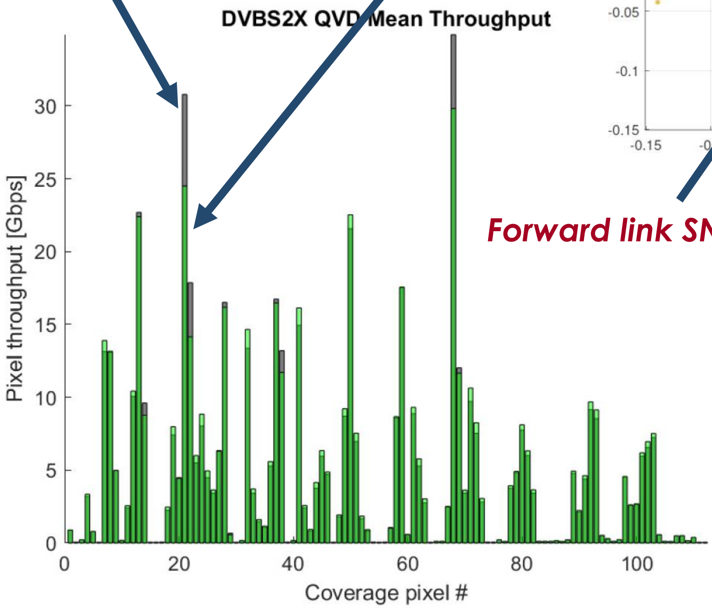
- **Key challenges:**
  - Larger number of beams means more and more non uniform traffic and payload complexity plus larger antenna aperture calling for deployable reflectors with associated risks
  - Large (semi)-active antennas to allow coverage and traffic request flexibility
  - Radio resource management challenging considering the uneven traffic
  - Interconnected gateways number cost is high – shift towards higher feeder link RF frequencies or optical space-to-ground links
  - User segment equipment and service cost is still an issue
  - GSO latency it is still representing an issue for certain applications requiring low-latency
  - Traffic distribution is very uneven -> requires high antenna spatial discrimination and smart radio resource management

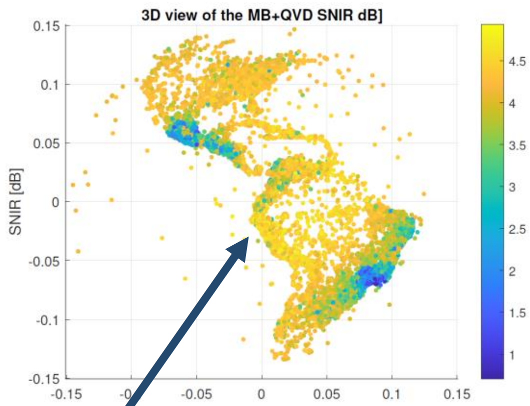
HTS GSO Systems Takeaway

- **The uneven traffic challenge for the system design**
  - The traffic distribution is very uneven -> requires high antenna spatial discrimination
  - Smart radio resource management solution is key

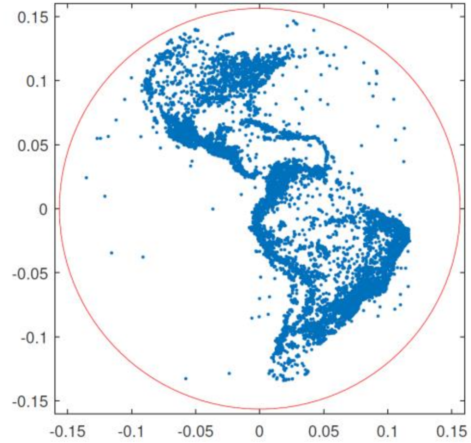
Gray bar=requested throughput

Green bar=offered throughput

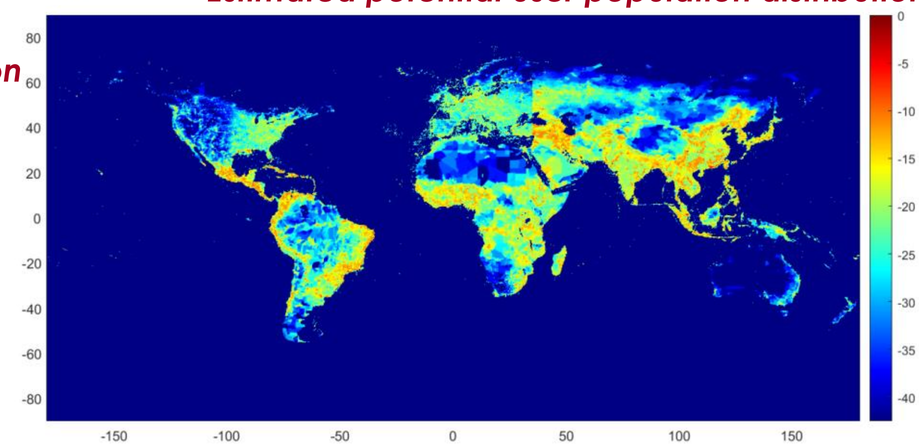




Forward link SNIR distribution

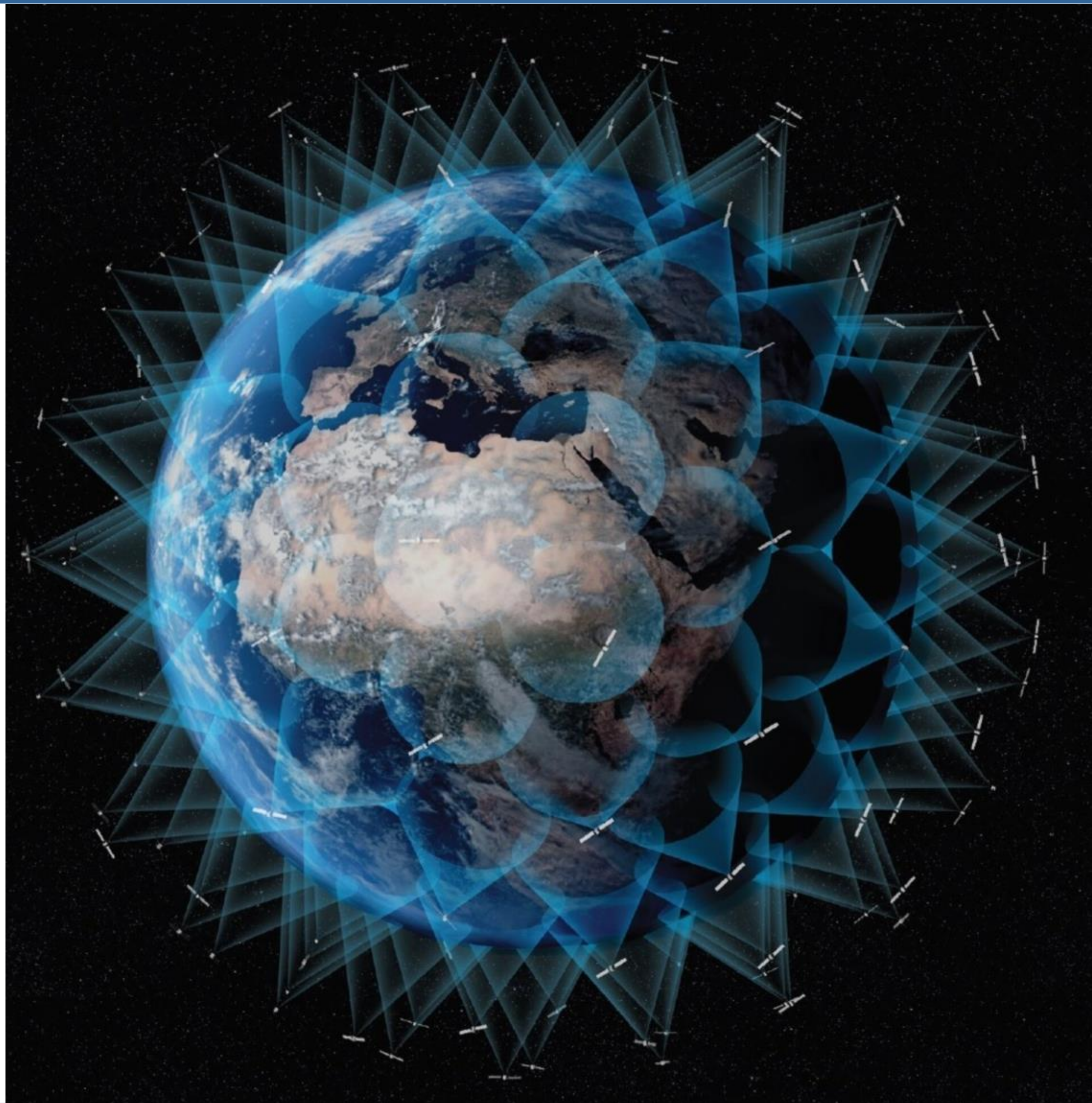


Estimated potential user population distribution



PART 2 - HIGH THROUGHPUT NGSO NETWORKS

A new area of concern – RF spectrum pollution



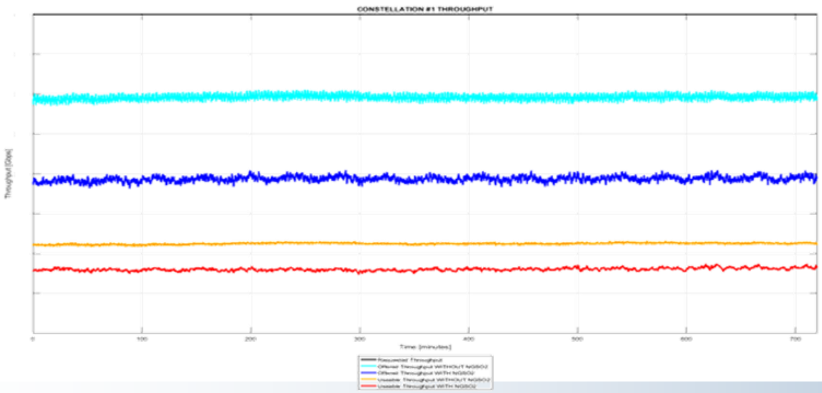
A new area of concern – RF spectrum pollution 1/2

NGSO (LEO/MEO) Megaconstellations of hundreds/thousands of satellite are rapidly building up - Radio Frequency spectrum cleanliness is endangered

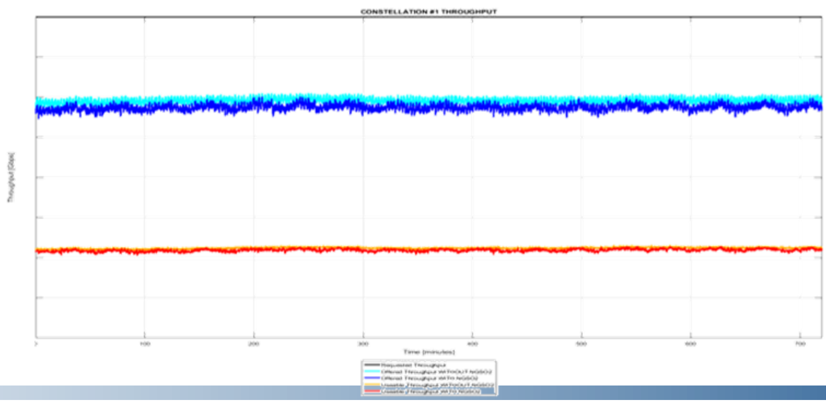
For mm-wave bands the main interference issues are related to:

- GSO to NGSO – countermeasures are in place and enforced by ITU
- NGSO to NGSO – FCC calls to avoid in-line interference (10 deg min sat angle separation)
    - Without operators' coordination there will be a large waste of spectrum resources in mm-wave bands
    - For mobile direct access a single global constellation will block the worldwide usage of the selected band – divide et impera approach?

UNCOORDINATED

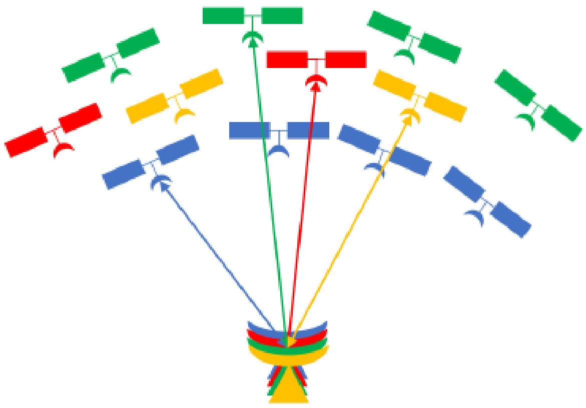


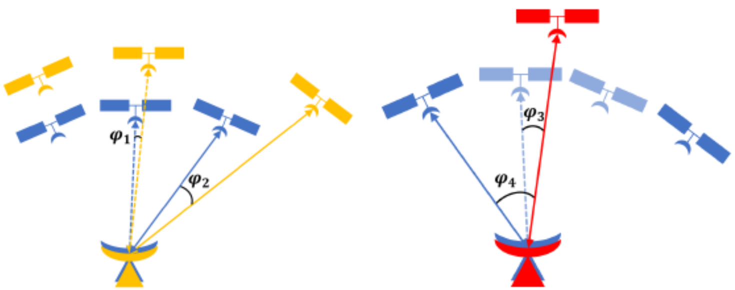
COORDINATED



A new area of concern – RF spectrum pollution 2/2

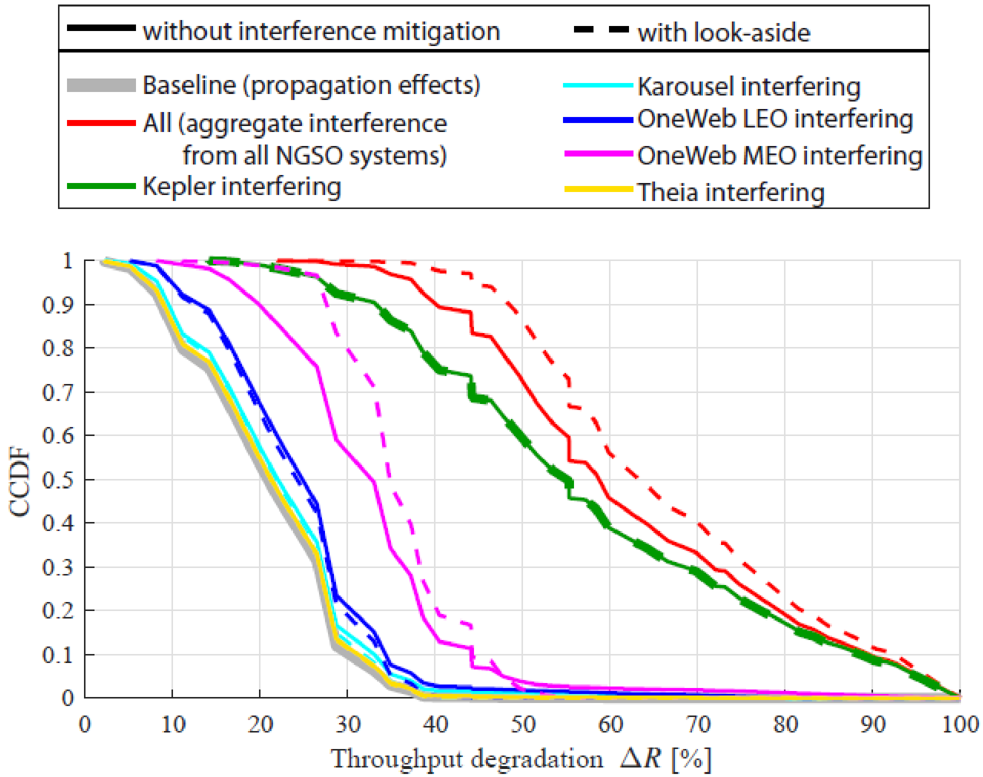
NGSO (LEO/MEO) Megaconstellations





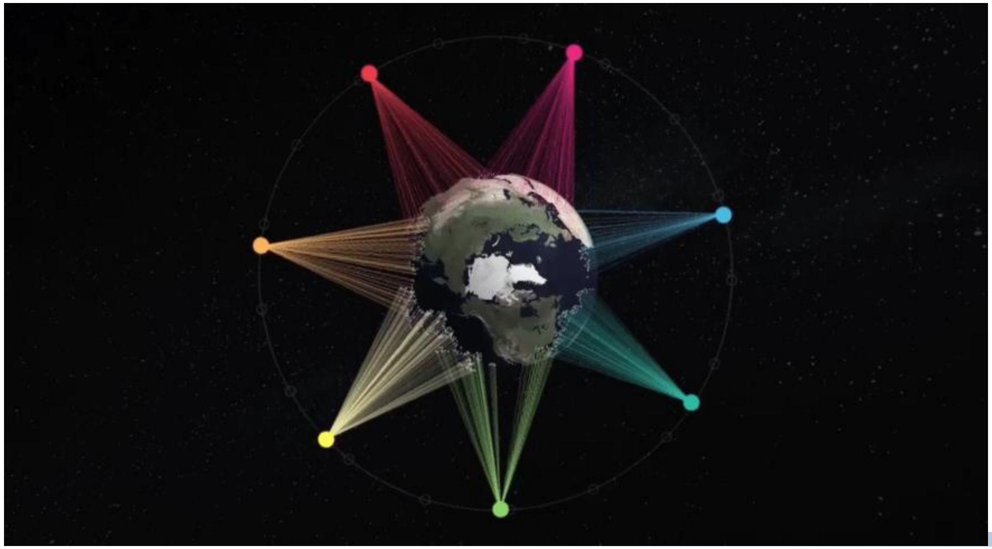
(a) Look-aside (b) GSO protection

Should We Worry About Interference in
Emerging Dense NGSO Satellite Constellations?



MEO O3B Broadband Constellation

- MEO constellation at an altitude of 8062 km for broadband access to unserved equatorial regions started by SES
- 20 satellites in equatorial orbit, 6 hours orbital period, operating at Ka-band
- Services:
  - Tier 1: national telecom operators and Internet providers, 3.5 m dish, 600 Mbps
  - Tier 2: cellular operators linking base stations, ships, 1-2 m dish, up to 155 Mbps
  - Tier 3: consumers and small business, 0.5-1 m dish and up to 155 Mbps
- 1st generation operational in 2002, 2nd generation expected in operation for 2024



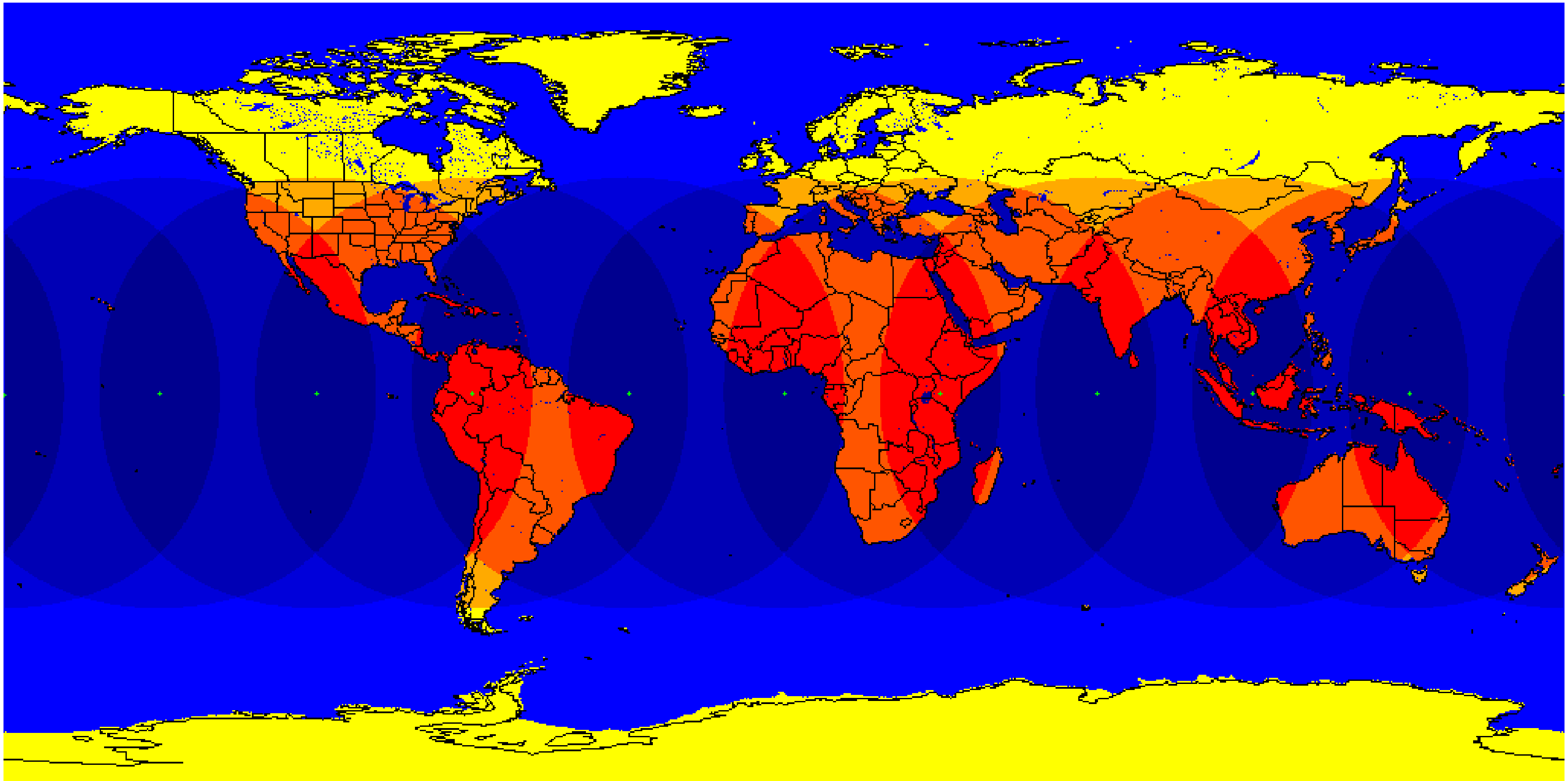
MEO O3B Broadband Constellation

O3B system architecture:

- 9 gateways serving 20 satellites, DVB-S2 air interface with ACM
- Make-before-break handover with two satellites active during handover phase

MEO O3B Broadband Constellation

O3B coverage



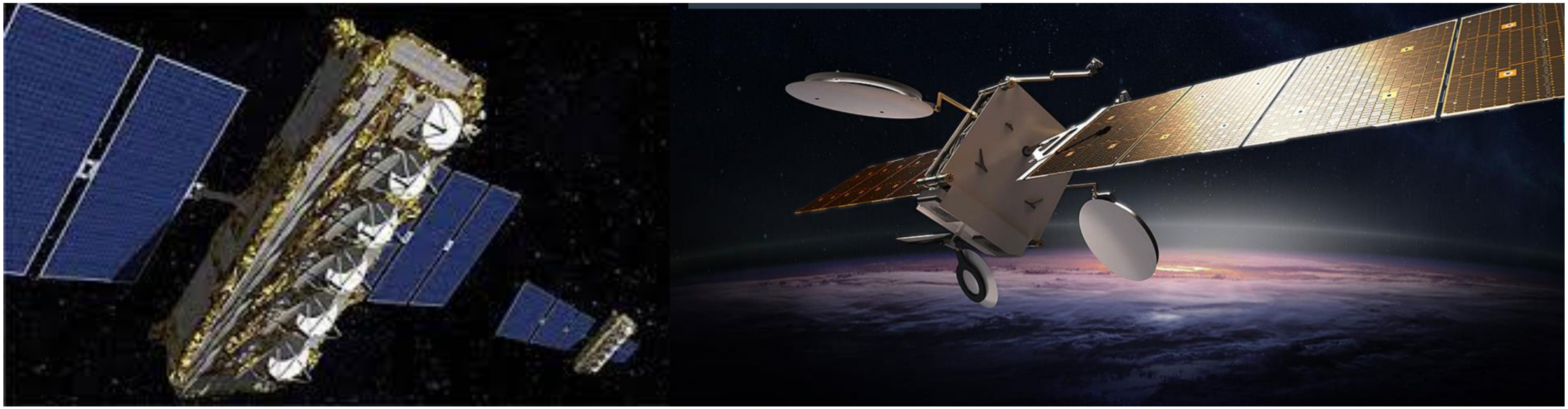
MEO O3B Broadband Constellation

The O3B 1G spacecraft payload (20 launched):

- Simple bent-pipe architecture connecting the 2 gateway(s) beams to the 10 user beams through mechanically steerable 27 cm antennas; TAS-F made

The O3B 2G spacecraft (4 launched, 11 planned in total):

- Designed with Boeing, software-defined satellites respond dynamically to user demand
- Electronically steered phased-array antennas support thousands of beams per satellite, each scaling from 50 Mbps to 10 Gbps



MEO O3B Broadband Constellation

- 2^{nd} generation (mPower) satellites being produced by Boeing in USA
- 11 satellites in MEO orbit planned
- Deployment initiated in December 2022 (2) with 2 more in Q2 2023, third launch being delayed due to some issue identified on the first fours satellites power modules
- Boeing's multi-orbit BSS-702X satellite bus with an all-electric propulsion system and a payload that can be reprogrammed from the ground to reallocate resources "on the fly"
- Electronically steered phased array antennas can provide up to 5000 spot beams per satellite each shaped and pointed as required to specifically distribute power and bandwidth to individual user's and, using the full Ka-band spectrum, enable uncontended speeds from 50 Mbit/s up to 10 Gbit/s

MEO O3B Broadband Constellation

The O3B ground segment (user terminal and gateways)

User Equipment

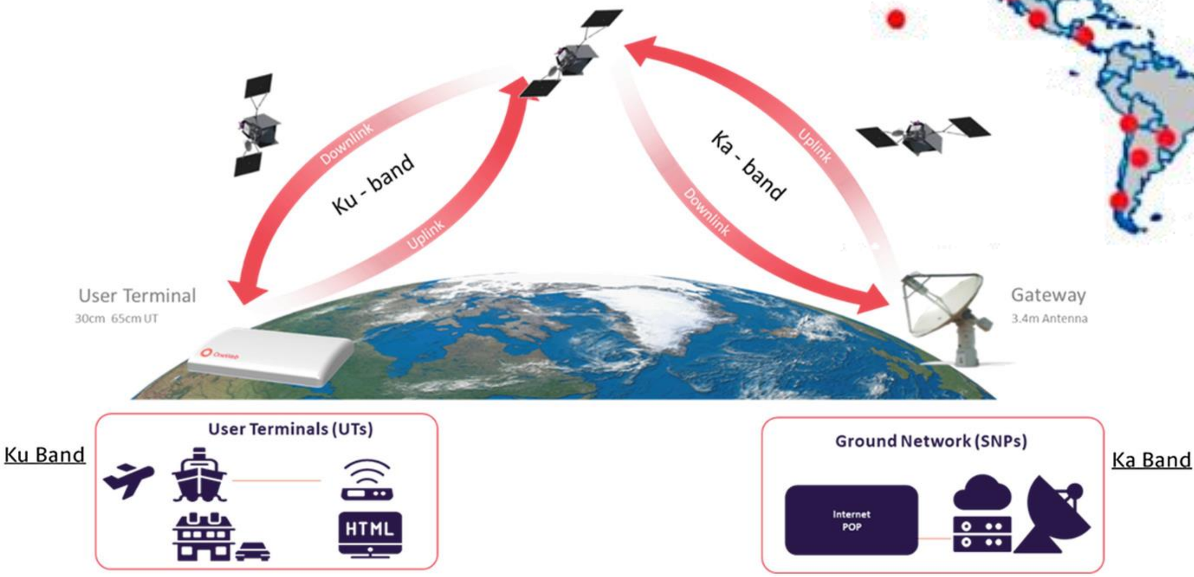
LEO OneWeb Broadband Constellation

- First LEO megaconstellation at an altitude of 1200 km for global broadband access
- 648 (588+spares) satellites in 12 orbital planes with 49 satellites each, 109 minutes orbital period, operating at Ku-band for the user link, Ka-band for the feeder link, no ISL
- Small satellites 150 kg, 50 W DC power each
- Constellation deployment started on February 2019, 634 satellites launched at May 23
- Services:
  - Mobility (maritime, aviation, land mobility, IoT)
  - Satellite broadband (corporate enterprise, small and medium business, consumer residential)

LEO OneWeb Broadband Constellation

OneWeb system architecture:

- 55-75 gateways serving the satellites with large number of antennas/gateway
- Make-before-break handover with two satellites active during handover phase

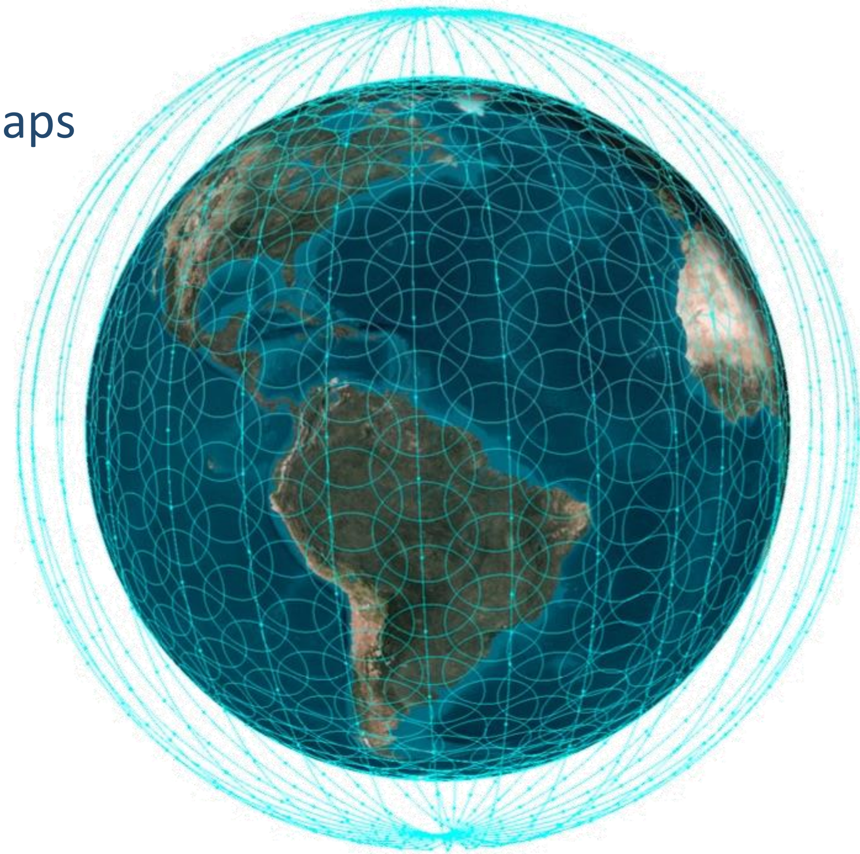


LEO OneWeb Broadband Constellation

OneWeb constellation

- 12 near polar orbit planes at 1,200 km (750 mi) altitude, at 86.4° orbital inclination
- Approaching the poles, beams are progressively switched off to avoid overlaps

Multi-satellite launch: spacecrafts stoved in fairing



LEO OneWeb Broadband Constellation

OneWeb payload

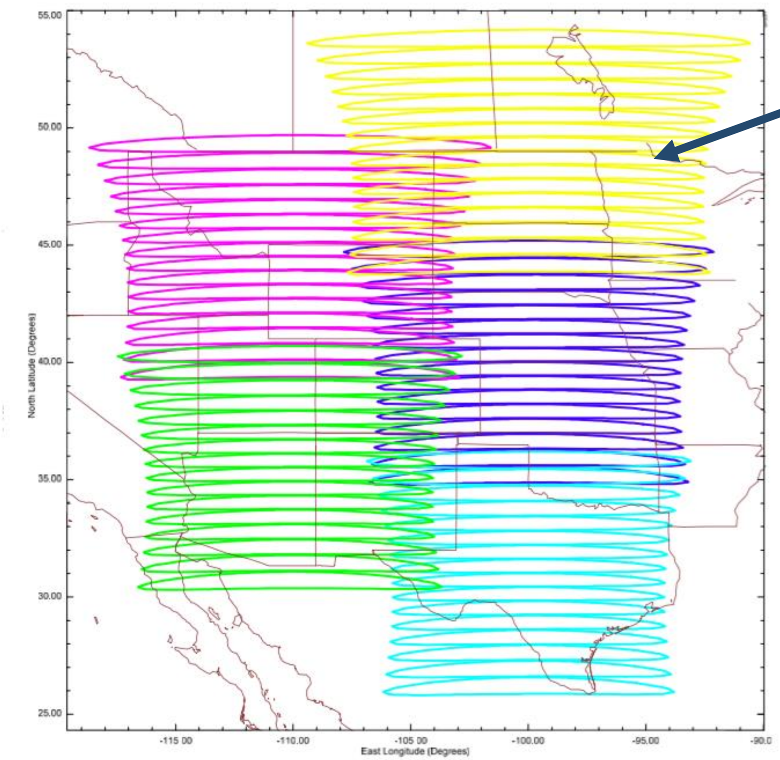
- Bent-pipe transponder single polar user link and dual polar feeder link (no ISL)
- Two Ka-band gateway feeder link steerable antennas with downlink power control
- 16 Ku-band venetian-blind fixed antenna for the user links with elliptical shape
- Attitude control allows adjusting the satellite pointing to avoid GEO interference
- Second generation satellite bids expected in 2023

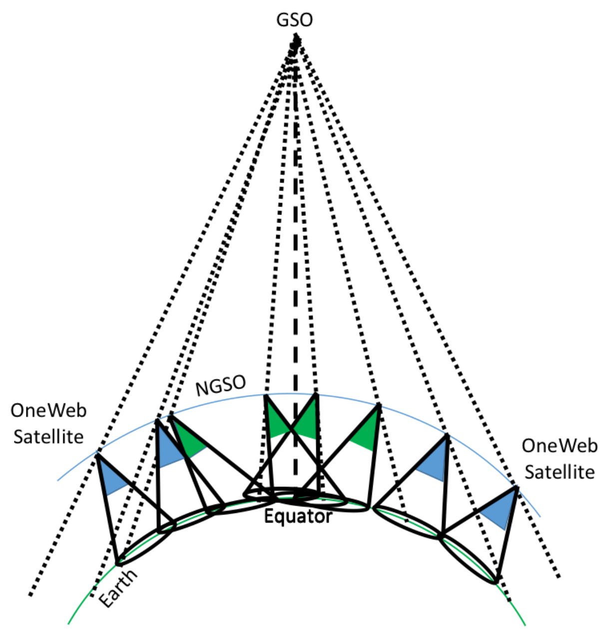
LEO OneWeb Broadband Constellation

OneWeb GEO interference avoidance approach:

- Progressive pitching of the satellite to avoid GEO arc interference
- Banana-shaped beams to better cope with the beam squinting operation at the equator

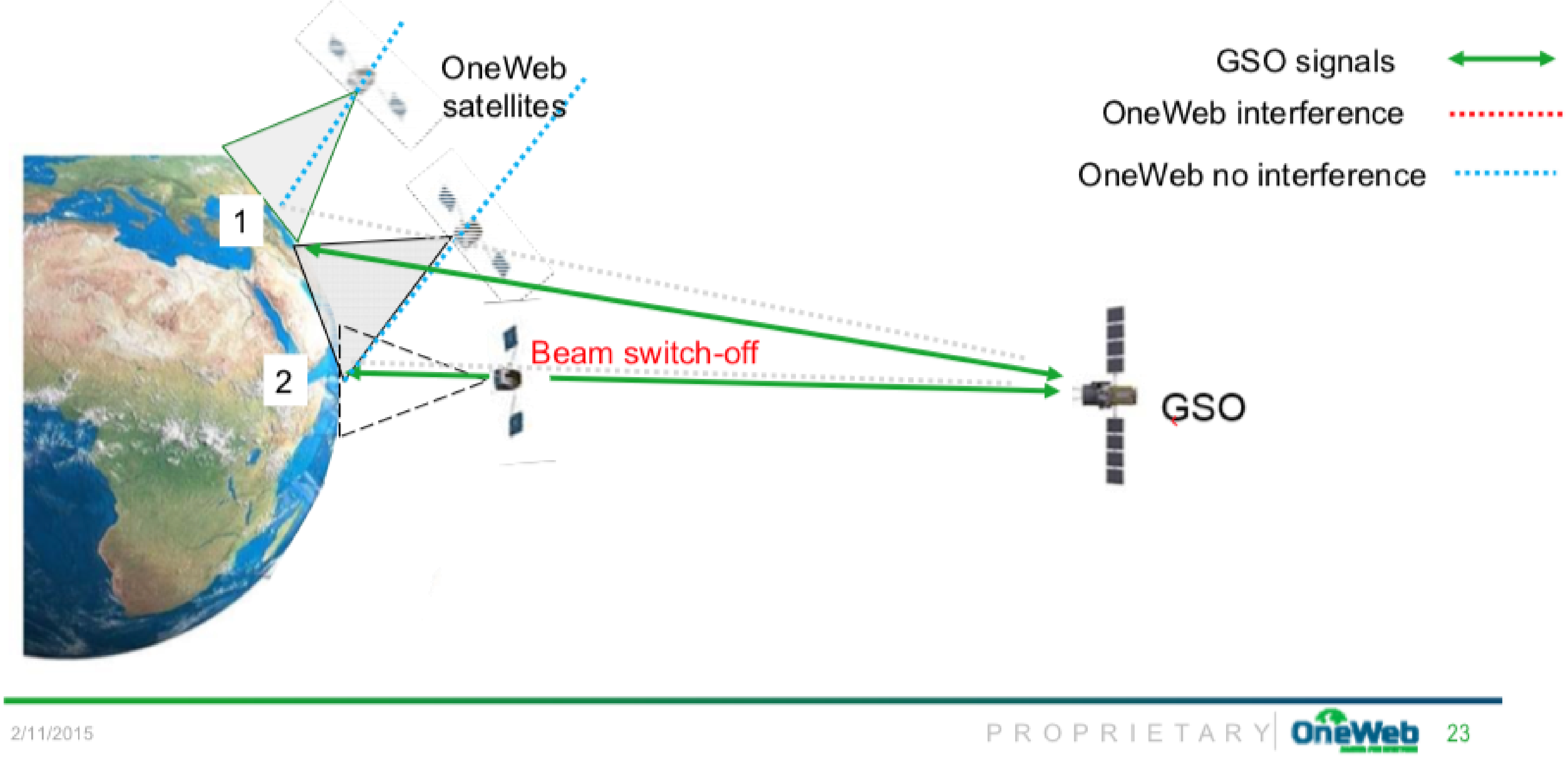
Venetian blind beam shape to ease the progressive pitching process





LEO OneWeb Broadband Constellation

- **With "progressive pitching" the satellite (patent pending)**



LEO OneWeb Broadband Constellation

OneWeb production facility in Florida – 2 satellites/day

See video:

https://vimeo.com/529924820

LEO OneWeb Broadband Constellation

OneWeb ground segment (user terminal and gateways)

User Equipment

Starlink LEO Broadband Constellation

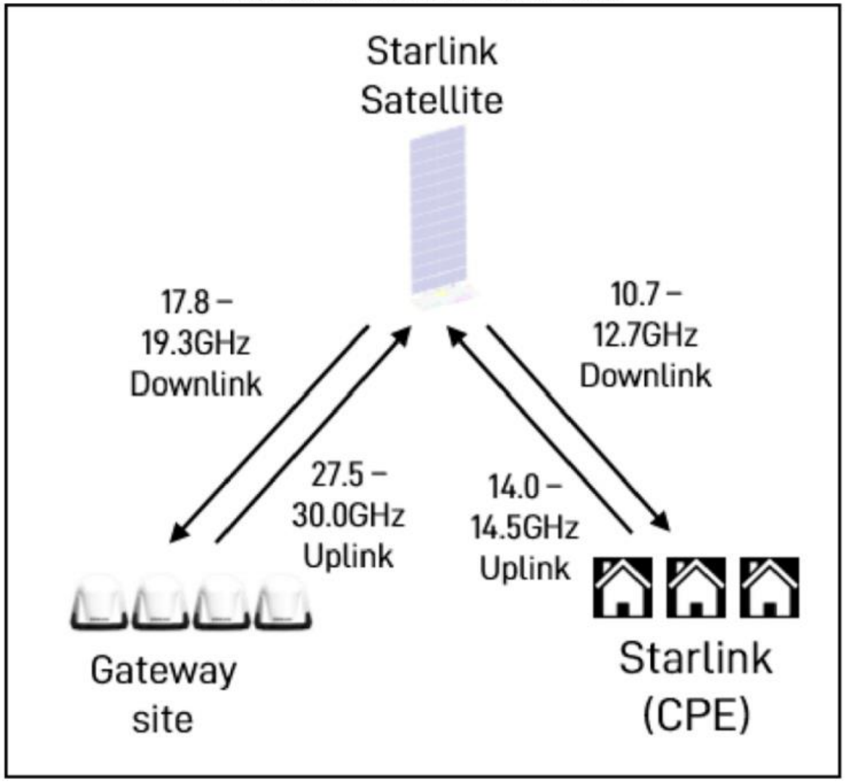
- LEO megaconstellation at an altitude of 335-550 km for global broadband access
- Steps 1-5: 4108 satellites @ 550 km in 72 orbital planes with 54, 70, 74, 81 degrees inclination operating at Ku-band for the user link, Ku/Ka-band for the feeder link (4519 already in orbit of which 4487 operational @ July 23)
- Step 6: 7518 satellites at 340 km with V-band addition for user/gateways
- Small satellites 260-290 kg, optical ISLs (4) being deployed in most recent satellites
- Services:
  - Satellite broadband (corporate enterprise, small and medium business, consumer residential)
  - Military and mobility support?

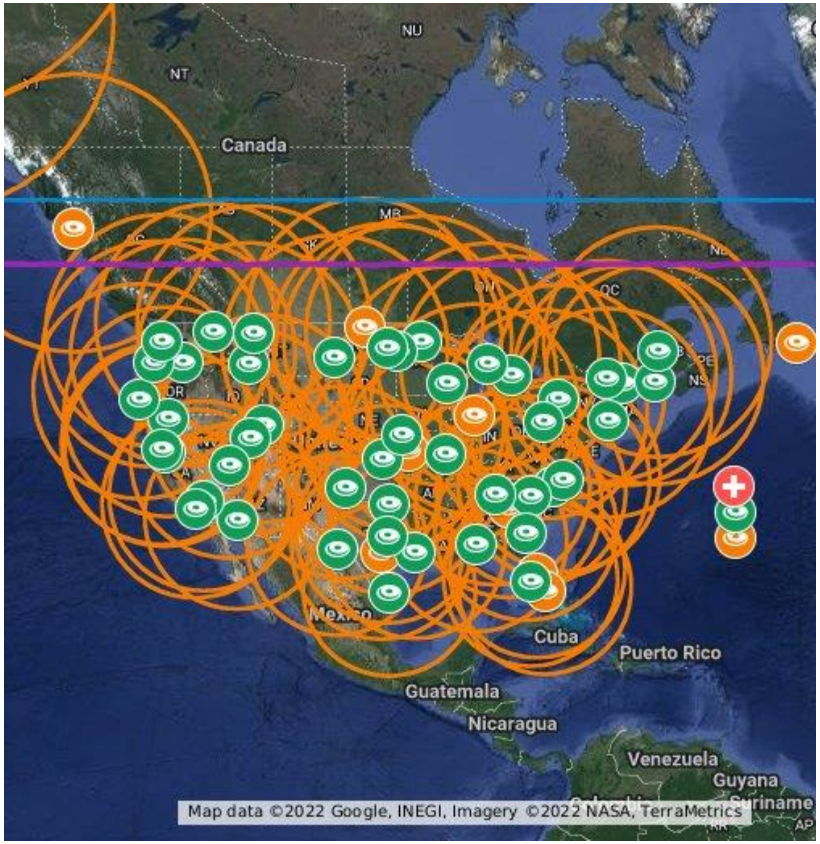
Starlink LEO Broadband Constellation

Starlink system architecture:

- 32 gateways filed in USA, unclear number worldwide
- Make-before-break handover with two satellites active during handover phase

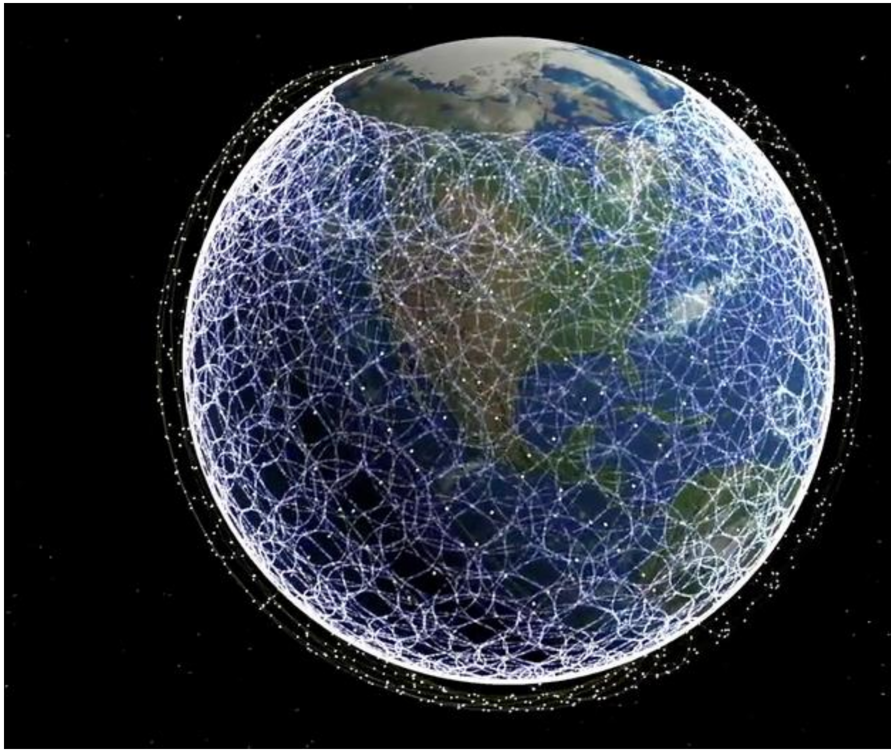
Starlink Network Architecture



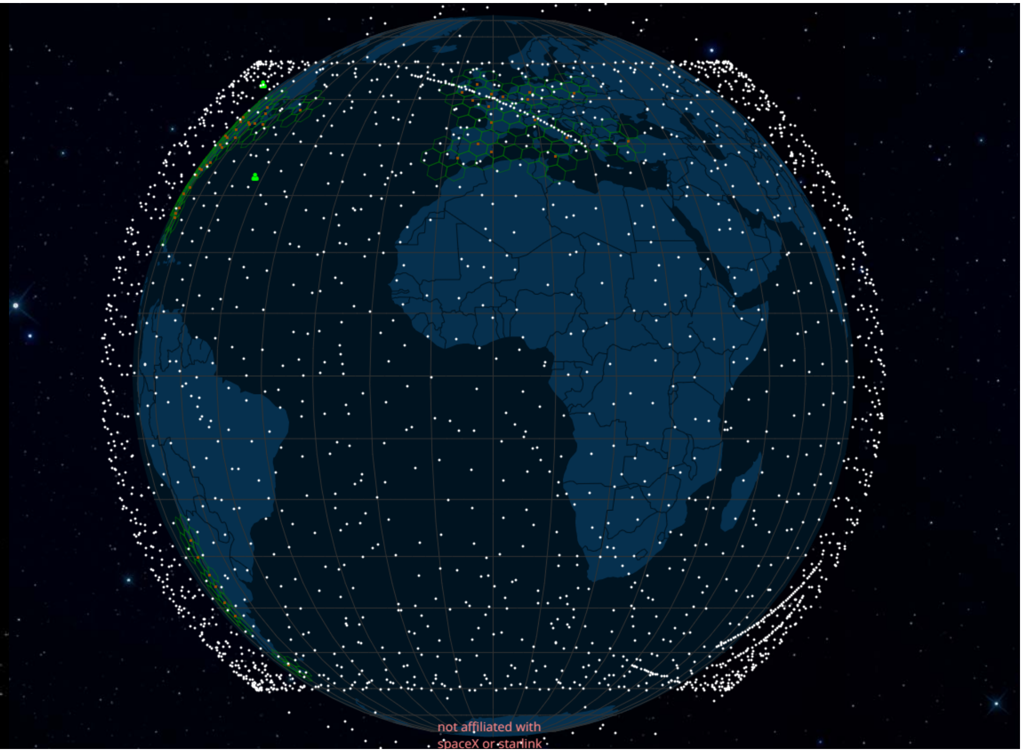


Starlink LEO Broadband Constellation

Starlink coverage: https://www.youtube.com/watch?v=bKj4GDNhH0Q



Planned

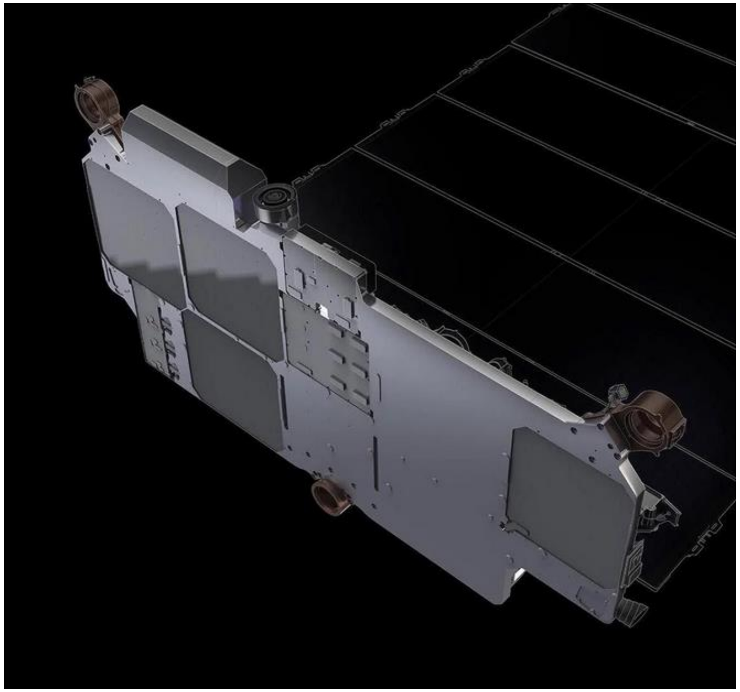


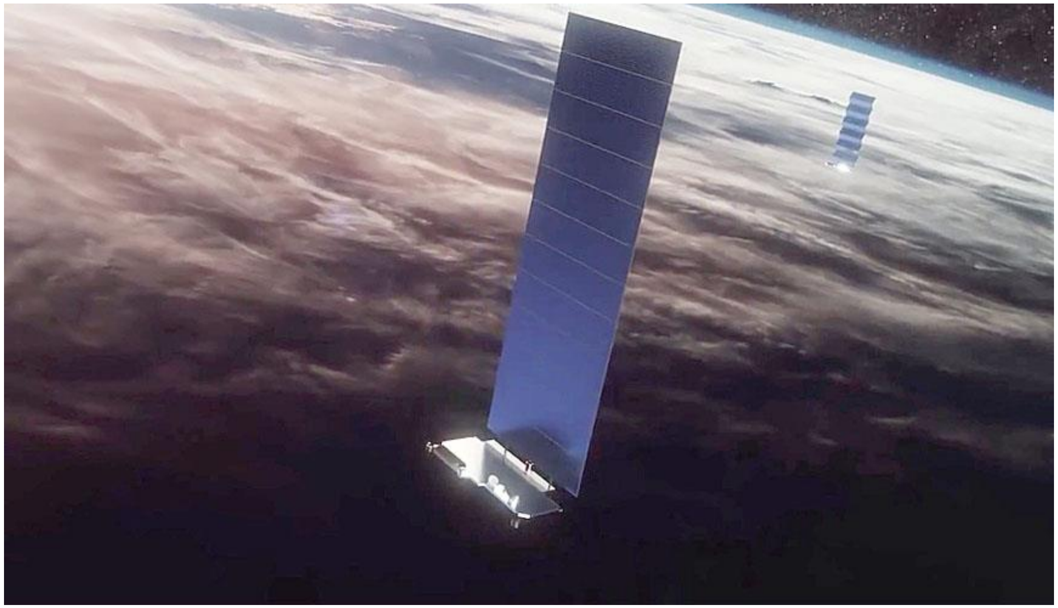
Current 30-10-22

Starlink LEO Broadband Constellation

Starlink satellite/payload

- Phased-array Ku-band antenna, on-board processing, ISL
- Two Ka-band gateway feeder link steerable antennas
- Likely use of beam hopping with 4 simultaneously active beams/satellite





Starlink LEO Broadband Constellation

Starlink Launch

- Stacked satellites allowing 60 satellites/launch on Falcon 9
- 400/launch planned with Starship
- 45 satellites/week produced

Starlink LEO Broadband Constellation

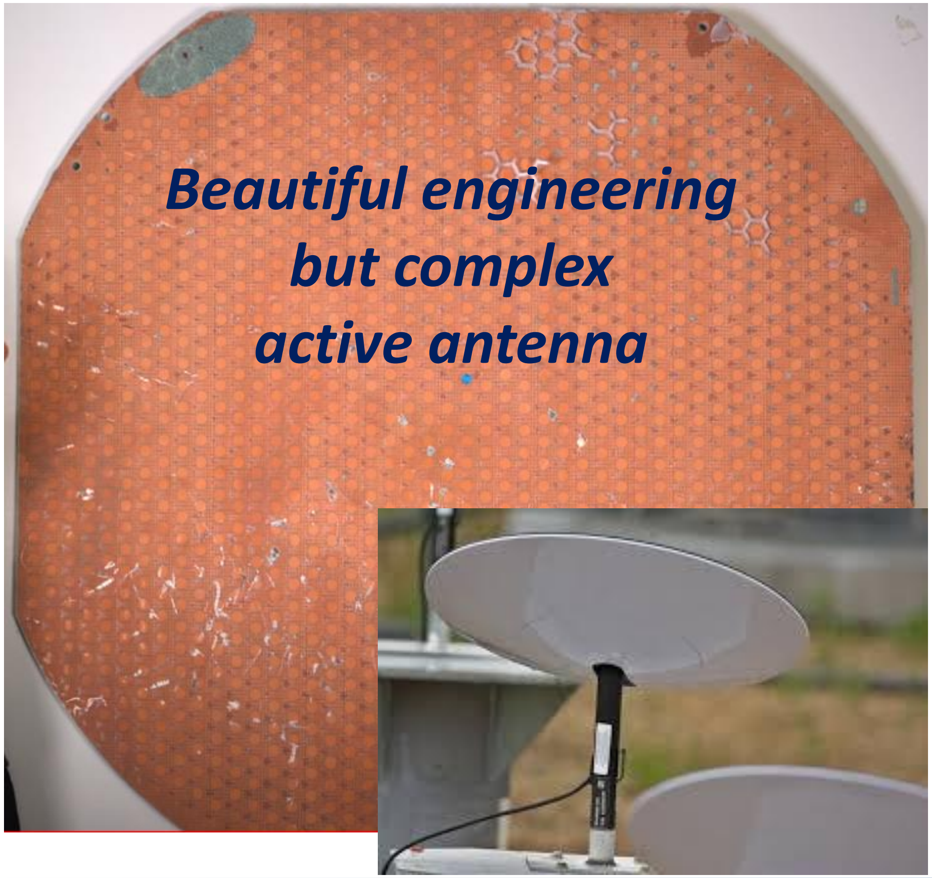
Starlink V2 mini satellites

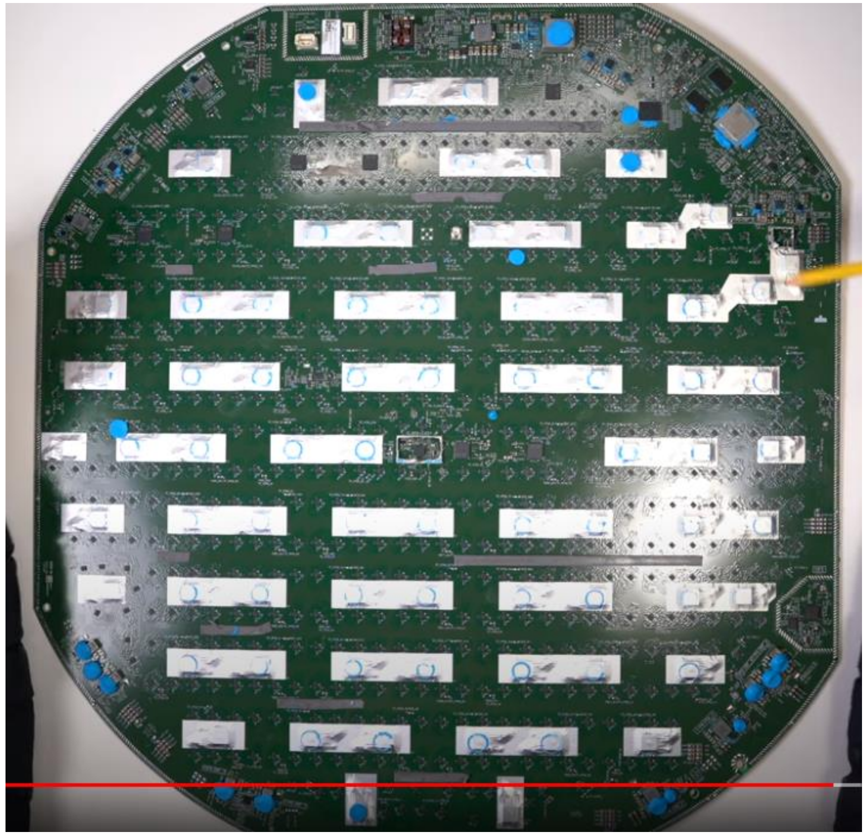
- Intermediate version of V2 satellites requiring Starship launcher
- 4 times the throughput of V1 satellites, bigger and heavier (800 kg vs GEN 1 295 kg)
- Stacked satellites allowing 22 satellites/launch on Falcon 9, 4.1 m wide satellite
- 99% reliability, lower brightness, operations below 600 km, advanced collision avoidance, 100% dismissible
- V2 will also include a mobile payload for direct to hand-held communications

Starlink ground segment

Starlink LEO Broadband Constellation

UE v1 mechanical/electronic steering antenna: sold at 499$, production cost 5 times as high – v2 has reduced the production cost, million samples produced





Starlink LEO Broadband Constellation

- Big effort in reducing cost and size of the user terminal:
  - Reduction in the number of beamformer ICs power consumption and cost!
  - Very large number of IPs protecting the technology

16 TR beamformers
-> 512 TR frontends (16x16x2)
-> 512 TRs, and ~1026 patches

20 TR beamformers
-> 640 TR frontends (20x16x2)
-> 640 TRs, and ~1280 patches

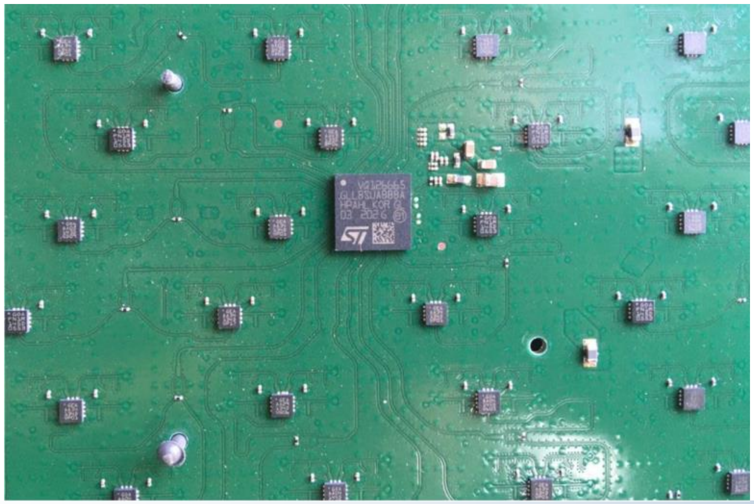
79 TR beamformers
-> 79x16 digital BFN paths
-> ~632 TR frontends
-> DBFN path per patch
-> ~1280 patches

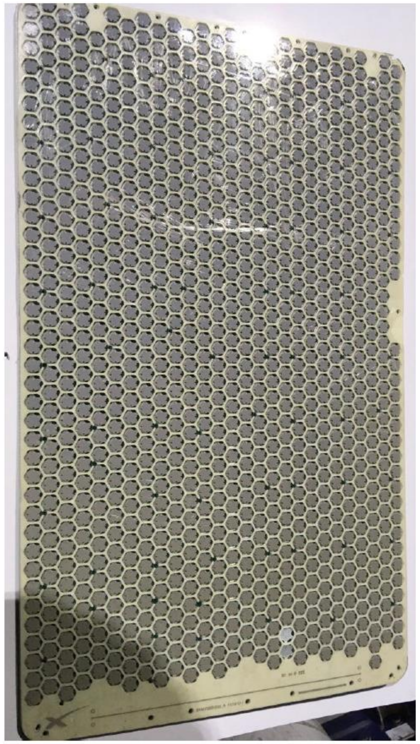
Dip. Ingegneria dell'Informazione
University of Pisa, Italy
Riccardo De Gaudenzi

Starlink LEO Broadband Constellation

The use of FDD/TDD allows to greatly simplify the user terminal:

- The terminal is not receiving and transmitting at the same time
- When not transmitting/receiving the beam hopped satellite can serve other beams
- No duplexer filters required
- Hybrid analogue/digital BFN with ST designed/produced chips

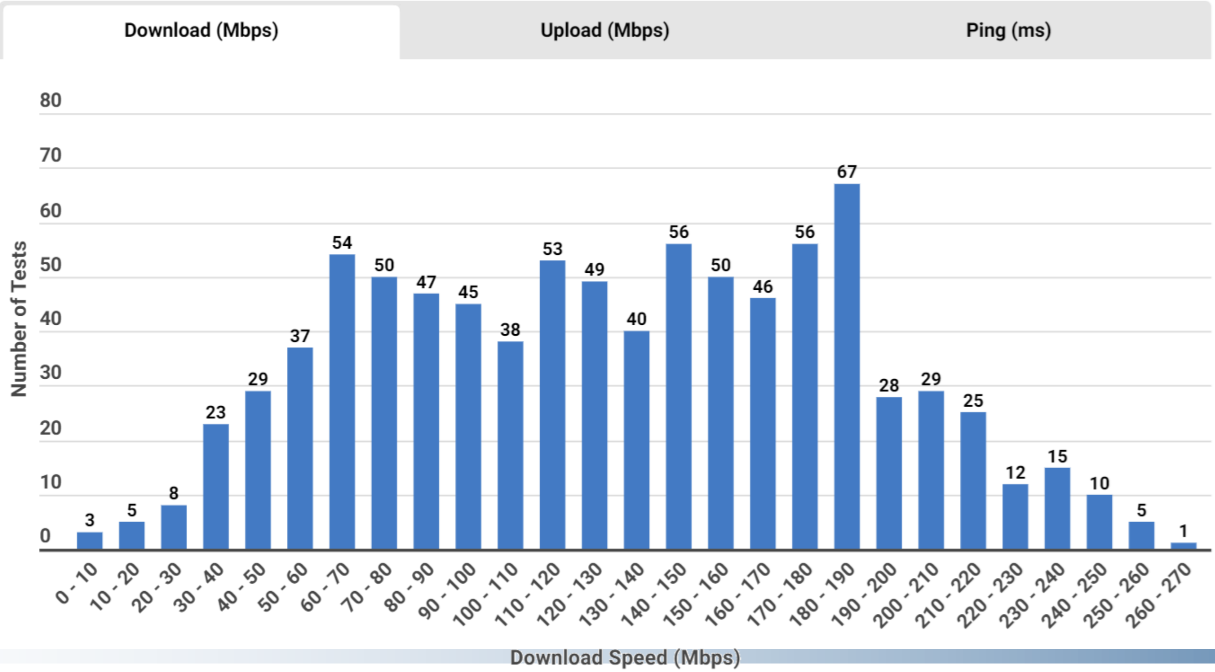




Starlink LEO Broadband Constellation

Starlink service cost/performance (2022):

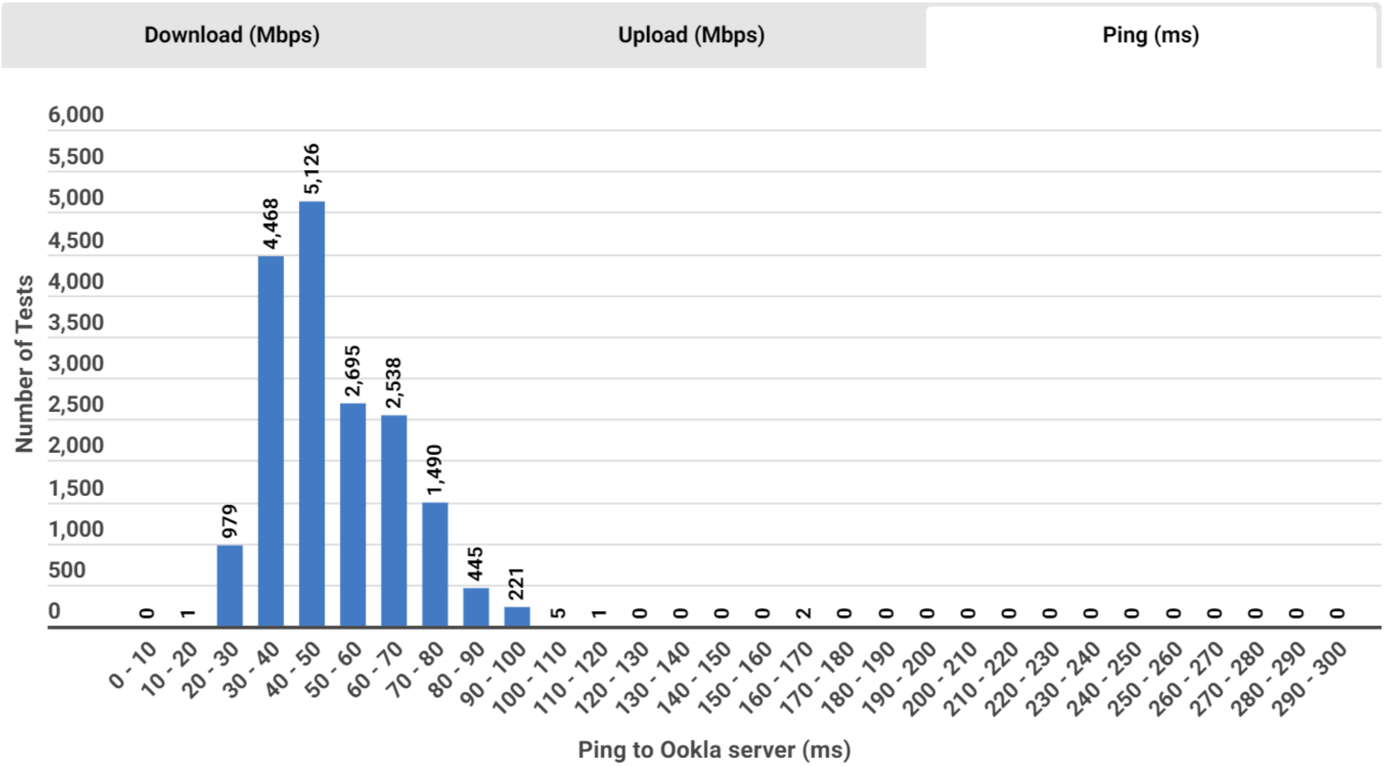
- Monthly fee private user: $ 135/month plus $599 for the UE with 1 TB data cap during peak hours
- Monthly fee business user: $ 2500/month
- The data rate effectively provided is highly variable lower than what advertised (300 Mbps)



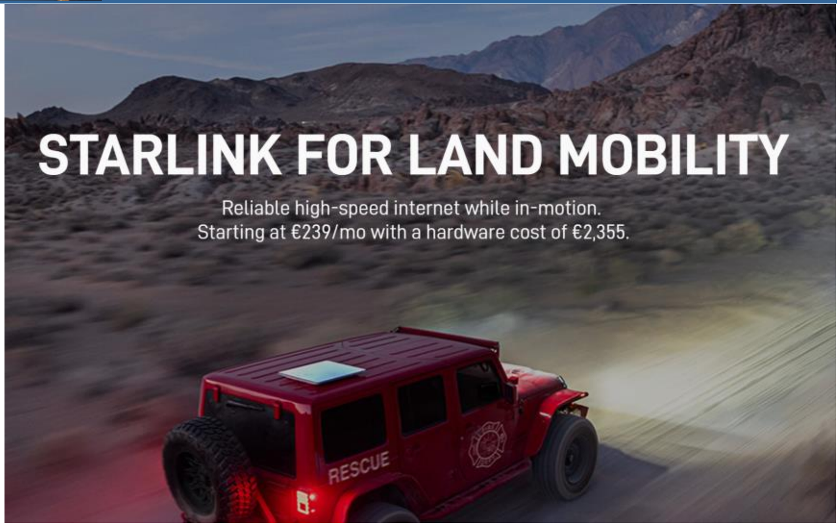
Starlink LEO Broadband Constellation

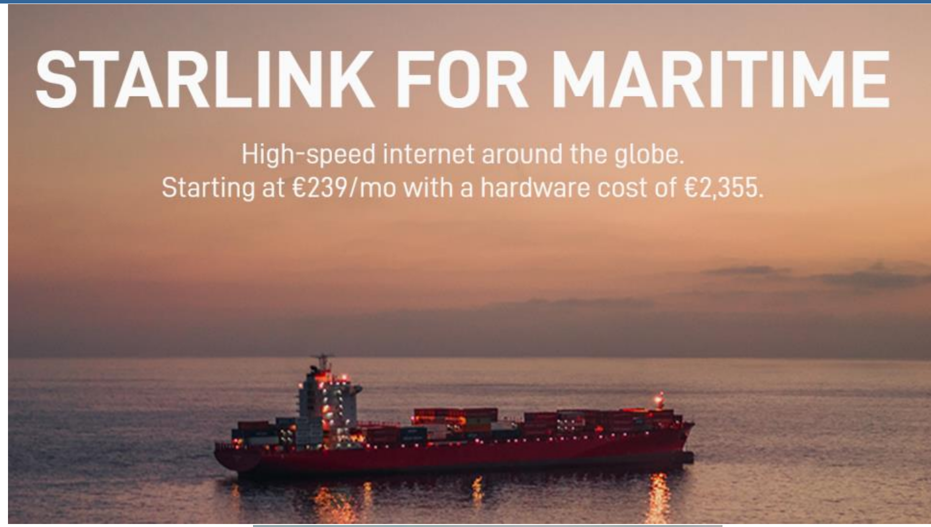
Starlink service cost/performance (2022):

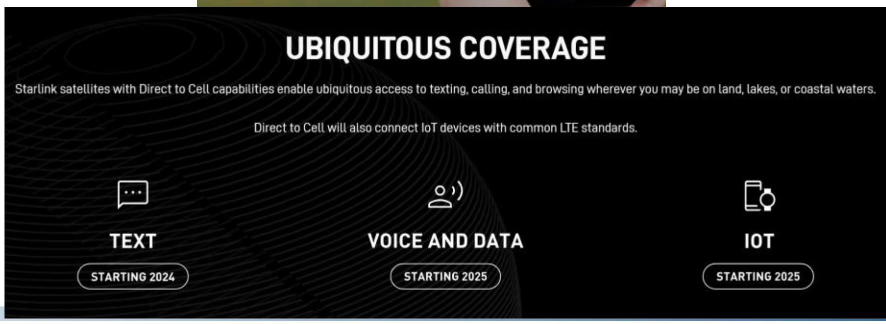
- Latency is also time dependent
- Dropouts in video applications observed



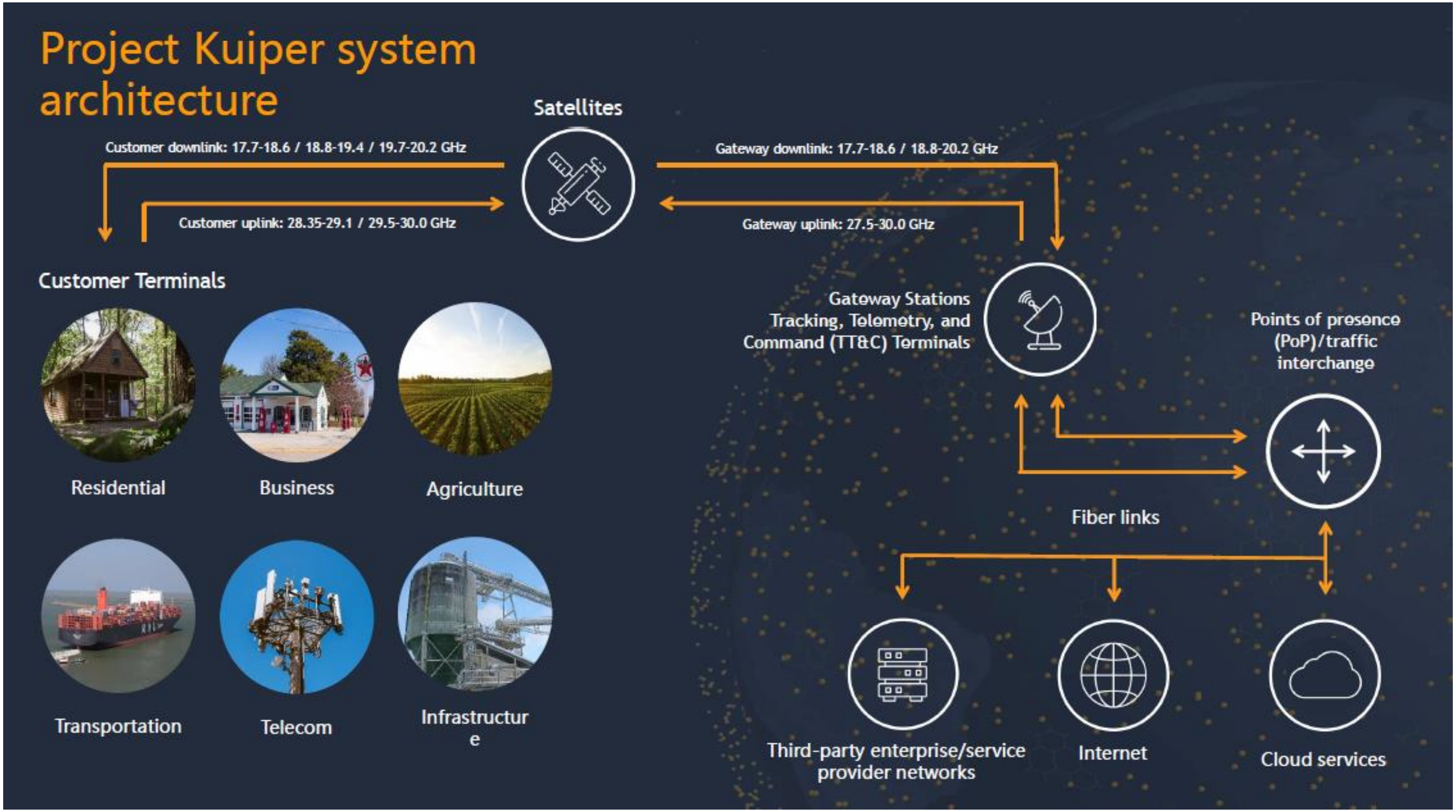
Starlink Mobile Service Offer







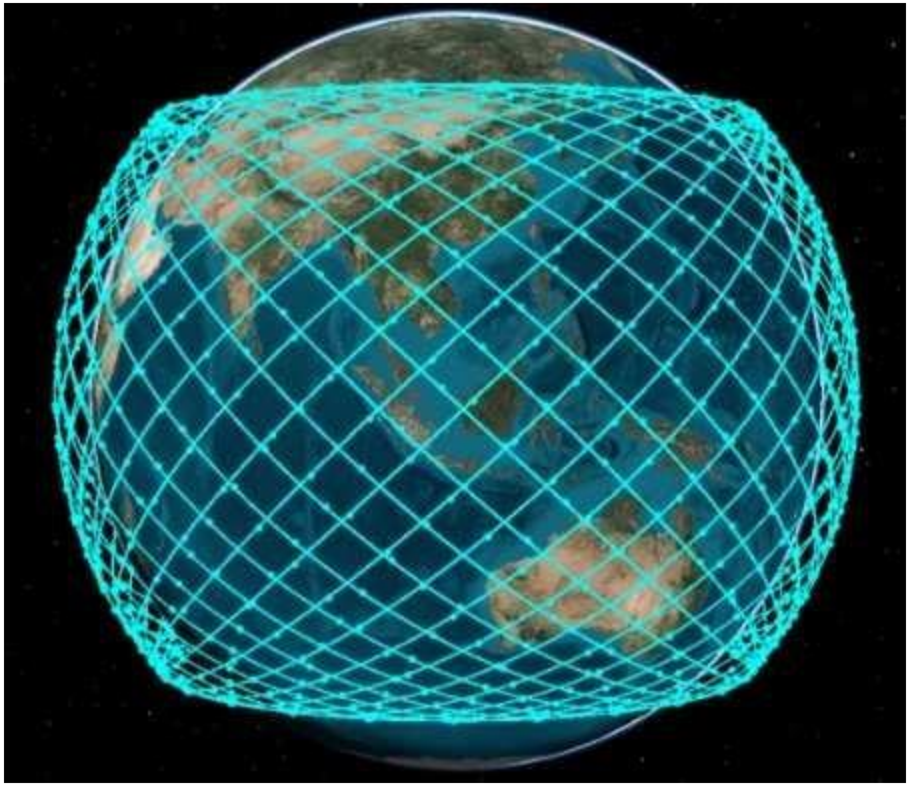
Amazon Kuiper Broadband Constellation



Amazon Kuiper Broadband Constellation

Project Kuiper

is a constellation of 3,236 low earth orbit (LEO) satellites delivering high-speed, low-latency broadband services on a global scale – planned system availability end of 2024 (TBC)



Orbital altitudes and service coverage

- Deployed in 98 orbital planes shells 590 km/610 km/630 km & 3 inclinations (33.0°/42.0°/51.9°, figure refers to shell 2, 42.0°)
- Service coverage reaches 56 degrees North and South Latitudes

Amazon Kuiper Broadband Constellation

Satellite System

- Ka-band customer links offering better performance than C and Ku-bands
- Phased array antennas communicate with customer terminals on the ground

Customer Terminals

- Single aperture, 12 in. diameter, Ka-band phased array
- Maximum throughput 400-1000 Mbps

Networking and Infrastructure

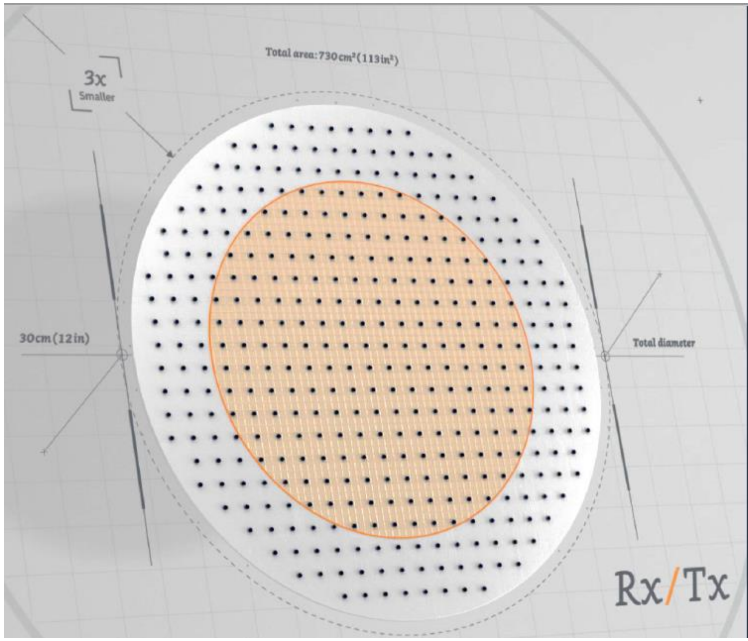
- Hundreds of gateway Earth stations around the world
- Software-defined networking to coordinate beams and allocate bandwidth
- End-to-end encryption between customer and administrative endpoints

Amazon Kuiper Broadband Constellation

First two Kuiper experimental satellites launched in October 2023 with ULA

- The series of tests will add real-world data from space to years of data collected from lab and field testing, providing additional insight into how the end-to-end Project Kuiper network performs across ground and space
- Learnings from the mission to help refine hardware, software, and infrastructure.
- First production satellites are on track for launch in the first half of 2024, expected to be in beta testing with early commercial customers by the end of 2024.

Amazon Kuiper Broadband Constellation

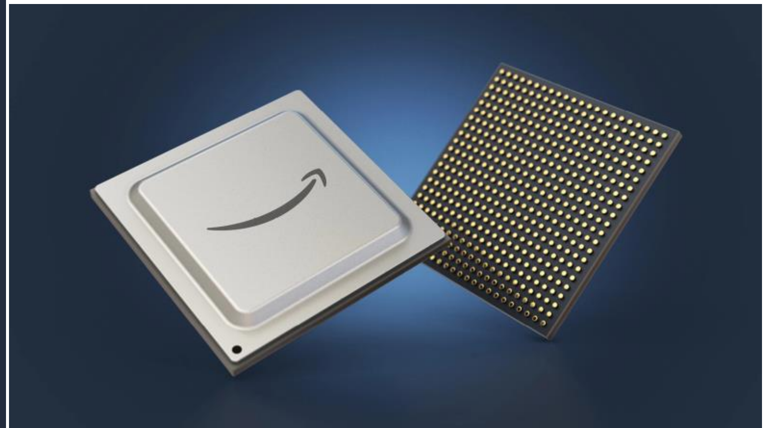


Project Kuiper Customer terminal antenna

Small, compact terminals allow customers to connect to the network and enjoy fast, reliable service at an affordable price.

Technical specs

Type:	Single Aperture Phased Array Antenna
Frequency:	Ka-band
Diameter:	12 in. (30 cm)
Max. Throughput:	400 Mbps
Downlink:	17.7-18.6 GHz 18.8-19.4 GHz 19.7-20.2 GHz
Uplink:	28.35-29.1 GHz 29.5-30.0 GHz



- Ultra compact 18x18 cm, 100 Mbps,
- High performance antenna 28x28 cm, 400 Mbps, 400$
- High bandwidth antenna 48x48 cm, 1000 Mbps
- Custom made chips for UE and GWs

Amazon Kuiper Broadband Constellation

HTS NGSO Systems Takeaways 1/2

- **New space approach is revolutionizing the HTS satellite ecosystem**
  - New big players (SpaceX, Amazon…) on top of more conventional operators (SES, Eutelsat, Intelsat…)
  - Constellations of thousand of satellites with optimized geometry
  - Very Low-Earth Orbiting Satellites, low latency, global coverage
  - Active antennas on-board with regeneration and ISL becoming a must
  - Satellites are produced in series at a pace and cost unthinkable few years ago
  - Tenths to hundreds of satellites / launch – many launches
  - First mass market production of electronically steerable active antennas for the user terminal
  - Starlink web-based marketing approach with DIY installation appears a promising approach

HTS NGSO Systems Takeaway 2/2

- **Key challenges:**
  - The spectrum is a scarce resource, very difficult to share the spectrum among different LEO constellations -> risk of "dividi et impera" approach reducing the performance of the single system
  - Regulatory and licensing aspects at national level may hamper the system penetration
  - Radio resource management challenging considering the uneven traffic
  - Potential issue with space debris management
  - User segment equipment cost is still an issue