NSR White Paper

Capabilities and Limitations of Non-GEO Constellations

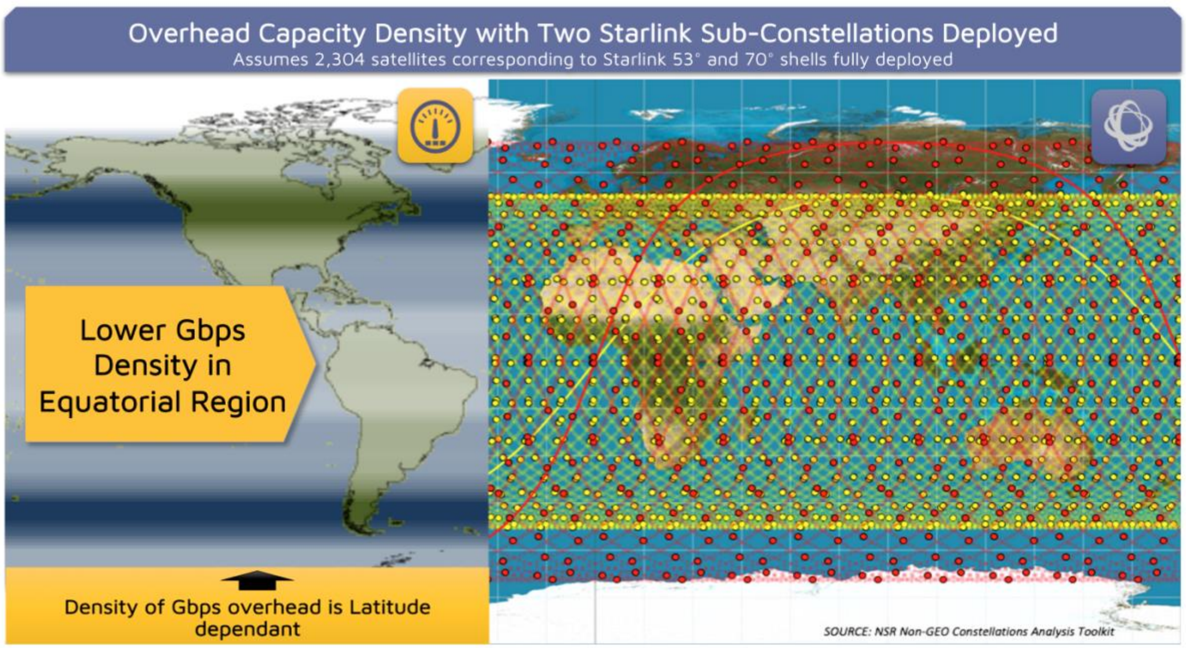
January 2022

NORTHERN SKY RESEARCH

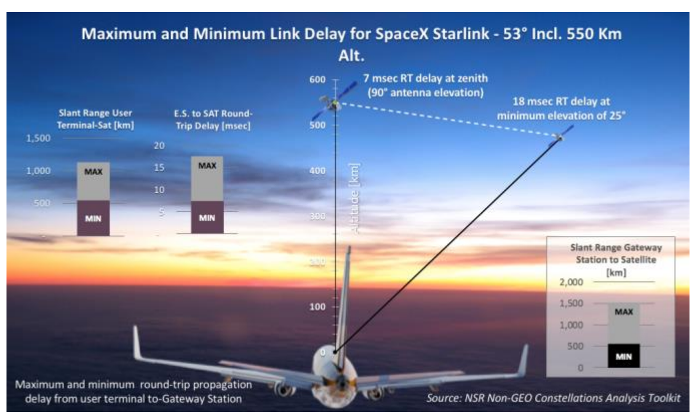
ABSTRACT

High-Throughput LEO[1] and MEO[2] satellite constellations[3] are taking center stage during a pivotal time for high-speed satcom, but intrinsic business-case and architectural facets will mold the multi-orbit, multi-band satellite paradigm. This white paper leverages NSR's Non-GEO Constellations Analysis Toolkit 2.0 (NCAT2) to factually dive into the capabilities and limitations of LEO constellations, and the LEO-GEO[4] complementation potential.

Using SpaceX as example, and assuming two Starlink[5] sub-constellations fully deployed, the paper follows a multiple-perspective approach to analysis: It includes a granular supply and demand assessment, interference-avoidance exclusion angles, ARPU and distribution considerations. The paper concludes with perspectives on how, in the future, LEOs may best interplay with well-established GEOs.



Today's fast-paced environment brings unprecedented opportunities for the telecommunications industry as a whole to make the most out of disruptive innovations and investments in space networks, both Non-GEO and GEO. However, orbital dynamics of LEO satellites drive the need to assess impacts differently, as not all LEO satellite capacity is either usable or uniformly distributed across the coverage regions.



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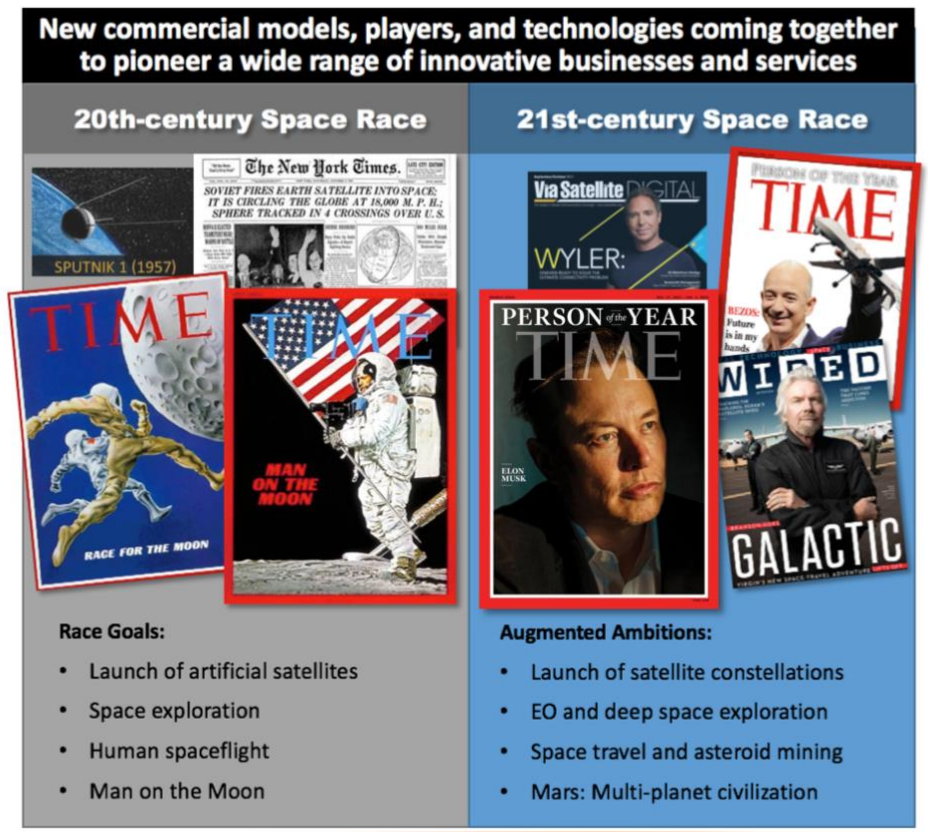
[1] Low Earth Orbit (LEO) is an Earth-centered orbit with an altitude of 2,000 km (1,200 mi) or less above sea level.
[2] Medium Earth Orbit (MEO) is the region of space around Earth above LEO and below GEO
[3] A satellite constellation is a group of artificial satellites working together as a system to provide continuous service
[4] Geosynchronous Equatorial Orbit (GEO), is a circular geosynchronous orbit 35,786 kilometers (22,236 miles) above the Equator and following the direction of Earth's rotation
[5] https://www.starlink.com/

INTRODUCTION: Constellations and the 21st Century Space Race

The satellite industry is in the midst of the largest transformation since the inception of satellite communications over five decades ago. There is an interesting parallel between today's drive for change and that of the "Space Race" era that unfolded in the late 50's between the United States and the Soviet Union. Starting with the successful launch of Sputnik-1, the first artificial satellite put into orbit in 1957, and peaking in 1969 with the landing of a Man on the Moon, this period gave birth to the satellite industry. Today, we are transiting into a new space race era, a "21st-Century Space Race"[6] that shares common goals with the old race, space exploration and launch of artificial satellites, however, it's taken to a much higher level. This modern Space Race involves the launch of thousands of satellites across different types of orbits, deep space exploration, space travel, asteroid mining, and -ultimately- Mars colonialization and a multi-planet civilization.

Aside from the magnitude of today's projects and ambitions, a key difference is the 21st-century space race is largely driven and funded by the private sector, attracting an enormous inflow of capital, fueling innovation.



The ongoing, unprecedented launch cadence of thousands of satellites placed into non-geostationary (LEO/MEO) orbits must be observed in the context of this new space race. The commercial sector is in the driver's seat of innovation, and the push for new paradigms in network economics have implications spanning across all users of space-based applications or programs – public or private, civil or military.

The game-changing characteristics of the so-called "mega-constellations" cannot be understated. Launch of thousands of satellites by SpaceX's Starlink, OneWeb -and potentially Amazon Kuiper, Telesat Lightspeed and other LEO initiatives in a future- not only promise to intensify competition in satellite HTS[7], but also foster new business paradigms with impacts in the broader telecommunications industry. Times of disruption drive the need to assess impacts in new ways. NSR provides clients with a set of analytical instruments leveraged internally at NSR to holistically assess LEO and MEO HTS constellations. This white paper provides sample uses of NSR's Non-GEO Constellations Analysis Toolkit, v2.0 (NCAT2)[8], designed to help assess the impact of constellations from architectural and business-case perspectives.

NSR's Non-GEO Constellations Analysis Toolkit, v2.0 (NCAT2)

Tools highlighted are those used to drive analysis for this white paper

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[6] 21st Century Space Race: Extracted from the appendix of "NSR White Paper: Satellite Ground Network Virtualization" https://www.nsr.com/wp-content/uploads/2020/03/NSR-White-Paper-Ground-Network-Virtualization-March2020-FINAL.pdf
[7] HTS: High Throughput Satellites
[8] https://www.nsr.com/?research=non-geo-constellations-analysis-toolkit-v2-0

NCAT2 is an assembly of easy-to-use analytical models that x-ray and benchmark LEO and MEO high-throughput satellite systems. The configurable, 360-degree NSR toolkit is meant for both business/strategy and technical professionals alike seeking in-depth understanding of Non-GEO high-throughput SATCOM.

Version 2.0 of NSR's popular NGSO toolbox has expanded in breadth and depth, augmenting the number of tools from 9 to 15, doubling the input and output data tables to 56 sub-constellations – comprising over 63 thousand satellites- and allowing users to conduct granular, territory-level assessments for fixed-data and mobility applications.

NCAT2 is pre-populated with FCC/ITU filing data – Q3.2021 - both granted and in-process for:

- Amazon Project Kuiper (LEO)
- AST Space Mobile (LEO)
- China GW-2 & GW-A59 (LEO)
- Kepler Communications (LEO)
- LYNK Global
- Mangata Networks (MEO)
- OneWeb (LEO phases 1 & 2)
- SES O3B (MEO)
- SES O3B (LEO IoT)
- SpaceX Starlink (LEO)
- SpaceX Starlink Gen2 (LEO & VLEO)
- SpaceX VLEO
- Telesat Lightspeed (LEO)
- Telesat VLEO
- Viasat (MEO & LEO)

Editable inputs let users evaluate system modifications and any other NGSO system/s.

THE LEO ARCHITECTURE "BLESSING AND CURSE"

An often-overlooked aspect of LEO satellite constellations is that, while operators deploy terabits of global capacity, orbits' low altitude limits satellite visibility of the Earth's surface, so constellation players are unable to steer most of the globally deployed capacity to the areas with the largest target population. The lower the altitude, the smaller the satellite's field of view (FoV), limiting opportunities for capacity steering.

This visibility limitation is compounded by the fact that addressable markets for connectivity are confined within a small portion of LEOs global footprint. Sir Arthur C. Clarke[9], an English science-fiction writer who conceptualized the geostationary (GEO) communications satellite, once made a wise comment that –paradoxically– today applies to the LEO addressability dilemma: *"How inappropriate to call this planet Earth when its quite clearly Ocean"*. Two thirds of Earth's surface is covered by water. In the sample case analyzed in this white paper, the addressable fixed-broadband population is distributed across a surface area that represents only 12.5% of the world surface (land and water), showcasing the absolute must for LEO operators to expand addressability towards mobility routes (aero/maritime/rail), so as to drive a more efficient business.

Since LEO satellites may not use full power throughout each orbital period, scaling back the LEO satellite power to what will be effectively used may drive design efficiencies at a CAPEX level (lower satellite weight and launch cost). When this is supplemented by a good choice of orbits, frequency bands and antenna elevation, well-designed LEO constellations may ultimately achieve decent global fill rates relative to their designed power balance but –regardless of choice– low altitude inevitably limits addressability.

Orbital inclination is another design factor affecting both coverage (latitude reach) and supply density. Over 75% of the globally addressable rural population for LEOs resides within 35 degrees of latitude north and south of the Equator. Yet, leading LEO-HTS operators deploy the highest capacity density (Gbps[10] proportionally overhead) above 35 degrees N/S to be able to serve high-ARPU[11] regions in the northern hemisphere. This, in turn, creates supply-demand imbalances in other regions or latitudes that satellite operators and educated users or distributors could attempt to leverage with various degrees of bargaining power.

> ***"How inappropriate to call this planet Earth when it is quite clearly Ocean"***
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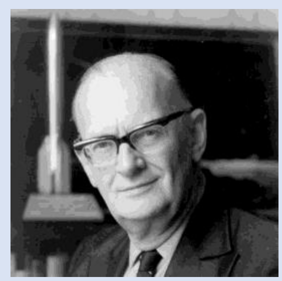
> 
>
> **Sir Arthur C. Clarke**
> Professional fiction writer
> (1917–2008)

Therefore, constellations low altitude can be considered a blessing for latency (low) and for spectrum reuse (high) but also a curse for addressability (constrained). The addressability limitation of low altitude is the main reason why LEO players must target not just fixed data applications (i.e. consumer/enterprise broadband, backhaul, etc) but also energy/mining distant locations and mobility routes (maritime, aero, rail, and eventually "connected cars"). Maximizing addressability is vital for constellation players to drive the lowest possible marginal cost per (usable) Mbps in order to be progressively more competitive.

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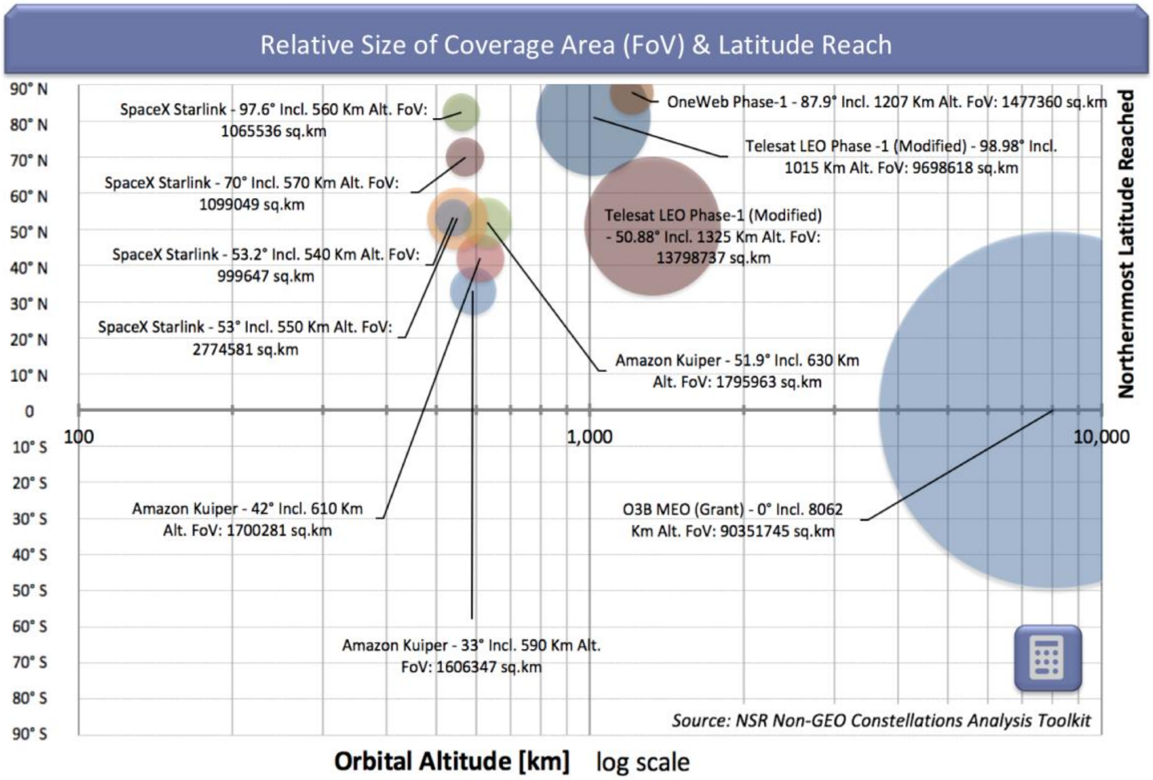
[9] Sir Arthur Charles Clarke was an English science-fiction writer, science writer, futurist, inventor, undersea explorer, and television series host. He co-wrote the screenplay for the 1968 film 2001: A Space Odyssey, widely regarded as one of the most influential films of all time.

[10] Gbps: Gigabits per second

[11] ARPU: Average Revenue per User

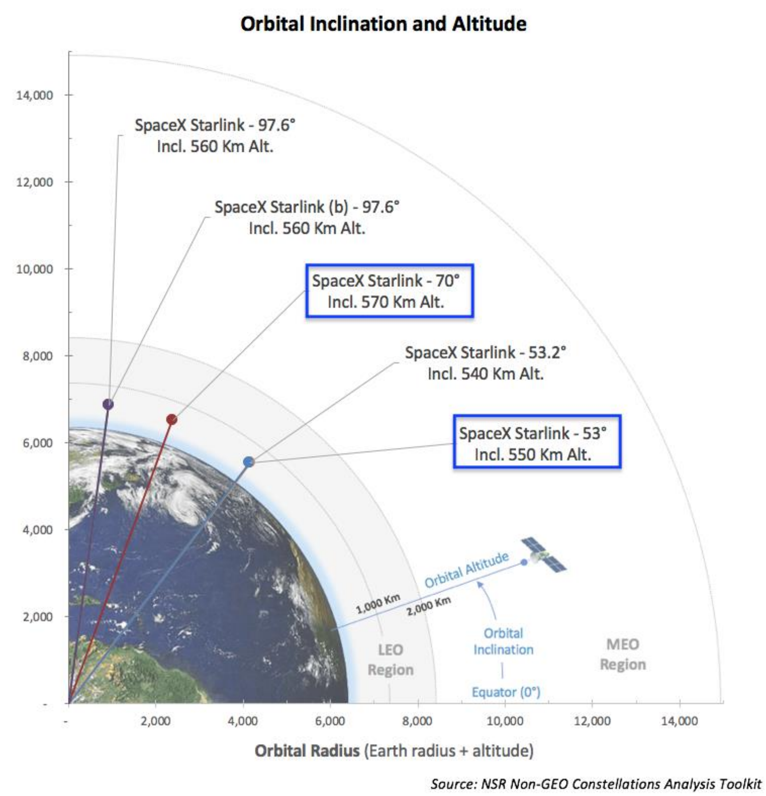


SAMPLE ANALYSIS:
Starlink Sub-Constellations

Sample NCAT2 simulations run to produce this white paper correspond to SpaceX's Starlink, considering two constellation shells fully deployed. For simplicity, this assessment assumes that SpaceX achieves "open skies" access in all visible territories worldwide for fixed-data and mobility markets, but note that NCAT2 allows the analysis to be conducted for a selectable list of countries. For instance, the China and Russia markets can be excluded in the analysis if simulation needs to assume that SpaceX will not have access to such territories. Any combination of included/excluded countries can be selected in the tool.

General assumptions for the sample-case analysis:

- **Supply**: Two Starlink sub-constellations (highlighted shells) fully deployed.
- **Demand**: Rural fixed-broadband combined with aero mobility (details below)



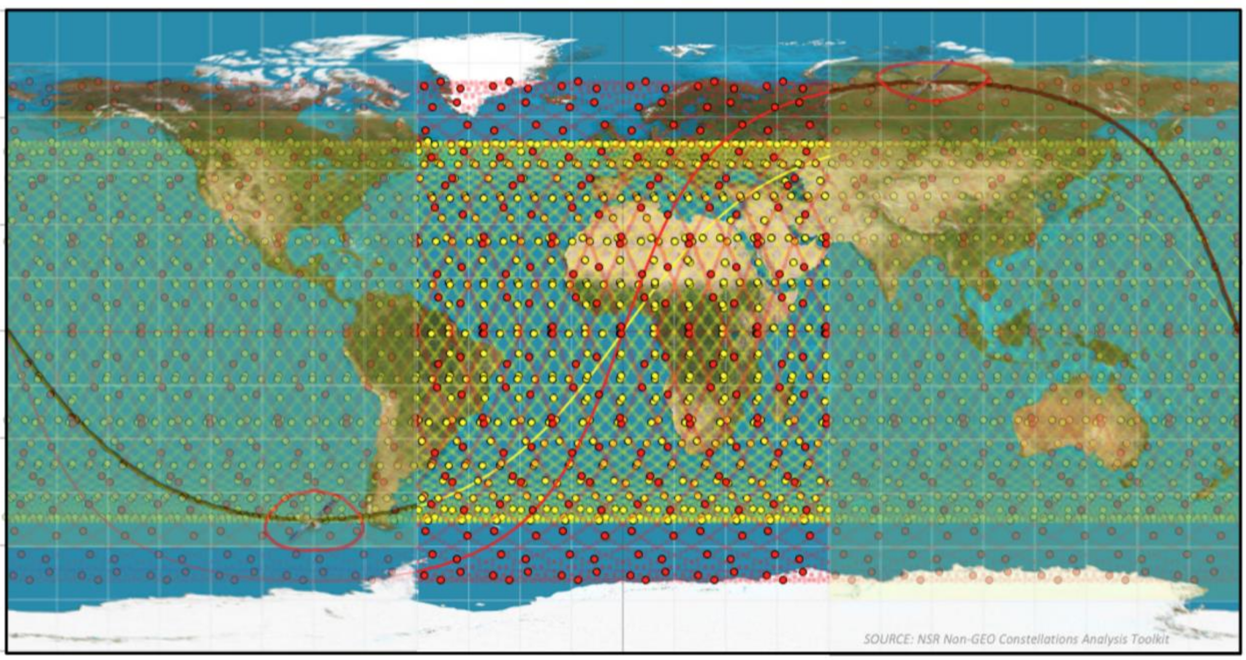
Starlink– 5-Shell FCC Grant

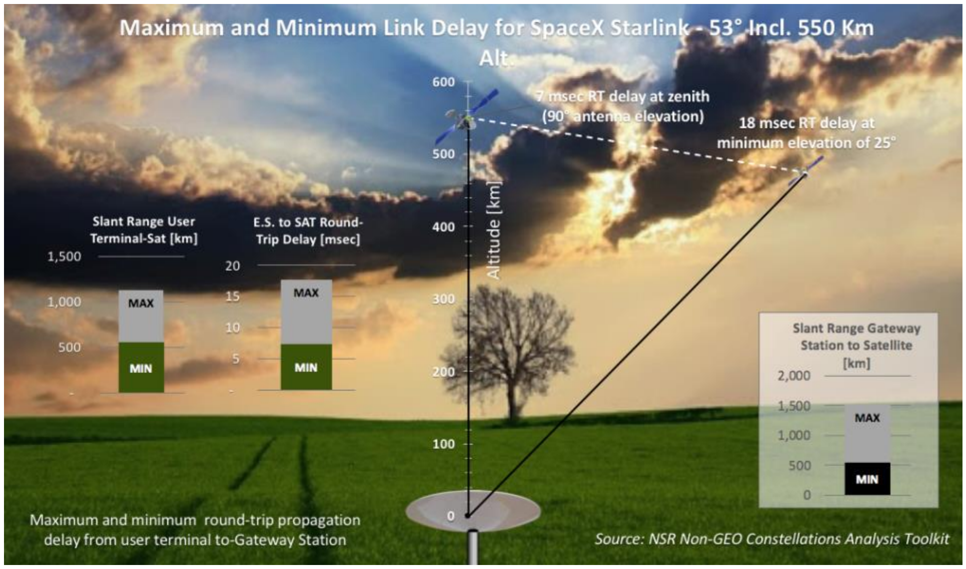
White paper assumes the two highlighted shells in the analysis.

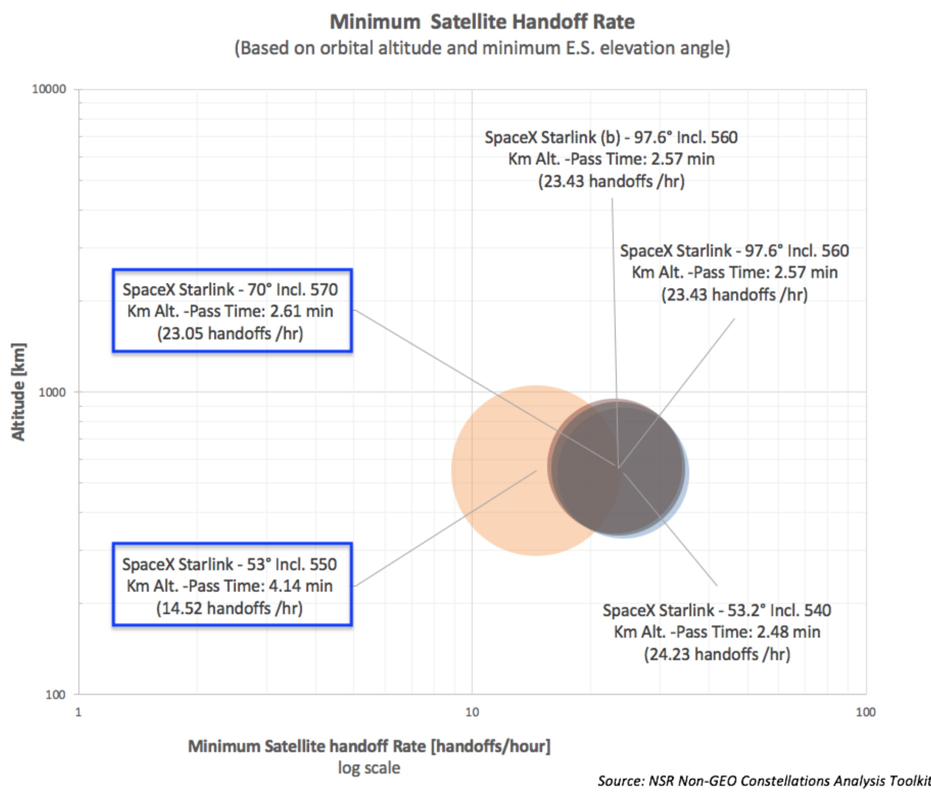
Orbit Type*	Orbital Planes			# of Planes	# Sats per Plane	# Sats per Shell	# Sats for final system**
	Altitude	Orbital Radius	Inclination				
	[km]	[km]	[degrees]				
Inclined	550	6,924	53	72	22	1,584	4,408
Inclined	540	6,914	53.2	72	22	1,584	
Polar	570	6,944	70	36	20	720	
Polar	560	6,934	97.6	6	58	348	
Polar	560	6,934	97.6	4	43	172	

Source: NCAT2 based on SpaceX FCC filings for "Gen-1 Starlink" Ku/Ka approved modifications. Blue-text cells in NCAT2 tools are editable to assess system modifications

53° and 70° Starlink Shells
Satellites, Orbital Routes and Field of View







Starlink has large capacity, but three aspects simultaneously affect LEO-HTS feasibility and economics between +- 30 or 35 degrees of latitude:

1. Supply-Demand: Higher density of target population coincides with lower density of Gbps deployed overhead;
2. Interference: More instances of potential interference with GEOs reduce the degrees of freedom;
3. ARPU: Generally low telecom ARPU in developing regions pushes for hybrid solutions.

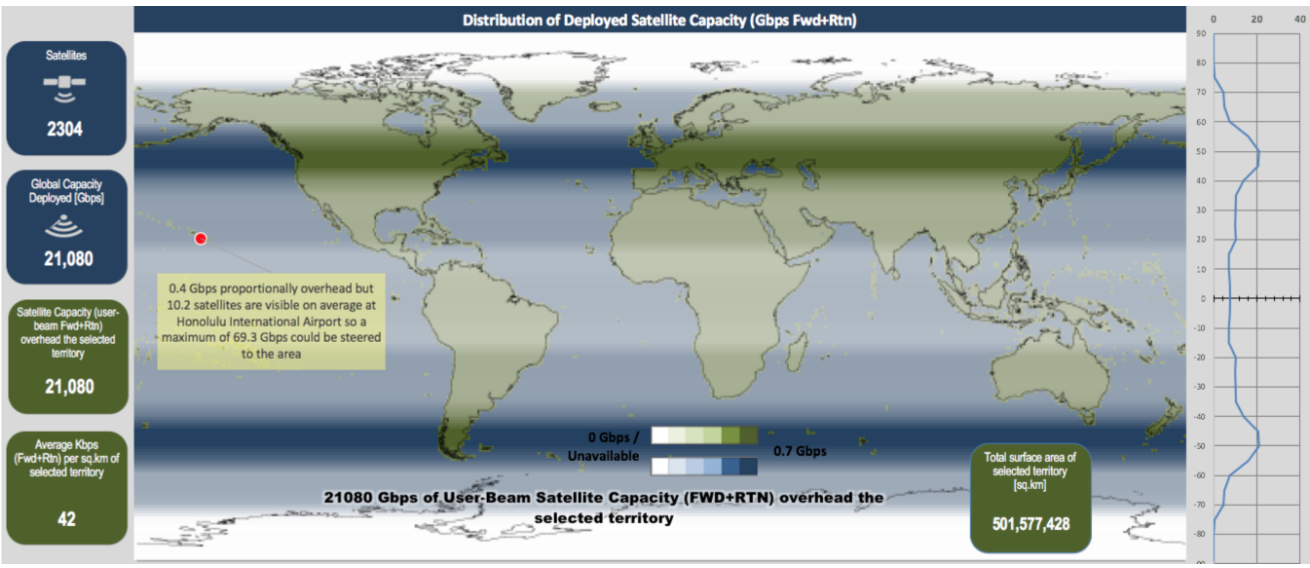
The following sections describe the analysis from these three perspectives, step by step.

PERSPECTIVE 1: Bandwidth Supply and Demand

Bandwidth Supply Model

The bandwidth supply model assumes full deployment of Starlink shell 1 (53° Inclination shell; completed by SpaceX) and shell 2 (70°inclination shell). User beam and satellite IP throughput are calculated in the toolkit (tool #5 "Throughput Link Budgeting") based on technical characteristics extracted from publicly available FCC filings and other assumptions (antenna size, look angles, margins, etc.). NCAT2 Tool 4 ("Satellites in of Sight") was leveraged to calculate the number of visible satellites based on latitude, as shown below.

Starlink shells 1 and 2 together comprise over 2,300 satellites beaming 21 Tbps (terabits per second) of user-beam Ku-band capacity globally. By virtue of orbital mechanics, such capacity is not distributed evenly as the number of visible satellites drives local supply density. The map shows the density of capacity supply that is proportionally overhead for the combined two-shell system.

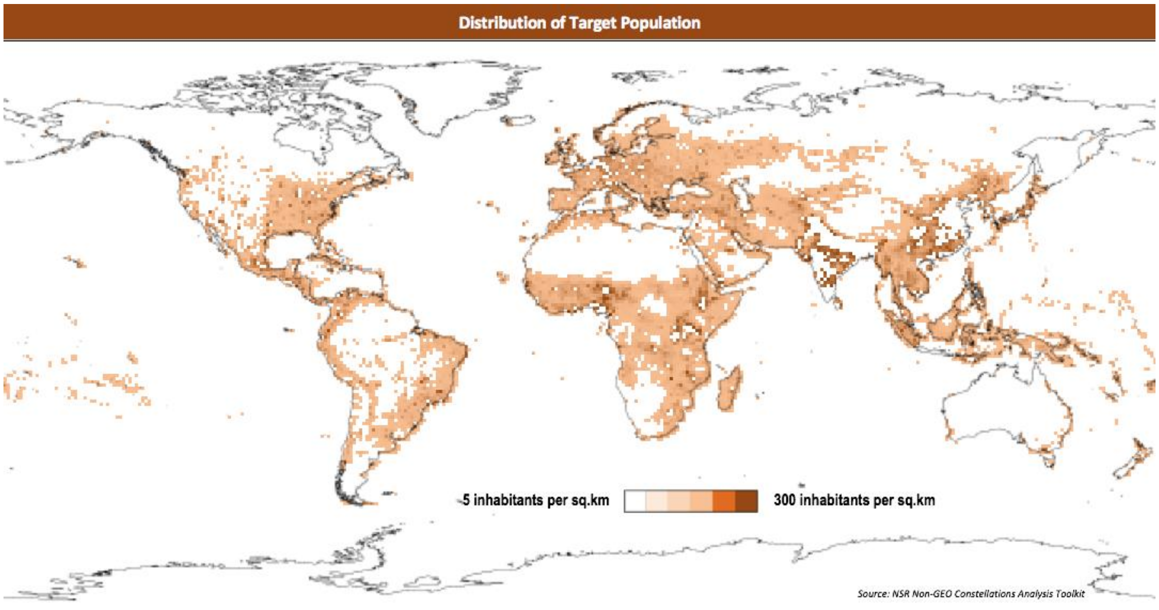


Fixed-Broadband Bandwidth Demand Model

The simulation assumes that target regions for fixed broadband services are those with a population density between 5 and 300 inhabitants per square kilometer (13 to 777 inhabitants per sq. mile). Areas with less than 400 inhabitants per sq.km are considered rural, and generally targeted by satellites (Non-GEO and GEO). A total of 3.48 billion people live in such regions (the "other 3 billion"), representing the global addressable population.

Model assumes a market capture for Starlink of 1% of such population (also editable in the tools), so roughly 35 million people are assumed connected to the Internet via the two Starlink sub-constellations. The simulation considers a 50/5 Mbps (downstream/upstream) service plan with a 40-to-1-average contention ratio (overbooking). Note that this analysis process can agnostically apply to scenarios combining (direct) residential broadband users and local mobile users reached indirectly via MNO[12] wireless backhaul.

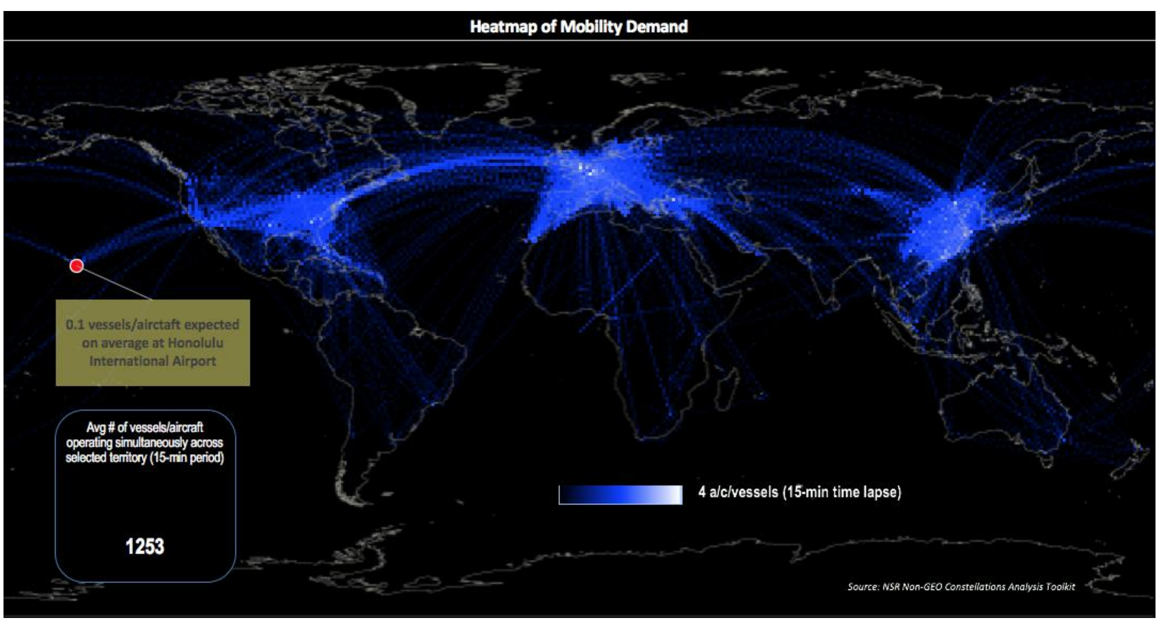
[12] MNO: Mobile Network Operator



Mobility Demand Model

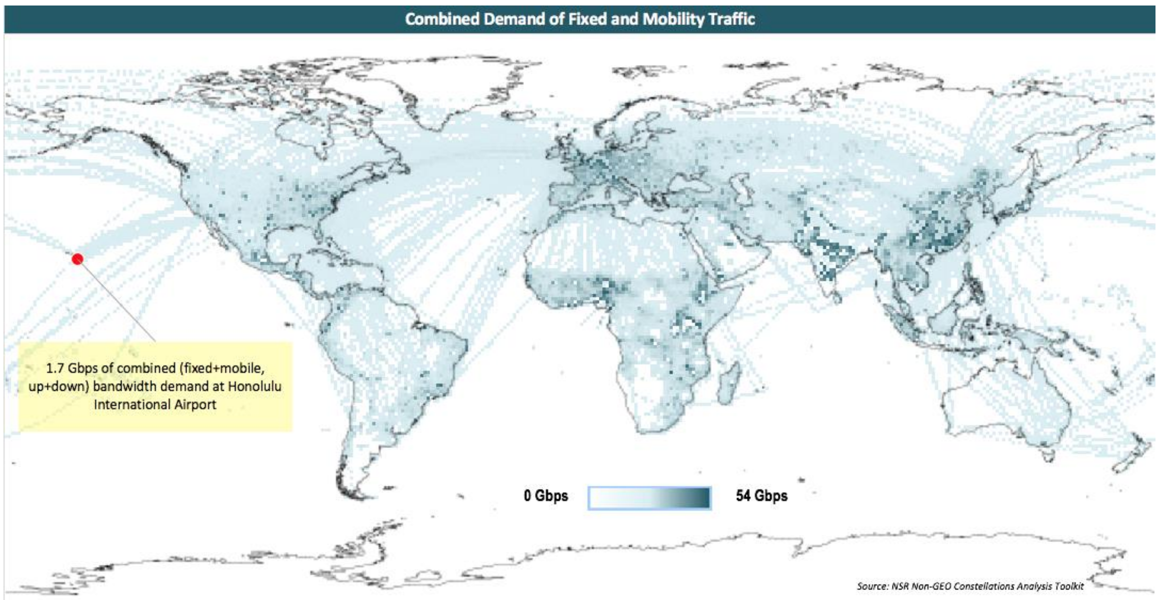
NSR used NCAT2 Tool 12 ("Mobility Heatmap") to run a simulation of in-flight entertainment and connectivity (IFEC) demand for a few major airlines, namely American Airlines, Air France, British Airways, Turkish Airlines, Ryanair and three major Chinese airlines. Data for airline routes was extracted from OpenFlights.org. Such data is not updated but nevertheless useful for this example. NSR produced "dummy" flight schedules for the airlines based on routes and average flight speed. Simulation was run across a 24 interval, so the number of aircraft present per degree of latitude and longitude shown below is the total day count.

For the combined demand analysis, the model assumes a service plan of 100/20 Mbps per aircraft without contention (committed information rate; all editable inputs in the tool).



Demand Assessment of Combined Fixed-Broadband and IFEC

Calculation of combined broadband and aero (IFEC[13]) capacity demand is based on the respective service plans described above, and the geographic distribution. For the combined bandwidth demand map, the number of aircraft per degree of lat/lon is the one from the heatmap tool divided by 48. This is because the aero heatmap simulation was for 24 hours so, assuming 12 hours of "peak flight time"; this would give a more realistic picture of the number of aircraft per lat/lon degree, per 15-minute time interval.



The global aggregate demand equals 62 Tbps[14], of which 48 Tbps correspond to fixed broadband, based on the configured inputs. Demand exceeds supply globally but concentrated in certain hot spots, as analyzed next.

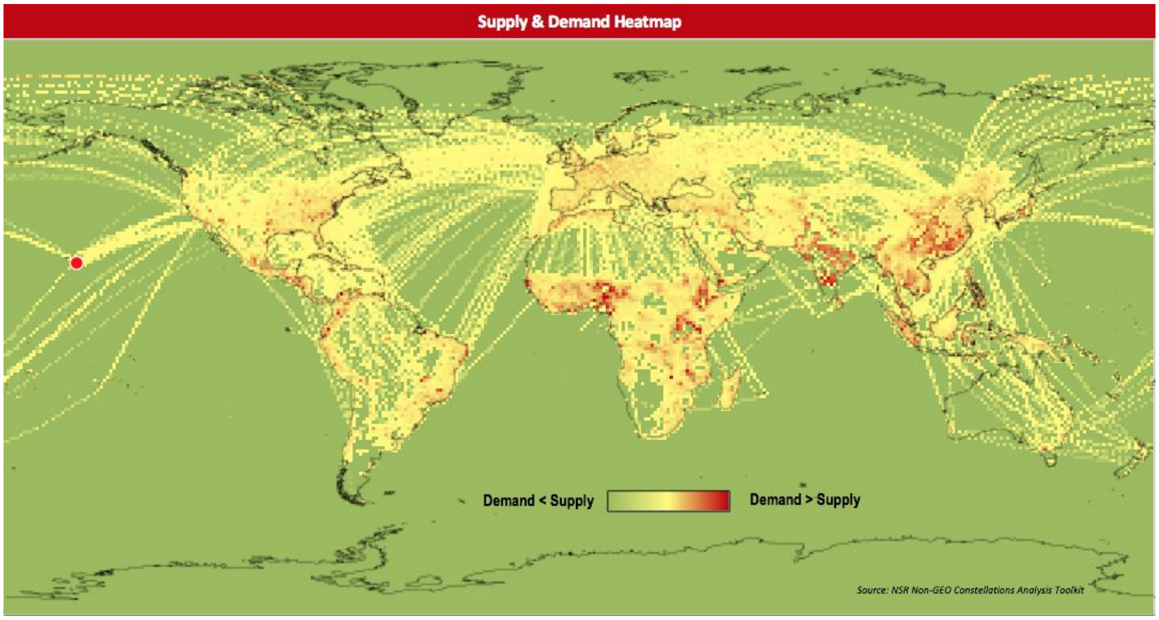
NCAT2 Model Output: Supply & Demand Heatmap Analysis

The NCAT2 Dashboard tool computes and compares supply and demand of bandwidth per degree of latitude and latitude to drive a "Supply & Demand Heatmap" analysis: Red dots in the map denote 1 deg. lat/lon spots where demand is higher than supply; and green areas are those where demand is lower than supply. Pure yellow areas illustrate a rather balanced supply and demand.

Supply is measured as "proportional overhead capacity" in the tool. Since there are multiple satellites visible, red spots could turn yellow (or green) if capacity is redirected or "stolen" from neighboring areas with lower demand. Operators' orchestration systems and bandwidth policing will certainly drive network optimization, but note that user beam steerability does not necessarily eliminate all red spots due to the small field of view of the LEO satellites (just hundreds of km radius) and operator's need to comply with the minimum exclusion angles required by the ITU to avoid interfering with GEO Ku band satellites, particularly around populated Equatorial regions (assessed separately in this white paper using another NCAT2 tool).

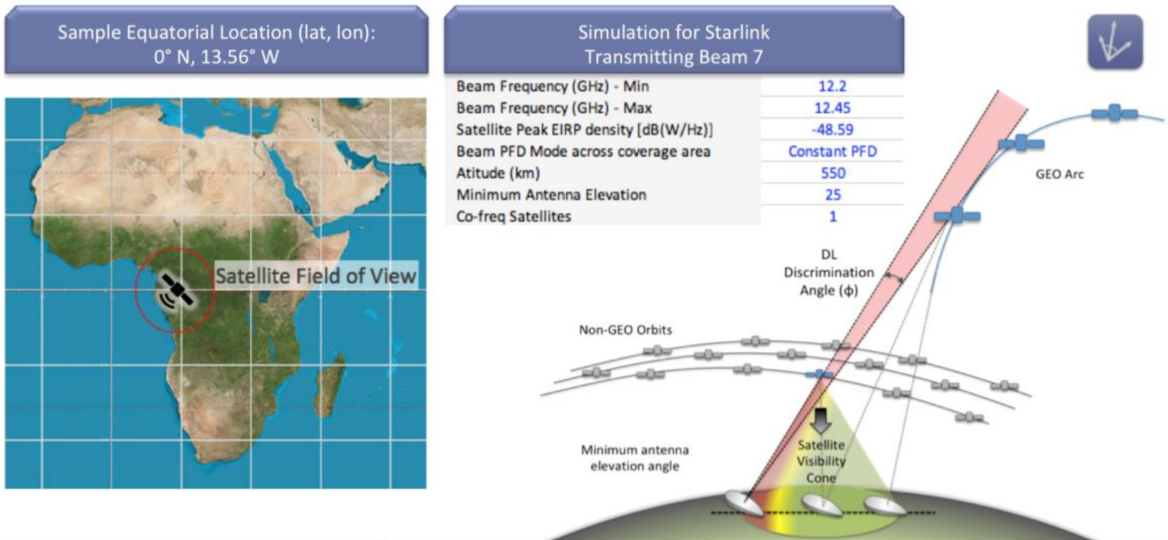
The NCAT2 dashboard tool provides summarized metrics for the analysis and detailed supply and demand data tables (per degree of lat/lon) in case users need to export data for use outside the NSR toolkit.

[13] IFEC: In-Flight Entertainment and Connectivity
[14] Tbps: Terabits per second



PERSPECTVE 2: Exclusion Angles for Interference Avoidance

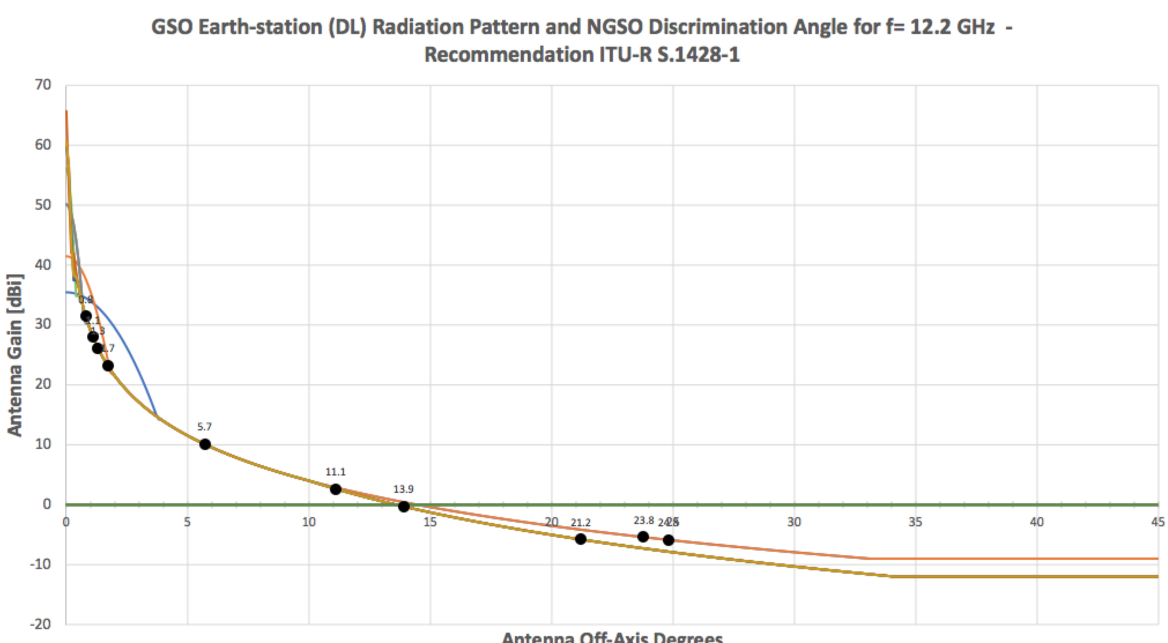
LEO satellites must not interfere with GEO services, which always have coordination priority. To accomplish this, LEOs need to comply with the equivalent power flux density (EPFD) limits defined in the ITU Radio Regulations. In practice, this means that LEOs need to establish exclusion zones (minimum discrimination angles) with respect to the GEO "Clarke Belt" arc. Given the dynamic nature of LEO constellations, operators' orchestration systems must trigger satellite handoffs whenever the EPFD limits are about to be exceeded due to the angle differential with GEO satellite transmissions. Below is a sample simulation of exclusion angles for the Ku-band (user beam) frequencies used by the SpaceX system when Starlink satellites (shell 1, 550 km altitude) fly over the Equator.



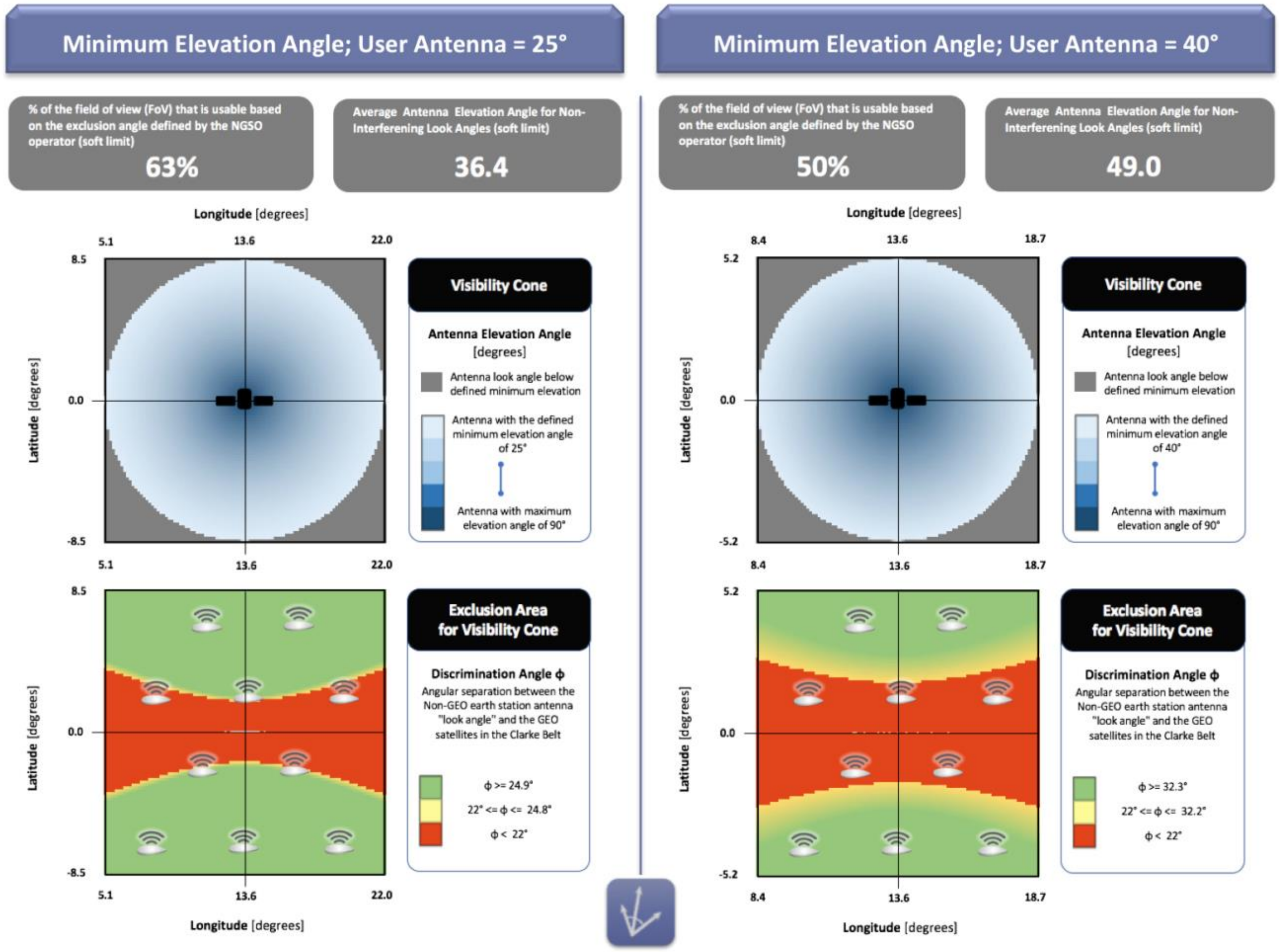
Applicable Tables from Article 22 of the ITU Radio Regulations -->	TABLE 22-1A				TABLE 22-4A				TABLE 22-4A1	
Frequency Band/s in ITU Table	10.7-11.7 in all ITU Regions; 11.7-12.2 in Region 2; 12.2-12.5 in Region 3; 12.5-12.75 in Regions 1 and 3				10.7-11.7 in all Regions; 11.7-12.2 in Region 2; 12.2-12.5 in Region 3; 12.5-12.75 in Regions 1 and 3 (from 31 December 2005)				Additional operational limits (all freq. bands)	
Table f= Min GHz	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7		
Table f= Max GHz	12.75	12.75	12.75	12.75	12.75	12.75	12.75	12.75		
GSO Reference antenna radiation pattern	Recommendation ITU-R S.1428-1				Orbital inclination of the geostationary satellite <=2.5 degrees					
Reference GSO earth station antenna diameter [m]	0.6	1.2	3.0	10.0	3.0	6.0	9.0	18.0	3.0	10.0
epfd limit for the constellation [dB(w/m2/40 kHz)] - from ITU Art.22	-175.4	-181.9	-190.5	-195.5	-161.3	-164.0	-165.5	-167.5	-182.0	-185.0
epfd limit for the constellation [dB(w/m2/MHz)]	-161.4	-167.9	-176.5	-181.5	-147.3	-150.0	-151.5	-153.5	-168.0	-171.0

Source: NSR Non-GEO Constellations Analysis Toolkit 2.0 (NCAT2)

NCAT2 Tool #11 calculates uplink and downlink discrimination angles for NGSO systems based on the Equivalent Power Flux Density (EPFD) limits of Article 22 of the ITU Radio Regulations, applicable to the FSS frequency bands.



Source: NSR Non-GEO Constellations Analysis Toolkit



Source: NSR Non-GEO Constellations Analysis Toolkit 2.0 (NCAT2)

Non-interfering operation is vital for the co-existence with the (populated) Ku-band GEO arc. This sample analysis for Starlink (using technical data extracted from FCC filings) concludes that the usefulness of satellites' field of view is reduced substantially when satellites fly over the Equator. Indeed, up to 50% of the satellites' FoV could be reduced for Starlink satellites in Equatorial regions, in order to fully avoid interference with Ku-band GEO satellites. While this does not necessarily result in wasted capacity when satellites have steerable beams (capacity could be directed elsewhere), it results in fewer "degrees of freedom" for capacity relocation, a problem that worsens with lower attitudes and higher minimum-elevation angle definitions for the ground antenna. Other visible satellites with higher discrimination angles that are operating nearby the area can take turns in dynamically supplying capacity to specific spots but sometimes with low look angles, which generally affect link IP throughput.

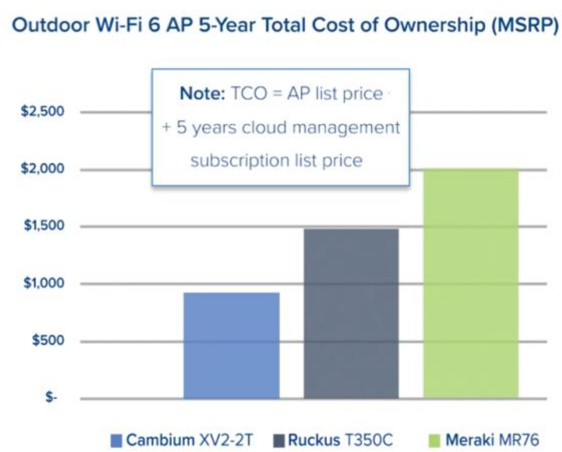
PERSPECTIVE 3: ARPU Considerations and Direct versus Hybrid Distribution

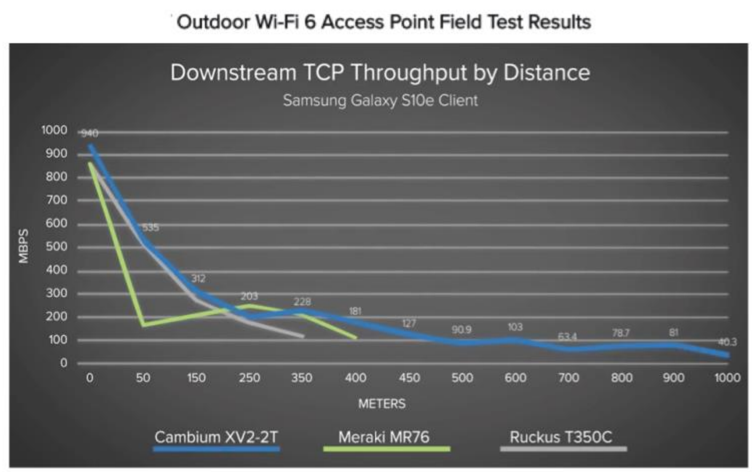
Constellations' business-case challenges are compounded by the fact that low-ARPU markets make it harder to justify – from a business case standpoint– the cost of MSA/FPA[15] LEO terminals, which are inherently more complex and expensive than GEO VSATs[16]. As a general rule, the lower the link data rate and/or service recurring rate, the more important to use inexpensive user terminals. Thus, depending on the application, a hybrid distribution approach may provide the lowest TCO[17] for LEOs.

NSR has emphasized the importance of hybrid networks and distribution partnerships for Non-GEO and a recent burst of announcements by major LEO players point at addressing the right pain areas. Announcements include:

- **Distribution Partnerships:** Verizon[18]-Amazon Kuiper (US), NEOM-OneWeb[19] (Middle East) and NSSLGlobal-Telesat[20]
- **Hybrid Distribution:** The Akiak Native Community in southwestern Alaska[21] becoming the first US community served by OneWeb via a hybrid satellite-wireless network.

The OneWeb deployment in Akiak is a prime example of the value of hybrid distribution. OneWeb worked with Pacific Dataport and Microcom to install the first OneWeb service in Alaska, making Akiak the first LEO-enabled village in the US. A dual-antenna LEO terminal communicates with the satellites overhead and connects to the community-wide distribution system, using Cambium[22] wireless technology.





Source: Cambium Networks

The business-case crossing points for the hybrid interplay are measurable. Using wireless access point pricing information (MSRP[23]) publicly shared by Cambium Networks, a sensitivity analysis can be run with NCAT2 (tool # 8) to identify crossing points benchmarking direct-to-consumer and hybrid distribution. The simulation illustrates that even considering a high-ARPU service; the direct-to-consumer approach is seriously challenged by the LEO-HTS terminal CAPEX.

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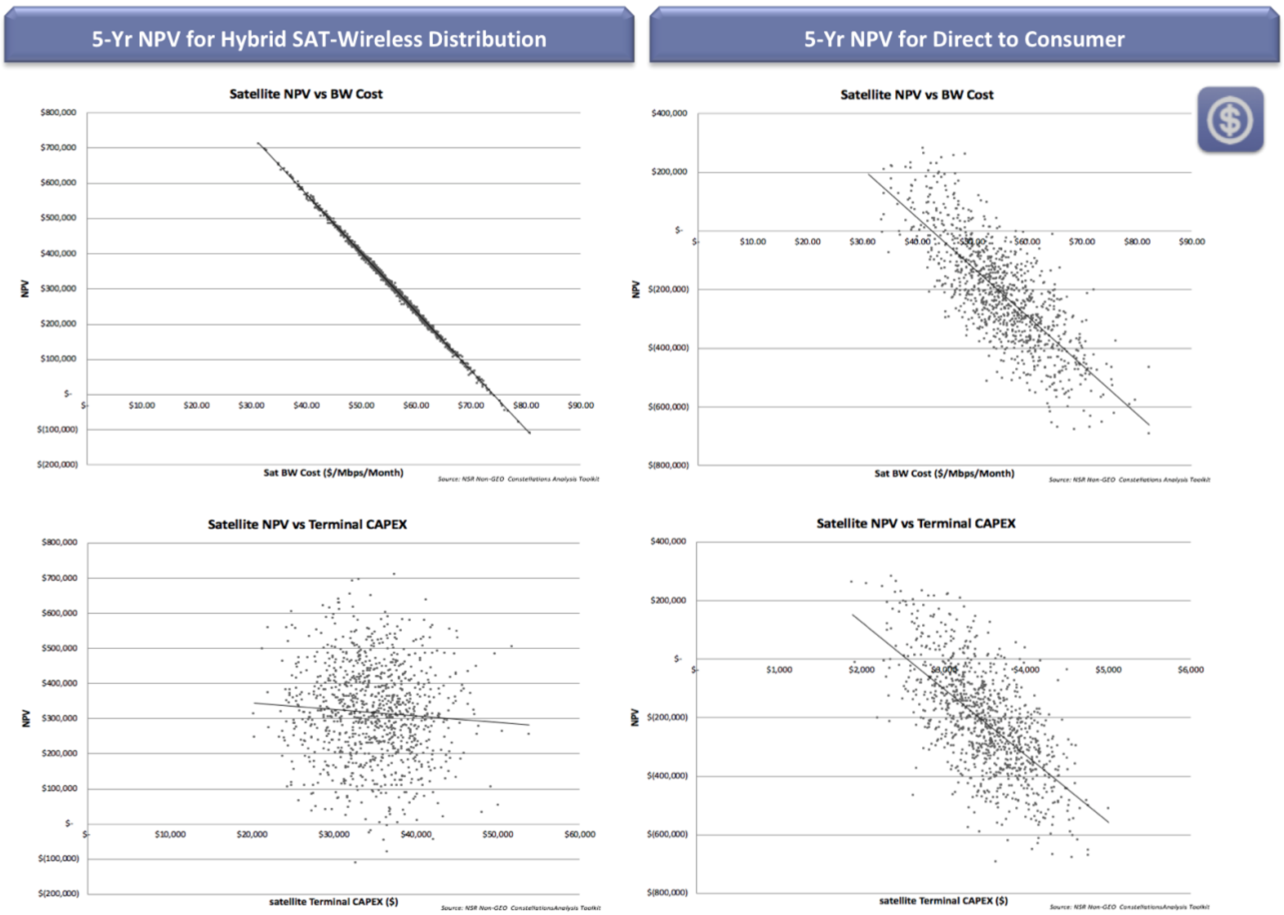
[15] MSA/FPA: Mechanically-Steered Antenna / Flat-Panel Antenna
[16] VSAT: Very Small Aperture Terminal
[17] TCO: Total Cost of Ownership
[18] https://www.verizon.com/about/news/5g-leo-verizon-project-kuiper-team
[19] https://oneweb.net/media-center/neom-tech-digital-holding-company-and-oneweb-sign-200m-jv-for-satellite-network
[20] https://www.telesat.com/press/press-releases/nsslglobal-and-telesat-announce-strategic-co-operation-agreement-for-telesat-lightspeed-leo-network/
[21] https://www.anchoragepress.com/news/southwest-alaska-tribe-takes-first-steps-toward-rural-broadband-service-with-new-satellite-system-oneweb/article_d983a11a-fea5-11eb-81cb-3b7d41077a88.html
[22] https://www.cambiumnetworks.com/
[23] MSRP: Manufacturer's suggested retail price



Satellite Beam Bandwidth (Download) & Monthly OPEX: 400 Mbps @ $30 to $80 per Mbps, per month	
Users, ARPU & Service Plan: 400 users, $100 ARPU, 10 Mbps downstream service (10 to 1 contention ratio)	
Satellite Terminal Cost: $40K to $100K (one redundant high-end system)	**Satellite Terminal Cost:** $2k to $5K (400 non-redundant FPA terminals)
Wireless (Last-Mile) TCO per site: $1K (400 sites)	$-
Note: 5 year NPV sensitivity analysis assumes 21% corp. tax rate, debt financing with 5% interest rate, a discount rate of 9% and 10% annual depreciation	

Source: NSR Non-GEO Constellations Analysis Toolkit 2.0 (NCAT2)

***Note**: Since NCAT2 is a configurable toolset (not an NSR report), this sample simulation focused on a consumer-grade service may not be representative of what satellite operators will provide and/or charge for such services.*

Conclusions from this sample NCAT2 sensitivity simulation are clear: Even ignoring the fact that direct-to-consumer links tend to be less efficient in the use of satellite spectrum when compared to a service via high-end aggregation antenna system, the project's net present value (5-year NPV for the service provider) becomes negative for the direct-to-consumer case as a result of the FPA terminal cost. Charts also illustrate why it becomes vital for the (consumer-centric) Starlink service to achieve a terminal manufacturing cost below $2,000.

LEO-GEO COMPLEMENTATION

While LEO constellations continue blanketing the globe, GEOs (and MEOs), being further away from Earth, can direct HTS spot-beam capacity more easily towards "hot spot" areas without wasting spectral resources and by leveraging low-cost VSATs. GEO-HTS systems (large to small GEOs) are thus ideally suited for capacity augmentation or complementation, not only around hot spots such as airports but also in low-ARPU populated regions within +/- 35 degrees of the Equator, where LEOs simultaneously exhibit lower density of overhead capacity and tighter interference-avoidance constraints (on top of expensive terminals).

Multi-orbit operation will certainly involve many service flavors and sweet spots that the industry will collectively find and develop solutions for, but two applications are driving the initial validation steps: Defense and mobility, as highlighted in two recent announcements:

- A multi-orbit Ku-band demonstration for the U.S. DoD involving OneWeb (polar LEO satellites), Intelsat[24] (GEO-HTS IS-37e Epic satellite) and various user terminals including Kymeta (flat panel antenna), SatCube and Intellian.
- SES[25] completion of multi-orbit Ka-band field tests using an Isotropic multi-link antenna, linking to a GEO satellite while simultaneously connected with an O3B satellite in medium earth orbit (MEO).

The main conclusion is that LEOs are –certainly- not precluded from being able to serve all covered regions and applications, but the described architectural and business-case aspects will encourage both Non-GEO and GEO players to gradually become more selective in "what battles to fight" and possibly partner for multi-orbit opportunities, depending on ARPU, competitiveness and applications. As an example, it will be difficult for LEOs to beat the CAPEX+OPEX service economics of GEO-VHTS satellites for contended broadband service plans but LEOs could provide a low-latency, high-speed, low-contention premium service to high ARPU niches, both residential and enterprise. For aero in-flight connectivity (IFEC), large LEO constellations bring the benefit of high look angles for the aircraft antenna, potentially diminishing "skew angle" issues and reducing drag via low-profile, lightweight flat-panel antennas.

[24] https://www.intelsat.com/newsroom/intelsat-and-oneweb-demo-global-multi-orbit-satellite-service-to-u-s-department-of-defense/
[25] https://www.ses.com/press-release/isotropic-systems-and-ses-redefine-global-satellite-services-first-ever-multi-orbit

White Paper Highlights

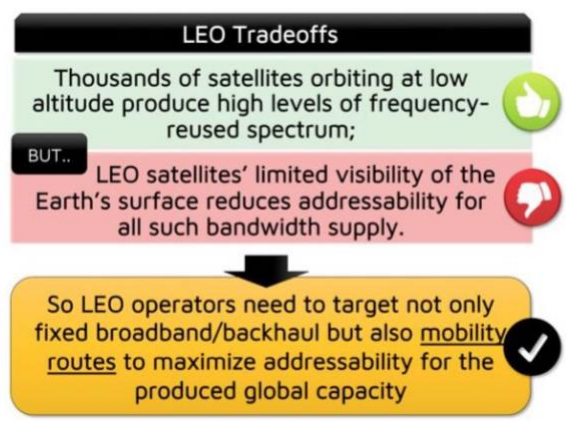
- While the amount of IP bandwidth produced by mega-constellations is enormous, not all is usable .. or sufficient.
- Capacity & Addressability: The combination of these two aspects leads to highly localized supply-demand dynamics and even buy/sell opportunities that –both– satellite operators and educated users or distributors could leverage with various degrees of bargaining power.
- The addressable fixed-broadband population is distributed across a surface area that represents only 12.5% of the world surface.
- Over 75% of the globally addressable rural population for LEOs resides within 35 degrees of latitude north and south of the Equator. However, leading LEO-HTS operators deploy the highest capacity density (Gbps proportionally overhead) above 35 degrees N/S to be able to serve high-ARPU regions in the northern hemisphere.
- Business-case and architectural facets will mold the multi-orbit, multi-band satellite paradigm.
- Multi-orbit operation will involve many service flavors and sweet spots that the industry will collectively find and develop solutions for, but two applications are driving the initial validation steps: Defense and mobility.
- GEO-HTS systems (large to small GEOs) are ideally suited for capacity complementation, not only around hot spots such as airports but also in regions where LEOs simultaneously exhibit lower density of overhead capacity and tighter interference-avoidance constraints.
- Commercial distribution partnerships and hybrid technologies for distribution will also come into play to drive both technical and commercial pipeline efficiencies.
- LEOs are not precluded from being able to serve all covered regions and applications, but architectural and business-case aspects will encourage both Non-GEO and GEO players to gradually become selective in 'what battles to fight'.

BOTTOM LINE

Satcom constellations beaming tens of Tbps are impacting the space sector and the broader telecom industry. Yet, when running demand-supply simulations on fixed-broadband and mobility datasets using NSR's Non-GEO Constellations Analysis Toolkit 2.0 (NCAT2), it becomes clear that, while the amount of IP bandwidth produced is enormous, not all is usable, or sufficient.

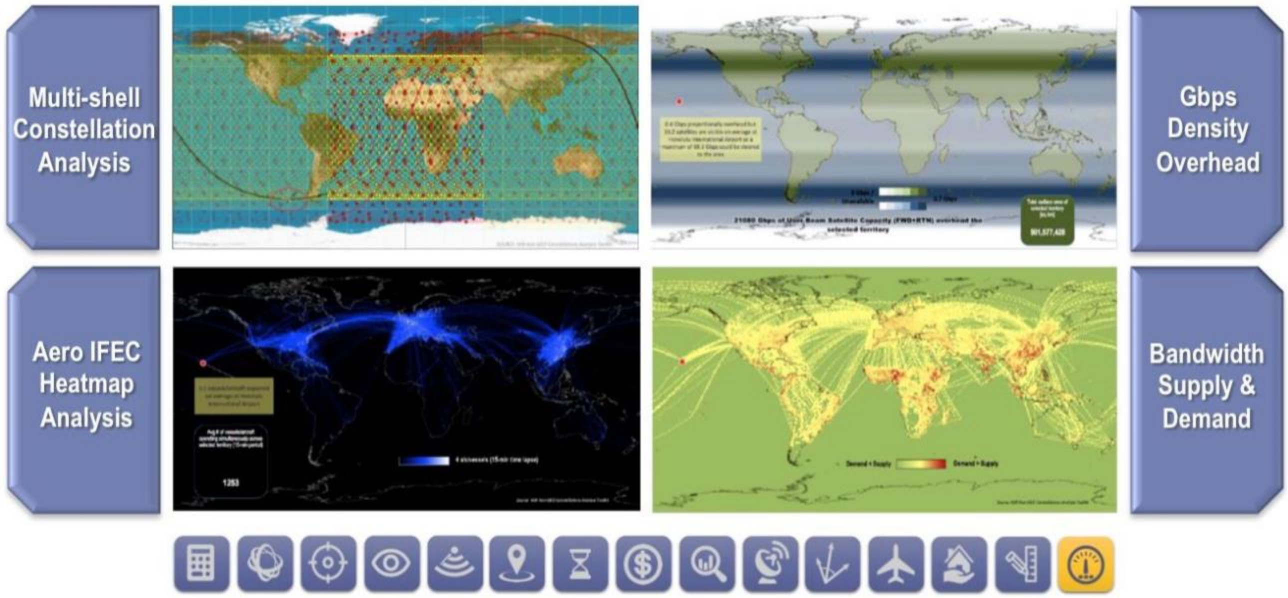
Two key aspects need to be considered simultaneously when analyzing bandwidth supply/demand dynamics and even future pricing strategies of LEO mega-constellations:

- Hundreds to thousands of satellites orbiting at low altitudes produce high levels of frequency-reuse 'spotbeam' HTS capacity.
- However, LEOs' limited visibility of the Earth's surface reduces addressability for all such bandwidth supply.



The combination of these two aspects leads to highly localized supply-demand dynamics and even buy/sell opportunities that –both– satellite operators and educated users or distributors could leverage with various degrees of bargaining power. This also means that LEO operators absolutely need to target fixed-data and mobility markets (aero/maritime/rail) simultaneously to maximize addressability and fleet-wide fill rates. Maximizing addressability is key towards the ultimate goal of minimizing the capital cost per usable Mbps, which is core to constellations' business case and long-term sustainability.

The satellite industry is in the midst of a major transformation with LEO constellations under the spotlight but supply-demand imbalances and interference avoidance complexities may foster GEO-LEO (and GEO-MEO) complementation to ultimately become the end game. Commercial distribution partnerships and hybrid technologies for distribution will also come into play to drive both technical and commercial pipeline efficiencies. It is hard to anticipate how much of complementation will be modulated by the various applications, but there is no doubt that such complementation will occur sooner or later, via either private-level coordination, provider partnerships, mergers and acquisitions or all.



Source: NSR Non-GEO Constellations Analysis Toolkit 2.0

About NCAT2

NSR's Non-GEO Constellations Analysis Toolkit 2.0 (NCAT2) is an assembly of flexible, configurable and easy-to-use quantitative models that x-ray and benchmark LEO/MEO high-throughput satcom constellations at architectural and business layers. The toolset provides a data-driven, unbiased vehicle for deep-diving into the intertwined technical and business aspects driving bandwidth supply, addressability and feasibility of leading mega-constellations, and their competitive standing versus terrestrial networks.

Benchmark SpaceX Starlink, SES O3B, OneWeb, Telesat Lightspeed, Amazon Kuiper, and (any) other LEO/MEO satellite system using the NSR toolbox. NCAT2 includes a multiplicity of analytical tools distributed across 15 Excel files (plus user guide and mobility datasets). Each tool has its own set of input variables, filters and calculation engines that drive output results, charts, maps, exportable data tables and visualizations.

About NSR

NSR is the leading global market research and consulting firm focused on the satellite and space sectors. NSR's global team, unparalleled coverage and anticipation of trends with a higher degree of confidence and precision than the competition is the cornerstone of all NSR offerings. First to market coverage and a transparent, dependable approach sets NSR apart as the key provider of critical insight to the satellite and space industries. Contact us at info@nsr.com to discuss how we can assist your business. Visit us at www.nsr.com