SPACEX NON-GEOSTATIONARY SATELLITE SYSTEM

ATTACHMENT A
TECHNICAL INFORMATION TO SUPPLEMENT SCHEDULE S

A.1 SCOPE AND PURPOSE

In 2018, the Commission authorized Space Exploration Holdings, LLC, a wholly owned subsidiary of Space Exploration Technologies Corp. (collectively, "SpaceX"), to construct, deploy, and operate a constellation of 4,425 non-geostationary orbit ("NGSO") satellites using Ku- and Ka-band spectrum.[1] Since then, the Commission has authorized SpaceX to relocate 1,584 satellites to an altitude of 550 km, where they would be able to achieve better performance and orbital debris mitigation characteristics without increasing interference to any other licensed user of the relevant spectrum, and to respace those satellites to place coverage and capacity more evenly and rapidly across more of the United States.[2] With this application, SpaceX proposes to build on the success of its earlier modifications in accelerating broadband deployment and increasing space safety by operating the remaining satellites in its Ku/Ka-band constellation at lower altitudes.

Specifically, SpaceX proposes to relocate the satellites that are currently authorized to operate at altitudes from 1,110 km to 1,325 km down to altitudes ranging from of 540 km to 570 km, and to make related changes to the operations of the satellites in these new lower shells of the constellation. This modification to the SpaceX Authorization will slightly reduce the total number of spacecraft in the constellation (from 4,409 to 4,408), meet all required protection criteria for other systems operating in the same frequencies, and cause no material overall

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1 *See Space Exploration Holdings, LLC*, 33 FCC Rcd. 148 (2018) ("*Initial Authorization*").

2 *See Space Exploration Holdings, LLC*, 34 FCC Rcd. 2526 (IB 2019) ("*First Modification*"); *Space Exploration Holdings, LLC*, 34 FCC Rcd. 12307 (IB 2019) ("*Second Modification*").

increase in radiofrequency interference. The modification will meet or exceed all space safety requirements and will reduce the potential for orbital debris through operation of the remainder of the constellation at lower altitudes. In addition, SpaceX requests that the Commission revise its license to include authority to perform telemetry, tracking, and control ("TT&C") functions during orbit-raising and de-orbit maneuvers, consistent with what is authorized by rule for geostationary orbit ("GSO") satellite systems,[3] as well as testing during the orbit-raising process. SpaceX requests no other technical changes to its authorization at this time, and certifies that all other technical information provided in its previous Ku/Ka-band applications, as modified, remains unchanged.[4]

This attachment contains the updated technical information with respect to the newly-proposed operations required under Part 25 of the Commission's rules that cannot be fully captured by the Schedule S software. The accompanying Schedule S reflects the system as it will operate once modified and fully deployed.[5]

A.2 OVERALL DESCRIPTION

This information is generally available in Attachment A ("Technical Information to Supplement Schedule S") to the Previous Applications. SpaceX now proposes a modification based on the success of the deployment of its first 362 satellites and in an effort to even further

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[3] *See* 47 C.F.R. §§ 25.282, 25.283.

[4] *See id.* § 25.117(c). *See also* Application for Approval for Orbital Deployment and Operating Authority for the SpaceX NGSO Satellite System, IBFS File No. SAT-LOA-20161115-00118 (Nov. 15, 2016); Application for Approval for Orbital Deployment and Operating Authority for the SpaceX NGSO Satellite System Supplement, IBFS File No. SAT-LOA-20170726-00110 (July 26, 2017); Application for Modification of Authorization for the SpaceX NGSO Satellite System, IBFS File No. SAT-MOD-20181108-00083 (Nov. 8, 2018); Application for Modification of Authorization for the SpaceX NGSO Satellite System, IBFS File No. SAT-MOD-20190830-00087 (Aug. 30, 2019). These applications are referred to collectively herein as the "Previous Applications."

[5] The Schedule S and the separate database of technical parameters include channel plans for each beam. Although we have submitted channel plans indicating that each beam will be divided uniformly into 50 MHz channels, SpaceX anticipates that these channels will often be bonded into various combinations to create larger effective channel sizes – or potentially subdivided into smaller ones – depending on operational needs.

enhance the already considerable space safety attributes of its NGSO constellation. Under the modification proposed herein, SpaceX would relocate the original shells of satellites authorized to operate at altitudes of 1,110 km to 1,325 km to create new lower shells of satellites operating at 540 km to 570 km. Table A.2-1 below summarizes the configuration of SpaceX's currently authorized NGSO constellation.

SpaceX Current Authorization					
Orbital Planes	72	32	8	5	6
Satellites per plane	22	50	50	75	75
Altitude	550 km	1,110 km	1,130 km	1,275 km	1,325 km
Inclination	53º	53.8º	74º	81º	70º

Table A.2-1. Summary of Currently Authorized NGSO Constellation

Table A.2-2 below summarizes the configuration under the proposed modification, with proposed changes identified in green.

SpaceX Proposed Modification					
Orbital Planes	72	72	36	6	4
Satellites per plane	22	22	20	58	43
Altitude	550 km	540 km	570 km	560 km	560 km
Inclination	53º	53.2º	70º	97.6º	97.6º

Table A.2-2. Summary of Proposed Modified Constellation

As with its current constellation, apogee and perigee will be maintained to within 30 km, and inclination will be maintained to less than 0.5 degree of the respective target values. The right ascension of the ascending nodes ("RAANs") will precess and span the full range of 0-360 degrees.

Operating these shells at lower altitude will significantly decrease each satellite's footprint on the Earth. To maintain suitable coverage, SpaceX will use a minimum elevation angle as low as 25 degrees for user beams. For gateway beams, SpaceX will generally observe the same 25 degree minimum elevation, although certain shells may use lower elevations in certain circumstances as discussed more fully in Section A.3.2 below.

SpaceX also requests that the Commission grant authority in its modified license for communications during transition phases before and after reaching authorized positions. This would include authority to perform TT&C functions during orbit-raising and de-orbit maneuvers, as is authorized by rule for GSO satellite systems.[6] This would also include authority for testing the Ku- and Ka-band communications payloads during the orbit-raising process, which would be conducted on a non-protected, non-harmful interference basis. Given that there are over 4,000 satellites in the constellation with a design life of five years, it is likely that SpaceX will be engaged in launch and de-orbit activities on an ongoing basis. Granting the requested authority as part of the space station license would obviate the need for SpaceX to file – and the Commission to process – a never-ending stream of applications for special temporary authority to cover operations as satellites are raised into and de-orbited out of the constellation.[7]

A.3 PREDICTED SPACE STATION ANTENNA GAIN CONTOURS

The antenna gain contours for the transmit and receive beams for a representative space station operating at 540 km, 560 km, and 570 km are embedded in the associated Schedule S, as required by Section 25.114(c)(4)(vi)(B). Below we describe the methodology for their presentation.

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6 *See* 47 C.F.R. §§ 25.282, 25.283.

7 Over the last eight months, SpaceX has been granted eleven space station STAs to cover orbit-raising and de-orbit activities for its constellation. It has received no reports of interference from any other licensed operator.

As in the Previous Applications, all downlink spot beams on each SpaceX satellite are independently steerable over the full field of view of the Earth. Yet earth stations communicate only with satellites above a minimum elevation angle. Figure A.3-1 below illustrates the steerable service range of satellite beams using generalized parameters.

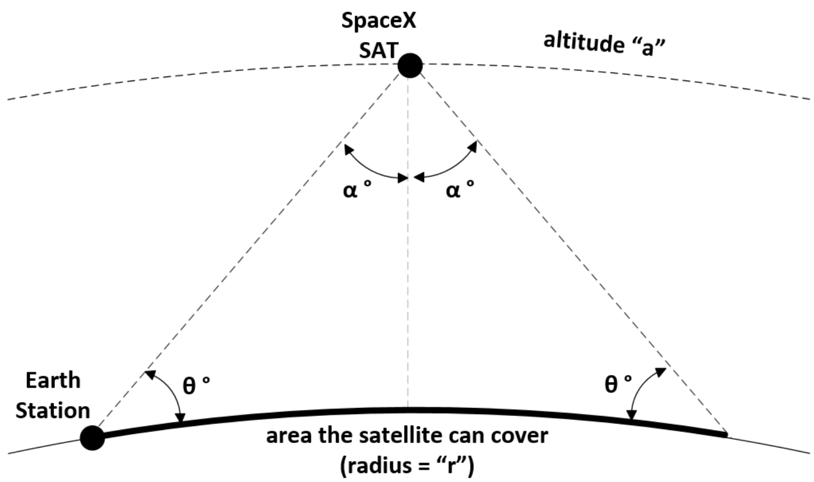

Figure A.3-1: Steerable Service Range of Satellite Beams

Tables A.3-1 and A.3-2 provide the specific values for the parameters in Figure A.3-1 for each of the new orbital altitudes proposed herein based on the minimum earth station elevation angle (θ) involved.

altitude "a" [km]	540	560	570
Max steering angle α [deg]	56.7	56.4	56.3
Coverage radius "r" [km]	926.8	954.6	968.4

Table A.3-1: Values for 25° Minimum Elevation Angle θ

altitude "a" [km]	540	560	570
Max steering angle α [deg]	66.7	66.3	66.1
Coverage radius "r" [km]	2037.3	2079.7	2100.5

Table A.3-2: Values for 5° Minimum Elevation Angle θ

A.3.1 Ku-Band Beams

The minimum elevation angle at which user terminals communicate with SpaceX satellites may be as low as 25 degrees. As discussed in the Previous Applications, beams from antennas using phased arrays widen incrementally as they are steered away from boresight.[8] As a result, the shape of a phased array beam at boresight is circular but becomes increasingly elliptical when steered away from boresight. The antenna beam contours provided in Schedule S illustrate this dynamic by plotting antenna gain contours (for both uplink and downlink beams) for operations at 540 km at nadir and at 25, 45, and 57 degrees away from nadir (which are essentially the same for 560 km and 570 km). As illustrated in Figure A.3.1-1 below with respect to operations at 540 km altitude, as the transmitting beam is steered, the power is adjusted to maintain a constant maximum power flux-density ("PFD") at the surface of the Earth, compensating for variations in antenna gain and path loss associated with the steering angle.

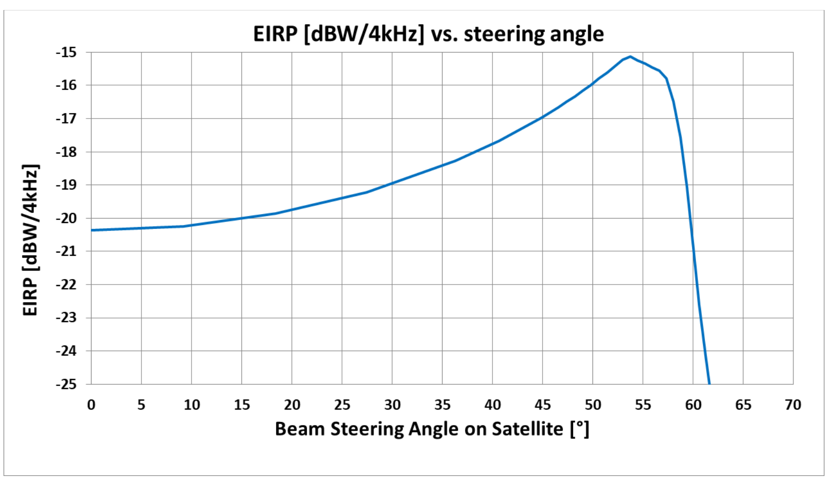

Figure A.3.1-1. EIRP Density Variation by Beam Steering Angle (540 km)

Table A.3.1-1 shows the maximum equivalent isotropically radiated power ("EIRP") density at each proposed new operating altitude.

8 For this purpose, we use "boresight" to refer to the direction normal to the phased array plane.

Altitude [km]	Max EIRP [dBW/4kHz]
540	-15.2
560	-15.0
570	-15.0

Table A.3.1-1: Maximum Ku-Band EIRP Density at Various Altitudes

For receiving beams, the antenna gain drops slightly as the beam slants away from nadir. As a result, the maximum G/T (8.4 dB/K) occurs at nadir, while the minimum G/T occurs at maximum slant (4.9 dB/K, for 25 degree earth station elevation angle).[9]

A.3.2 Ka-Band Gateway Beams

Here again, gateways communicate only with satellites above a specified minimum elevation angle. Generally speaking, this angle may be as low as 25 degrees. However, there will be exceptions in certain cases in order to achieve increased coverage. Specifically, satellites in the high inclination shells operating at altitudes of 560 km and 570 km will observe a minimum elevation angle of five degrees for gateways located inside the polar regions (i.e., above 62 degrees latitude).

As with Ku-band beams, the shape of the gateway beam becomes elliptical as it is steered away from the boresight. The antenna beam contours provided in Schedule S illustrate this dynamic by plotting antenna gain contours (for both uplink and downlink gateway beams) for operations at 540 km at nadir and at 20, 45, 57, and 66 degrees away from nadir (which are essentially the same for 560 km and 570 km). As illustrated in Figure A.3.2-1 below with respect to operations at 540 km altitude, as a satellite steers the transmitting beam, it adjusts the power (in both polarizations) to maintain a constant PFD at the surface of the Earth.

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9 Section 25.114(c)(4)(v) requires both the minimum and maximum saturation flux density ("SFD") values for each space station receive antenna that is connected to transponders. The concept of SFD only applies to "bent pipe" satellite systems, and thus is not relevant to the constellation. However, because the Schedule S software requires a numerical entry for SFD (which must be different for maximum and minimum), SpaceX has entered values of "0" and "-0.1."

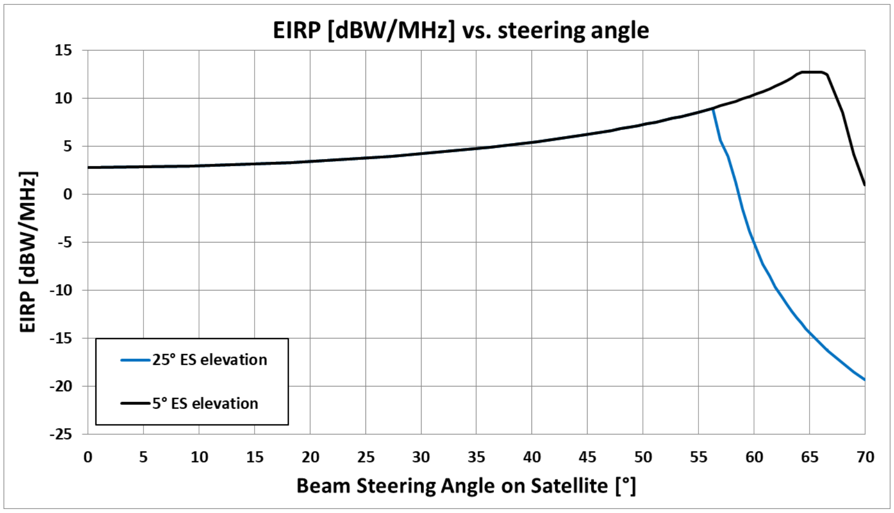

Figure A.3.2-1: EIRP Density Variation by Beam Steering Angle

Each satellite transmits two beams at the same frequency (with right hand and left hand circular polarization ("RHCP" and "LHCP")), with up to eight satellites beaming transmissions to a gateway location, for a maximum of sixteen co-frequency beams. SpaceX will adjust power in order to achieve the PFD levels indicated above. The maximum EIRP density for all proposed altitudes is 12.7 dBW/MHz. For receiving beams, G/T will remain constant at 11.5 dB/K.

A.3.3 Ku-Band and Ka-Band TT&C Beams

This information is available in Attachment A to the Previous Applications and in Schedule S attached hereto.

A.4 GEOGRAPHIC COVERAGE

The Commission has found that the SpaceX constellation, when fully deployed, will satisfy all applicable geographic coverage requirements.[10] The proposed modification will not alter that conclusion.

[10] *See* SpaceX Authorization, ¶ 33.

A.5 TT&C CHARACTERISTICS

A complete description of the SpaceX TT&C subsystem is provided with the Previous Applications.[11]

A.6 CESSATION OF EMISSIONS

This information is available in Attachment A to the Previous Applications.

A.7 COMPLIANCE WITH PFD LIMITS

Under the proposed modification, SpaceX would operate the new shells of satellites at a much lower altitude – i.e., 540-570 km rather than 1,110-1,325 km. To account for the lower orbits, SpaceX also plans to operate those satellites at a much reduced EIRP, which will reduce the PFD created at the Earth's surface. To illustrate, Tables A.7-1 and A.7-2 below show the PFD calculation for operations at 540 km, both at maximum slant and at nadir, for Ku-band user beams and Ka-band gateway beams, respectively. In each case, the table reflects operations at the lowest proposed altitude – and, for the Ka-band, accounting for both polarizations – which presents a worst case, maximum PFD scenario without considering any of the operational constraints discussed above.

Parameter	Nadir	25° ES elev
EIRP density [dBW/Hz]	-56.4	-51.6
EIRP in 4kHz [dBW/4kHz]	-20.4	-15.6
EIRP in 1MHz [dBW/MHz]	3.6	8.4
Distance to Earth [km]	540.0	1105.2
Spreading loss [dB]	125.6	131.9
PFD in 4 kHz [dB(W/m^2/4kHz)]	-146.0	-147.4
PFD in 1 MHz [dB(W/m^2/1MHz)]	-122.0	-123.4

Table A.7-1. PFD at the Surface of the Earth Produced by Ku-band Downlink Transmissions (540 km)

[11] *See, e.g.,* Previous Applications, Sections A3.3, A.5, and Schedule S.

Parameter	Nadir	25° ES elev	5° ES elev
EIRP density [dBW/Hz]	-57.7	-51.4	-47.3
EIRP in 1MHz [dBW/MHz]	6.3	12.6	12.7
Distance to Earth [km]	540.0	1105.2	2180.7
Spreading loss [dB]	125.6	131.9	137.8
PFD in 1 MHz [dB(W/m^2/1MHz)]	-123.3	-123.3	-125.1

Table A.7-2. PFD at the Surface of the Earth Produced by Ka-band Downlink Transmissions (540 km)

In addition, because the satellite downlink transmit power is adjustable on orbit, SpaceX has the ability to manage the satellites' PFD levels during all phases of the mission, as needed.

Below, we plot these PFD values against the relevant PFD limits applicable in the various frequency bands used by the SpaceX system.

A.7.1 PFD Limits in the Ku-Band

The PFD limits imposed by the Commission and the International Telecommunication Union ("ITU") in the Ku-band apply on a per-satellite basis. In its Previous Applications, SpaceX demonstrated that it would comply with applicable per-satellite PFD limits by assessing operations at the lowest planned altitude (at that time, 1,110 km) and at service latitudes up to approximately ±55°, which presents a worst case, maximum PFD scenario. But under the proposed modification, SpaceX would operate satellites at altitudes as low as 540 km and at much reduced EIRP. In this section, we conduct a similar worst-case analysis for the new lowest shell.

The Commission and ITU have adopted different downlink PFD limits for different portions of the Ku-band spectrum used by the SpaceX system. For each of these limits, we demonstrate compliance by plotting the relevant limit and the worst-case PFD of a satellite operating in the proposed 540 km shell with earth stations at a minimum elevation angle of 25 degrees. The first set of limits applies across the 10.7-11.7 GHz band.[12]

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[12] *See* 47 C.F.R. § 25.208(b); ITU Rad. Regs., Table 21-4.

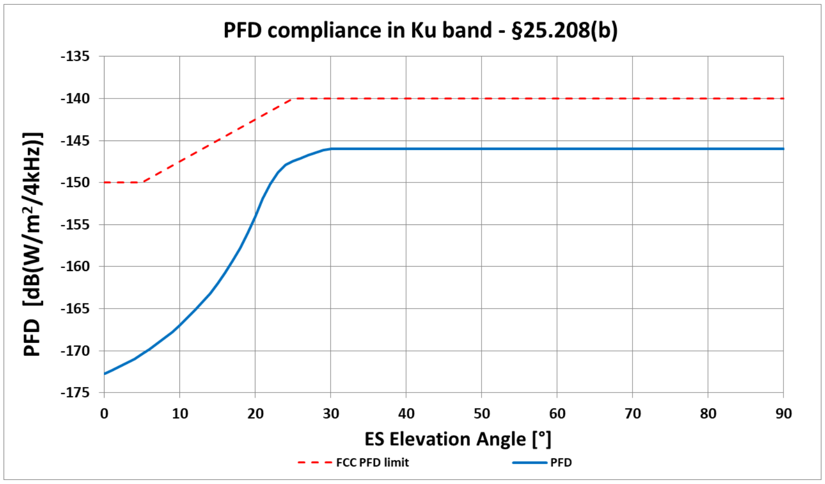

Figure A.7.1-1. Compliance with Downlink PFD Limits in the 10.7-11.7 GHz Band (540 km)

The ITU Radio Regulations include PFD limits across the 11.7-12.7 GHz band that are effectively 2 dB higher than the PFD limits in the 10.7-11.7 GHz band plotted above.[13] Accordingly, given that the modified system will comply with the lower limits applicable in the 10.7-11.7 GHz band, it will also comply with the limits applicable in the 11.7-12.7 GHz band.[14]

Section 25.208(o) of the Commission's rules specifies low elevation PFD limits that apply in the 12.2-12.7 GHz band to protect the Multichannel Video and Data Distribution Service ("MVDDS"). Figure A.7.1-2 below shows that satellites in the proposed 540 km shell will comply with these limits as well.

13 *See* ITU Radio Regs., Table 21-4.

14 In the Ku-band, SpaceX will operate TT&C downlinks in the 12.15-12.25 GHz band. The maximum EIRP for the TT&C links is always below the minimum EIRP radiated in any direction by the user links in this band. As a result, the PFD created when TT&C links in this band are active falls significantly below the PFD created due to operational links in all cases. Because, as demonstrated above, the Ku-band operational links comply with the applicable PFD limits, the TT&C downlinks necessarily will do so as well. Moreover, SpaceX plans to deploy only two TT&C earth stations in the U.S. – one on the East Coast and one on the West Coast. Areas outside the immediate vicinity of those facilities would be unaffected by their operations. Accordingly, SpaceX's TT&C operations in this band should prompt no concern.

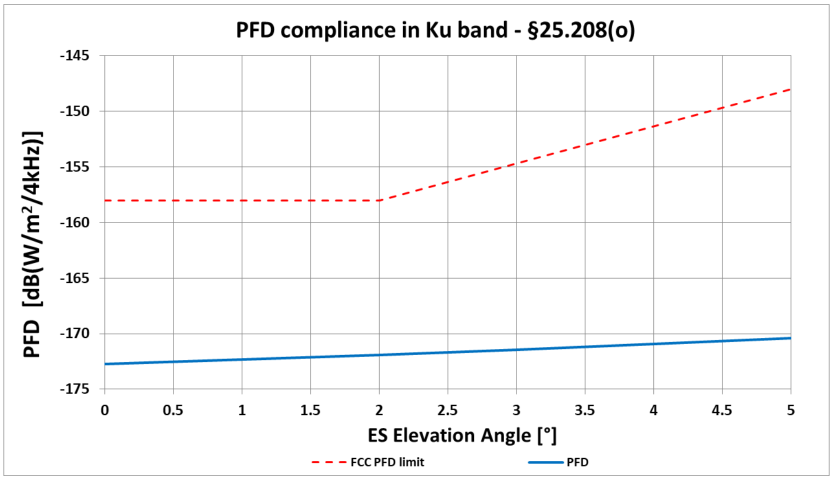

Figure A.7.1-2. Compliance with Downlink PFD Limits in the 12.2-12.7 GHz Band (540 km)

Operations at this lowest shell provide a worst-case PFD scenario, yet still remain compliant. Accordingly, all Ku-band downlink transmissions from SpaceX satellites operating in the modified constellation will comply with all applicable Commission and ITU PFD limits.

A.7.2 PFD Limits in the Ka-Band

The ITU has adopted a single set of PFD limits for NGSO systems across the entire 17.7-19.3 GHz band, which the Commission has incorporated by reference into its rules as well.[15] Unlike the limits applicable to the Ku-band, here the limits are expressed as a function of the number of satellites in the entire NGSO system, without any consideration to whether the satellites are in view of the terrestrial system or whether the satellites are turned on or off. These limits can be stated as follows:

- -115-X dB(W/m^2) in any 1 MHz band for angles of arrival between 0 and 5 degrees above the horizontal plane;
- -115-X+((10+X)/20)(δ-5) dB(W/m^2) in any 1 MHz band for angles of arrival δ (in degrees) between 5 and 25 degrees above the horizontal plane; and
- -105 dB(W/m^2) in any 1 MHz band for angles of arrival between 25 and 90 degrees above the horizontal plane.

[15] *See* ITU Radio Regs., Table 21-4; 47 C.F.R. § 25.108(a)(2).

Where X is defined as a function of the number of satellites in the NGSO FSS constellation, n, as follows:

- X = 0 dB for $n \leq 50$
- X = (5/119) (n - 50) dB for $50 < n \leq 288$
- X = (1/69) (n + 402) dB for $n > 288$

For the modified SpaceX system, the value of "n" is 4,408, and therefore X is equal to 69.71 dB according to the above formulae. This results in the PFD masks for gateway and TT&C operations shown in Figures A.7.2-1 and A.7.2-2 below, respectively.

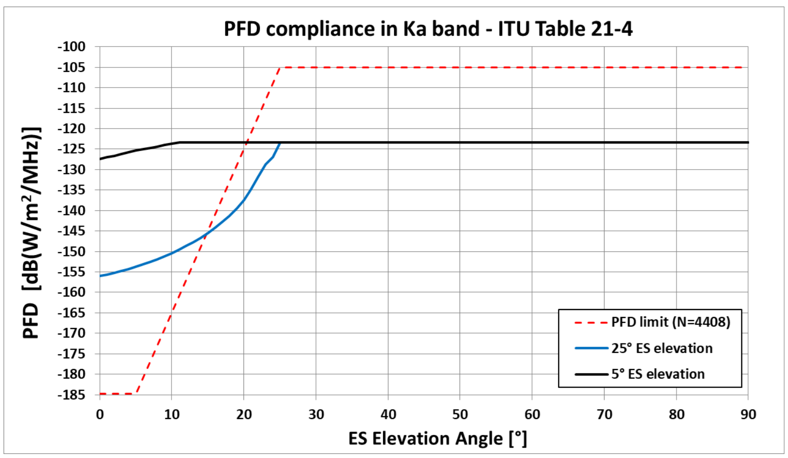

Figure A.7.2-1. SpaceX Gateway Compliance with Downlink PFD Limits in the 17.7-19.3 GHz Band

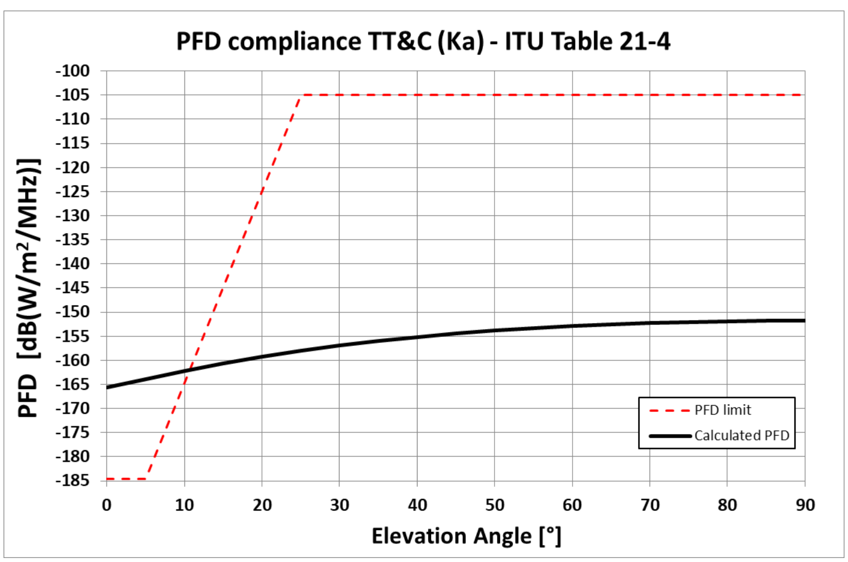

Figure A.7.2-2. SpaceX TT&C Compliance with Downlink PFD Limits in the 17.7-19.3 GHz Band

As shown in these figures, the modified SpaceX system complies with the PFD limits specified by the Commission and the ITU at most elevation angles by a significant margin, but at low elevation angles – below about twenty degrees – the flawed calculation technique appears to yield a result that exceeds the limit.

In Attachment A to its Previous Applications, SpaceX argued that the ITU methodology for establishing the PFD limits was not developed with capability to scale up for application to dynamically controlled NGSO constellations with more than 840 satellites. In granting the *Initial Authorization*, the Commission agreed with several points raised by SpaceX, "in particular that the ITU limits were derived for constellations up to 840 satellites and under worst case assumptions."[16] Rather than grant a waiver of these PFD limits, the Commission imposed a condition under which SpaceX must, before starting operation, file a modification application with a technical showing demonstrating that its operation will protect a fixed-service station with the characteristics described in Recommendation ITU-R SF.1483.[17] SpaceX has made such showings in connection with previous modifications. As discussed below, SpaceX makes a renewed showing with respect to the modification proposed herein.

A.8 INTERFERENCE ANALYSES

The Commission has recognized that a proposed modification to an NGSO authorization should be granted where it "does not present any significant interference problems and is otherwise consistent with Commission policies."[18] In this case, the lowering of existing SpaceX satellites

16 *See Initial Authorization*, ¶ 35.

17 *See id.*

18 *Teledesic LLC*, 14 FCC Rcd. 2261, ¶ 5 (IB 1999). *See also The Boeing Co.*, 18 FCC Rcd. 12317, ¶ 7 (IB 2003). ("In recognition of the length of time it takes to construct a satellite system, the rapid pace of technological change, and the goal of promoting more efficient use of the radio spectrum, the [Commission] has granted such requests

will not have any significant impact on other users of the Ku- and Ka-band spectrum. To demonstrate this fact, SpaceX has included with this Technical Attachment three analyses of the interaction between its system as modified and other licensed systems in the band.

A.8.1 Interference Protection for GSO Satellite Networks

Pursuant to Section 25.146 of the Commission's rules, SpaceX hereby certifies that its NGSO constellation, as modified, will comply with the applicable equivalent power flux-density ("EPFD") limits set forth in Article 22 of the ITU Radio Regulations, which have been incorporated by reference into the Commission's rules.[19] As corroboration, SpaceX provides in Annex 1 to this Technical Attachment an updated analysis demonstrating that its modified constellation will continue to comply with applicable EPFD limits.[20] The Commission's rules and the *Initial Authorization* contemplate that, prior to initiation of service, the ITU Radiocommunication Bureau will issue a "favorable" or "qualified favorable" finding regarding the constellation's compliance with those EPFD limits.[21] When the Commission granted the *First Modification*, it waived the requirement that SpaceX receive such a finding from the ITU *prior to* commencing operations, but retained the requirement that SpaceX receive such a finding at some

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in cases where the proposed modification presents no significant interference problem and is otherwise consistent with Commission policies." (internal citation omitted)).

[19] *See* 47 C.F.R. § 25.146(a)(2).

[20] SpaceX will also operate its system in some portions of Ka-band spectrum where no EPFD limits exist (the 28.6-29.1 GHz uplink and 18.8-19.3 GHz downlink frequency bands, where NGSO satellite use is designated as primary). According to ITU procedures applicable to these frequency ranges, coordination between NGSO and GSO networks is on a first-come, first-served basis. *See* ITU Radio Regs. No. 9.11A. SpaceX is actively engaged in coordination negotiations with GSO operators and is confident that compatibility with all GSO satellite networks in these bands can be achieved. In addition, Resolution 76 of the ITU Radio Regulations includes limits on aggregate $EPFD_{down}$ produced by all co-frequency satellites of all NGSO FSS systems operating in certain Ku- and Ka-bands. SpaceX is prepared to work with other NGSO FSS operators to ensure compliance with the applicable limits.

[21] 47 C.F.R. § 25.146(a)(3). This is also a condition of SpaceX's authorization. *See* SpaceX Authorization, ¶ 40n.

point and adjust its operations as necessary to satisfy ITU requirements, essentially allowing SpaceX to proceed only at its own risk.[22] SpaceX will continue to proceed on that basis.

A.8.2 Interference with Respect to Other NGSO Satellite Systems

SpaceX has engineered its system with technical flexibility that will facilitate the necessary coordination with other NGSO satellite systems and is committed to achieving mutually satisfactory agreements. Because the proposed modification will slightly decrease the total number of satellites (from 4,409 to 4,408) and relocate many of them to operate at lower altitude, fewer of them will be visible above the minimum elevation angle at any particular time throughout the United States. The Commission has previously recognized this factor as demonstration that a modification will not increase interference to other NGSO systems.[23] In addition, by operating at lower altitude, these satellites will be able to transmit and receive at lower EIRP levels – another factor that will reduce the potential for interference.

To confirm and quantify these observations, SpaceX performed an analysis that considers the dynamic, time-varying interference expressed as a cumulative distribution function ("CDF") of the interference-to-noise ratio ("I/N"), for varying percentages of time. The I/N CDF is derived from a time-domain simulation of the two NGSO systems over a long enough time to produce meaningful statistics. The analysis considers the effect of the proposed modification on one NGSO system hypothetically operating in the Ku-band (OneWeb) and two operating in the Ka-band (Telesat and O3b). That analysis, set forth in Annex 2 to this Technical Attachment, demonstrates that the modification would have no material effect on the interference environment of other NGSO systems.

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22 *See First Modification*, ¶¶ 28, 37. *See also Second Modification*, ¶ 10 (finding that further waiver is unnecessary in light of requirement for ultimate ITU determination).

23 *See Teledesic*, ¶ 13.

A.8.3 Interference With Respect to Terrestrial Networks

As demonstrated above, the SpaceX constellation as modified will comply with all relevant PFD limitations in the Ku-band. In addition, Annex 3 to this Technical Attachment presents an updated analysis to demonstrate that SpaceX's operations will continue to satisfy the condition imposed to protect terrestrial fixed services operating in a portion of the Ka-band. Accordingly, SpaceX requests that the Commission find that it has satisfied the condition of the *Initial Authorization* by demonstrating that its operations will protect a fixed-service station with the characteristics described in Recommendation ITU-R SF.1483.

A.8.4 Interference With Respect to the Radio Astronomy Service

This information is available in Attachment A to the Previous Applications.

A.8.5 Coordination With GSO FSS Earth Stations in the 10.7-12.75 GHz Band

This information is available in Attachment A to the Previous Applications.

A.9 COORDINATION WITH U.S. GOVERNMENT OPERATIONS

This information is available in Attachment A to the Previous Applications.

A.10 ITU FILINGS FOR SPACEX

SpaceX is preparing the modified system information for ITU publication and will submit this information when complete. SpaceX will unconditionally accept all consequent ITU cost-recovery responsibility for the filings.

A.11 ORBITAL DEBRIS MITIGATION

An overview of orbital debris mitigation information is available in Attachment A to the Previous Applications. Maintaining a clean orbital environment is a fundamental consideration for SpaceX, which is planning to launch its Falcon 9 vehicles into orbital altitudes dozens of times this year alone for its commercial and government customers, as well as undertaking Dragon cargo missions to the International Space Station ("ISS") for NASA and Dragon Crew missions that will carry astronauts to the ISS. SpaceX is implementing an aggressive and effective space-debris mitigation plan, leveraging its nearly two decades of technical and operational experience in cost-effectively deploying large, complex space systems to support other operators.

As demonstrated from the operations of its constellation to date, operating at a lower altitude offers several attractive features both during nominal operation and in unplanned scenarios. In particular, moving satellites to the proposed lower shells would yield tangible benefits, including:

- Rapid, passive disposal in the unlikely event of a failed spacecraft
- Self-cleaning debris environment in general
- Reduced fuel requirements and thruster wear
- Benign ionizing radiation environment
- Fewer NGSO operators affected by the SpaceX constellation

These benefits directly address the Commission's concerns with respect to system reliability, and in particular reliability of the method for de-orbiting spacecraft.[24]

As discussed in Previous Applications, SpaceX intends to perform an active disposal of all of its satellites at the end of their life, in which the satellites first drop to a perigee of approximately 300 km while maintaining an apogee at approximately 540 km to 570 km. For the new lower shells of satellites, this "active" phase of the deorbit sequence will take a few weeks for each vehicle, after which several weeks to months of "passive" disposal follow, with the exact time depending on solar activity. Even this phase is not fully passive – to minimize the risk of debris even further, SpaceX satellites will continue to perform conjunction avoidance until the high

[24] *See Initial Authorization*, ¶ 15. These benefits are discussed in greater detail in pages 38-44 of the Technical Attachment for IBFS File No. SAT-MOD-20181108-00083.

atmospheric torques from low altitudes cause the vehicle to be uncontrollable.[25] At all times during this descent, including the period during which they will traverse the orbital altitude of the ISS and other NASA assets, the spacecraft will retain sufficient fuel to perform maneuvers. After all propellant is consumed, the spacecraft will be reoriented to maximize the vehicle's total cross-sectional area. Finally, the spacecraft will begin to passivate and power down.

While SpaceX expects its satellites to perform nominally and deorbit actively as described above, in the unlikely event a vehicle is unable to finish its planned disposal maneuver, the denser atmospheric conditions at the 540-570 km altitude provide fully passive redundancy to SpaceX's active disposal procedures. The natural orbital decay of a satellite at 1,110-1,325 km requires hundreds of years to enter the Earth's atmosphere, but the lower satellites will take less than five years to do so, even considering worst-case assumptions. Due to the very lightweight design of the new spacecraft, SpaceX achieves a very high area-to-mass ratio on its vehicles. Combined with the natural atmospheric drag environment at lower altitude, this high ratio ensures rapid decay even in the absence of the nominally planned disposal sequence. Thus, even assuming an extreme worst-case scenario – i.e., the spacecraft fails while in the operational orbit, has no attitude control, and solar activity is at a minimum – the longest decay time is still only approximately 4.5-5.5 years. The time to satellite demise from various altitudes is illustrated in Figure A.11-1 below.[26]

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[25] The 300 km target does not account for a fuel margin stack-up reserved for other uses. In the vast majority of cases, any remaining margin would allow satellites to expedite demise. SpaceX will reserve at least 70 m/s of delta-V – a measure of the impulse required for a given maneuver or, here, the capability to perform those maneuvers if necessary – to deliver the described de-orbit functionality.

[26] This figure shows demise time as a function of altitude, using ballistic coefficients corresponding to the SpaceX spacecraft. Solid curves show conditions around solar minimum, characteristic of the current atmosphere, and dashed curves show conditions around solar maximum, characteristic of the atmosphere in the early/mid 2020s. The black curves assume that propulsion has failed, but the vehicle can still orient itself into a high-drag attitude. The blue curves assume that the Attitude Determination & Control System ("ADCS") has also failed, and the vehicle is unable to hold a specific attitude. As discussed above, at 540-570 km all cases demise in less than 5.5 years.

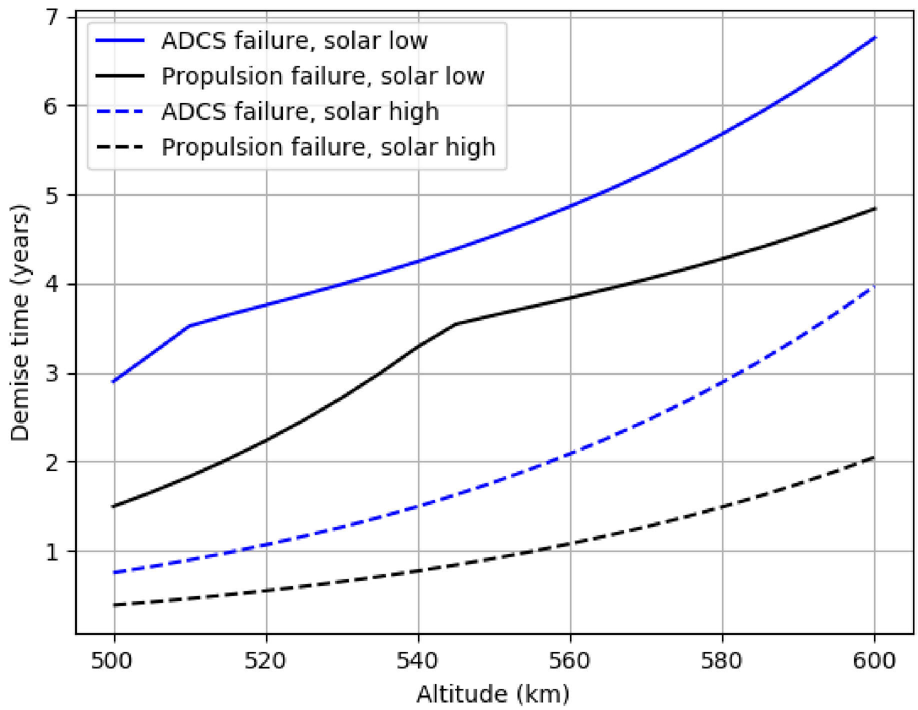

Figure A.11-1. Demise Time at Various Altitudes

In reality, this confluence of worst-case assumptions is unlikely to be realized for a number of reasons, not the least of which is that overall solar activity is ramping up into the next decade, meaning a more realistic worst-case decay time of one to three years. But even assuming the unlikely five-year decay period, SpaceX satellites will reach demise well within the prevailing 25-year deorbit standard. In fact, SpaceX will exceed new stricter parameters NASA recently determined for safe operation of large constellations[27] by achieving a 100% success rate of post-mission disposal within about five years even assuming worst-case conditions, directly addressing one concern previously identified by the Commission.[28] Nonetheless, SpaceX's nominal disposal plan that it anticipates for nearly every spacecraft will result in a lifetime of less than six months

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[27] *See* J.-C. Liou, *et al.*, *NASA ODPO's Large Constellation Study*, ORBITAL DEBRIS QUARTERLY NEWS, at 4-7 (Sept. 2018) (suggesting that post-mission disposal within five years at a 99% success rate would mitigate the debris concern related to large NGSO constellations), https://orbitaldebris.jsc nasa.gov/quarterly-news/pdfs/odqnv22i3.pdf.

[28] *See Initial Authorization*, ¶ 15 and n.55.

after SpaceX initiates disposal, an advantage of operating at the lower altitude proposed in the modification. Moreover, due to SpaceX's decision to minimize risk by using a low injection altitude of no more than approximately 350 km, in the unlikely event any satellites after the initial launch experience immediate failure upon deployment, they would decay to the point of demise very quickly – as little as two weeks to at most eight months depending on the solar cycle.

Collision Risk

SpaceX has made clear that it intends to conduct active maneuvers to avoid collisions with both debris and other spacecraft throughout the life of its satellites, even through the de-orbit phase until the spacecraft enters the atmosphere. As the Commission has recognized, because SpaceX has invested in advanced propulsion capabilities for its satellites, collision risk is considered to be zero (or near zero).[29]

Due to SpaceX's decision to minimize risk by using a low injection altitude, in the unlikely event any satellites after the initial launch experience immediate failure upon deployment, they would decay to the point of demise very quickly – as little as two weeks to at most eight months depending on the solar cycle. Consistent with the prevailing NASA safety standard, which the Commission has regularly relied upon for orbital debris mitigation assessments,[30] the probability of accidental collision between a spacecraft passing through low-Earth orbit and space objects larger than 10 cm in diameter is calculated to be less than 0.001. Specifically, using NASA's Debris Assessment Software ("DAS"), the probability of collision between a space object larger

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29 *See, e.g., First Modification*, ¶ 22.

30 *See* Requirement 4.5-1, NASA Technical Standard, Process for Limiting Orbital Debris, NASA-STD-8719.14A (with Change 1), at 32 (May 25, 2012), https://standards.nasa.gov/standard/nasa/nasa-std-871914. *See also Mitigation of Orbital Debris in the New Space Age*, 33 FCC Rcd. 11352, ¶ 6 (2018) ("Both applicants and the Commission, however, have relied in a number of cases on standards and related assessment tools, such as the technical standards and related software tools developed by NASA for its space activities, to, respectively, prepare such orbital debris plans and assess their adequacy.").

than 10 cm in diameter and a SpaceX satellite if rendered totally incapacitated immediately following orbital injection at 350 km is shown in Table A.11-1 below:

	Solar Minimum	Solar Maximum
Stowed Configuration	0.000000303	0.000000114
Deployed Configuration	0.000000274	0.000000137

Table A.11-1: Collision Risk of Incapacitated Satellite

Accordingly, SpaceX satellites satisfy the NASA safety standard by several orders of magnitude.

As is clear from Table A.11-1, one of the key assumptions in the DAS analysis is the stage of the solar cycle at the time of de-orbit.[31] During solar-max, the atmosphere swells up, making re-entry occur much more rapidly than during periods of solar-min. SpaceX expects a majority of its launches will happen at or near periods of solar-max. However, in the interest of showing a full range of outcomes, SpaceX has also provided a collision estimate assuming a local solar minimum such as that expected in the year 2029. As Table A.11-1 demonstrates, the probability of collision satisfies the NASA standard under all of these scenarios.

SpaceX will continue to take a number of steps to ensure that its constellation does not unduly affect other constellations. First, SpaceX has implemented autonomous conjunction avoidance technology on its spacecraft and expects to continue to upgrade that capability as it gains operational experience. Second, as stated above, SpaceX will perform nominal conjunction avoidance at all stages of flight. To aid with its other conjunction avoidance efforts, SpaceX has worked closely with the Combined Space Operations Center ("CSpOC," formerly known as the

[31] By contrast, the vehicle configuration (i.e., stowed vs. deployed) has relatively little effect on collision risk because the risks involved are offsetting. In other words, the smaller area of a stowed satellite reduces the likelihood of collision but also increases the time required for atmospheric demise. A fully deployed satellite presents a larger area for collision but experiences more drag and thus de-orbits more quickly.

Joint Space Operations Center ("JSpOC")), and will provide it or other relevant regulatory agencies with forecasts of vehicle positions, during both ballistic and propulsive phases of flight. SpaceX will also provide such forecasts through secure interfaces to other operators, if communication is necessary beyond CSpOC.

Beyond these active steps that SpaceX had always planned, the move to a lower altitude will bring the additional benefit of increasing the space between large NGSO constellations that do not use smallsats, such as OneWeb, Boeing, and Telesat. The Commission has authorized two such NGSO systems (OneWeb and Telesat) and is considering a third (Boeing) that will operate at altitudes between 1,000 km and 1,248 km.[32] These systems will operate at altitudes that could extend through SpaceX's currently authorized orbits at 1,110-1,325 km. SpaceX recognizes that the Commission has authorized Spire Global ("Spire") to deploy cubesats at a variety of altitudes from 400 km to 650 km,[33] and has authorized Kepler Communications ("Kepler") to deploy microsatellites in near-polar orbits at a range of altitudes from 500 km to 600 km.[34] SpaceX will engage Spire, Kepler, and any other system seeking to operate at the same nominal orbital ranges sought by SpaceX in this modification to carefully coordinate physical operations to ensure that their respective constellations can coexist safely.

Further, operating at lower altitude means that SpaceX satellites will transit through fewer systems during orbit raising or end-of-life disposal. In its Previous Applications, SpaceX planned to transition all of its satellites from approximately 400 km to altitudes of 1,110 km and above.

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32 *See WorldVu Satellites Limited*, 32 FCC Rcd. 5366 (2017); *Telesat Canada*, 32 FCC Rcd. 9663 (2017); The Boeing Company, Application for Authority to Launch and Operate an NGSO System in the FSS, IBFS File No. SAT-LOA-20170301-00028 (Mar. 17, 2017).

33 *See, e.g.*, Letter from George John to Marlene H. Dortch, IBFS File No. SAT-LOA-20151123-00078 (June 28, 2018) (Annual Report for IBFS Call Sign S2946).

34 *See Kepler Communications Inc.*, 33 FCC Rcd. 11453 (2018).

By using a lower operational altitude for its spacecraft, SpaceX will eliminate any risk from physical interaction with these SpaceX satellites for other systems operating in the 570 km to 1,325 km range – some of the most congested altitudes in low-Earth orbit.

Post-Mission Disposal

As discussed above, SpaceX anticipates that its satellites in the proposed lower shells will reenter the Earth's atmosphere within approximately six months after completion of their mission – much sooner than the international standard of 25 years. The spacecraft's small mass and predominantly aluminum construction maximize the likelihood of atmospheric demise on re-entry. As SpaceX previously stated, all Starlink satellites launched after the first deployment will be fully demisable upon atmospheric re-entry, and no components will survive to reach the Earth's surface. Accordingly, the modification will have no effect on the risk of human casualty – which will remain zero for all launches from here on.

ENGINEERING CERTIFICATION

I hereby certify that I am the technically qualified person responsible for preparation of the engineering information contained in this application, that I am familiar with Part 25 of the Commission's rules, that I have either prepared or reviewed the engineering information submitted in this application, and that it is complete and accurate to the best of my knowledge and belief.

/s/ *Mihai Albulet*

Mihai Albulet, PhD
Principal RF Engineer
SPACE EXPLORATION TECHNOLOGIES CORP.

April 17, 2020
Date

ANNEX 1

POTENTIAL INTERFERENCE WITH RESPECT TO OTHER NGSO SATELLITE SYSTEMS

SpaceX has engineered its Starlink system with the technical flexibility that will facilitate the necessary coordination with other NGSO satellite systems and is committed to achieving mutually satisfactory agreements. To demonstrate this point, SpaceX performed an analysis of the effect of the proposed modification on downlink and uplink interference using the characteristics of three NGSO systems authorized through the Commission's most recent Ku/Ka-band processing round – OneWeb for Ku-band and Telesat and O3b for Ka-band.

The analysis considers the dynamic, time-varying interference expressed as a cumulative distribution function ("CDF") of the interference-to-noise ratio ("I/N"), for varying percentages of time. The I/N CDF is derived from a time-domain simulation of the two NGSO systems over a long enough time to produce meaningful statistics, using random antenna pointing. The corresponding interference levels before and after the modification are calculated and plotted. To present a worst-case assessment of the interference environment, the analysis also assumes that the two systems do not implement any interference mitigation strategies. As demonstrated below, the new interference levels resulting with the modification are mostly less than (and at worst equal to) the interference levels that would have been experienced with the current constellation in the noise-dominated environment (i.e., I/N $\leq$ 0 dB). In the interference-dominated environment (i.e., I/N > 0 dB), the victim system already typically experiences at least 3 dB receiver de-sensitivity (if not 15 dB or more) and the two systems are not likely able to share the spectrum in a meaningful way outside of band segmentation both with and without the proposed modification. Though some of the following plots show a theoretical increase in interference after the proposed modification at fairly high I/N levels, in practice the two systems would need to implement band segmentation even before reaching such a highly interference-dominated environment. Hence, this proposed modification will not increase the potential interference into these NGSO systems operating in areas where true spectrum-sharing options may be available with the currently authorized system. It also will not increase the likelihood of exceeding the Commission's -12.2 dB (6% $\Delta T/T$) threshold above which parties will be required to either split the spectrum or coordinate.[1]

In conducting the analysis, SpaceX used the following assumptions.

For downlink interference from SpaceX satellites to a victim earth station:

1. The SpaceX earth station is collocated with the victim earth station. Locations at 35°N and 75°N latitude are considered in this simulation.[2]

2. The victim earth station can communicate with any satellite in its own system following the rules applicable for that system (e.g., the GSO avoidance angle or minimum elevation angle). All possible valid cases are considered in evaluating the I/N CDF.

3. The SpaceX system places one co-frequency beam per Ku-band spot and four or eight co-frequency beams per Ka-band spot (for the before and after cases, respectively), and any satellite in view meeting the GSO avoidance angle and the minimum elevation angle is eligible. SpaceX satellites are chosen randomly for consideration in evaluating the I/N CDF, and operate at the power flux-density levels described in the original application and this proposed application.

4. The results are set forward in Figures A1-1 through A1-6 below. Note that this

1 47 C.F.R. § 25.261(c).

2 Note that SpaceX ran its simulation with multiple latitudes and achieved similar results for both the downlink and uplink analysis. Accordingly, it chose to provide results for two latitudes that are representative of its primary service area.

simulation is conservative (i.e., it overestimates I/N), as it does not consider the effects of atmospheric attenuation.

For uplink interference from SpaceX earth stations to victim satellites:

1. The SpaceX earth station is collocated with an earth station from the other system. Locations at 35°N and 75°N latitude are considered in this simulation.

2. The other system's earth station can communicate with any satellite in its own system following the rules applicable for that system (e.g., the GSO avoidance angle or minimum elevation angle). All possible valid cases are considered in evaluating the I/N CDF.

3. In the SpaceX system, one co-frequency tracked satellite in Ku-band and four or eight co-frequency tracked satellites in Ka-band (for the before and after cases, respectively) can receive simultaneously from an earth station. Any satellite in view meeting the GSO avoidance angle and the minimum elevation angle is eligible. SpaceX satellites are randomly chosen for consideration in evaluating the I/N CDF.

4. The results are set forth in Figures A1-7 through A1-12 below. Note that this simulation is conservative (i.e., it overestimates I/N), as it does not consider the effects of atmospheric attenuation.

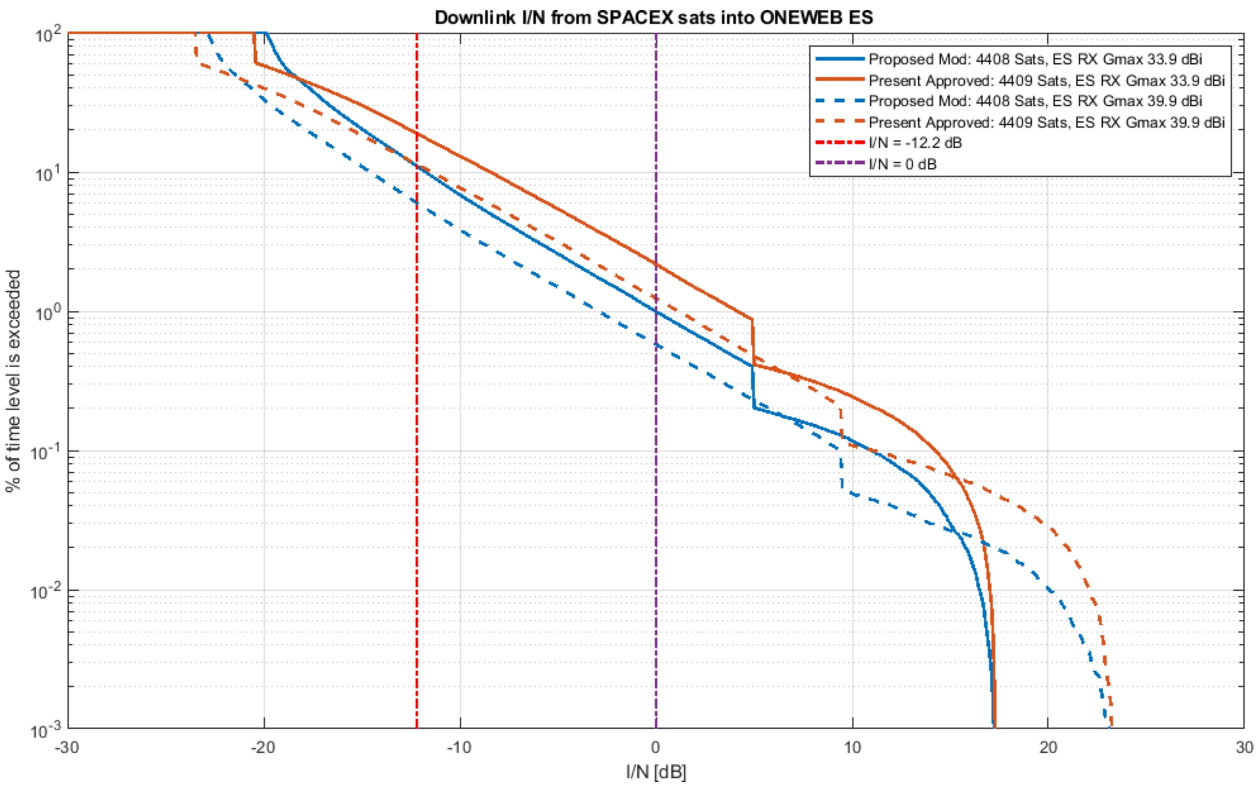


Figure A1-1. Downlink Comparison for Various OneWeb Antennas at 35ºN (Ku-band)

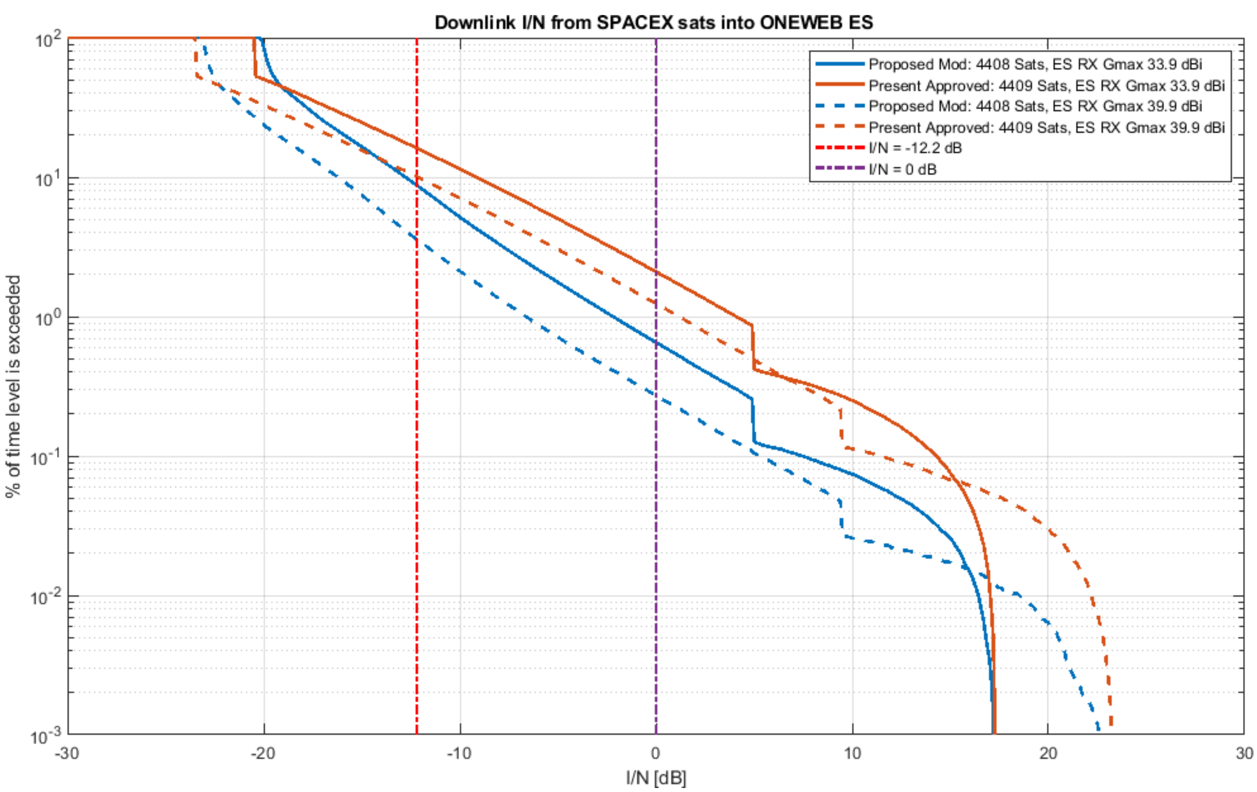


Figure A1-2. Downlink Comparison for Various OneWeb Antennas at 75ºN (Ku-band)

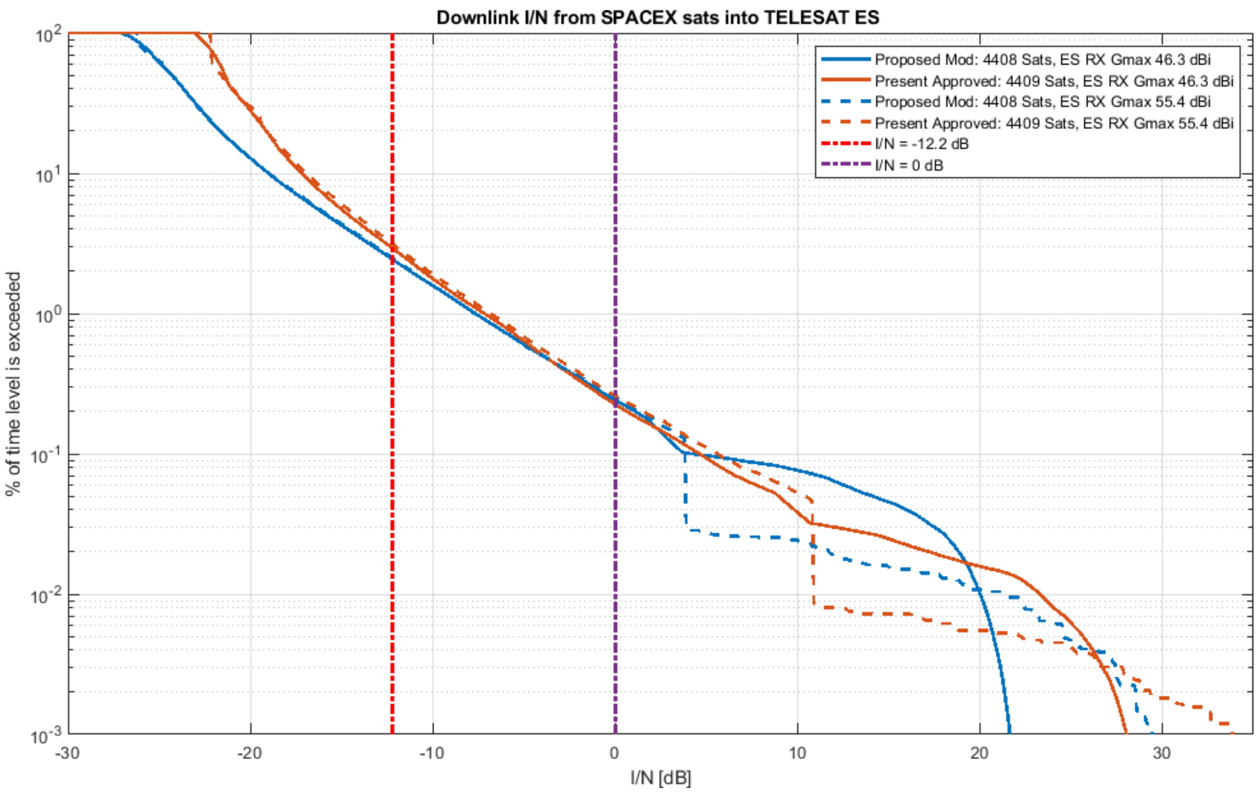


Figure A1-2. Downlink Comparison for Various Telesat Antennas at 35ºN (Ka-band)

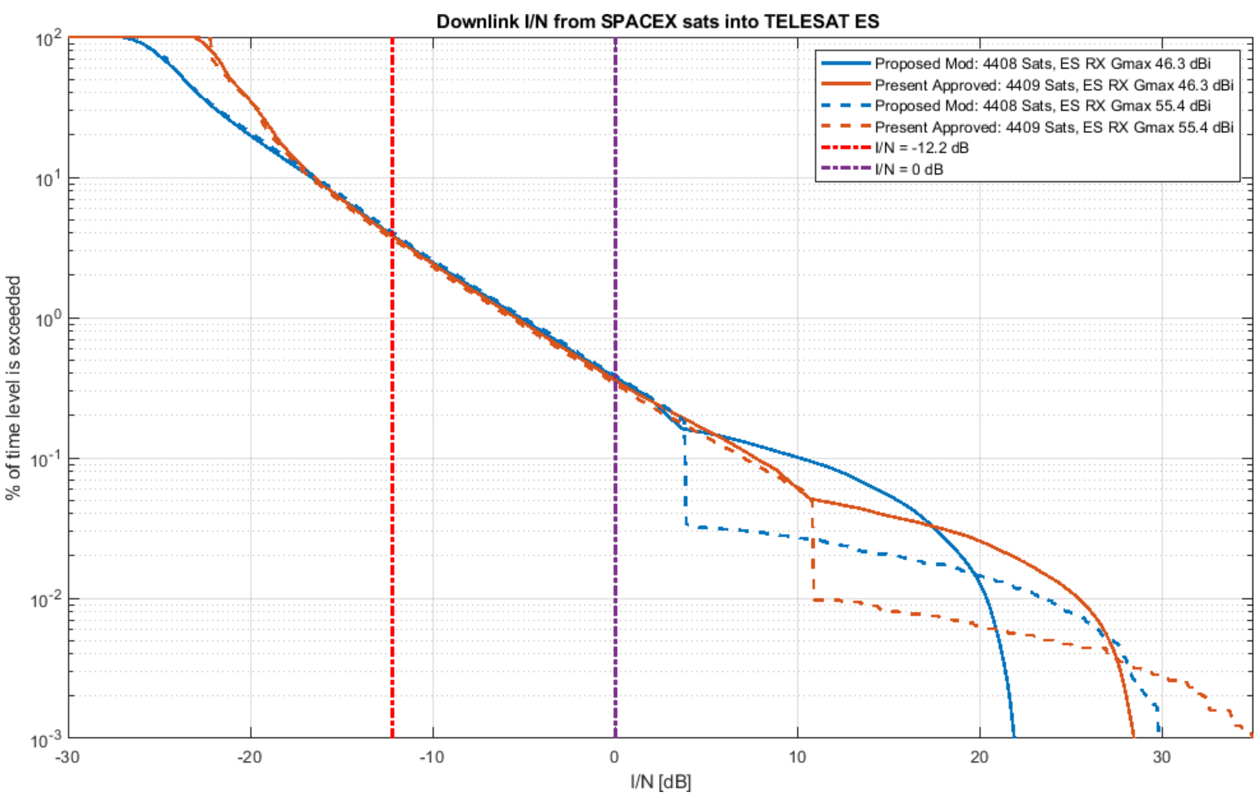


Figure A1-3. Downlink Comparison for Various Telesat Antennas at 75ºN (Ka-band)

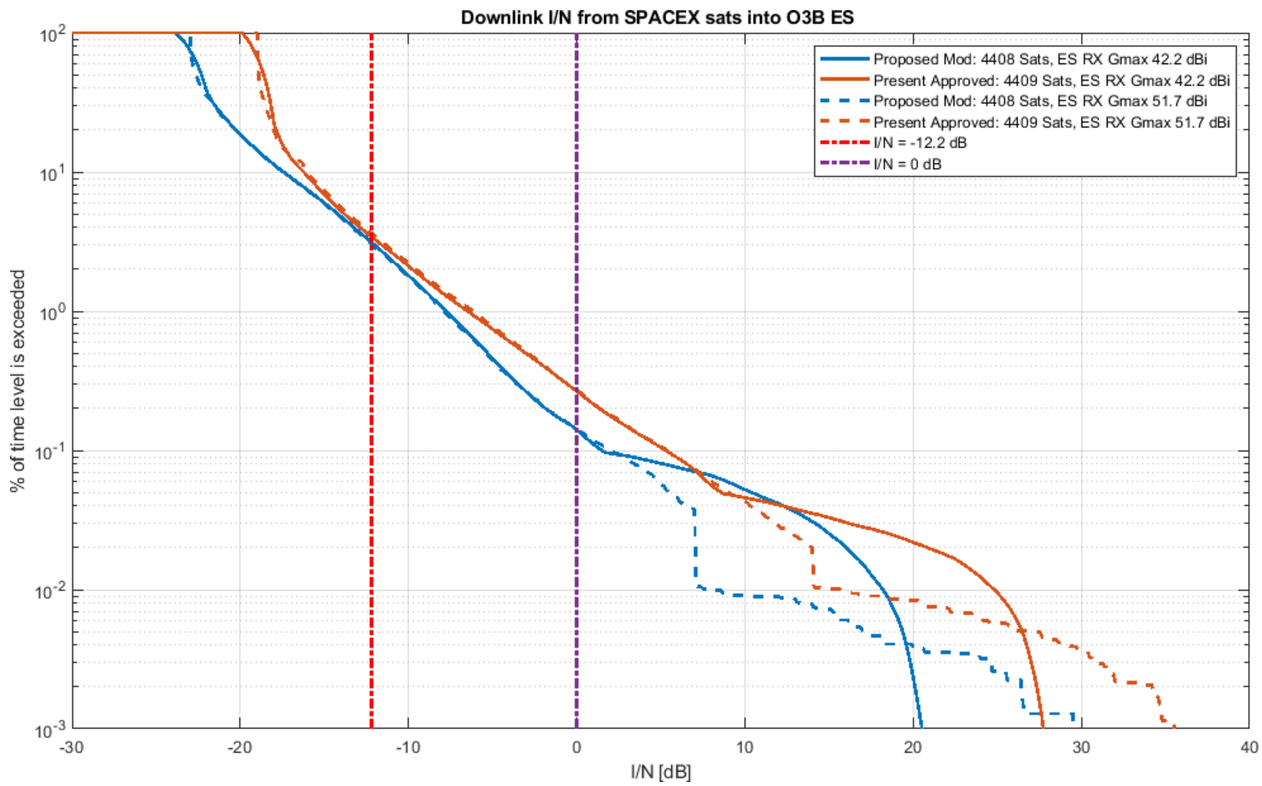


Figure A1-5. Downlink Comparison for Various O3B Antennas at 35ºN (Ka-band)

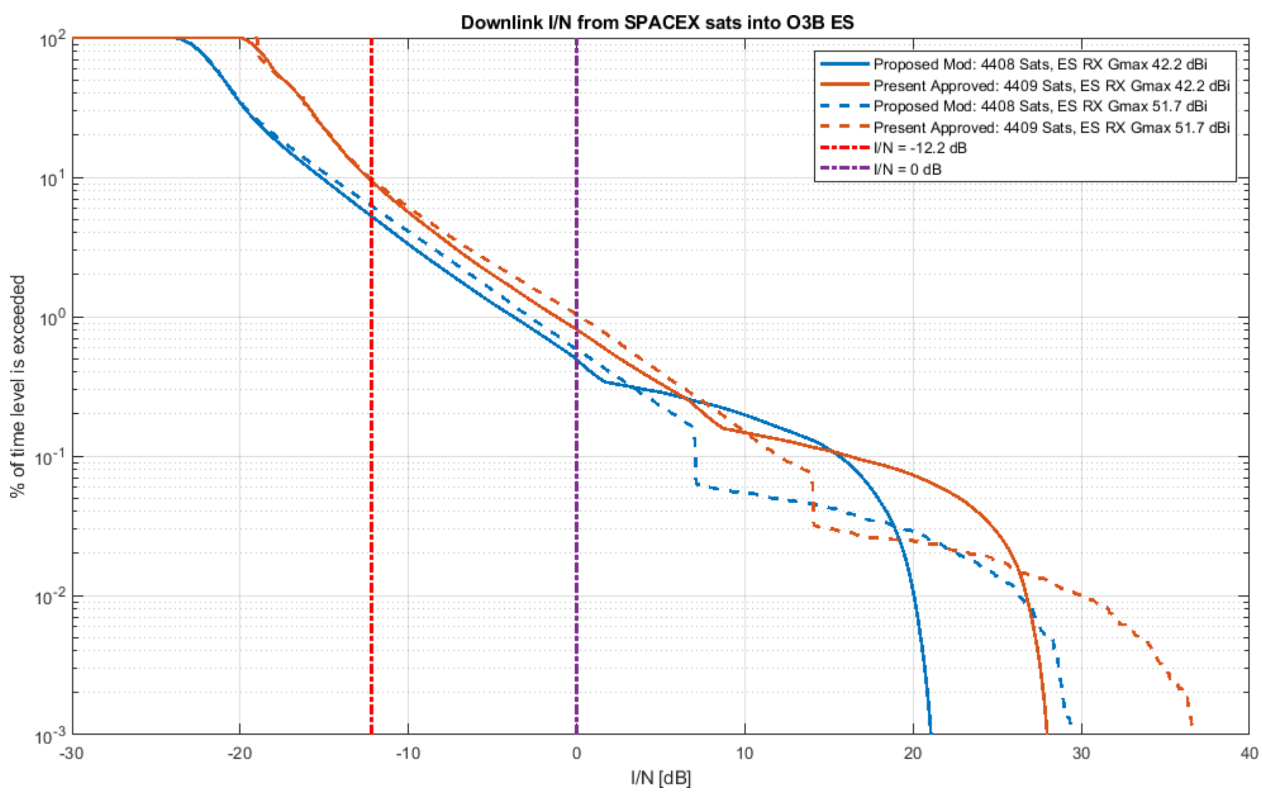


Figure A1-6. Downlink Comparison for Various O3B Antennas at 75ºN (Ka-band)

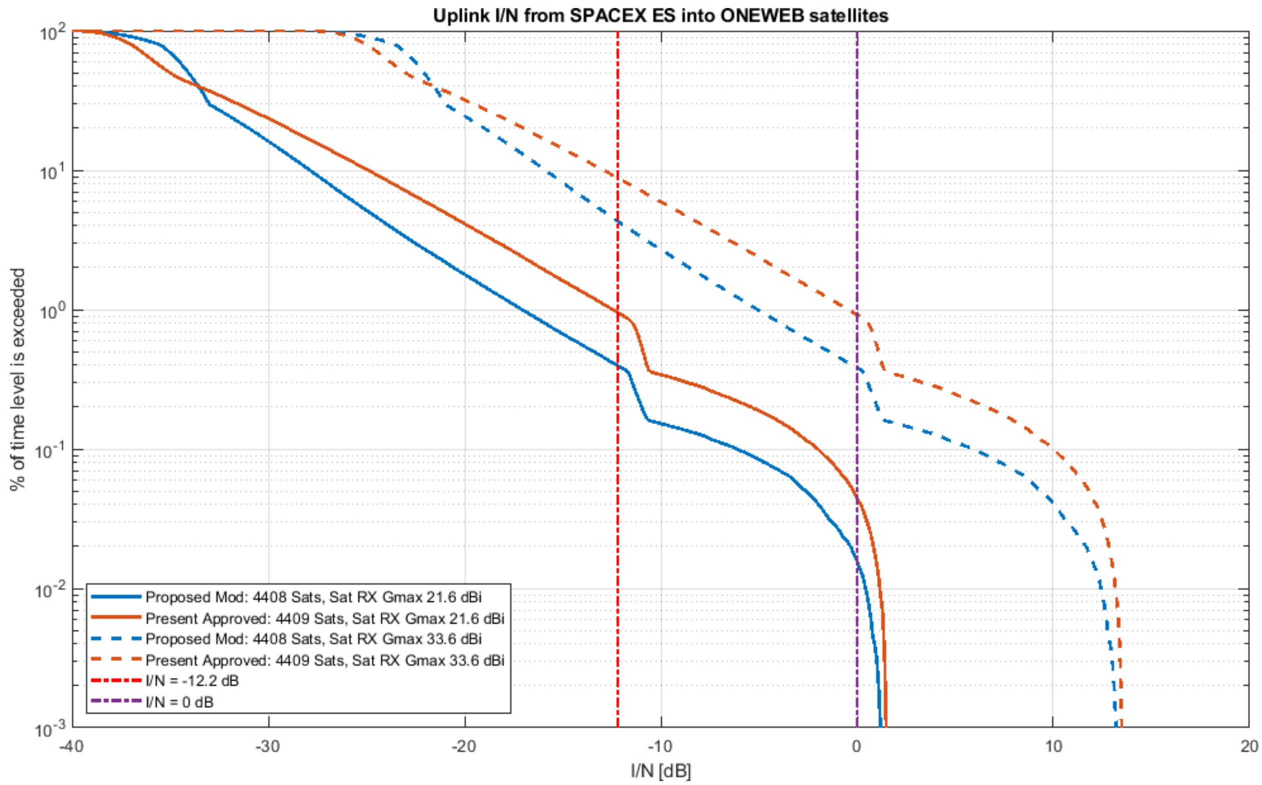


Figure A1-7. Uplink Comparison for Various OneWeb Antennas at 35ºN (Ku-band)

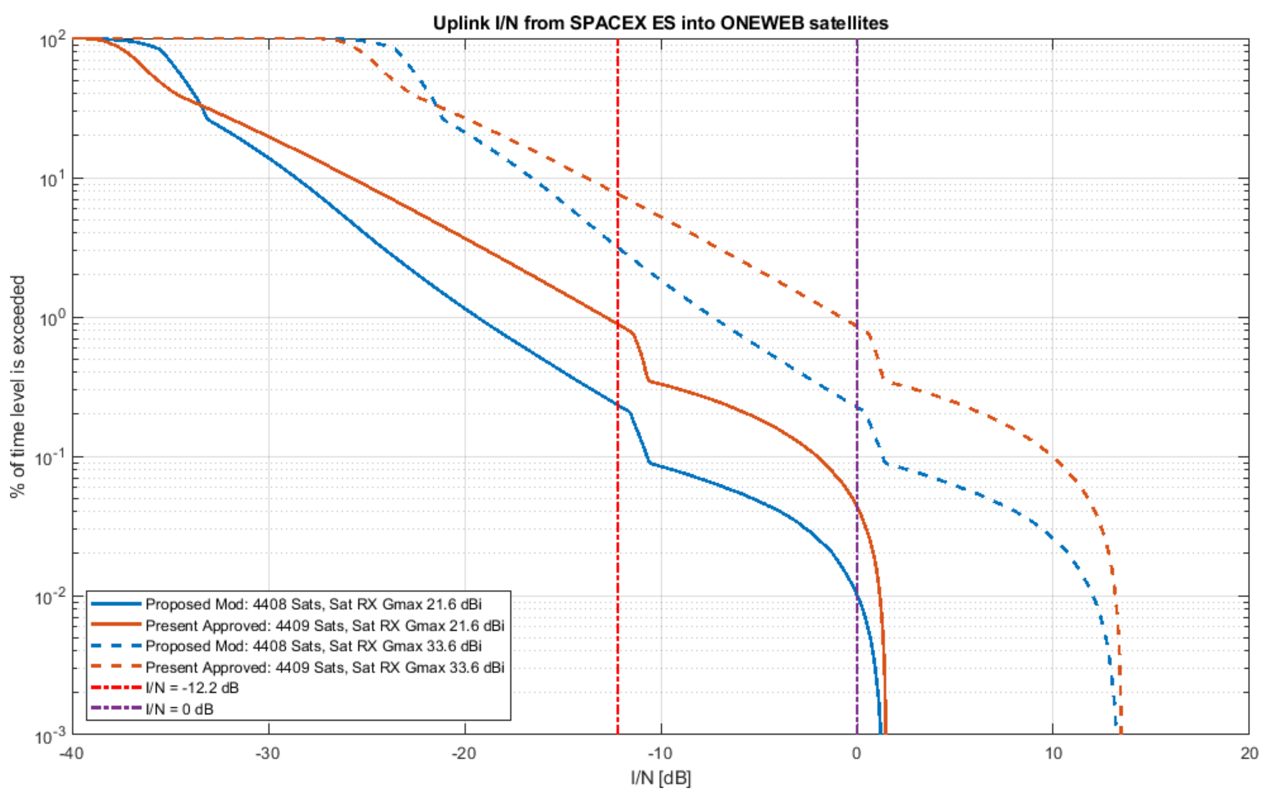


Figure A1-8. Uplink Comparison for Various OneWeb Antennas at 75ºN (Ku-band)

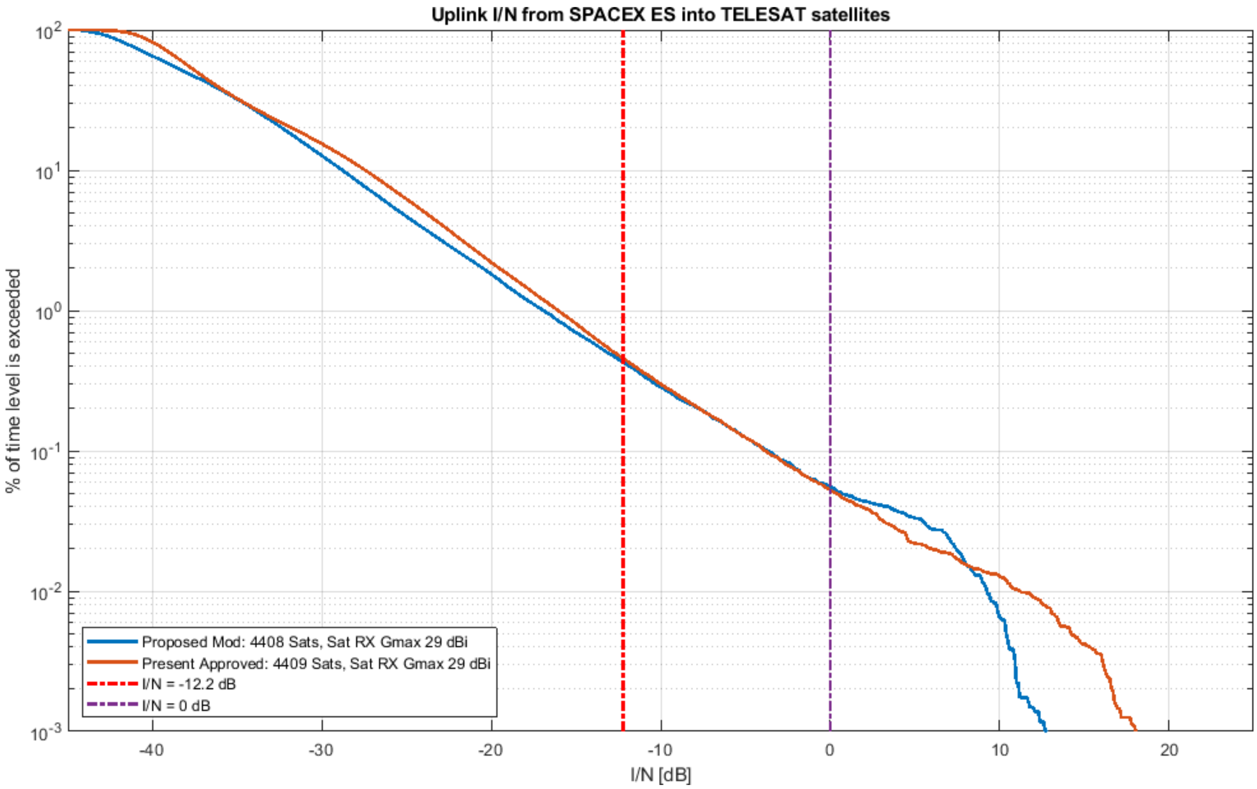


Figure A1-9. Uplink Comparison for Typical Telesat Antenna at 35ºN (Ka-band)

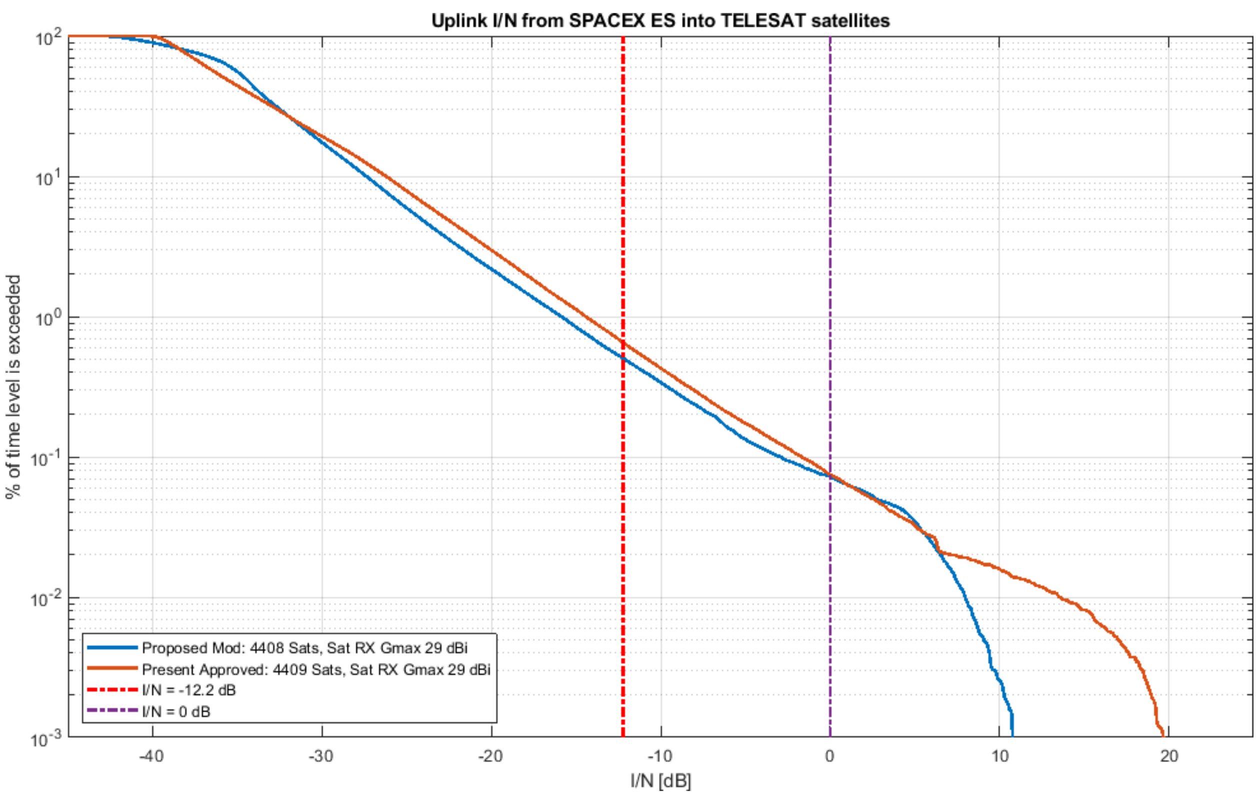


Figure A1-10. Uplink Comparison for Typical Telesat Antenna at 75ºN (Ka-band)

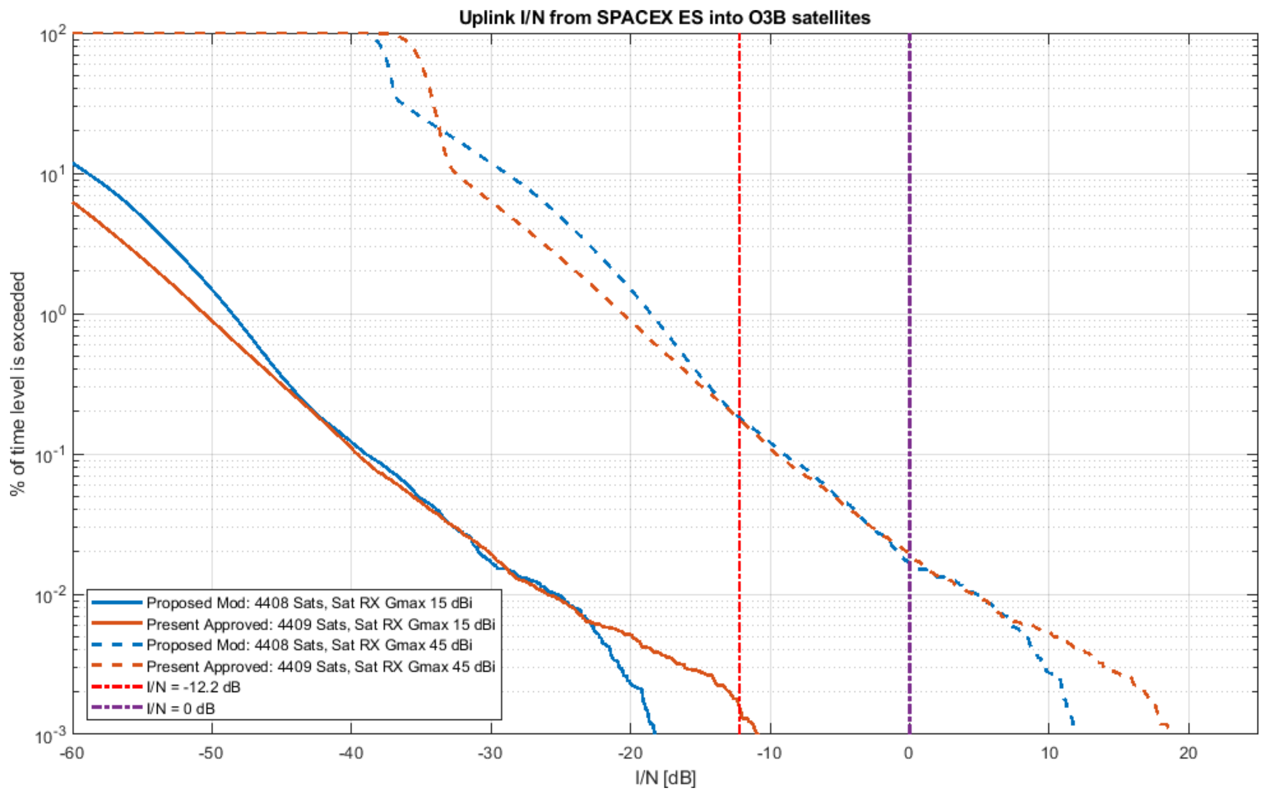


Figure A1-11. Uplink Comparison for Various O3B Antennas at 35ºN (Ka-band)

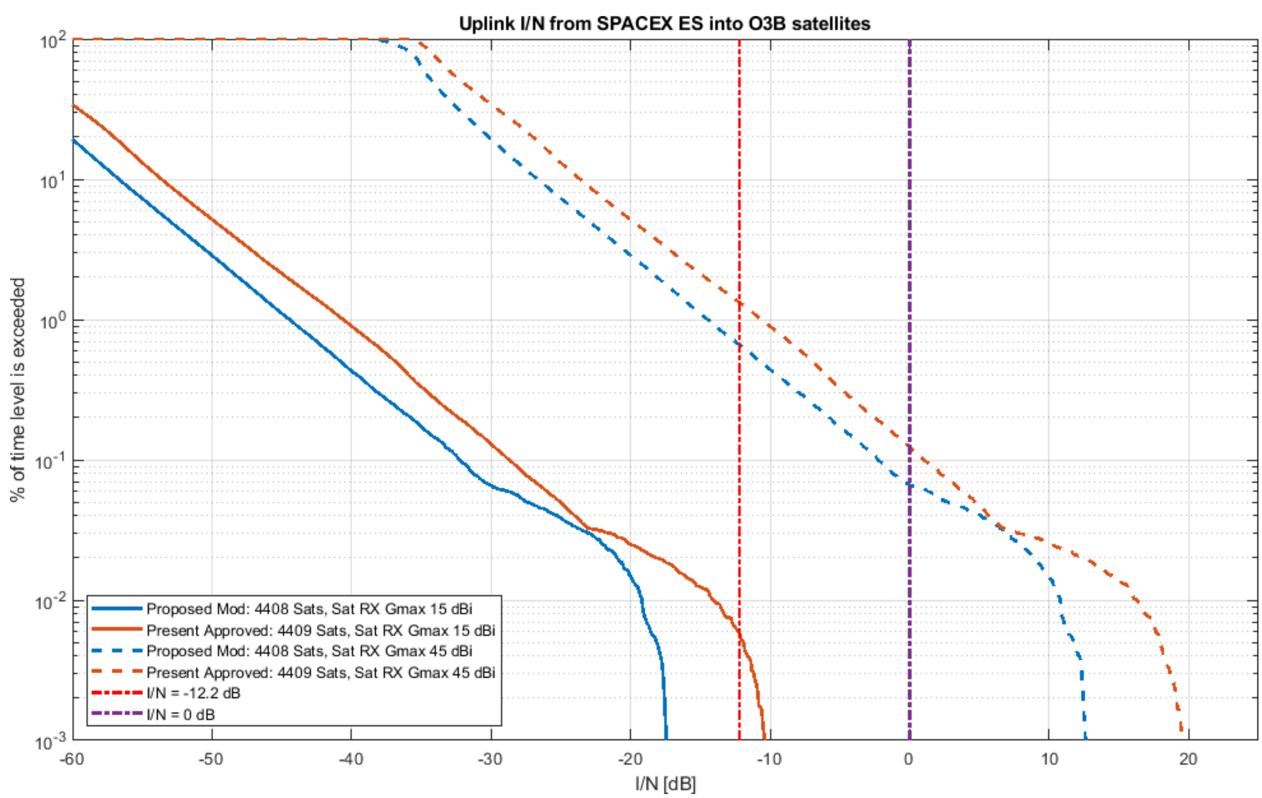


Figure A1-12. Uplink Comparison for Various O3B Antennas at 75ºN (Ka-band)

ANNEX 2

POTENTIAL INTERFERENCE TO GSO SATELLITE SYSTEMS

A. Demonstration of EPFD Compliance for Ku-Band Operations

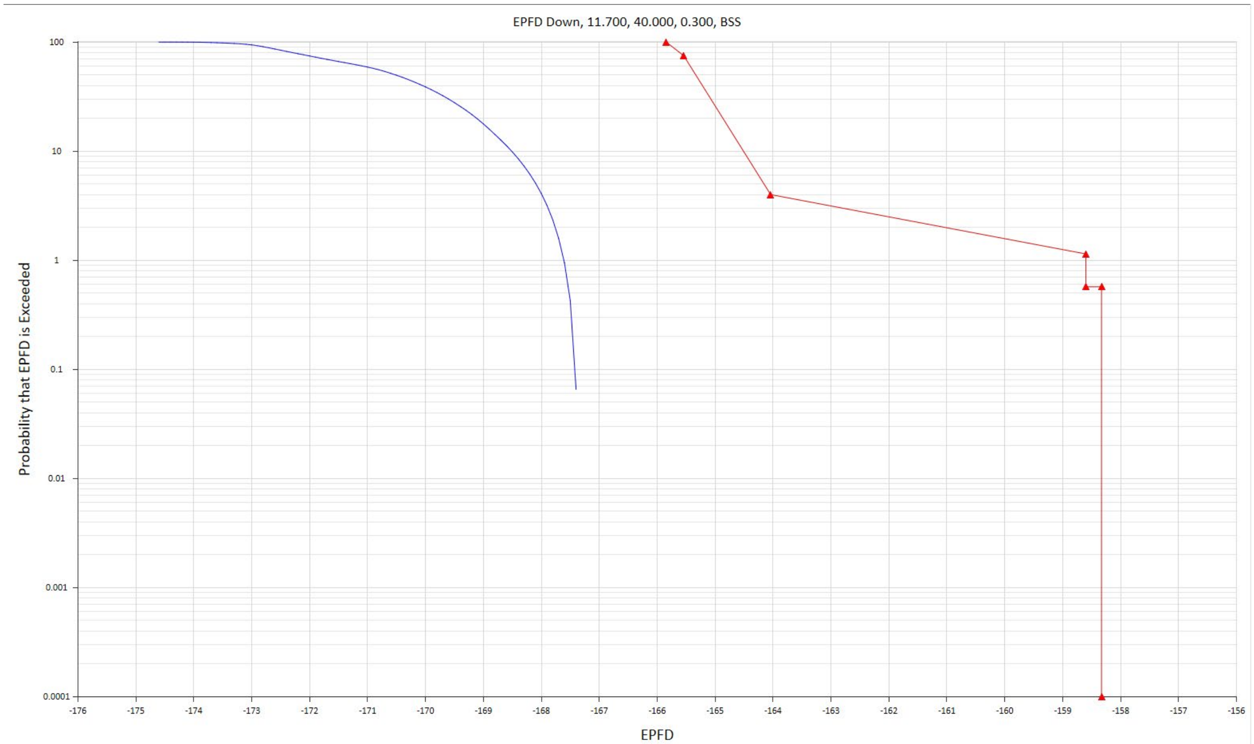
The following analysis demonstrates that the Ku-band operations of the SpaceX NGSO satellite system, as modified, will comply with the applicable equivalent power flux-density ("EPFD") limits set forth in Article 22 of the ITU Radio Regulations, which have been incorporated by reference into the Commission's rules.[1] For this purpose, SpaceX has used the latest version of the ITU-approved computer program developed by Transfinite Systems ("Transfinite") for determining compliance with the EPFD single-entry validation limits.

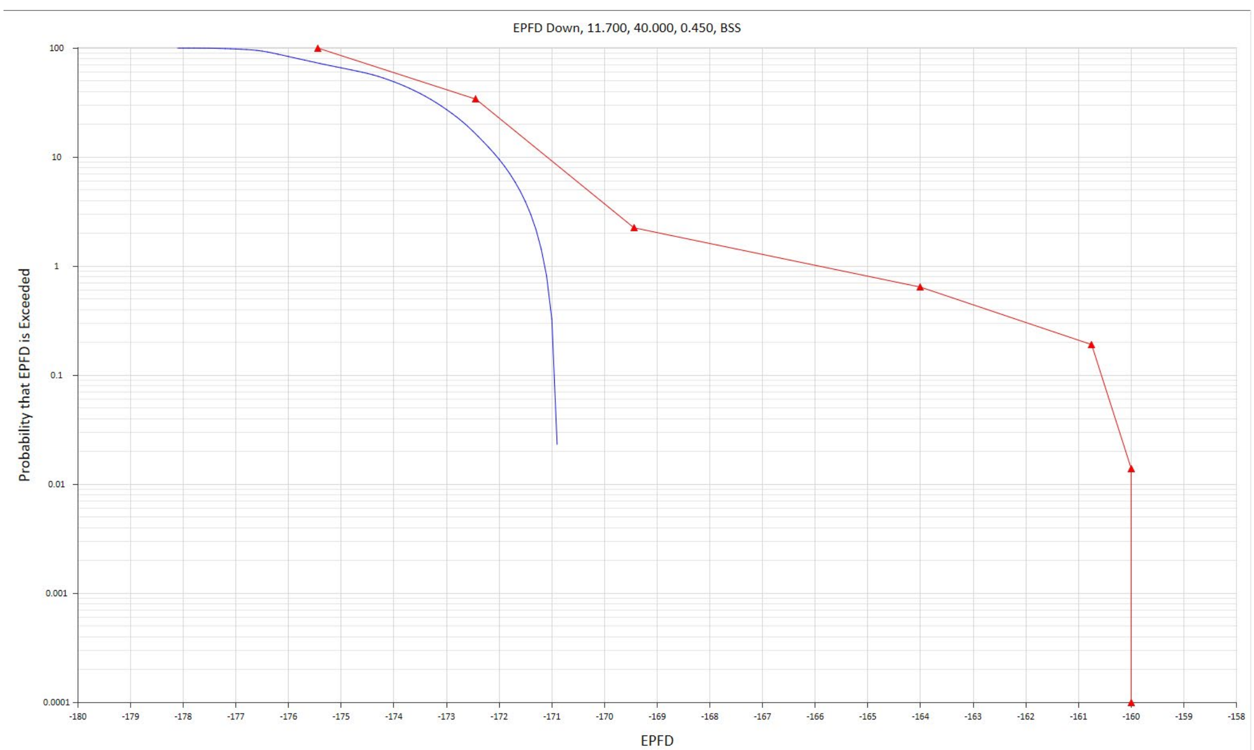
The figures below present the results of the Transfinite analysis with respect to the space-to-Earth direction ($EPFD_{down}$), the Earth-to-space direction ($EPFD_{up}$), for transmissions between satellites in orbit where spectrum is allocated bi-directionally ($EPFD_{is}$), and for TT&C uplink transmissions. The satellite system consists of a deployment of 4,408 satellites operating at a range of altitudes between 540 and 570 km with a minimum earth station elevation angle of 25 degrees. The labeling of each diagram provides the relevant details for each analysis generated by the software. On each diagram, the resulting EPFD level is shown by the blue curve and the EPFD mask that applies is shown by the red line.

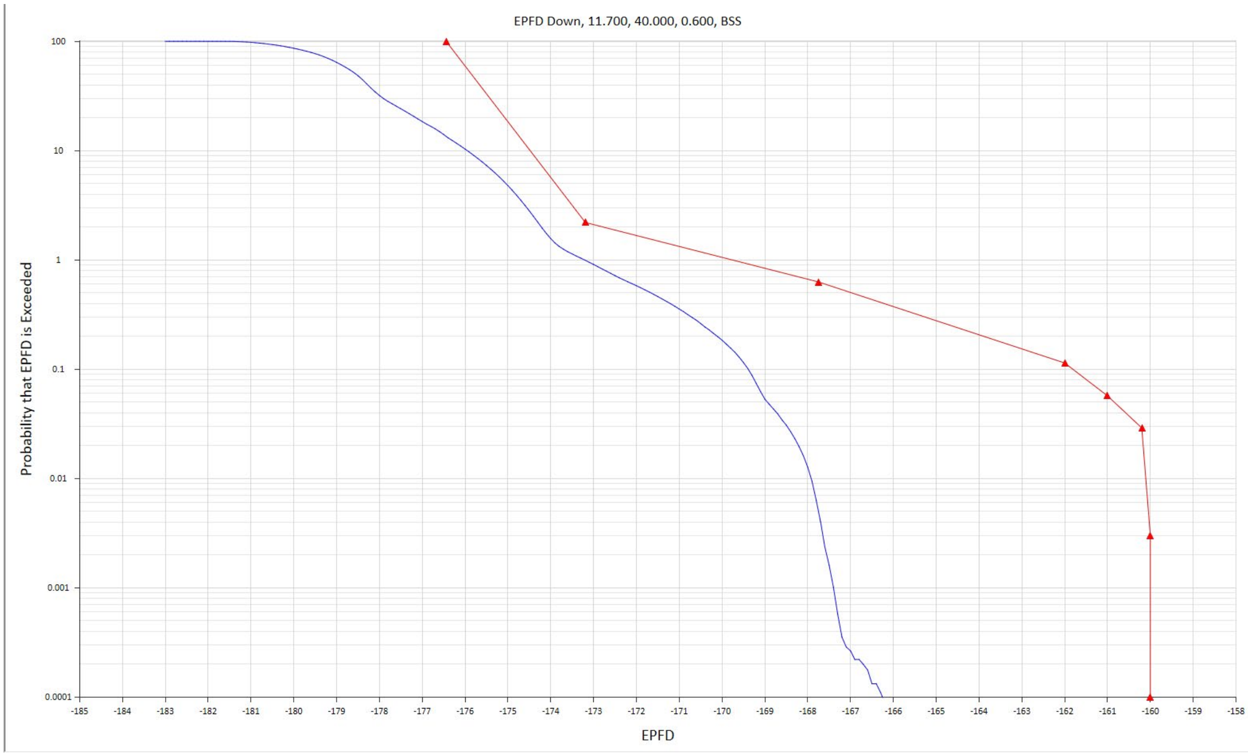
As these diagrams demonstrate, SpaceX's modified NGSO system will continue to comply with all EPFD limits applicable to its Ku-band operations. SpaceX will make the data files underlying this analysis available to interested parties upon request.

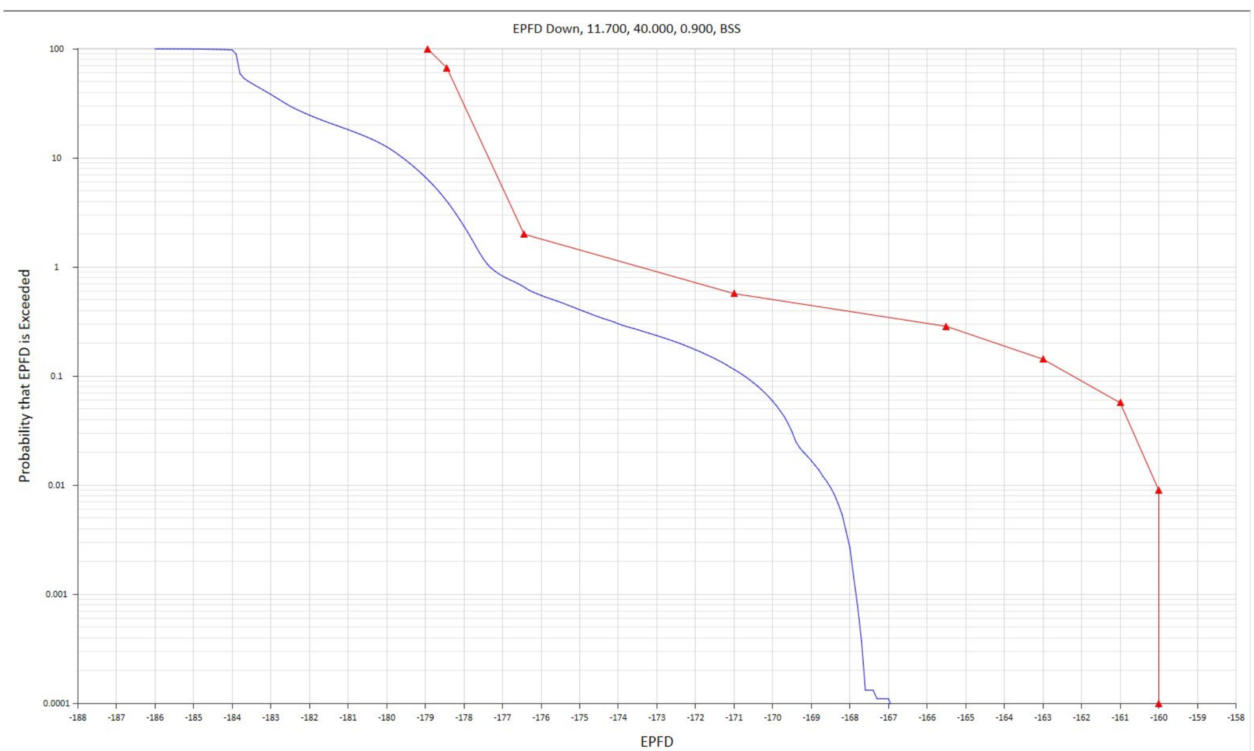
1 *See* 47 C.F.R. § 25.146(a)(2).

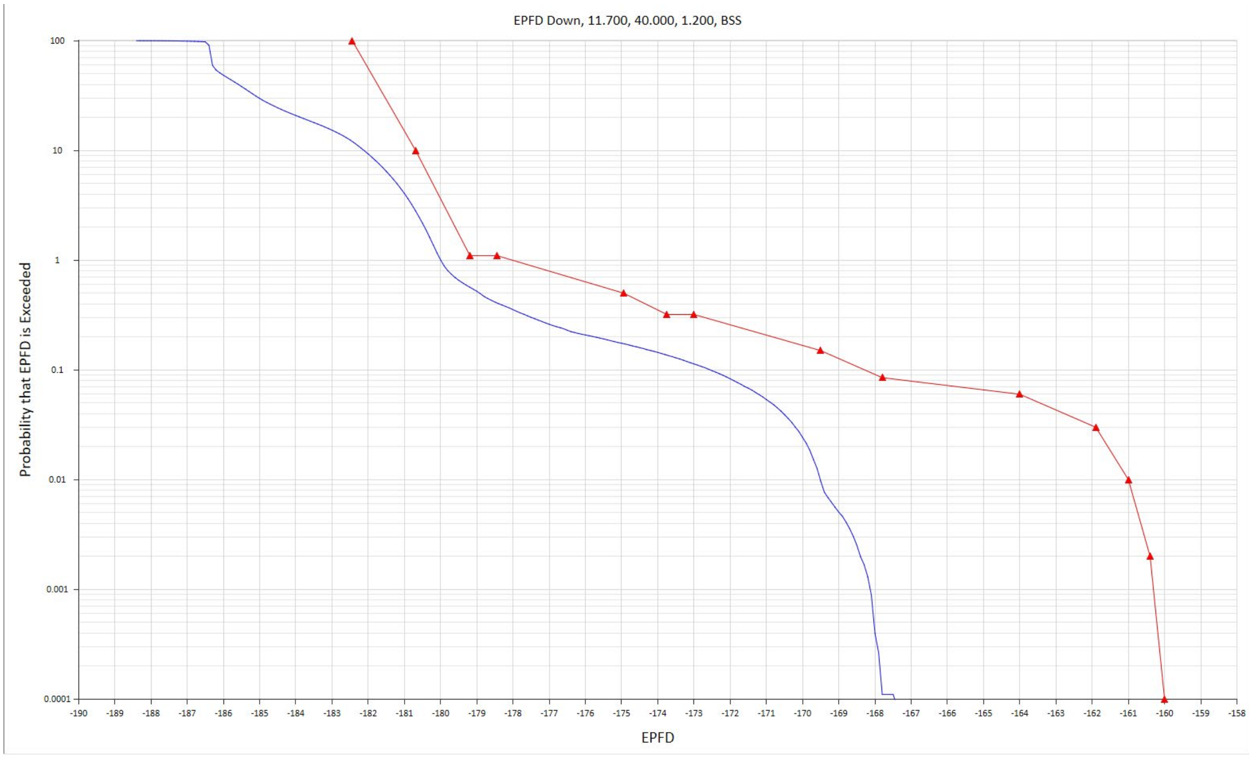
OUTPUTS FOR EPFD$_{DOWN}$ ASSESSMENT OF BSS LIMITS

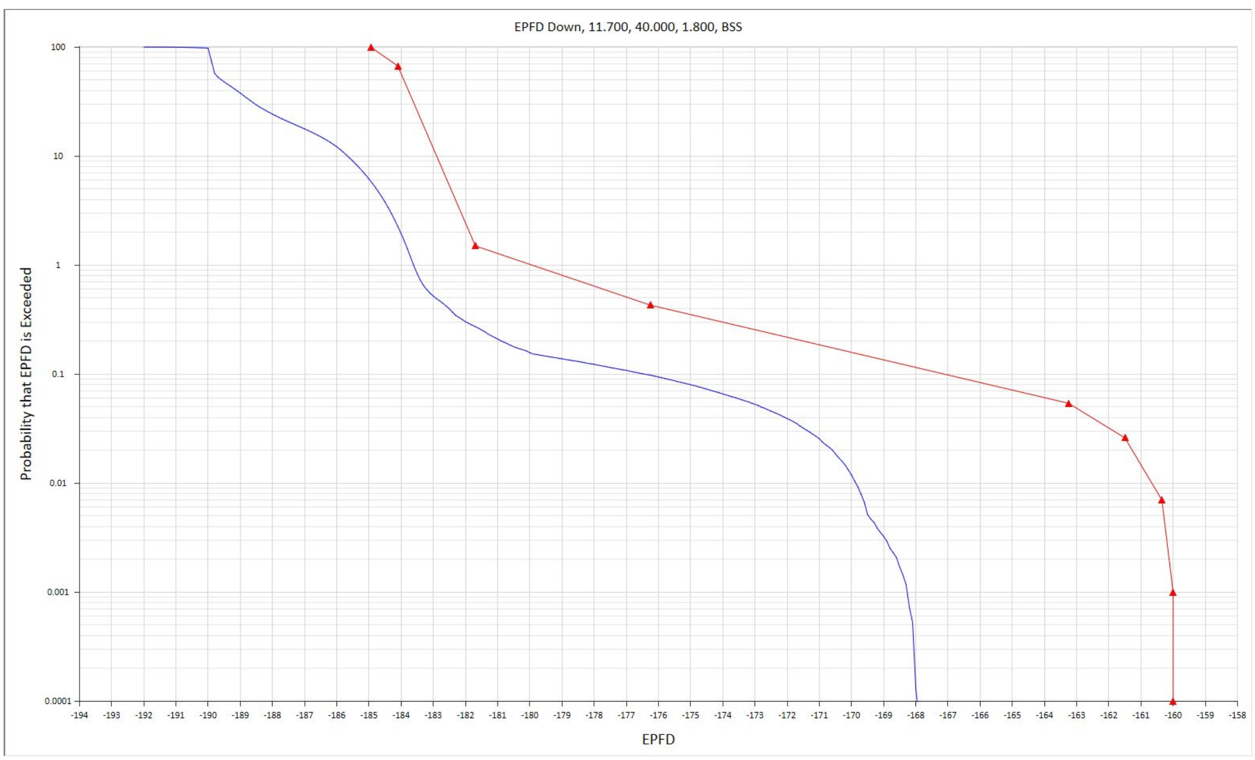





EPFD Down, 11.700, 40.000, 0.600, BSS
Probability that EPFD is Exceeded
EPFD


EPFD Down, 11.700, 40.000, 0.900, BSS
Probability that EPFD is Exceeded
EPFD


EPFD Down, 11.700, 40.000, 1.200, BSS
Probability that EPFD is Exceeded
EPFD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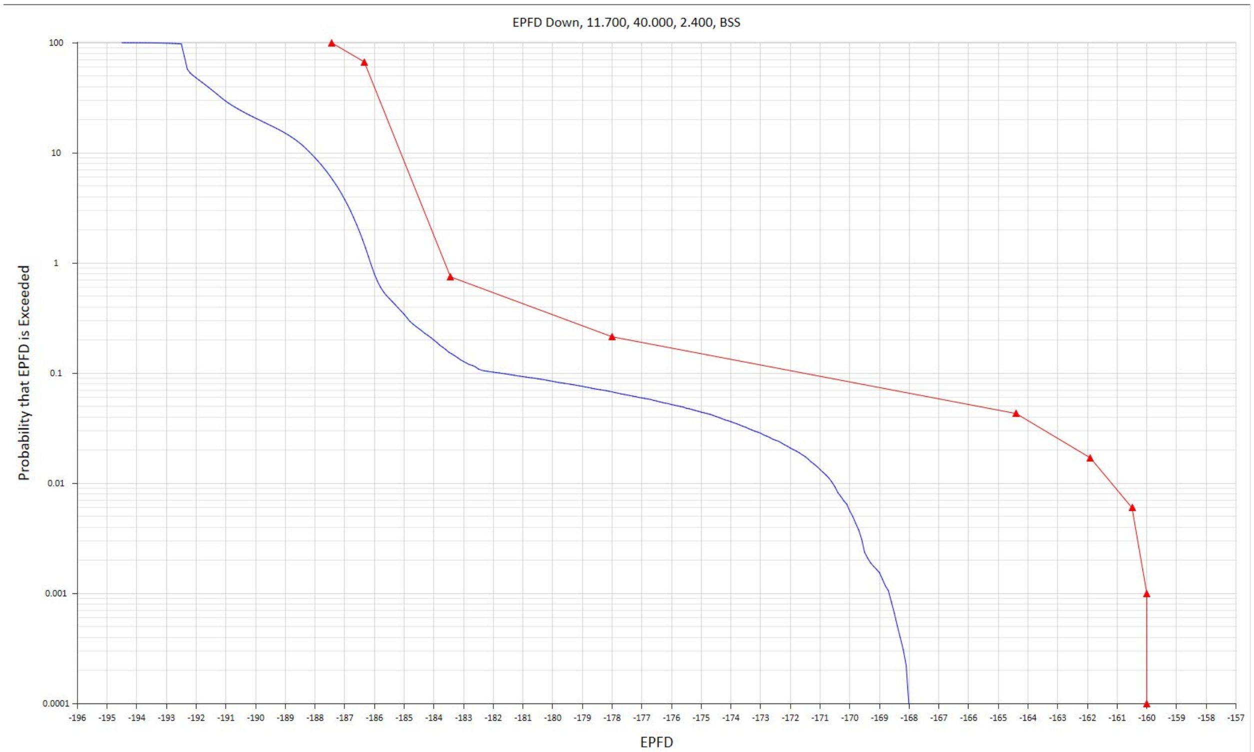
Probability that EPFD is Exceeded
EPFD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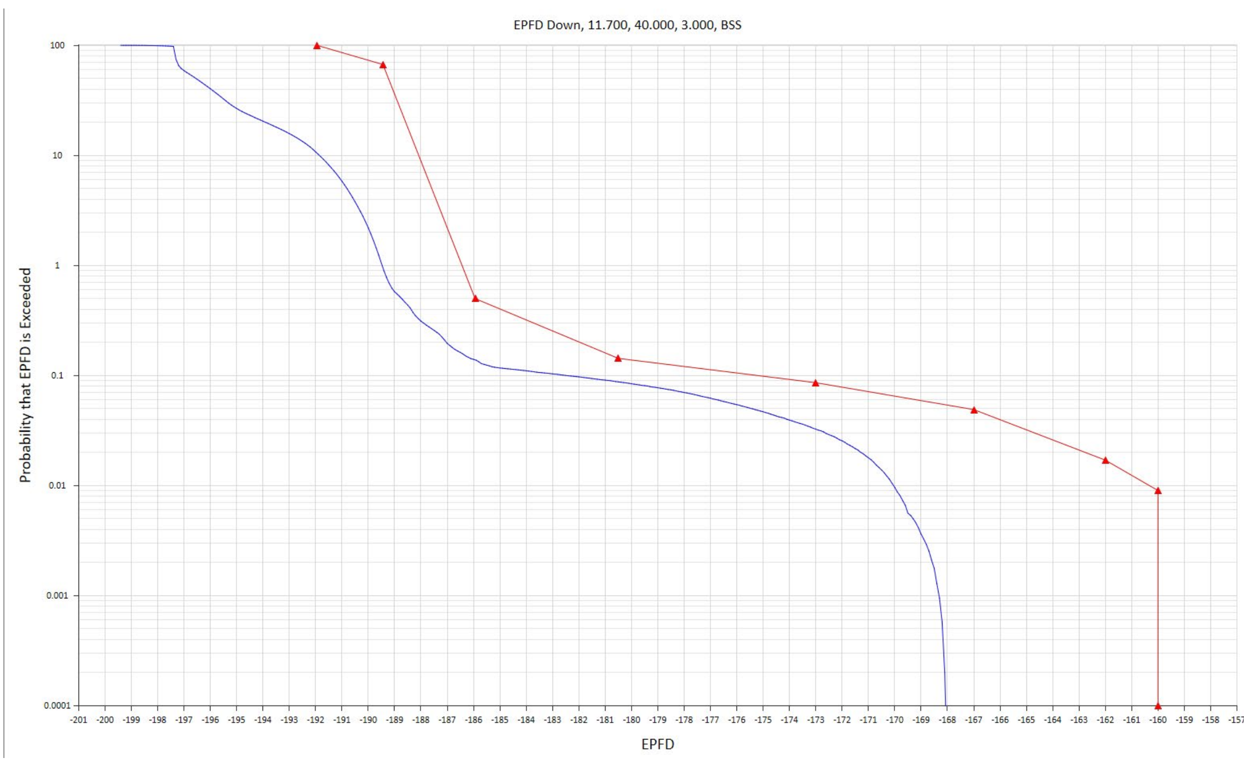
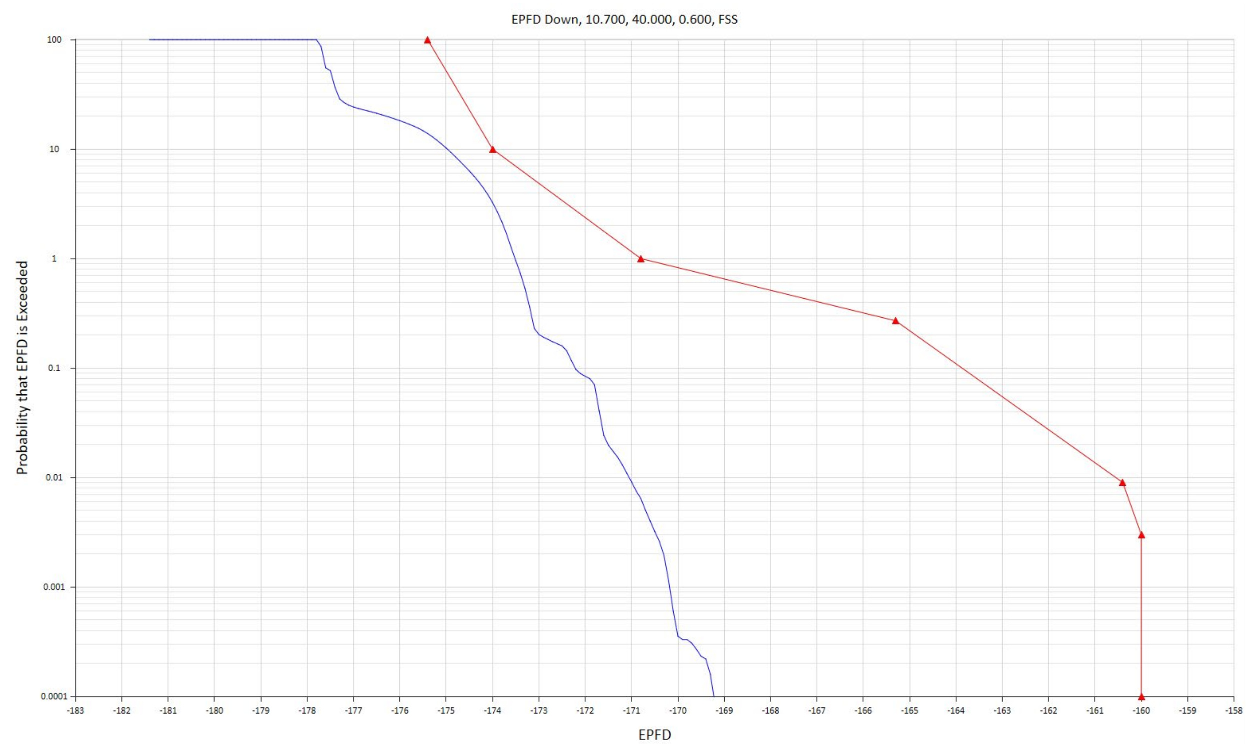
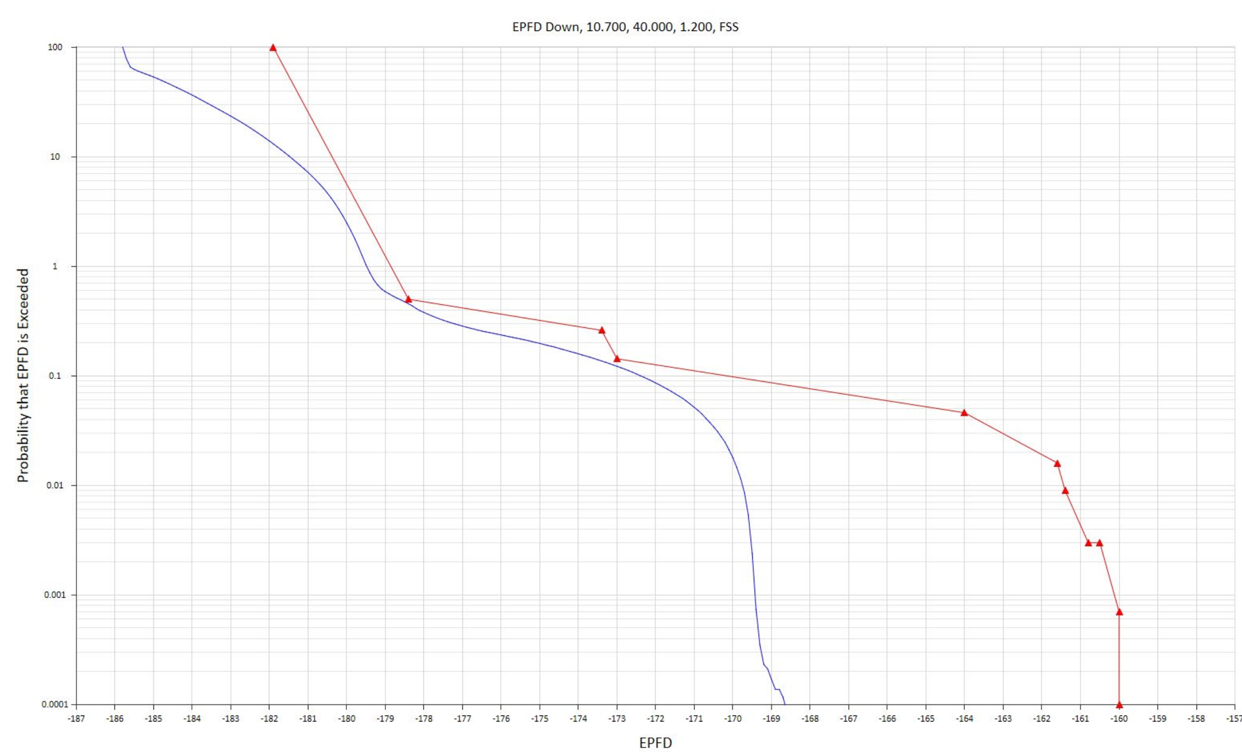
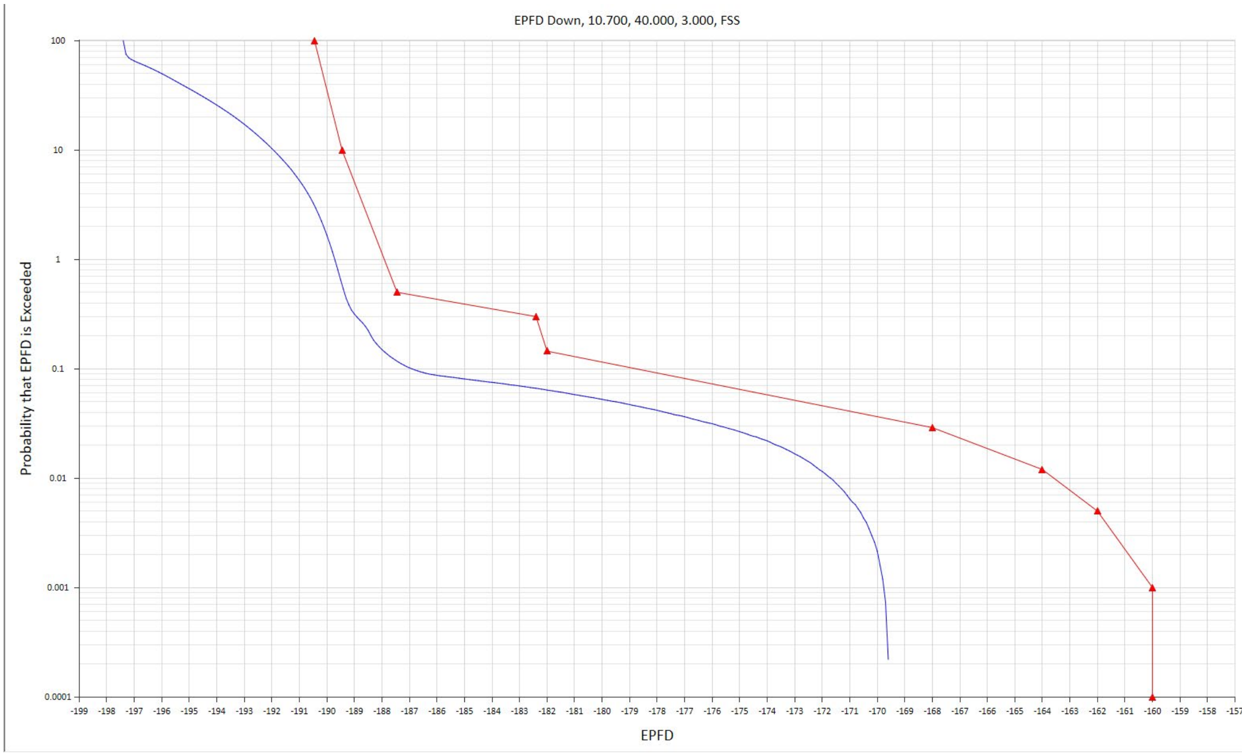
EPFD

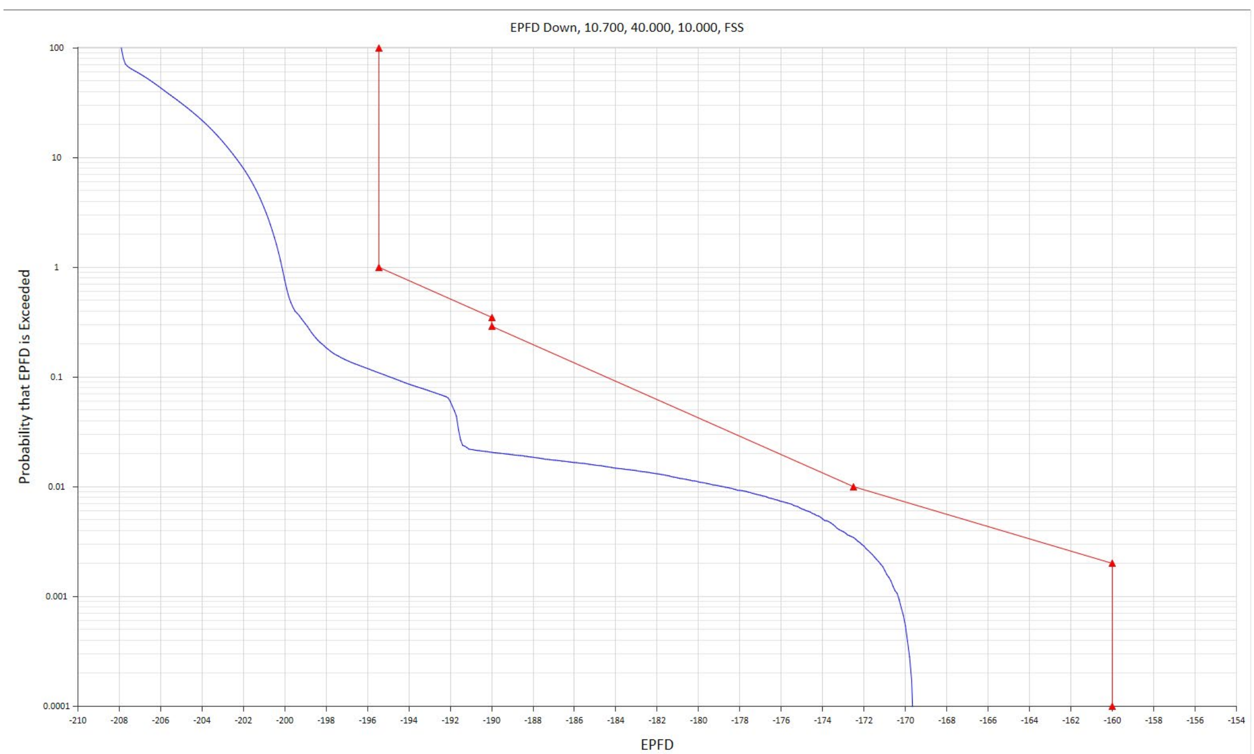

EPFD Down, 11.700, 40.000, 3.000, BSS
Probability that EPFD is Exceeded
EPFD

OUTPUTS FOR EPFD$_{DOWN}$ ASSESSMENT OF FSS LIMITS

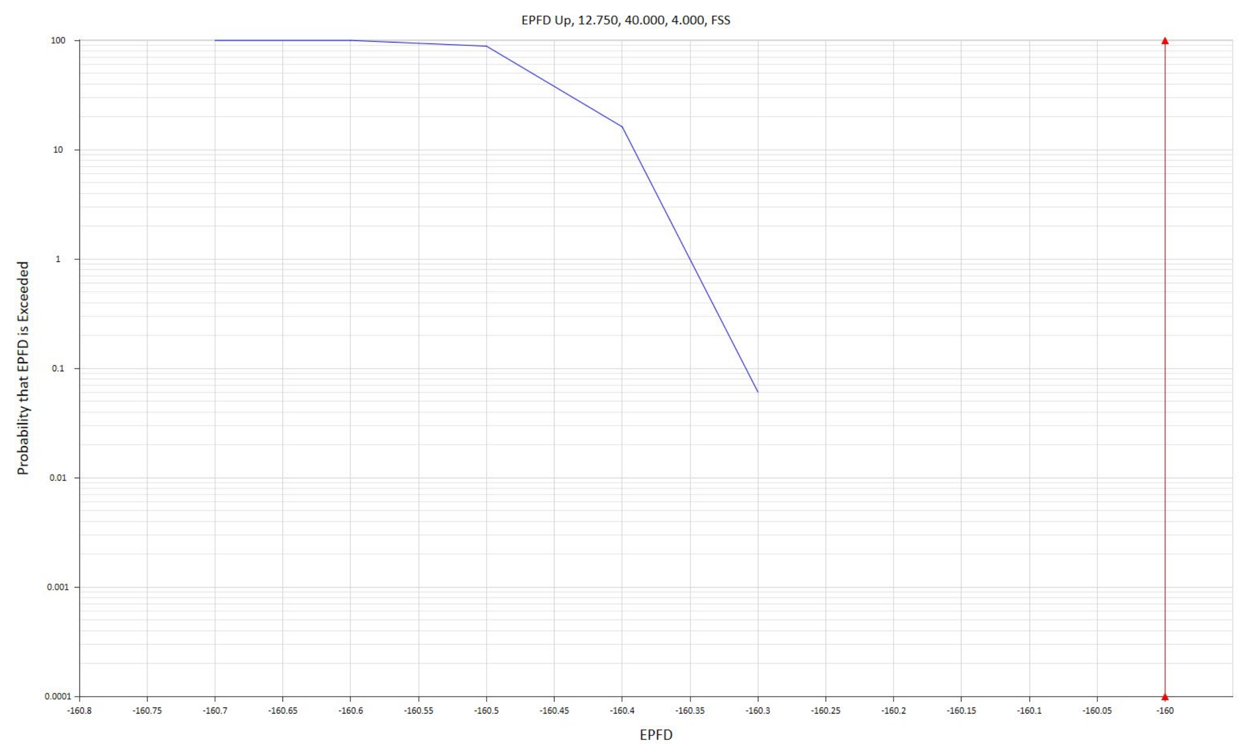


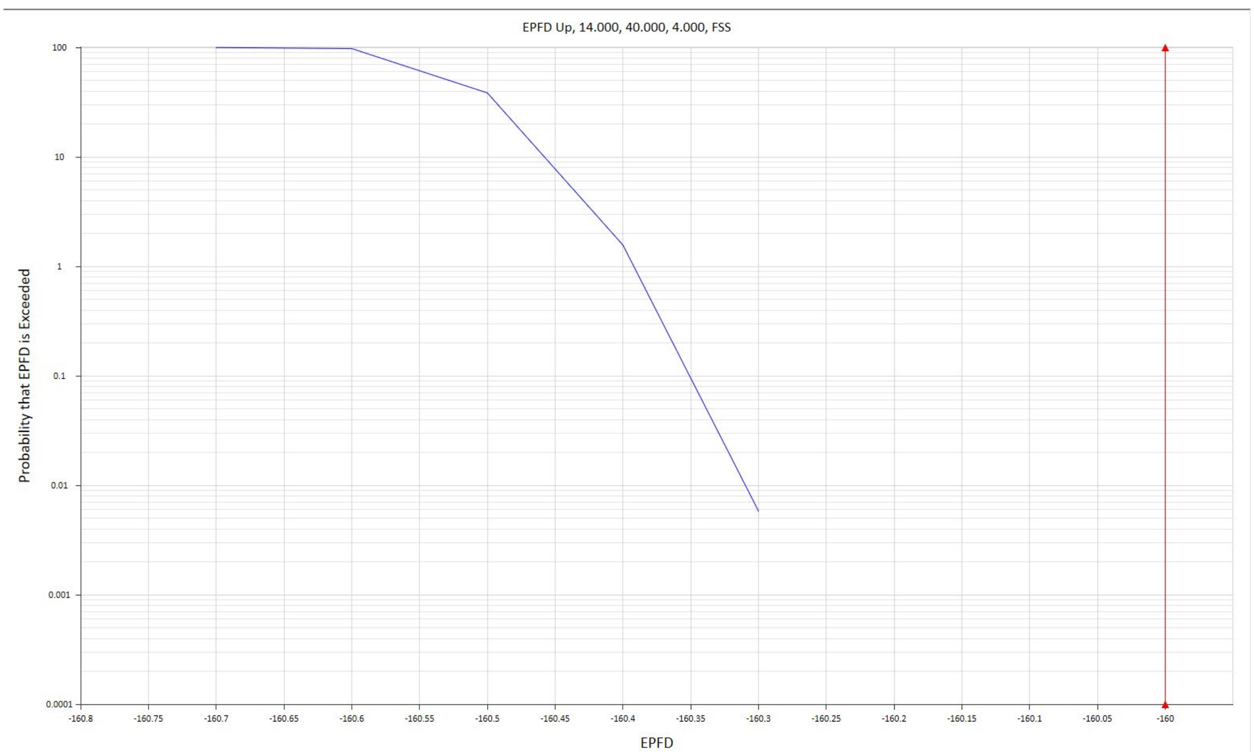



EPFD Down, 10.700, 40.000, 3.000, FSS
Probability that EPFD is Exceeded
EPFD

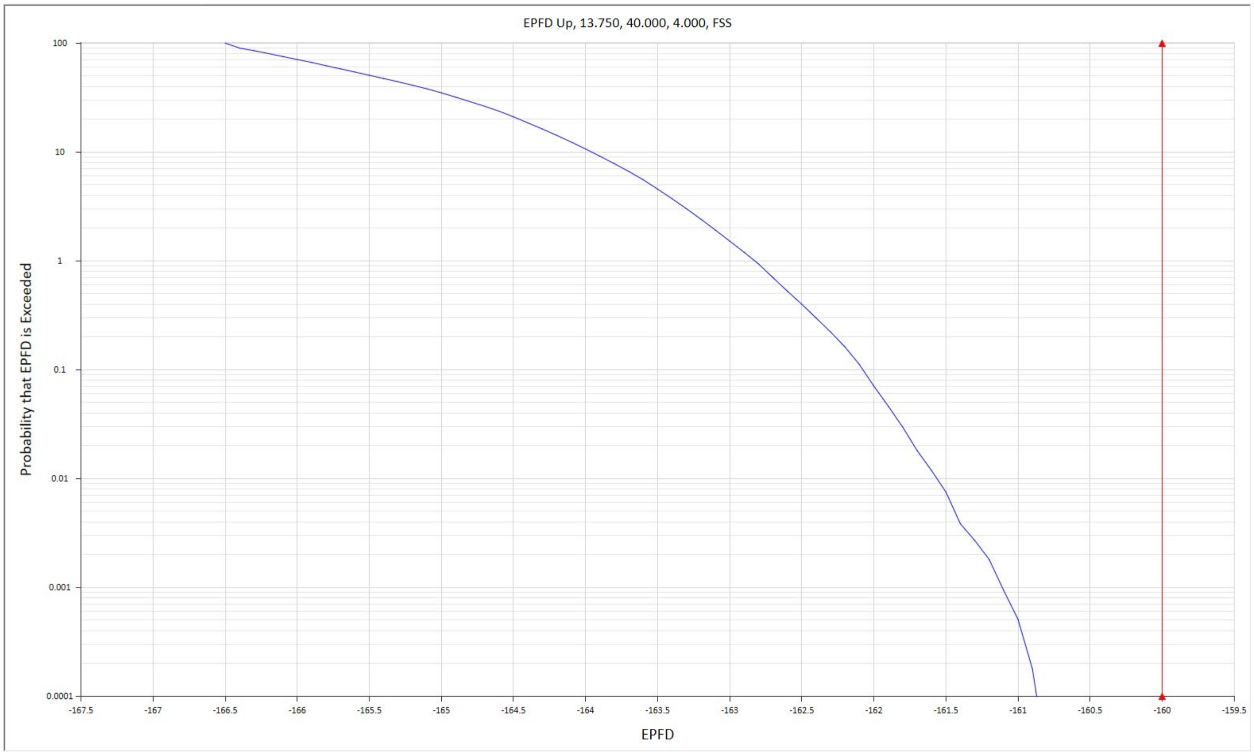

EPFD Down, 10.700, 40.000, 10.000, FSS
Probability that EPFD is Exceeded
EPFD

OUTPUTS FOR EPFD$_{UP}$ ASSESSMENT

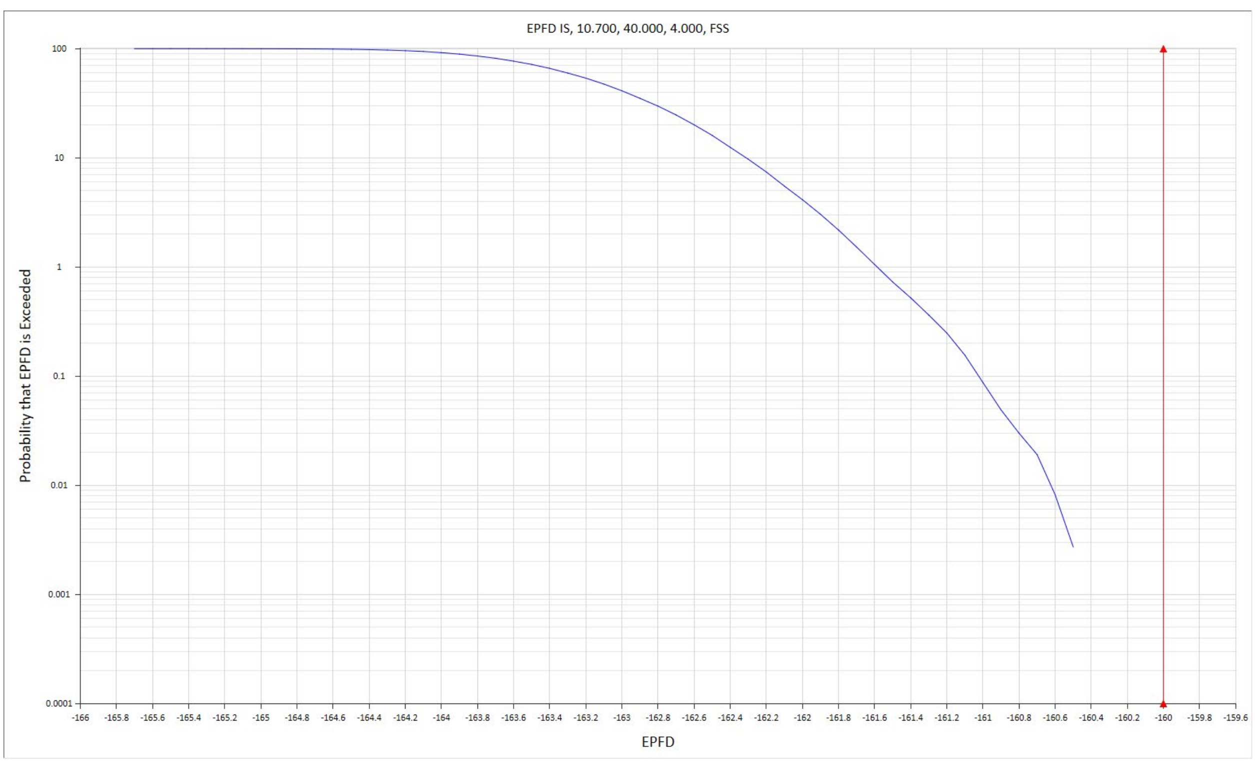




TT&C



OUTPUT FOR EPFD$_{IS}$ ASSESSMENT



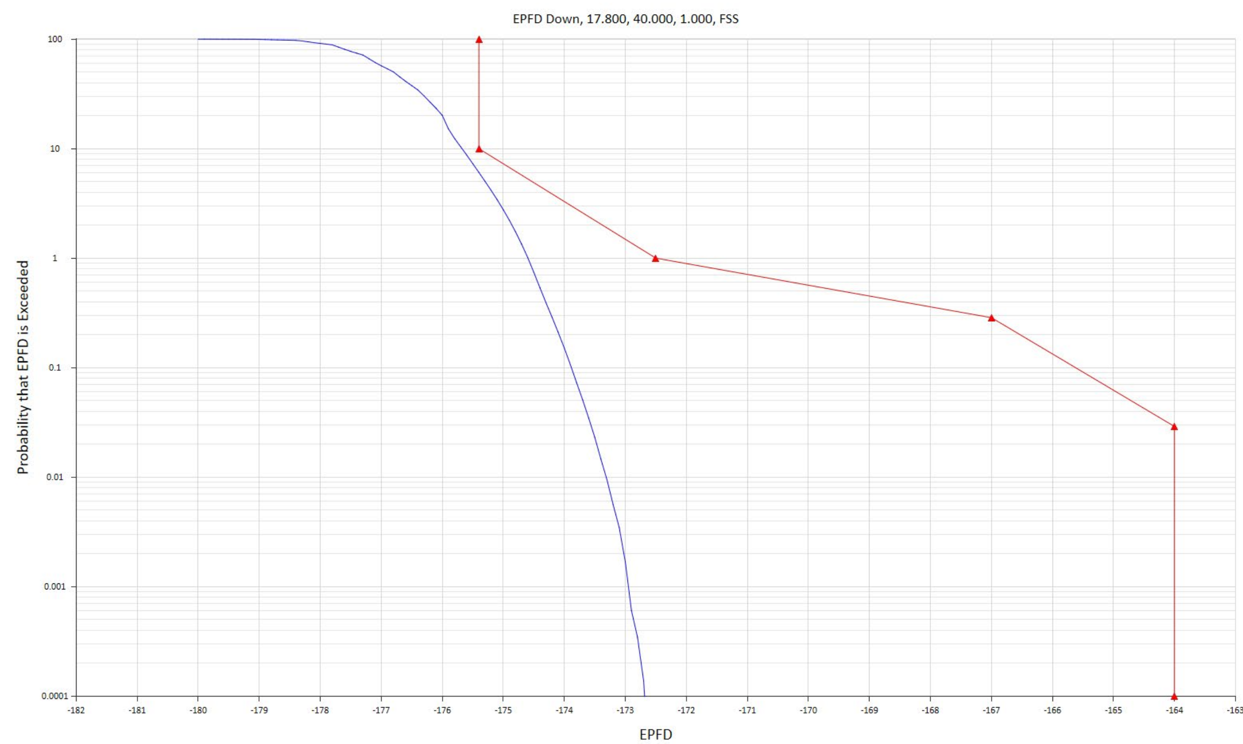
B. Demonstration of EPFD Compliance for Ka-Band Operations

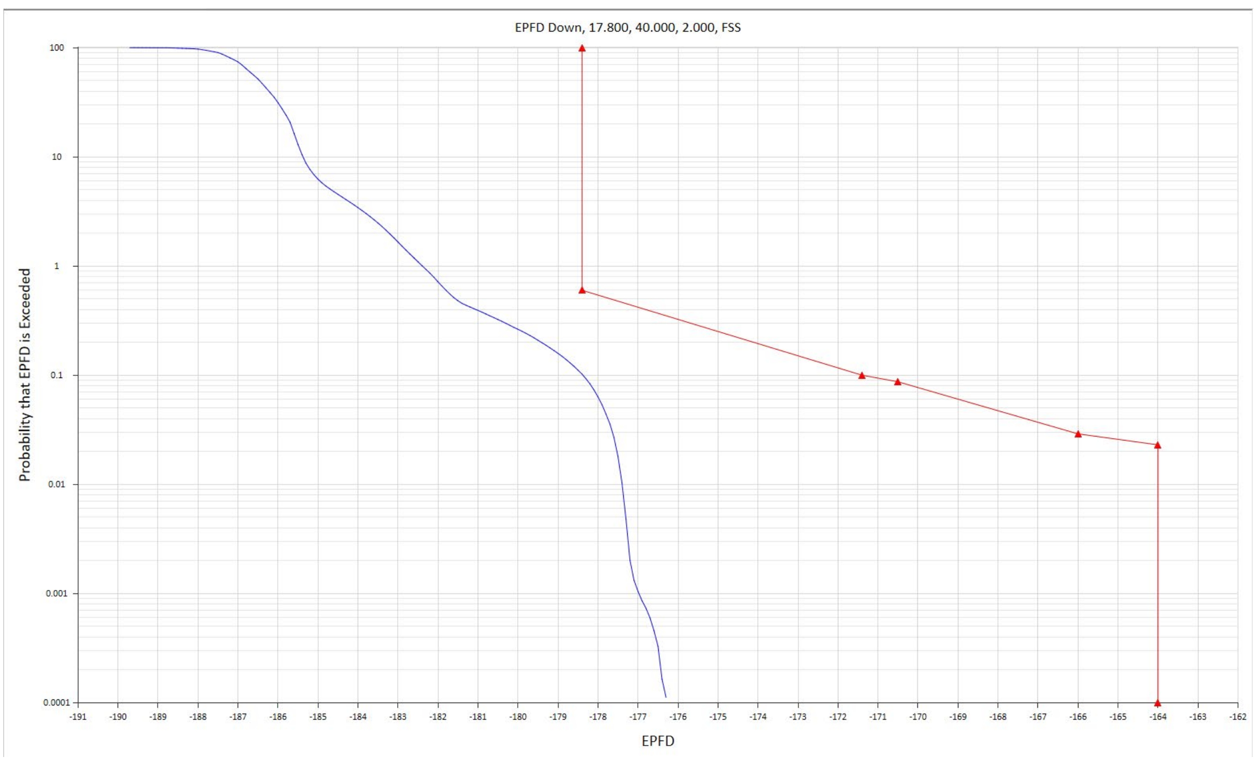
This annex demonstrates that the Ka-band operations of the SpaceX NGSO satellite system, as modified, will comply with the applicable EPFD limits. For this purpose, SpaceX has used the latest version of the ITU-approved computer program developed by Transfinite for determining compliance with the EPFD single-entry validation limits.

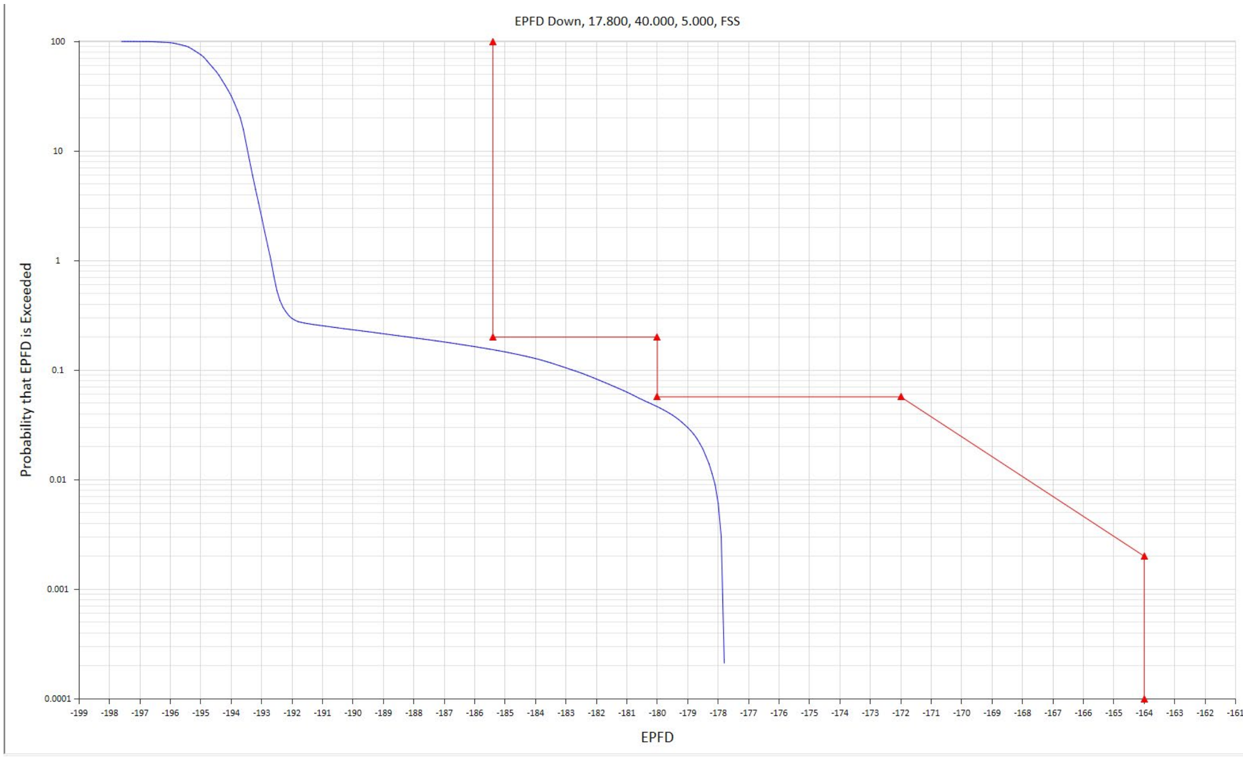
The figures below present the results of the Transfinite analysis with respect to the space-to-Earth direction ($EPFD_{down}$), the Earth-to-space direction ($EPFD_{up}$), for transmissions between satellites in orbit where spectrum is allocated bi-directionally ($EPFD_{is}$), and for TT&C transmissions. The satellite system consists of a deployment of 4,408 satellites operating at an altitude between 540 and 570 km with a minimum earth station elevation angle of 5 degrees. The labeling of each diagram provides the relevant details for each analysis generated by the software. On each diagram, the resulting EPFD level is shown by the blue curve and the EPFD mask that applies is shown by the red line.

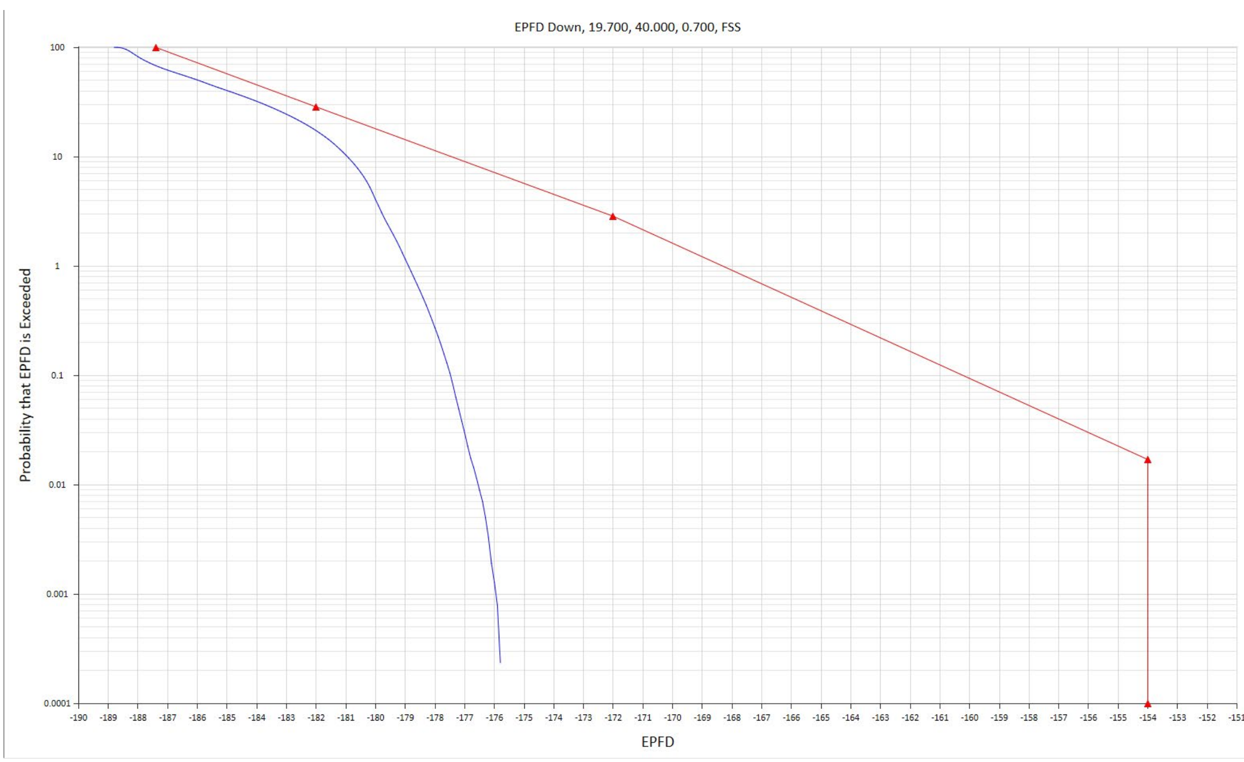
As these diagrams demonstrate, SpaceX's modified NGSO system will continue to comply with all EPFD limits applicable to its Ka-band operations. SpaceX will make the data files underlying this analysis available to interested parties upon request.

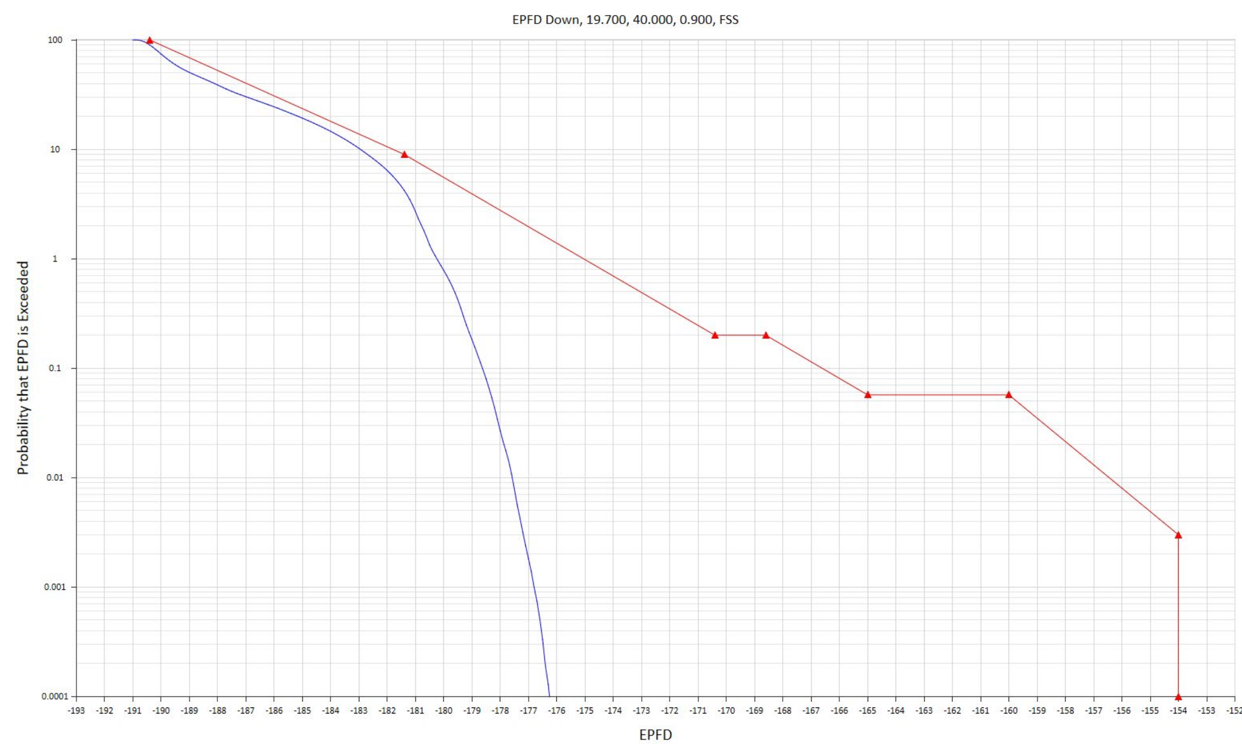
OUTPUTS FOR EPFD$_{DOWN}$ ASSESSMENT

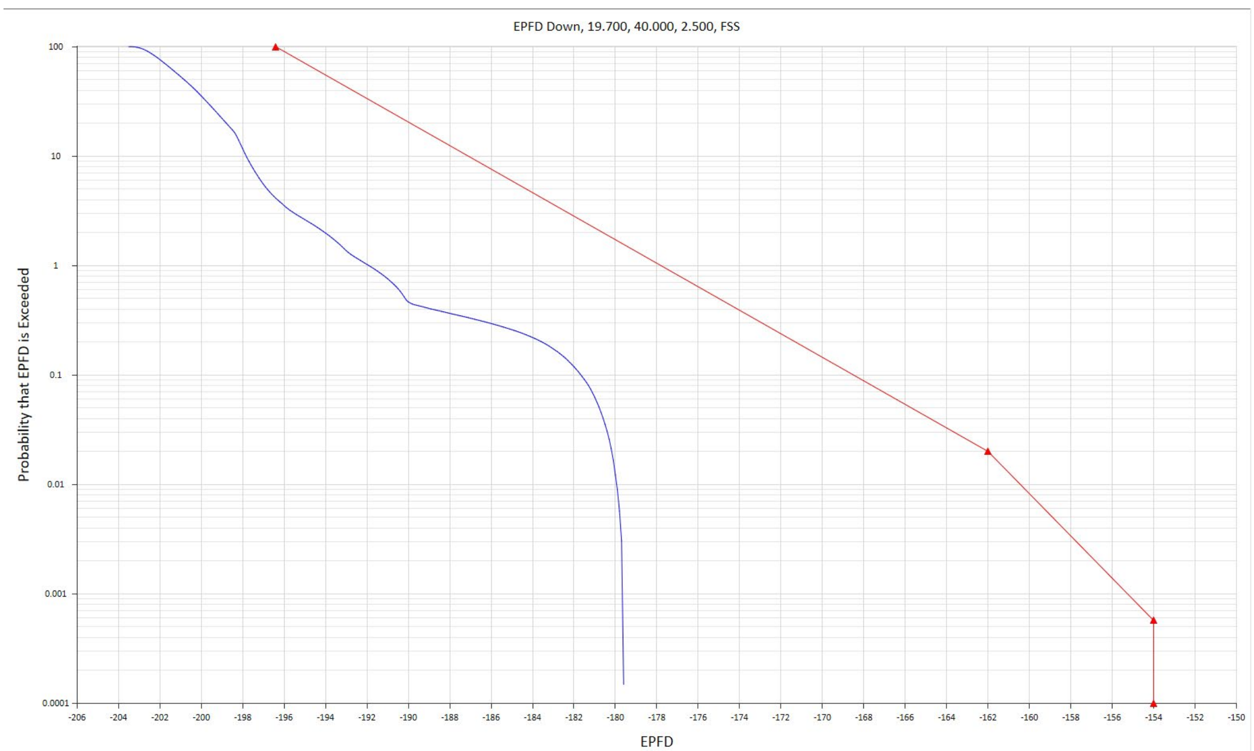


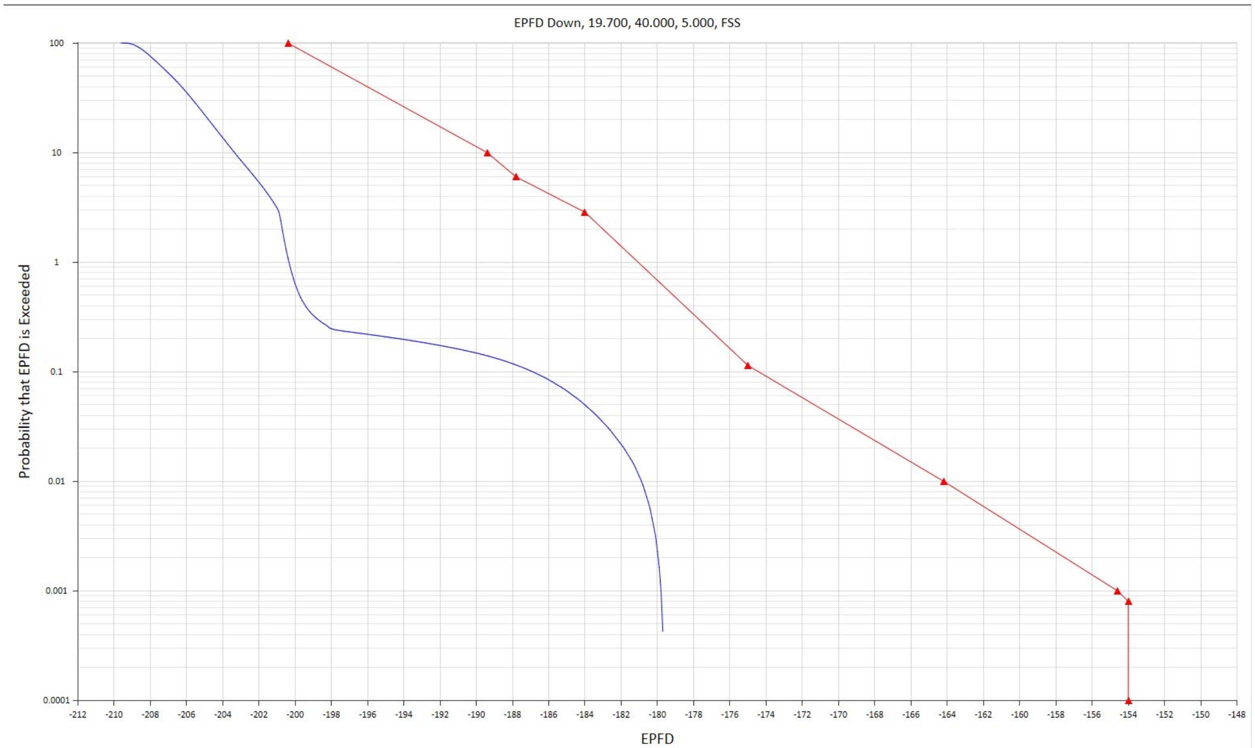



EPFD Down, 17.800, 40.000, 5.000, FSS
Probability that EPFD is Exceeded
EPFD

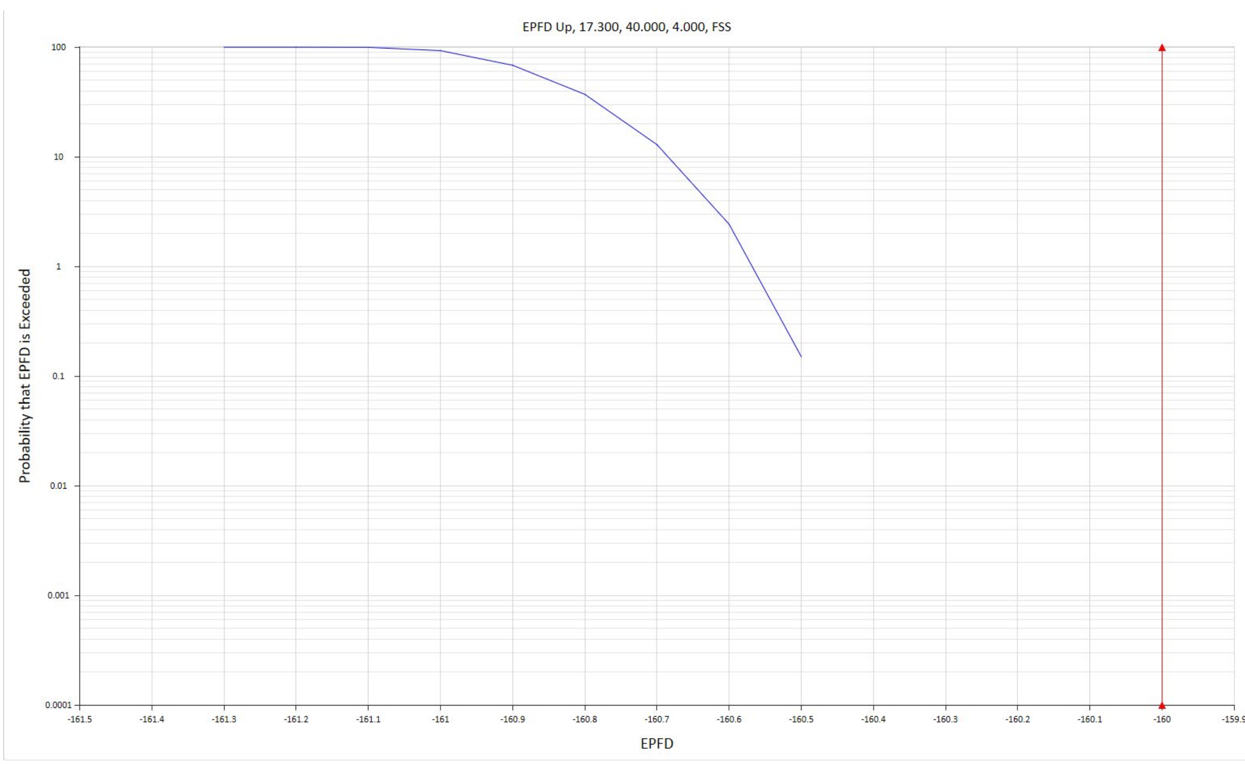

EPFD Down, 19.700, 40.000, 0.700, FSS
Probability that EPFD is Exceeded
EPFD

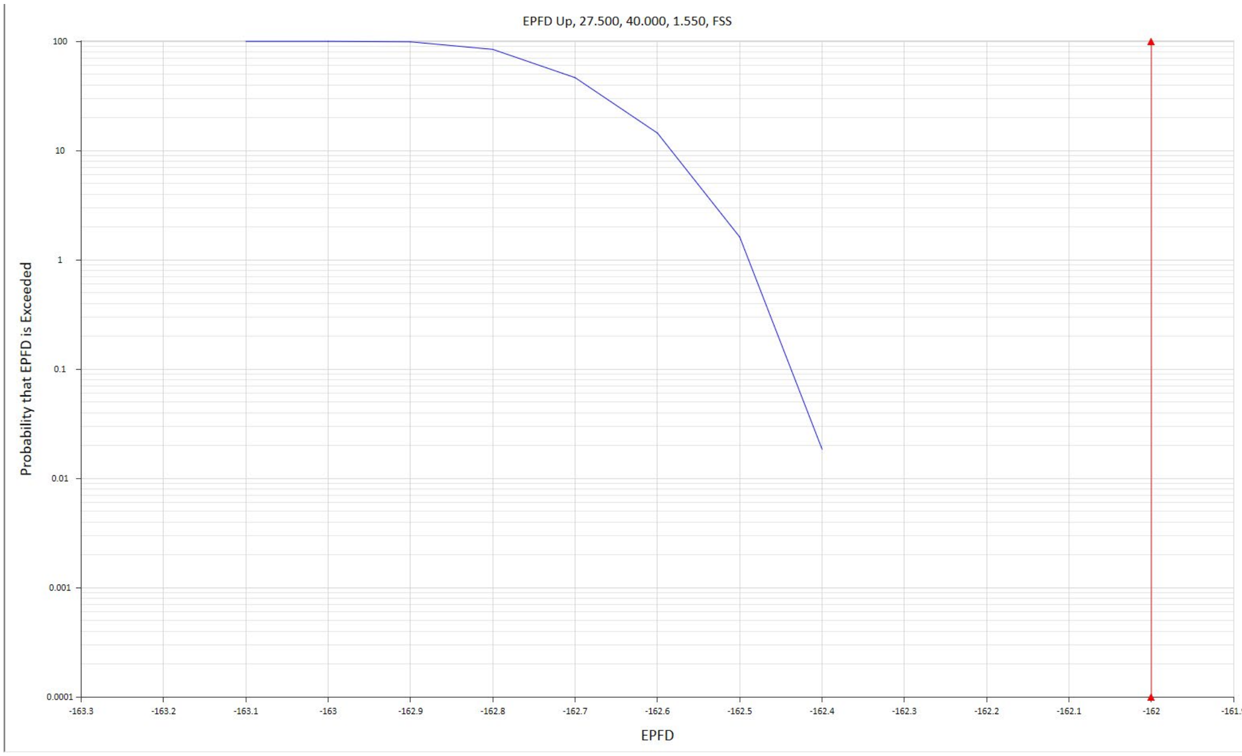

EPFD Down, 19.700, 40.000, 0.900, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-193 -192 -191 -190 -189 -188 -187 -186 -185 -184 -183 -182 -181 -180 -179 -178 -177 -176 -175 -174 -173 -172 -171 -170 -169 -168 -167 -166 -165 -164 -163 -162 -161 -160 -159 -158 -157 -156 -155 -154 -153 -152
EPFD

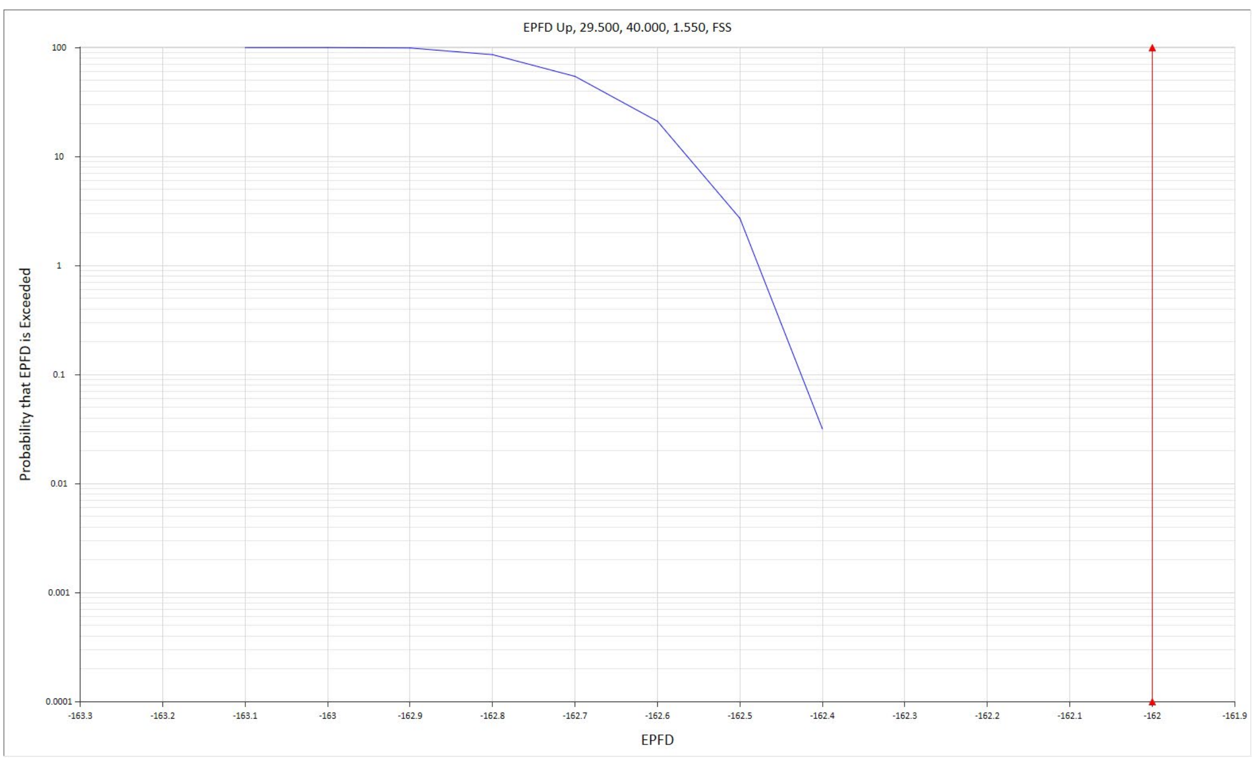

EPFD Down, 19.700, 40.000, 2.500, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-206 -204 -202 -200 -198 -196 -194 -192 -190 -188 -186 -184 -182 -180 -178 -176 -174 -172 -170 -168 -166 -164 -162 -160 -158 -156 -154 -152 -150
EPFD



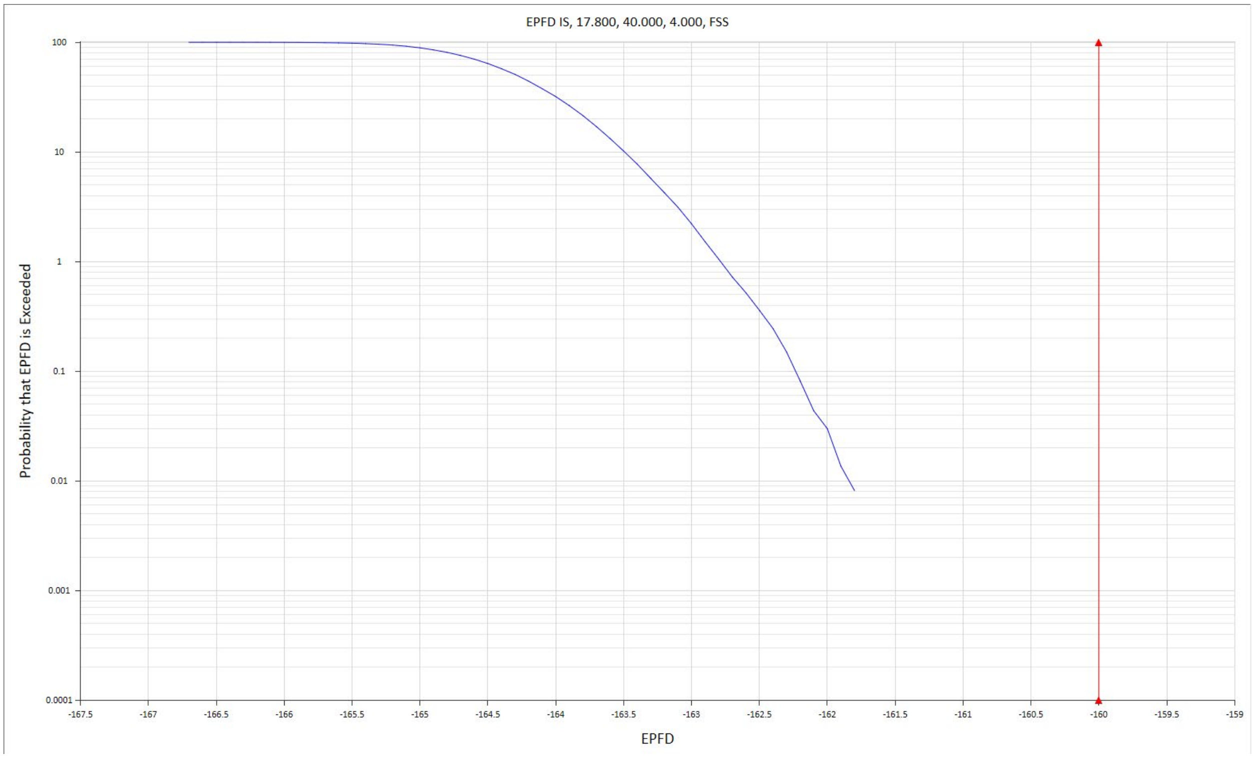
OUTPUT FOR EPFD$_{UP}$ ASSESSMENT




EPFD Up, 27.500, 40.000, 1.550, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-163.3
-163.2
-163.1
-163
-162.9
-162.8
-162.7
-162.6
-162.5
-162.4
-162.3
-162.2
-162.1
-162
-161.9
EPFD


EPFD Up, 29.500, 40.000, 1.550, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-163.3
-163.2
-163.1
-163
-162.9
-162.8
-162.7
-162.6
-162.5
-162.4
-162.3
-162.2
-162.1
-162
-161.9
EPFD

OUTPUTS FOR EPFD$_{IS}$ ASSESSMENT



ANNEX 3

POTENTIAL INTERFERENCE TO KA-BAND FIXED SERVICE SYSTEMS

In the SpaceX Initial Authorization, the Commission imposed a condition under which SpaceX must, before starting operation, file a modification application with a technical showing demonstrating that its operation will protect a fixed-service ("FS") station with the characteristics described in Recommendation ITU-R SF.1483.[1] SpaceX made such a showing in connection with its recent modification, which the Commission found to satisfy the condition.[2] Nonetheless, in an abundance of caution, we make that showing below for the SpaceX constellation modified as proposed herein. For purposes of this analysis, SpaceX used the following assumptions:

1. FS link characteristics per Rec. ITU-R SF.1483

Parameters	Specifications
Elevation Angles	0° and 2.2°
FS Antenna Height (m)	0
FS Antenna Gain (dBi)	32, 38, and 48
FS Antenna Pattern	Per Rec. ITU-R F.1245
Latitude (degrees)	24° N, 45° N, 60° N
Atmospheric Attenuation	Not considered (conservative)
Feeder Loss (dB)	3
Polarization Loss	0, per Rec. ITU-R F.1245 (Note 7)
Rx Thermal Noise (dBW/MHz)	-139

1 *See Space Exploration Holdings, LLC*, 33 FCC Rcd. 3391, ¶ 35 (2018).

2 *See Space Exploration Holdings, LLC*, 34 FCC Rcd. 2526, ¶ 29 (IB 2019).

In addition to the test latitudes suggested by Rec. ITU-R SF.1483, SpaceX has performed the analysis with an FS station at 75°N latitude in light of the polar orbits proposed for some of its satellites.

2. SpaceX proposed modified constellation

Parameter	Proposed Modification (4408 Satellites)				
Altitude (km)	550	540	560	560	570
Inclination	53º	53.2º	97.6º	97.6º	70º
Orbital Planes	72	72	4	6	36
Satellites Per Plane	22	22	43	58	20
Total Satellites	1584	1584	172	348	720

3. Protection criteria used in this analysis per Rec. ITU-R F.1495:

    a. Long-term: I/N should not exceed –10 dB for more than 20% of the time in any year.
    b. Short-term: I/N should not exceed +14 dB for more than 0.01% of the time in any month, and I/N should not exceed +18 dB for more than 0.0003% of the time in any month.

For a given FS victim antenna gain, latitude, and elevation, the analysis considers the worst-case antenna pointing. Because SpaceX operates with up to eight co-frequency beams per spot in Ka-band, the analysis considers beams from the eight satellites whose beams would be closest to boresight for the terrestrial antenna and also includes the contribution of the sidelobes from all other SpaceX satellites in view. Note that this is a conservative analysis, as it does not account for the mitigating effect of atmospheric attenuation.

The results are shown in Figures A3-1 to A3-8 below. In each case, the results are shown for the full proposed modified SpaceX constellation at a minimum elevation angle of 5 degrees. Note that in all cases, the aggregate I/N are lower than Rec. ITU-R F.1495 long-term and short-term limits.

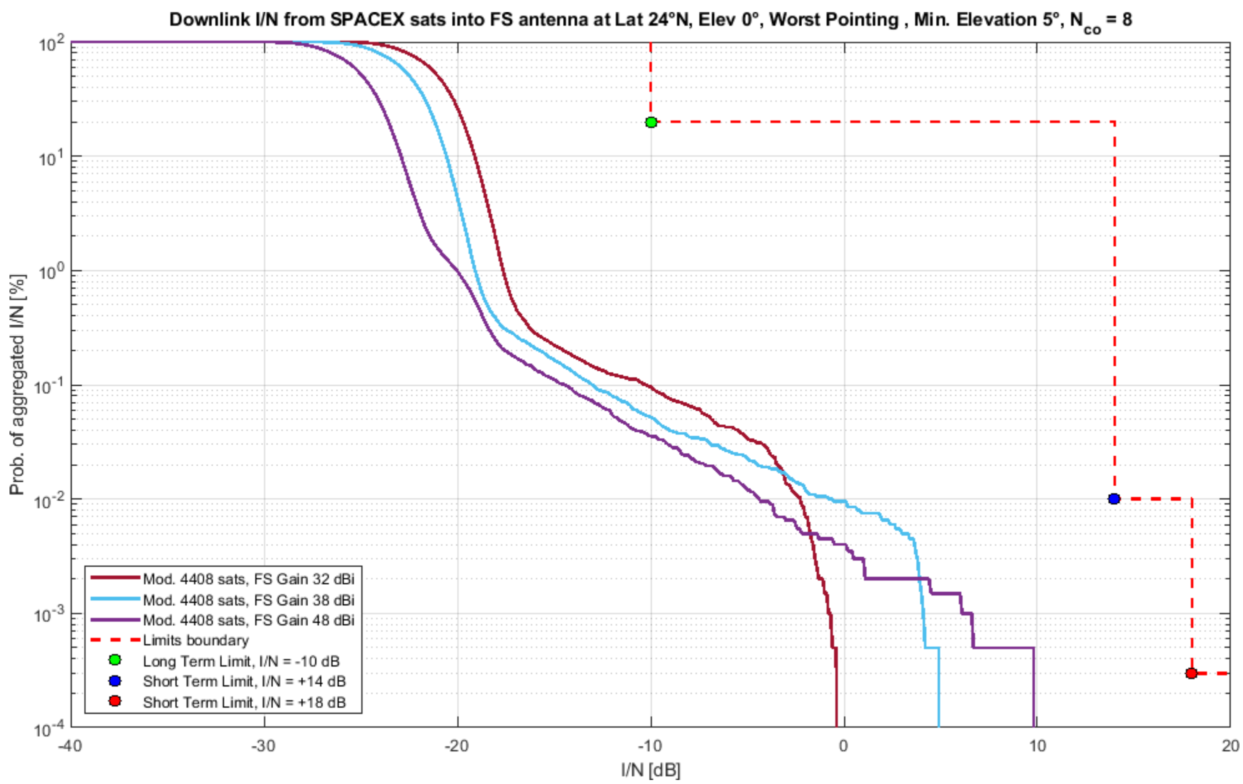


Figure A3-1. FS Station: Latitude 24°N, Elevation 0°

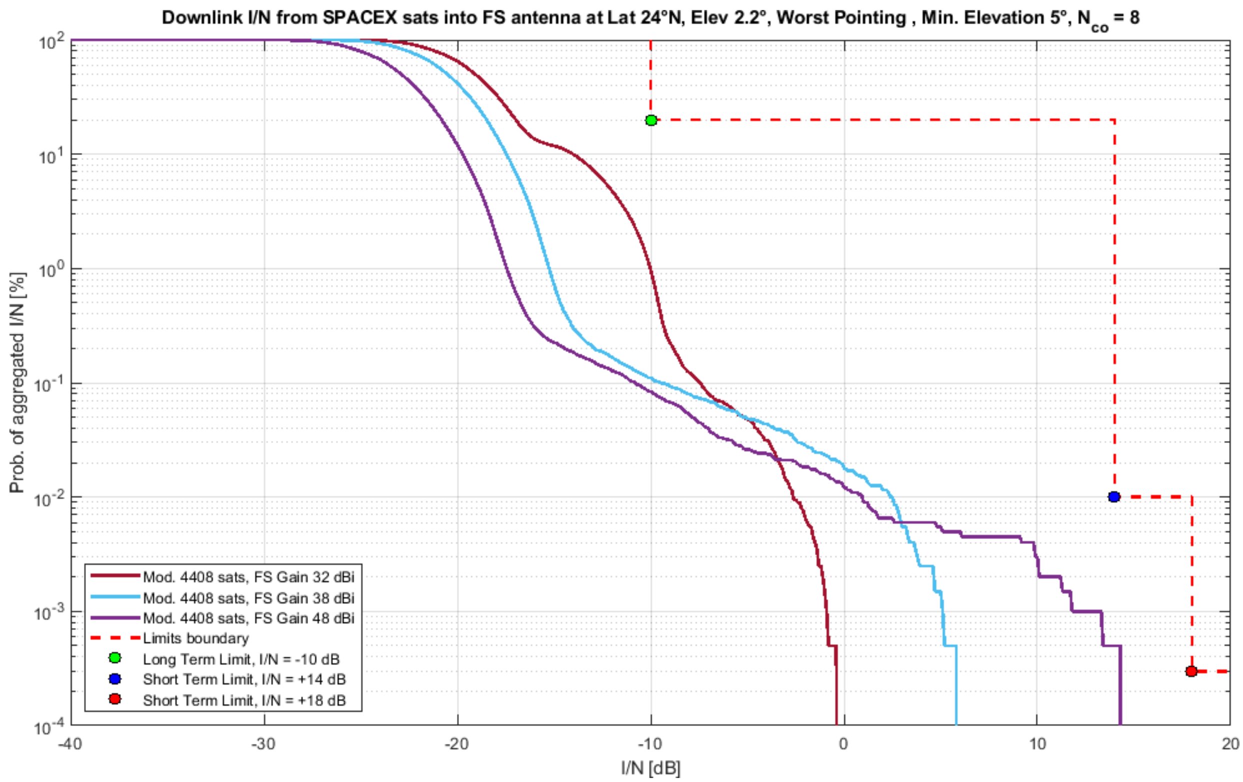


Figure A3-2. FS Station: Latitude 24°N, Elevation 2.2°

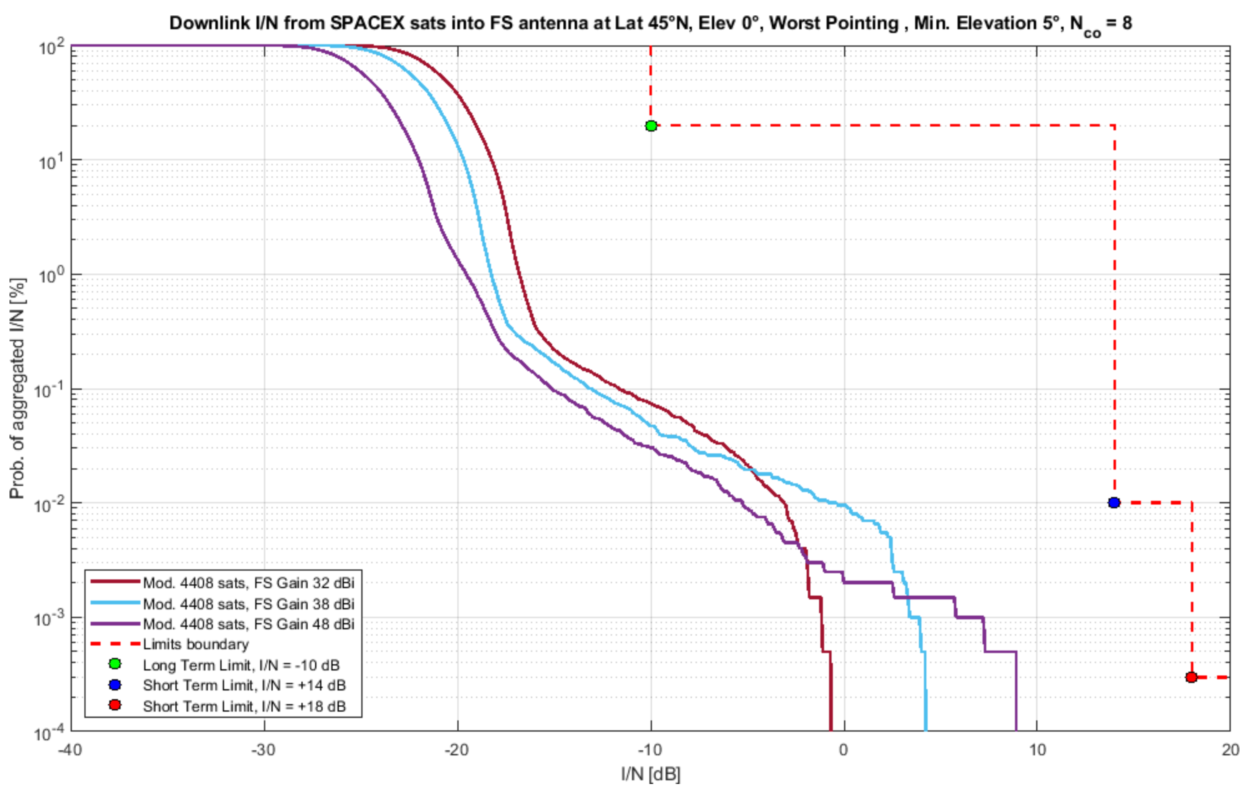


Figure A3-3. FS Station: Latitude 45°N, Elevation 0°

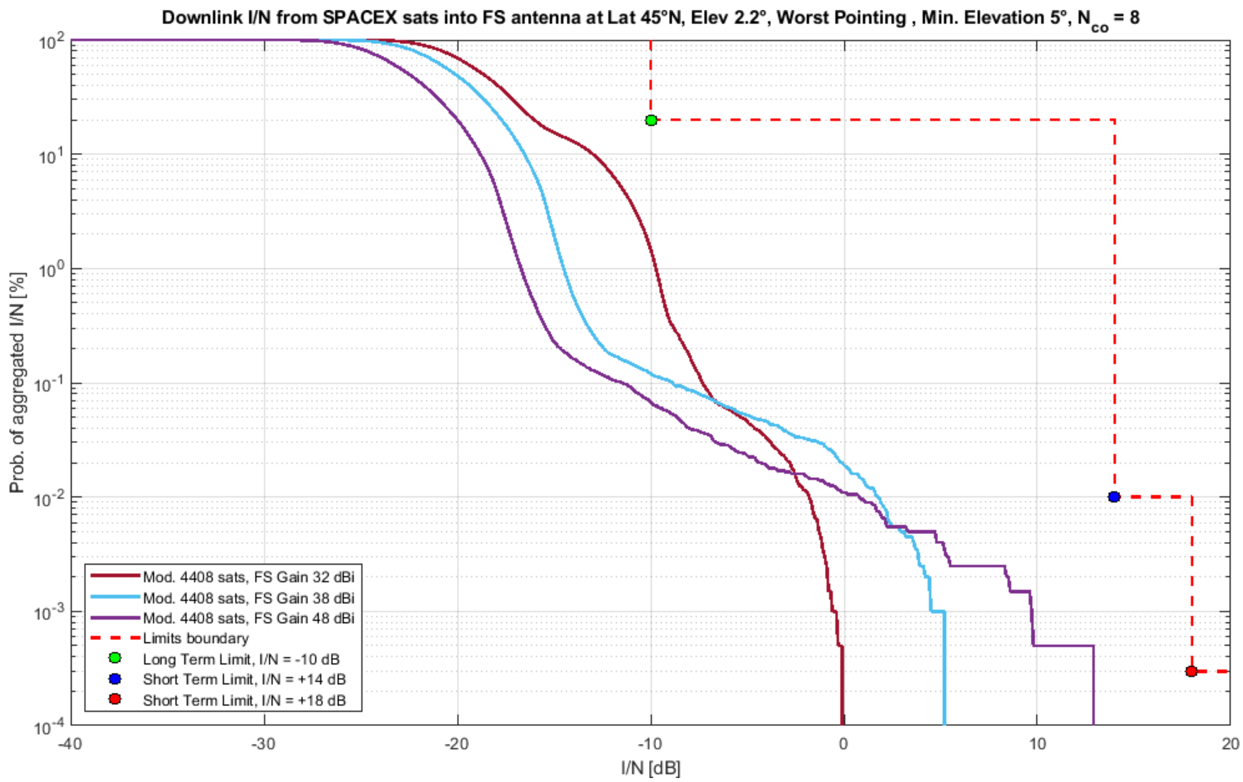


Figure A3-4. FS Station: Latitude 45°N, Elevation 2.2°

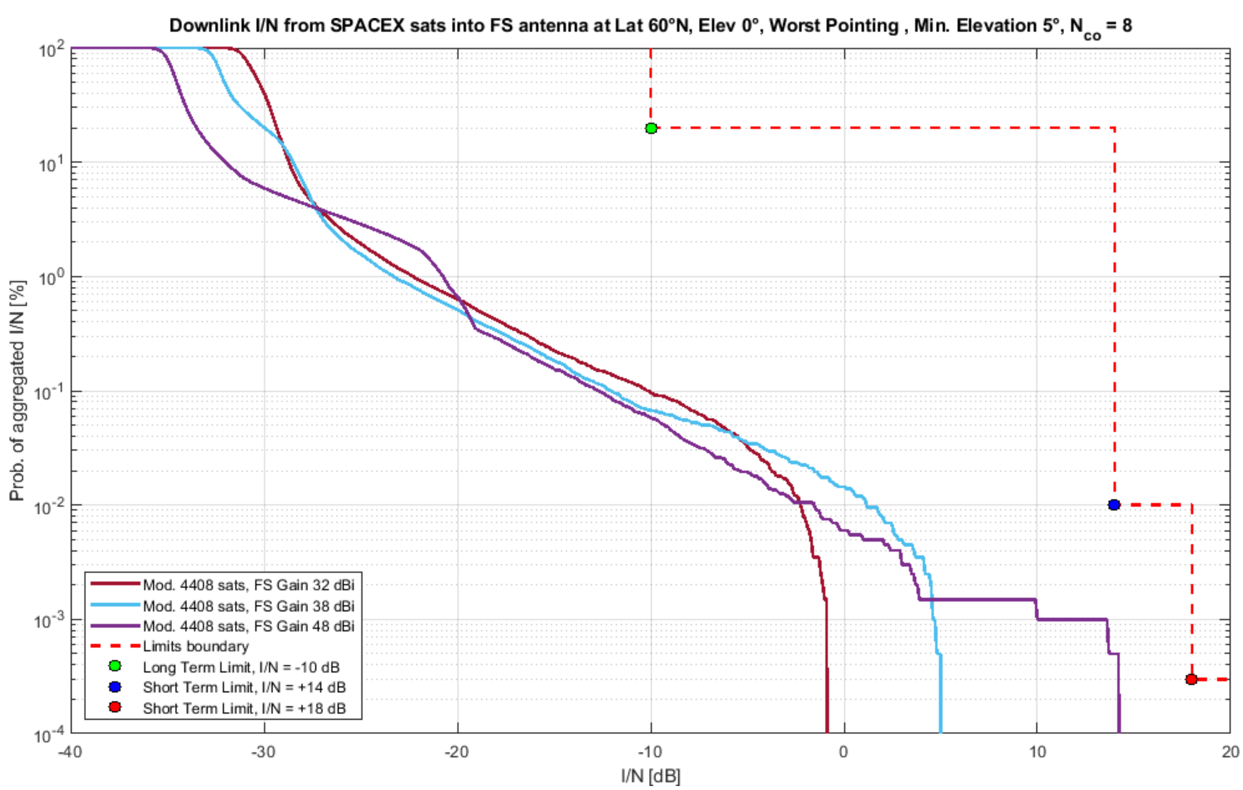


Figure A3-5. FS Station: Latitude 60°N, Elevation 0°

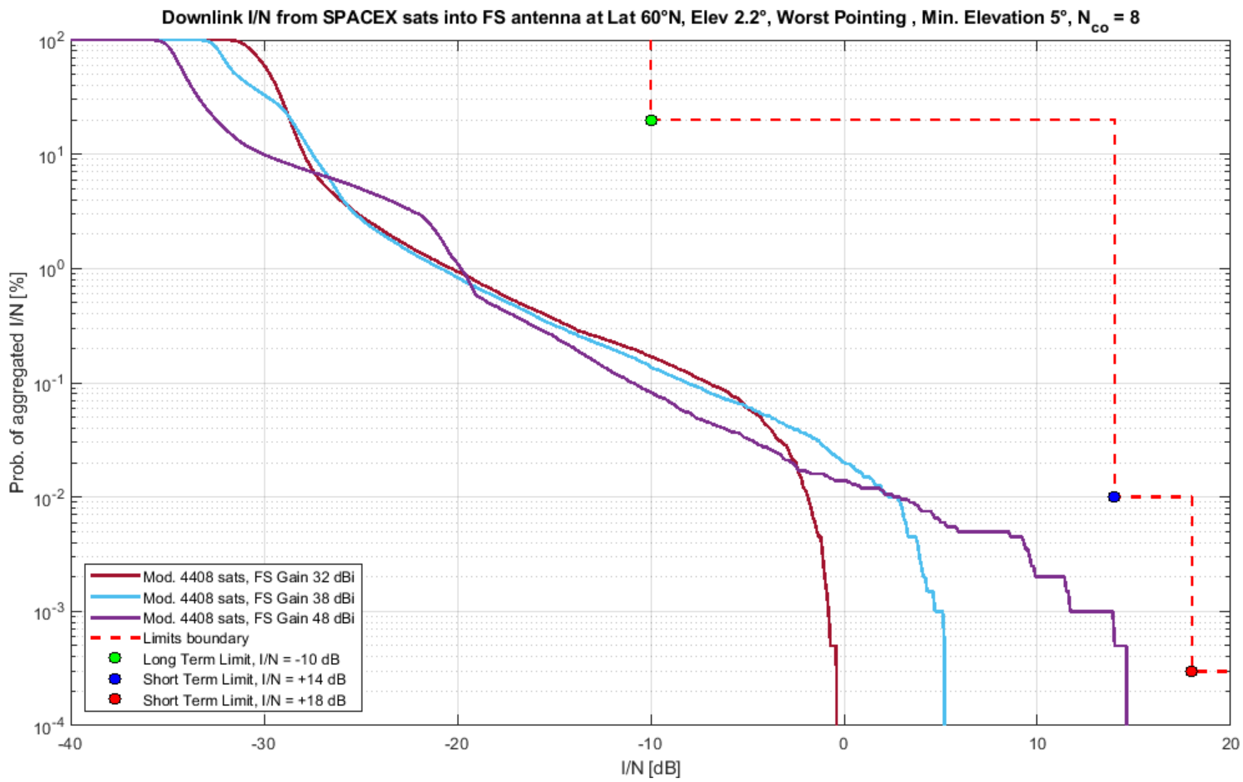


Figure A3-6. FS Station: Latitude 60°N, Elevation 2.2°

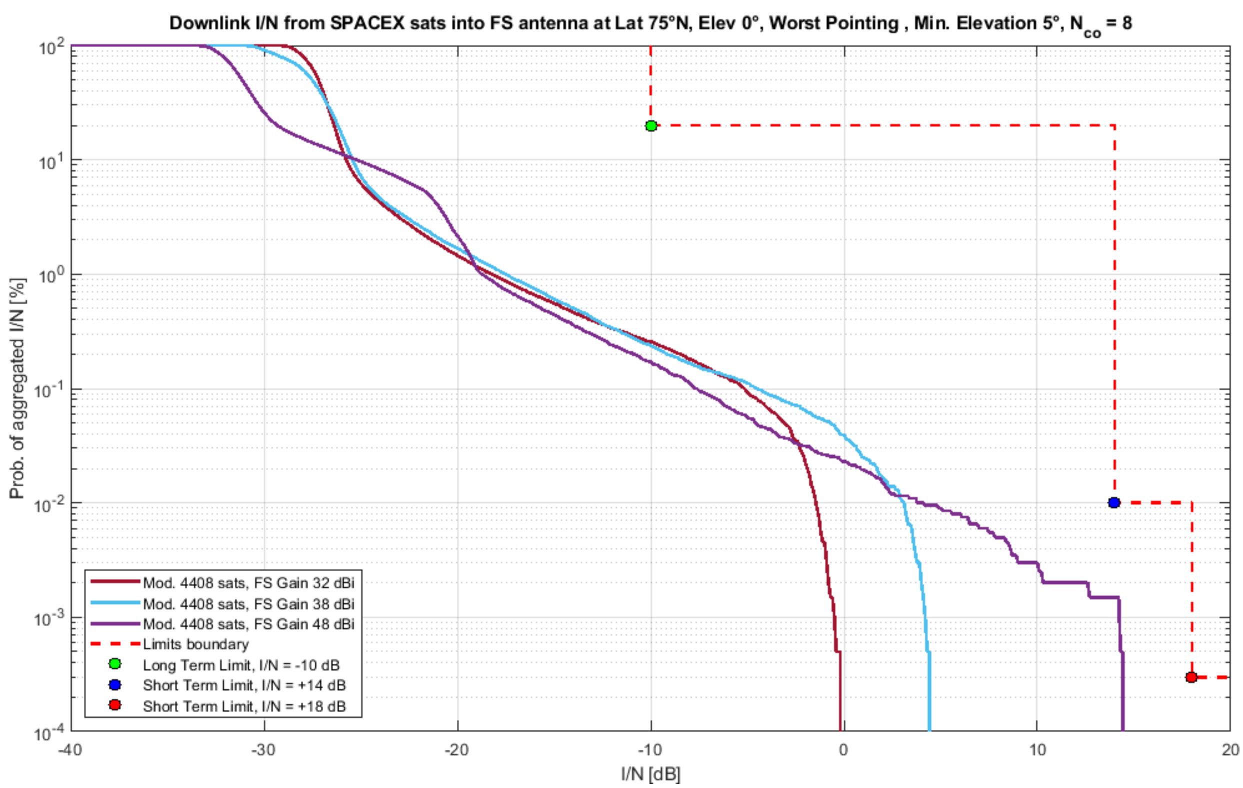


Figure A3-7. FS Station: Latitude 75°N, Elevation 0°

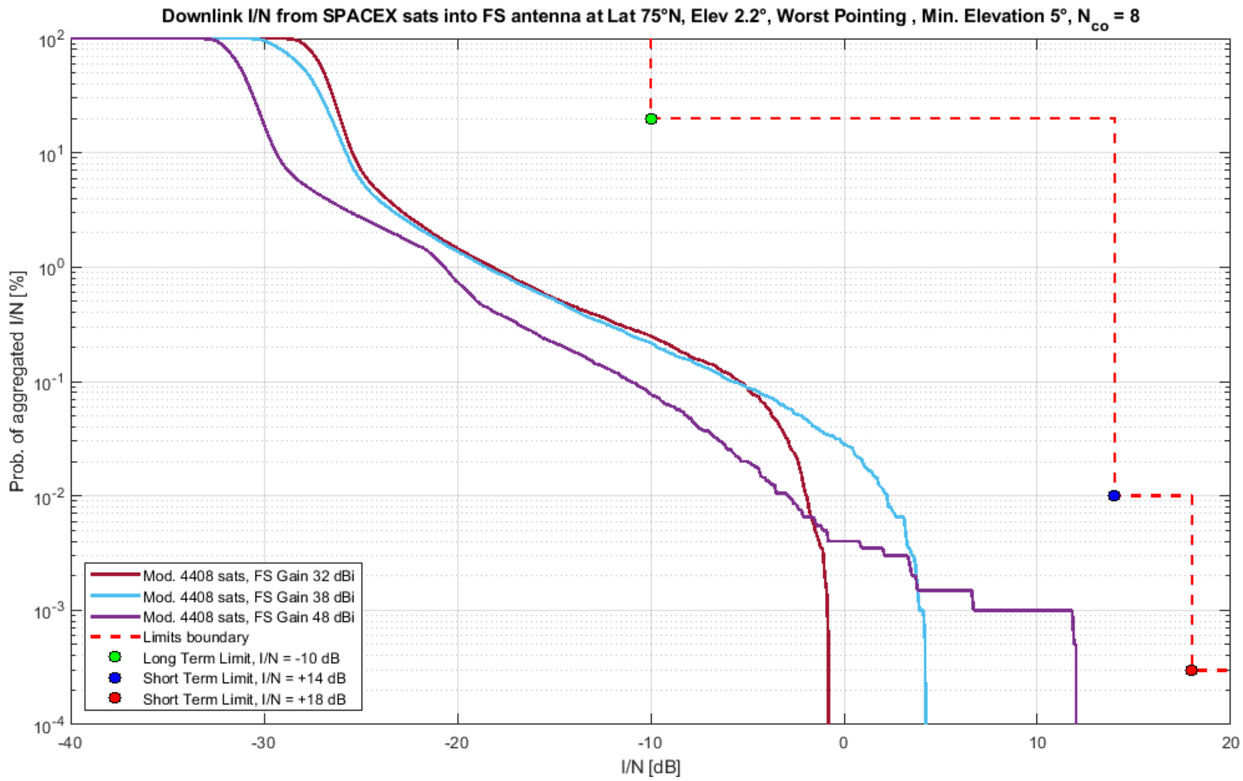


Figure A3-8. FS Station: Latitude 75°N, Elevation 2.2°