SPACEX NON-GEOSTATIONARY SATELLITE SYSTEM

ATTACHMENT A
TECHNICAL INFORMATION TO SUPPLEMENT SCHEDULE S

A.1 SCOPE AND PURPOSE

On March 29, 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] With this application, SpaceX seeks to modify its license to reflect constellation design changes resulting from a rigorous, integrated, and iterative process that will accelerate the deployment of its satellites and services. Specifically, SpaceX proposes to relocate 1,584 satellites previously authorized to operate at an altitude of 1,150 km to an altitude of 550 km, and to make related changes to the operations of the satellites in this new lower shell of the constellation. This modest modification to the SpaceX Authorization will slightly reduce the total number of spacecraft in the constellation, meet all required protection criteria for other systems operating in the same frequencies, and cause no overall 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 part of the constellation at a lower altitude. SpaceX requests no other technical changes to its authorization at this time, and certifies that all other technical information provided in its original Ku/Ka-band applications remains unchanged.[2]

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

2 *See* 47 C.F.R. § 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). These materials are collectively referred to herein as the "Original Applications."

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. For the Commission's convenience, SpaceX has included in the accompanying Schedule S the information filed as part of the Original Applications with revisions associated with relocating one orbital shell from 1,150 km to 550 km as proposed in this application. The accompanying Schedule S therefore reflects the system as it will operate once modified and fully deployed.[3]

A.2 Overall Description

This information is generally available in Attachment A ("Technical Information to Supplement Schedule S") to the Original Applications.

Under the modification proposed herein, SpaceX would reduce the number of satellites and relocate the original shell of 1,600 satellites authorized to operate at 1,150 km to create a new lower shell of 1,584 satellites operating at 550 km.[4] Table A.2-1 below summarizes the resulting changes in the orbital configuration of the constellation.

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3 Technical information submitted using the electronic Schedule S and the separate database of technical parameters may differ in presentation from parameters submitted with SpaceX's previous applications to operate in these bands. For example, while this modification makes no changes to the bands SpaceX seeks to use, the submitted technical data adopts a different approach for dividing this spectrum into "beams" relative to the previous applications. This merely reflects a simplified approach to portraying this technical information relative to the previous applications, which adopted a larger number of artificial separations due to the electronic Schedule S's identification of a larger number of nominally separate, but contiguous, frequency bands.

4 This will result in a reduction of the total constellation by 16 satellites.

Parameter	Original Authorization	Proposed Modification
Orbital Planes	32	24
Satellites Per Plane	50	66
Total Satellites	1,600	1,584
Altitude	1,150 km	550 km
Inclination	53°	53°

Table A.2-1. Summary of Proposed Modification

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. In addition, SpaceX has designed orbits that feature large self-conjunction miss distances, meaning that, in order to ensure that two SpaceX satellites will never collide, SpaceX satellites need only maintain a position with a tolerance no larger than 60 km along-track in the worst case, or even greater distances at earlier stages of the roll-out. It is unlikely this full along-track margin will ever be used, but these highly conservative tolerances further improve the robustness of the SpaceX system. Despite these large system tolerances, however, SpaceX will maintain extremely accurate information about the location of each satellite, and make this information available to other operators through its shared ephemeris data.

In the initial phase, SpaceX will launch and operate first-generation satellites that it has designed specifically to support a faster pace of deployment with a simplified design to streamline the construction process and continuously add features to subsequent generations of spacecraft. For example, SpaceX initially will use Ku-band spectrum for communications between satellites and both gateways and user terminals, and then incorporate dual Ku/Ka-band chipsets and other supporting technologies to phase in the use of Ka-band spectrum for gateway communications as it populates its constellation. Similarly, SpaceX initially will use parabolic antennas for its gateway earth stations, and introduce phased array alternatives as the system evolves. The frequency usage during these two phases is summarized in Table A.2-2 below.

Type of Link and Transmission Direction	Initial Frequency Ranges[5]	Final Frequency Ranges
User Downlink Satellite-to-User Terminal	10.7 – 12.7 GHz	10.7 – 12.7 GHz
Gateway Downlink Satellite to Gateway	10.7 – 12.7 GHz	10.7 – 12.7 GHz 17.8 – 18.6 GHz 18.8 – 19.3 GHz 19.7 – 20.2 GHz
User Uplink User Terminal to Satellite	14.0 – 14.5 GHz	12.75 – 13.25 GHz[6] 14.0 – 14.5 GHz
Gateway Uplink Gateway to Satellite	14.0 – 14.5 GHz	14.0 – 14.5 GHz 27.5 – 29.1 GHz 29.5 – 30.0 GHz
TT&C Downlink	12.15 – 12.25 GHz	12.15 – 12.25 GHz 18.55 – 18.60 GHz
TT&C Uplink	13.85 – 14.00 GHz	13.85 – 14.00 GHz

Table A.2-2. Summary of Phased Frequency Usage

SpaceX requests authority to operate the proposed lower shell in both the "initial" and "final" configurations set forth above. A more precise description of the frequency and channelization plan for the SpaceX system, including the initial phase of the lower shell, is included in Schedule

[5] During the "initial" phase of deployment, SpaceX will use the same Ku-band spectrum for user terminals and gateways, but will use spatial diversity to avoid self-interference.

[6] SpaceX will use this band in the United States only with individually-licensed earth stations. *See* SpaceX Authorization, ¶ 40(g). No such limitations would apply outside the U.S. In the future, SpaceX may seek authority to operate blanket-licensed user terminals in the U.S. as well.

S accompanying this application.

Operating this shell at lower altitude will significantly decrease each satellite's footprint on the Earth. To maintain suitable coverage during the very early stages of initial deployment, SpaceX may periodically use a minimum elevation angle as low as 25 degrees for this initial shell. Then, as further satellites are deployed to populate the remainder of the constellation, SpaceX will revert to a 40 degree minimum elevation angle for all user and gateway beams.

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 550 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.

A.3.1 Ku-Band Beams

As in the Original Applications, all Ku-band downlink spot beams on each SpaceX satellite are independently steerable over the full field of view of the Earth. Yet, user terminals (and gateways during the initial deployment phase) communicate only with satellites 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. Consequently, as shown in Figure A.3.1-1 below, each satellite operating at an altitude of 550 km in the shell being modified will provide service only up to 56.55 degrees away from boresight (nadir) at service initiation and up to 44.85 degrees at full deployment. These satellites can provide service up to approximately ±57° latitude; coverage to service points beyond this range will be provided by satellites included in SpaceX's polar orbits.

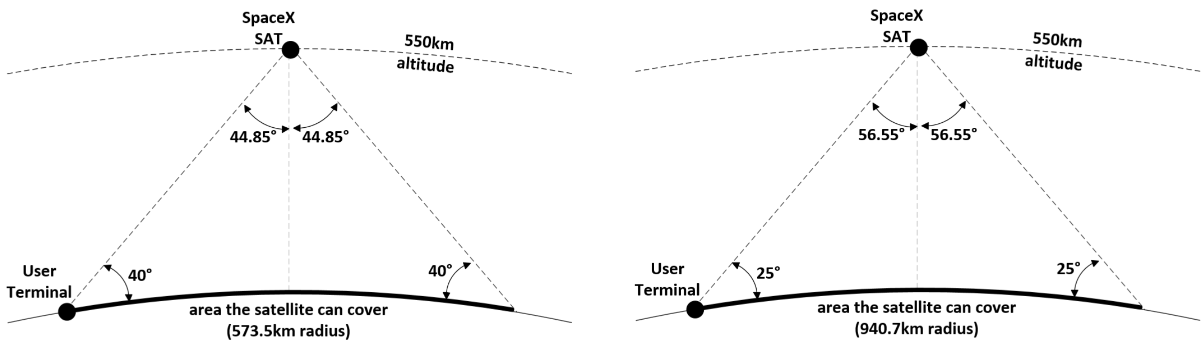

Figure A.3.1-1: Steerable Service Range of Ku-band Beams (550 km)
At Full Deployment and Initial Launch

As discussed in the Original Applications, beams from antennas using phased arrays widen incrementally as they are steered away from boresight.[7] 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 gateway beams) at nadir and at 20, 45, and 57 degrees away from nadir. As illustrated in Figure 3.1-2 below, as the transmitting beam is steered, the power is adjusted to maintain a constant power flux-density ("PFD") at the surface of the Earth, compensating for variations in antenna gain and path loss associated with the steering angle.

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

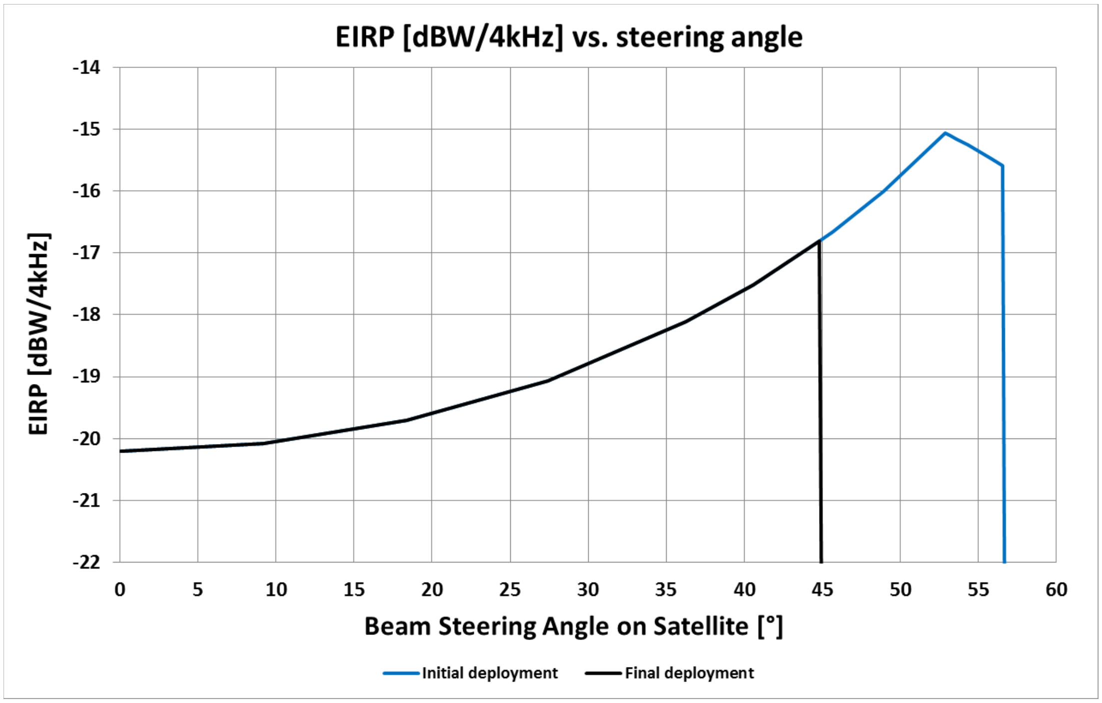

Figure A.3.1-2. EIRP Density Variation by Beam Steering Angle

For the initial deployment, the highest equivalent isotropically radiated power ("EIRP") density is -15.75 dBW/4kHz and occurs at about 53 degree steering angle (corresponding to about 30 degree elevation for the earth station). For the final deployment, the highest EIRP density is -16.82 dBW/4kHz and occurs at about 45 degree steering angle (corresponding to 40 degree elevation for the earth station).[8] 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 the initial deployment and 6.4 dB/K for the final deployment).[9]

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8 Note that the EIRP density levels discussed above apply for user beams, for which the SpaceX system will place only one co-frequency beam per spot. Because up to four satellites can beam co-frequency transmissions to a gateway location, SpaceX will compensate by reducing EIRP accordingly (up to 6 dB) to maintain this maximum EIRP density.

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."

A.3.2 Ka-Band Gateway Beams

As with the beams discussed above, Ka-band gateway downlink spot beams on SpaceX satellites are independently steerable over the full field of view of the Earth. Here again, gateways communicate only with satellites above a minimum elevation angle. When SpaceX first initiates service, this angle may be as low as 25 degrees, but this will increase until it reaches 40 degrees as the constellations deploys more fully. Each satellite transmits two beams at the same frequency (with right hand and left hand circular polarization ("RHCP and LHCP")). Up to four satellites can beam transmissions to the gateway location, for a maximum of eight co-frequency beams.

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) at nadir and at 20, 45, and 57 degrees away from nadir.

As the satellite at 550 km steers the transmitting beam, it adjusts the power (in both polarizations) to maintain a constant PFD at the surface of the Earth. As illustrated in Figure A.3.2-1 below, the highest EIRP density for the initial deployment is 15.70 dBW/MHz and occurs at about 57 degree steering angle (corresponding to a 25 degree elevation for the earth station). For the final deployment, the highest EIRP density is 12.88 dBW/MHz and occurs at about 45 degree steering angle (corresponding to 40 degree elevation for the earth station).

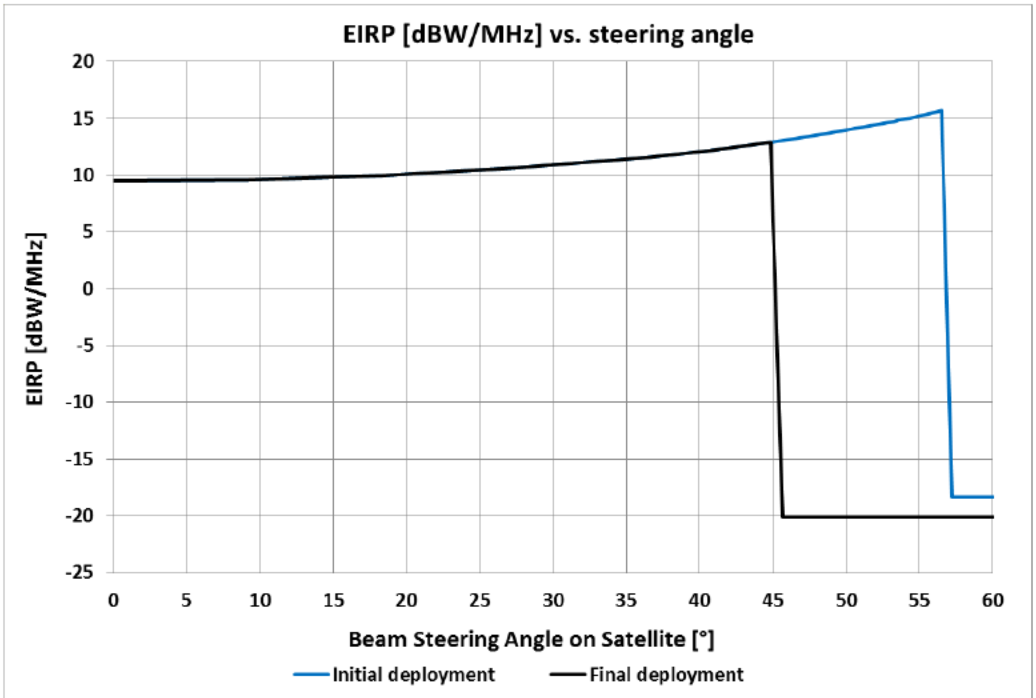

Figure A.3.2-1: EIRP Density Variation by Beam Steering Angle

For receiving beams, the antenna gain drops slightly as the beam slants away from nadir. As a result, the maximum G/T (13.7 dB/K) occurs at nadir, while the minimum G/T (11.1 dB/K) occurs at about 57 degree steering angle.

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

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

A.4 Geographic Coverage

The Commission has found that the SpaceX constellation, when fully deployed, will satisfy all applicable geographic coverage requirements.[10]

A.5 TT&C Characteristics

A complete description of the SpaceX TT&C subsystem is provided with the Original

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

Applications.[11]

A.6 CESSATION OF EMISSIONS

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

A.7 COMPLIANCE WITH PFD LIMITS

Under the proposed modification, SpaceX would operate the new shell of satellites at a much lower altitude of 550 km. To account for the lower orbit, SpaceX also plans to operate those satellites at a much reduced EIRP, which will reduce the PFD created at the Earth's surface. Tables A.7-1 and A.7-2 below show the PFD calculation for the lower shell, both at maximum slant and at nadir, for Ku-band user/gateway beams and Ka-band gateway beams, respectively. In each case, the table reflects operations at 550 km and at service latitudes up to approximately ±57°, which presents a worst case, maximum PFD scenario.

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

	At nadir	At slant (25° elev) Initial Deployment	At slant (40° elev) Final Deployment
EIRP density [dBW/Hz]	-56.22	-51.60	-52.84
EIRP in 4kHz [dBW/4kHz]	-20.20	-15.58	-16.82
EIRP in 1MHz [dBW/MHz]	3.78	8.40	7.16
Distance to Earth [km]	550.00	1123.42	812.11
Spreading loss [dB]	-125.80	-132.00	-129.18
PFD in 4 kHz [dB(W/m^2/4kHz)]	-146.00	-147.59	-146.00
PFD in 1 MHz [dB(W/m^2/1MHz)]	-122.02	-123.61	-122.02

Table A.7-1. PFD at the Surface of the Earth Produced by Ku-band User/Gateway Downlink Transmissions (550 km)

	At nadir	At slant (25° elev) Initial Deployment	At slant (40° elev) Final Deployment
EIRP density [dBW/Hz]	-50.50	-44.30	-47.12
EIRP in 1MHz [dBW/MHz]	9.50	15.70	12.88
Distance to Earth [km]	550.00	1123.42	812.11
Spreading loss [dB]	-125.80	-132.00	-129.18
PFD in 1 MHz [dB(W/m^2/1MHz)]	-116.30	-116.30	-116.30

Table A.7-2. PFD at the Surface of the Earth Produced by Ka-band Gateway Downlink Transmissions (550 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 Original 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. Operations of those upper shells will remain unchanged, meaning that the prior showings remain valid for the unmodified portions of the constellation. But under the proposed modification, SpaceX would operate satellites at the much lower altitude of 550 km and at much reduced EIRP. In this section, we conduct a similar worst-case analysis for the new lower 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 for the initial deployment by plotting the relevant limit and the worst-case PFD of a satellite operating in the proposed lower shell (*i.e.*, at an altitude of 550 km serving latitudes up to approximately ±57°) against elevation angles, and also plot the relevant limit based on the worst case for the entire constellation (as modified) at final deployment. The first set of limits applies across the 10.7-11.7 GHz band.[12]

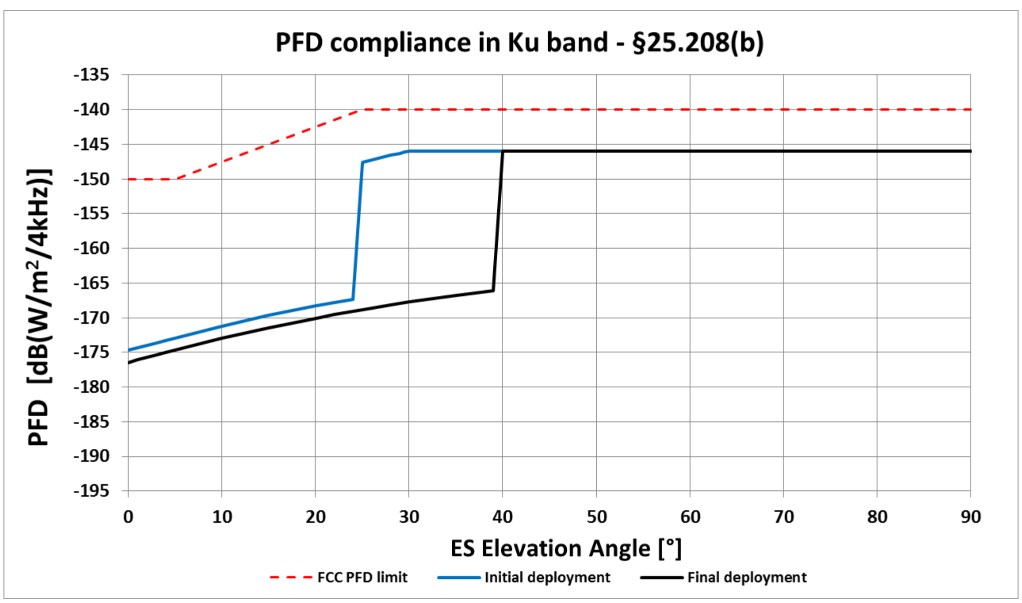

Figure A.7.1-1. Compliance with Downlink PFD Limits in the 10.7-11.7 GHz Band

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

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 the initial and final deployments will comply with these limits as well.

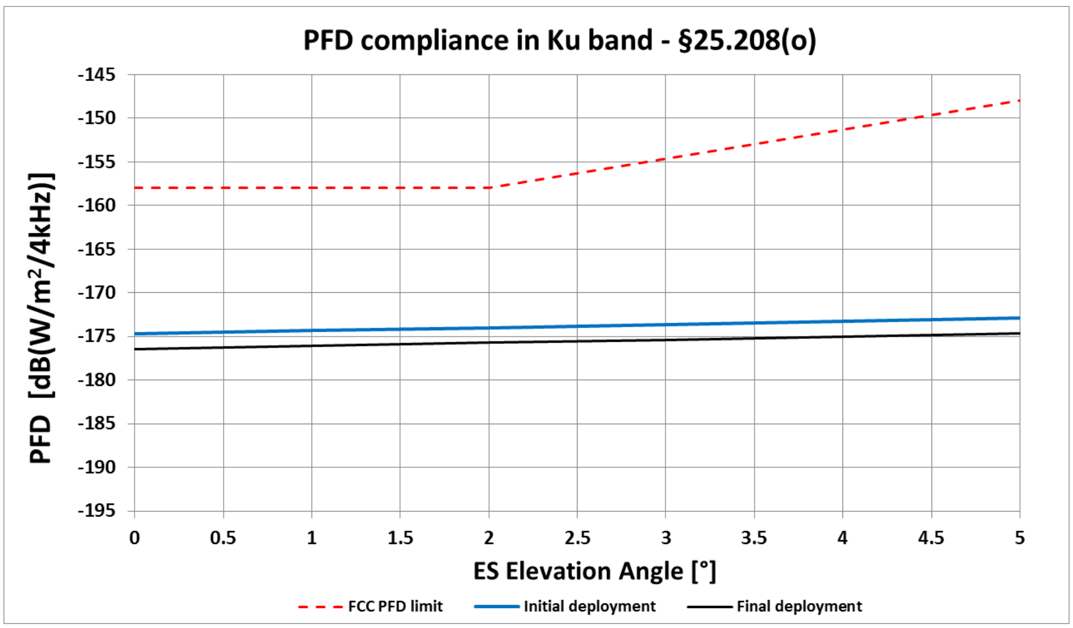

Figure A.7.1-2. Compliance with Downlink PFD Limits in the 12.2-12.7 GHz Band

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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.

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.

  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 1,584 for the initial deployment and 4,409 for the final deployment, and therefore X is equal to 28.78 dB and 69.72 dB, respectively, according to the above formulae. This results in the PFD masks for gateway and TT&C operations shown in Figures A.7.2-1 through A.7.2-4 below, for the initial and final deployments.

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

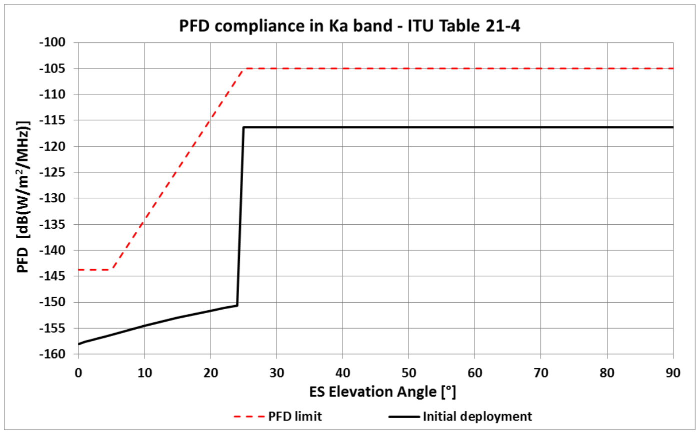


Figure A.7.2-1. SpaceX Initial Gateway Compliance with Downlink PFD Limits in the 17.7-19.3 GHz Band

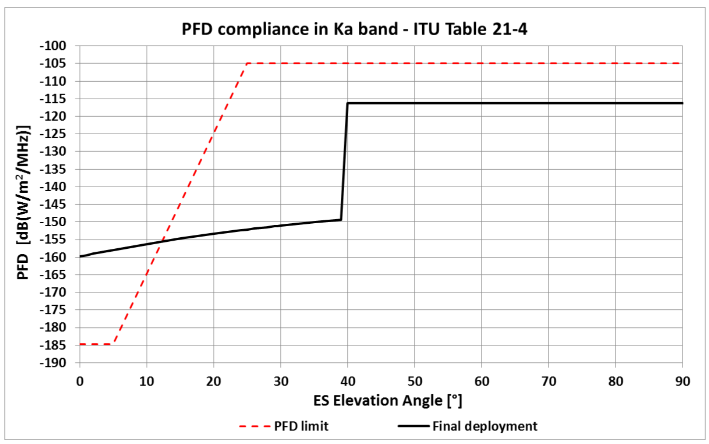


Figure A.7.2-2. SpaceX Final Gateway Compliance with Downlink PFD Limits in the 17.7-19.3 GHz Band

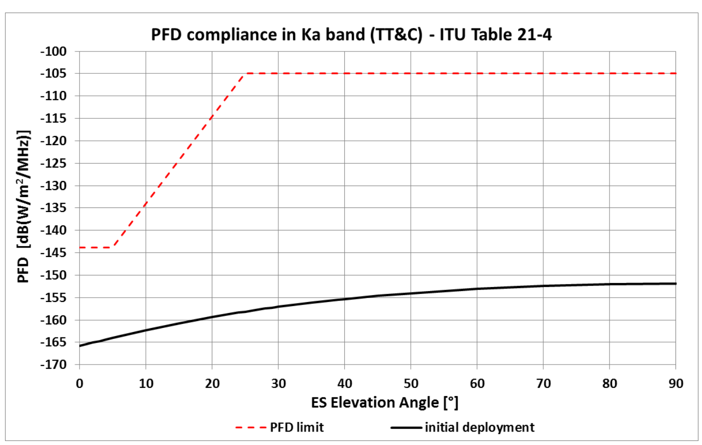


Figure A.7.2-3. SpaceX Initial TT&C Compliance with Downlink PFD Limits in the 17.7-19.3 GHz Band

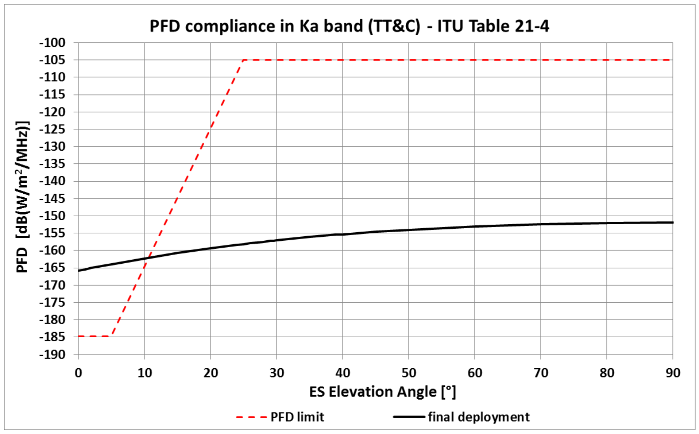


Figure A.7.2-4. SpaceX Final TT&C Compliance with Downlink PFD Limits in the 17.7-19.3 GHz Band

As shown in these figures, the initial deployment of the modified SpaceX system complies with the PFD limits specified by the Commission and the ITU in all respects. In the final deployment phase, the system complies at most elevation angles by a significant margin, but at very low elevation angles – below about twelve degrees –the flawed calculation technique appears to yield a result that exceeds the limit.

In Attachment A to its Original 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 SpaceX 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] Accordingly, we make that

16 *See* SpaceX Authorization, ¶ 35.

17 *See id.*

showing below for the SpaceX constellation as modified to include the lower shell. For purposes of this analysis, SpaceX used the following assumptions:

1. FS link characteristics per Recommendation 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, 45, 60
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

2. SpaceX Constellation as modified

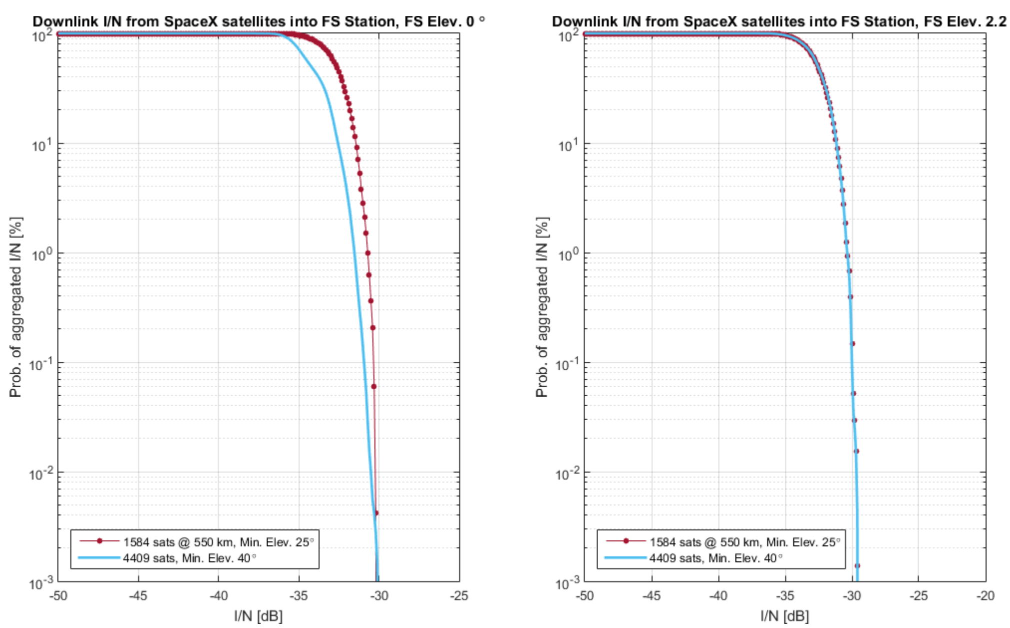
Parameters	Full Constellation					Initial Deployment
Orbit Alt. (km)	550	1110	1130	1275	1325	550
Min. Elevation	40°					25°
# Planes	24	32	8	5	6	24
# Sats/Plane	66	50	50	75	75	66
Total Sats/Shell	1584	1600	400	375	450	1584

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

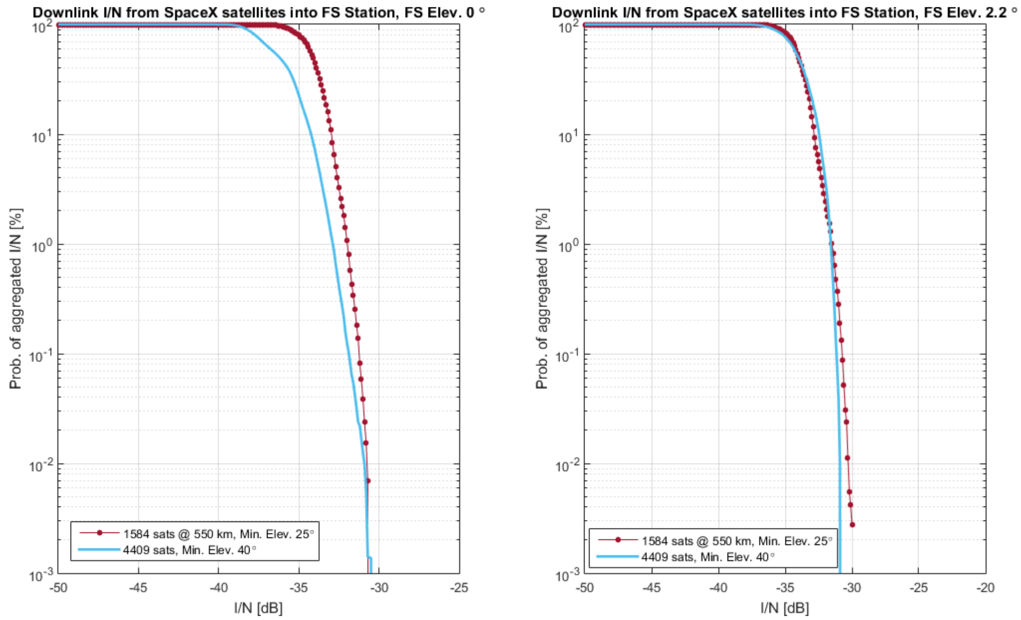
    a. Long-term: I/N should not exceed –10 dB for more than 20% of the time in any year.
    b. Short-term: I/N should not exceed +14 dB for more than 0.01% of the time in any month, and I/N should not exceed +18 dB for more than 0.0003% of the time in any month.

For a given FS victim antenna gain, latitude, and elevation, the worst case when changing azimuth (*i.e.*, highest interference) is shown. Note that this is a conservative analysis as it does not account for the mitigating effect of atmospheric attenuation.

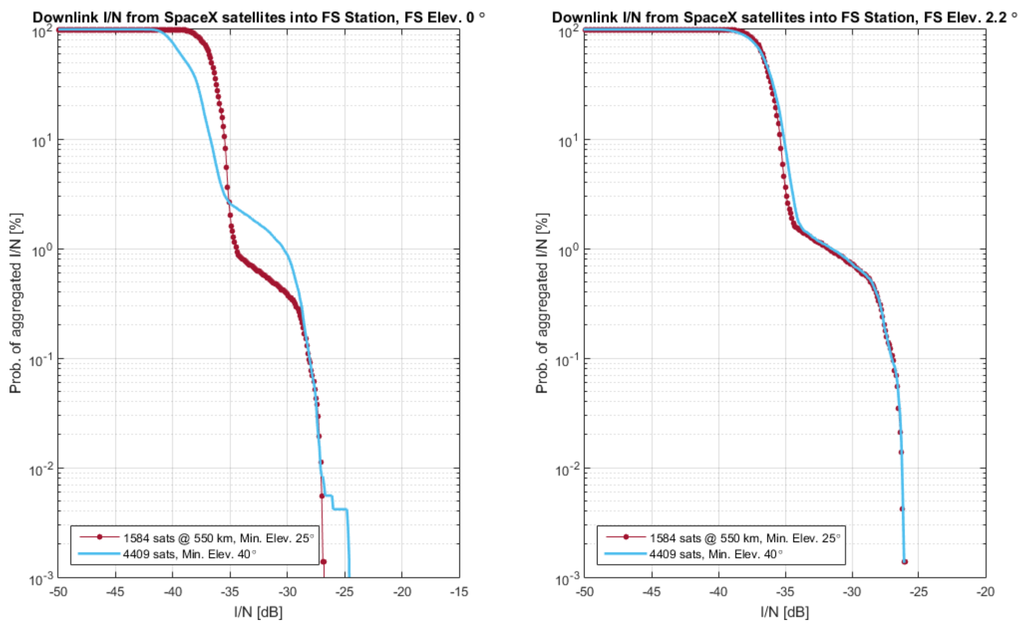
The results are shown in the figures below. Note that in all cases, the aggregate I/N complies with the long-term limit of -10 dB by a significant margin, which necessarily demonstrates compliance with the less stringent short-term limits.



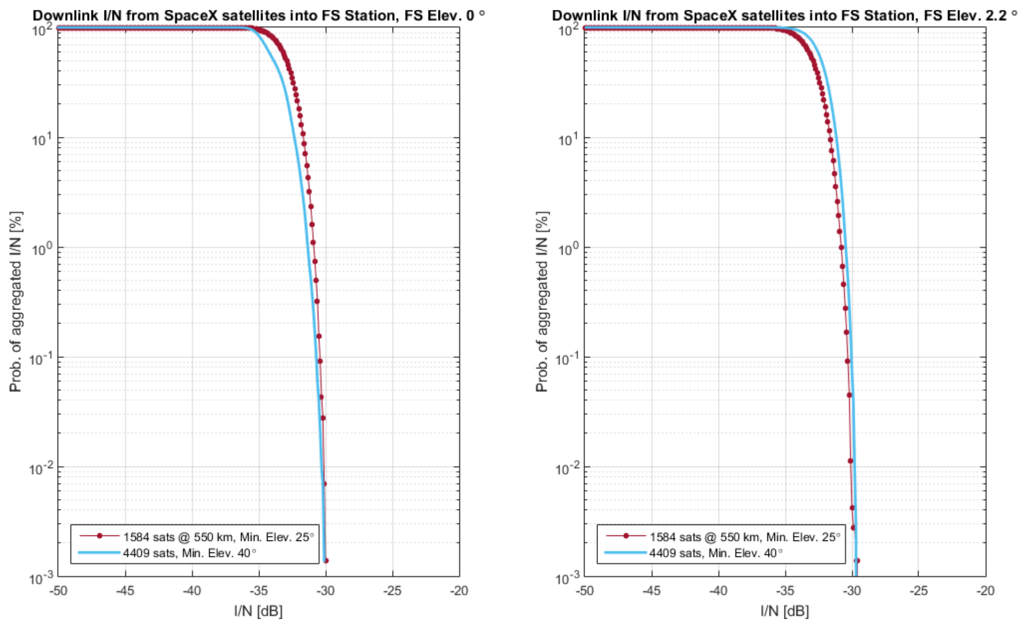
FS Station: Lat. 24°, Max. Gain: 32 dBi



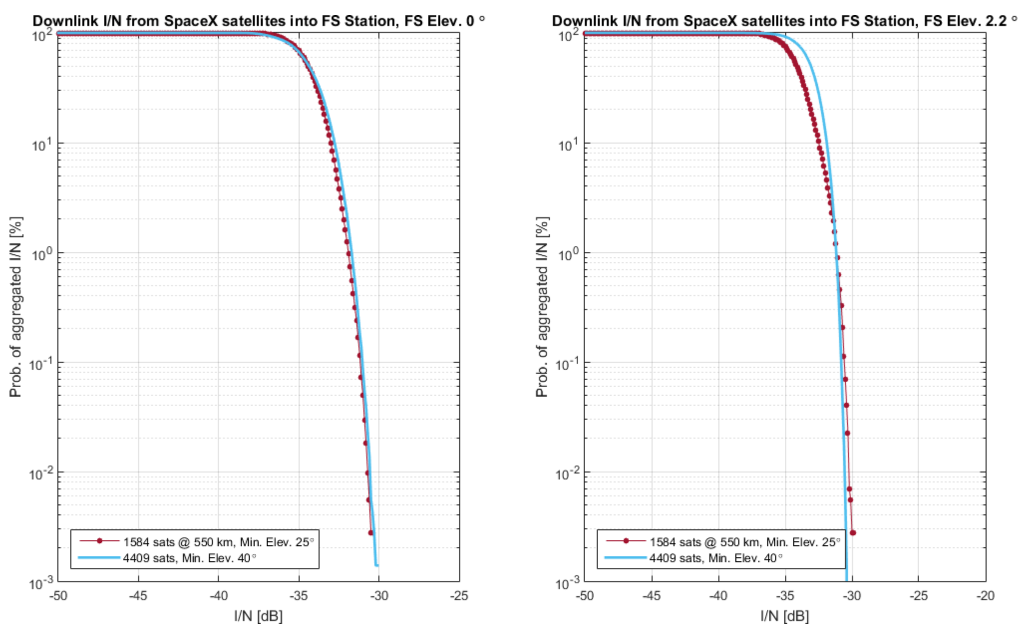
FS Station: Lat. 24°, Max. Gain: 38 dBi



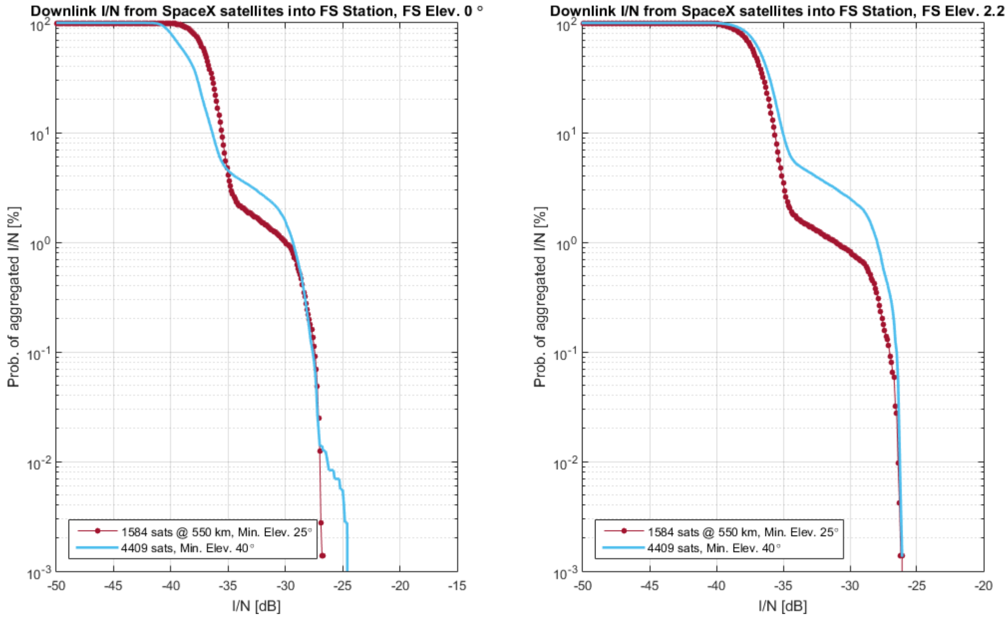
FS Station: Lat. 24°, Max. Gain: 48 dBi



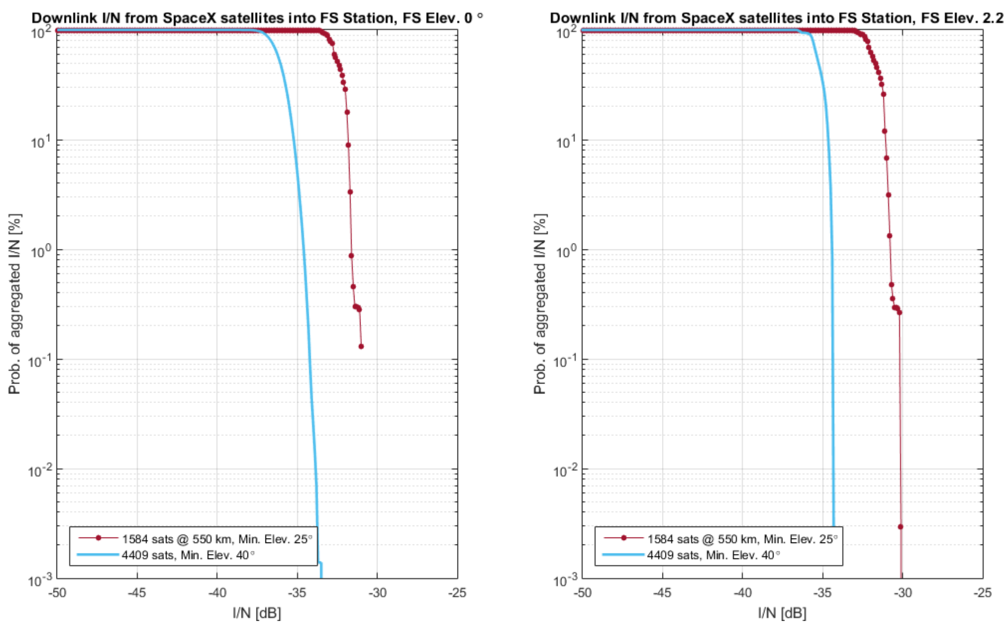
FS Station: Lat. 45°, Max. Gain: 32 dBi



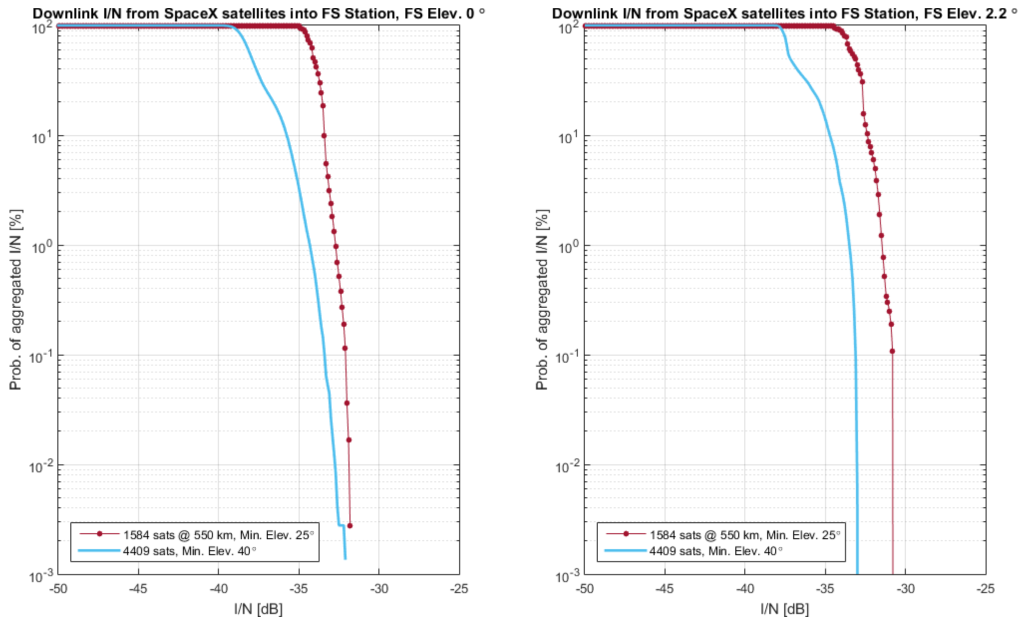
FS Station: Lat. 45°, Max. Gain: 38 dBi



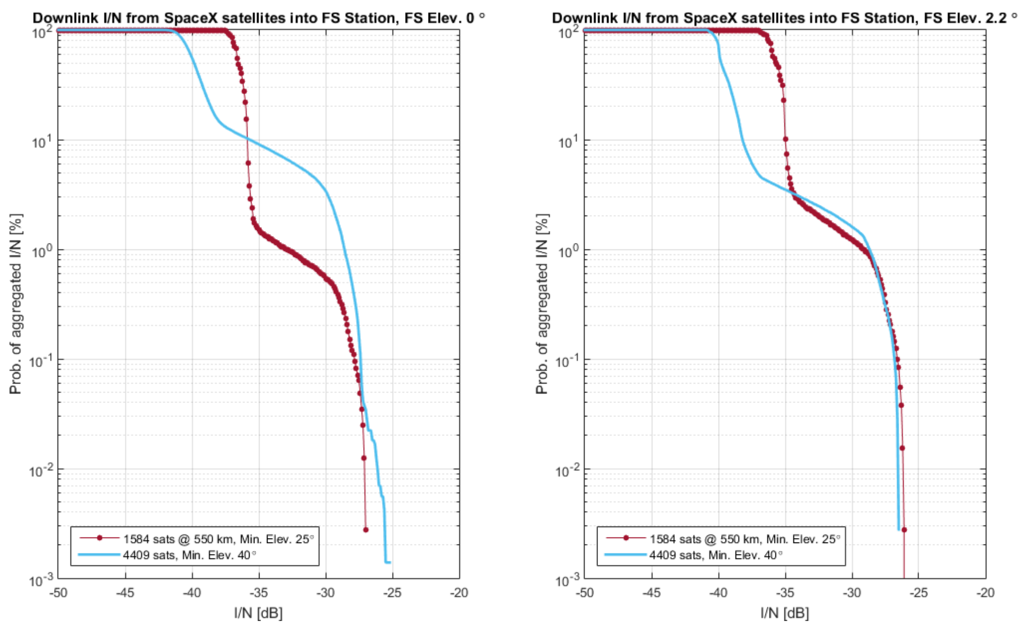
FS Station: Lat. 45°, Max. Gain: 48 dBi



FS Station: Lat. 60°, Max. Gain: 32 dBi



FS Station: Lat. 60°, Max. Gain: 38 dBi



FS Station: Lat. 60°, Max. Gain: 48 dBi

Accordingly, SpaceX requests that the Commission find that it has satisfied the condition of the SpaceX Authorization by demonstrating that its operations will protect a fixed-service station with the characteristics described in Recommendation ITU-R SF.1483.

A.8 INTERFERENCE ANALYSES

The frequency ranges SpaceX proposes to use in Ku-band and Ka-band are shared with other services in the U.S. table of frequency allocations. SpaceX has engineered its NGSO system design to achieve a high degree of flexibility to facilitate spectrum sharing with other authorized satellite and terrestrial systems. In addition, the changes proposed in this modification will not increase interference to any other authorized spectrum user in these bands.

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.[18] The Commission's rules and the SpaceX Authorization also 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.[19] SpaceX's original ITU filings were submitted several years ago, yet the ITU still has not completed its EPFD evaluation. Because the ITU filings related to the proposed modification are just now being submitted to the ITU, and given the ITU's volume of pending filings, the ITU is unlikely to render an EPFD finding on a timeframe that will match SpaceX's aggressive constellation deployment schedule. Accordingly, in support of a waiver of the requirement for an ITU finding, SpaceX provides in Annexes 1 and 2 the results of an EPFD analysis using ITU-approved software developed by Transfinite Systems to demonstrate compliance with all applicable EPFD single entry validation limits in the Ku- and Ka-bands,

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[18] *See* 47 C.F.R. § 25.146(a)(2).

[19] *Id.* at § 25.146(a)(3). This is also a condition of SpaceX's authorization. *See* SpaceX Authorization, ¶ 40n.

respectively. SpaceX will submit the input databases underlying these analyses to the Commission under separate cover.

SpaceX will also operate its system in some portions of Ka-band spectrum where no EPFD limits exist. These are the 28.6-29.1 GHz uplink and 18.8-19.3 GHz downlink frequency bands, which are designated for NGSO satellite use on a primary basis under the Commission's Ka-band frequency plan.[20] According to ITU procedures applicable to these frequency ranges, coordination between NGSO and GSO networks is on a first-come, first-served basis.[21] 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.[22] SpaceX is prepared to work with other NGSO FSS operators to ensure compliance with the applicable limits.

A.8.2 Interference with Respect to Other NGSO Satellite Systems

SpaceX has engineered its system with the technical flexibility that will facilitate the necessary coordination with other NGSO satellite systems, and is committed to achieving mutually satisfactory agreements. Moreover, the proposed modification will not increase interference to any other NGSO system operating in the bands used by SpaceX satellites. Because the proposed modification will slightly decrease the total number of satellites by 16 satellites (from 4,425 to 4,409) and relocate 1,584 of them to operate at lower altitude, fewer of them will

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20 *See* 47 C.F.R. § 2.106 and NG165.

21 *See* ITU Radio Regs. No. 9.11A.

22 *See id.*, Res. 76.

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 of the effect of the proposed modification on downlink and uplink interference using the characteristics in the ITU filings of a proposed NGSO system operating in both the Ku- and 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. 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, because the new interference levels resulting with the modification are no worse (and often better) than the interference levels that would have been experienced with the original constellation for all percentages of time, the modification will not increase the potential interference into other NGSO systems.

In conducting this analysis, SpaceX used the following assumptions.

<u>For downlink interference from SpaceX satellites to a victim earth station</u>:

1. The SpaceX earth station is collocated with the victim earth station. Locations at 0°,

[23] *See Teledesic*, ¶ 13. Although SpaceX plans to transmit to earth stations during the initial deployment at elevation angles as low as 25 degrees, the area covered by these satellite beams is still less than 80% of the area of the beams transmitted from 1,150 km with a 40 degree elevation angle. Once the lower shell is transitioned to a 40 degree minimum elevation angle, the beam coverage will be less than 30% of the coverage from 1,150 km.

20°, 40°, and 50° latitude are considered in this simulation.

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 only one co-frequency beam per spot and any satellite in view meeting the GSO avoidance angle and the minimum elevation angle is eligible. All possible cases are considered in evaluating the I/N CDF.
4. Note that this 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 0°, 20°, 40°, and 50° latitude are considered in this simulation.
2. The other system 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 uses only one co-frequency earth station per spot (in the uplink) and any satellite in view meeting the GSO avoidance angle and the minimum elevation angle is eligible. All possible cases are considered in evaluating the I/N CDF.
4. Note that this simulation is conservative (*i.e.*, it overestimates I/N), as it does not consider the effects of atmospheric attenuation.

Proposed Ku-band NGSO System

To assess the potential impact of the modification on an NGSO system operating in the Ku-band, SpaceX used the characteristics of the IK-NGSO-A10K-1 network filed with the ITU, for a victim earth station with 35.1dBi antenna gain. The minimum elevation angle specified for this network is 3 degrees. The other relevant downlink parameters for this system are summarized in Table A.8.2-1 below.

Apogee	Perigee	Inclination	# Orbit planes	Sat/plane	RAAN plane spacing	Sub-Constellation Design	Assoc. ES Rx Gain	Rx ES Sys. Noise T [K]	Rx ES Co-pol Ref. Pattern
10355	10355	55	3	8	120	SC-1	31.6	125	Rec. S.580-6
		45	3	8		SC-2	35.1		
		35	3	8		SC-3	37.6		
		28.5	3	8		SC-4	41.1		
		55	2	8	180	SC-5	47.1		
		45	2	8		SC-6	50.9		
		35	2	8		SC-7	52.6		
		28.5	2	8		SC-8	55.1		

Table A.8.2-1. Downlink Parameters of 1K-NGSO-A10K-1 Ku-band System

The results of the analysis for a victim earth station located at each of the four latitudes considered in the simulation are set forth in Figures A.8.2-1 through A.8.2-4 below. In each case, the figure plots the probability of aggregate I/N levels for the SpaceX constellation as originally proposed and as modified.[24]

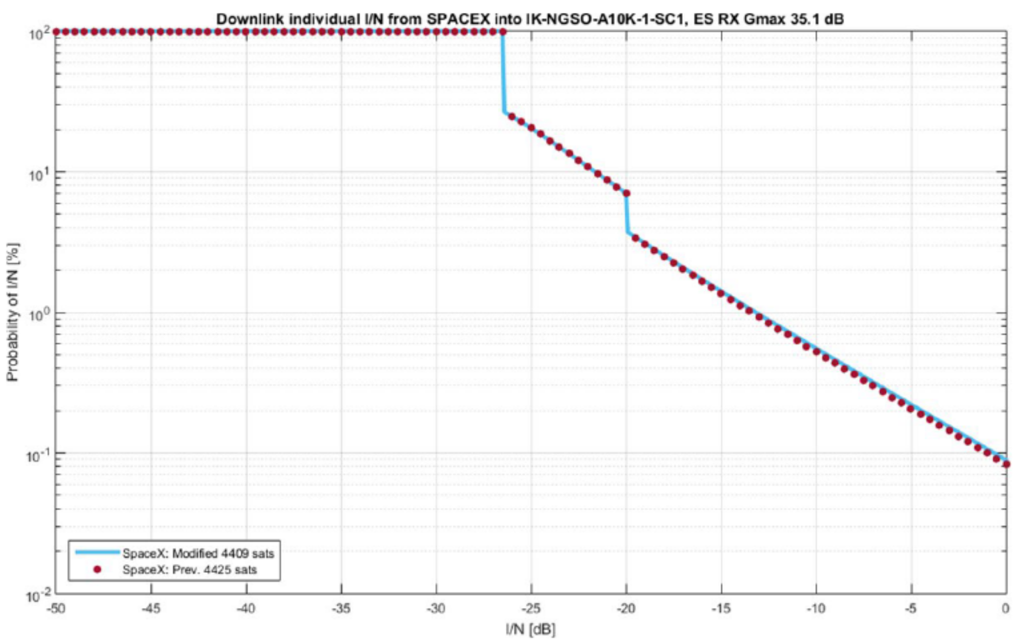

Figure A.8.2-1. Results for Earth Station at 0° Latitude

24 Note that the aggregate I/N shown in the following plots is limited to 0 dB, as any interference above that level would effectively preclude operations in the absence of some mitigation strategies.

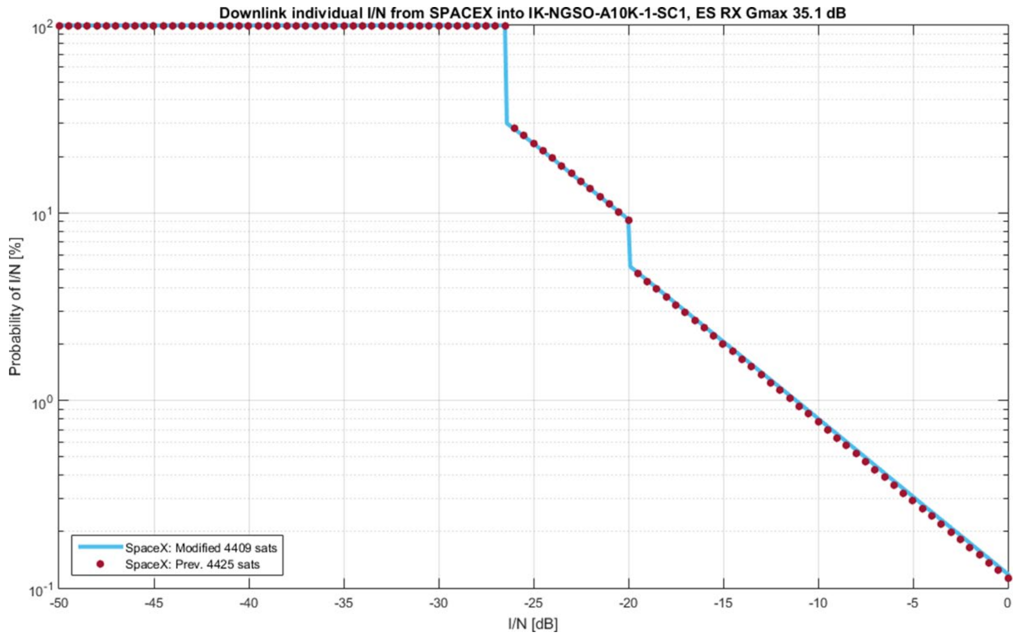

Figure A.8.2-2. Results for Earth Station at 20° Latitude

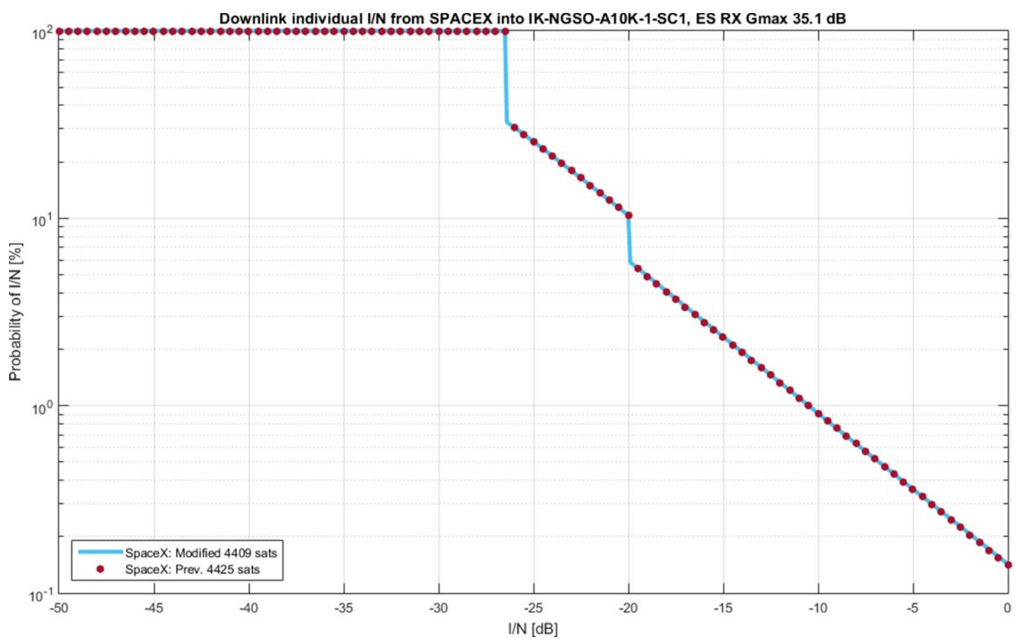

Figure A.8.2-3. Results for Earth Station at 40° Latitude

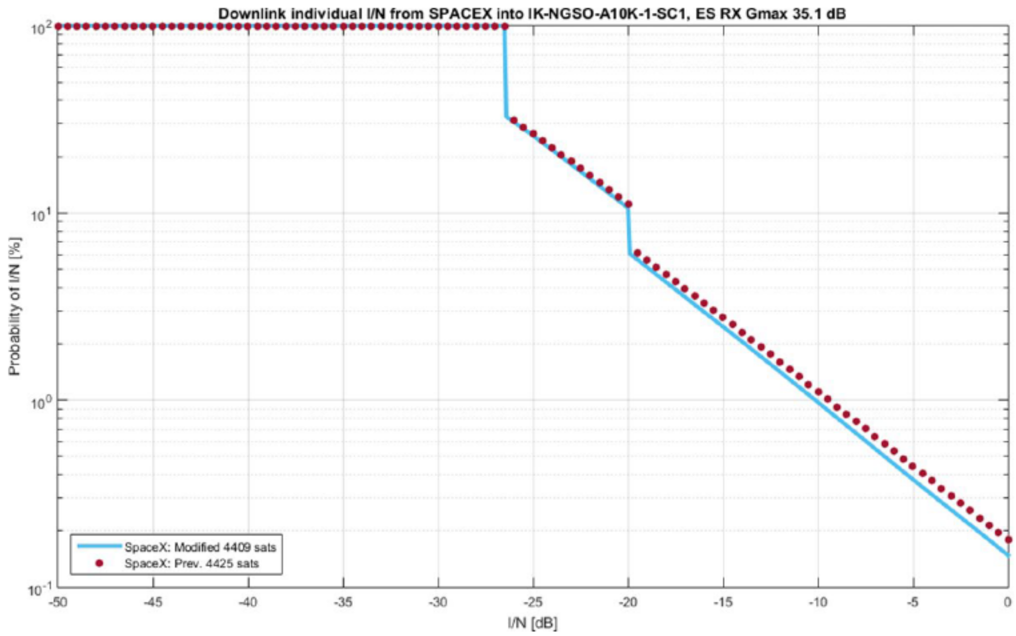

Figure A.8.2-4. Results for Earth Station at 50° Latitude

SpaceX performed a similar analysis for the Ku-band uplink of the proposed 1K-NGSO-A10K-1 system, for a victim satellite with 40 dBi antenna gain. Here again, the stated minimum elevation angle that this system's earth stations will use is 3 degrees, and the other relevant parameters are set forth in Table A.8.2-2 below.

<table>
<tr><th>Apogee</th><th>Perigee</th><th>Inclination</th><th># Orbit planes</th><th>Sat/plane</th><th>RAAN plane spacing</th><th>Rx Sat. Antenna Gain</th><th>Rx Sat Sys. Noise T [K]</th></tr>
<tr><td rowspan="8">10355</td><td rowspan="8">10355</td><td>55</td><td>3</td><td>8</td><td rowspan="4">120</td><td rowspan="8">40</td><td rowspan="8">550</td></tr>
<tr><td>45</td><td>3</td><td>8</td></tr>
<tr><td>35</td><td>3</td><td>8</td></tr>
<tr><td>28.5</td><td>3</td><td>8</td></tr>
<tr><td>55</td><td>2</td><td>8</td><td rowspan="4">180</td></tr>
<tr><td>45</td><td>2</td><td>8</td></tr>
<tr><td>35</td><td>2</td><td>8</td></tr>
<tr><td>28.5</td><td>2</td><td>8</td></tr>
</table>

Table A.8.2-2. Uplink Parameters of 1K-NGSO-A10K-1 Ku-band System

The results of the analysis for a victim satellite communicating with an earth station located at each of the four latitudes considered in the simulation are set forth in Figures A.8.2-5 through A.8.2-8 below.

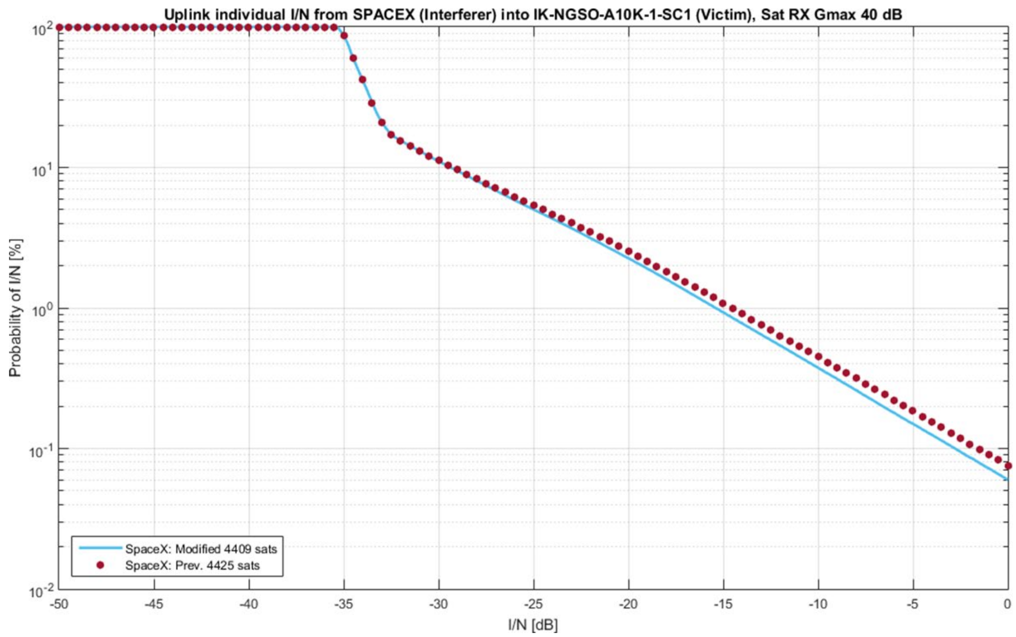

Figure A.8.2-5. Results for Earth Station at 0° Latitude

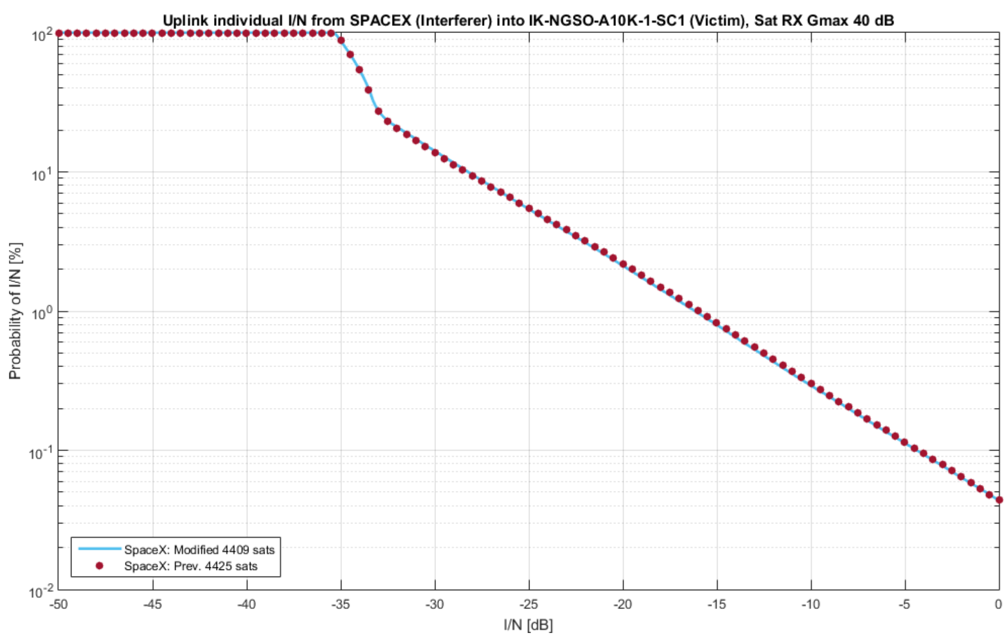

Figure A.8.2-6. Results for Earth Station at 20° Latitude

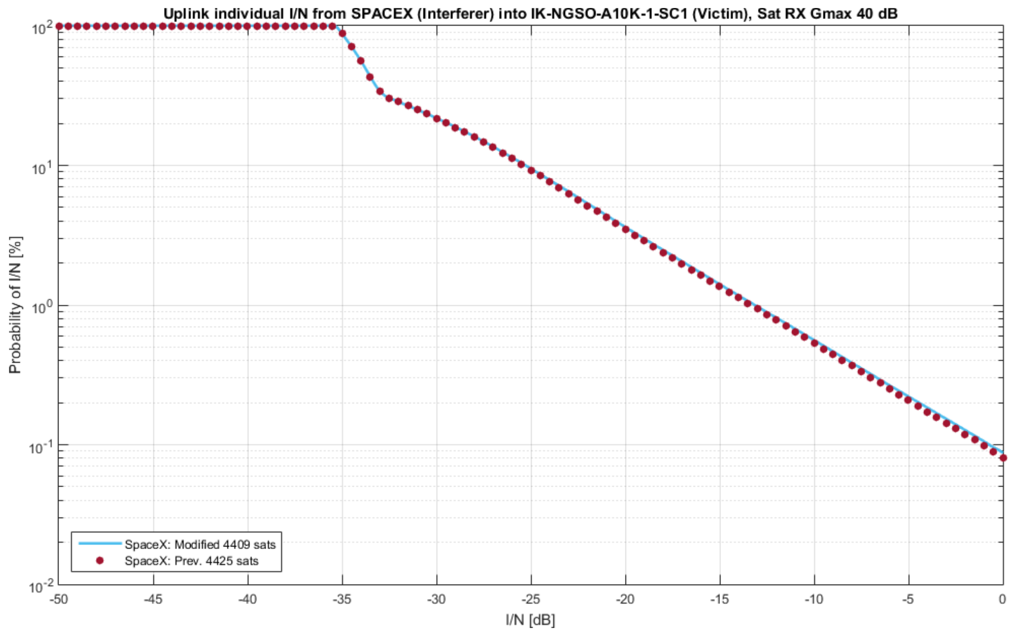

Figure A.8.2-7. Results for Earth Station at 40° Latitude

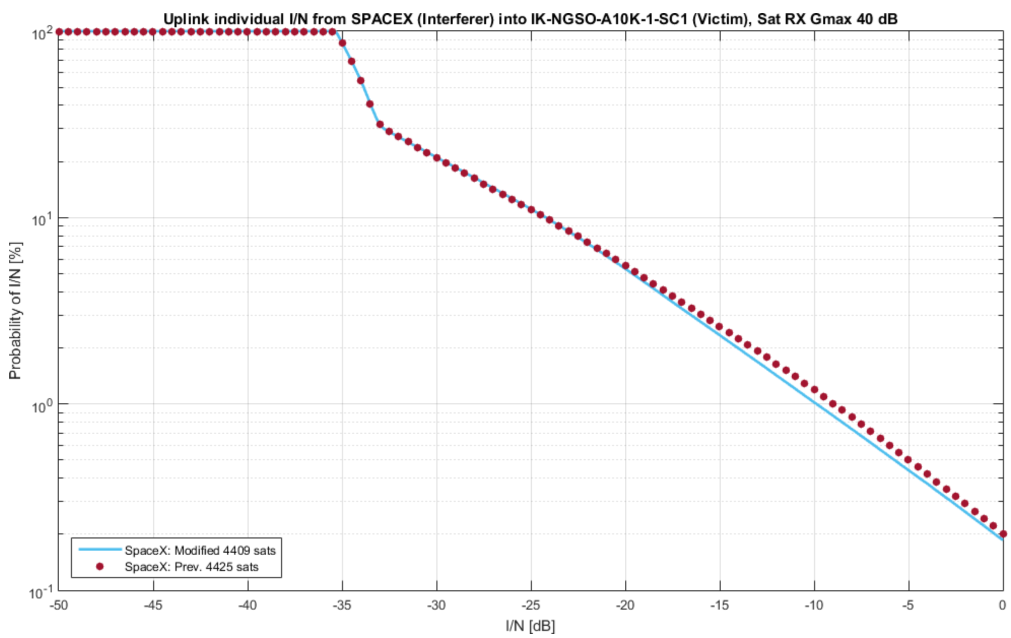

Figure A.8.2-8. Results for Earth Station at 50° Latitude

As the figures presented above demonstrate, the modified constellation would cause no more interference into the Ku-band operations of IK-NGSO-A10K-1 network than would the original constellation.

Proposed Ka-band NGSO System

SpaceX also used the characteristics of the IK-NGSO-A10K-1 network filed with the ITU to assess the potential effect of the modification on Ka-band NGSO systems. For the downlink analysis, SpaceX used a victim earth station with 39.5 dBi antenna gain and the stated minimum elevation angle of 3 degrees. The other relevant downlink parameters for this system are summarized in Table A.8.2-3 below.

Apogee	Perigee	Inclination	# Orbit planes	Sat/plane	RAAN Plane Spacing	Sub-Constellation Design	Assoc. ES Rx Gain	Rx ES Sys. Noise T [K]	Rx ES Co-pol Ref. Pattern
10355	10355	55	3	8	120	36	31.6	150	Rec. S.580-6
		45	3	8		39.5	35.1		
		35	3	8		42	37.6		
		28.5	3	8		45.5	41.1		
		55	2	8	180	51.5	47.1		
		45	2	8		55.3	50.9		
		35	2	8		57	52.6		
		28.5	2	8		59.5	55.1		

Table A.8.2-3. Downlink Parameters of 1K-NGSO-A10K-1 Ka-band System

The results of the analysis for a victim earth station located at each of the four latitudes considered in the simulation are set forth in Figures A.8.2-9 through A.8.2-12 below.

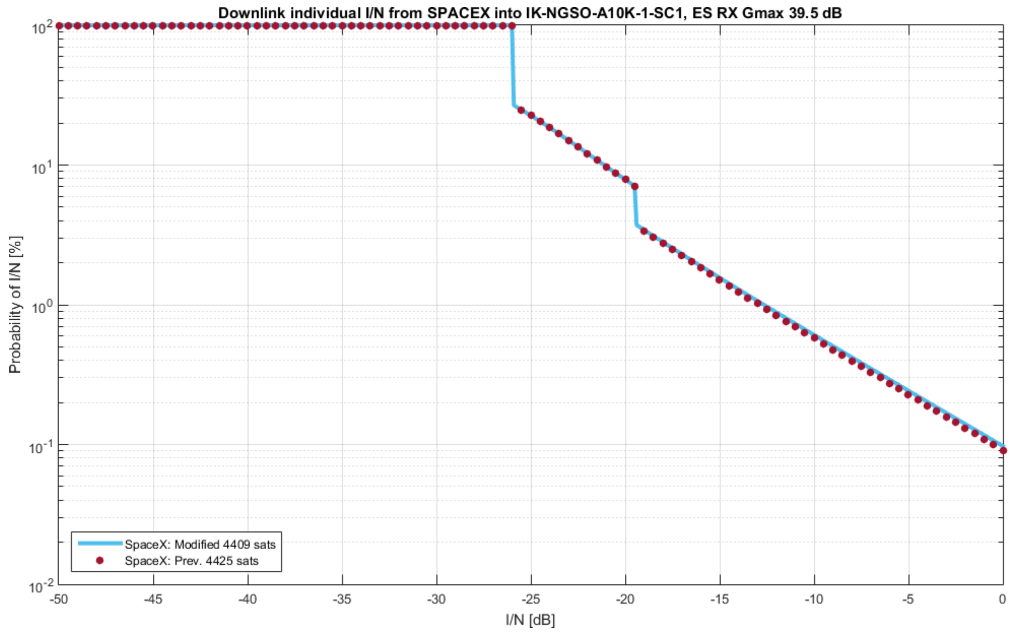

Figure A.8.2-9. Results for Earth Station at 0° Latitude

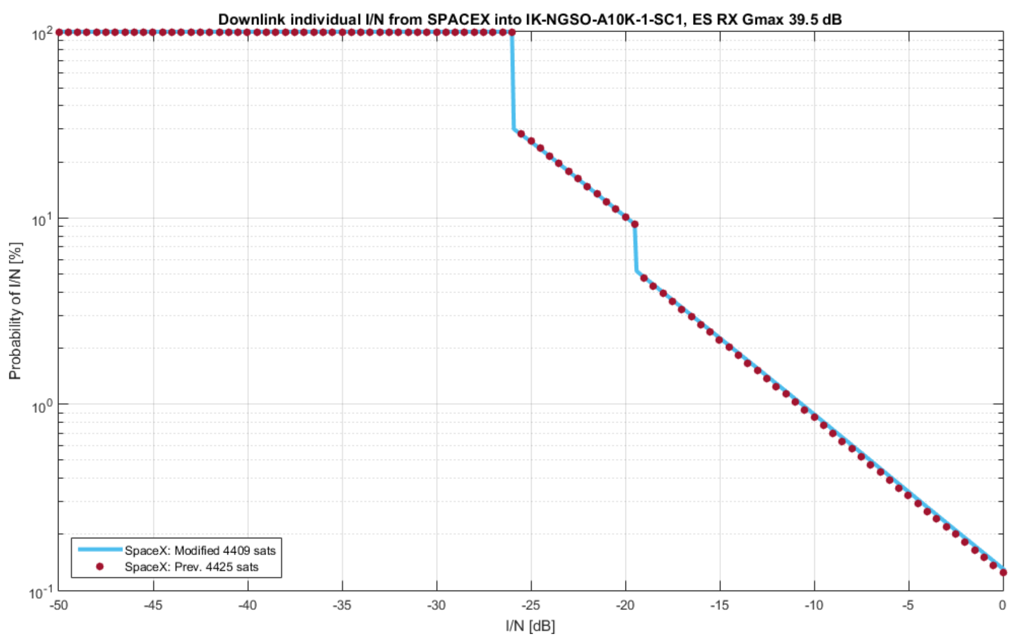

Figure A.8.2-10. Results for Earth Station at 20° Latitude

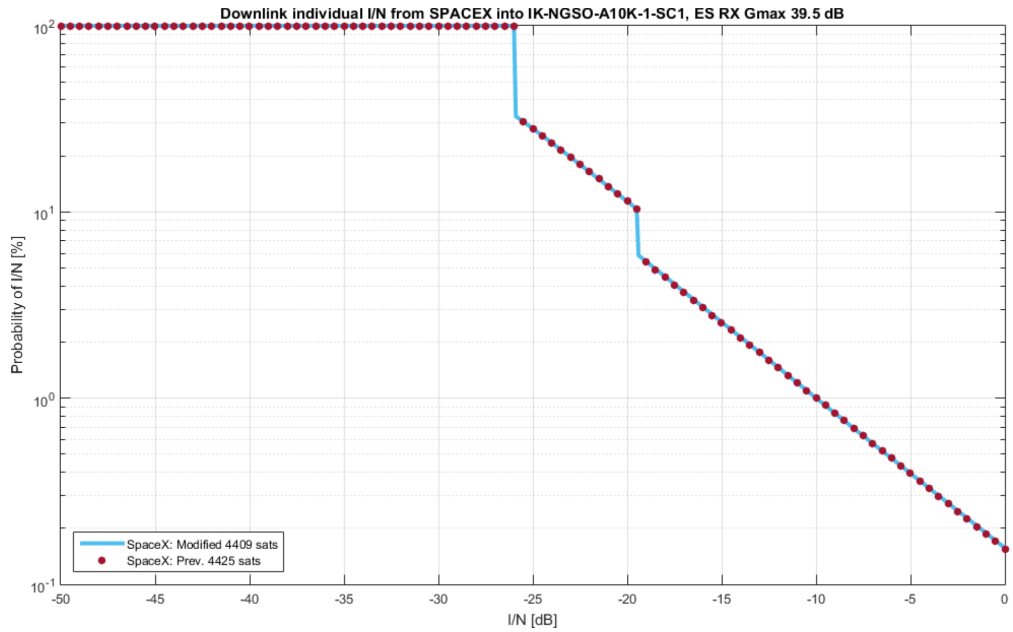

Figure A.8.2-11. Results for Earth Station at 40° Latitude

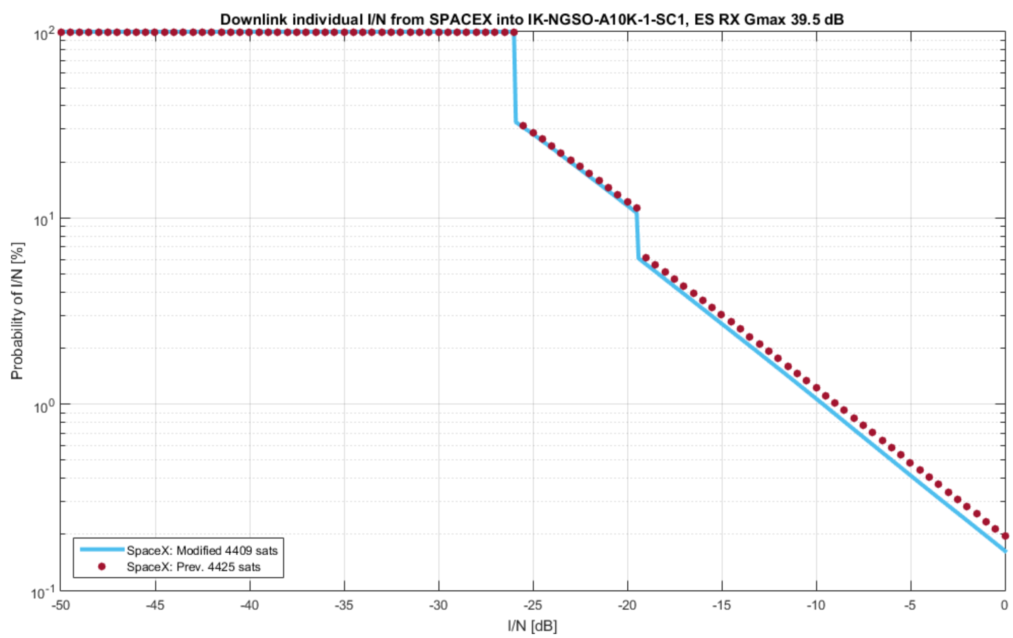

Figure A.8.2-12. Results for Earth Station at 50° Latitude

SpaceX performed a similar analysis for the Ka-band uplink of the proposed 1K-NGSO-A10K-1 system, for a victim satellite with 50 dBi antenna gain. Here again, the stated minimum elevation angle that this system's earth stations will use is 3 degrees, and the other relevant parameters are set forth in Table A.8.2-4 below.

Apogee	Perigee	Inclination	# Orbit planes	Sat/plane	RAAN Plane Spacing	Rx Sat. Antenna Gain	Rx Sat Sys. Noise T [K]
10355	10355	55	3	8	120	50	600
		45	3	8			
		35	3	8			
		28.5	3	8			
		55	2	8	180		
		45	2	8			
		35	2	8			
		28.5	2	8			

Table A.8.2-4. Uplink Parameters of 1K-NGSO-A10K-1 Ka-band System

The results of the analysis for a victim satellite communicating with an earth station located at each of the four latitudes considered in the simulation are set forth in Figures A.8.2-13 through A.8.2-16 below.

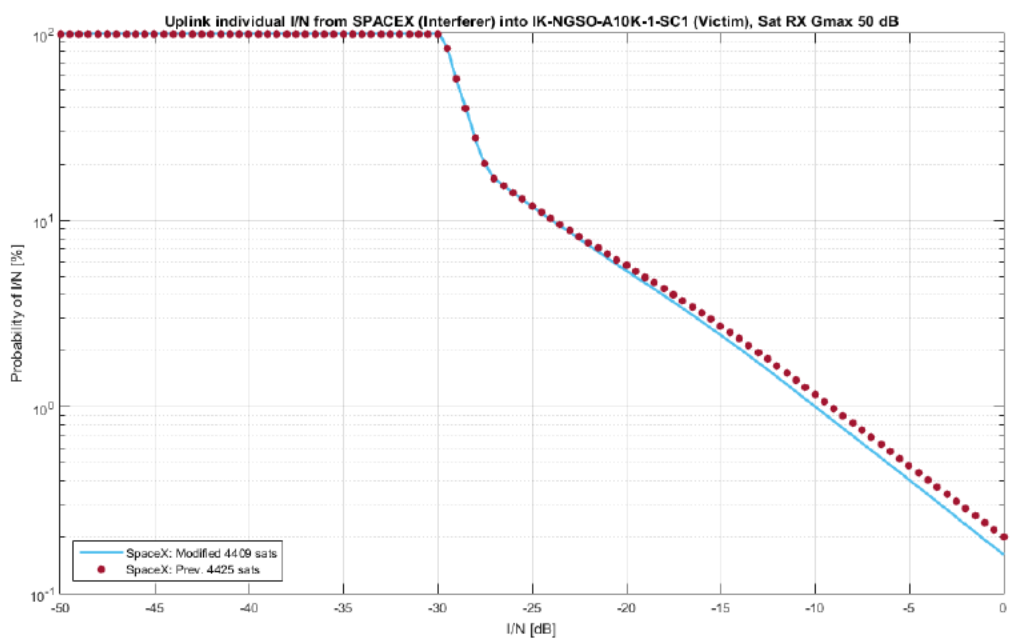

Figure A.8.2-13. Results for Earth Station at 0° Latitude

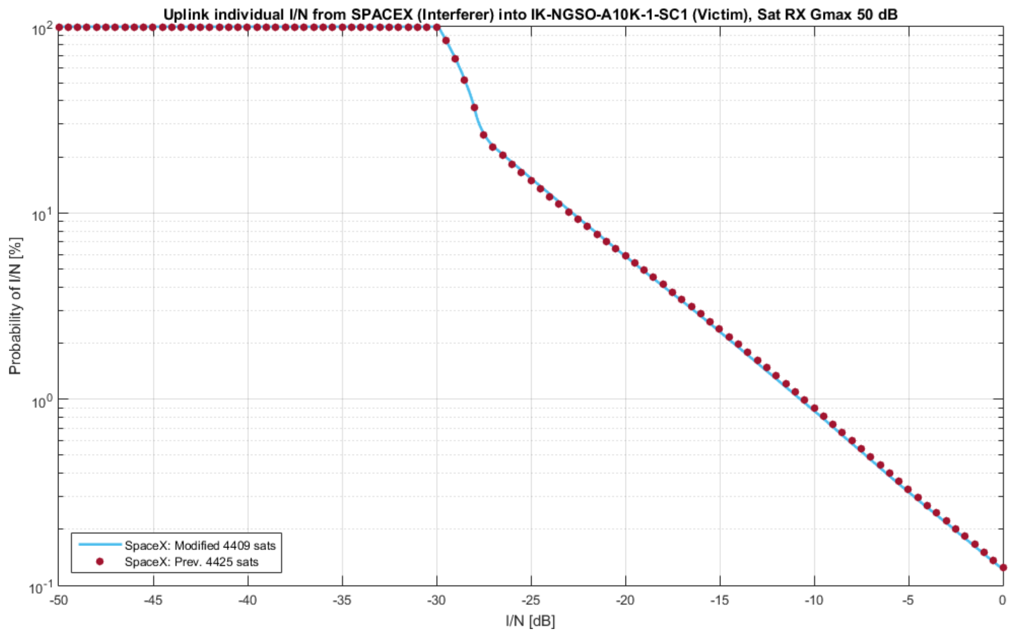

Figure A.8.2-14. Results for Earth Station at 20° Latitude

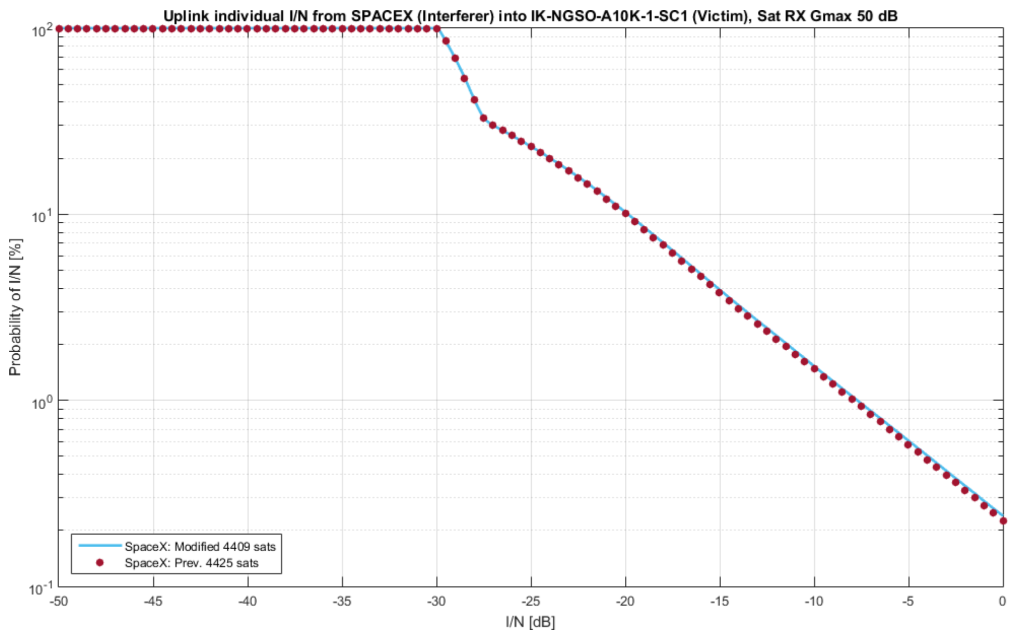

Figure A.8.2-15. Results for Earth Station at 40° Latitude

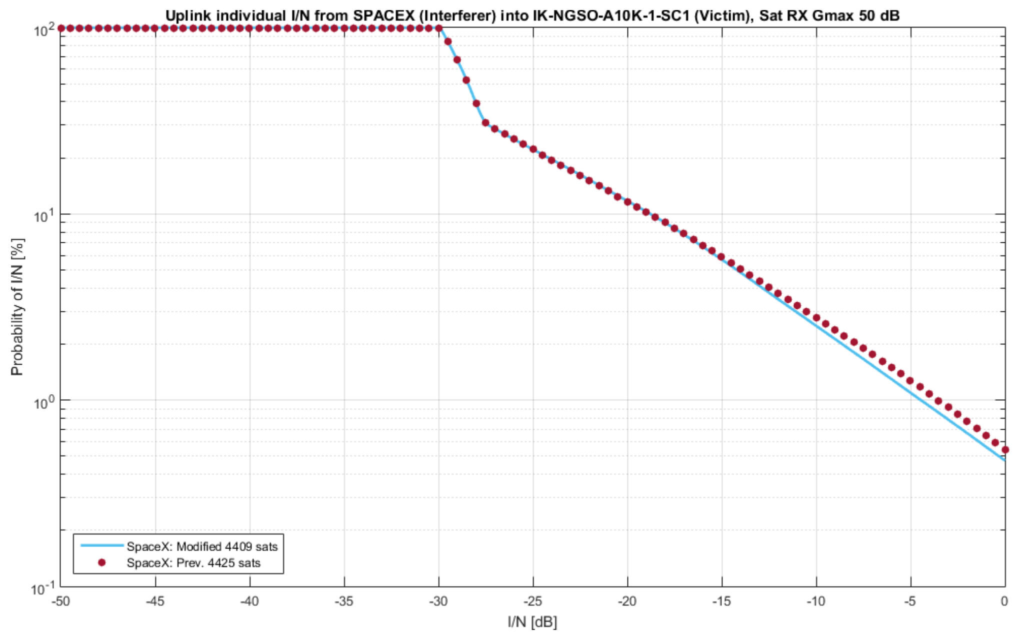

Figure A.8.2-16. Results for Earth Station at 50° Latitude

As the figures presented above demonstrate, the modified constellation would cause no more interference into the Ka-band operations of IK-NGSO-A10K-1 network than would the original licensed constellation.

A.8.3 Interference With Respect to Terrestrial Networks

This information is available in Attachment A to the Original Applications. In addition, as demonstrated above, the SpaceX constellation as modified will comply with all relevant PFD limitations in the Ku-band, and will protect terrestrial operations in the Ka-band as well.

A.8.4 Interference With Respect to the Radio Astronomy Service

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

A.9 Coordination With U.S. Government Operations

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

A.10 ITU FILINGS FOR SPACEX

SpaceX is preparing the modified system information for ITU publication and will submit this information shortly. 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 Original Applications. Maintaining a clean orbital environment is a fundamental consideration for SpaceX, which is planning to launch its Falcon 9 vehicles into orbital altitudes at least 22 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, in 2019, 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 SpaceX's Microsat 2A and 2B experimental satellites, 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 shell would yield the following five key benefits:

- 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.[25] We discuss each of these benefits in more detail below.

Rapid, Passive Disposal

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 550 km. For the new lower shell 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 atmospheric torques from low altitudes cause the vehicle to be uncontrollable.[26] 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, drawing batteries down to a safe level and powering 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 550 km provide fully passive redundancy to SpaceX's active disposal procedures. The natural orbital decay of a satellite at 1,150 km requires hundreds of years to enter the Earth's atmosphere, but the lower satellites at an altitude of 550 km will take less than five

[25] *See* SpaceX Authorization, ¶ 15.

[26] 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.

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 550 km, 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 (circular at 550 km), has no attitude control, and solar activity is at a minimum – the longest decay time is still only approximately 4.5-5 years. The time to satellite demise from various altitudes is illustrated in Figure 11.1-1 below.[27]

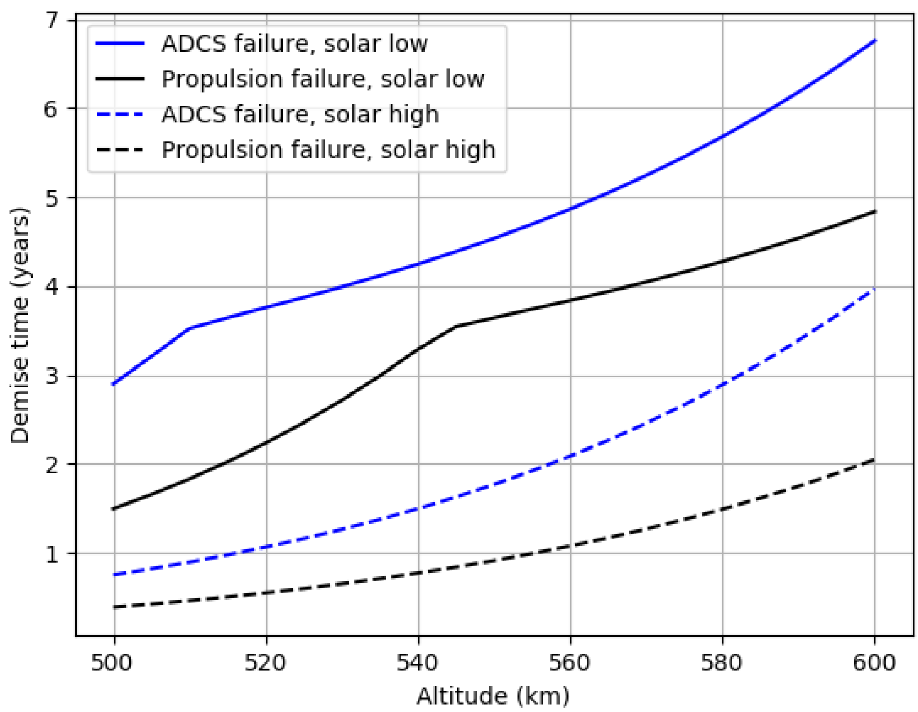

Figure A.11-1. Demise Time at Various Altitudes

[27] 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 550 km all cases demise in less than 5 years.

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 1 to 3 years. But even assuming the unlikely 5-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[28] by achieving a 100% success rate of post-mission disposal within 5 years even assuming worst-case conditions, directly addressing one concern previously identified by the Commission.[29] Nonetheless, SpaceX's nominal disposal plan that it anticipates for nearly every spacecraft will result in a lifetime of less than six months after SpaceX initiates disposal, an advantage of operating at the lower altitude proposed in the modification.

Self-Cleaning Debris Environment

As an initial matter, SpaceX expects that operating at lower altitude will further reduce any risk that a satellite could fail, resulting in less risk of any spacecraft fragmentation. But in the unlikely event that some fragmentation does occur, the same atmospheric conditions at 550 km that accelerate satellite disposal will also provide additional protection from debris. Orbital debris at the currently authorized orbital altitude of 1,150 km could last centuries before decaying into the atmosphere. By comparison, the natural lifetime of any fragments at the proposed lower 550 km altitude should be orders of magnitude shorter – down to days or weeks in many cases. This means generally a lower risk of orbital debris of any kind, including in the unlikely case in which debris unexpectedly results from SpaceX's operations.

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[28] *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), available at https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv22i3.pdf.

[29] *See* SpaceX Authorization, ¶ 15 and n.55.

In addition to the environmental benefits of the lower altitude, SpaceX considers the lower altitude an additional safeguard for space safety. The planned strategy continues to feature multiple technical steps to prevent any fragmentation from occurring. SpaceX spacecraft will nominally continue to perform active conjunction avoidance at all stages of flight. During the mission, batteries and various critical areas of the propulsion subsystem will be instrumented with fault detection, isolation, and recovery (similar or in many cases identical to flight-proven methods utilized onboard the SpaceX Dragon capsule for its missions to ISS) to continually monitor and preclude conditions that could result in the remote possibility of energetic discharge and subsequent generation of debris. Additionally, SpaceX ensures that critical components are resilient against impacts from microparticles present in the space environment. Yet in the unlikely event that each of these layers of safeguards fails, operating at the 550 km altitude provides a passive back-up mechanism that will quickly and efficiently eliminate orbital debris due to natural drag, thereby reducing the risk for the SpaceX constellation as well as the LEO environment as a whole.

Reduced Fuel Requirements and Thruster Wear

SpaceX plans to insert its satellites upon launch at a relatively low altitude, after which each satellite will undergo initial testing before performing orbit raising maneuvers to reach its operational altitude. In its Original Applications, SpaceX planned to transition its satellites from approximately 400 km to the 1,150 km orbital shell. For its proposed operations at 550 km, SpaceX expects the insertion altitude for the modified 1,584 satellites generally to be 300-350 km, depending on solar activity. Even with this slightly lowered insertion altitude, the total orbit raise required to reach operating altitude is dramatically less than for the 1,150 km destination of the original shell. Correspondingly, this altitude requires less fuel for orbit raising and leaves more propellant to maintain orbit once the satellite arrives at its new maximum altitude. In fact, even though the thrust to overcome ongoing atmospheric drag at 550 km is significantly higher than at 1,150 km, SpaceX has been able to decrease the overall work required by the Hall-effect electric propulsion system by at least 50% with respect to the original design.

Benign Ionizing Radiation Environment

Operating at lower altitude also increases the reliability of the spacecraft by reducing the intensity of the radiation environment, which results in less risk of radiation-induced failure. This leads to a greater likelihood that a satellite reaches its full operational life and finishes its entire nominal disposal sequence. Ensuring that all satellites in the constellation deorbit nominally also ensures the safety profile of the constellation.

Fewer Existing Operators Affected By SpaceX Constellation

SpaceX will continue to take a number of steps to ensure that its constellation does not unduly affect other constellations. First, 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 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 1,200 km.[30] These systems will operate at altitudes that could extend through SpaceX's currently authorized orbit at 1,150 km. SpaceX recognizes that the Commission has authorized Spire Global to deploy cubesats at a variety of altitudes from 400 km to 650 km,[31] and that it is currently considering an application filed by Kepler Communications that proposes to operate microsatellites in near-polar orbits at a range of altitudes from 500 km to 600 km.[32] SpaceX will engage Spire, Kepler, and any other system seeking to operate at the same nominal orbital planes 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 the first 1,584 SpaceX satellites will transit through fewer systems during orbit raising or end-of-life disposal. In its Original Applications, SpaceX planned to transition all of its satellites from approximately 400 km to 1,150 km. By using a lower operational altitude for its first deployment of spacecraft, SpaceX will eliminate any risk from physical interaction with these SpaceX satellites for other systems operating in the 550 km to 1,150 km range – some of the most congested altitudes in LEO.

Post-Mission Disposal

As discussed above, SpaceX anticipates that its satellites in the proposed lower shell will reenter the Earth's atmosphere within approximately six months after completion of their mission – much sooner than the international standard of 25 years.

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30 *See WorldVu Satellites Limited*, 32 FCC Rcd. 5366 (2017); *Telesat Canada*, 32 FCC Rcd. 9663 (2017); IBFS File No. SAT-LOA-20170301-00028.

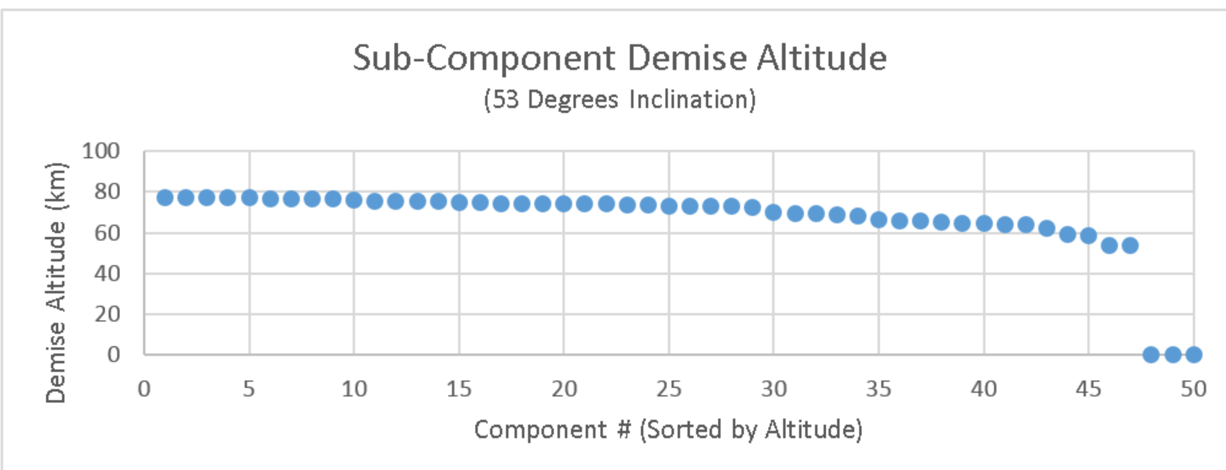
31 *See, e.g.*, Letter from George John to Marlene H. Dortch, IBFS File No. SAT-LOA-20151123-00078 (June 28, 2018) (annual report for IBFS call sign S2946).

32 *See* IBFS File No. SAT-PDR-20161115-00114. Kepler has described a variety of orbital parameters for the system, but in general it appears to consist of 7 orbital planes (20 satellites per plane) in circular near-polar sun synchronous orbits at an approximate altitude of 500-600 kilometers.

Atmospheric Demise

The spacecraft's small mass and predominantly aluminum construction maximize the likelihood of atmospheric demise on re-entry. To verify this, SpaceX utilized NASA's Debris Assessment Software ("DAS"). As demonstrated below, the SpaceX design remains below the necessary demise threshold, even using worst-case satellite configurations.

To perform the DAS analysis, the satellite was broken down into 50 major components, each defined with its own shape, material, mass and dimensions. Components were modeled in a nested fashion; a child component would not be exposed to aerodynamic heating until its nesting parent component completely burned up. This enabled conservative re-entry survivability analysis of common problematic components. DAS models the release of all root components 79 km above the surface; the demise altitudes of all modeled components are shown in the following figure:



Several objects were identified as components of interest. These were objects with distinct mass, quantity, or shape factors that made them of particular concern during re-entry analysis. Those components and their corresponding demise altitudes are given in the table below:

Component	Demise (km)
Phased Arrays	68.9
Propellant Tank	68.2
Structural Panel	66.4
Batteries	66.0
Regulator	53.9

Although SpaceX made efforts to avoid the use of components resistant to disintegration, some scenarios were unavoidable at this time. DAS analysis indicates that three unique components may have a chance of reaching the Earth's surface with sufficient energy to result in human casualty.[33] These components are listed in the table below.

Component	Qty.	Material	Mass (kg)	Total DCA (m^2)
Thruster Internals	1	Iron	1.66	0.47
Reaction Wheels	4	Stainless Steel	1.18	2.37
Comms. Components	4	Silicon Carbide	1.43	2.34

Comparing these results against those from the Original Applications yields the following observations. First, the total DCA of the communications components has decreased slightly, from 2.79 m^2 to 2.34 m^2. Second, by far the biggest change is the addition of steel reaction wheels, which were not a potential source of human casualty risk in the prior analysis. SpaceX plans to deploy two versions of its initial satellites with slightly different configurations and each will only carry a subset of the components identified above.[34] Each of these configurations yields

33 The Debris Casualty Area is a function of the dimensions of an average person and of the specific debris fragment. The model does not consider more complicated aspects, such as sheltering within structures. The total casualty area is the sum of the casualty areas of all surviving debris fragments that reach the ground with kinetic energy greater than 15 joules.

34 The first version includes the iron thruster and steel reaction wheels, whereas later iterations will add a silicon carbide component, while replacing the wheels with a fully demisable alternative. Even a worst-case configuration that includes all three components (a configuration that SpaceX does not intend to deploy) yields a risk of 1:10,700, which still meets the NASA requirement.

a Risk of Human Casualty rate of 1:19,800,[35] satisfying the requirement of 1:10,000 established by NASA in NASA-STD-8719.14.

The tables provided above summarize the results of a first-order DAS re-entry analysis. As a first-order tool, at times DAS has been known to provide conservative results. For example, DAS does not model partial ablation, which would have favorably affected the outcome of the model. This, and similar factors, are more accurately accounted for by analysis using NASA's proprietary Object Reentry Survival Analysis tool ("ORSAT"), a common step superseding DAS analysis. SpaceX currently has an open contract with NASA's Orbital Debris Program Office for carrying out higher fidelity satellite ORSAT analysis, though those results are not yet available. Moreover, the DAS analysis does not take into consideration the degree to which people would be located within structures that would provide shelter from potential impact. According to NASA, even lightly-sheltered structures provide protection against falling debris with up to a few kilojoules of kinetic energy.[36] Given that the DAS analysis assumes that debris with as little as 15 joules will result in human casualty, any level of shelter would significantly reduce the likelihood of injury.

DAS Accordance

As shown in the screen shot below, the DAS assessment concludes that SpaceX's anticipated de-orbit plan for the orbital shell proposed at 550 km satisfies all applicable requirements under NASA-STD-8719.14.[37]

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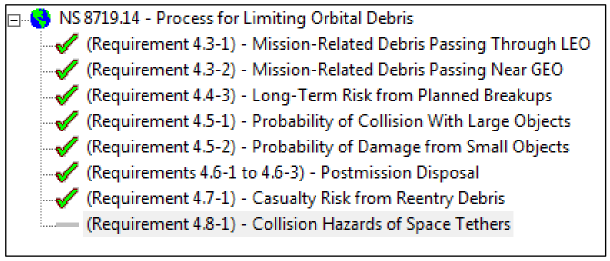
35 DAS is sig-fig limited. While the DCA of each configuration varies slightly, DAS reports a risk of 1:19,800 for both scenarios.

36 *See* NASA Standard 8719.14A at § 4.7.3(d).

37 Requirement 4.8-1, related to Collision Hazards of Space Tethers, does not apply to SpaceX's satellites.


NS 8719.14 - Process for Limiting Orbital Debris
(Requirement 4.3-1) - Mission-Related Debris Passing Through LEO
(Requirement 4.3-2) - Mission-Related Debris Passing Near GEO
(Requirement 4.4-3) - Long-Term Risk from Planned Breakups
(Requirement 4.5-1) - Probability of Collision With Large Objects
(Requirement 4.5-2) - Probability of Damage from Small Objects
(Requirements 4.6-1 to 4.6-3) - Postmission Disposal
(Requirement 4.7-1) - Casualty Risk from Reentry Debris
(Requirement 4.8-1) - Collision Hazards of Space Tethers

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.

November 8, 2018

Date

ANNEX 1

Demonstration of EPFD Compliance for Ku-Band Operations

This annex demonstrates that the Ku-band operations of the SpaceX non-geostationary orbit ("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.[2]

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 gateway and TT&C uplink transmissions, with respect to two stages of constellation deployment. The first set of diagrams presents the analysis of an initial deployment of 1,584 satellites operating at an altitude of 550 km with a minimum earth station elevation angle of 25 degrees. The second set of diagrams presents the analysis of the final deployment of 4,409 satellites (including 1,584 satellites at 550 km) operating with a minimum earth station elevation angle of 40 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.

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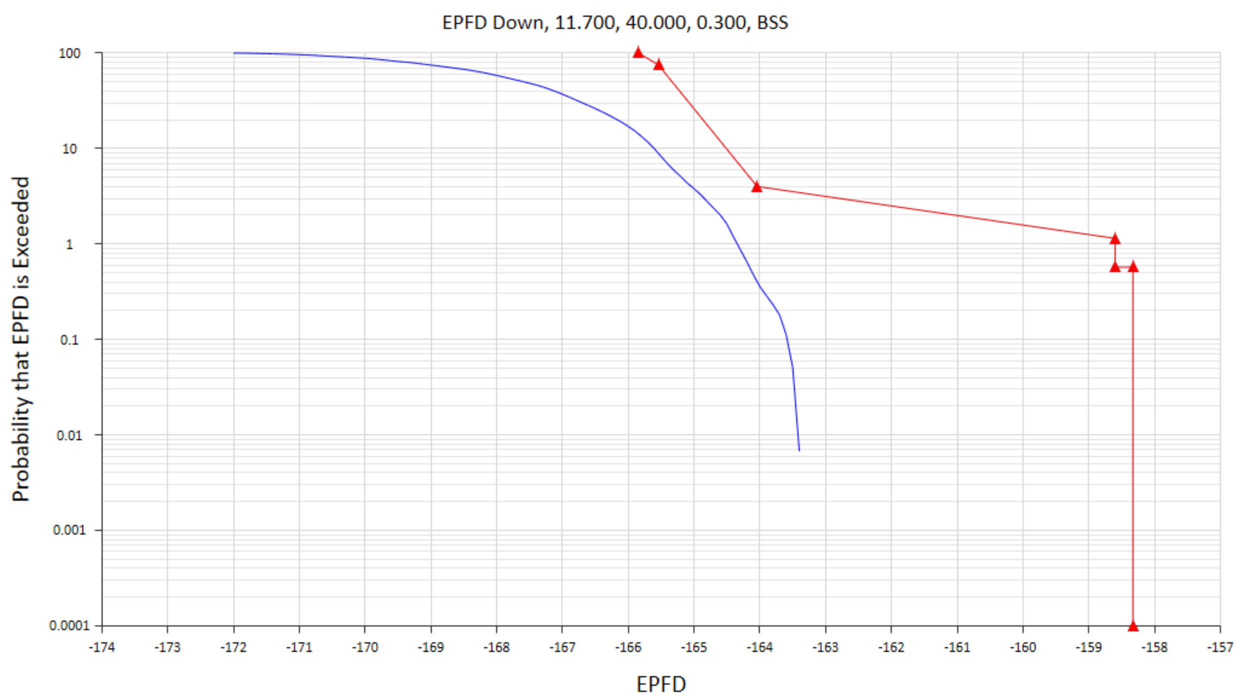
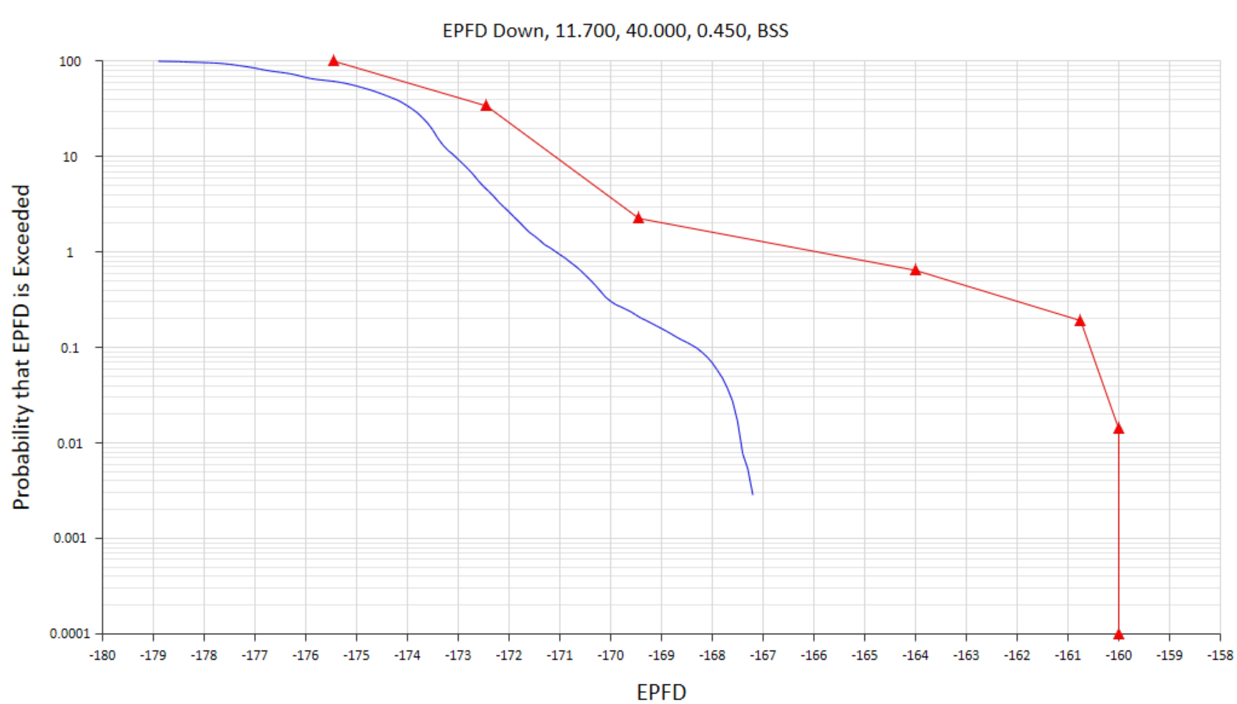
1 *See* 47 C.F.R. § 25.146(a)(2).

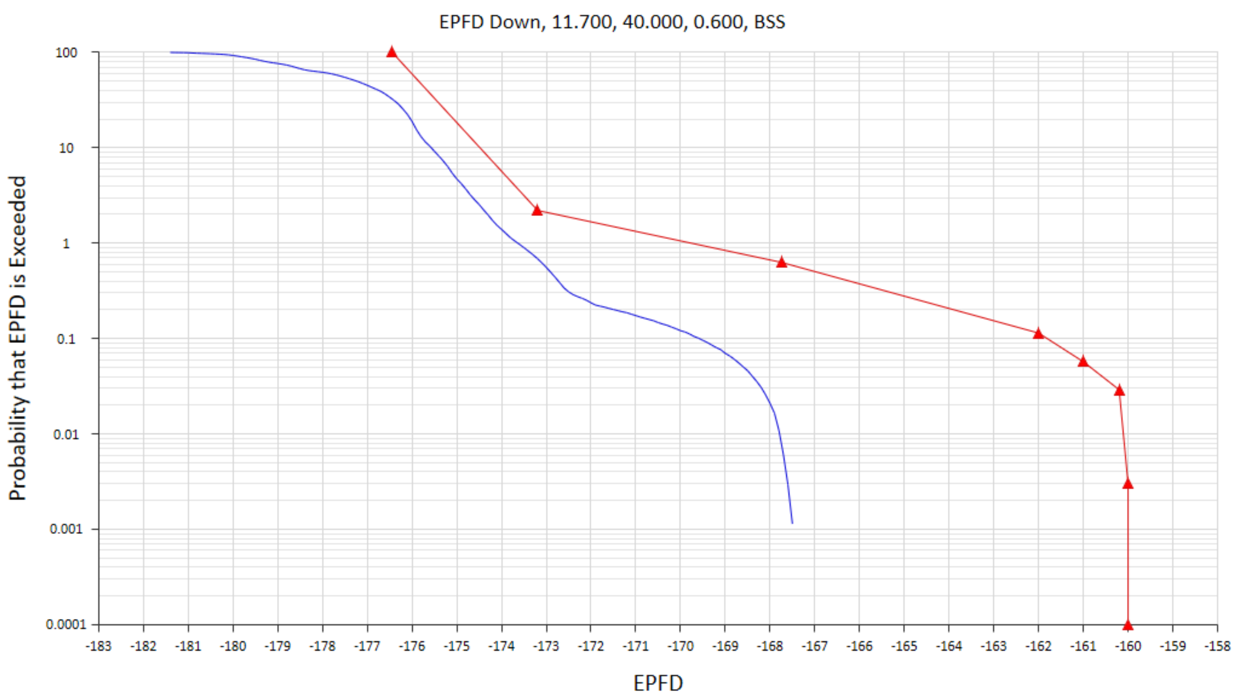
2 SpaceX is also submitting under separate cover the input files that will allow the Commission to confirm this analysis.

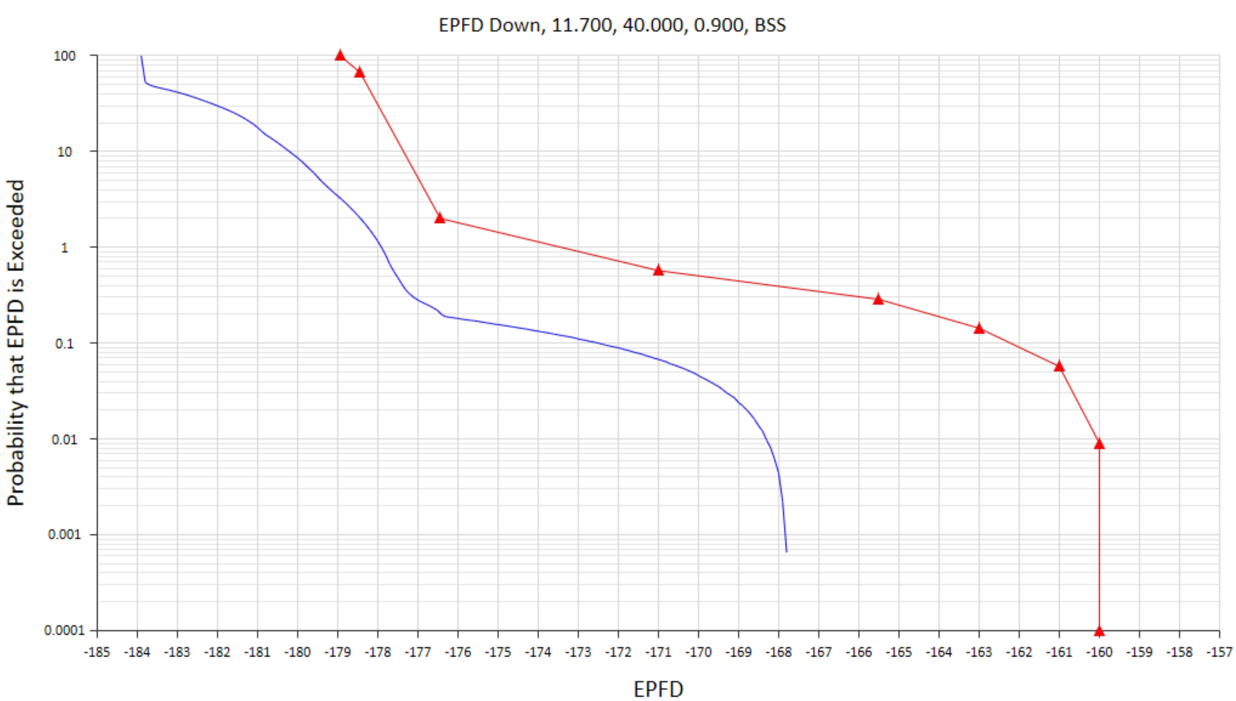
ANALYSIS OF INITIAL DEPLOYMENT

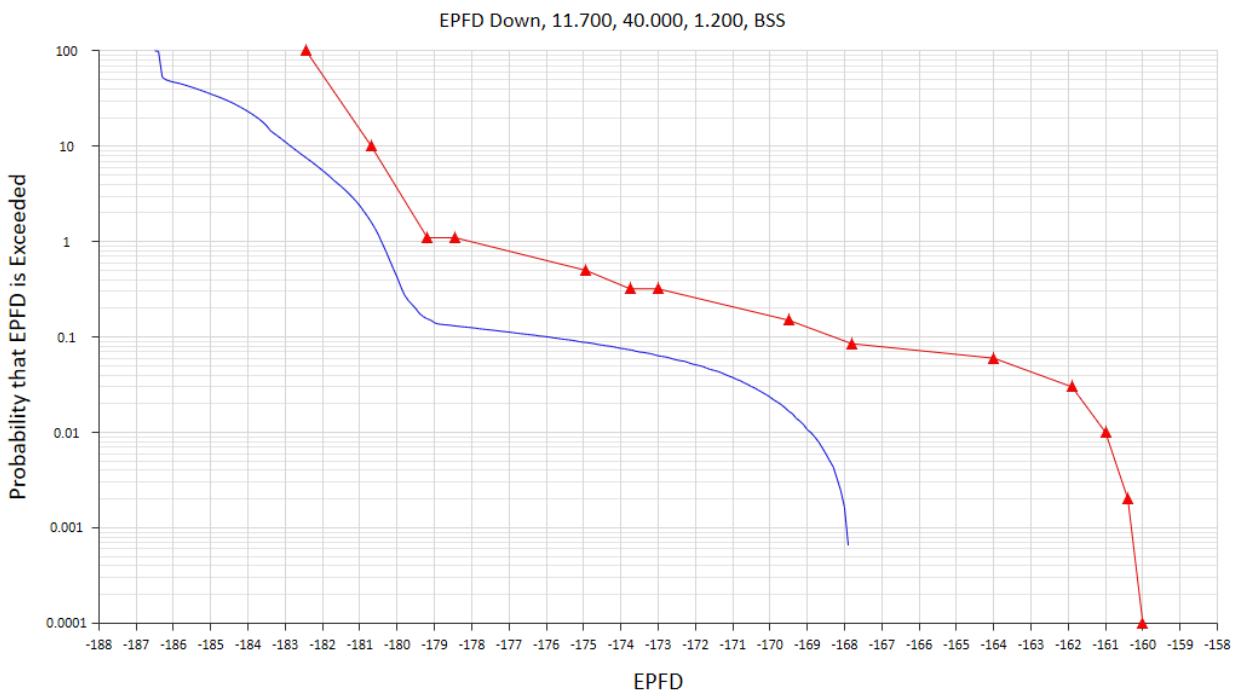
OUTPUTS FOR EPFD$_{DOWN}$ ASSESSMENT OF BSS LIMITS

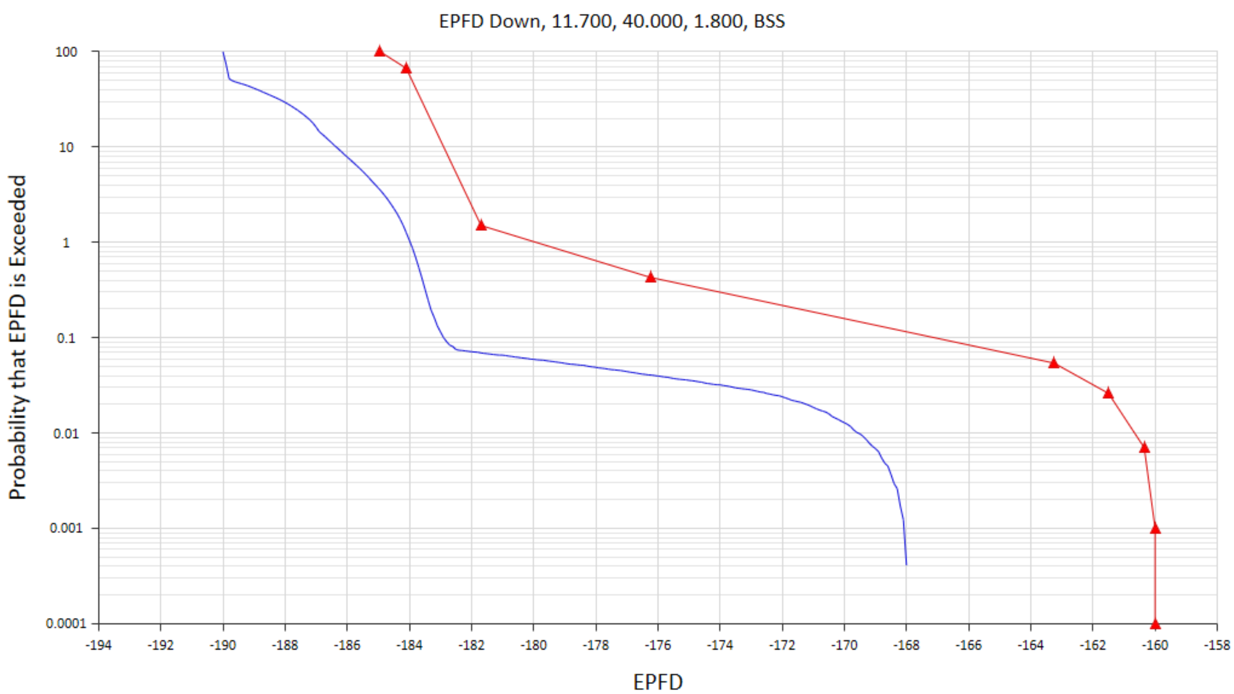


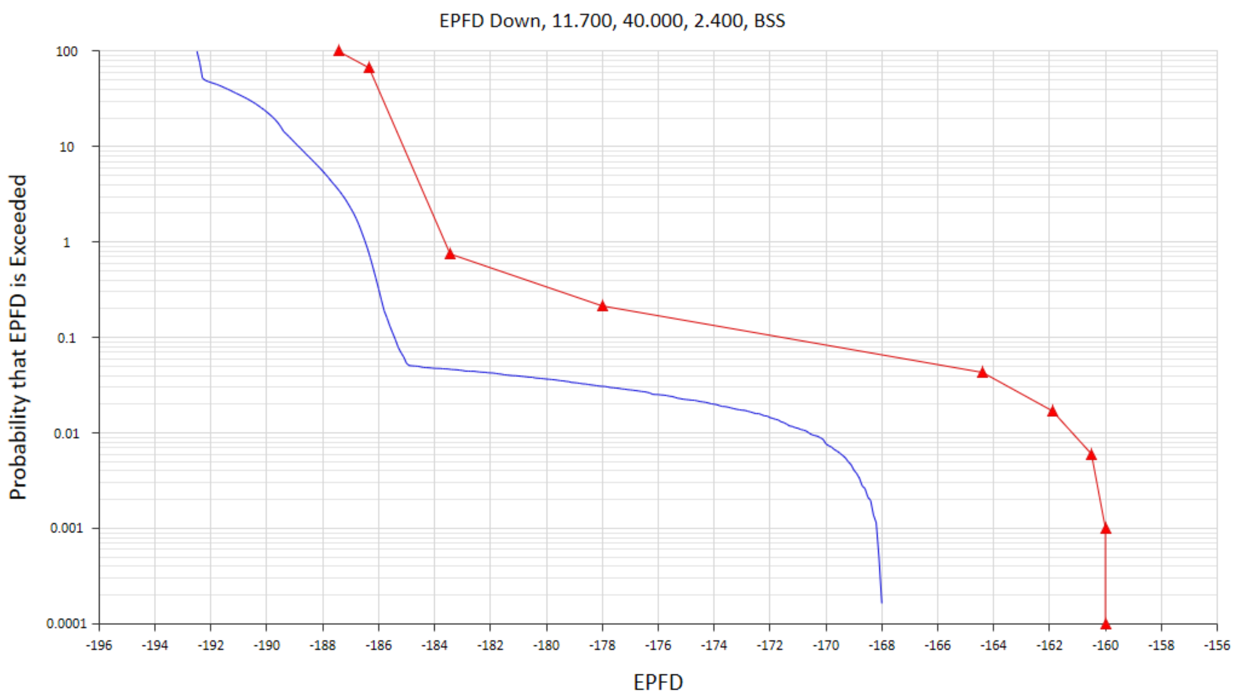


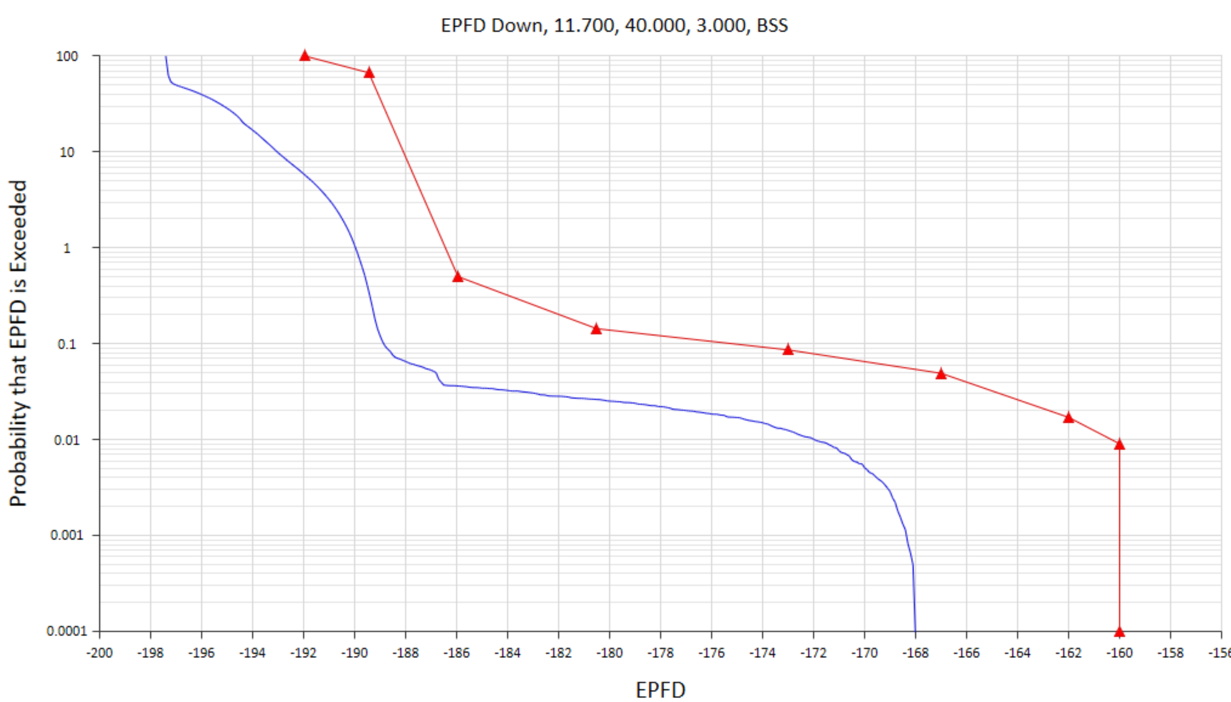

EPFD Down, 11.700, 40.000, 0.600, BSS
Probability that EPFD is Exceeded
EPFD


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

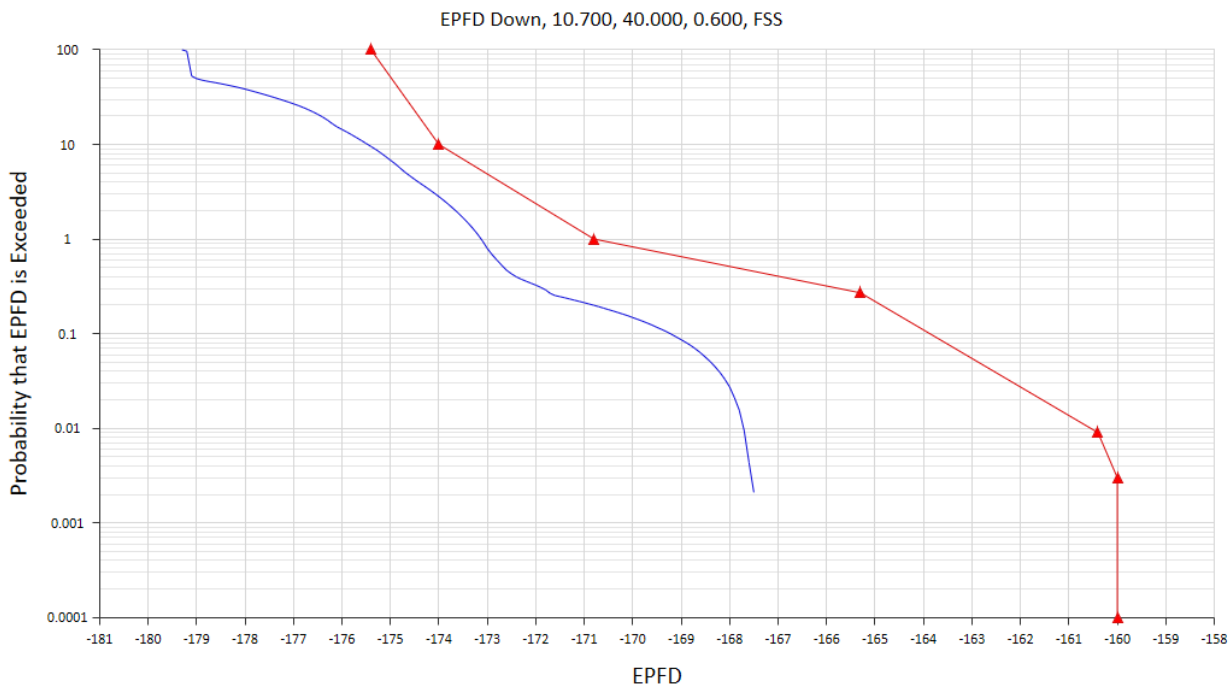

EPFD Down, 11.700, 40.000, 1.200, BSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-188 -187 -186 -185 -184 -183 -182 -181 -180 -179 -178 -177 -176 -175 -174 -173 -172 -171 -170 -169 -168 -167 -166 -165 -164 -163 -162 -161 -160 -159 -158
EPFD

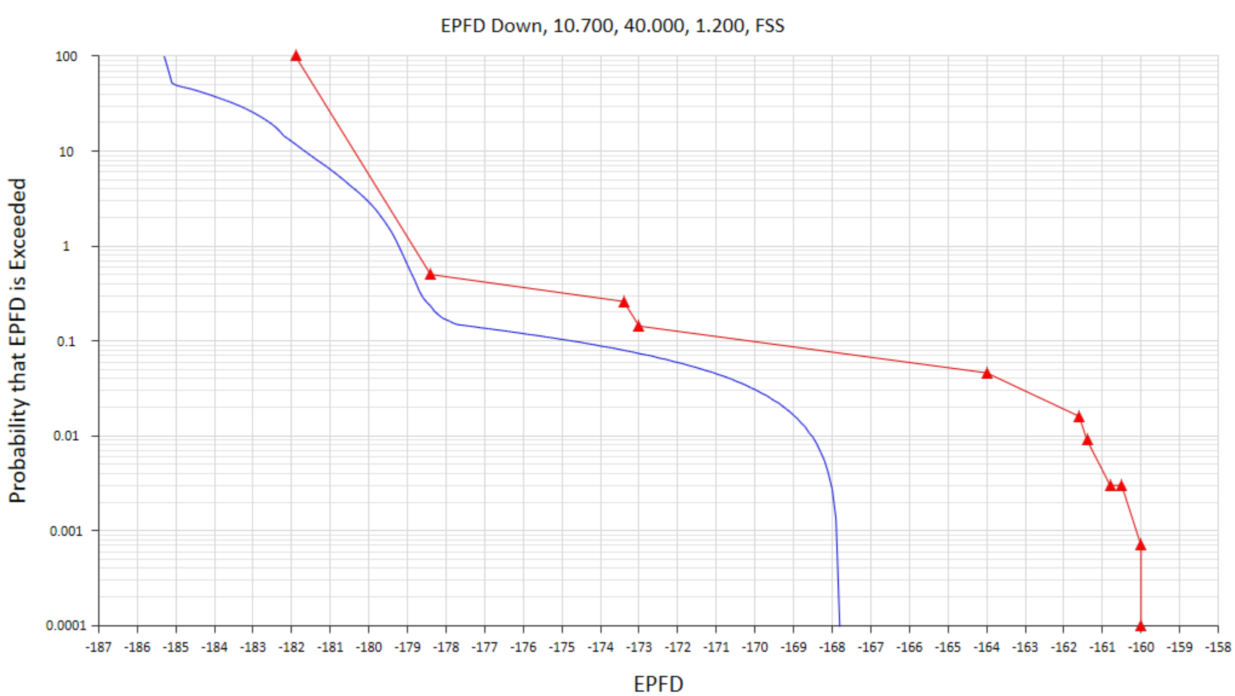

EPFD Down, 11.700, 40.000, 1.800, BSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-194 -192 -190 -188 -186 -184 -182 -180 -178 -176 -174 -172 -170 -168 -166 -164 -162 -160 -158
EPFD

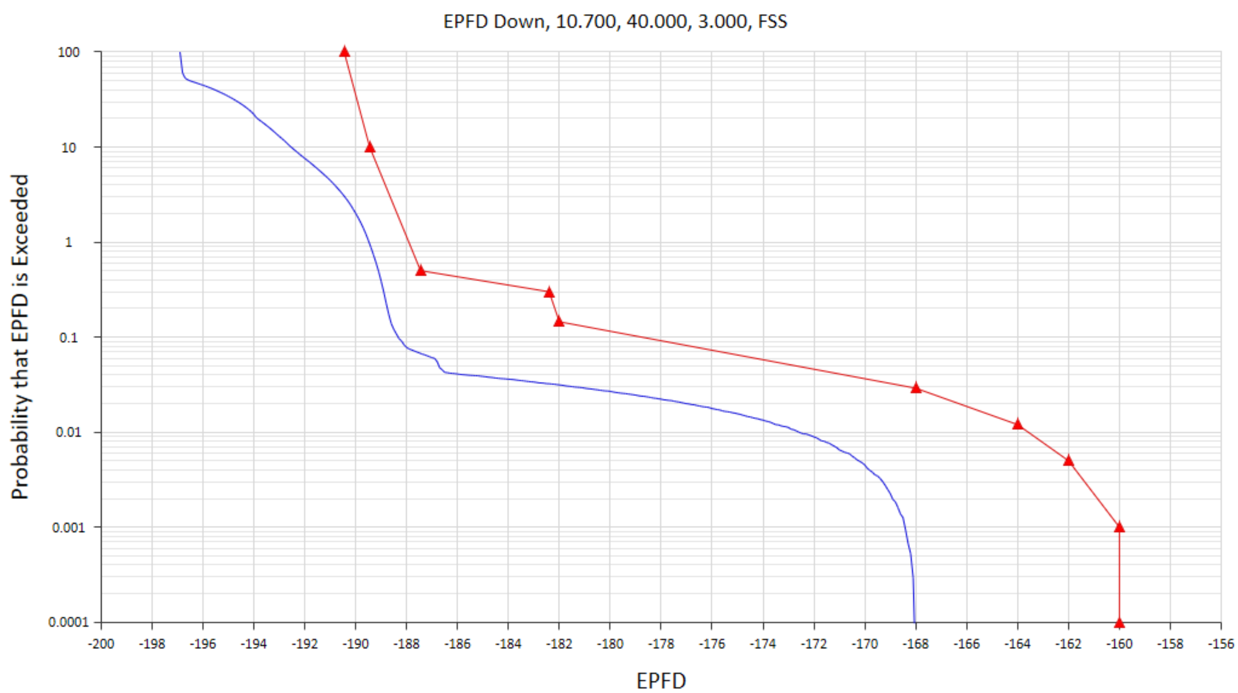

EPFD Down, 11.700, 40.000, 2.400, BSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-196
-194
-192
-190
-188
-186
-184
-182
-180
-178
-176
-174
-172
-170
-168
-166
-164
-162
-160
-158
-156
EPFD

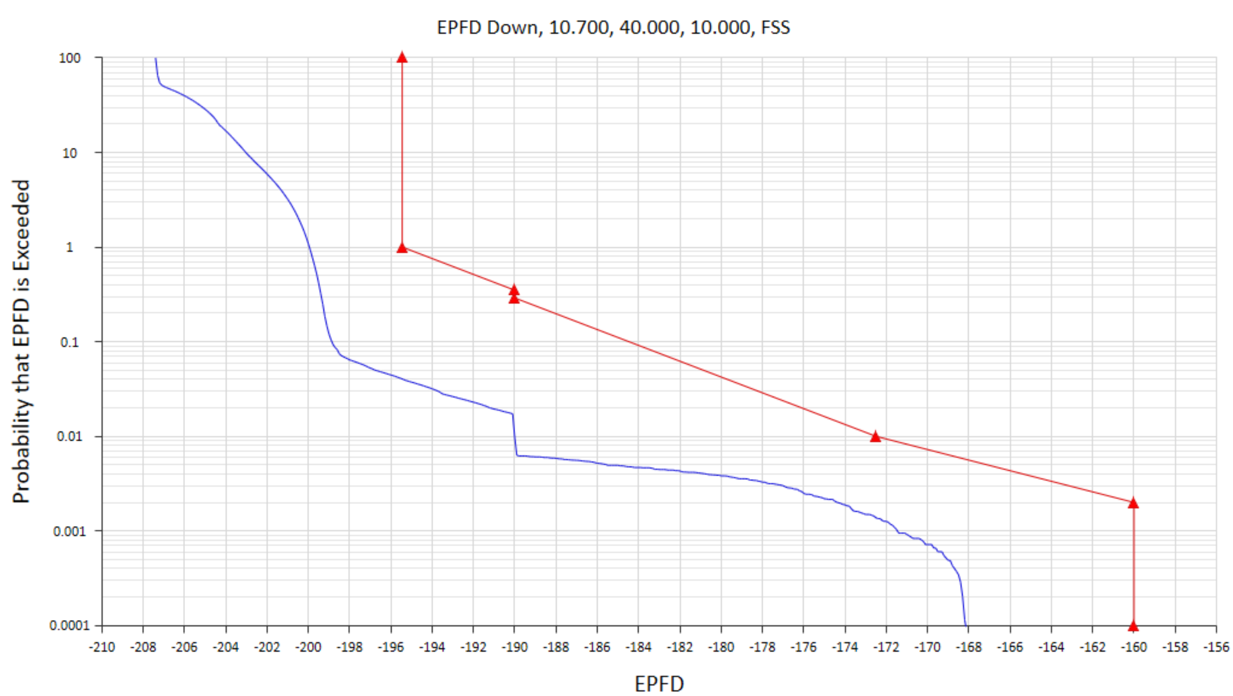

EPFD Down, 11.700, 40.000, 3.000, BSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-200
-198
-196
-194
-192
-190
-188
-186
-184
-182
-180
-178
-176
-174
-172
-170
-168
-166
-164
-162
-160
-158
-156
EPFD

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

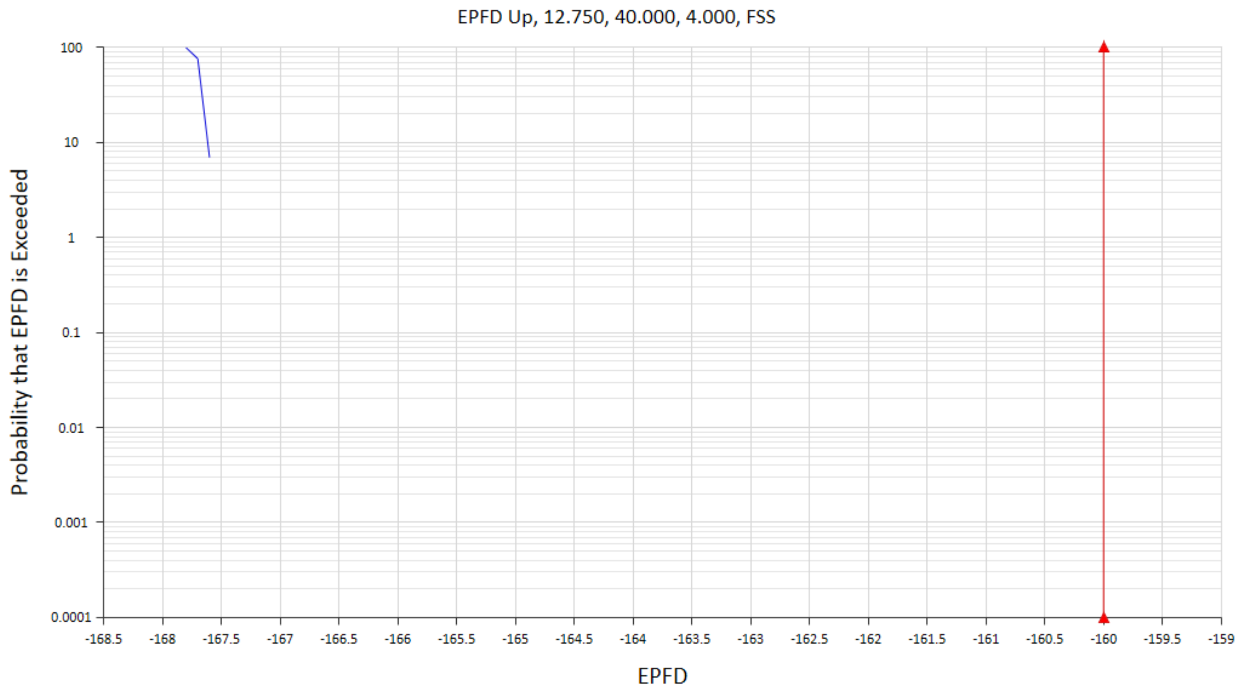


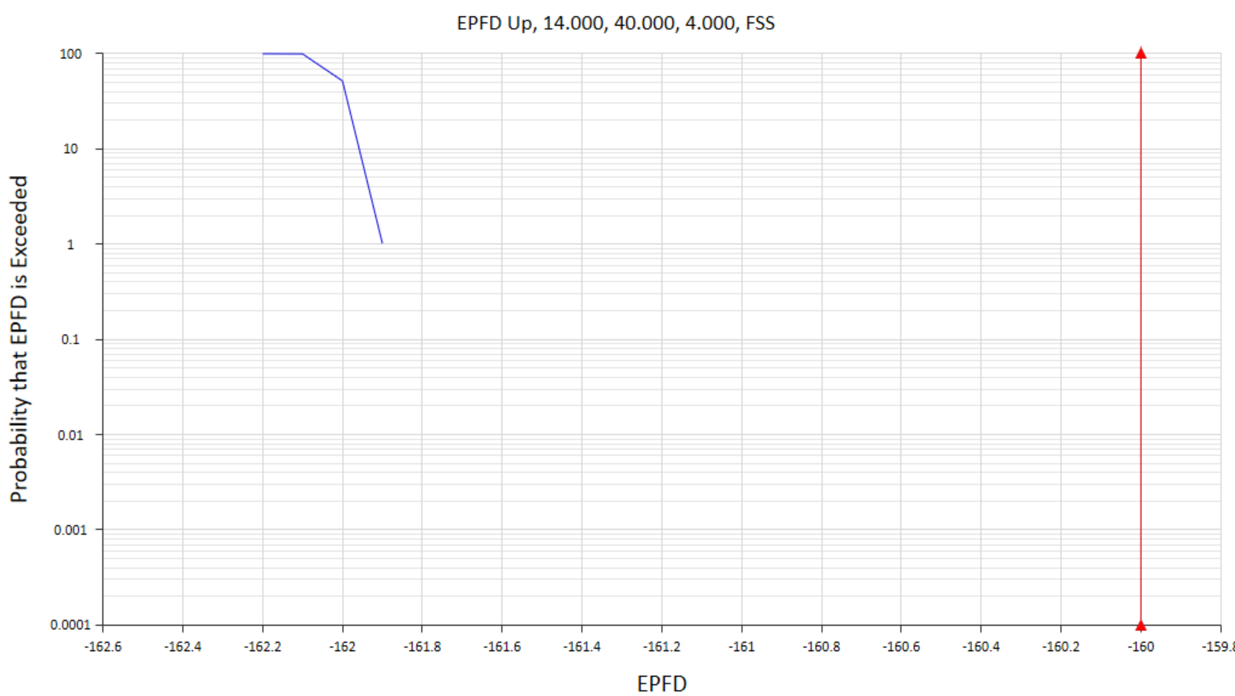



EPFD Down, 10.700, 40.000, 3.000, FSS
Probability that EPFD is Exceeded
EPFD

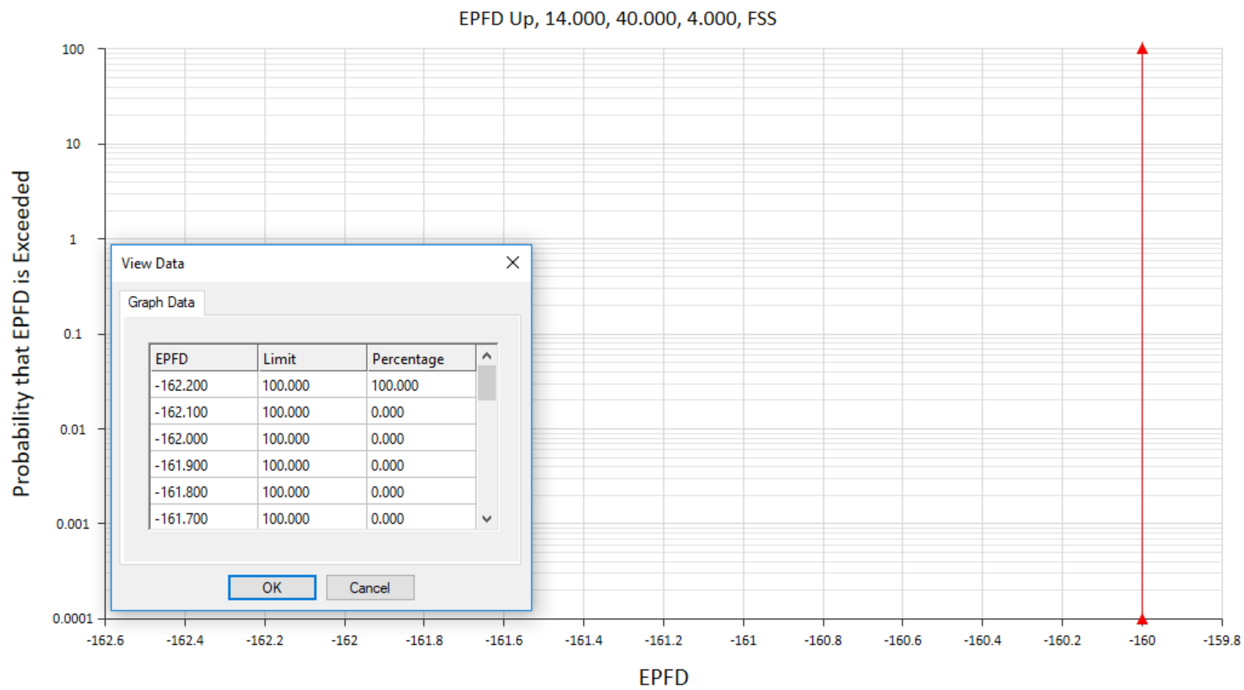

EPFD Down, 10.700, 40.000, 10.000, FSS
Probability that EPFD is Exceeded
EPFD

OUTPUTS FOR EPFD$_{UP}$ ASSESSMENT

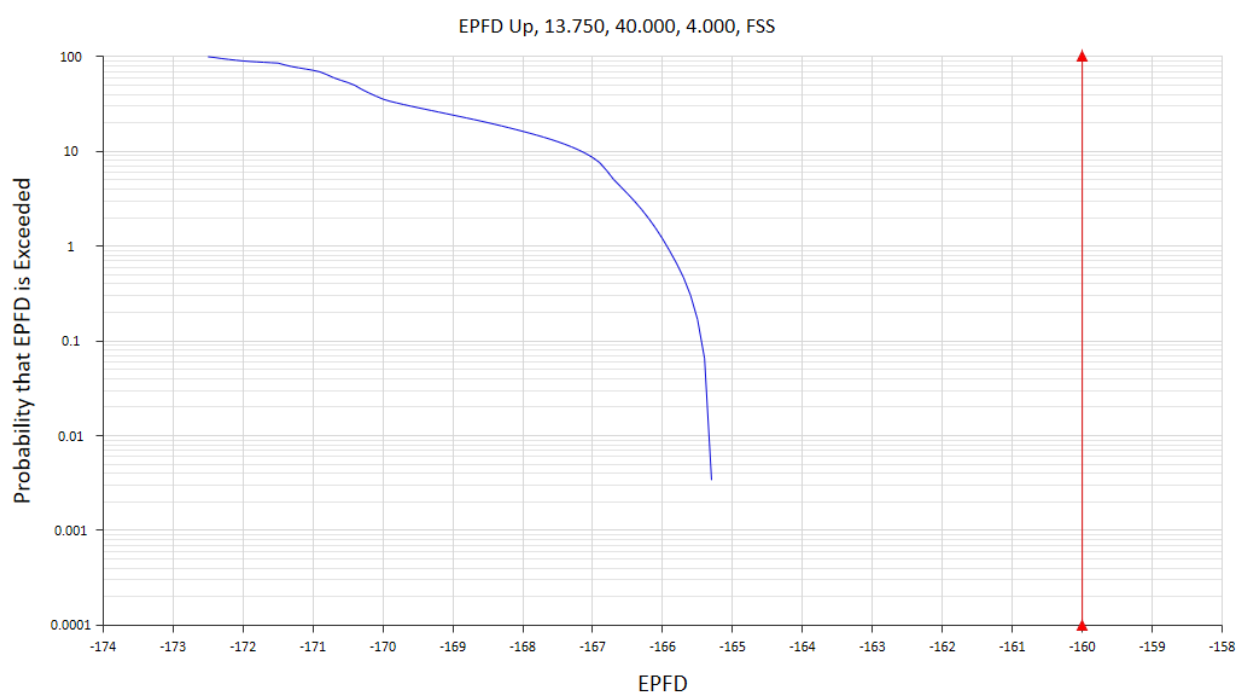




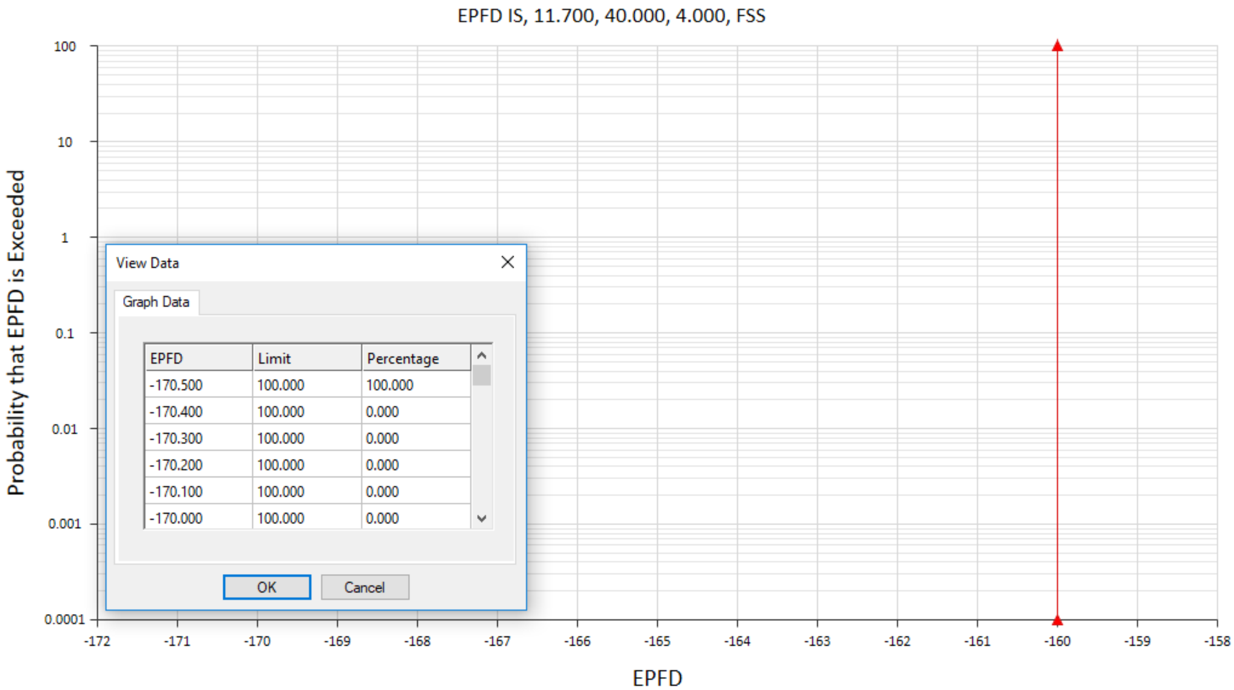
Gateway


EPFD Up, 14.000, 40.000, 4.000, FSS
Probability that EPFD is Exceeded
EPFD
View Data
Graph Data
EPFD | Limit | Percentage
-162.200 | 100.000 | 100.000
-162.100 | 100.000 | 0.000
-162.000 | 100.000 | 0.000
-161.900 | 100.000 | 0.000
-161.800 | 100.000 | 0.000
-161.700 | 100.000 | 0.000
OK
Cancel

TT&C

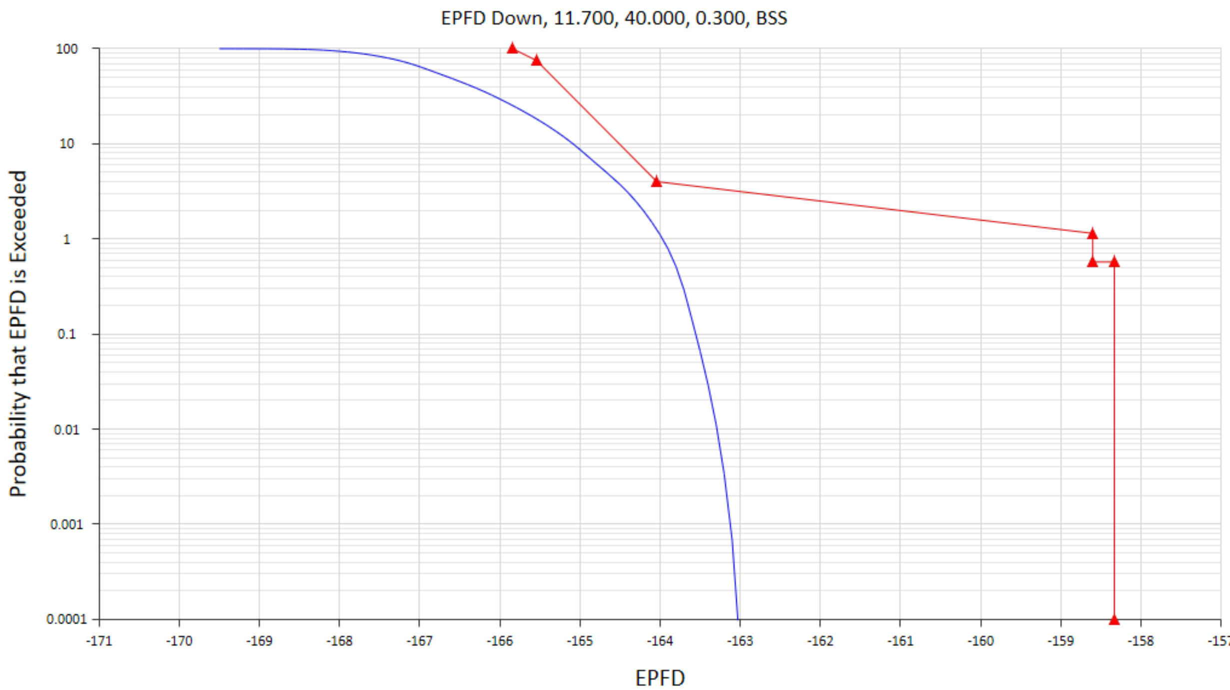

EPFD Up, 13.750, 40.000, 4.000, FSS
Probability that EPFD is Exceeded
EPFD

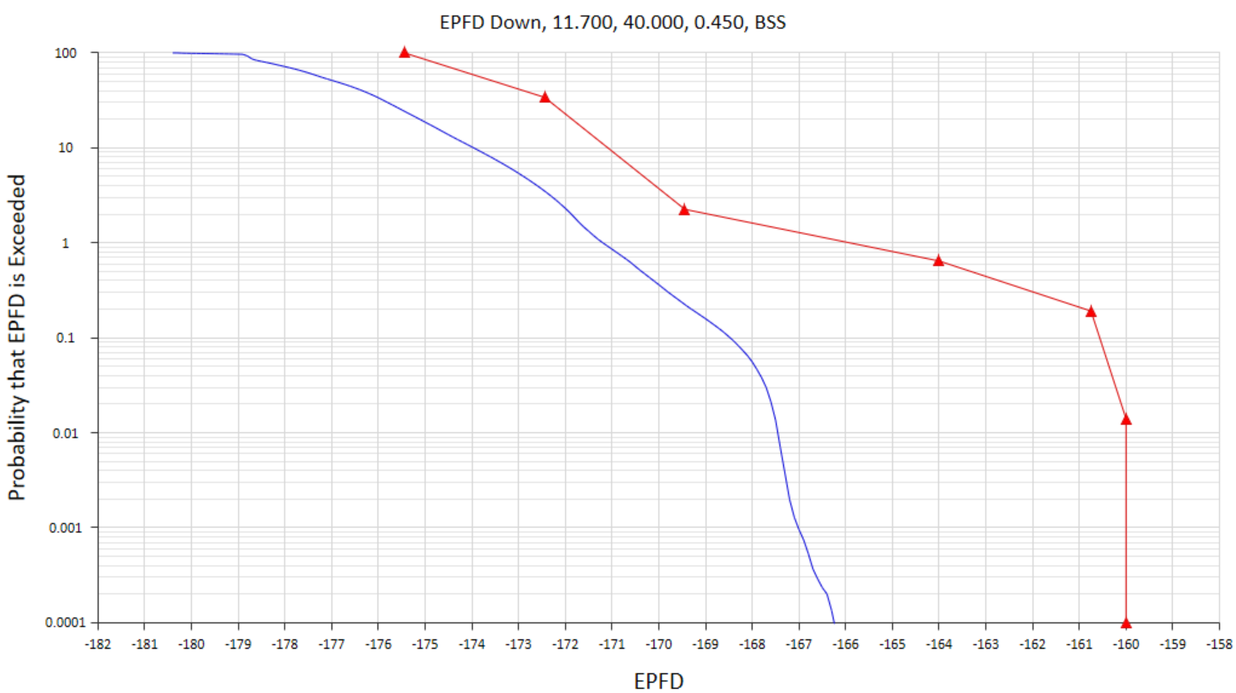
OUTPUTS FOR EPFD$_{IS}$ ASSESSMENT

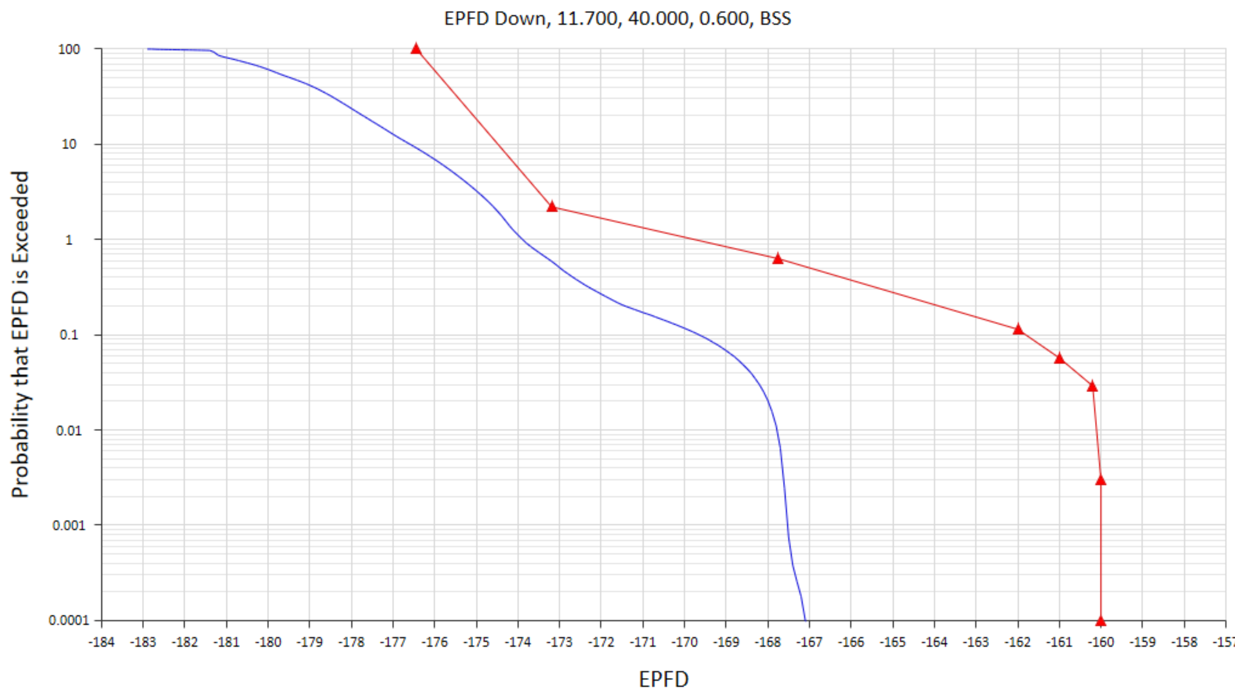


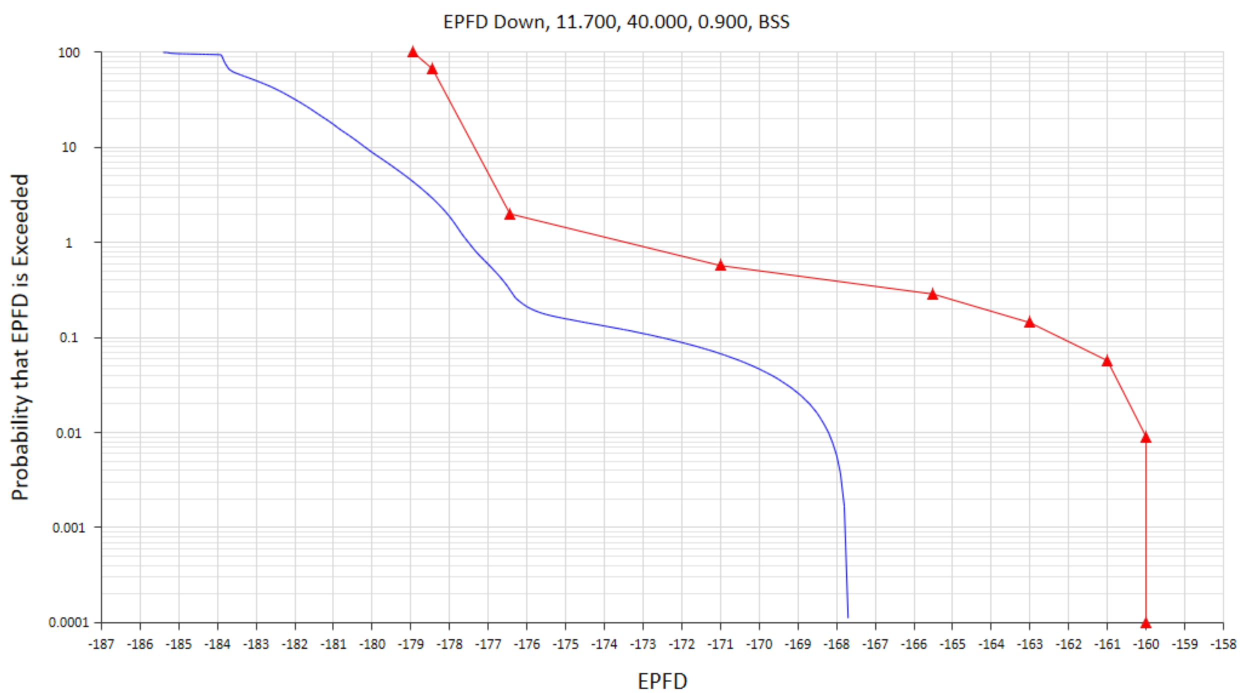
ANALYSIS OF FINAL DEPLOYMENT

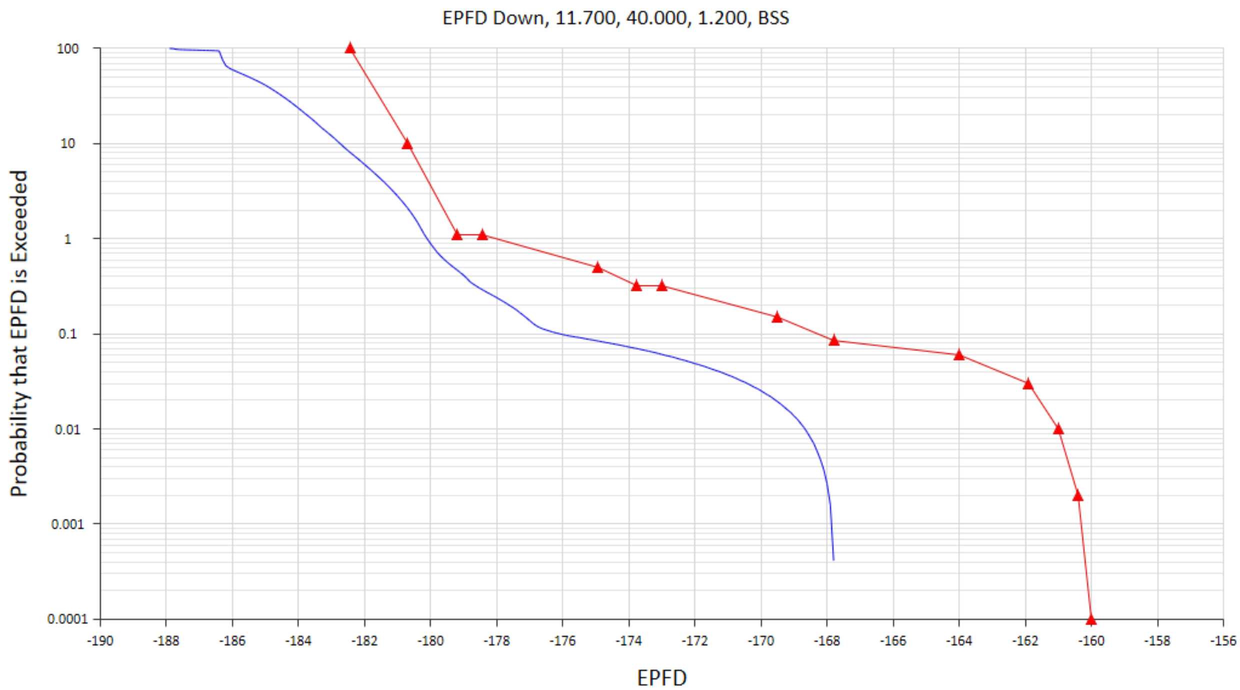
OUTPUTS FOR EPFD$_{DOWN}$ ASSESSMENT OF BSS LIMITS

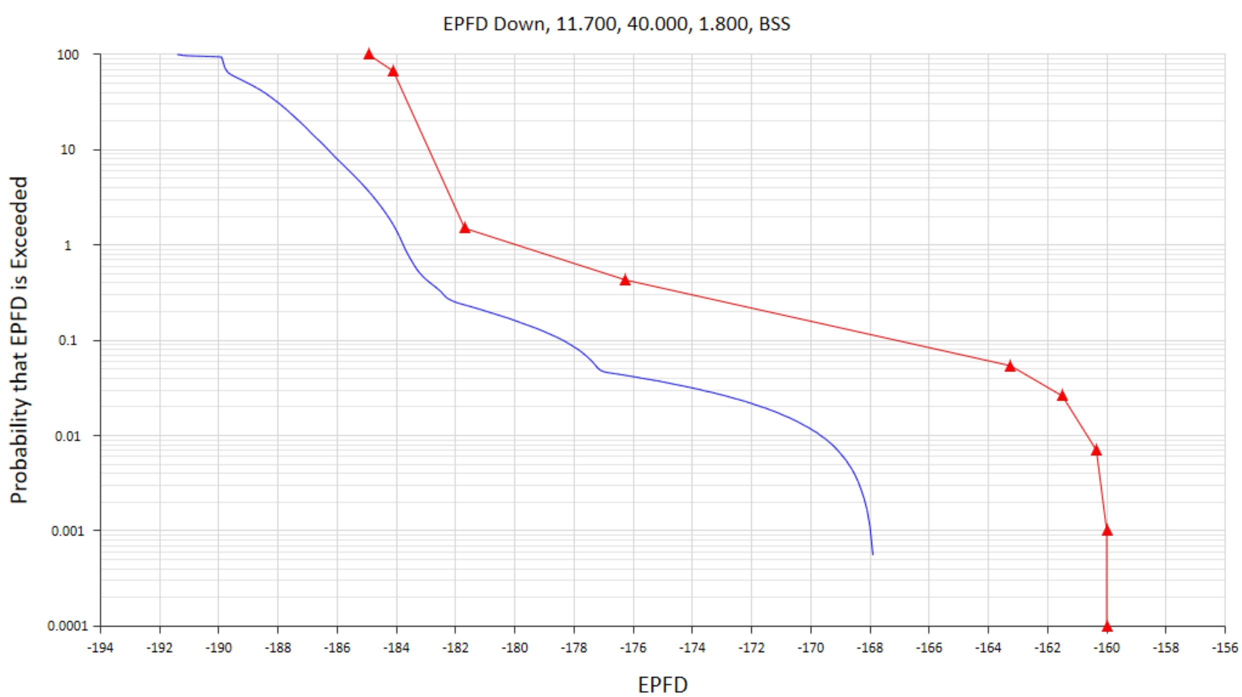


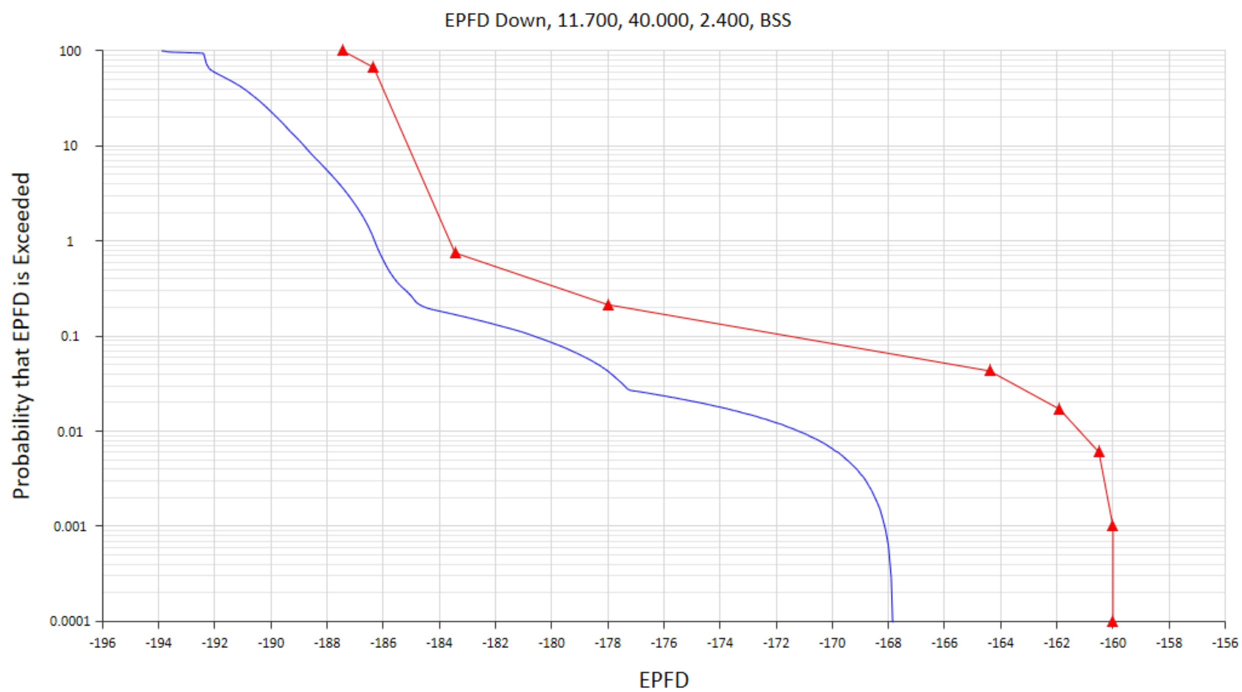


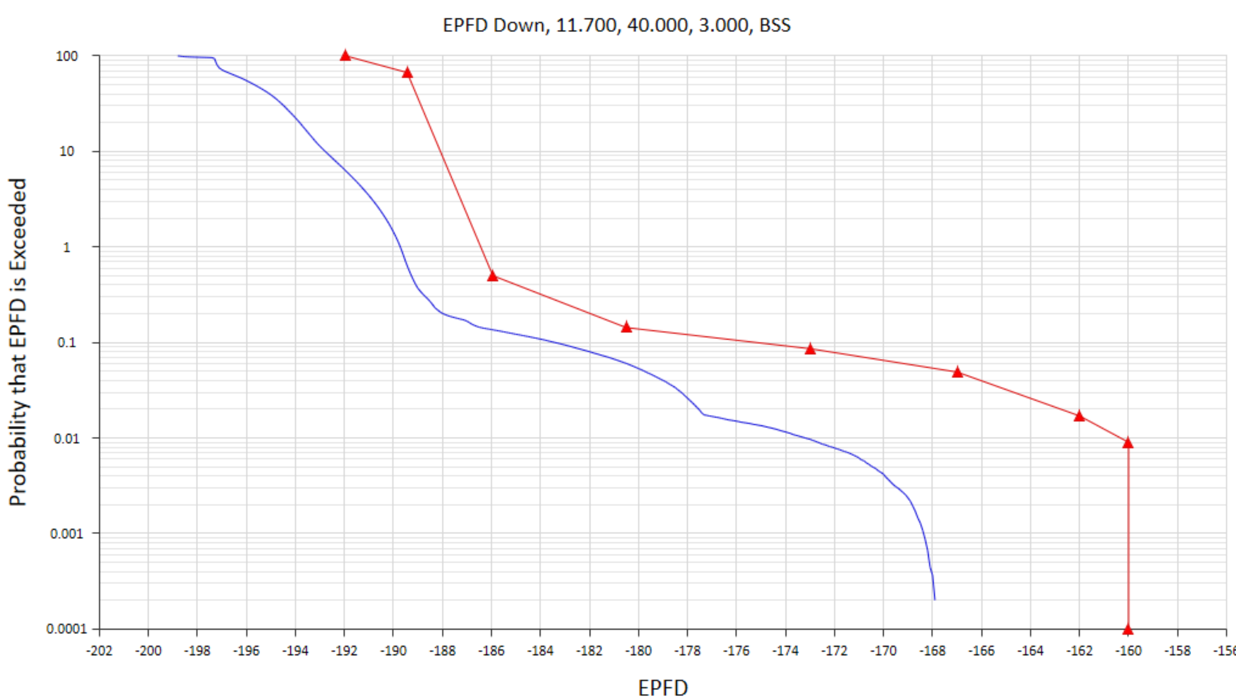

EPFD Down, 11.700, 40.000, 0.600, BSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-184 -183 -182 -181 -180 -179 -178 -177 -176 -175 -174 -173 -172 -171 -170 -169 -168 -167 -166 -165 -164 -163 -162 -161 -160 -159 -158 -157
EPFD


EPFD Down, 11.700, 40.000, 0.900, BSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-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
EPFD

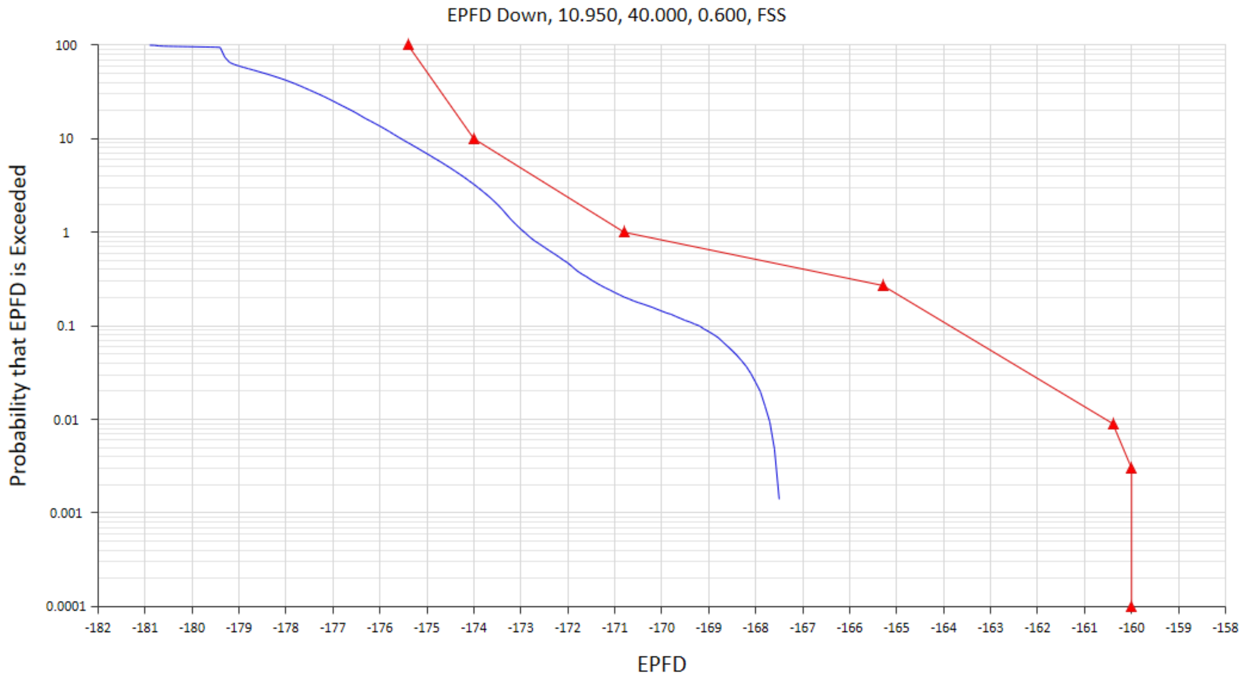

EPFD Down, 11.700, 40.000, 1.200, BSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-190
-188
-186
-184
-182
-180
-178
-176
-174
-172
-170
-168
-166
-164
-162
-160
-158
-156
EPFD

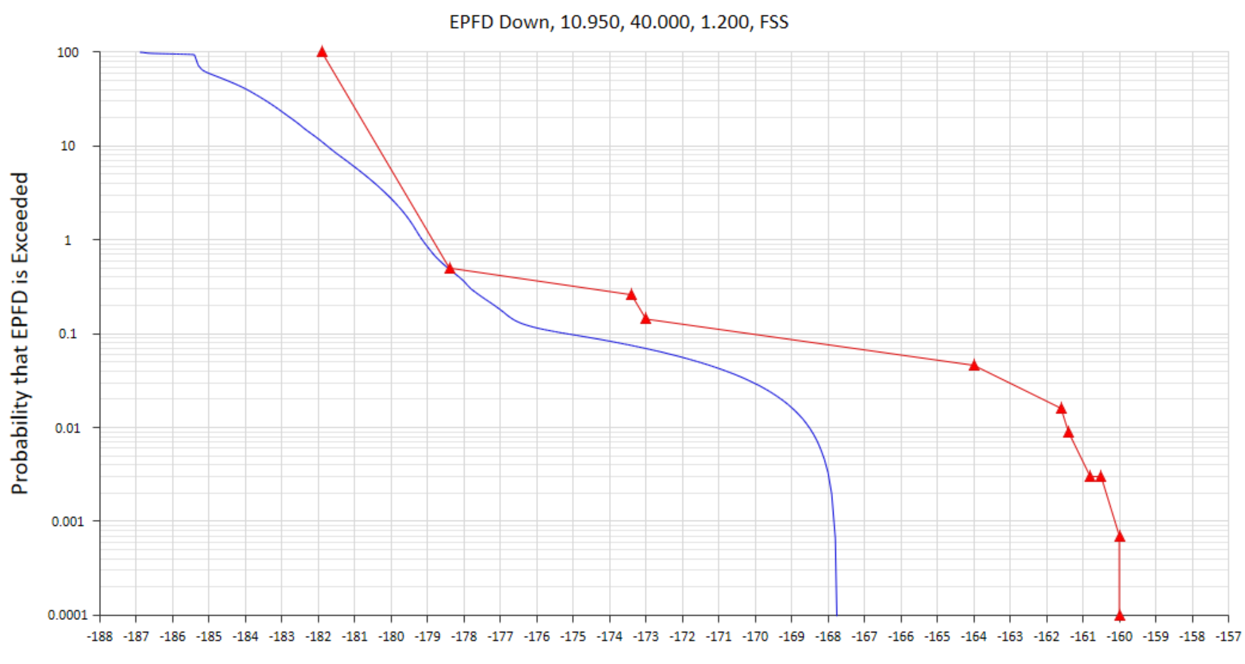

EPFD Down, 11.700, 40.000, 1.800, BSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-194
-192
-190
-188
-186
-184
-182
-180
-178
-176
-174
-172
-170
-168
-166
-164
-162
-160
-158
-156
EPFD

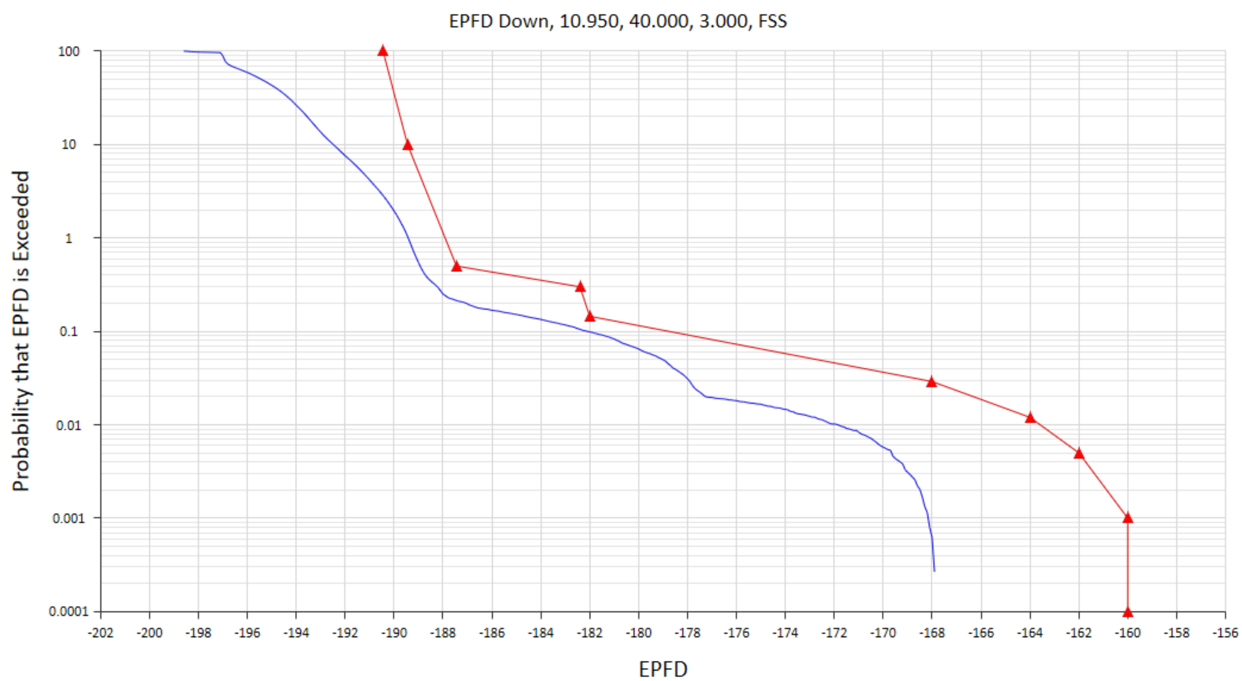

EPFD Down, 11.700, 40.000, 2.400, BSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-196 -194 -192 -190 -188 -186 -184 -182 -180 -178 -176 -174 -172 -170 -168 -166 -164 -162 -160 -158 -156
EPFD

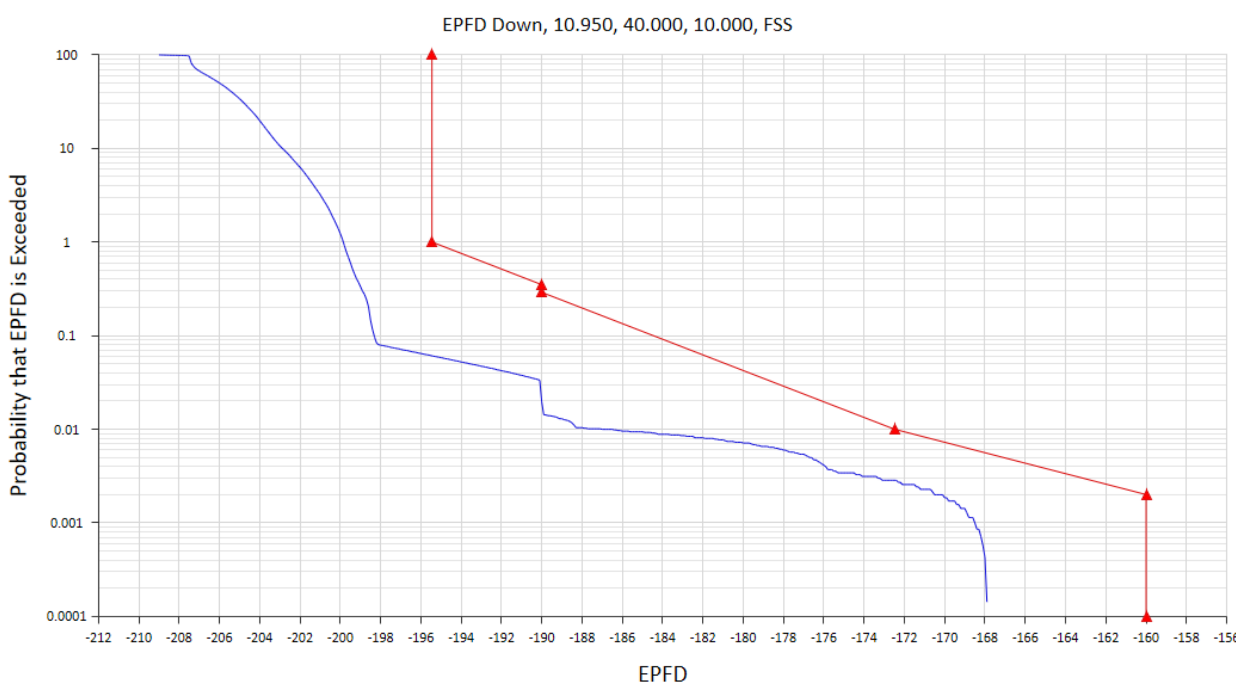

EPFD Down, 11.700, 40.000, 3.000, BSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-202 -200 -198 -196 -194 -192 -190 -188 -186 -184 -182 -180 -178 -176 -174 -172 -170 -168 -166 -164 -162 -160 -158 -156
EPFD

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

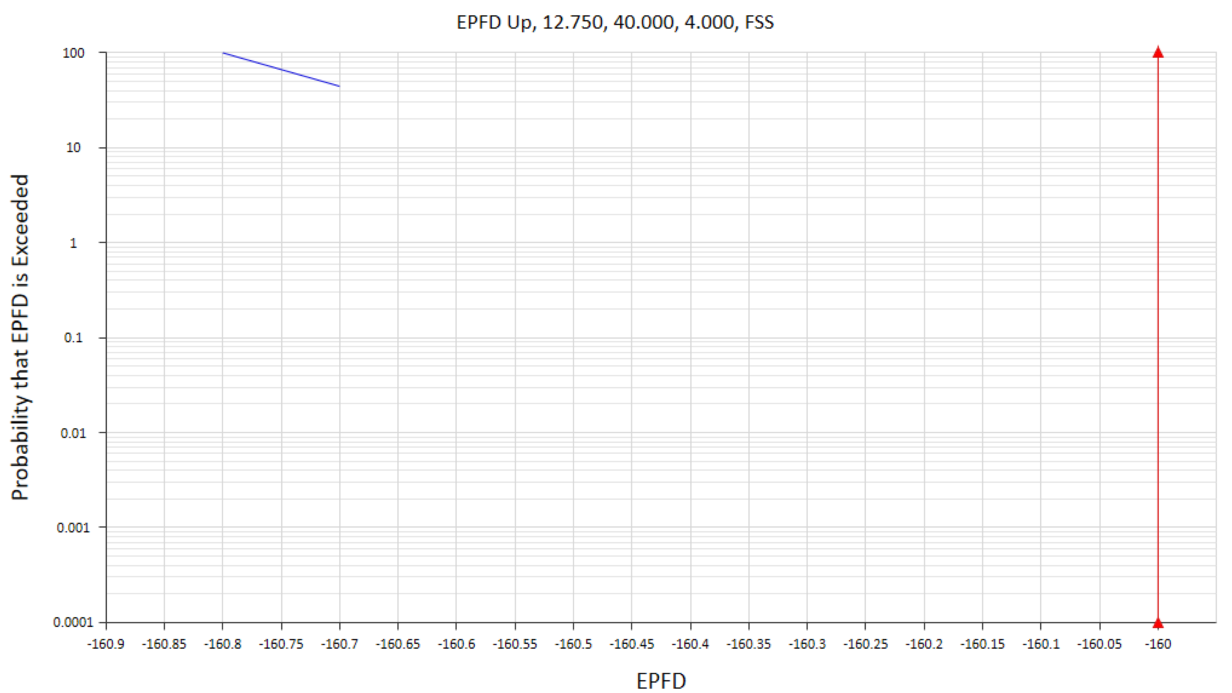


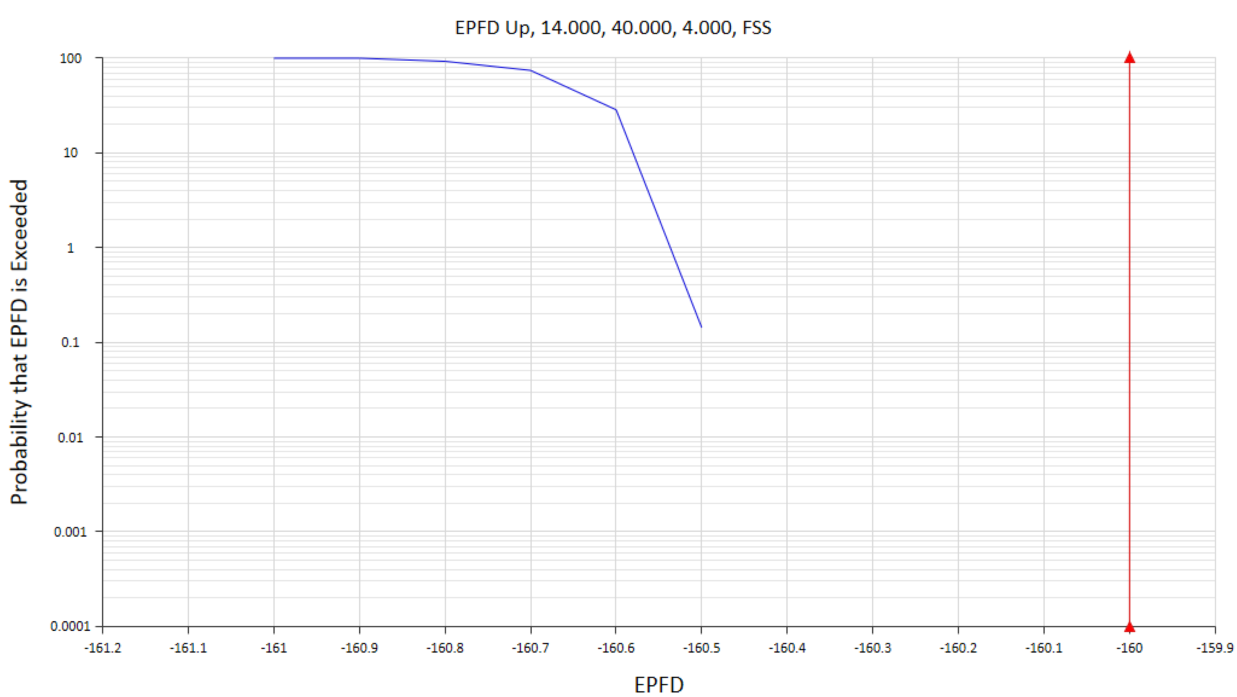



EPFD Down, 10.950, 40.000, 3.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-202 -200 -198 -196 -194 -192 -190 -188 -186 -184 -182 -180 -178 -176 -174 -172 -170 -168 -166 -164 -162 -160 -158 -156
EPFD

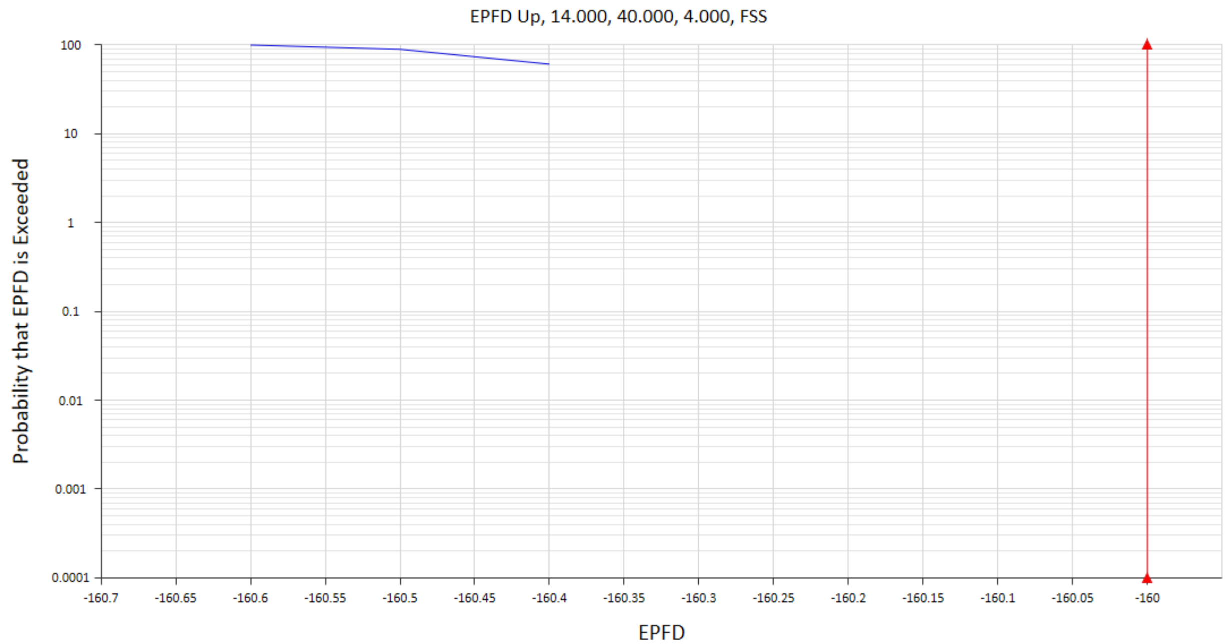

EPFD Down, 10.950, 40.000, 10.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-212 -210 -208 -206 -204 -202 -200 -198 -196 -194 -192 -190 -188 -186 -184 -182 -180 -178 -176 -174 -172 -170 -168 -166 -164 -162 -160 -158 -156
EPFD

OUTPUTS FOR EPFD$_{UP}$ ASSESSMENT

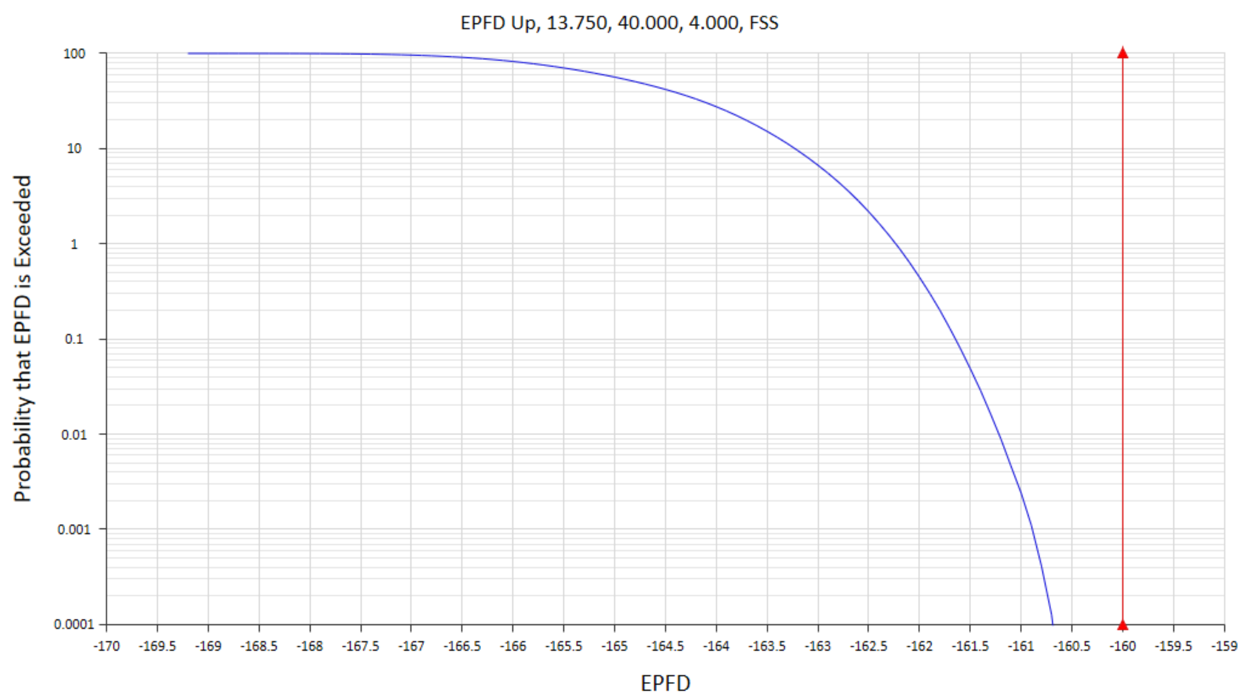




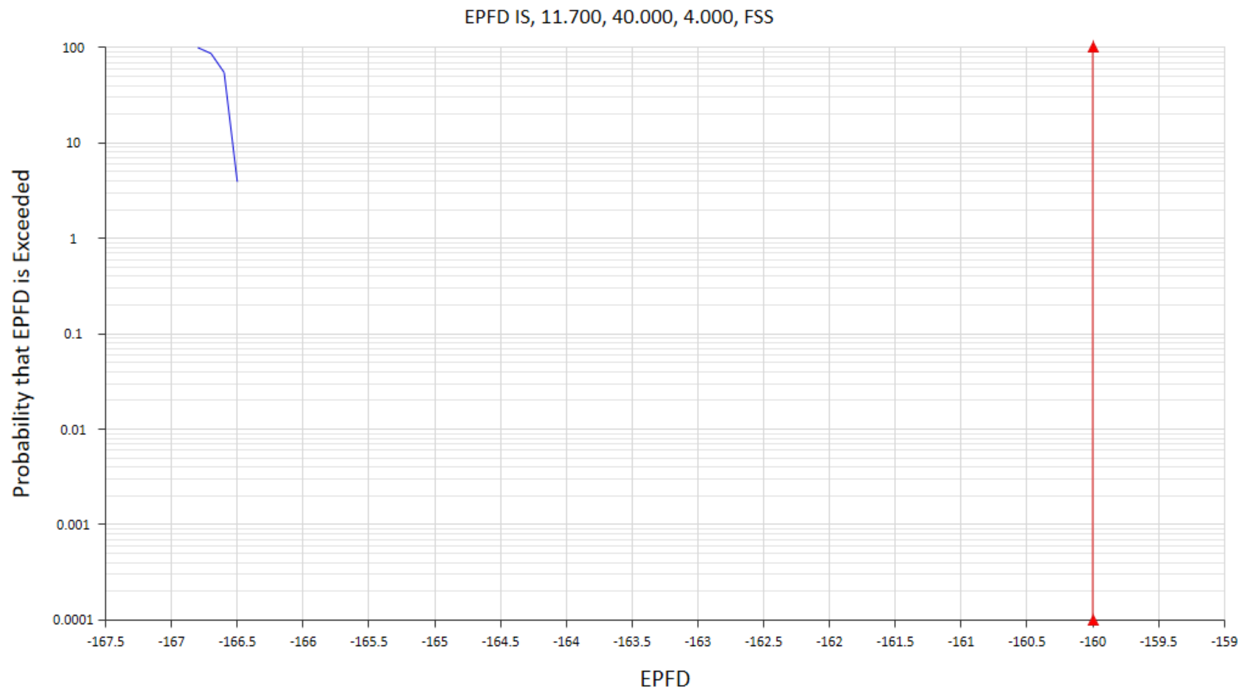
Gateway


EPFD Up, 14.000, 40.000, 4.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-160.7
-160.65
-160.6
-160.55
-160.5
-160.45
-160.4
-160.35
-160.3
-160.25
-160.2
-160.15
-160.1
-160.05
-160
EPFD

TT&C


EPFD Up, 13.750, 40.000, 4.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-170
-169.5
-169
-168.5
-168
-167.5
-167
-166.5
-166
-165.5
-165
-164.5
-164
-163.5
-163
-162.5
-162
-161.5
-161
-160.5
-160
-159.5
-159
EPFD

OUTPUT FOR EPFD$_{IS}$ ASSESSMENT



ANNEX 2

Demonstration of EPFD Compliance for Ka-Band Operations

This annex demonstrates that the Ka-band operations of the SpaceX non-geostationary orbit ("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.[3] 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.[4]

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, with respect to two stages of constellation deployment. The first set of diagrams presents the analysis of an initial deployment of 1,584 satellites operating at an altitude of 550 km with a minimum earth station elevation angle of 25 degrees. The second set of diagrams presents the analysis of the final deployment of 4,409 satellites (including 1,584 satellites at 550 km) operating with a minimum earth station elevation angle of 40 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.

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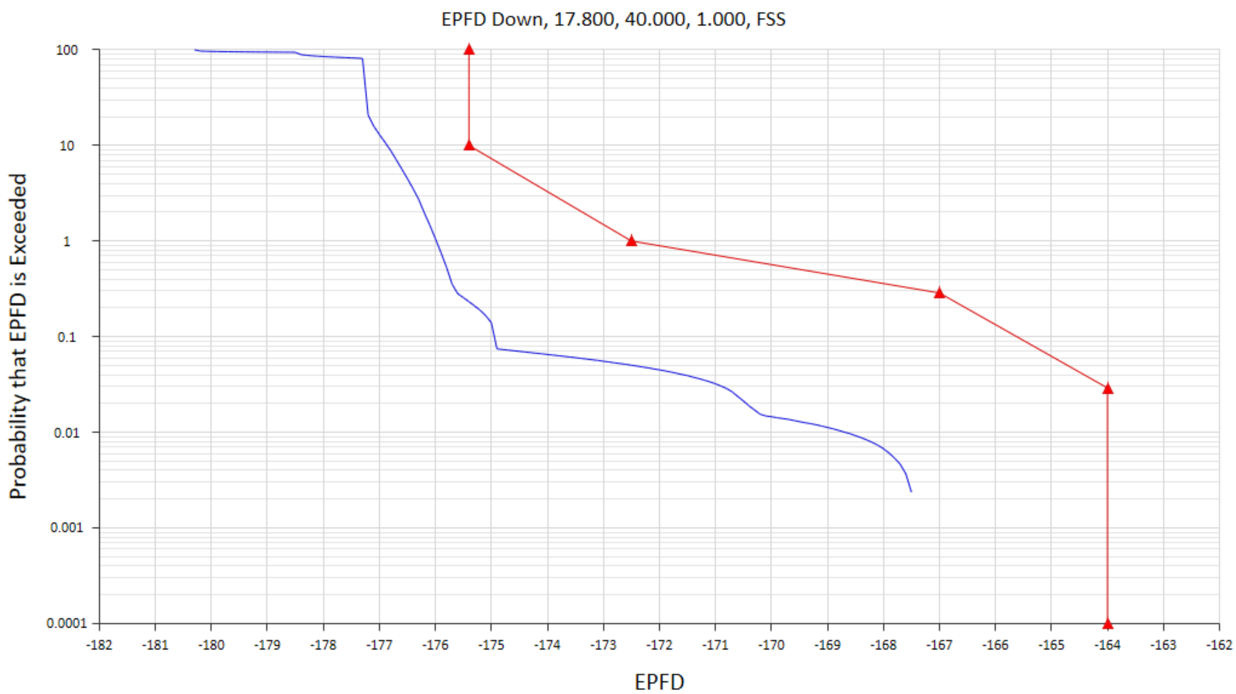
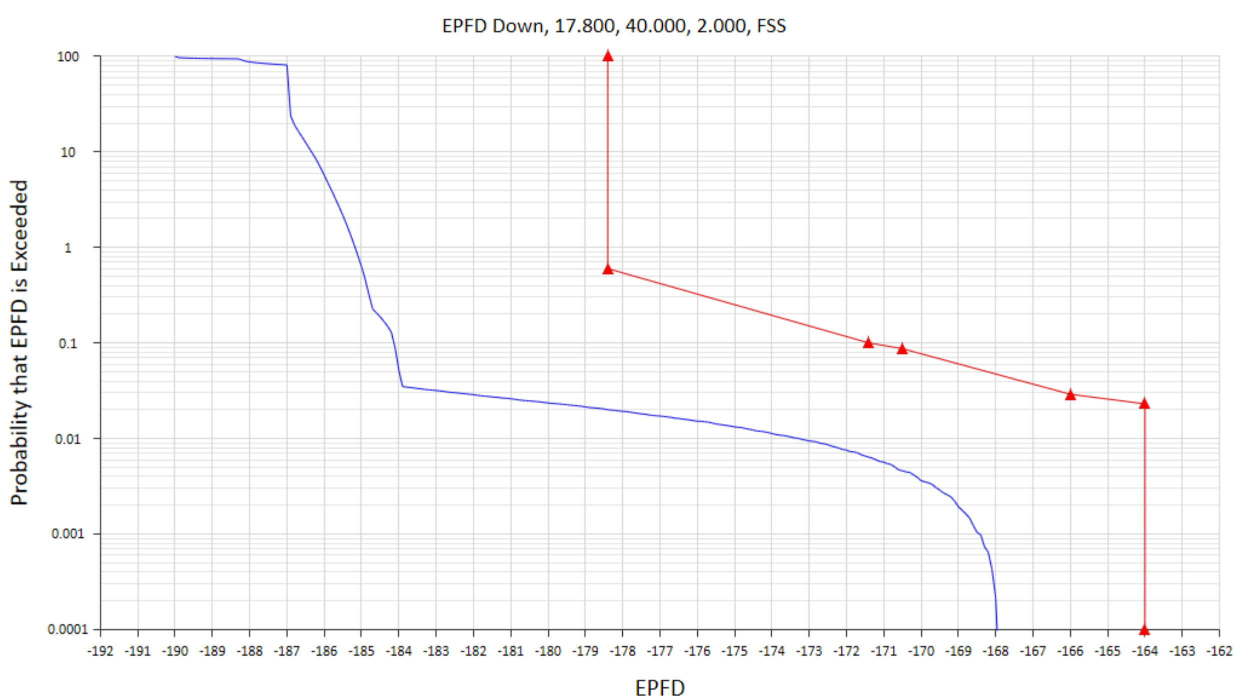
3 *See* 47 C.F.R. § 25.146(a)(2).

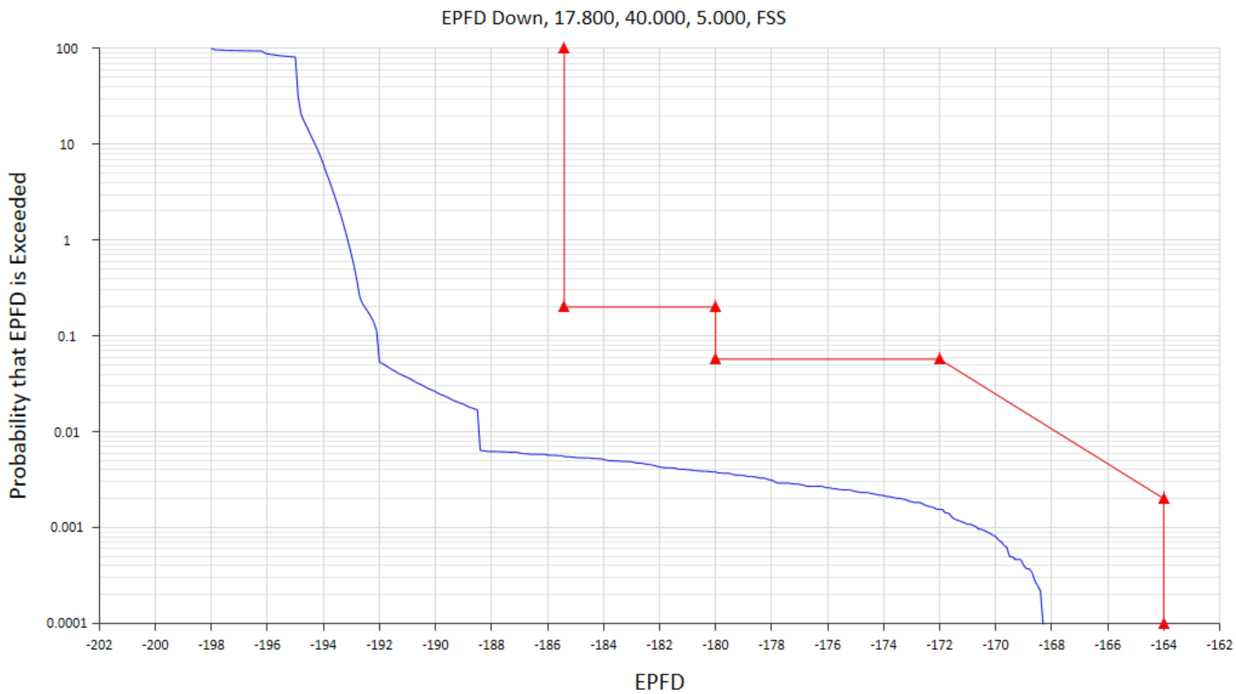
4 SpaceX is also submitting under separate cover the input files that will allow the Commission to confirm this analysis.

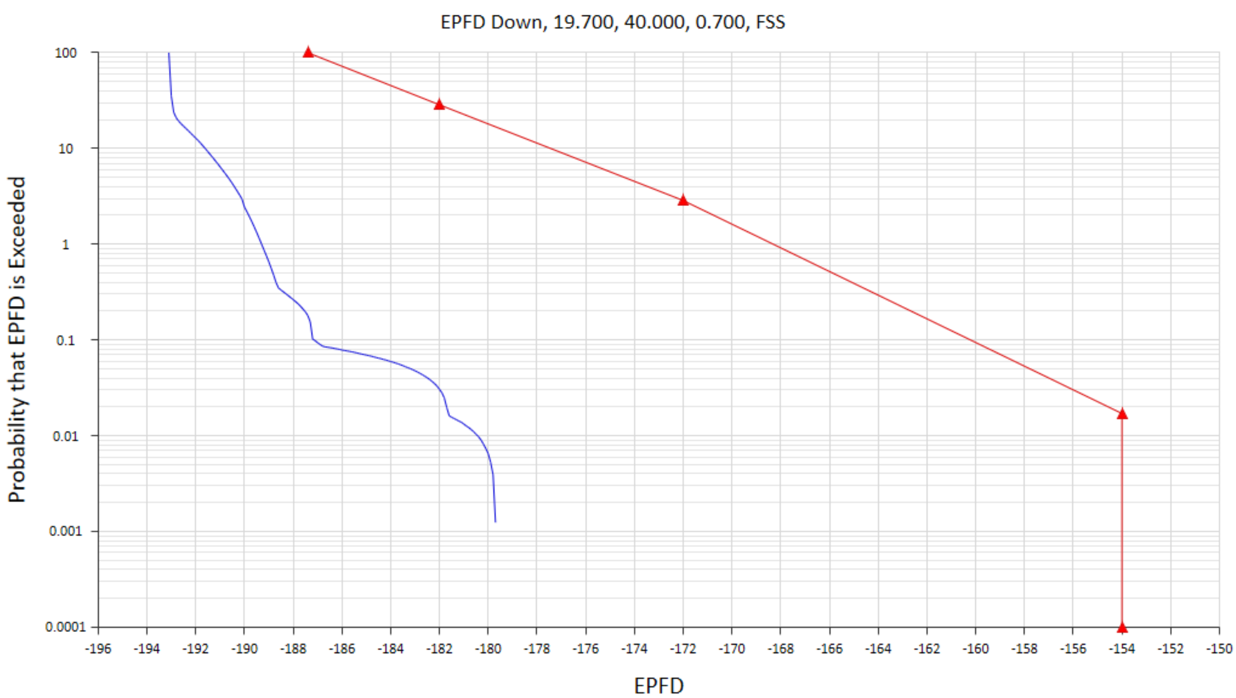
ANALYSIS OF INITIAL DEPLOYMENT

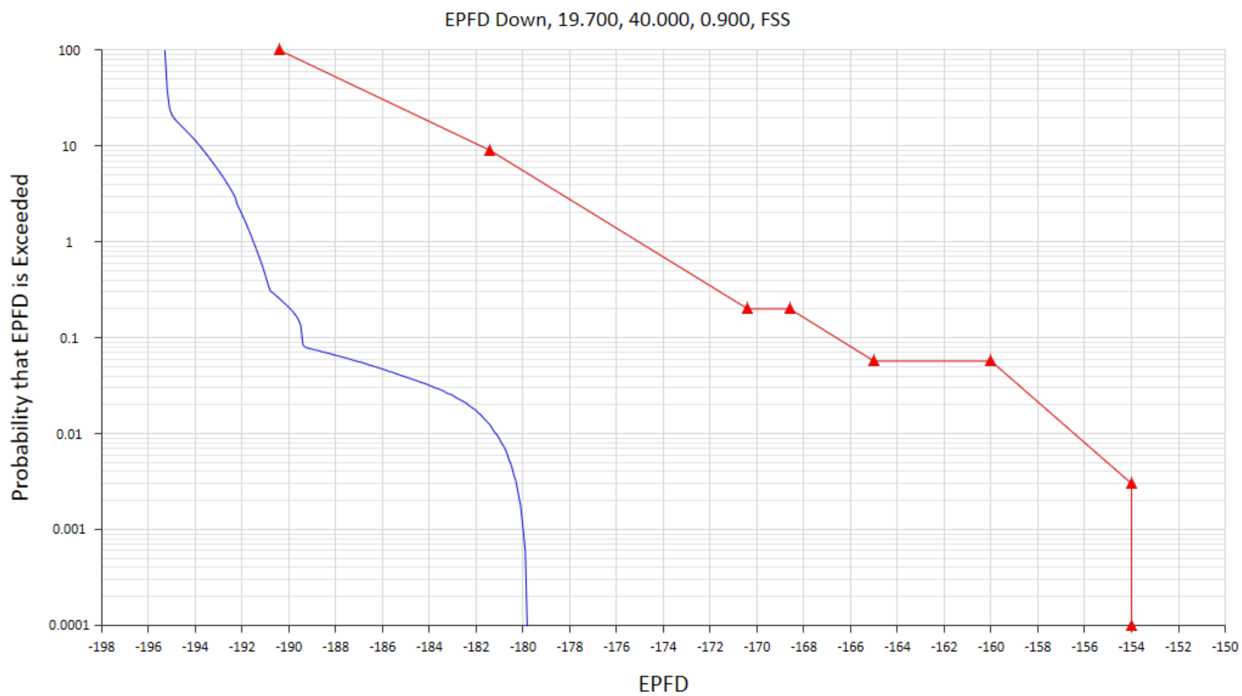
OUTPUTS FOR $EPFD_{DOWN}$ ASSESSMENT

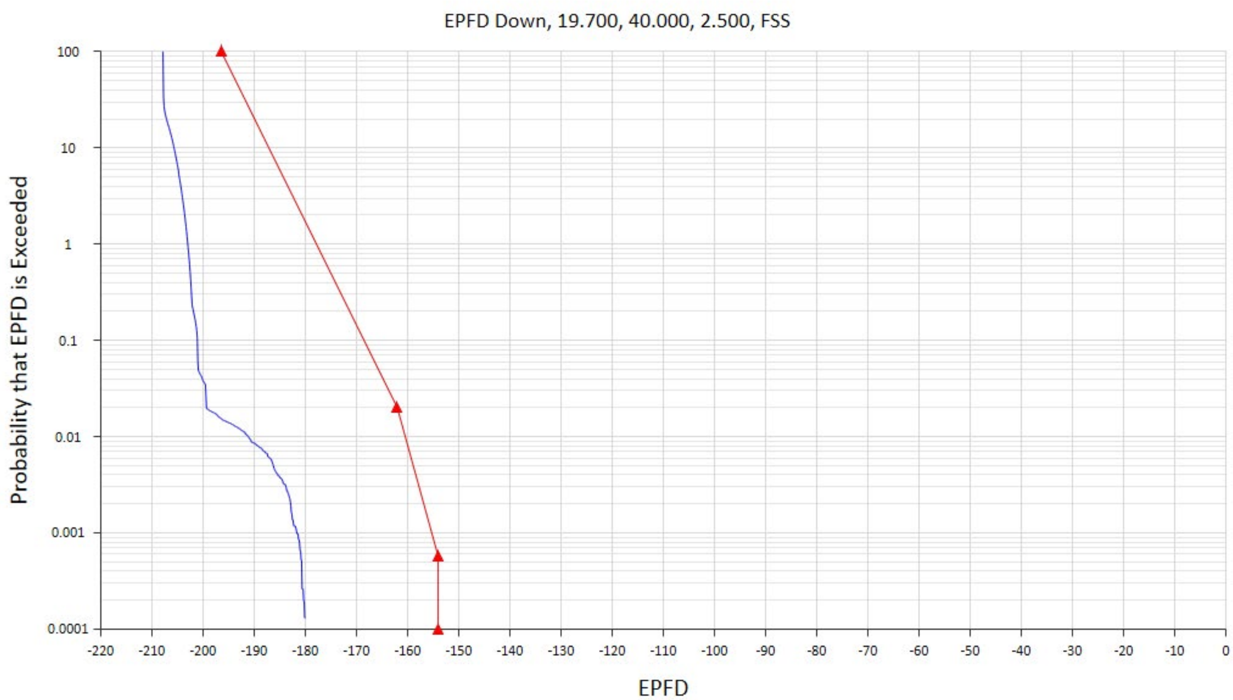


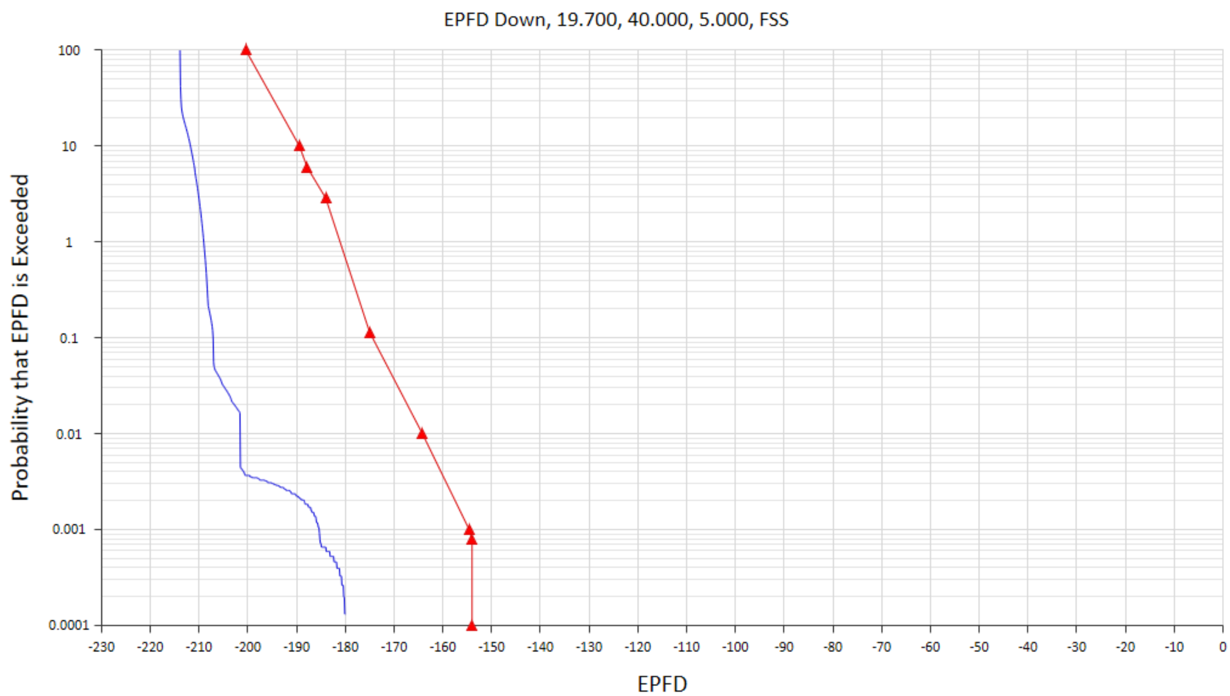



EPFD Down, 17.800, 40.000, 5.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-202 -200 -198 -196 -194 -192 -190 -188 -186 -184 -182 -180 -178 -176 -174 -172 -170 -168 -166 -164 -162
EPFD

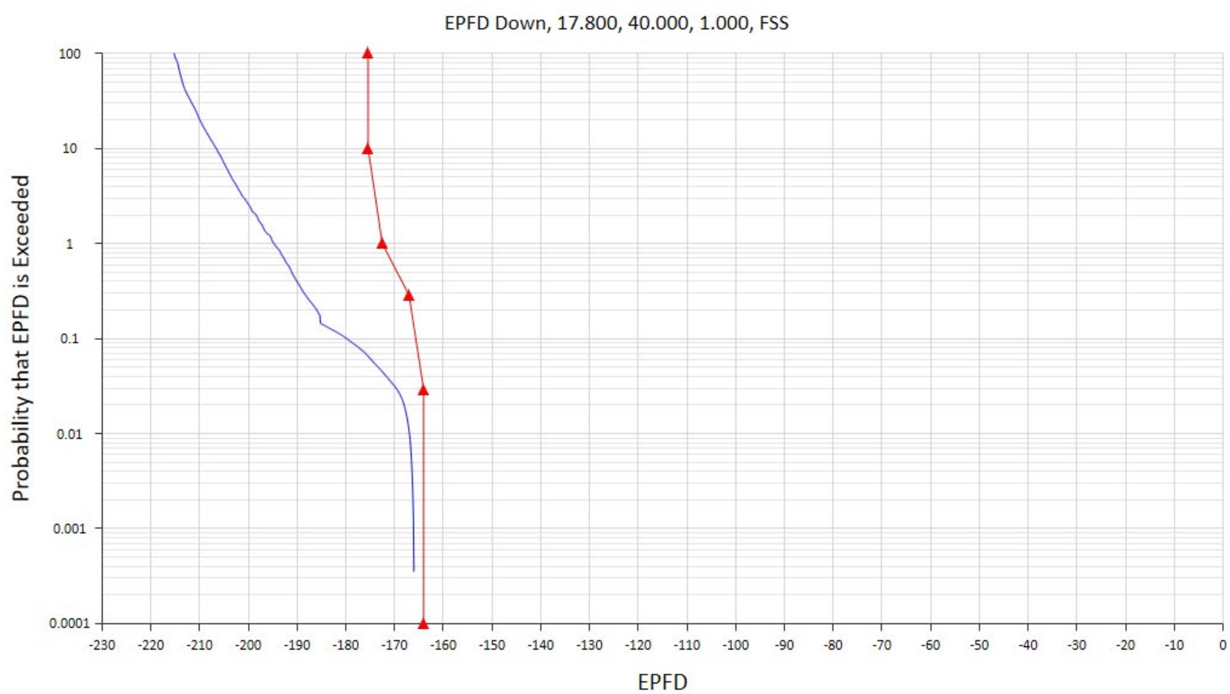

EPFD Down, 19.700, 40.000, 0.700, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-196 -194 -192 -190 -188 -186 -184 -182 -180 -178 -176 -174 -172 -170 -168 -166 -164 -162 -160 -158 -156 -154 -152 -150
EPFD


EPFD Down, 19.700, 40.000, 0.900, FSS
Probability that EPFD is Exceeded
EPFD
100
10
1
0.1
0.01
0.001
0.0001
-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

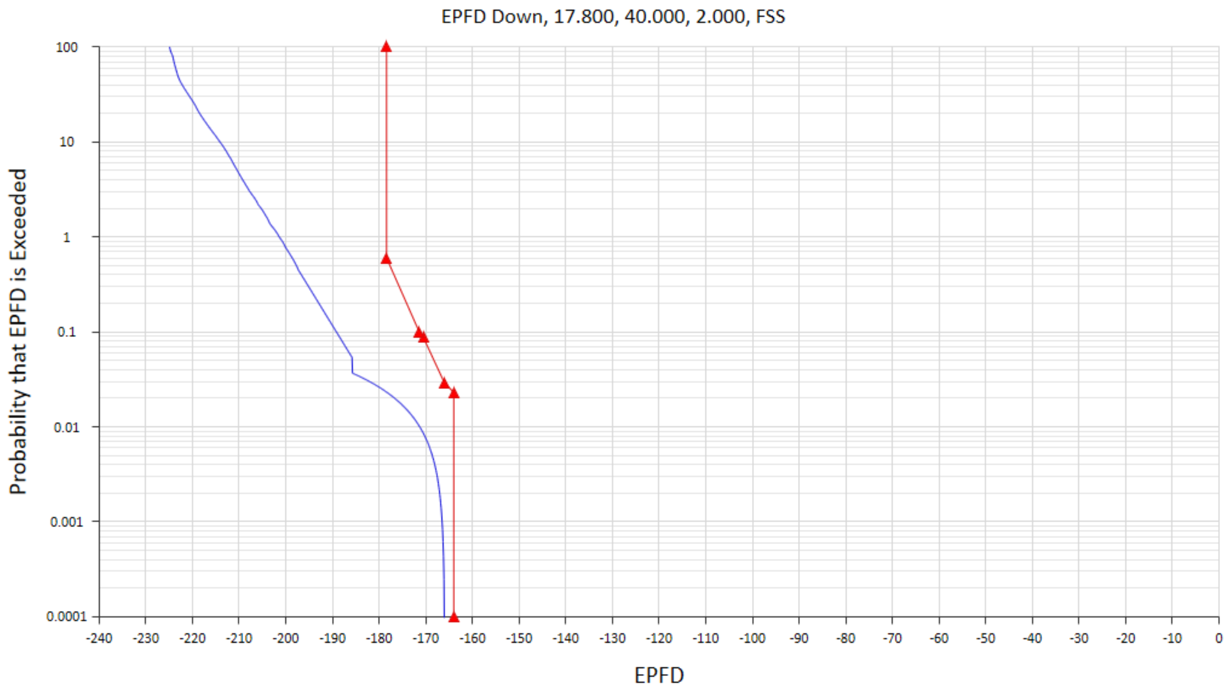

EPFD Down, 19.700, 40.000, 2.500, FSS
Probability that EPFD is Exceeded
EPFD
100
10
1
0.1
0.01
0.001
0.0001
-220
-210
-200
-190
-180
-170
-160
-150
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0


EPFD Down, 19.700, 40.000, 5.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-230 -220 -210 -200 -190 -180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
EPFD

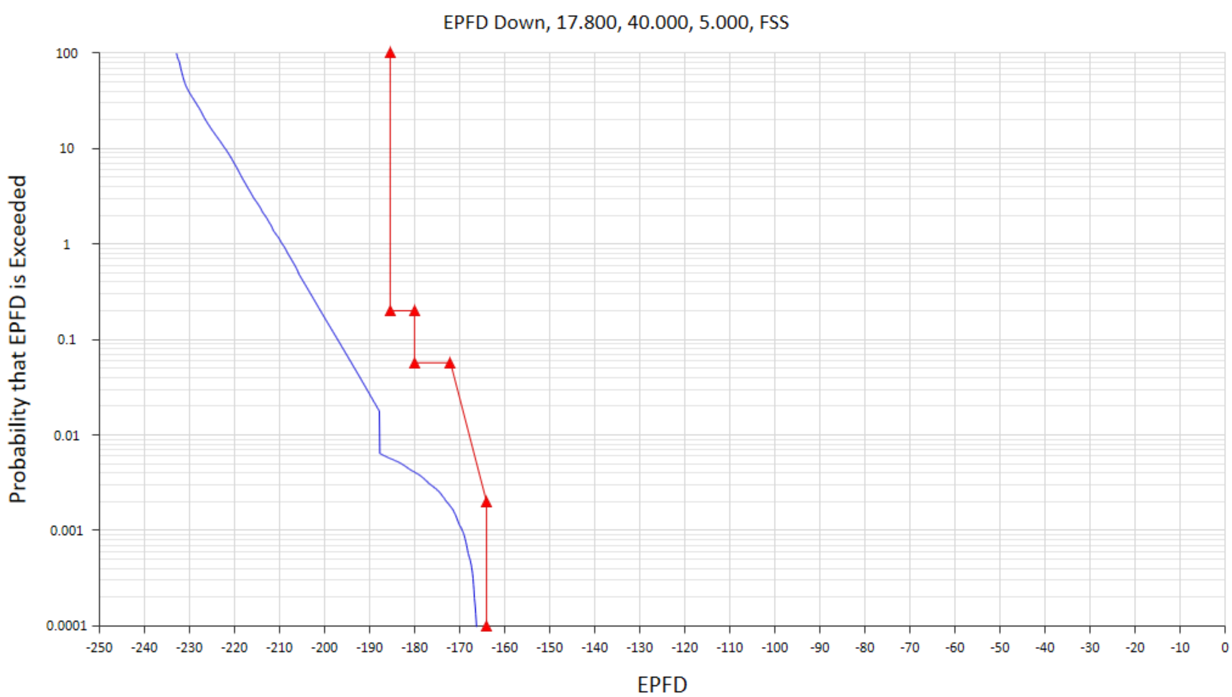
TT&C


EPFD Down, 17.800, 40.000, 1.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-230 -220 -210 -200 -190 -180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
EPFD

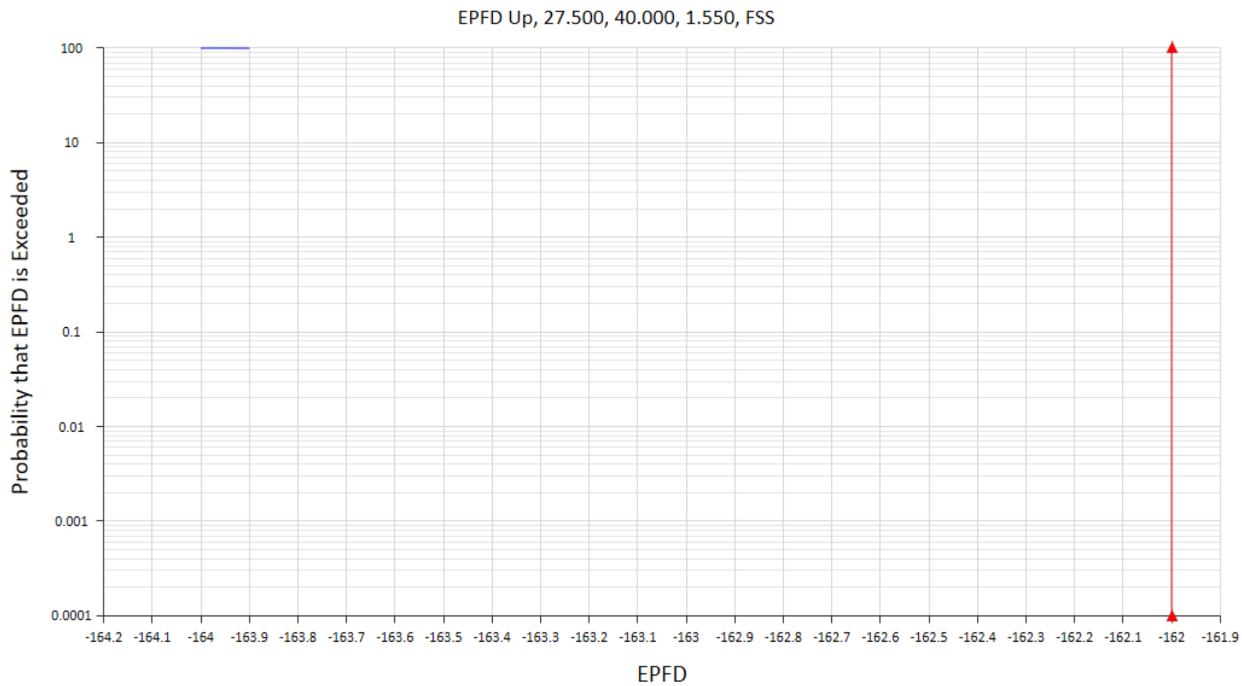
TT&C


EPFD Down, 17.800, 40.000, 2.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-240 -230 -220 -210 -200 -190 -180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
EPFD

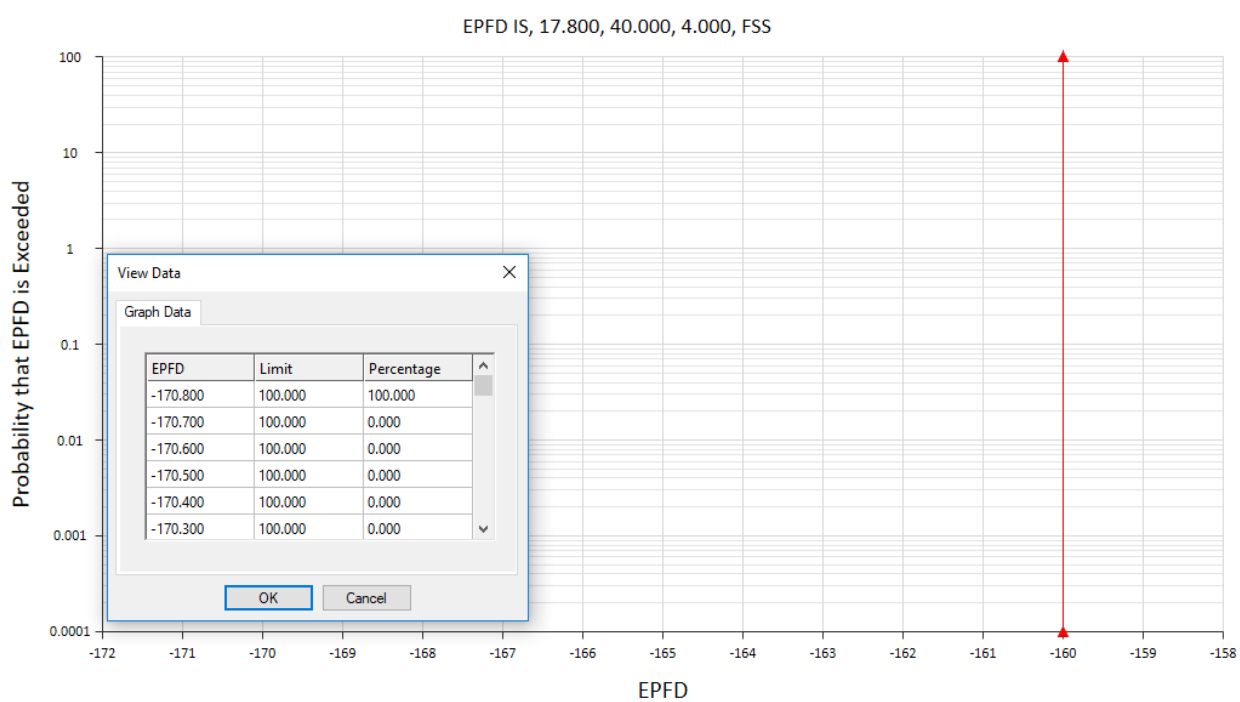
TT&C


EPFD Down, 17.800, 40.000, 5.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-250 -240 -230 -220 -210 -200 -190 -180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
EPFD

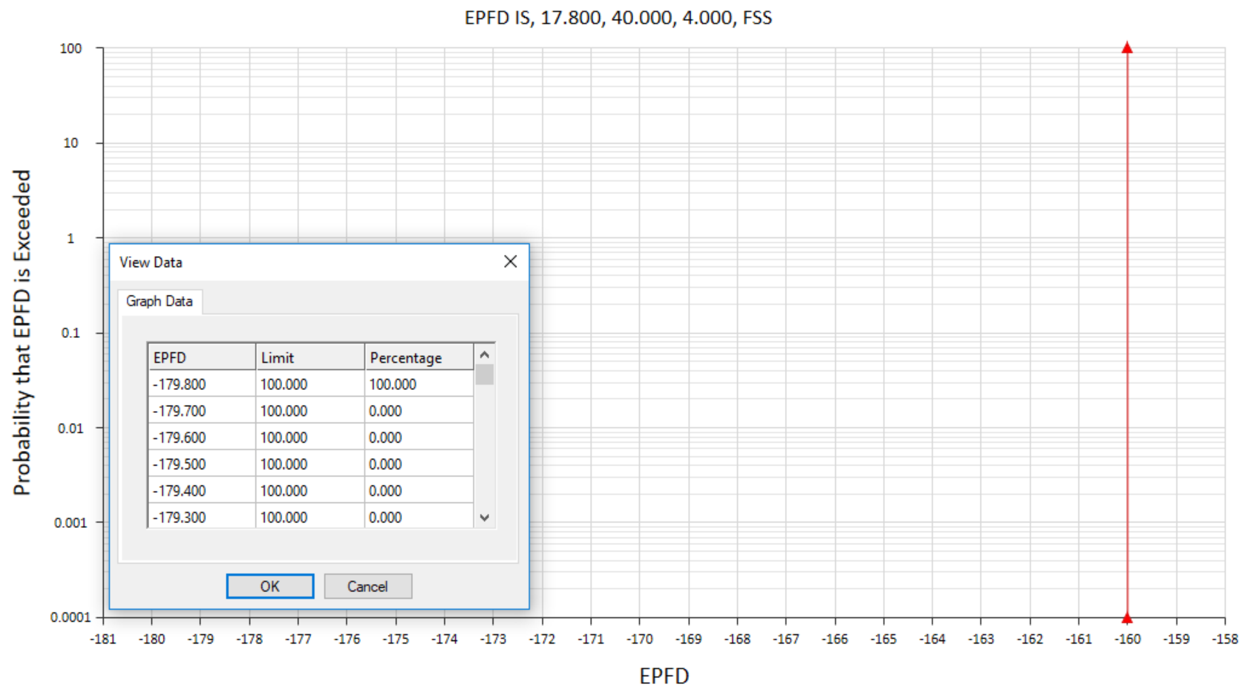
OUTPUT FOR EPFD$_{UP}$ ASSESSMENT



OUTPUTS FOR EPFD$_{IS}$ ASSESSMENT

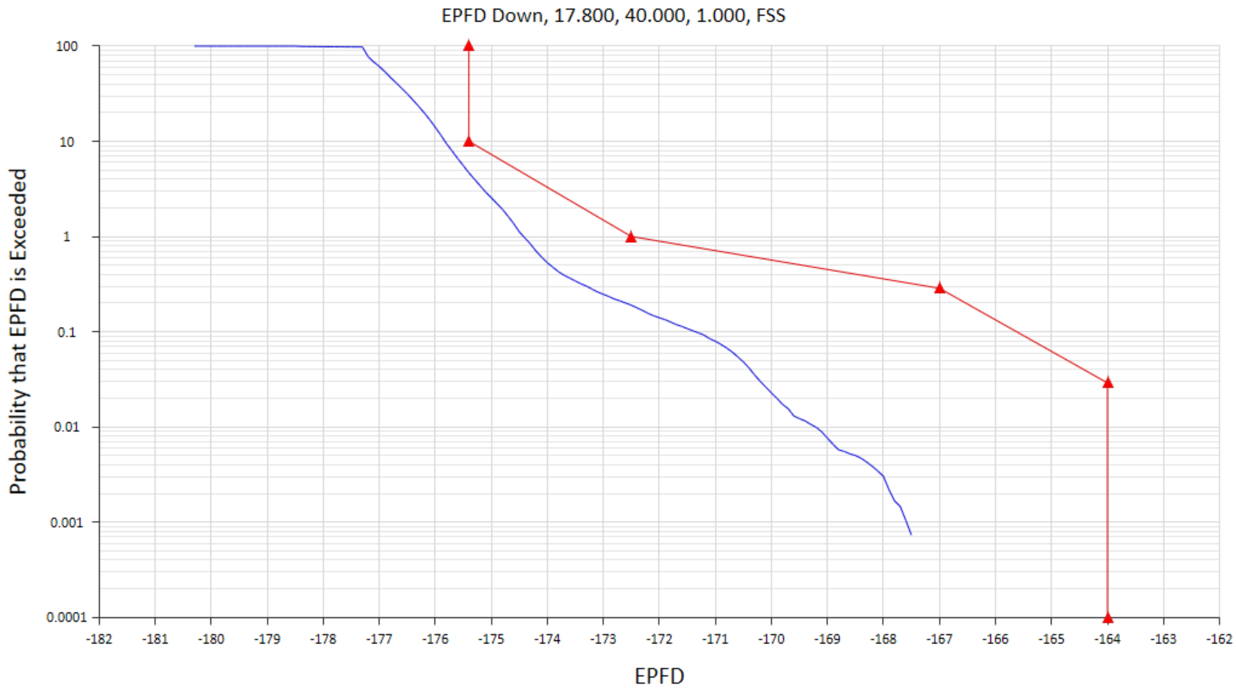


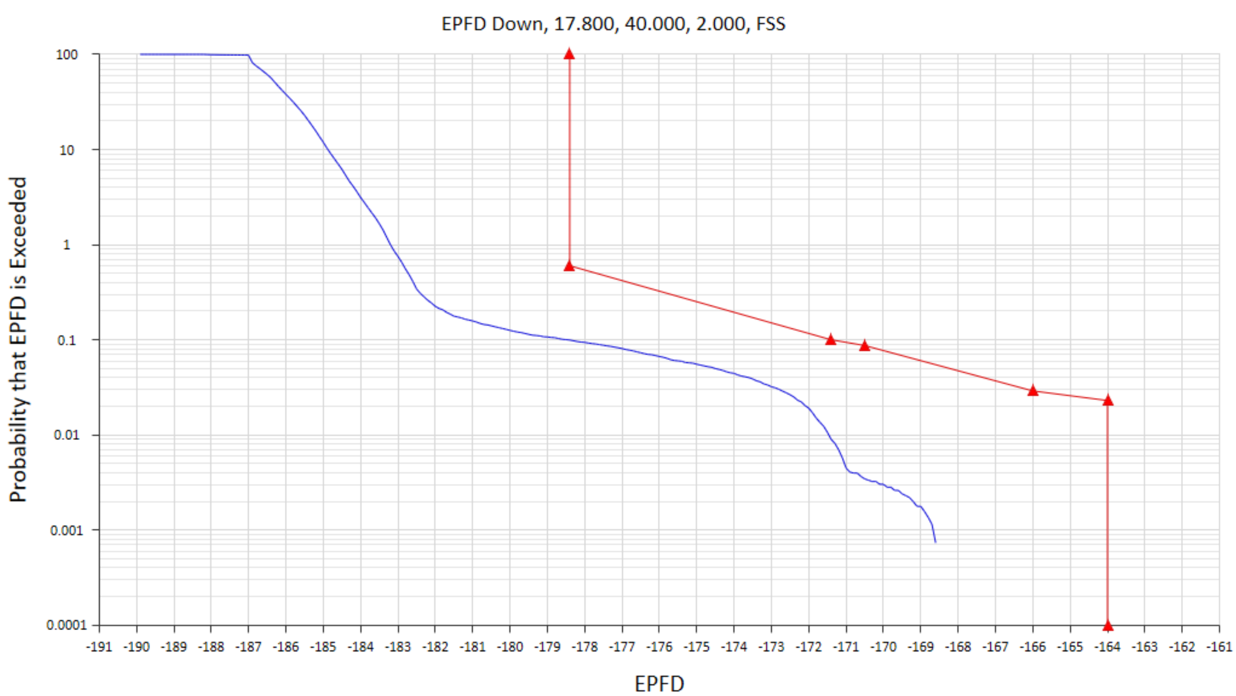
TT&C

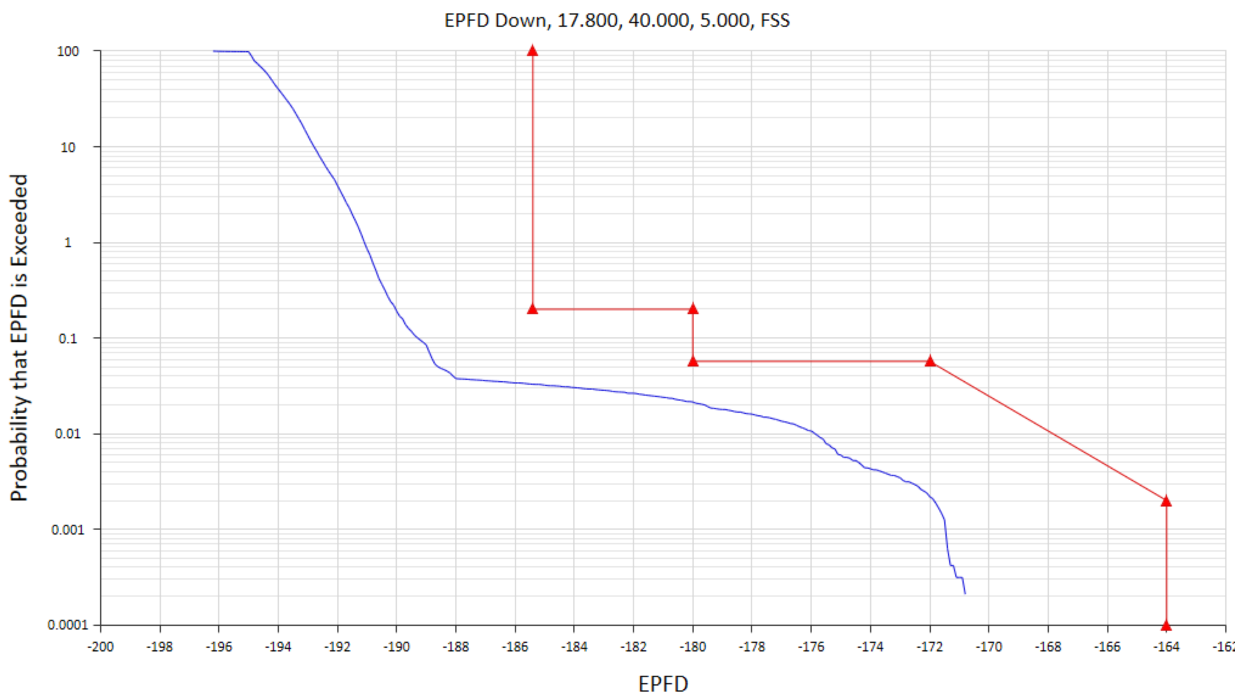

EPFD IS, 17.800, 40.000, 4.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-181
-180
-179
-178
-177
-176
-175
-174
-173
-172
-171
-170
-169
-168
-167
-166
-165
-164
-163
-162
-161
-160
-159
-158
EPFD
View Data
Graph Data
EPFD
Limit
Percentage
-179.800
100.000
100.000
-179.700
100.000
0.000
-179.600
100.000
0.000
-179.500
100.000
0.000
-179.400
100.000
0.000
-179.300
100.000
0.000
OK
Cancel

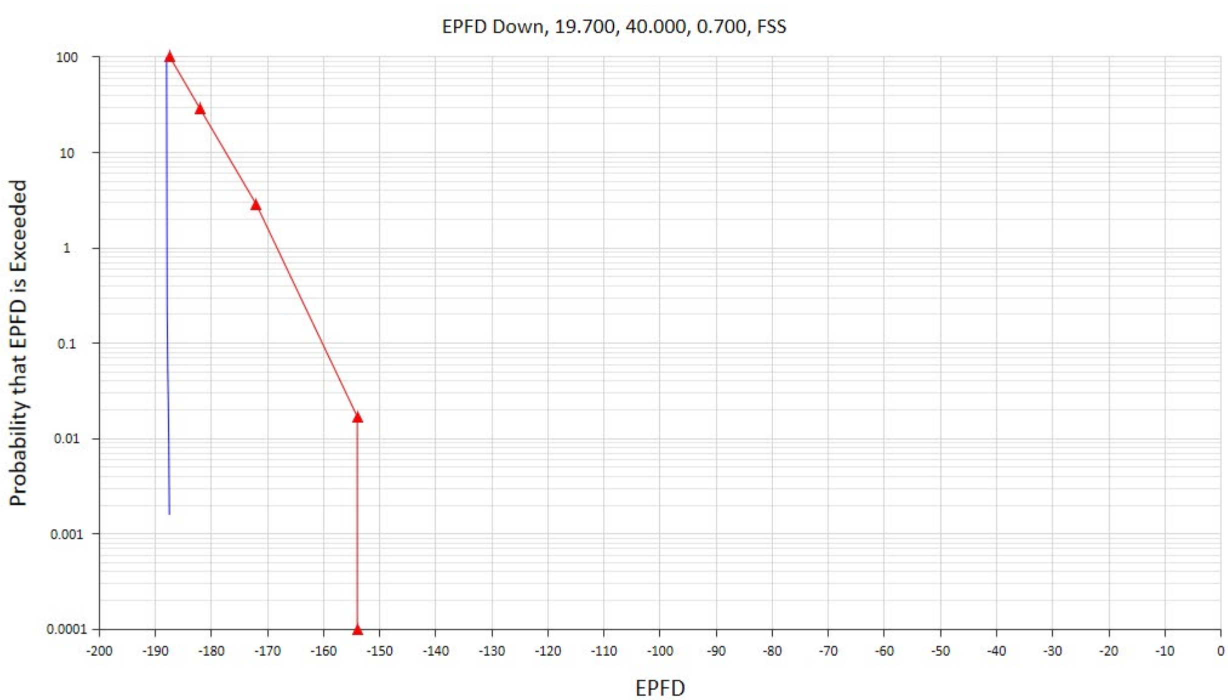
ANALYSIS OF FINAL DEPLOYMENT

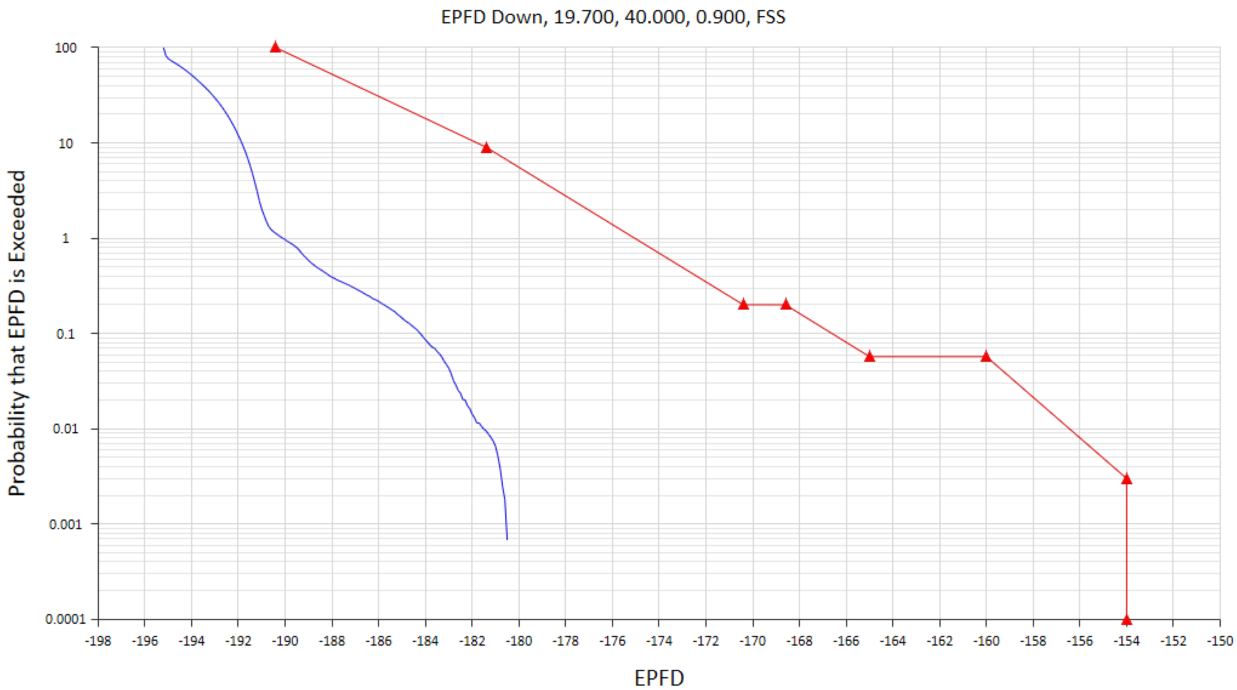
OUTPUTS FOR $EPFD_{DOWN}$ ASSESSMENT

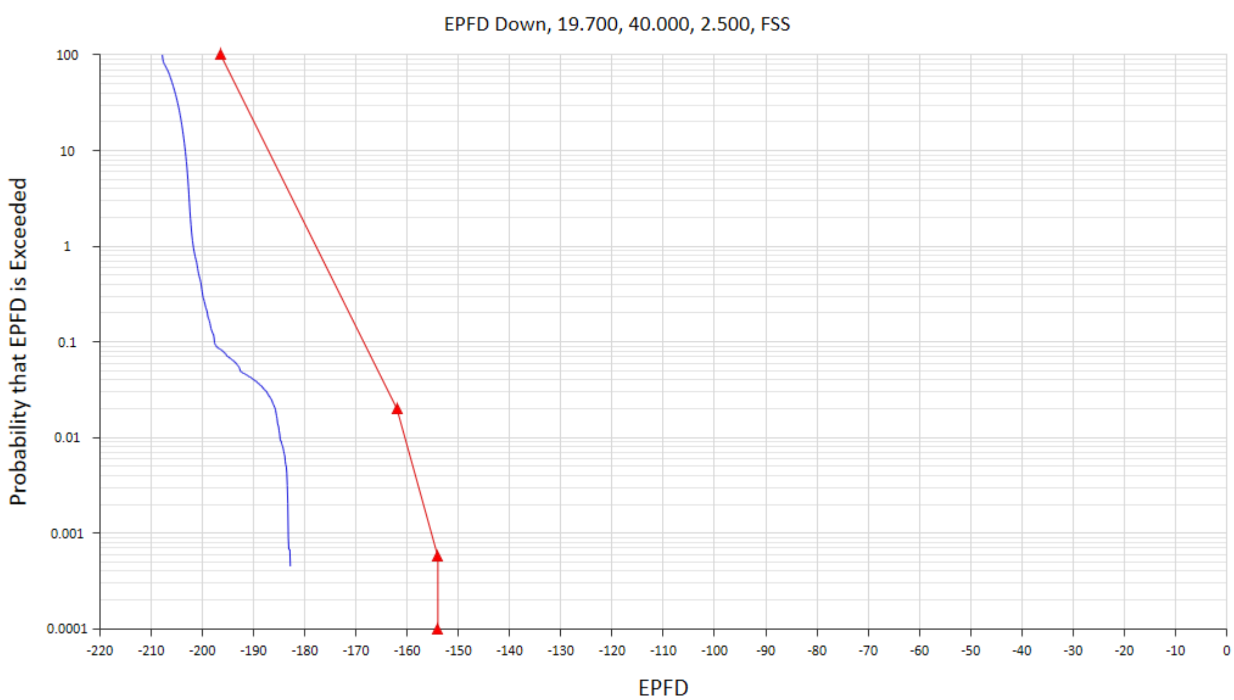


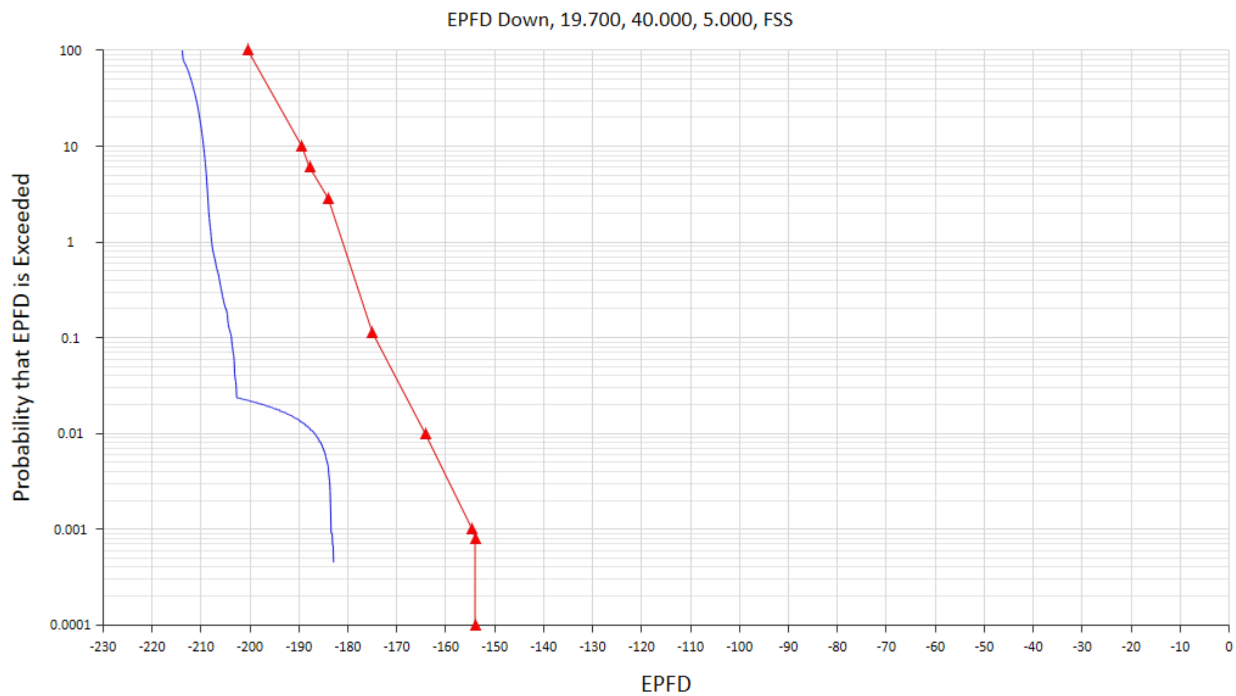



EPFD Down, 17.800, 40.000, 5.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-200
-198
-196
-194
-192
-190
-188
-186
-184
-182
-180
-178
-176
-174
-172
-170
-168
-166
-164
-162
EPFD

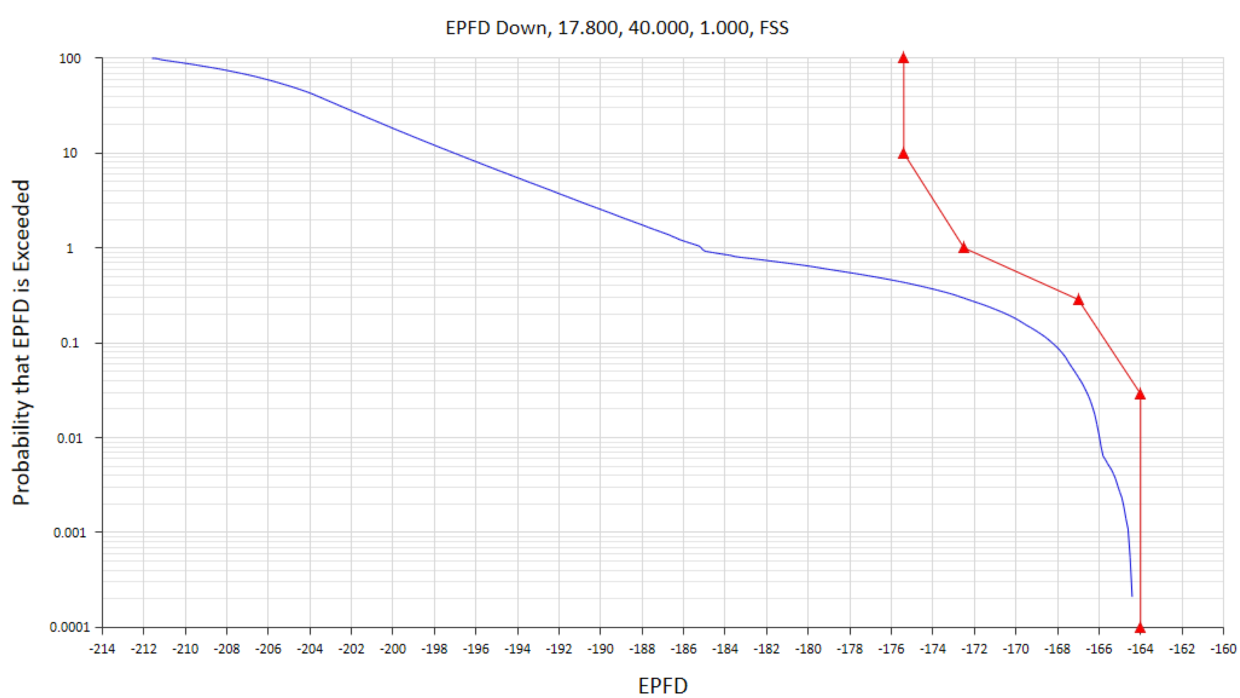

EPFD Down, 19.700, 40.000, 0.700, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-200
-190
-180
-170
-160
-150
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
EPFD


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
-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

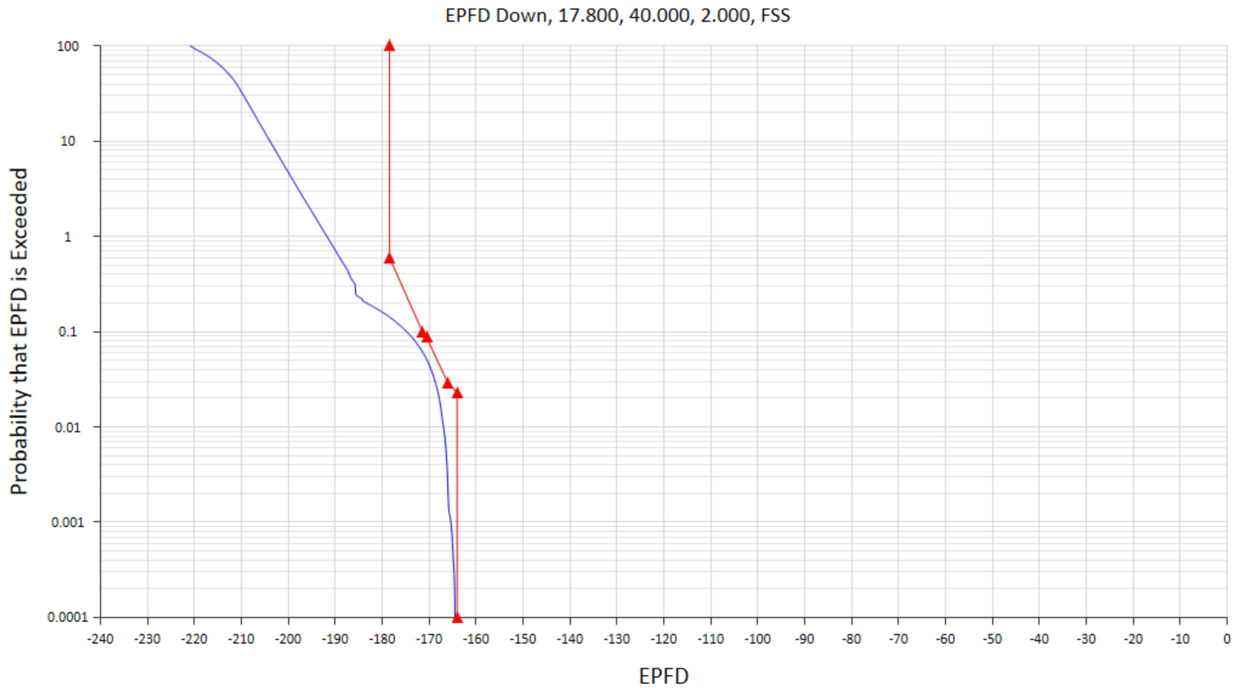

EPFD Down, 19.700, 40.000, 2.500, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-220
-210
-200
-190
-180
-170
-160
-150
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
EPFD


EPFD Down, 19.700, 40.000, 5.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-230
-220
-210
-200
-190
-180
-170
-160
-150
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
EPFD

TT&C

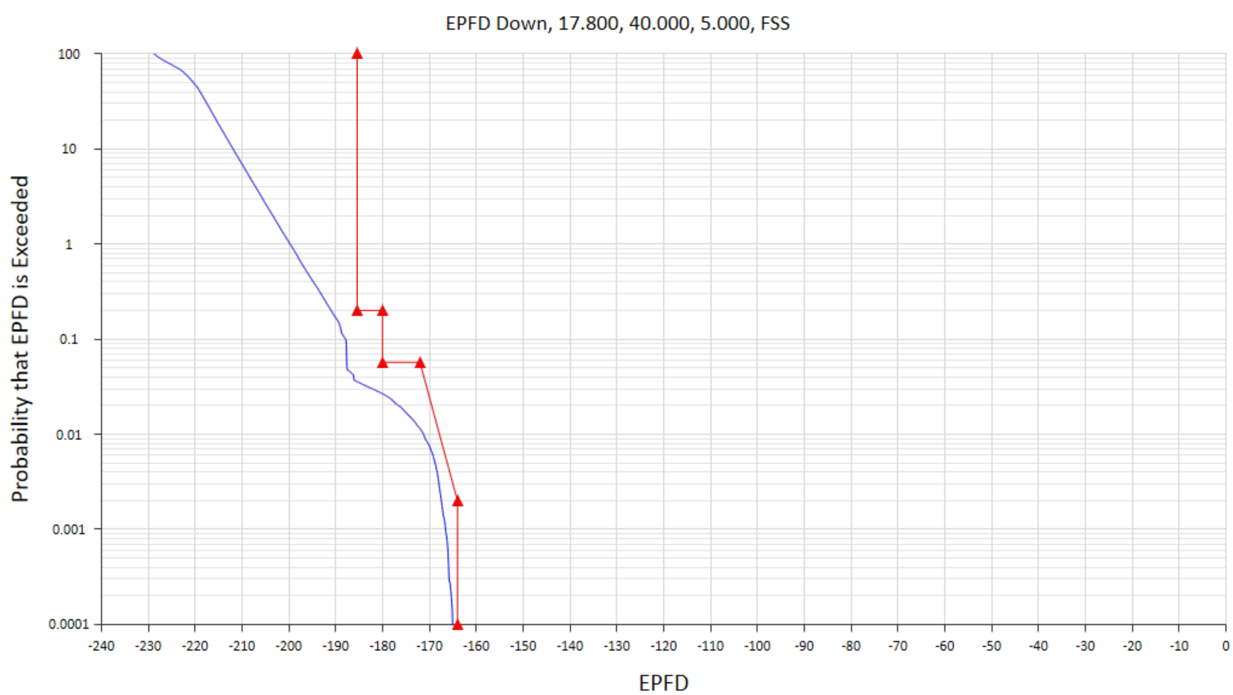

EPFD Down, 17.800, 40.000, 1.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-214
-212
-210
-208
-206
-204
-202
-200
-198
-196
-194
-192
-190
-188
-186
-184
-182
-180
-178
-176
-174
-172
-170
-168
-166
-164
-162
-160
EPFD

TT&C



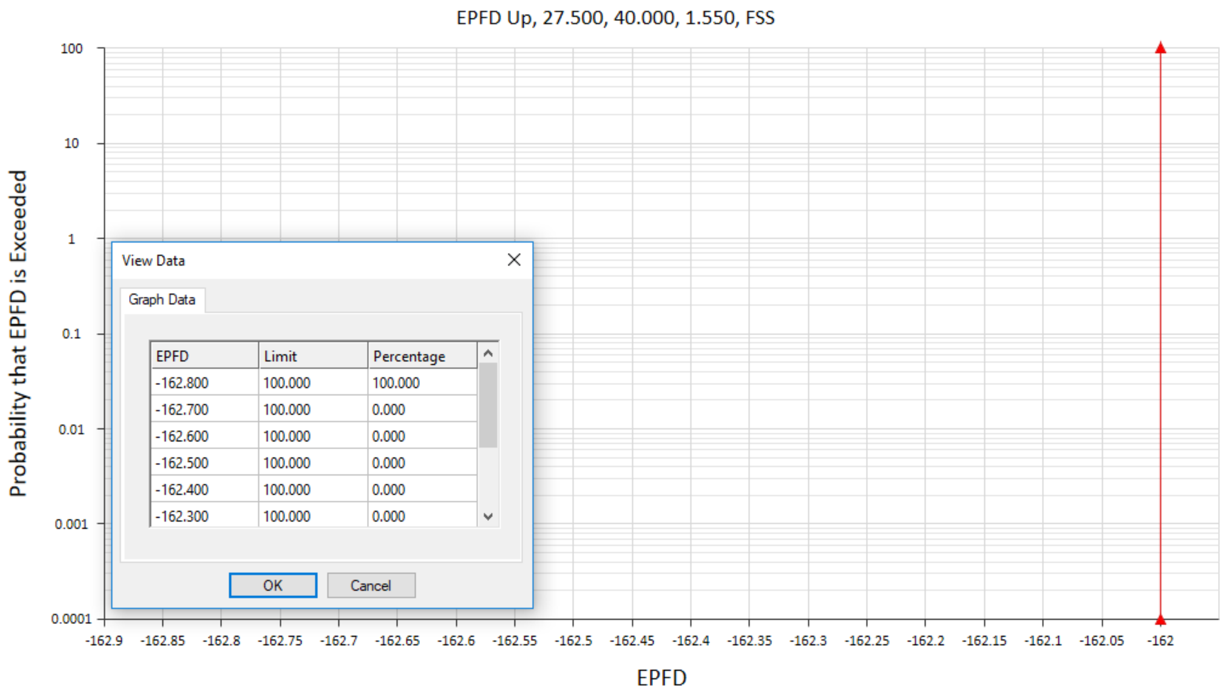
EPFD Down, 17.800, 40.000, 2.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-240 -230 -220 -210 -200 -190 -180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
EPFD

TT&C

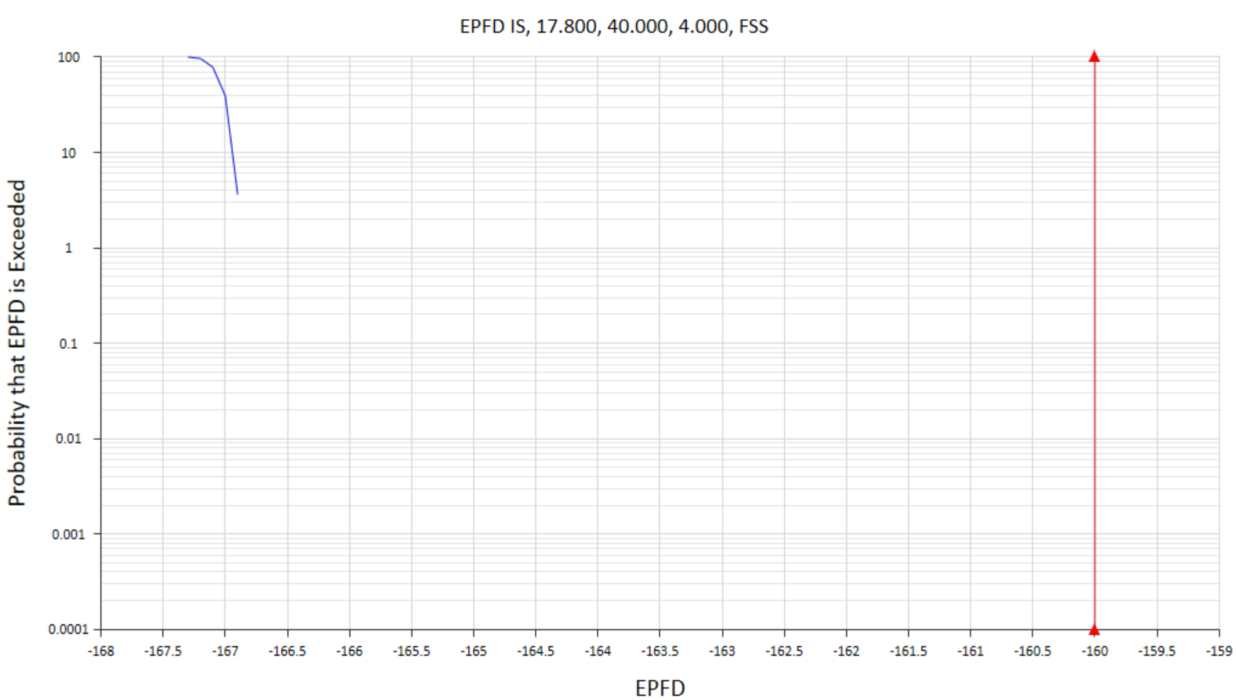


EPFD Down, 17.800, 40.000, 5.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-240 -230 -220 -210 -200 -190 -180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
EPFD

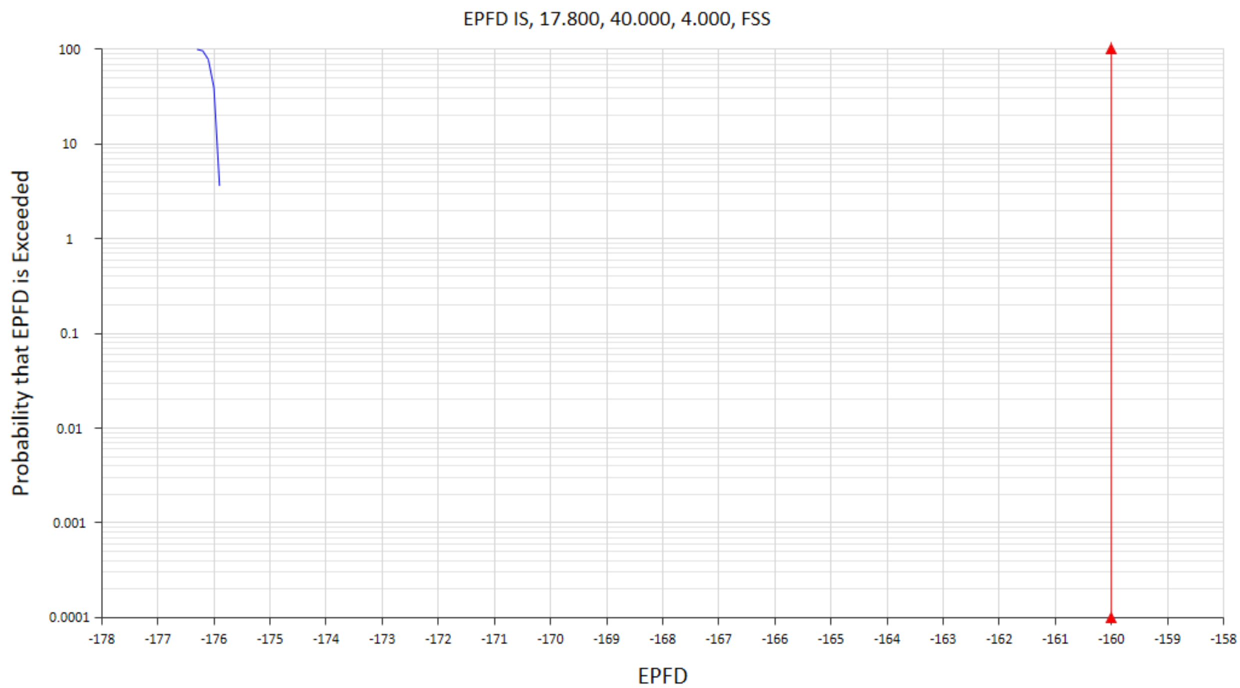
OUTPUT FOR EPFD$_{UP}$ ASSESSMENT



OUTPUTS FOR EPFD$_{IS}$ ASSESSMENT



TT&C



EPFD IS, 17.800, 40.000, 4.000, FSS
Probability that EPFD is Exceeded
100
10
1
0.1
0.01
0.001
0.0001
-178
-177
-176
-175
-174
-173
-172
-171
-170
-169
-168
-167
-166
-165
-164
-163
-162
-161
-160
-159
-158
EPFD