April 5, 2021

<u>BY ELECTRONIC FILING</u>

Ms. Marlene H. Dortch
Secretary
Federal Communications Commission
45 L Street, NE
Washington, DC 20554

Re: Viasat, Inc., *Ex Parte* Presentation
Long-Form Application of Space Exploration Technologies Corp., Auction 904
File Number 0009149922 *et al.*;[1]
The Rural Digital Opportunity Fund (Auction 904), AU Docket No. 20-34;
Rural Digital Opportunity Fund, WC Docket No. 19-126;
Petition of Starlink Services, LLC for Designation as an Eligible Telecommunications Carrier, WC Docket No. 09-197;
Application of Space Exploration Holdings, LLC for Modification of Authorization for the SpaceX NGSO Satellite System, IBFS File No. SAT-MOD-20200417-00037;
Expanding Flexible Use of the 12.2-12.7 GHz Band, WT Docket No. 20-443

Dear Ms. Dortch:

Consistent with calls from both the legislature and the industry,[2] Viasat is writing to urge the Commission to fully and thoroughly examine the pending RDOF long-form application of SpaceX, applying the same policies that the Commission established late last spring and applied to all other applicants proposing to provide "Above Baseline" service by low-earth orbit ("LEO") satellites in Auction 904.

As demonstrated in the enclosed report entitled "Analysis of the Starlink System's Ability to Satisfy SpaceX's RDOF Commitments," the Starlink system falls short in satisfying SpaceX's RDOF commitments in a number of material respects ("Starlink RDOF Report").

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1 Neither SpaceX's long-form application nor the file number assigned to that application is publicly available at present. Viasat has referenced above the file number assigned to SpaceX's short-form application.

2 *See, e.g.,* Letter from The Honorable James E. Clyburn, Member of Congress, *et al.* to The Honorable Ajit Pai, Chairman, Federal Communications Commission, at 1 (Jan. 19, 2021), *available at* https://walberg.house.gov/sites/walberg.house.gov/files/WalbergFCCRDOFletter.pdf; Fiber Broadband Association & NTCA, *Starlink RDOF Assessment Final Report* (Feb. 8, 2021) (appended to Letter from Fiber Broadband Association & NTCA to FCC, WC Docket No. 19-126 and AU Docket No. 20-34 (Feb. 8, 2021).

- **With respect to geographic areas that contain 13% of SpaceX's provisionally awarded RDOF locations**, the geographic density of those locations exceeds Starlink's capability to serve them with RDOF-compliant service, *unless* SpaceX violates another obligation to the Commission—the commitment in its pending modification application to operate in a particular manner (the "Nco=1 commitment").[3] At these numerous RDOF locations, *SpaceX cannot satisfy **both** the Nco=1 commitment underlying its pending modification application, **and** its RDOF service obligations. These problem locations exist in **66%** of the states in which SpaceX is a provisional winner.*
- **With respect to a number of large geographic areas containing provisionally awarded RDOF locations,** even the complete 4,408 satellite Starlink configuration does not have enough satellites within view to deliver enough bandwidth to meet the combination of Above Baseline performance requirements (100 Mbit/s downstream speed with an 80/80 availability, 2 TB per month per location and 100 msec latency). This is the case even if each visible satellite were *fully dedicated* to serve only the set of RDOF locations that can see those exact same Starlink satellites, and even if SpaceX were to violate its Nco=1 commitment. *Starlink is unable to consistently serve all of those locations.*
- **With respect to the entirety of SpaceX's provisionally awarded RDOF locations**, a significant shortfall exists in SpaceX's ability to serve the minimum required number of RDOF locations with Above Baseline service, even with the complete 4,408 satellite Starlink configuration.

The Starlink RDOF Report calculates these shortfalls under a best-case scenario under which SpaceX has *absolutely zero* non-RDOF-based demand for Starlink capacity in the relevant areas. The identified capacity shortfalls would be even more severe if the analysis factored in the capacity SpaceX uses, or will use, for other purposes, such as other residential or commercial service offerings, or service to mobile terminals that traverse these areas.

This evidence that *SpaceX cannot satisfy both the Nco=1 limit underlying its pending modification application, and its RDOF obligations* is a serious matter that must be considered ***before*** the Commission acts on that modification application or SpaceX's RDOF long-form application. SpaceX's ability to operationally comply with its Nco=1 commitment is both (i) a

[3] SpaceX relies on compliance with its NCO=1 commitment to establish compliance with equivalent power flux density (EPFD) limits. *See* Letter from SpaceX to FCC, IBFS File No. SAT-MOD-20200417-00037, Att. at 3 (Apr. 2, 2021) ("SpaceX Apr. 2 Letter"). As SpaceX itself explains, "The United States and other administrations, acting through the International Telecommunication Union ('ITU'), have developed EPFD limits designed to protect geostationary orbit ('GSO') satellite systems against interference from non-geostationa1y orbit ('NGSO') satellite systems. The Commission has effectively adopted those limits and the ITU's analysis of them, requiring that NGSO operators (1) certify that they will comply with the EPFD limits, and (2) receive a 'favorable' or 'qualified favorable' EPFD finding by the ITU prior to initiation of service." *See* Letter from SpaceX to FCC, IBFS File No. SAT-MOD-20200417-00037 and WT Docket No. 20-443, at 1 (Mar. 9, 2021) (footnotes omitted).

critical underpinning of the claim that its pending modification application would not increase interference, and (ii) an issue of major contention in that proceeding.[4]

With respect to the shortfalls demonstrated in the Starlink RDOF Report, the simplest explanation may be that *SpaceX bid beyond its capabilities in Auction 904,[5] despite the Commission's express warning that doing so would constitute a default and lead to possibly significant forfeitures*.[6]

As detailed in the Starlink RDOF Report, the significant shortfalls in Starlink capacity exist because of a fundamental disconnect between (i) the maximum capacity of each of Starlink's 4,408 satellites, and (ii) and the geographic density of the specific RDOF-locations that SpaceX bid and provisionally won. That disconnect would not have been known to the Commission when approving SpaceX's short-form application, because the express purpose of the short-form stage was to determine whether "an applicant is eligible to bid for a performance tier and latency combination."[7]

It bears emphasis that a *fundamental difference* exists between (i) the "short, narrative responses" and "preliminary design" that must be provided to establish performance tier and latency bidding eligibility at the short-form stage (when the number and density of RDOF locations to be served is unknowable),[8] and (ii) a long-form application that must demonstrate a provisional winner's ability to serve the very specific locations that it bid and won, taking into account their geographic density and other relevant considerations that would reveal limitations on the performance of the network proposed to be employed. The long-form stage is precisely where the Commission anticipated addressing these matters:

> If the applicant becomes qualified to bid in Auction 904 and subsequently becomes a winning bidder, Commission staff will evaluate the information submitted in the long-form application . . . to determine whether an applicant is reasonably capable of meeting its Rural Digital Opportunity Fund auction obligations *in the specific areas where it has winning bids*.
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> . . .

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4 *See, e.g.,* Letter from DISH to FCC, IBFS File No. SAT-MOD-20200417-00037, WT Docket No. 20-443, and WC Docket No, 09-197 (Mar. 24, 2021), and various filings on the issue referenced therein.

5 Other possible motivations for doing so are beyond the scope of this letter.

6 *See Rural Digital Opportunity Fund*, 35 FCC Rcd 686, at ¶¶ 114-117 (2020) ("*RDOF Order*"); *Rural Digital Opportunity Fund Phase I Auction Scheduled for October 29, 2020; Notice and Filing Requirements and Other Procedures for Auction 904*, Public Notice, 35 FCC Rcd 6077, at ¶ 64 (2020) ("*RDOF Procedures PN*").

7 *Id.*

8 In the short-form application, the Commission deliberately limited the technical information that applicants needed to provide prior to the auction, requiring only that applicants answer specific questions intended to "elicit short, narrative responses" that would establish that the applicant had "developed a preliminary design or business case" for meeting RDOF obligations. *Id.* ¶ 69.

> A determination at the short-form stage that an applicant is eligible to bid for a performance tier and latency combination *would not preclude* a determination at the long-form application stage that an applicant does not meet the technical qualifications for the performance tier and latency combination and thus will not be authorized to receive Rural Digital Opportunity Fund support.[9]

In addition to the demonstrated shortfalls in Starlink's ability to satisfy RDOF requirements, public data show that Starlink is not providing consistent 100/20 Mbit/s speeds today, while serving a number of "beta" test users that amount to less than 2% of the number of provisionally awarded RDOF locations, despite having about 30% (1,300) of the complete 4,408 satellite constellation already in orbit. That is, SpaceX would have to increase the performance per satellite by more than an order of magnitude, compared with what it is has achieved after about 10 months of "beta" service in order to provide the equivalent of Above Baseline service to the existing "beta" customers. And even the reports of "beta" performance likely understate Starlink's limitations because "beta" customers have been selected in the most favorable geographic locations.[10]

As detailed below:

- Given the combination of Starlink specifications, as described in SpaceX's own documents, it appears that SpaceX could never satisfy the combination of Above Baseline RDOF requirements with its complete 4,408 constellation given the combination of geographic areas and density of locations that SpaceX itself chose to bid in the RDOF auction.
- That inability to satisfy SpaceX's RDOF commitments remains the case even if SpaceX were to exceed its Nco=1 commitment, because the total amount of Starlink capacity available over the entire RDOF cohort is insufficient—no matter how SpaceX may choose to spread its bandwidth.
- Significant limitations exist on SpaceX's ability to modify its network design to increase available capacity, and no *a priori* assumptions can be made about SpaceX's ability to do so.
- Significant doubt exists about SpaceX's ability to operate Starlink consistently with the pending modification application and still satisfy the 100 msec latency metric.

It is essential that the Commission fully address these matters at the long-form application stage, particularly given: (i) the massive size of SpaceX's provisional award; (ii) the preclusion of SpaceX competitors from participating in Auction 904 on equal footing with SpaceX; and (iii) calls for transparency in the Commission's Auction 904 determinations. Below, Viasat discusses these and other matters that are relevant to assessing SpaceX's inability to use Starlink to satisfy its RDOF commitments:

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9 *Id.* ¶ 64 (emphasis supplied).

10 *See* Michael Kan, *SpaceX's Starlink Targets January for Wider Public Beta Test*, PCMAG (Nov. 23, 2020), *available at* https://www.pcmag.com/news/spacexs-starlink-targets-january-for-wider-public-beta-test.

- Technical constraints on the ability of the Starlink network to serve the required number of specific, geographically distributed, and geographically dense RDOF locations with 100/20 Mbit/s speeds and a 2 Terabyte per month usage allowance.
- Technical constraints on the ability of the Starlink network to meet the 100 msec latency requirement with respect to those locations.
- Legal and technical constraints on SpaceX's spectrum rights and its ability to modify the Starlink network to increase capacity to meet demand.

As the Commission has already recognized:[11]

- "Auction 904 is not the appropriate venue to test unproven technologies using universal service support."
- "The record demonstrates significant concern regarding applicants that propose to use technologies that have not been widely deployed to offer services at high speeds or low latency, or have not been deployed at all on a commercial basis to retail consumers."

Each of these constraints must be fully analyzed to minimize the risk of a SpaceX default and the resulting adverse consequences on unserved locations, the integrity of Auction 904, and even the integrity of future auctions that could occur before an ultimate SpaceX default on its Auction 904 obligations becomes evident.

The issues discussed in this letter and the Starlink RDOF Report are relevant to each of the proceedings identified above, in which the performance and capabilities of Starlink have been asserted as a basis for Commission action.

I. Background

In June 2020, the Commission expressed great skepticism about the ability of any LEO service provider to meet the Commission's "low latency" performance metric in the absence of a "real-world performance example" of a "low earth orbit network capable of providing a mass market retail broadband service to residential consumers that could meet the Commission's 100 [msec] round-trip latency requirements."[12] The Commission further provided: "In the absence of such a real-world performance example, Commission staff could not conclude at this time that such a short-form applicant is reasonably capable of meeting the Commission's low latency requirements.[13]

At the same time, the Commission declined to rely on promises by SpaceX to deploy service to residential customers in the near term. Indeed, the Commission was unwilling to accept existing "trial" or "limited" deployments as evidence that an RDOF-compliant LEO deployment would be reasonably likely to occur. As the Commission explained:

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[11] *RDOF Procedures PN* ¶ 98.

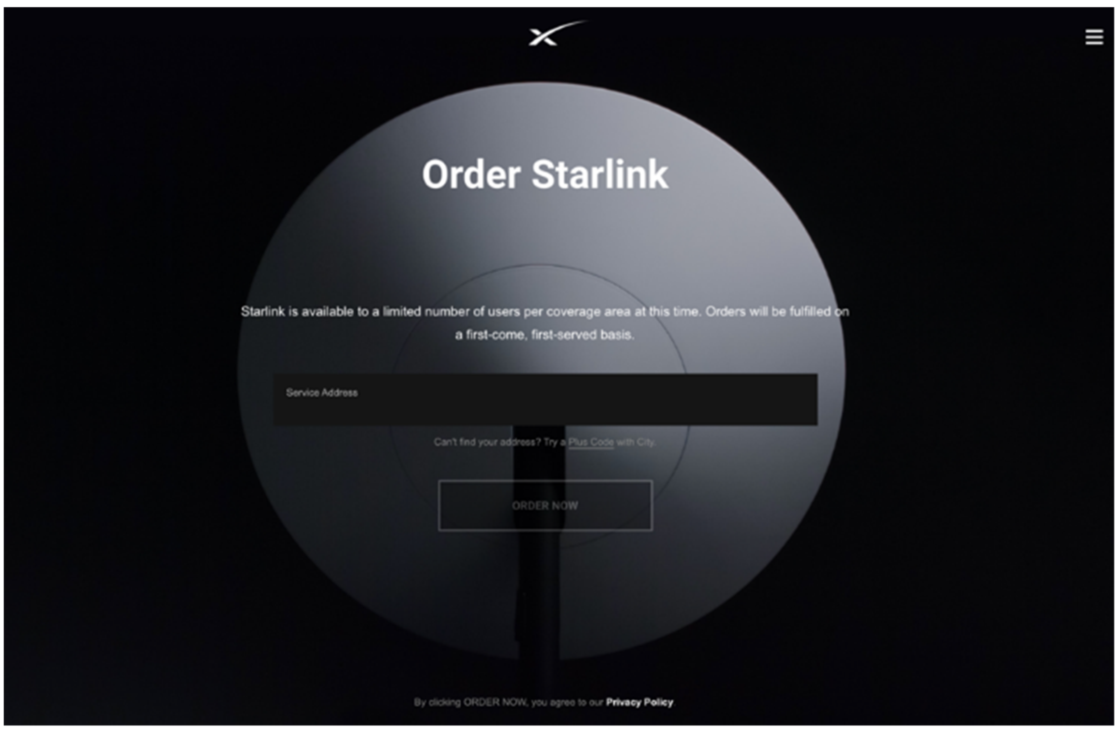
[12] *Id.* ¶ 111.

[13] *Id.*

> These kinds of trials or limited service offerings are not as instructive as mass market deployment; when services are offered on a commercial basis there is more of an opportunity to observe how networks using a particular technology perform *under varied real-world conditions or how networks use the technology at scale to meet demand*.[14]

Even after expressing this uncertainty, the Commission left open the possibility that applicants could demonstrate the viability of LEO satellite systems, whether based on data and experience drawn from other satellite systems or otherwise, and it accepted SpaceX's short-form application to the exclusion of all others that also proposed a low-latency RDOF offering.[15]

Now, nearly ten months since the issuance of RDOF Procedures Public Notice, SpaceX is still not providing "mass market retail broadband service" to "residential customers." All that exists today is a very limited Starlink "beta" service, self-described by SpaceX as being "available to a limited number of users per coverage area at this time" on a "first-come, first-served basis" (as reflected in the below screenshot from the Starlink website):[16]



[14] *Id.* ¶ 103 & n.235 (emphasis supplied) (citing Comments of Space Exploration Technologies Corp., AU Docket No. 20-34, at 4, 8 (Mar. 27, 2020), and SpaceX's claim that it "will now begin to offer its Starlink broadband service for consumers—first in the United States and Canada—by the end of 2020").

[15] The inability of Starlink to satisfy the RDOF performance requirements that the Commission has adopted, as discussed below, is a far more significant matter than whether Starlink qualifies as a "real-world performance example"—particularly given the significant lack of clarity and consistency with respect to that concept and its application at the Commission.

[16] *See* https://www.starlink.com/ (last visited Mar. 31, 2021).

The Starlink website also makes clear that this service has limited functionality—*i.e.,* SpaceX explains that there will be "brief periods of no connectivity at all."[17]

As discussed below, SpaceX still is not providing consistent 100/20 Mbit/s speeds, and the Starlink network has not been tested under "varied real-world conditions" nor has it "used [LEO] technology at scale to meet demand."

To point out the obvious, merely having about 1,300 satellites in orbit simply is not the same as providing consistent, reliable connectivity that satisfies RDOF requirements. The difficulty in meeting RDOF obligations arises from having to reliably satisfy the required high level of consistent performance (*e.g.,* 80% of the required speeds provided 80% of the time; required latency metric met 95% of the time; and doing so even when each location has a 2 TB/month usage allowance and those locations are geographically distributed in the specific census blocks provisionally won). While there are a number of ways an applicant could demonstrate its ability to satisfy those obligations, the deployment of large numbers of satellites that are not consistently providing 100/20 Mbit/s service is not one of them. And, as the Commission knows well, RDOF performance metrics represent a *minimum* required service level,[18] and are not satisfied by occasionally meeting or exceeding a given metric. Rather, the ability to satisfy those metrics is greatly affected by the worst test results.

As detailed when SpaceX's short-form application was pending, anecdotes by SpaceX of selective measurements on a lightly loaded network simply are not satisfactory evidence of an ability to meet the Commission's statistically based performance tests—nor an ability to meet a specific combination of Above Baseline performance metrics for the specific locations provisionally won.[19] As discussed below, measured data show that Starlink has not in fact been able to deliver *any* level of service reliably and consistently for the past nine months—even with locations that are specifically chosen to suit Starlink's geographic constraints. This low level of "beta" performance with about 1,300 satellites in orbit, and geographic distributions that are far more favorable to Starlink than the RDOF location distribution, is very concerning.

Moreover, Starlink satellites are not performing to design expectations. Indeed, publicly available data suggest that fundamental issues may exist with Starlink that could prevent those satellites from ever reliably delivering sub-100 msec latency or speeds of 100/20 Mbit/s—even with geographic distributions that are "easier" than those SpaceX selected with its provisionally won bids.[20] Furthermore, while it is generally understood that satellites can serve "anywhere," it

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17 *Id.*

18 *See RDOF Procedures PN* ¶ 15 ("In the auction, the Commission will accept bids for service at one of four performance tiers, each with its own *minimum* download and upload speed and usage allowance, and for either high or low latency service, as shown in the tables below.") (emphasis supplied).

19 *See* Letter from Viasat to FCC, IBFS File No. SAT-MOD-20200417-00037 (Oct. 5, 2020) ("Viasat Oct. 5 Letter"); *see also* Letter from Hughes Network Systems, LLC to FCC, IBFS File No. SAT-MOD-20200417-00037 (Sep. 21, 2020); Letter from Viasat, Inc. to FCC, IBFS File No. SAT-MOD-20200417-00037 (Sep. 17, 2020) ("Viasat Sep. 17 Letter"); Letter from Viasat, Inc. to FCC, IBFS File No. SAT-MOD-20200417-00037 (Sep. 24, 2020); Letter from Viasat, Inc. to FCC, IBFS File No. SAT-MOD-20200417-00037 (Sep. 25, 2020) ("Viasat Sep. 25 Letter").

20 *See supra* Sections II and III; *see also* Viasat Sep. 25 Letter.

is also true that all satellite networks face constraints related to the geographic density of their end users.

Under these circumstances:

- There does not appear to be any rational (and legitimate) explanation for why *only SpaceX* (among all LEO applicants) was allowed to bid an Above Baseline and 100 msec latency LEO service and provisionally win almost $900 million in subsidies; and
- It is imperative that the pending SpaceX long-form application be subject to careful scrutiny, especially given that the exact RDOF locations to be served are now known, and that each of the assumptions underlying that application be fully and rigorously tested.[21]

Even if issues about the *current* performance of Starlink could be resolved in SpaceX's favor, it is still critical to evaluate *over the relevant RDOF performance period*:

- All of the factors that affect estimated Starlink capacity—and thus SpaceX's expected ability to serve the specific and geographically concentrated RDOF locations with 100/20 Mbit/s service and a 2 Terabyte monthly usage allowance, including all factors that determine the aggregate capacity of each Starlink satellite, the capacity of each of the beams on each satellite, and the peak information rate for the Starlink user terminal (based on supporting information provided by SpaceX);
- All of the factors that affect the likelihood that Starlink will be able to support service that meets the Commission's 100 msec latency requirement, considering diverse end-user and gateway locations, the performance of its user terminals, and connections to different FCC-designated internet exchange points (IXPs); and
- Constraints on Starlink's ability to use its conditionally authorized spectrum, and to modify its system to increase capacity.

II. Technical Constraints on SpaceX's Ability to Serve Covered Locations With 100/20 Mbit/s Service and a 2 Terabyte Monthly Usage Allowance

SpaceX provisionally won RDOF support covering 642,925 locations.[22] SpaceX's eligibility to bid on this support was premised on its commitment to make available Above Baseline service, consisting of 100/20 Mbit/s speeds, ≥ 2 TB/month, and latency ≤ 100 msec

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[21] The Commission also should examine whether, and to what extent, the RDOF locations that SpaceX bid and provisionally won are consistent with the geographic assumptions embedded in its short-form application.

[22] *See Rural Digital Opportunity Fund Phase I Auction (Auction 904) Closes; Winning Bidders Announced*, 35 FCC Rcd 13888 (Dec. 7, 2020).

using Ku- and Ka-band spectrum over its Starlink LEO network.[23] SpaceX is conditionally authorized to operate a Ku/Ka-band LEO network to consist of approximately 4,400 satellites.[24]

As detailed below, Starlink *is not consistently providing 100/20 Mbit/s service today, and cannot support all required RDOF Locations with RDOF compliant service.*

A. Starlink Is Not Providing Consistent 100/20 Mbit/s Service Today

Based on the performance of the Starlink network to date, there is no valid basis on which to conclude that Starlink will be able to provide reliable and consistent 100/20 Mbit/s speeds—even for the most favorable distribution of users, let alone for the difficult challenges presented by the density of the RDOF locations associated with its provisionally winning bids. *Almost nine months since the filing of SpaceX's short-form application, publicly available speed tests of that network still show speeds* ***well below 100/20 Mbit/s,***[25] as reflected in the 200 days of daily averages depicted in Figures 1 and 2.

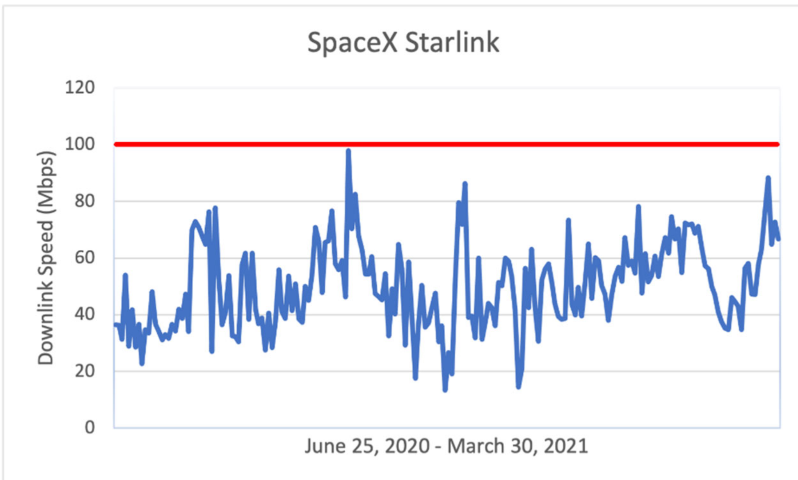

Figure 1: Measured Starlink Downlink Speeds

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[23] *See* Auction 904 File Number 0009149922 (SpaceX short-form application). SpaceX's short-form application sought eligibility to bid based solely on the use of Ku- and Ka-band spectrum. SpaceX has separately informed the Commission of its belief that its V-band conditional authorization is "not suitable for user service." *See* Letter from SpaceX to FCC, IBFS File No. SAT-MOD-20200417-00037 and RM-11768, Att. at 6 (Dec. 28, 2020) (explaining that V-band spectrum is "[n]ot suitable for user service") ("SpaceX Dec. 28 Letter").

[24] *See Space Exploration Holdings, LLC*, 34 FCC Rcd 12307 (2019).

[25] *See* TestMy.net, SpaceX Starlink, https://testmy.net/hoststats/spacex_starlink (showing, since June 2020, average download speed of 44.33 Mbit/s, average upload speeds of 10.4 Mbps) (last visited Mar. 31, 2021). Figures 1 and 2 below are derived from data provided on the TestMy.net web site.

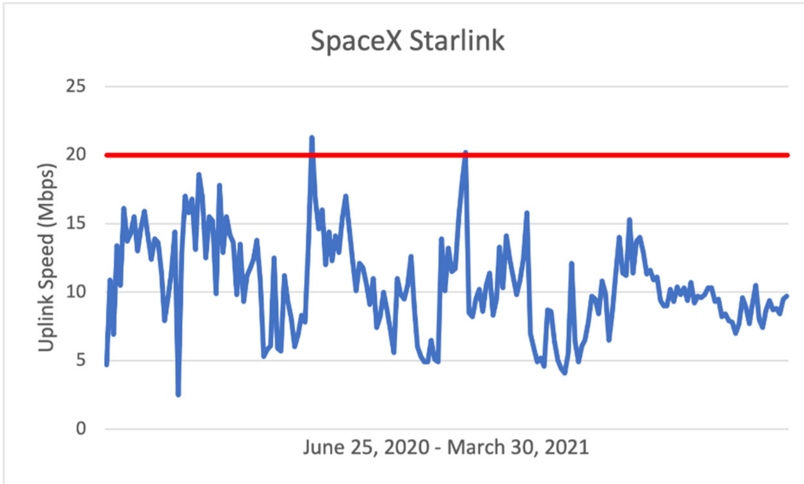

Figure 2: Measured Starlink Uplink Speeds

Nor would focusing on the most recent 1,000 speed tests[26] change this conclusion. Those more limited data still reveal an average downlink speed well below 100 Mbit/s (only 67.3 Mbit/s), and an average uplink speed well below 20 Mbit/s (only 9.3 Mbit/s), as shown in Figure 3.

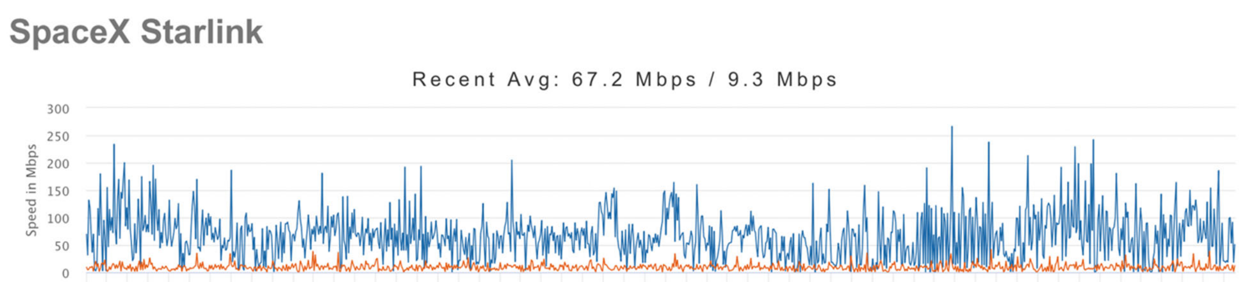

Figure 3: Last 1,000 Measured Starlink Speeds (downlink depicted in blue; uplink in red)

It would be no answer to this historical Starlink performance to refer to periodic instances of download speeds above 100 Mbit/s (or uplink speeds above 20 Mbit/s). Compliance with the Commission's performance metric for Above Baseline, 100/20 Mbit/s, speeds will be driven by the *worst* quintile of tests, not the best (*e.g.*, top decile or quintile). Moreover, it is relatively easy to produce favorable results by shifting bandwidth from one group of users to another when they are contending for the same bandwidth. The only meaningful conclusions that can be reached about Starlink performance require an analysis of the entire cohort of speed tests as a group.

26 https://testmy.net/hoststats/spacex_starlink (last 1,000 tests) (last visited Apr. 4, 2021).

Furthermore, as Viasat previously explained,[27] this type of data is a troubling sign that each individual Starlink satellite may not be able to reliably and consistently deliver 100/20 Mbit/s speeds to an individual terminal, even when very few terminals share access to that satellite at any given time. The nature of the problem becomes even more apparent considering that: (i) even if SpaceX were operating a full constellation of 4,408 satellites, on average only 206 satellites would be visible from SpaceX's provisional RDOF locations at any particular time at a minimum elevation angle of 40 degrees; and (ii) at times as few as 185 satellites would be visible at that same minimum elevation angle.[28]

Under best-case conditions, each Starlink satellite would need to be able to serve an average of 2,184 RDOF locations given: (i) SpaceX's obligation to serve approximately 450,000 locations (70% of 642,925); and (ii) that it would have an average of 206 Ku/Ka band satellites available at any time to serve those RDOF locations at 40 degrees. That means having to serve 45x more locations than Starlink is supporting today, but having only about 2.4x more satellites available (*i.e.,* ~ 3,100) to deploy than are in orbit today (with some of those ~1,300 in-orbit satellites themselves being inoperable).[29] Notably, SpaceX still needs further authority to deploy over 90% of those additional satellites.[30]

Individual Starlink user terminals will be served by only a single satellite at any instant in time. The amount of time required for a speed test (measured in seconds) is much shorter than the time that a terminal typically will connect to an individual satellite (measured in minutes). Therefore, a majority of speed tests would not involve a handover from one Starlink satellite to another, and thus should provide a reasonable representation of the speed performance of an individual Starlink satellite.[31]

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27 *See* Viasat Oct. 5 Letter at 2-3. While SpaceX's short-form application was pending, Viasat submitted for the record public data indicating that the average Starlink download speed over the most recent four-month period had been 39.6 Mbit/s—over 60% below the Commission's 100 Mbit/s requirement. Viasat also explained that SpaceX had not: (i) indicated whether the tests it claimed to have performed measured service speeds; or (ii) publicly provided data about any speed tests, or the methodologies employed in the tests it touted at the time.

28 SpaceX's pending application to modify its NGSO system license seeks authority to serve end users at elevation angles as low as 25° with all 4,408 satellites. That change from its current authority to do so at elevation angles 40° and greater is an issue of contention in that proceeding. At a 25° minimum elevation angle, the number of satellites able to serve SpaceX's provisional RDOF locations on average would be 295, and at times as few as 280 would be available. The RDOF implications of operating at that lower angle are discussed in the Starlink RDOF Report.

29 *See* https://planet4589.org/space/stats/megacon/starbad.html.

30 Under conditions to SpaceX's existing authorizations, the Commission must grant a separate modification application (*e.g.,* the pending third modification application) approving SpaceX's specific orbital debris mitigation plans before SpaceX can deploy satellites beyond the 1,594 that are fully authorized under its existing authorization. *See Space Exploration Holdings, LLC*, DA 21-34, at 7–8 & n.48, ¶¶ 14–15, 11, ¶ 19(t) (Jan. 8, 2021); *see also Space Exploration Holdings, LLC*, 33 FCC Rcd 3391 (2018); 34 FCC Rcd 2526 (2019).

31 It is highly unlikely that merely increasing the number of Starlink satellites would improve the performance of any individual satellite to a given individual user terminal. Adding more satellites would improve the number of satellites in view at any given point in time, could help to mitigate potential outages due to not having a satellite in view, could reduce the number of subscribers on an individual satellite when the system is fully operating, and could provide other benefits. But it would not change the performance of a given satellite.

Moreover, these measurements are occurring on a Starlink network that is very lightly loaded. By one account, there are only about 10,000 "users"[32] around the world (and fewer in the United States), using approximately 30% of the total number of conditionally authorized Ku/Ka band Starlink satellites. It is unclear if this reported number of "users" includes multiple end users at a single location (in which case the number of locations served could be far lower).

It is well understood that measured speeds on shared networks (such as satellites) are typically determined in the peak busy periods by provisioning (or oversubscription) ratios that further reduce the measured speed available to any individual subscriber on the satellite link, based on user demand statistics. Classic queuing theory tells us the relationship between offered load on a network and wait times (one on the many components of a total latency budget)[33] as a function of network capacity. As illustrated in Figure 4 below, the wait time is small as long as the offered load is well below capacity, but it increases dramatically (as 1/(1-(load/capacity))) when the offered load approaches capacity and begins to congest the network.

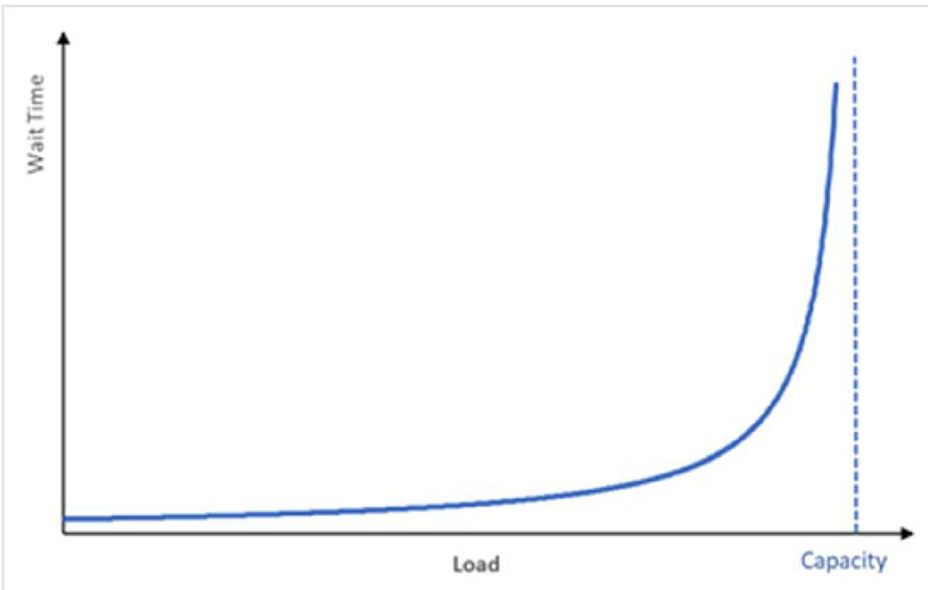

Figure 4: Queuing Delay vs. Load

Notably, the link parameters specified in SpaceX's license applications would be expected to support data rates far higher than those being reported. By way of example, speeds of 300 Mbit/s could be provided to as many as 66 simultaneous users per satellite *if*: (i) each satellite were actually capable of supporting an average of 20 Gbit/s of throughput (as SpaceX claims);[34] (ii) satellite payloads actually function consistently with the network design for a given

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[32] *See* Kate Duffy, *SpaceX is dominating orbit with its Starlink satellites, making the risk of space-traffic collision a serious hazard, industry experts say*, BUSINESS INSIDER (Mar. 28, 2021), *at* https://www.businessinsider.com/elon-musk-spacex-starlink-satellites-dominate-orbit-industry-experts-2021-3.

[33] *See* Letter from Viasat to FCC, IBFS File No. SAT-MOD-20200417-00037, at 4-6 (Sep. 25, 2020).

[34] *See e.g.*, Space Exploration Holdings, LLC, IBFS File No. SAT-LOA-20161115-00118, Narrative at 5 (Nov. 15, 2016) ("Each satellite in the SpaceX System provides aggregate downlink capacity to users ranging from 17 to 23 Gbps, depending on the gain of the user terminal involved. Assuming an average of 20 Gbps . . .").

application (in this case, residential service); and (iii) user terminals actually had the processing power to handle such speeds. Given that SpaceX has asserted the potential for gigabit speeds to individual users with Starlink,[35] it is somewhat unexpected and concerning that user terminals would not be consistently achieving 100/20 Mbit/s already.

These data call into question any assurances that SpaceX has provided in its long-form application. The Commission should ask SpaceX to reconcile the apparent inconsistency between its representations in its applications and Starlink's performance to date as reflected in the speed tests described above. Notably, SpaceX has had over nine months since these speed tests commenced to resolve issues with optimizing the speed provided through a single satellite. SpaceX also should be asked to reconcile these issues with the geographic constraints imposed by the exact locations of its provisionally winning RDOF bids.

As discussed below, a comparison of the theoretical capabilities of Starlink with the Commission's RDOF requirements provides even more reason to question SpaceX's long-form assurances.

B. Starlink Cannot Support All Required RDOF Locations With 100/20 Mbit/s Service and a 2 Terabyte Monthly Usage Allowance

As detailed in the Starlink RDOF Report, Starlink would not be able to provide RDOF-compliant service to all of its provisionally awarded locations, even if its network were both: (i) modified as proposed in its pending modification application; and (ii) fully deployed. Significant shortfalls still would exist in SpaceX's ability to provide RDOF-compliant service to many locations that must be covered. There just is not enough Starlink capacity (bandwidth) available in the specific geographic locations that SpaceX bid for and provisionally won.

The capacity shortfalls described below were calculated under a best-case scenario in which SpaceX has absolutely zero non-RDOF-based demands for Starlink capacity in these areas. The identified capacity shortfalls would be even more severe if the analysis factored in the capacity SpaceX uses, or will use, for other purposes, such as other residential or commercial service offerings, or service to mobile terminals that traverse these areas.

First, as depicted in the following Figure 4, with respect to geographic areas that contain 13% of SpaceX's provisionally-awarded RDOF locations, the geographic density of those locations exceeds Starlink's capability to serve them with RDOF-compliant service, *unless* SpaceX violates another commitment to the Commission (the Nco =1 commitment).

As noted above, SpaceX's ability to operationally comply with its Nco=1 commitment is an issue of major contention in the pending modification application proceeding. Complying with the Nco=1 commitment is essential for protecting other shared uses of the Ku band (satellite TV, VSATs, etc.).[36] Committing to limit the "number of co-frequency simultaneously

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35 *See, e.g.*, *id.* at 2 ("[T]he system will be able to provide high bandwidth (up to 1 Gbps per user), low latency broadband services for consumers and businesses in the U.S. and globally."); *id.* at 5 ("The system will be able to provide broadband service at speeds of up to 1 Gbps per end user.").

36 *See supra* n.3 and n.4.

transmitting satellites serving a given point on Earth"[37] limits the total equivalent power flux density (EPFD) produced by Starlink at that location. Specifying Nco=1 as a means of EPFD compliance is a design choice SpaceX made to comply with its license, which requires that it constrain EPFD levels to protect of GSO satellites.[38] SpaceX recently "confirmed that it has always operated its Ku-band downlinks to user terminals consistent with Nco =1 as that parameter is defined by the ITU for its EPFD analysis and will continue to do so in the future."[39]

The evidence in the Starlink RDOF Report that *SpaceX cannot satisfy **both** the Nco=1 limit underlying the interference analysis in its pending modification application, **and** its RDOF obligations*, is a serious matter that must be considered **before** the Commission acts on either that application or SpaceX's RDOF long-form application. *These problems areas exist in 66% of the states in which SpaceX is a provisional winner* (23 of 35 states),[40] as shown in Figure 5.

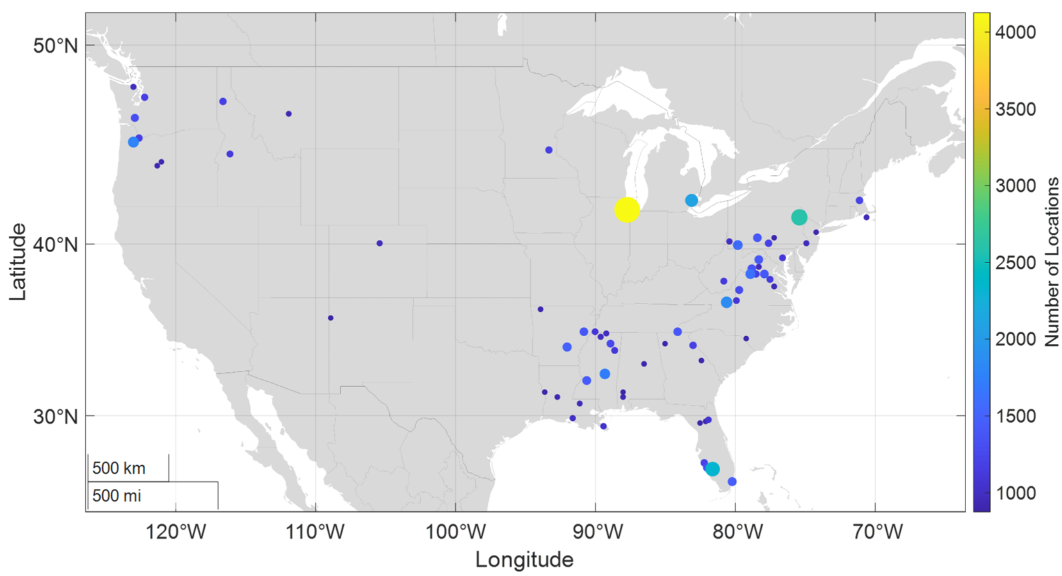

Figure 5: 22-km Diameter Areas Where SpaceX Cannot Meet RDOF Commitment[41] (number of locations per area illustrated by circle size and color)

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37 *See* SpaceX Apr. 2 Letter at 1.

38 *See Space Exploration Holdings, LLC*, IBFS File No. SAT-MOD-20200417-00037, DA 21-34, at ¶ 19 (Jan. 8, 2021). SpaceX could have designed its system, for example, to use an Nco=2.

39 *See* SpaceX Apr. 2 Letter, Att at 3.

40 As discussed in the Starlink RDOF Report, the 870 locations per area threshold is based on a Starlink capacity calculation that factors in overhead and derating for coexistence with Radio Astronomy, GSO, and NGSO services. If these factors were totally ignored, the threshold would be 1,370 locations, and there still would be 17 locations in 9 states representing 26% of the states in which SpaceX has received provisional awards and 5% of SpaceX's total provisionally awarded RDOF locations.

41 The smallest Starlink Ku-band transmit beam (22 km) supports the highest density of users in a given area. The 22 km value is the beam diameter at the sub-satellite point, *i.e.,* when the satellite is directly overhead, at 90° elevation. At lower elevation angles, the beam size becomes significantly larger and the location-density driven Starlink capacity shortfall increases. Insufficient capacity to cover geographically dense RDOF locations is the root source of SpaceX's RDOF capacity shortfall problem.

Table 1 below shows the breakdown by state. The only option SpaceX has to meet its RDOF commitment in these areas with its 4,408 Starlink satellites would be to violate its Nco=1 commitment—a commitment to limit operations so that each point on earth is illuminated in the Ku band at a given frequency only by at most a single satellite at a time. Adding more satellites would not help because all of the available spectrum has already been used in those areas.

State	Number of Areas with Over 870 SpaceX RDOF Locations	Number of SpaceX RDOF Locations in Those Areas
Alabama	3	2,731
Arkansas	3	3,802
Colorado	1	987
Florida	7	9,175
Georgia	3	3,013
Idaho	2	2,314
Illinois	1	4,126
Louisiana	5	4,847
Maryland	1	1,108
Massachusetts	2	2,174
Michigan	1	2,083
Minnesota	1	1,174
Mississippi	6	7,519
Montana	1	938
New Jersey	2	1,887
New Mexico	1	877
North Carolina	2	2,280
Oregon	4	4,795
Pennsylvania	7	9,880
Tennessee	1	1,095
Virginia	11	14,334
Washington	2	2,476
West Virginia	1	1,124
Total	68	84,739

Table 1: Breakdown by State of 22-km Diameter Areas Where SpaceX Cannot Meet RDOF Commitments

Second, because of the high concentration of provisionally awarded locations, the complete 4,408 satellite Starlink configuration would not have enough capacity to serve many provisionally awarded locations, even if each visible satellite were *fully dedicated* to serve only the set of RDOF locations that can see those exact same Starlink satellites. *Starlink would be unable to consistently serve all of those locations.* These simulation results are summarized in Figure 6 below.

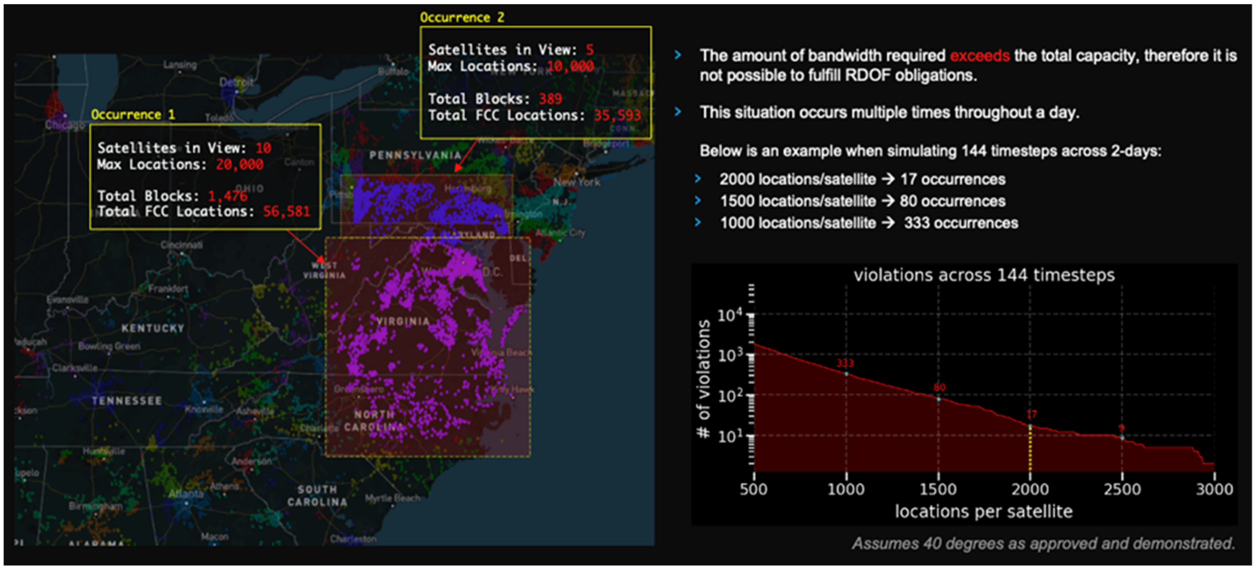

Figure 6: Capacity Violations as a Function of Number of Locations Per Satellite

This analysis also shows that SpaceX would fail to meet its RDOF obligations even if it were to ignore the Nco=1 requirement by "double illuminating" a given location. There is insufficient total bandwidth available on the satellites visible at these areas to serve the concentration of locations there. Exceeding the Nco=1 constraint in some beams would lead to shortfalls of capacity in other beams because of the limited total capacity on the satellites visible at these locations (number of visible satellites times capacity per satellite).

Third, even when Starlink capacity is tested for adequacy against *all* of the 642,925 provisionally-awarded locations, analysis reveals a significant shortfall in the capacity of the complete 4,408 Starlink system to serve the minimum required number of RDOF locations at the Above Baseline tier (70% of 642,925). This is shown in Table 2 below, where *a value of 100% would represent satisfaction of SpaceX's commitment to have enough capacity to support 70% of covered locations with Above Baseline service* (*i.e.,* 450,047 locations, or 70% of 642,925). The "derated" values in Table 2 include downward adjustments in theoretical capacity to account for the impact of the limitations on spectrum use discussed in Section IV below.

	40° Mask		25° Mask	
	No Derating	Derated	No Derating	Derated
400 Mbps	59%	53%	75%	65%
600 Mbps	61%	56%	78%	68%

Table 2: Shortfalls in Starlink's Capacity to Serve Minimum Required RDOF Locations (450,047 location baseline; 100% = compliance; less than 100% = shortfall)

Public information indicates that Starlink consumer terminals have a limited ability to electronically scan the sky,[42] meaning that a terminal cannot reliably communicate with every one of the Starlink satellites "visible" from horizon to horizon from the terminal's location. Rather, antenna performance begins to degrade approximately +/- 30° away from the face of the antenna, and the operational limit appears to be approximately +/- 40°.

The Starlink RDOF Report factors in this design limitation by analyzing the ability to serve covered RDOF locations with all satellites "visible" at a minimum elevation angle of +/- 40°. The 100° "visibility" range used in that analysis is broader than the scan range of the Starlink consumer terminal, and thus likely overstates the results in SpaceX's favor.

Given SpaceX's low latency commitment, and as discussed in Section III, it is prudent to assume a 40° elevation mask, as the Starlink RDOF Report does, but that report also includes calculations with a 25° mask in the event SpaceX can demonstrate how it can operate with a 25° mask and still satisfy the 100 msec latency requirement. Even in that case, a significant capacity shortfall exists, and Starlink cannot support with Above Baseline service 70% of all covered locations (*i.e.,* 450,047 locations, or 70% of the 642,925 provisionally awarded), as shown in Table 2 above.

III. Technical Constraints on Starlink's Ability to Meet 100 msec Latency Requirements.

In addition to satisfying relevant requirements with respect to speed and usage allowances, SpaceX must be able to provide ≤ 100 msec latency service on a fully loaded LEO network. SpaceX's long-form application must establish its ability to consistently satisfy this requirement.

As an initial matter, SpaceX has sought authority to operate the entire Starlink constellation at minimum elevation angles of 25°.[43] As detailed in the Starlink RDOF Report, use of this low an elevation angle is incompatible with the existing Starlink user terminal, given SpaceX's 100 msec latency commitment. Operating at elevation angles lower than 40° requires mechanically repointing the antenna.[44] Mechanical repointing takes about 0.067 of a second per degree of movement. Slewing even as little as a few degrees would require buffering in excess of SpaceX's entire 100 msec (or 0.1 second) low latency commitment in order to smooth over the loss of signal during a satellite handover.

Notably, no "real-world performance example" exists of a Starlink consumer antenna able to operate across that full range of elevation angles with a minimum 25°, nor is there any public indication of concrete steps toward developing and deploying such a terminal for RDOF.

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[42] *See, e.g.,* https://arstechnica.com/civis/viewtopic.php?f=2&t=1472589&start=120; *see also* IBFS File No. SES-LIC-20190211-00151, Narrative at A-1 (Feb. 11, 2019) ("SpaceX Service's [sic] user terminals will communicate only with those SpaceX satellites that are visible on the horizon above a minimum elevation angle. In the very early phases of constellation deployment and as SpaceX first initiates service, this angle may be as low as 25 degrees, but this will return to 40 degrees as the constellation is deployed more fully and more satellites are in view of a given end-user.") (footnote omitted).

[43] *See* IBFS File No. SAT-MOD-20200417-00037, Technical Attachment at 4-6 (Apr. 17, 2020).

[44] *See* IBFS File No. SES-LIC-20190211-00151, Narrative at A-1 n.2 (Feb. 11, 2019).

The Commission has suggested that this sort of risky technological development project is not what RDOF is intended to support.

Moreover, the Commission has recognized that additional network elements can affect the ability to satisfy the 100 msec latency requirement:

> Propagation delay in a satellite network does not alone account for latency in other parts of the network such as processing, routing, and transporting traffic to its destination. Short-form applicants seeking to bid as a low latency provider using low earth orbit satellite networks will face a substantial challenge demonstrating to Commission staff that their networks can deliver real-world performance to consumers below the Commission's 100 ms low-latency threshold.[45]

The Commission defines this "low-latency" threshold as "95% or more of all peak period measurements of network round trip latency [being] at or below 100 milliseconds[.]"[46]

A. Relevance to Latency of Representative Operating Conditions

The Commission requires that latency testing be conducted during a peak period defined as "between 6:00 p.m. and 12:00 a.m. local time, including weekends."[47] The Commission has explained that testing during this period "demonstrates the performance users can expect when the Internet in their local area is experiencing highest demand from users."[48]

Thus, it should be apparent that any valid measurements of latency on a network must account for the very significant effects of peak busy period loading, and geographic clustering of end users as well. This is consistent with basic principles that guide the design of broadband systems, as discussed above, with respect to the impact of traffic loading on network performance.

Stated another way, even an entirely terrestrial broadband network might not be able to meet the RDOF-required level of latency performance if that network is not correctly engineered, is not working as expected, or cannot be readily modified to increase capacity. That is why any measured performance data presented must be carefully examined to determine whether those data consist of statistically valid measurements gathered under representative operating conditions.

Thus, no valid conclusions can be drawn about whether the Starlink network is likely to be able to consistently operate at less than the 100 msec latency level that must be achieved as to

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45 *See RDOF Procedures PN* ¶ 112 (footnote omitted).

46 *See Rural Digital Opportunity Fund*, Report and Order, 35 FCC Rcd 686 (2020), at ¶ 32 ("*RDOF Order*").

47 *See Connect America Fund*, Order on Reconsideration, 34 FCC Rcd 10109, at ¶ 20 (2019) ("*Performance Measures Reconsideration Order*").

48 *See Connect America Fund*, Order, 33 FCC Rcd 6509, at ¶ 22 (2018) ("*Performance Measures Order*").

the "overall network"[49] in the absence of adequate data about a fully functioning network under representative operating conditions. Such conditions would include, among other things:

(i) Multiple customers simultaneously accessing the Starlink network with some frequency, and with bandwidth demands consistent with a 2 Terabyte per month usage allowance;

(ii) A wide variety of data types being transmitted during the measurements;

(iii) A diverse distribution of (A) customers within the geographically distributed locations reflected in SpaceX's provisional RDOF selection; (B) satellites, satellite beams and elevation angles being employed;[50] and (C) different gateways across the network (which may be located at varying distances from FCC-designated points-of-presence); and

(iv) The reality that only a small portion of the overall Starlink constellation is available to serve a given location at a given point in time.

B. Relevance to Latency of Geographic Diversity of Network Elements

As Viasat has explained previously, traffic to or from an individual Starlink user may be routed through different, geographically dispersed gateways at different times (or even during a single communications session), depending on the user's geographic location and the density of subscribers in the surrounding area.[51] Each such gateway may connect to an IXP with different propagation and queueing paths and statistics, and packets from different gateways somehow must be integrated into a single uninterrupted data stream.

The geographically diverse nature of the many components of the overall Starlink network (*e.g.,* end-user locations, gateway locations, terrestrial transport paths, IXP locations) can have a significant impact on performance measurements. Path delay between various locations will have a statistical distribution, *including* due to propagation delay, packet processing, and congestion on the terrestrial networks used to connect different Starlink gateways to FCC-designated IXPs.[52]

When a Starlink end user connects to different gateways, and those gateways connect to a packet integration and assembly point, additional terrestrial network propagation, processing, and/or buffering requirements exist beyond those required for purely terrestrial networks (where an individual user is more likely to always be connected to the same network point of presence—*e.g.*, gateway, tower, or local fiber node). Thus, the terrestrial component of the latency associated with the many different Starlink gateways is affected not just by the propagation distance to the FCC-designated IXPs, but also by the network issues associated with routing packets—such as congestion, switching, buffering, packet integration from multiple gateways for

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49 *Id.*

50 Approximately 15 ms of free-space propagation delay alone exists at 550 km when both gateways and user terminals operate at their lowest specified elevation angle—25 degrees.

51 *See* Viasat Sep. 17 Letter at 3-4; Viasat Sep. 25 Letter at 6.

52 *See* Viasat Oct. 5 Letter at 5.

each individual user (different users are likely to have different integrations), and the processing needed to ensure that packets are not dropped due to gateway hand-offs and duplicate packets are not introduced.

This is why any assertions about latency measurements taken with respect to the Starlink network must be examined closely to determine whether those measurements involved communications with different gateways across the network located at varying distances from FCC-designated points-of-presence.

C. Relevance to Latency of Gateway Connections with FCC-Designated IXPs

Latency testing for RDOF purposes *may not occ*ur with a peering point of a subsidy-recipient's own choosing. Rather, *it must consist* of suitable testing "between the customer premise of an active subscriber and an *FCC-designated* IXP,"[53] with sixteen metropolitan areas designated as containing such locations.[54] The Commission has provided that:

> For testing purposes, we define an FCC-designated IXP as any building, facility, or location housing a public Internet gateway that has an active interface to a qualifying ASN. Such a building, facility, or location could be either within the provider's own network or outside of it. We use the term "qualifying ASN" to ensure that the ASN can properly be considered a connection to the public Internet. . . . *The criteria we use to determine FCC-designated IXPs are designed to ensure that the peering point is sufficiently robust such that it can be considered a connection to the public Internet and not simply another intervening connection point*. We designate 44 major North American ASNs using CAIDA's ranking of Autonomous Systems and other publicly available resources as "safe harbors."[55]

SpaceX has previously indicated its intention to collocate its gateways at Internet peering points.[56] If such sites were used in the latency tests on which SpaceX relies, those tests would not factor in the additional latency inherent in the various terrestrial paths between the Starlink gateway earth stations and FCC-designated IXPs. Of the approximately 60 Starlink gateway locations now licensed or pending licensing before the Commission, *only 2 are within the metropolitan areas of FCC-designated IXPs*,[57] and over 90% more are located more than 10 nautical miles from those same areas. Figure 7 below depicts the relationship of those Starlink gateways to FCC-designated IXPs.

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53 *See Performance Measures Reconsideration Order* ¶ 13 (emphasis supplied).

54 *See Performance Measures Order* ¶ 20 (adding six new locations to ten existing FCC-designated IXPs).

55 *See Performance Measures Reconsideration Order* at ¶ 19 (footnotes omitted; emphasis supplied).

56 *See* Elon Musk tweet, October 2, 2020 ("As we're able to put more ground stations on roofs of server centers, legacy Internet latency will be zero."), https://twitter.com/elonmusk/status/1311923618679607298.

57 *See Performance Measures Order* at ¶ 20 (specifying the sixteen metropolitan areas as New York City, NY; Washington, DC; Atlanta, GA; Miami, FL; Chicago, IL; Dallas-Fort Worth, TX; Los Angeles, CA; San Francisco, CA; Seattle, WA; Denver, CO; Salt Lake City, UT; St. Paul, MN; Helena, MT; Kansas City, MO; Phoenix, AZ; and Boston, MA).

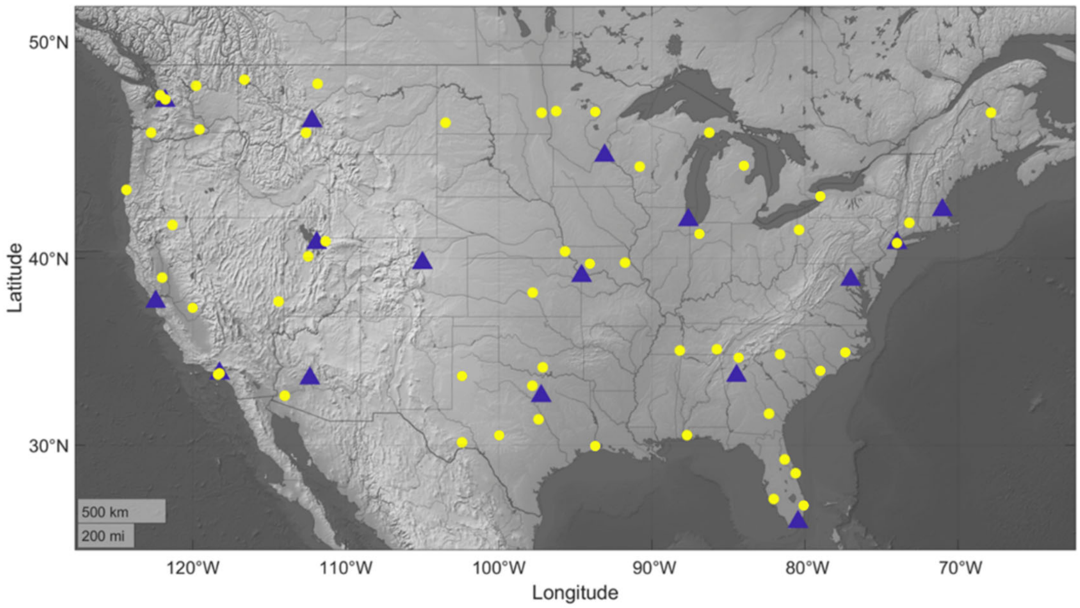

Figure 7: Starlink Gateway (yellow circles) and FCC IXP (blue triangles) Locations

Notably, the Commission has specifically rejected prior attempts to measure latency on only part of the relevant network paths.[58]

In light of the apparent difference between the peering points that SpaceX plans to use and the FCC-designated peering points for RDOF purposes, it is particularly important that the Commission closely examine any latency tests that SpaceX has provided to ensure consistency with RDOF requirements. Among other things, with respect to any measured data presented to attempt to establish satisfaction of the Commission's low latency requirement:

(i) The methodology used and data collected must be statistically valid and otherwise consistent with the Commission's testing mandates;

(ii) The measurements must reflect fully loaded *network* operations, be conducted *only* during peak busy periods, and include a suitable number of *boundary cases*—including the full range of elevation angles and gateway locations to be employed (which, again, affect latency); and

(iii) The data must be representative of the geographic diversity of the overall Starlink network once fully deployed, including end-user, gateway, terrestrial transport, and FCC-designated IXP locations throughout the service area, and the manner in which multiple gateways (and even more than are licensed today) would be used in combination to connect end-users.

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58 *See Performance Measures Reconsideration Order* ¶ 15 ("Adopting WTA's proposal to conduct its required tests over only half of the full testing span would only provide us with insight into the customer experience on half of the network between the customer and the IXP.").

IV. Starlink Constraints Due to NGSO Spectrum Limitations

SpaceX's spectrum license is subject to a variety of constraints that impair full theoretical use of its spectrum authorization, as well as limit its ability to modify the Starlink network to increase capacity by adding more satellites or changing the design of SpaceX's conditionally authorized satellites.

A. Starlink Capacity Reductions Due to Band-Splitting and Coordination

As the Commission is aware, Starlink shares spectrum with other NGSOs, and SpaceX must expect to access less than the full amount of spectrum covered by its LEO network authorization during alignments with other NGSOs that cause more than a certain level of interference, defined as $\geq 6\%$ $\Delta T/T$ (which equates to a -12.2 dB I/N). During such alignments, the affected NGSOs must equally divide the spectrum used in the relevant band for the duration of the interference events.[59] The net effect is an expected reduction of capacity. As a general matter, the number of expected band-splitting events scales with the size of the NGSO constellations involved.

The Starlink Ku/Ka-band network currently shares spectrum with eight other NGSOs authorized in the same processing round. As detailed in the Starlink RDOF Report, simply considering the impact of sharing spectrum with OneWeb yields an expected capacity reduction of about 5%.

Notably, this capacity reduction estimate reflects the impact of band-splitting only with respect to OneWeb, and does not account for any of the other seven NGSO constellations from the same round. Factoring in those other constellations would yield greater expected capacity reductions.

B. Starlink Capacity Reductions Due to Change in Spectrum Priority

Starlink's spectrum rights remain a matter of major contention in its modification application proceeding. A number of parties have demonstrated that Starlink should no longer enjoy its current priority rights because of the significant interference impact of that proposed modification on other Commission-authorized NGSO constellations.[60]

Should Starlink lose that priority, two factors would affect the amount of spectrum available to it, and thus the capacity of the Starlink network:

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59 *See* 47 C.F.R. § 25.261(c).

60 *See, e.g.,* Letter from SES Americom, Inc. and O3b Limited to FCC, IBFS File No. SAT-MOD-20200417-00037 (Mar. 18, 2021).

- Starlink would likely be required to coordinate with the other eight *prior-round* NGSO constellations, or otherwise demonstrate it would not cause them harmful interference, resulting in an unpredictable impact on Starlink capacity.[61]
- Starlink would likely be required to share the Ku/Ka band on equal terms with the other eight NGSO constellations authorized, or expected to be authorized, by the Commission in the *current processing round*. The Kuiper constellation alone would consist of over 3,200 satellites.[62] OneWeb seeks to operate almost 6,400 additional satellites,[63] and Telesat seeks to operate almost 1,600 more.[64] Any required band-splitting with over 11,000 additional satellites would undoubtedly reduce the available Starlink capacity.

C. Constraints on the Ability to Modify Starlink to Add Capacity

Because of the manner in which the Ku and Ka bands that Starlink utilizes is shared with other NGSO constellations, Commission policy imposes constraints on SpaceX's ability to modify its network to increase capacity by, for example:

- Increasing the number of satellites in the Starlink constellation;
- Increasing the number of beams employed on a given Starlink satellite;
- Changing the beam patterns employed on a Starlink satellite;
- Increasing the number of co-frequency uses per Starlink satellite; or
- Increasing the power density of the communications carriers employed on Starlink.[65]

Any of these changes could increase the number of times other NGSO systems would be required to reduce spectrum as a result of an increase in the number of predicted "band-splitting" events caused by a modified Starlink design. Thus, any of these changes would have to be evaluated with respect to the potential to create "significant interference problems" and make sharing with other NGSOs "significantly more difficult."[66] No *a priori* assumptions can be made about SpaceX's ability to implement such changes without adversely affecting the interference

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[61] *See Kuiper Systems, LLC*, 35 FCC Rcd 8324, at ¶ 34 (2020) (finding an "insufficient basis to treat Kuiper on an equal basis with earlier authorized systems under section 25.261 of the Commission rules" and requiring Kuiper to "coordinate to prevent harmful interference to operational systems licensed or granted U.S. market access in the previous NGSO FSS processing rounds"); *see also id.* at ¶ 50 (allowing Kuiper to alternatively demonstrate that it will not cause harmful interference to any prior-round system).

[62] *See id.* at ¶¶ 4, 58 (authorizing deployment of 3,236 satellites).

[63] *See* IBFS File No. SAT-APL-20210112-00007, Narrative at 1 (Jan. 12, 2021) (seeking authority for 6,372 additional satellites).

[64] *See* IBFS File No. SAT-MPL-20200526-00053, Narrative at 1-2 (May 26, 2020) (seeking authority for 1,554 additional satellites).

[65] A geostationary orbit satellite network has much more flexibility to implement changes to increase capacity as long as it satisfies the Commission's two-degree-spacing policies with respect to satellites in adjacent orbital locations.

[66] *See Teledesic LLC*, 14 FCC Rcd 2261, at ¶ 7 (1999).

environment, and as a result, altering SpaceX's spectrum rights in a manner that further limits the spectrum and capacity available for use with the Starlink system.

D. Starlink Capacity and Coverage Reductions for Other Reasons

1. Spectrum Limitations

While SpaceX nominally has access to 2 GHz of Ku-band downlink spectrum with which to serve RDOF subscribers, SpaceX has represented to the Commission that at least 250 MHz (or 12.5%) of this spectrum is not usable for that purpose. More specifically, SpaceX explained that "$\geq$ 250MHz of spectrum" is "not usable" because it must serve as a "guard band to protect Radio Astronomy [operating] in 10.6-10.7 GHz."[67] The capacity-reducing impact of this spectrum reduction is discussed in Section 4 of the Starlink RDOF Report.

2. GSO Protection

SpaceX is required to abide by certain equivalent power flux density (EPFD) limits in the Ku band. In order to do so, SpaceX has indicated that it will maintain a suitable avoidance from the geostationary orbit (GSO) arc.[68] Accounting for the 18° avoidance angle that SpaceX now says it intends to employ, the average expected impact on the system proposed in the pending modification application (4,408 satellites) is an expected 4.5% reduction in capacity over the CONUS, as discussed in Section 4 of the Starlink RDOF Report.

3. Impact of Unresolved Rulemakings

Starlink's spectrum authorizations remain subject to the outcome of various rulemakings,[69] including the Commission's *Orbital Debris* proceeding. In that proceeding, the

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67 *See* SpaceX Dec. 28 Letter, Att. at 6.

68 *See* IBFS File No. SAT-LOA-20161115-00118, Technical Attachment at 40 and Annex 1-1 (Nov. 15, 2016). SpaceX's ITU filings indicate that it plans to operate its modified system with a GSO arc avoidance areas of ±18 degrees.

69 *See, e.g.*, *Space Exploration Holdings, LLC*, 33 FCC Rcd 3391, at ¶ 17 (2018) ("*SpaceX Initial Authorization Order*") ("We note that, as with the OneWeb Order, Telesat Canada Order, and Space Norway Order, grant of the SpaceX application will not prejudge any decision, including a contrary action, in any future rulemaking proceedings. Rather, decisions of general applicability in such proceedings will be based on the totality of comments and proposals in those proceedings, including SpaceX's. Accordingly, in addition to being subject to any future proceedings, SpaceX would have to comply with any new orbital debris requirements."); *id.* ¶ 19 ("Below, we condition this grant of authority in response to comments and as warranted in the public interest. These conditions relate to . . . avoidance of interference, orbital debris mitigation, [and] future rulemakings[.]"); *id*. ¶ 40(r) ("This authorization is subject to modification to bring it into conformance with any rules or policies adopted by the Commission in the future. Accordingly, any investments made toward operations in the bands authorized in this order by SpaceX in the United States assume the risk that operations may be subject to additional conditions or requirements as a result of any future Commission actions."); *see also, e.g., Space Exploration Holdings, LLC*, 34 FCC Rcd 2526, at ¶ 22 (2019) ("We condition our grant of SpaceX's modified operations on the requirement that SpaceX comply with any rules or policies that result from the orbital debris proceeding and any other applicable proceeding, now or in the future.").

Commission has proposed to adopt an aggregate collision risk metric[70] that could significantly constrain SpaceX's ability to deploy the full number of satellites originally contemplated given its high experiential failure rate, and further limit network capacity.

Notably, a leading expert has just made the following call to action to address the "complete catastrophe" that could be on the horizon with respect to the unprecedented numbers of satellites being launched into LEO: "[F]irms should stop launching satellites when the number hits 1,000 and monitor them for a while to see if any problems crop up, such as design flaws."[71]

Moreover, considerable questions exist about the continued ability of SpaceX to rely on access to another 25% of its downlink spectrum to serve RDOF subscribers. Namely, the 12.2-12.7 GHz band is the subject of a pending Commission proceeding that is examining the possible introduction of 5G mobile services in that band.[72]

V. <u>Conclusion</u>

The complete 4,408 Starlink constellation likely cannot satisfy the Commission's RDOF performance requirements for Above Baseline service *with respect to speeds, usage allowances, or 100 msec latency*.

As detailed in the Starlink RDOF Report, a rigorous engineering analysis has identified significant shortfalls in the Starlink capacity needed to satisfy SpaceX's RDOF obligations. These shortfalls exist because of a fundamental disconnect between (i) the maximum capacity of each of Starlink's 4,408 satellites, and (ii) and the geographic density of the specific RDOF-locations that SpaceX bid and provisionally won. These facts would not have been ascertainable at the short-form stage and must be examined in processing SpaceX's long-form application.

It bears emphasis that the shortfalls would be even more severe if the Commission factors in the capacity SpaceX uses, or will use, for non-RDOF purposes, such as other residential or commercial service offerings, and service to mobile terminals that traverse these areas.

The simplest explanation for the identified RDOF capacity shortfalls may be that *SpaceX bid beyond its capabilities in Auction 904.* If so, that would constitute a default and give rise to potentially significant forfeitures.[73]

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70 *See Mitigation of Orbital Debris in the New Space Age*, Report and Order and Further Notice of Proposed Rulemaking, 35 FCC Rcd 4156, at ¶ 159 (2020); *see also id.* ¶ 160 (proposing reliability standards); *SpaceX Initial Authorization Order* ¶ 15 ("[W]e agree with NASA that the unprecedented number of satellites proposed by SpaceX and the other NGSO FSS systems in this processing round will necessitate a further assessment of the appropriate reliability standards of these spacecraft, as well as the reliability of these systems' methods for deorbiting the spacecraft").

71 *See supra,* n.32.

72 *See Expanding Flexible Use of the 12.2-12.7 GHz Band*, Notice of Proposed Rulemaking, WT Docket No. 20-443, FCC 21-13 (Jan. 15, 2021).

73 *See RDOF Order* ¶¶ 114-117.

The Starlink RDOF Report also demonstrates that *SpaceX cannot satisfy **both** the Nco=1 commitment underlying its pending modification application, **and** its RDOF obligations.* SpaceX's ability to operationally comply with its Nco=1 commitment is essential for protecting other shared uses of the Ku band (satellite TV, VSATs, etc.). *This is a serious matter that must be considered **before** the Commission acts on either that application SpaceX's RDOF long-form application*.

For these reasons, consideration of SpaceX's long-form application should be based on (i) a rigorous methodology provided by SpaceX indicating how a fully functioning Starlink network is designed to achieve sub-100 msec latency and 100/20 Mbit/s speeds to all locations required to be covered, with a 2 Terabyte monthly usage allowance, coupled with (ii) a statistically valid analysis of measurements of that network actually operating under fully-representative conditions, and communicating with FCC-designated IXPs throughout the network.

The Commission also should: (i) evaluate why *SpaceX still is not consistently providing 100/20 Mbit/s service*; (ii) consider that the Starlink network has not been tested under "*varied real world conditions*" or "*used at scale to meet demand*;" and (iii) evaluate the impact of SpaceX's inability to use all of its authorized spectrum, and its inability to freely modify its conditionally-authorized network to increase capacity to meet demand.

Respectfully submitted,

/s/

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DECLARATION OF MARK A. STURZA

I, Mark A. Sturza, hereby make the following declarations under penalty of perjury:

1. I am President of 3C Systems Company, which has acted as consultant to Viasat, Inc. ("Viasat") regarding the matters addressed in the foregoing letter and the Starlink RDOF Report.

2. I prepared the engineering information submitted in the foregoing letter and Starlink RDOF Report otherwise have reviewed its substance, which is complete and accurate to the best of my knowledge, information and belief.

/s/

Mark A. Sturza
President
3C Systems Company

April 5, 2021

Analysis of the Starlink System's Ability to Satisfy SpaceX's RDOF Commitments

A disciplined engineering analysis shows that the Starlink system is unable to fulfill SpaceX's RDOF commitments. Three different approaches were used to evaluate Starlink's ability to serve the 624,925 RDOF locations SpaceX has been provisionally awarded. All three show that Starlink will fall short.

The first two analyses are existence proofs using simple assumptions that are most favorable to SpaceX, but that readily establish the existence of serious shortfalls. The third is a more comprehensive analysis of the total SpaceX RDOF obligation.

The first analysis shows that there are multiple small clusters where the density of the RDOF locations provisionally awarded exceeds available Starlink capacity unless SpaceX violates other commitments to the Commission.

The second analysis shows that in a number of larger areas, the complete 4,408 satellite Starlink system does not have a sufficient number of satellites available at times to serve the provisionally awarded locations in those areas.

The third analysis shows that the complete 4,408 satellite Starlink system can provide RDOF Above Baseline service to only a portion of all of the RDOF locations for which SpaceX is required to have sufficient available capacity.

1 There are Multiple Locations Where the Density of SpaceX's RDOF Locations Exceeds Starlink's Capability

SpaceX has repeatedly stated that the maximum number of co-frequency satellites operating in the Ku-band to and from any point on the Earth is 1 ($N_{co} = 1$)[1]. Link budget analysis of the parameters SpaceX has provided in its FCC filings[2] suggest that the maximum supportable forward link data rate to a user terminal (UT) in a 250 MHz channel is approximately 600 Mbps[3]. Partitioning the 10.7 to 12.7 GHz downlink band into 8 channels of 250 MHz and counting dual polarization, the maximum Starlink forward link capacity to any point on the Earth is 8 x 2 x 600 Mbps = 9.6 Gbps[4]. This capacity could be provided by one satellite transmitting both polarizations in all 8 channels, by each of eight satellites transmitting both polarizations in a different one of the 8 channels, or by other combinations. The key point is that with a maximum of one co-frequency satellite transmitting to any point on the Earth at a

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1 For example, see Letter from SpaceX to FCC, IBFS File No. SAT-MOD-20200417-00037, Att. at 3 (Apr. 2, 2021).

2 Xia et al., "Beam Coverage Comparison of LEO Satellite Systems Based on User Diversification," IEEE Access, v. 7, Dec 2019, pp. 181656-181667.

3 The information rate capacity per beam when used for Starlink residential service is more likely to be around 400 Mbps, versus the 600 Mbps value used in this analysis – but it is shown that Starlink cannot meet its obligations even if each beam did support 600 Mbps for residential terminals.

4 This is an extremely optimistic estimate that does not account for the derating factors discussed in Section 4.

given time, the maximum forward link capacity to Starlink UTs at that point is 9.6 Gbps, regardless of which satellites are transmitting in each of the 8 channels.

The minimum Ku-band satellite transmit beam on the Earth's surface, per SpaceX's Mod 3 application, is a 22-km diameter spot[5]. If a second beam overlapped this spot and transmitted in a channel co-frequency with a channel the first beam was using, that would violate SpaceX's Nco = 1 commitment. Clearly, if SpaceX's RDOF locations within a 22-km diameter spot require more than 9.6 Gbps of forward link traffic, Starlink is not capable of supporting SpaceX's RDOF commitment. With the most optimistic calculation of Starlink capacity, Starlink could support a maximum of 1,370 RDOF locations in a 22-km diameter spot area. The 1,370 is best case, calculated as[6]:

$$9.6\ Gbps\ per\ area \times \frac{1}{0.7\ to\ account\ for\ the\ 70\%\ take\ rate} \times \frac{1}{10\ Mbps\ per\ location\ provisioning}$$

However, that simple calculation does not account for the various overhead and derating factors that are further discussed in Section 4. Optimistically assuming 600 Mbps per 250-MHz channel and adjusting for those factors, the 1,370 is reduced by a factor of 0.8 to 1,096 (20% overhead due to waveform overhead and oversubscription headroom) and including derating factors for spectrum sharing, it is further reduced to 870 locations (1,096 x 0.794).

The positions and number of locations for each of the census blocks provisionally awarded to SpaceX were analyzed to identify 22-km diameter spot areas that include more than 870 locations.[7] There are 68 of these areas with over 870 RDOF locations that SpaceX has committed to serve. They represent 84,739 of the locations SpaceX has been provisionally awarded in 23 States[8], or over 13% of the total SpaceX RDOF locations.

Figure 1 shows the locations of these areas. All the areas are 22-km in diameter, the larger circles on the plot indicate areas with larger numbers of SpaceX RDOF locations. Of the 68 areas, 17 contain more than 1,370 SpaceX RDOF locations, and 4 contain more than 2,000[9]. The largest, near Chicago, Illinois, contains 4,126 SpaceX RDOF locations. The 17 areas with over 1,370 locations include 31,101 RDOF locations SpaceX has committed to serve and represent 5% of the locations in 9 states. With either threshold, SpaceX clearly has a problem.

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5 This is for a Ku-band transmit beam at the sub-satellite point, i.e., when the satellite is at 90° elevation. At lower elevation angles, the beam size becomes significantly larger.

6 As discussed in Section 4, the 10 Mbps provisioning is consistent with the 2 TB cap for the Above Baseline service, assuming ~7% peak busy hour usage.

7 This analysis assumes that SpaceX has absolutely zero non-RDOF-based demands for Starlink capacity in these areas. If it did use capacity for other purposes, such as for mobile terminals that traverse these areas, that would make the problem even worse.

8 23 out of the 35 States in which SpaceX received provisional awards.

9 These 17 areas are important in that even in the most optimistic analysis that included the 70% take rate and ignored all overhead and derating factors, Starlink cannot support these areas.

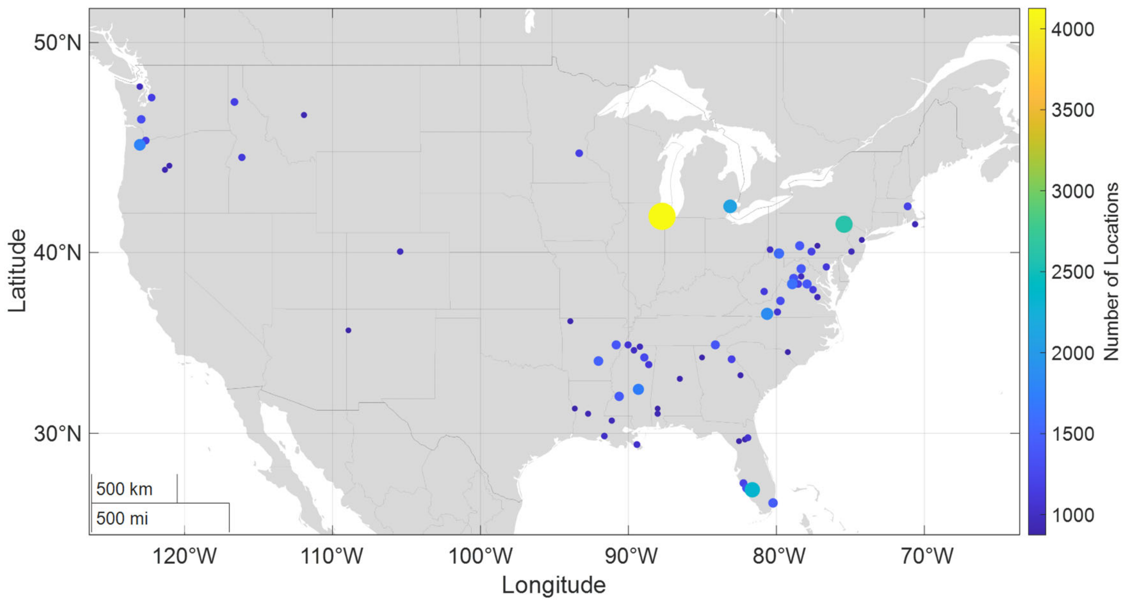

Figure 1 – 22-km Diameter Areas Where SpaceX Cannot Meet its RDOF Commitment (Number of locations in each area illustrated by circle size and color)

Table 1 shows the breakdown by state. For each state, the number of areas with over 870 and with over 1,370 SpaceX RDOF locations is shown. Also shown are the total numbers of SpaceX RDOF locations within those areas where SpaceX cannot meet its RDOF commitments.

The only option SpaceX has to meet its RDOF commitment in these areas would be to violate its commitment to the FCC to limit operation so that each point on earth is illuminated in the Ku band at a given frequency only by a single satellite at a time (the Nco = 1 commitment)[10]. Adding more satellites would not help because all of the available spectrum has already been used in those areas.

10 See Letter from SpaceX to FCC, IBFS File No. SAT-MOD-20200417-00037, Att. at 3 (Apr. 2, 2021).

Table 1 – Breakdown by State of 22-km Diameter Areas Where SpaceX Cannot Meet its RDOF Commitments

	Areas with Over 870 SpaceX RDOF Locations		Areas with Over 1,370 SpaceX RDOF Locations	
State	Number of Areas	Number of SpaceX RDOF Locations in Those Areas	Number of Areas	Number of SpaceX RDOF Locations in Those Areas
Alabama	3	2,731	-	-
Arkansas	3	3,802	2	2,885
Colorado	1	987	-	-
Florida	7	9,175	2	3,783
Georgia	3	3,013	-	-
Idaho	2	2,314	-	-
Illinois	1	4,126	1	4,126
Louisiana	5	4,847	-	-
Maryland	1	1,108	-	-
Massachusetts	2	2,174	-	-
Michigan	1	2,083	1	2,083
Minnesota	1	1,174	-	-
Mississippi	6	7,519	2	3,154
Montana	1	938	-	-
New Jersey	2	1,887	-	-
New Mexico	1	877	-	-
North Carolina	2	2,280	1	1,384
Oregon	4	4,795	1	1,779
Pennsylvania	7	9,880	3	5,599
Tennessee	1	1,095	-	-
Virginia	11	14,334	4	6,310
Washington	2	2,476	-	-
West Virginia	1	1,124	-	-
Total	68	84,739	17	31,101

2 There are Multiple Areas Where Starlink Has Insufficient Satellites Continuously Available to Support SpaceX's RDOF Commitments

Another simple method to quantitatively measure Starlink's ability to support SpaceX's RDOF commitments is to look at each satellite's location at an instance in time relative to areas of SpaceX obligations and see if there are occasions where – even if each visible satellite was *fully dedicated* only to the set of RDOF locations that can see those exact same satellites – the available capacity would fall short of that required to serve those locations, because of the high concentration of obligated locations. In such instances, Starlink would be unable to *consistently* serve all of the locations.[11]

Figure 2 summarizes the results of this aspect of the simulation – which is also described in further detail in Section 3. Assuming 20 Gbps per satellite[12] with 10 Mbps provisioning per location and ignoring overhead and derating, 17 different occurrences[13] of groups of SpaceX RDOF locations that fail the test were identified. When overhead and derating are factored in, as discussed in Section 4, the number of occurrences increases exponentially because of the resulting reduction in Starlink capacity and the lower numbers of supportable RDOF locations per satellite. It is very important to note that this analysis shows SpaceX would fail to meet its RDOF Above Baseline obligation even if Starlink were to ignore the Nco=1 requirement. There is insufficient total capacity (number of visible satellites times capacity per satellite) available to serve these concentrations of locations.

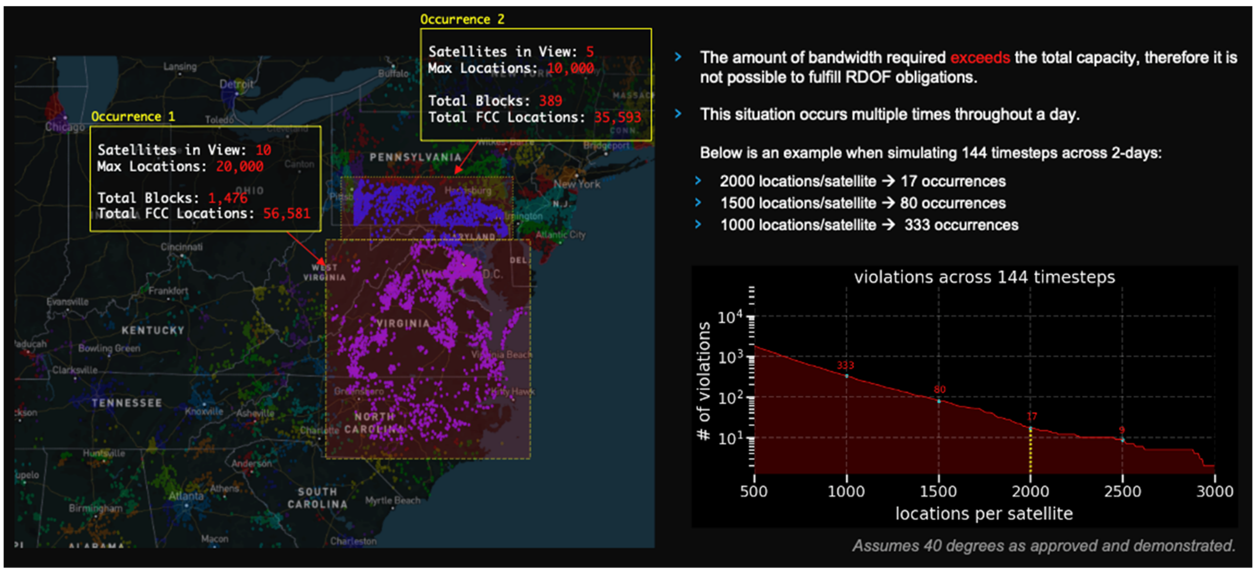

Figure 2 – Capacity Violation Results as a Function of Number of Locations Per Satellite

[11] This analysis also assumes that none of Starlink's capacity in these RDOF regions is allocated to non-RDOF demands for Starlink capacity.

[12] Space Exploration Holdings, LLC, IBFS File No. SAT-LOA-20161115-00118, Narrative at 5 (Nov. 15, 2016) ("Each satellite in the SpaceX System provides aggregate downlink capacity to users ranging from 17 to 23 Gbps, depending on the gain of the user terminal involved. Assuming an average of 20 Gbps . . .").

[13] An 'occurrence' exists when a group of census blocks all have the exact same satellites in view at the same instance in time, and total demand for bandwidth (sum of all locations) exceeds the total capacity those satellites can possibly provide.

3 The Complete 4,408 Satellite Starlink System Supports Above Baseline RDOF Service to Only a Portion of All RDOF Locations SpaceX Must Have Capacity to Serve

A series of detailed simulations were performed to estimate the Starlink system's ability to fulfill SpaceX's RDOF commitments, parameterized over a range of performance and operational conditions. The simulations employed the industry standard SGP4 simplified perturbations model to calculate the dynamic orbital position of each Starlink satellite within the Starlink 4,408-satellite constellation (as proposed to be modified) as a function of time. Each simulation iteration considered the positions of the satellites at 144 distinct timesteps. At each timestep, the simulation compared the locations of the satellites to the locations of each of the 19,234 provisionally-awarded RDOF Census Block Groups, containing in aggregate 642,925 RDOF eligible locations. Two user terminal elevation mask criteria (40° and 25°) were used to identify the specific set of Starlink satellites visible to each location at each timestep. The simulation then employed a "greedy" algorithm approach to optimally distribute the locations across the set of visible satellites, applying the minimum 70% subscriber take rate of Above Baseline service to determine the capacity required to be available for RDOF purposes. Satellites were allocated locations up a maximum per-satellite limit, as determined by the parameterized values selected for each run. The final output of each run was the percentage of provisionally awarded RDOF locations that were able to be successfully allocated to a satellite over each of the run's 144 timesteps.[14]

In this more detailed simulation analysis, the ability of Starlink to meet its RDOF obligations given a range of parameterized values was tested, as described in more detail in Section 4, included maximum downlink capacity per satellite (ranging from 4 to 20 Gbps), provisioning rate per subscriber (ranging from 3.6 Mbps to 10 Mbps per location), beam capacity per 250 MHz of spectrum (400 and 600 Mbps), and elevation mask angles of 40° and 25°. The relatively wide range of downlink capacity-per-satellite values reflects uncertainty regarding the number of steerable user beams that are actually implemented on each Starlink satellite, up to and including the average capacity per Starlink satellite as stated in the SpaceX application[15]. An overhead margin of 20% (600 Mbps beam assumption) or 25% (400 Mbps beam assumption) was applied, to ensure adequate headroom to achieve the required 80/80 RDOF speed performance metric with the required 2 TB/month usage allowance, and to account for physical layer, network management, oversubscription ration, and other overheads.

The simulation results, summarized in ***Table 2***, show that Starlink cannot meet SpaceX's RDOF commitments. A value of 100% is needed to meet the commitment to have enough bandwidth available to support 70% of the obligated locations, as required by the RDOF rules (i.e., 70% of 642,925, or 450,047). Even with the overly optimistic assumptions of no derating, 25° elevation mask, and 600 Mbps per 250 MHz channel, Starlink can only support 78% of the required 450,047 locations. The parameters used to generate ***Table 2*** include 20 Gbps per satellite raw information capacity, 70% take

[14] This simulation assumes that SpaceX has absolutely zero non-RDOF-based demands for Starlink capacity in areas where it has RDOF commitments. If it did use capacity for other purposes, such as for mobile terminals that traverse these areas, that would make the problem even worse.

[15] Space Exploration Holdings, LLC, IBFS File No. SAT-LOA-20161115-00118, Narrative at 5 (Nov. 15, 2016) ("Each satellite in the SpaceX System provides aggregate downlink capacity to users ranging from 17 to 23 Gbps, depending on the gain of the user terminal involved. Assuming an average of 20 Gbps . . .").

rate, 20% overhead for 600 Mbps per 250 MHz channel and 25% overhead for 400 Mbps per 250 MHz channel, and 10 Mbps per location provisioning. Those parameters are further discussed in Section 4.

Table 2 – Shortfalls in SpaceX's Ability to Serve Minimum Required Number of RDOF Locations (Derated values include RA, NGSO Sharing, and GSO Arc Avoidance)

	40° Mask		25° Mask	
	No Derating	Derated	No Derating	Derated
400 Mbps	59%	53%	75%	65%
600 Mbps	61%	56%	78%	68%

Appendix 1 describes the results of the simulation more fully and depicts the breadth of the sensitivity analysis performed.

4 Parameters Used in This Analysis

4.1 Provisioning and Average Usage

The Starlink system is shared by many users, thus the total capacity available must be able to serve both average usage and peak speed commitments. Peak speed commitments result in the need to reserve capacity as headroom, discussed later, but here we focus on average usage. For each TB per month that a user consumes, a system needs to have 5.2 Mbps of capacity available per user in the peak busy hour[16]. Different ISPs and different research organizations report a relatively broad range of current average consumption per household – which depends to some extent on the type and quality of broadband service to those households being measured. Average household consumption already exceeds 400 GB/month with many estimates significantly higher[17]. Consistent with historical increases in average consumption during the busy hour (currently estimated at an annual growth rate of about 22% to 35%[18], due to rapid growth in "cord cutting", video streaming, and greater bandwidth demands

[16] Assuming a typical 7% of daily consumption occurring in the peak busy hour.

[17] OpenVault, referenced in the Commission's Urban Rate Survey as an authoritative "similar data source" (DA 20-1409 Released: November 30, 2020 Wireline Competition Bureau and Office of Economics And Analytics Announce Results Of 2021 Urban Rate Survey for Fixed Voice and Broadband Services, Posting of Survey Data And Explanatory Notes, And Required Minimum Usage Allowance For Eligible Telecommunications Carriers WC Docket No. 10-90 at p. 4) measured 483 GB/month average usage in 4Q2020, https://www.telecompetitor.com/clients/openvault/2020/Q4/report/LP/index.html. Measurement on behalf of the Wall St. Journal showed consumption of 413 GB/month in the Fall of 2020, https://www.wsj.com/articles/americans-working-from-home-face-internet-usage-limits-11603638000.

[18] Cisco's Visual Networking Index has been a standard industry reference on internet trends and has established a clear difference between general and peak busy hour growth rates, noting for example "Although average Internet traffic has settled into a steady growth pattern, busy hour traffic (or traffic in the busiest 60-minute period of the day) continues to grow more rapidly than average Internet traffic. Service providers plan network capacity according to peak rates rather than average rates. Between 2017 and 2022, global busy hour Internet use will grow at a CAGR of 37 percent, compared with 30 percent for average Internet traffic.", https://newsroom.cisco.com/press-release-content?articleId=1955935. OpenVault's year-over-year estimates of usage over several quarters in the range of 1Q2018 to 4Q2020 have ranged from 27% to 47% with 40% for the most recent 4Q2020 to 4Q2019, https://www.telecompetitor.com/clients/openvault/2020/Q4/report/LP/index.html. Comcast in its 2020 Network Report notes 38% usage growth in 2020 and 29% usage growth in 2019 prior to the pandemic in

due to school from home, work from home, and video socializing), the required rate will grow materially in the next few years (i.e., to 0.78 TB per month by the initial RDOF buildout date in December 2024 and to well over 2 TB per month by 2029 – even using low end estimates for current usage and growth rates). Given that RDOF requires a 10-year support commitment and that the Above Baseline Tier requires a minimum 2 TB monthly usage allowance from the beginning of service, 10 Mbps provisioning is the baseline value used in this analysis.

4.2 Elevation Mask

SpaceX's pending application to modify its NGSO system license seeks authority to serve end users at elevation angles as low as 25° with all 4,408 satellites. That change from its current authority to do so at elevation angles 40° and greater is an issue of contention in that proceeding.

The physical characteristics of Starlink's user terminal (UT) aka "Dishy", for example the spacing of the phased array elements, are consistent with a vertically oriented beam unable to cover below 40° elevation angle relative to the horizon[19]. This is entirely consistent with SpaceX's current authority to operate with a 40° elevation mask. As SpaceX has applied for permission to operate its entire system with a 25° elevation mask and is presumably claiming this flexibility in its capacity calculations, both elevation angle masks are considered in this report.

However, use of a 25° elevation angle is incompatible with the Starlink UT, because of SpaceX's RDOF 100 ms latency commitment. As noted in SpaceX's blanket earth station application,[20] operating at elevation angles lower than 40° requires mechanically repointing the antenna. Mechanically repointing an antenna with the characteristics of the Starlink UT might be expected to change azimuth at a rate of 10°/s to 40°/s; observing and timing the slew rate of Starlink's own UT as shown in a teardown demonstrates a rate of approximately 15°/s.[21] Slewing even as little as a few degrees would require buffering in excess of SpaceX's entire 100 ms low latency budget in order to smooth over the loss of signal during a satellite handover.

Given SpaceX's low latency commitment, it is prudent to assume a 40° elevation mask, and we have done so, but we have also included calculations with a 25° mask in the event SpaceX can demonstrate how it can operate with a 25° mask and still satisfy the 100 ms latency requirement.

4.3 Headroom

Communication systems achieve less than their raw or theoretical throughput for a number of reasons including, preambles, guard time intervals, acquisition and handover, control/traffic signaling, and

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overall usage (peak busy hour growth would be higher) (Comcast 2020 Network Report, https://corporate.comcast.com/press/releases/comcast-2020-network-performance-data. Though Covid-19 has accentuated growth, peak busy hour growth rates approaching and exceeding 30% were common prior to the pandemic.

19 https://arstechnica.com/civis/viewtopic.php?f=2&t=1472589&start=120. Any flat faced antenna is subject to degradation on the order of the cosine of the angle from boresight; this effect would already cause some material loss between 30° and 40° for this antenna; in addition any irregularity in manufacturing of the array will degrade directivity further from the ideal.

20 IBFS File No. SAT-MOD-20200417-00037, Technical Attachment at 4-6 (Apr. 17, 2020).

21 https://hackaday.com/2020/11/25/literally-tearing-apart-a-spacex-starlink-antenna/.

monitoring/management traffic. Even in a well-designed system, these limitations will accumulate to several percent of traffic.

In addition, any commitment to a speed requirement, such as achieving 80% of a target speed on 80% of tests as required by RDOF, necessitates reserving headroom so that locations can be adequately served in the many instances where users compete for bandwidth. A graphical depiction of the statistically required headroom is shown in Figure 3. This headroom is a simple linear function of the "oversubscription ratio" between the total number of users sharing a single pool of information rate (e.g., a satellite beam) and the number that could share it if all were actively consuming their full obligated data rate all the time; to make this clear we will refer to it as "oversubscription headroom".

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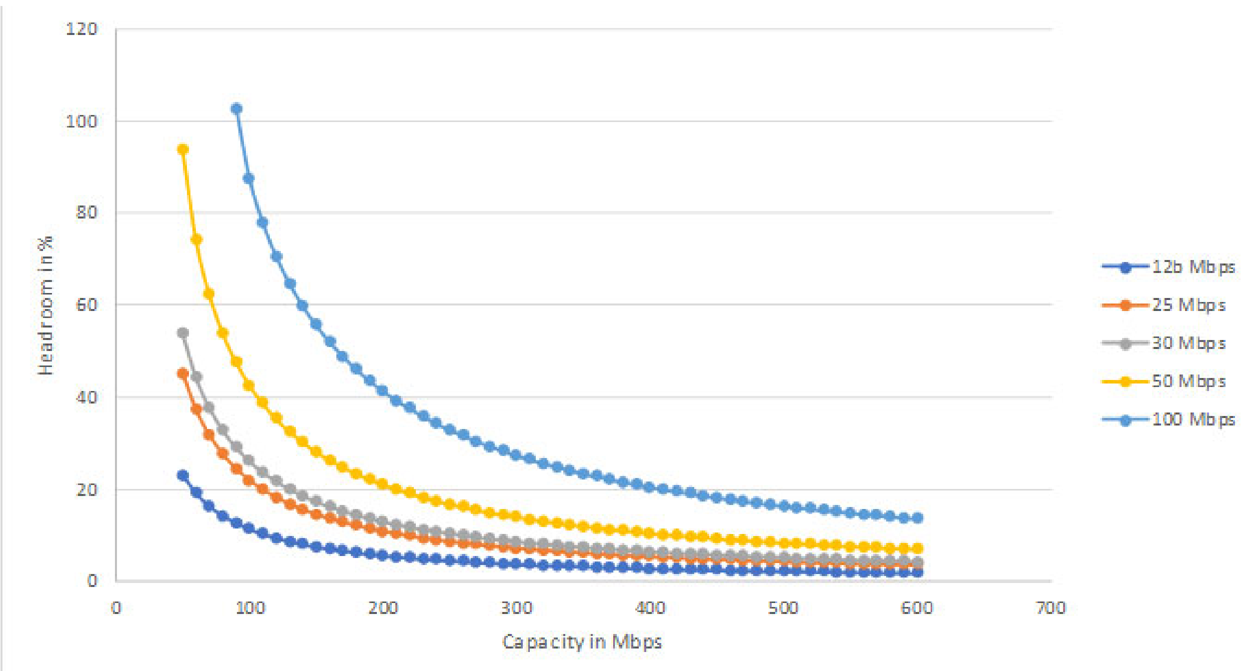

Figure 3 – Headroom Estimate for 80/80 SLA

As noted above, estimated link budgets for the Starlink system suggest a *maximum* throughput per 250 MHz forward downlink carrier of ~600 Mbps. Such budgets do not include compromises typically made for consumer grade terminals in which specifications such as phase noise are significantly relaxed in return for cost savings. A reasonable expectation would be that consumer terminals achieve one-half to two-thirds of the throughput that might be expected on a more expensive enterprise terminal. Consequently, both enterprise grade performance at 600 Mbps, and consumer grade performance at 400 Mbps, are considered in this report. From Figure 3, a 600 Mbps peak speed necessitates ~15% overhead for oversubscription headroom alone for a 100 Mbps speed commitment and adding another 5% for all other forms of physical layer and network overhead results in 20% total overhead. Similarly, a 400 Mbps peak speed necessitates 20% for oversubscription headroom and an additional 5% for other forms of overhead, resulting in 25% in total overhead.

4.4 Spectrum and Interference Based Derating

As discussed below, SpaceX faces a 12.5% reduction in capacity due to spectrum constraints needed in order to coexist with Radio Astronomy, another 4.5% reduction to coexist with GSO networks, and a further 5% reduction to coexist with other NGSO systems in the 10.7 to 12.7 GHz band. These coexistence mitigations are independent; hence the total resulting capacity derating is given by:

$$1 - (1 - 0.125) \times (1 - 0.045) \times (1 - 0.05) = 0.206\ (20.6\%)$$

Thus, if Starlink's raw forward link capacity actually is 20 Gbps per satellite on average,[22] its useful capacity has to be derated to 15.88 Gbps per satellite. Note that this does not include the derating for separate overhead or oversubscription headroom allocations discussed above. Further detail on each of these spectrum constraints is described in the sections below.

4.4.1 Sharing with Radio Astronomy

While SpaceX nominally has access to 2 GHz of Ku-band downlink spectrum (the 10.7 to 12.7 GHz band) with which to serve RDOF locations, SpaceX has represented to the Commission that at least 250 MHz (or 12.5%) of this spectrum is not usable for that purpose. More specifically, SpaceX explained that "≥ 250MHz of spectrum" is "not usable" because it must serve as a "guard band to protect Radio Astronomy [operating] in 10.6-10.7 GHz."[23] This represents losing access to 12.5% of forward downlink spectrum, and results in a 12.5% capacity derating.

4.4.2 Sharing with Other NGSOs

Starlink shares spectrum with other NGSO systems, and SpaceX must expect to access less than the 2 GHz of Ku-band downlink spectrum (the 10.7 to 12.7 GHz band) covered by its LEO system authorization during alignments with other NGSO systems that result in an excess of 6% $\triangle T/T$ (-12.2 dB I/N). During such alignments, the affected NGSO systems must equally divide the spectrum used in the relevant band for the duration of the interference events.[24] The net effect is an expected reduction of capacity. As a general matter, the number of expected band-splitting events scales with the size of the NGSO constellations involved.

Starlink currently shares spectrum with eight other NGSO systems authorized in the same processing round. The next-largest constellation in that round is OneWeb's. **Figure 4**, from SpaceX's pending LEO network modification application,[25] depicts their prediction of how often band-splitting events can be expected to occur with respect to the OneWeb system. SpaceX expects to exceed the band-splitting trigger about 10% of the time with OneWeb downlinks, yielding an expected capacity reduction of about 5% (loss of 50% of the spectrum 10% of the time)—a 5% capacity derating.

While the FCC's rule does not require band splitting if the operators can coordinate, no details of any such coordination agreements are publicly available. Further, while coordination could be used to

[22] Space Exploration Holdings, LLC, IBFS File No. SAT-LOA-20161115-00118, Narrative at 5 (Nov. 15, 2016) ("Each satellite in the SpaceX System provides aggregate downlink capacity to users ranging from 17 to 23 Gbps, depending on the gain of the user terminal involved. Assuming an average of 20 Gbps . . .").

[23] *See* SpaceX Dec. 28 Letter, Att. at 6.

[24] *See* 47 C.F.R. § 25.261(c).

[25] *See* IBFS File No. SAT-MOD-20200417-00037, Technical Attachment, at A1-4, Figure A1-1 (Apr. 17, 2020).

reduce the operational burden of band splitting, for example by preplanning, it is unclear how it could mitigate the loss of capacity.

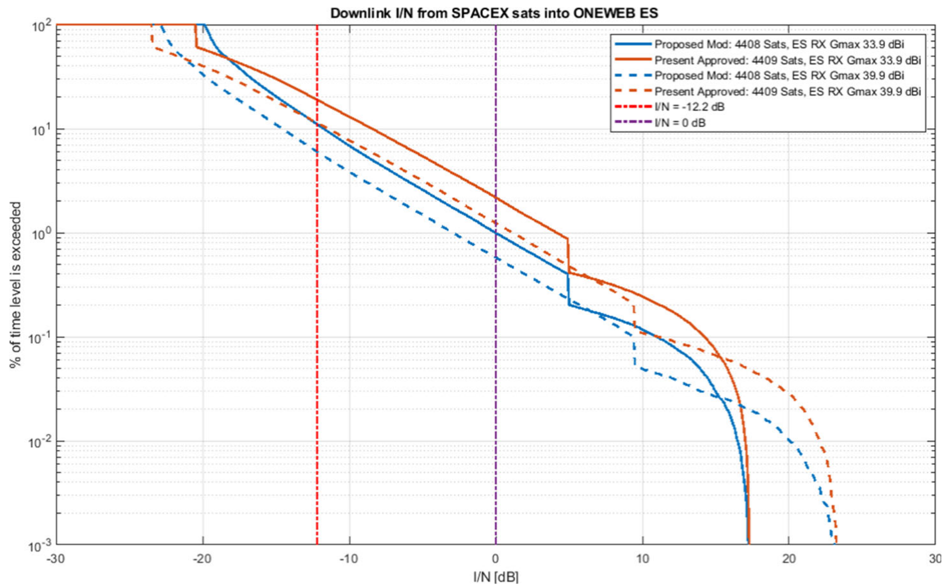

Figure 4 – Plot from SpaceX's Mod 3 Application Showing Downlink I/N from SpaceX Satellites into OneWeb ES

4.4.3 Sharing with GSOs

SpaceX's authorization in the 10.7 – 12.7 GHz spectrum is conditioned on complying with ITU Art. 22 EPFD limits. As evidenced by SpaceX's ITU filings, SpaceX plans to fulfill this obligation by enforcing an 18° avoidance angle relative to the GSO arc. This means that SpaceX will not operate a satellite-UT pair that has a line-of-sight vector passing within 18° of the GSO arc.

A simulation study was conducted to evaluate the impact of this avoidance angle on capacity. The Starlink Mod 3 (4,408 satellite) constellation was modeled with the RDOF locations that SpaceX has been conditionally awarded. The simulation results show that for an average of 4.5% of the time, the avoidance angle constraint would prevent operation of a particular satellite-UT pair, effectively derating SpaceX's capacity by 4.5%.

SpaceX has not publicly explained how it might mitigate this expected loss of capacity.

Appendix 1: Simulation Results

The following **Figures 5-12** show the simulation results at selected combinations covering the complete parameter space. All the simulations were based on the requirement that RDOF recipients must have enough bandwidth to support at least a 70% of the locations they are obligated to serve and at the Above Baseline service level. The results are summarized in **Table** 3.

The assumptions that are the most favorable to Starlink are shown in Figure 9. Even if each Starlink beam supports a 600 Mbps information rate to a residential terminal and each terminal can operate at an elevation angle down to 25° while meeting the 100 msec latency requirement, Starlink could still only deliver enough bandwidth for ~1 TB/month to the 70% of locations SpaceX is obligated to serve under RDOF. That is, at best, using unrealistically favorable assumptions, SpaceX would only meet about half its obligation for consumption. Looking at it another way, Starlink could only deliver 2 TB/month to about 78% of the total number of locations SpaceX is obligated to serve (again best case).

The assumptions that are far more likely, and least favorable to Starlink, are depicted in Figure 8. That set of assumptions assumes 400 Mbps information rate per beam, 25% network and oversubscription overhead, a 40° minimum elevation angle (electronic steering), and derates the available spectrum for the factors identified (radio astronomy, in-line events with OneWeb, and 18° geostationary arc avoidance). In that scenario SpaceX would meet its obligation of 2 TB/month/location (10 Mbps provisioning) for 53% of the locations SpaceX is obligated to serve.

The other lines in the table and figures illustrate various other combinations of the parameters considered. None of them is sufficient to meet the SpaceX's RDOF obligations.

Table 3 – Summary of Simulation Results

Elevation Mask	Network and Oversubscription Overhead	Raw Information Rate per Beam	Derating	Figure	Provisioning Level That Could Be Delivered to All Required Locations[26]
40°	20%	600 Mbps	0%	Figure 5	None of those considered
			20.6%	Figure 6	None of those considered
	25%	400 Mbps	0%	Figure 7	None of those considered
			20.6%	Figure 8	None of those considered
25°	20%	600 Mbps	0%	Figure 9	5.2 Mbps (1 TB/month/location)
			20.6%	Figure 10	3.6 Mbps (0.8 TB/month/location)
	25%	400 Mbps	0%	Figure 11	3.6 Mbps (0.8 TB/month/location)
			20.6%	Figure 12	None of those considered

[26] Minimum of 70% of total number of locations.

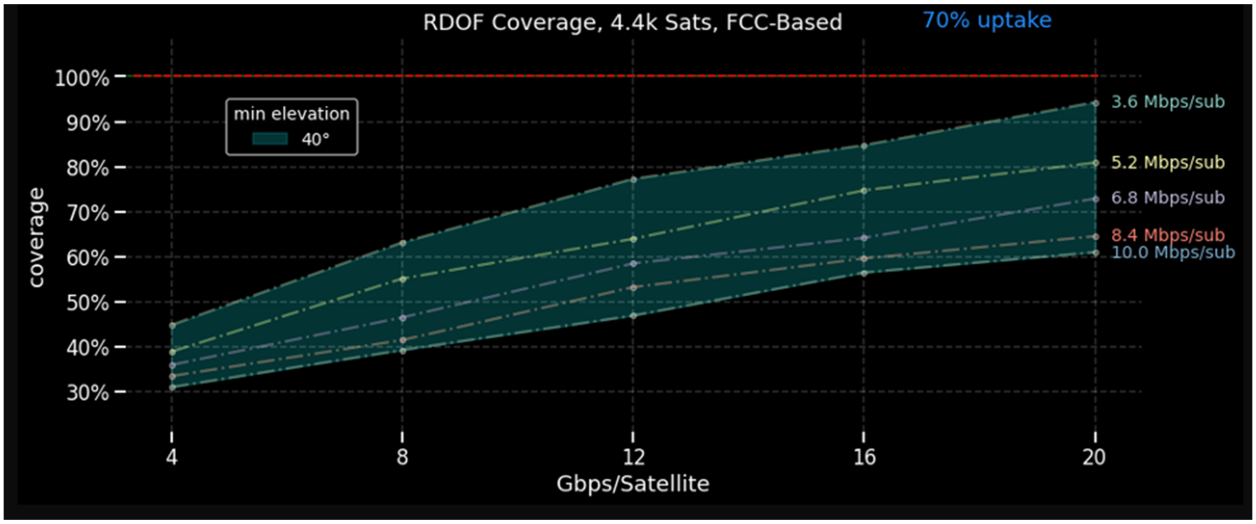

Figure 5 – 40° Mask, 20% Network and Oversubscription Overhead, No Spectrum Derating

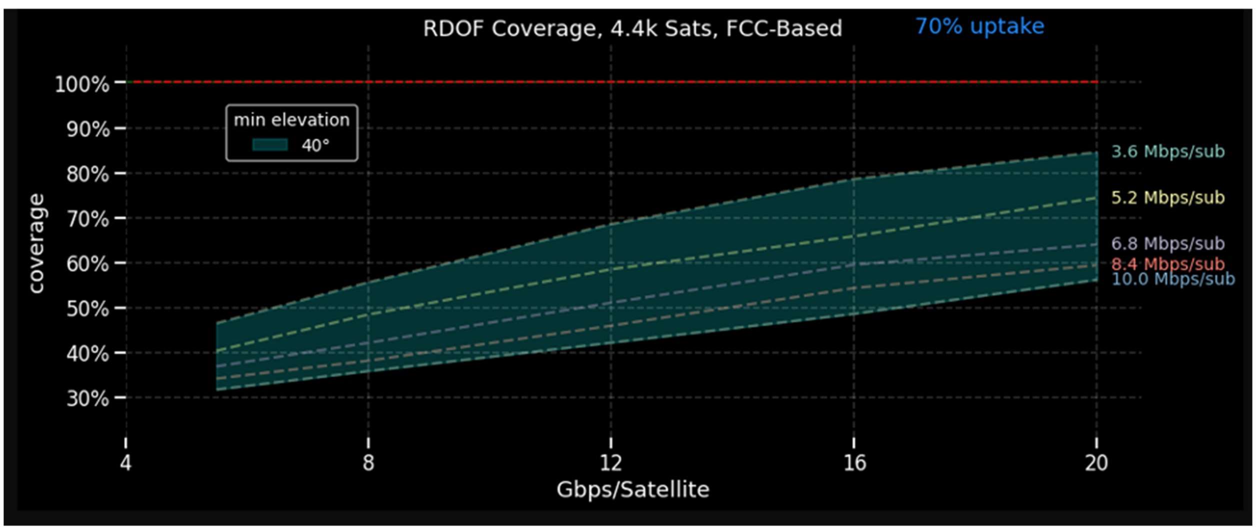

Figure 6 – 40° Mask, 20% Network and Oversubscription Overhead, With 20.6% Spectrum Derating

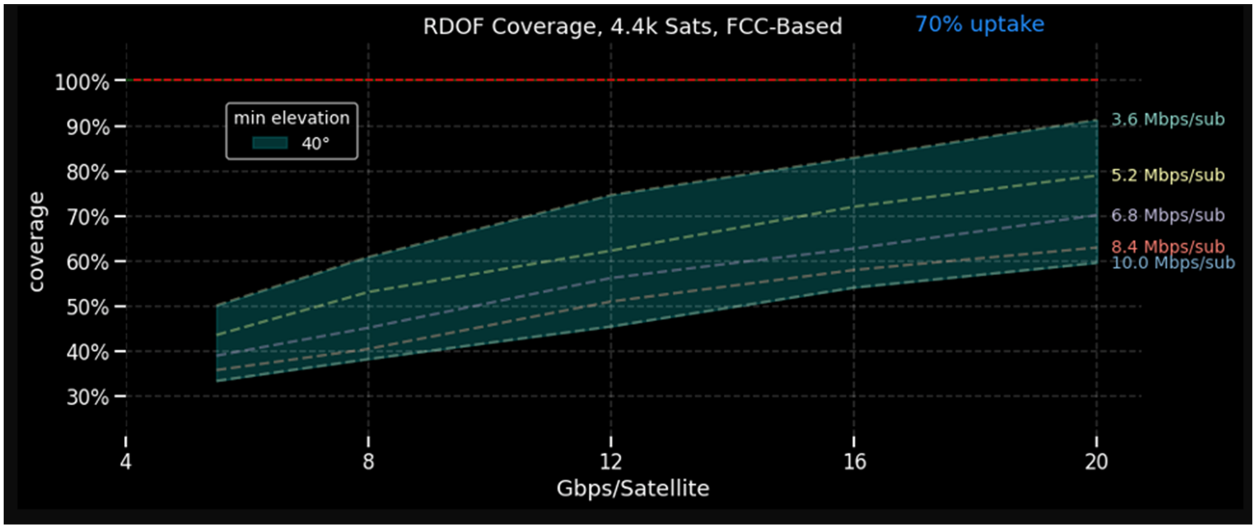

Figure 7 – 40° Mask, 25% Network and Oversubscription Overhead, No Spectrum Derating

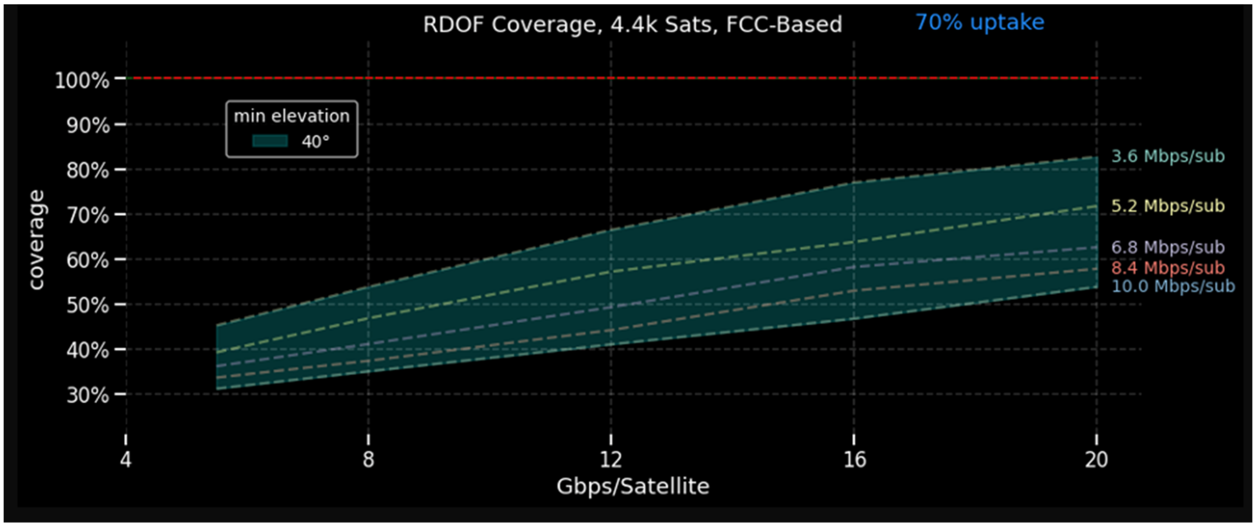

Figure 8 – 40° Mask, 25% Network and Oversubscription Overhead, 20.6% Spectrum Derating

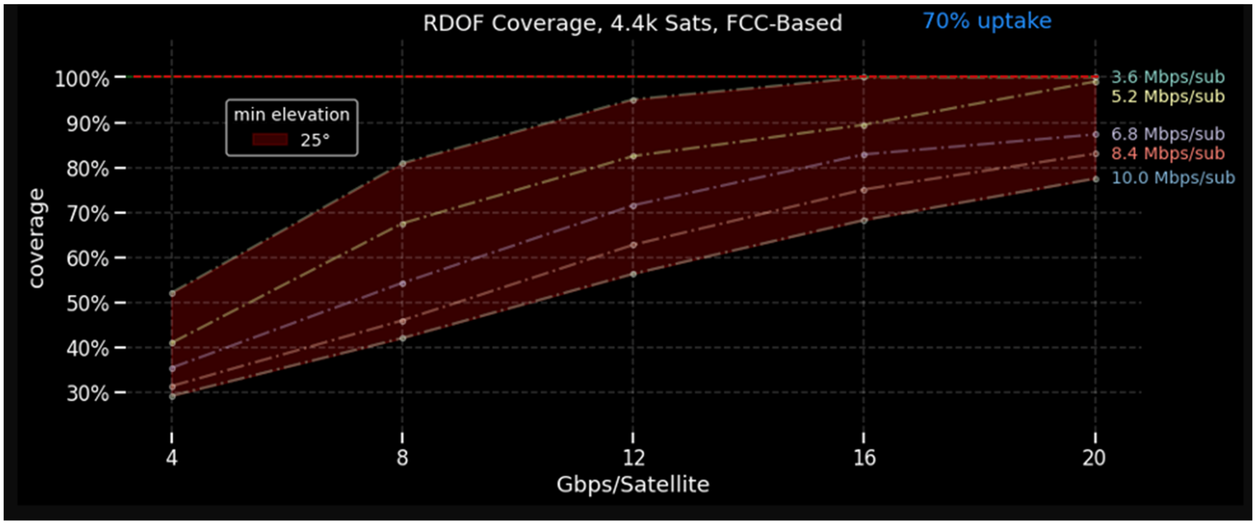

Figure 9 – 25° Mask, 20% Network and Oversubscription Overhead, No Spectrum Derating

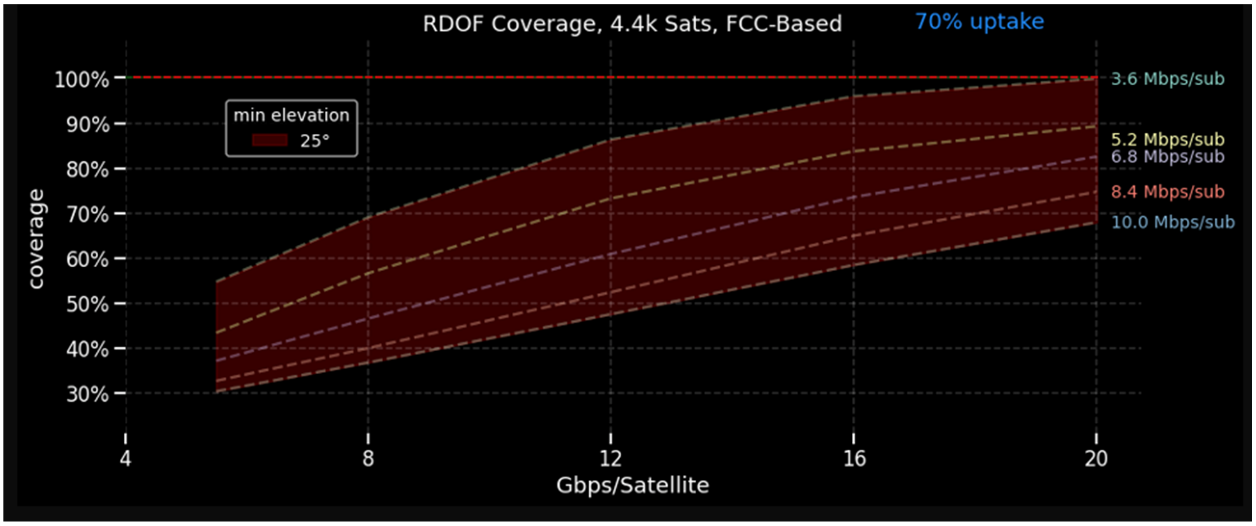

Figure 10 – 25° Mask, 20% Network and Oversubscription Overhead, 20.6% Spectrum Derating

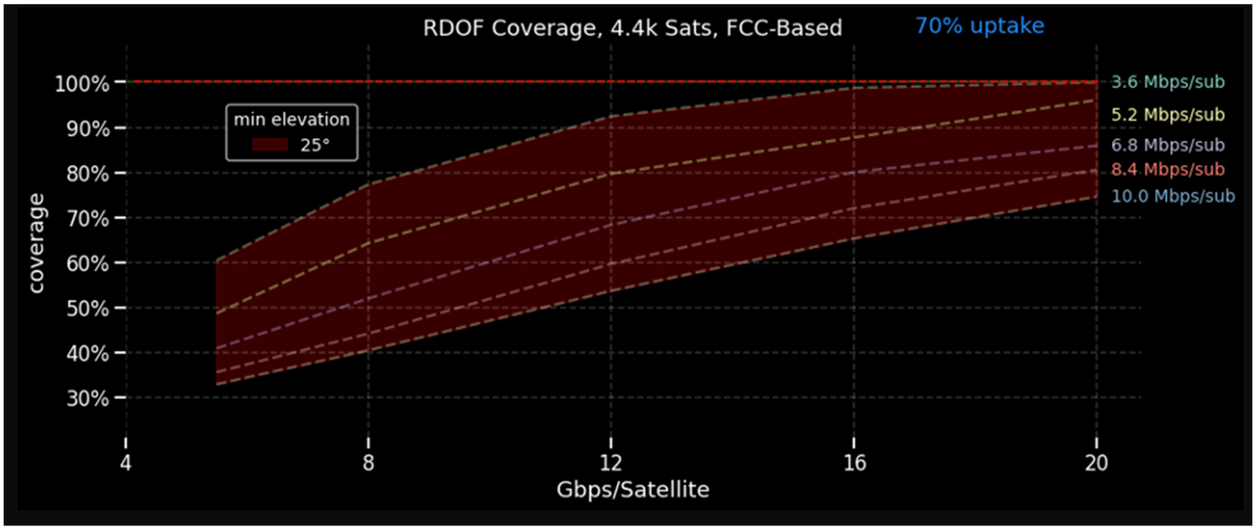

Figure 11 – 25° Mask, 25% Network and Oversubscription Overhead, No Spectrum Derating

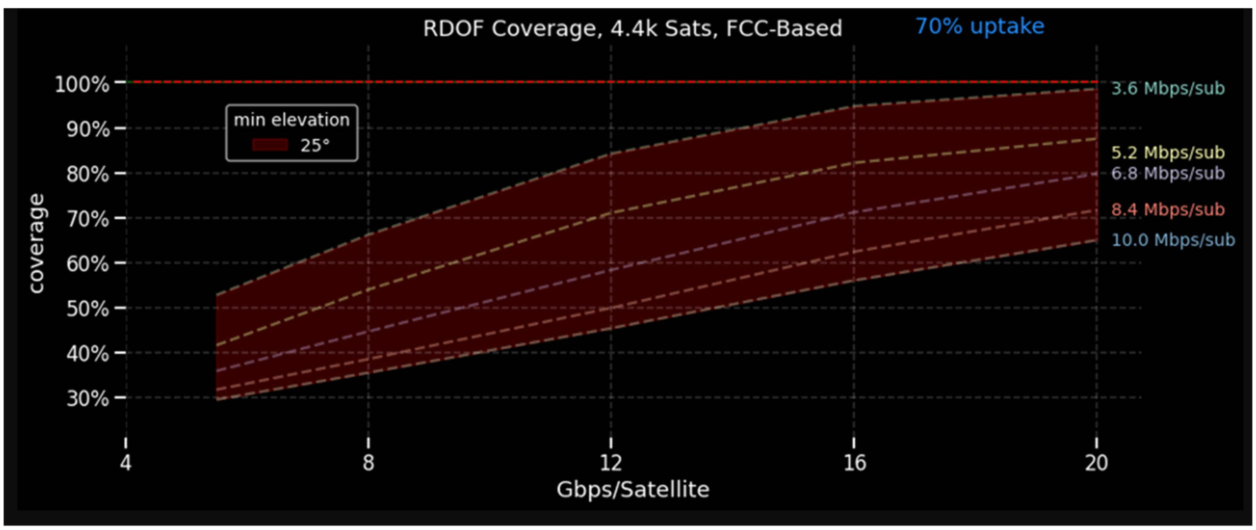

Figure 12 – 25° Mask, 25% Network and Oversubscription Overhead, 20.6% Spectrum Derating