SPACEX NON-GEOSTATIONARY SATELLITE SYSTEM

ATTACHMENT A
TECHNICAL INFORMATION TO SUPPLEMENT SCHEDULE S

SCOPE AND PURPOSE

The Commission authorized Space Exploration Holdings, LLC ("SpaceX") on March 29, 2018, to construct, deploy, and operate a constellation of 4,425 non-geostationary orbit ("NGSO") satellites using Ku- and Ka-band spectrum.[1] Earlier this year, the Commission authorized SpaceX to relocate 1,584 satellites to an altitude of 550 km, where they would be able to achieve better performance and orbital debris mitigation characteristics without increasing interference to any other licensed user of the relevant spectrum.[2] SpaceX has begun the process of deploying its system by launching 60 satellites in May. Through extensive study of orbital formations and spacecraft performance, SpaceX has identified a system architecture that will enable deployment in a way that will provide robust broadband service to more Americans more quickly. Based on the success of its revolutionary deployment process, SpaceX has confirmed its ability to populate three planes with a single launch. By then reorganizing the same satellites at the same altitude, SpaceX can place coverage and capacity more evenly and rapidly across more of the U.S., accelerating broadband service to middle and southern states, as well as to Hawaii, Puerto Rico, and the U.S. Virgin Islands.

With this application, SpaceX seeks to modify its license to implement that system architecture. It involves only an adjustment of the orbital spacing of SpaceX's satellites operating at the 550 km altitude, increasing the number of orbital planes while commensurately decreasing

[1] *See Space Exploration Holdings, LLC*, 33 FCC Rcd. 3391 (2018) ("SpaceX Initial Authorization").

[2] *See Space Exploration Holdings, LLC*, 34 FCC Rcd. 2526 (IB 2019) ("SpaceX Modification").

the number of satellites in each plane. As summarized in Table 1, it would simply increase the number of orbital planes from 24 to 72, with a corresponding decrease in the number of satellites in each plane from 66 to 22. This adjustment would not change the total number of satellites, operational altitude, or inclination of the orbital planes. Nor would the modification change the radio frequency characteristics of the individual satellites or the beneficial orbital debris mitigation characteristics of their operation at this lower altitude.

Parameter	Current Authorization	Proposed Modification
Orbital Planes	24	72
Satellites Per Plane	66	22
Total Satellites	1,584	1,584
Altitude	550 km	550 km
Inclination	53°	53°

Table 1. Summary of Proposed Modification

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.[3]

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. In particular, it includes several analyses that demonstrate that any impact of the proposed modification on other spectrum users would be negligible. For the Commission's convenience, SpaceX has included in the accompanying Schedule S the information

[3] *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)); Application for Modification of Authorization for the SpaceX NGSO Satellite System, IBFS File No. SAT-MOD-20181108-00083 (Nov. 8, 2018).

filed as part of the previous applications with revisions associated with respacing satellites in the orbital shell at 550 km as proposed in this application. The accompanying Schedule S therefore reflects the system as it will operate once modified and fully deployed.

As mentioned above, SpaceX has already launched a tranche of satellites that are currently operating in compliance with its existing authorization. SpaceX requests that any modification granted in this proceeding include authority to reposition those satellites as appropriate to come into conformity with the newly authorized orbital parameters.[4]

SPECTRUM SHARING ANALYSES

The Commission has recognized that a proposed modification to an NGSO authorization should be granted where it "does not present any significant interference problems and is otherwise consistent with Commission policies."[5] In this case, the respacing of existing SpaceX satellites will not have any significant impact on other users of the Ku- and Ka-band spectrum. To demonstrate this fact, SpaceX has included in this Technical Attachment three analyses of the interaction between its system as modified and other licensed systems in the band.

- ***Annex 1*** presents an analysis that considers the dynamic, time-varying interference expressed as a cumulative distribution function ("CDF") of the interference-to-noise ratio ("I/N"), for varying percentages of time. The I/N CDF is derived from a time-domain simulation of the two NGSO systems over a long enough time to produce meaningful statistics. The analysis considers the effect of the proposed modification on two NGSO

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4 To the extent some satellites would need to be moved to other planes, such repositioning would involve lowering their altitude and then re-raising them to the authorized altitude in the proper plane(s).

5 *Teledesic LLC*, 14 FCC Rcd. 2261, ¶ 5 (IB 1999). *See also The Boeing Co.*, 18 FCC Rcd. 12317, ¶ 7 (IB 2003). ("In recognition of the length of time it takes to construct a satellite system, the rapid pace of technological change, and the goal of promoting more efficient use of the radio spectrum, the [Commission] has granted such requests in cases where the proposed modification presents no significant interference problem and is otherwise consistent with Commission policies.").

systems hypothetically operating in the Ku-band (OneWeb and Kepler) and two operating in the Ka-band (Telesat and O3b). That analysis demonstrates that the modification would have a negligible effect on the interference environment of other NGSO systems.

- ***Annex 2*** presents an updated analysis demonstrating that SpaceX will continue to comply with 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.[6] Pursuant to Section 25.146(a)(2) of the Commission's rules, SpaceX hereby certifies that its NGSO constellation, as modified, will comply with the applicable EPFD limits.[7]

- ***Annex 3*** presents an updated analysis to demonstrate that SpaceX's operations will also continue to satisfy the condition imposed to protect terrestrial fixed services operating in a portion of the Ka-band.[8]

As these analyses confirm, merely respacing the SpaceX satellites already authorized to operate at the 550 km altitude will present no significant interference issues for other systems that share spectrum bands with the Starlink constellation.

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[6] *See* 47 C.F.R. §§ 25.108(c)(3) and (9), 25.146(c) (incorporating ITU Radio Regs., Article and 22). The Commission has found these limits sufficient to prevent harmful interference to other spectrum licensees. *See, e.g.*, *Amendment of Parts 2 and 25 of the Commission's Rules to Permit Operation of NGSO FSS Systems Co-Frequency with GSO and Terrestrial Systems in the Ku-Band Frequency Range*, 16 FCC Rcd. 4096, ¶¶ 39, 72 (2000) ("the single-entry and aggregate EPFD limits we are adopting also define the level of acceptable interference from a NGSO FSS system into a GSO FSS system under our rules").

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

[8] *See* SpaceX Initial Authorization, ¶¶ 35 and 40q.

ORBITAL DEBRIS MITIGATION

The proposed modification will have no impact on the orbital debris mitigation characteristics of the Starlink constellation. The number of satellites, operational altitude and inclination, and spacecraft characteristics will not change – only the spacing (based on the right ascension of ascending node ("RAAN")) will change slightly. RAAN will not affect de-orbit mechanics or the time it takes for inoperable satellites to demise in the atmosphere. While in some very specific orbits a change in RAAN could materially affect collision risk,[9] generally speaking RAAN has no such impact. Indeed, NASA's Debris Assessment Software ("DAS") does not even have a field to enter RAAN when assessing collision risk – only satellite lifetime, altitude, and inclination (as well as some parameters specific to the vehicle itself), none of which will change with this modification. Moreover, SpaceX has implemented autonomous conjunction avoidance technology on its spacecraft and expects to continue to upgrade that capability as it gains operational experience. The Commission previously found that SpaceX's estimate "is well within accepted boundaries for collision risk, even with worst-case assumptions that go well beyond any realistic scenario."[10]

SpaceX still intends to perform an active disposal of all 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

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9 For example, satellites in sun-synchronous orbits tend to be clustered at certain RAAN. However, even if sun-synchronous satellites are present at nearby altitudes, they would be precessing at different rates than the Starlink satellites – and no RAAN that SpaceX selected would materially affect the probability of an encounter.

10 SpaceX Modification, ¶ 22.

conjunction avoidance until the high atmospheric torques from low altitudes cause the vehicle to be uncontrollable. 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. 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. Moreover, due to SpaceX's decision to minimize risk by using the low injection altitude of 350 km, in the unlikely event any satellites after the initial launch experience immediate failure upon deployment, they would decay to the point of demise very quickly – as little as two weeks to at most eight months depending on the solar cycle. None of this is in any way changed by the proposed modification.

The spacecraft's small mass and predominantly aluminum construction maximize the likelihood of atmospheric demise on re-entry. As SpaceX previously stated, all Starlink satellites launched after the first deployment will be fully demisable upon atmospheric re-entry, and no components will survive to reach the Earth's surface. Accordingly, the modification will have no effect on the risk of human casualty – which will remain zero for all launches from here on.

ENGINEERING CERTIFICATION

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

/s/ *Mihai Albulet*

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

August 30, 2019

Date

ANNEX 1

POTENTIAL INTERFERENCE WITH RESPECT TO OTHER NGSO SATELLITE SYSTEMS

SpaceX has engineered its Starlink system with the technical flexibility that will facilitate the necessary coordination with other NGSO satellite systems and is committed to achieving mutually satisfactory agreements. Moreover, the proposed modification will not increase interference to any other NGSO system operating in the bands used by Starlink satellites. To confirm this fact, SpaceX performed an analysis of the effect of the proposed modification on downlink and uplink interference using the characteristics of four NGSO systems authorized through the Commission's most recent Ku/Ka-band processing round – OneWeb and Kepler for Ku-band and Telesat and O3b for Ka-band.

The analysis considers the dynamic, time-varying interference expressed as a cumulative distribution function ("CDF") of the interference-to-noise ratio ("I/N"), for varying percentages of time. The I/N CDF is derived from a time-domain simulation of the two NGSO systems over a long enough time to produce meaningful statistics, using two different methodologies for antenna pointing: (1) highest elevation and (2) random. 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 virtually indistinguishable from the interference levels that would have been experienced with the current constellation, the modification will not increase the potential interference into other NGSO systems.

In conducting this analysis, SpaceX used the following assumptions.

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

1. The SpaceX earth station is collocated with the victim earth station. Locations at 20°N and 50°N latitude are considered in this simulation.[1]
2. The victim earth station can communicate with any satellite in its own system following the rules applicable for that system (*e.g.*, the GSO avoidance angle or minimum elevation angle). All possible valid cases are considered in evaluating the I/N CDF.
3. The SpaceX system places one co-frequency beam per Ku-band spot and four co-frequency beams per Ka-band spot, and any satellite in view meeting the GSO avoidance angle and the minimum elevation angle is eligible. SpaceX satellites are chosen based on highest elevation or random selection for consideration 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 20°N and 50°N 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 one co-frequency beam per Ku-band spot and four co-frequency beams per Ka-band spot (in the uplink), and any satellite in view meeting the GSO avoidance angle and the minimum elevation angle is eligible. SpaceX satellites are chosen based on highest elevation or random selection for consideration 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.

[1] Note that SpaceX ran its simulation with multiple latitudes and achieved similar results. Accordingly, it chose to provide results for two latitudes that are representative of its primary service area.

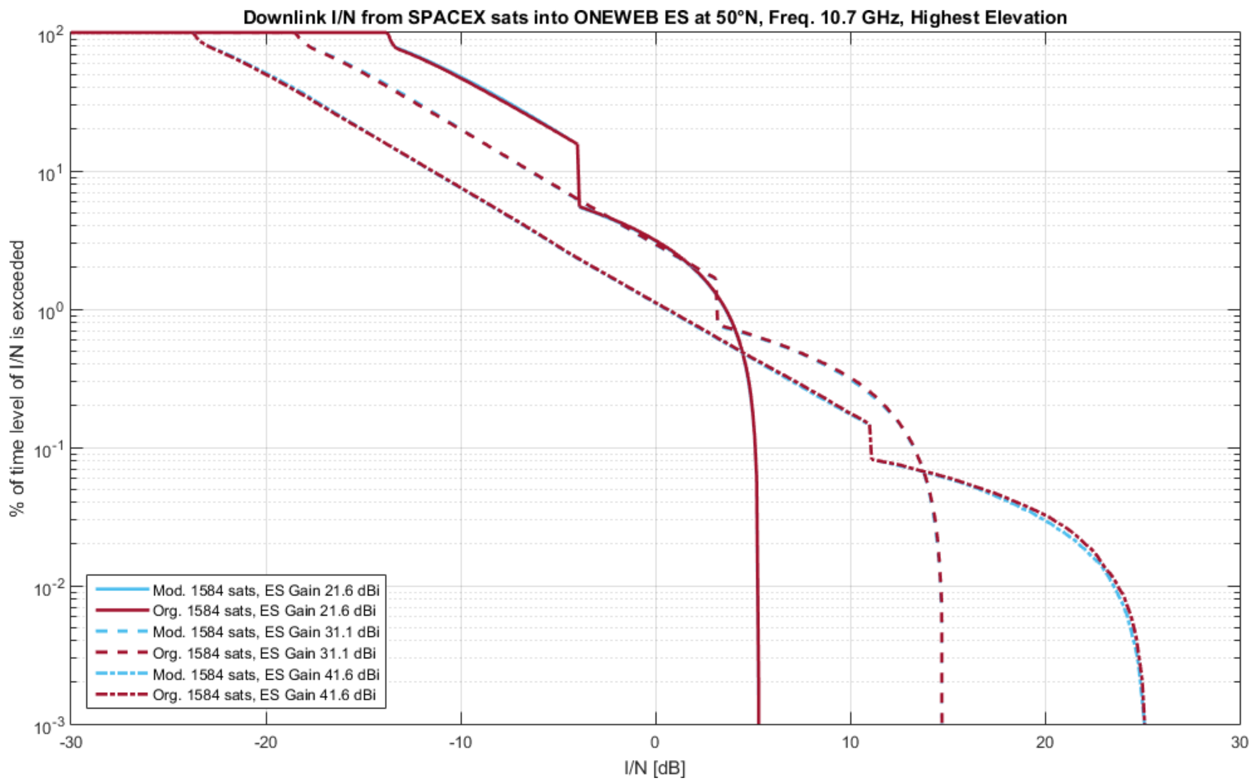


Figure A1-1. Downlink Comparison for Various OneWeb Antennas at 50ºN for Modified 550 km Shell — Highest Elevation

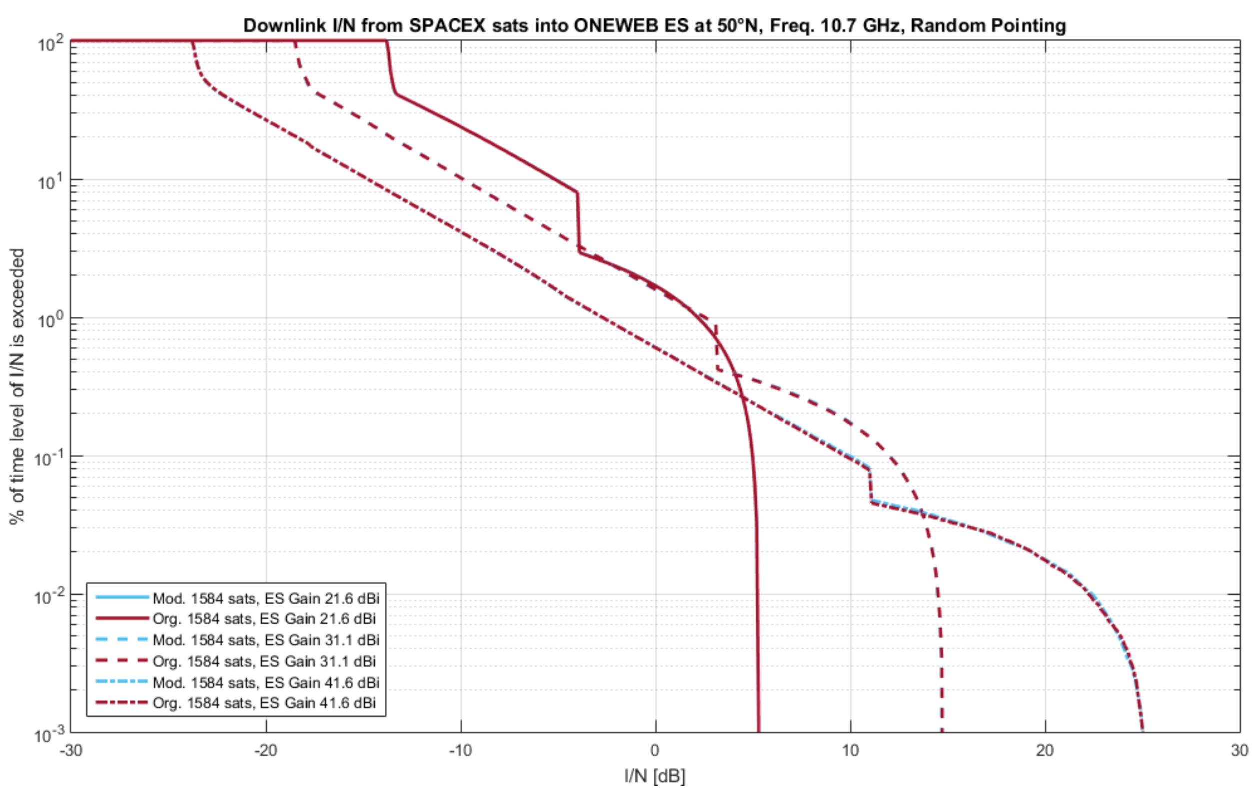


Figure A1-2. Downlink Comparison for Various OneWeb Antennas at 50ºN for Modified 550 km Shell — Random Pointing

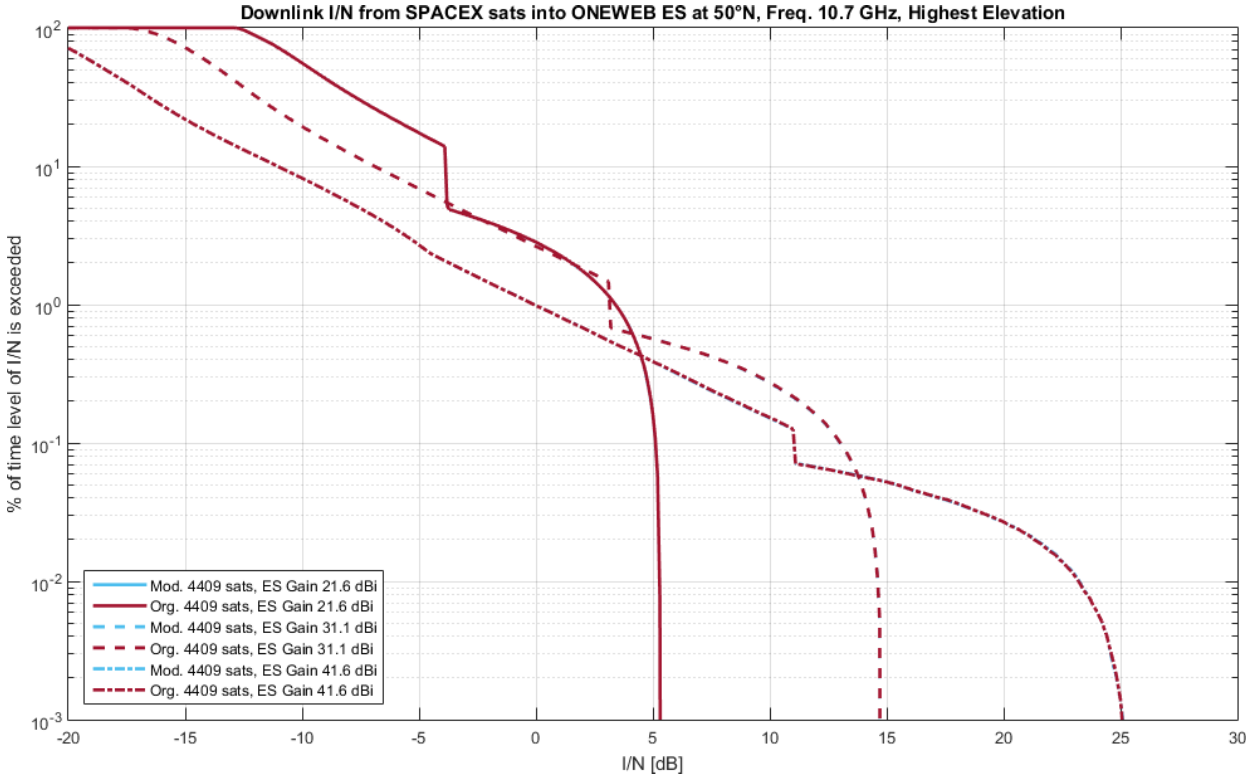


Figure A1-3. Downlink Comparison for Various OneWeb Antennas at 50ºN for Full SpaceX Constellation — Highest Elevation

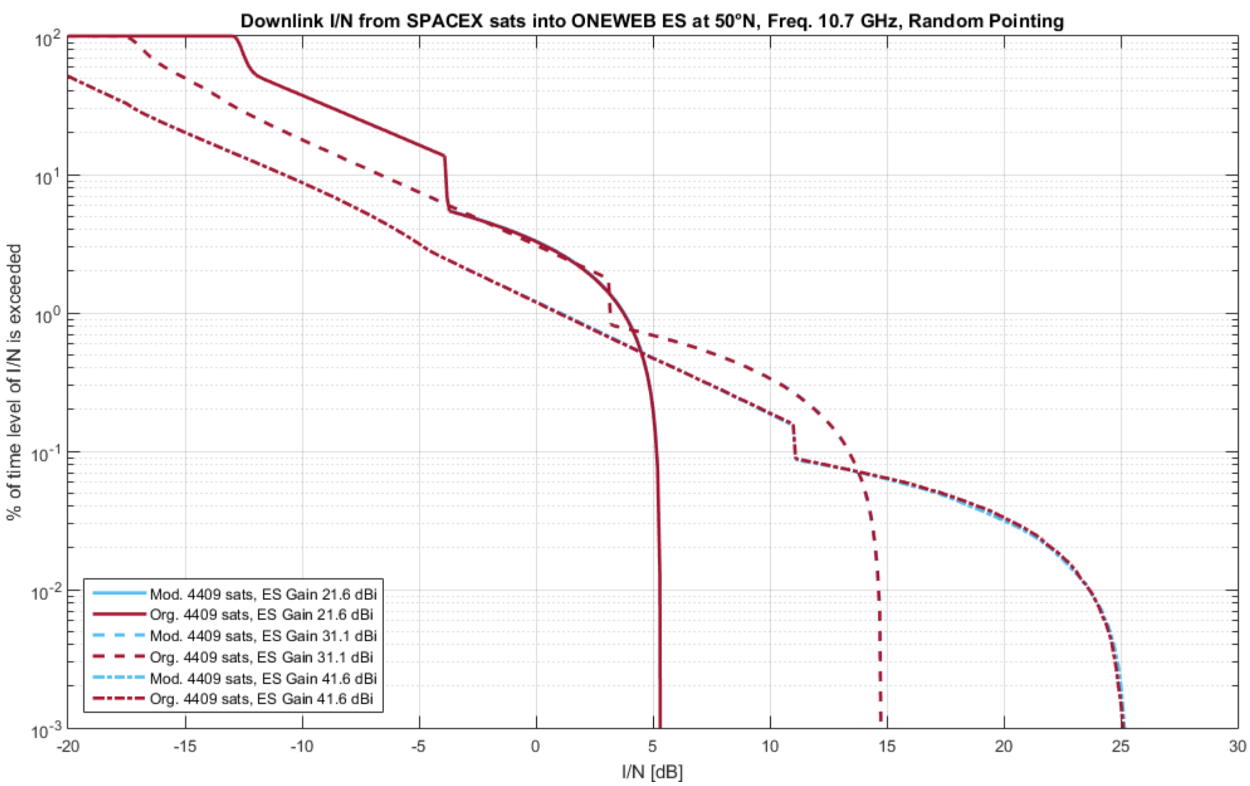


Figure A1-4. Downlink Comparison for Various OneWeb Antennas at 50ºN for Full SpaceX Constellation — Random Pointing

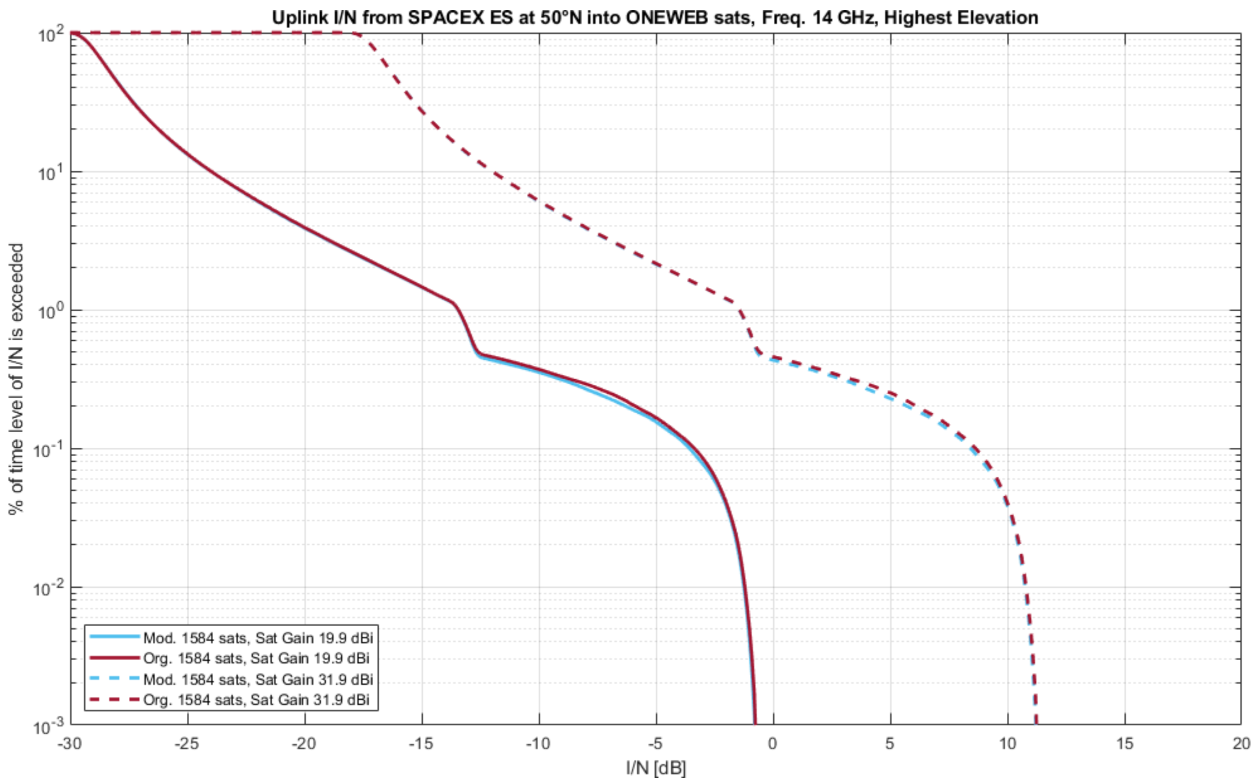


Figure A1-5. Uplink Comparison for Various OneWeb Antennas at 50ºN for Modified 550 km Shell — Highest Elevation

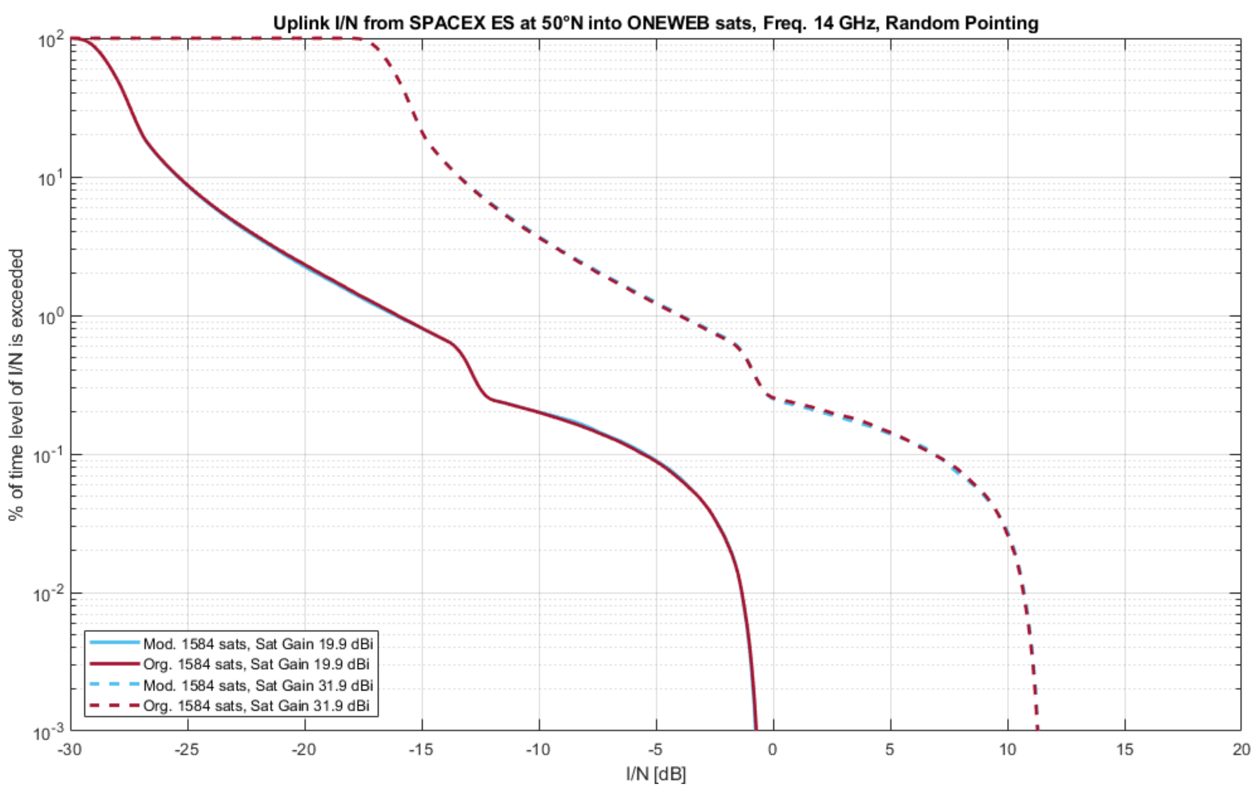


Figure A1-6. Uplink Comparison for Various OneWeb Antennas at 50ºN for Modified 550 km Shell — Random Pointing

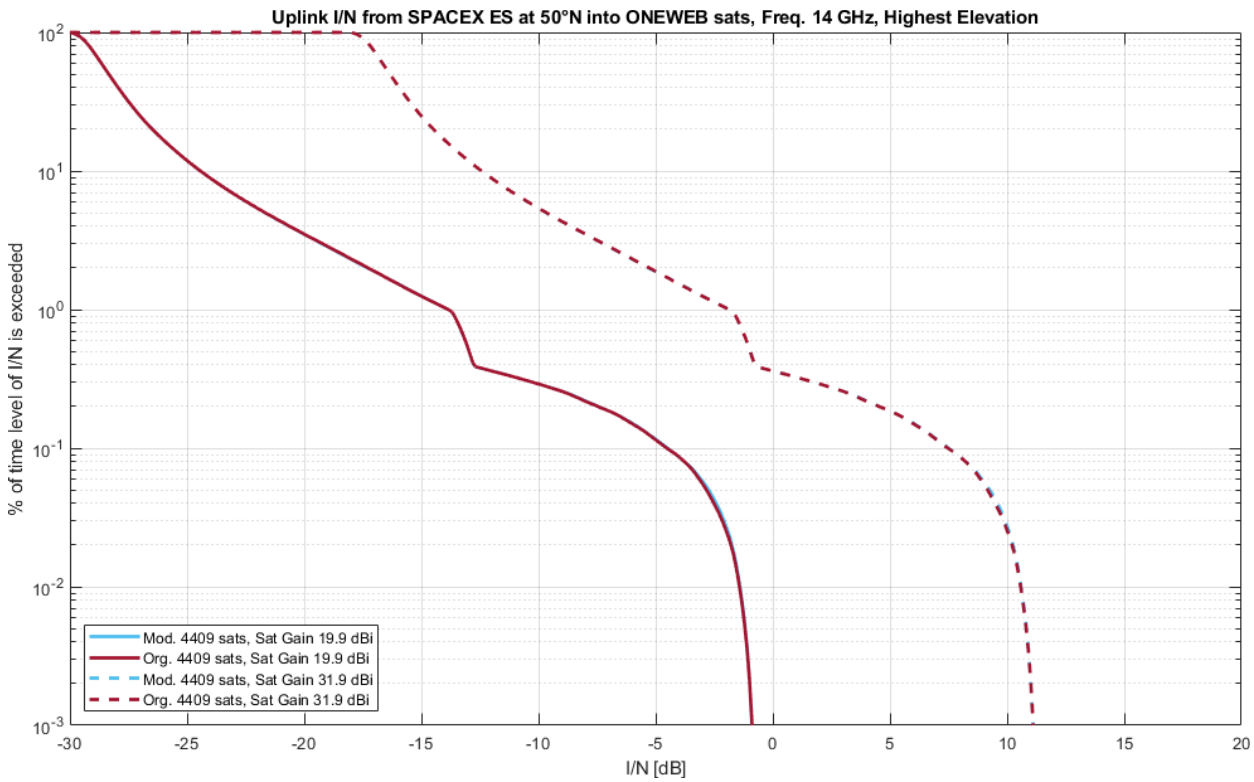


Figure A1-7. Uplink Comparison for Various OneWeb Antennas at 50ºN for Full SpaceX Constellation — Highest Elevation

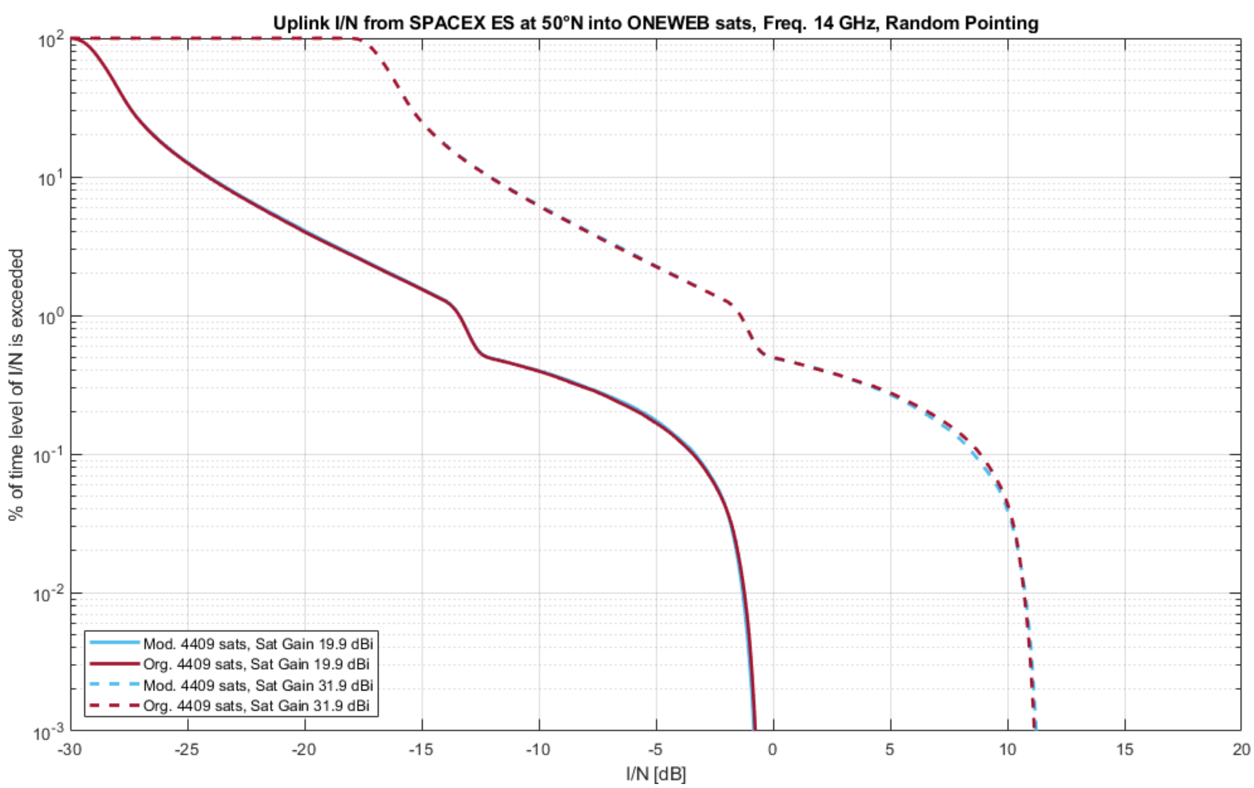


Figure A1-8. Uplink Comparison for Various OneWeb Antennas at 50ºN for Full SpaceX Constellation — Random Pointing

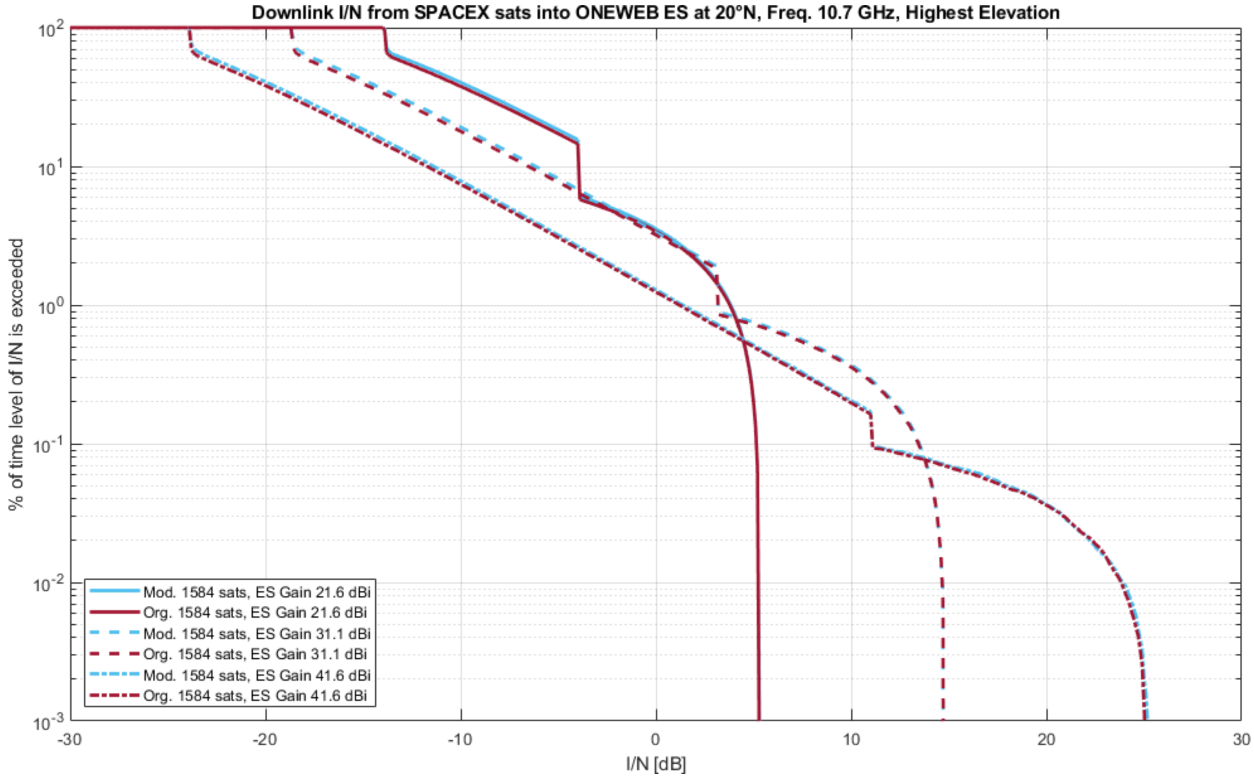


Figure A1-9. Downlink Comparison for Various OneWeb Antennas at 20ºN for Modified 550 km Shell — Highest Elevation

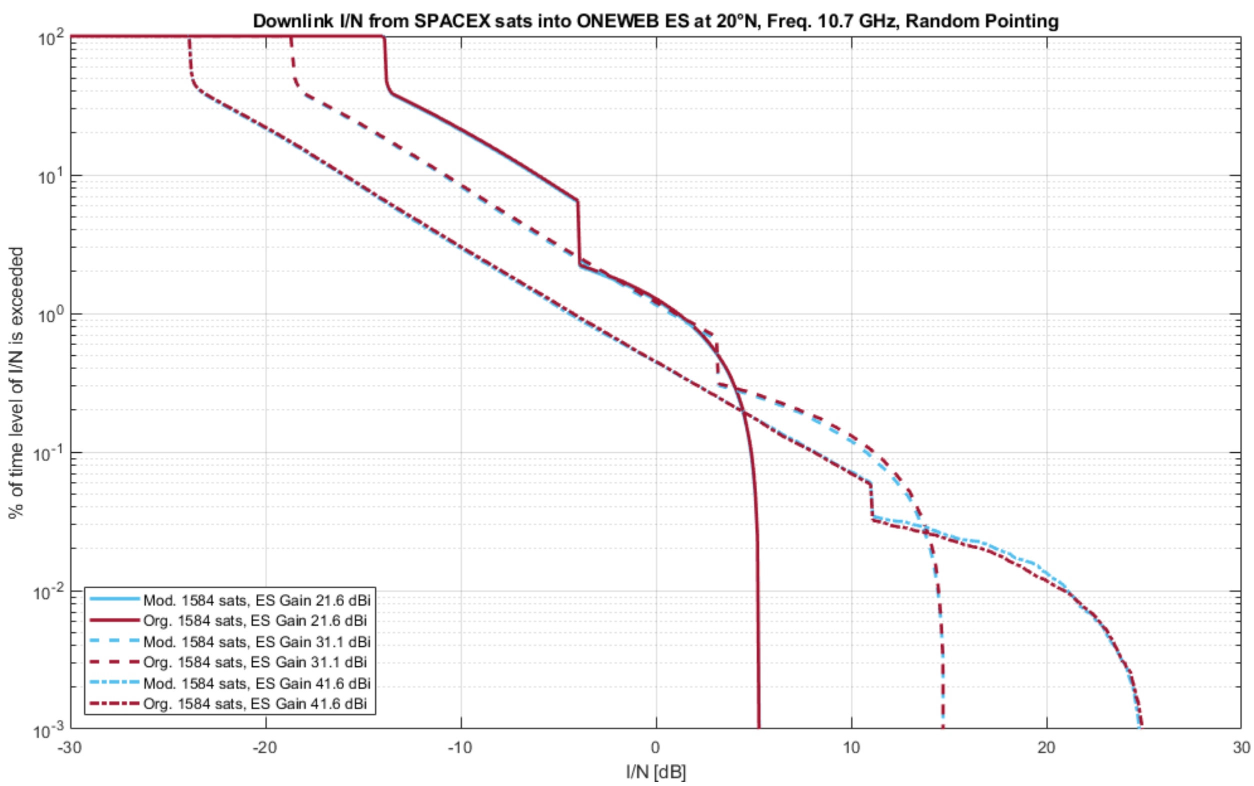


Figure A1-10. Downlink Comparison for Various OneWeb Antennas at 20ºN for Modified 550 km Shell — Random Pointing

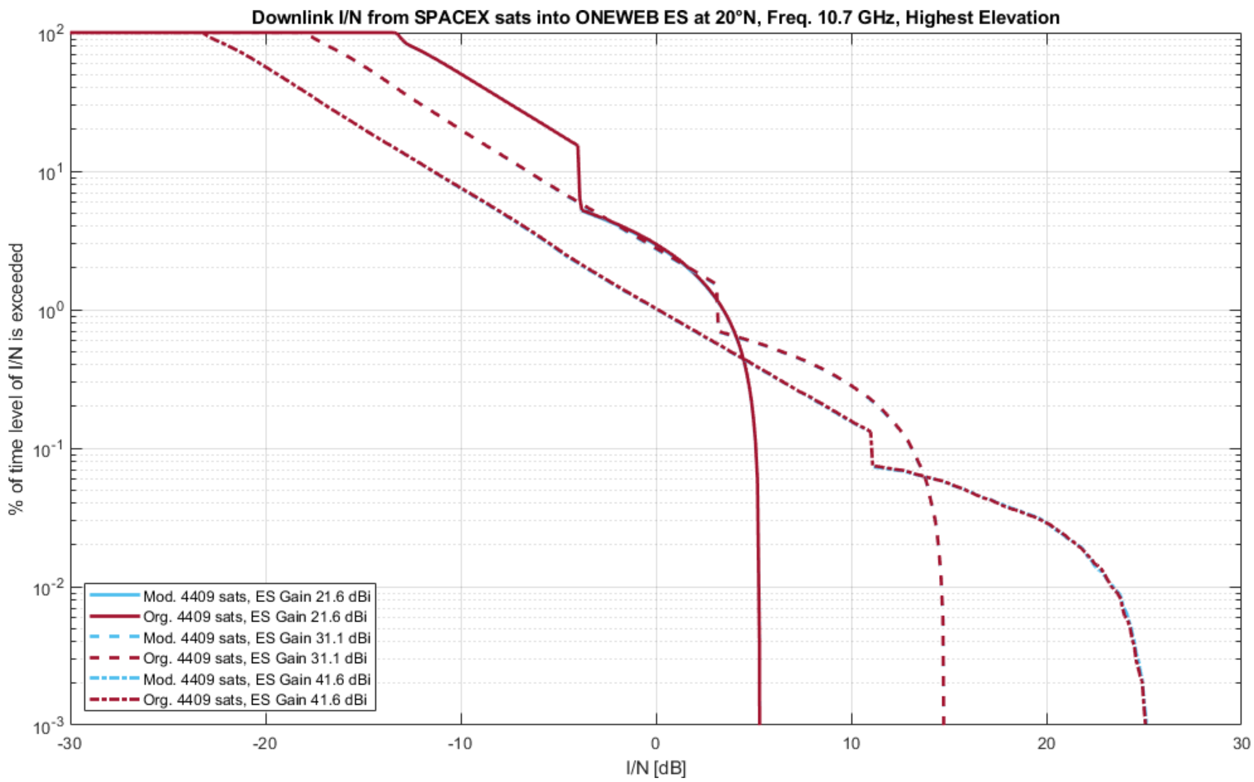


Figure A1-11. Downlink Comparison for Various OneWeb Antennas at 20ºN for Full Space Constellation — Highest Elevation

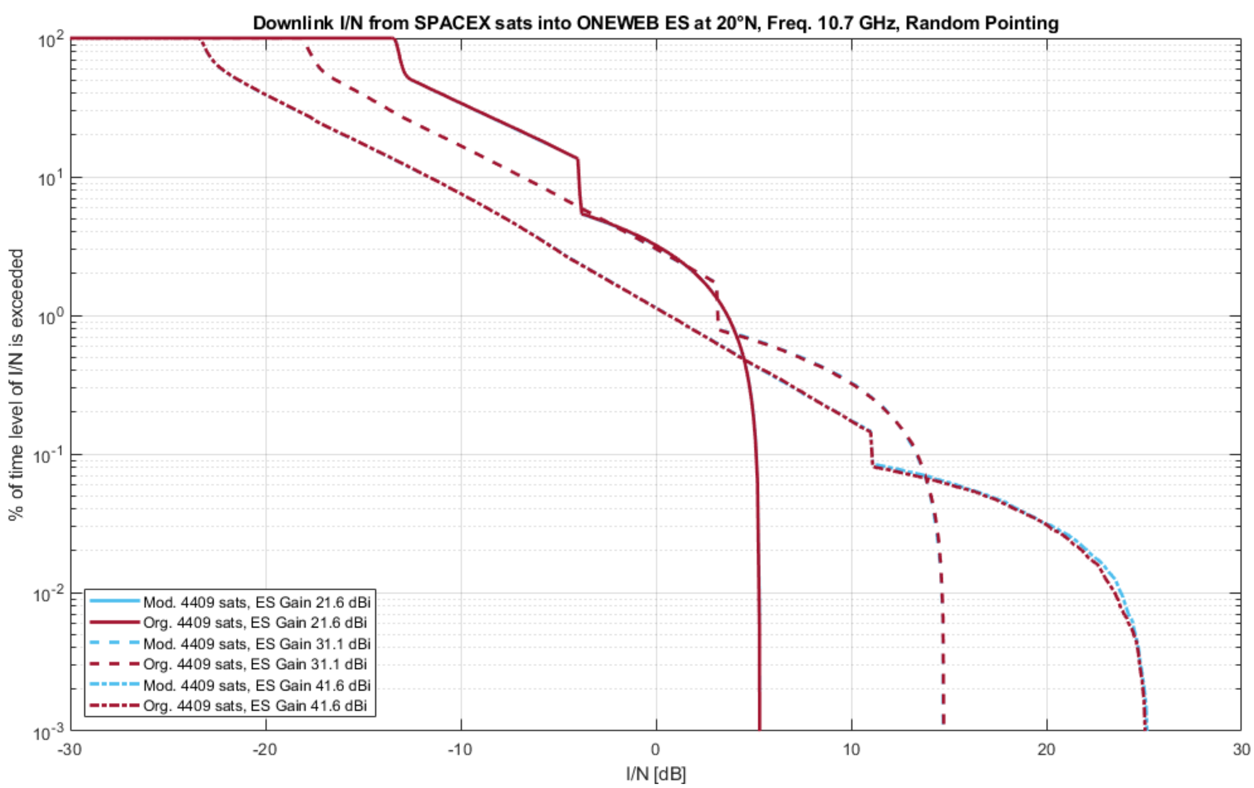


Figure A1-12. Downlink Comparison for Various OneWeb Antennas at 20ºN for Full SpaceX Constellation — Random Pointing

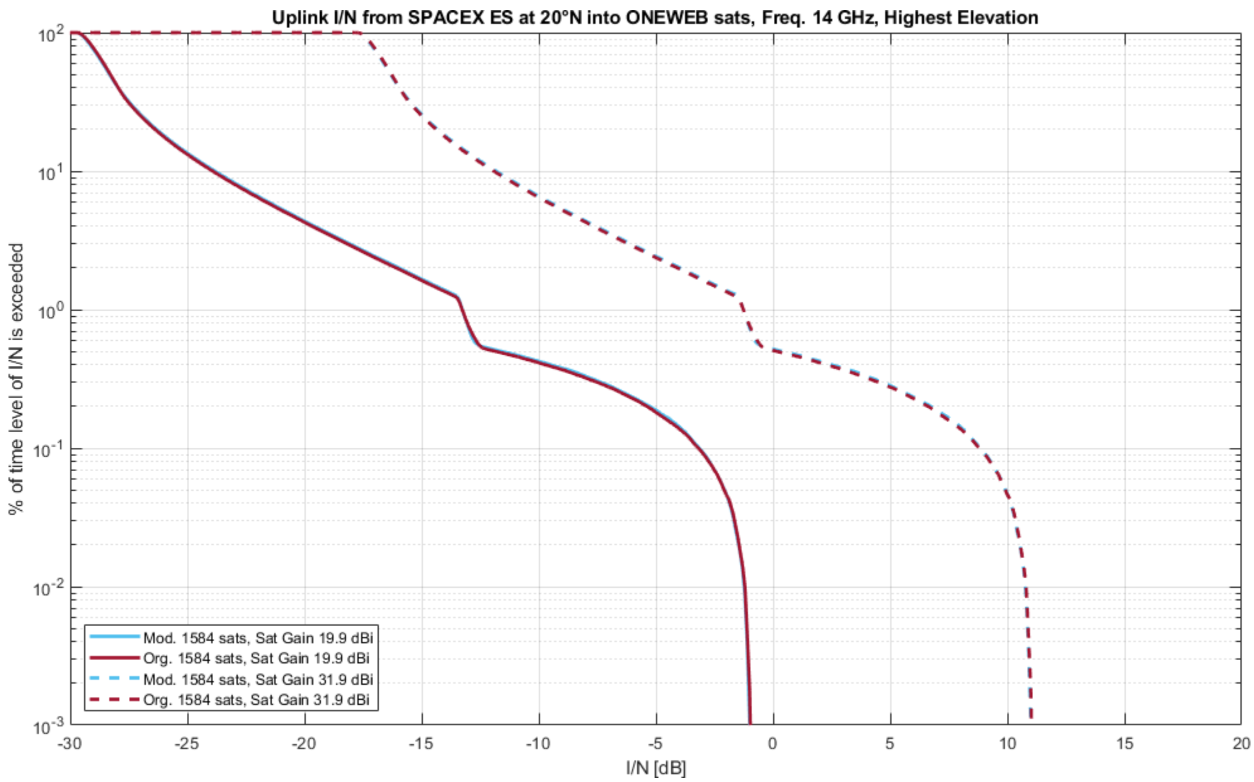


Figure A1-13. Uplink Comparison for Various OneWeb Antennas at 20ºN for Modified 550 km Shell — Highest Elevation

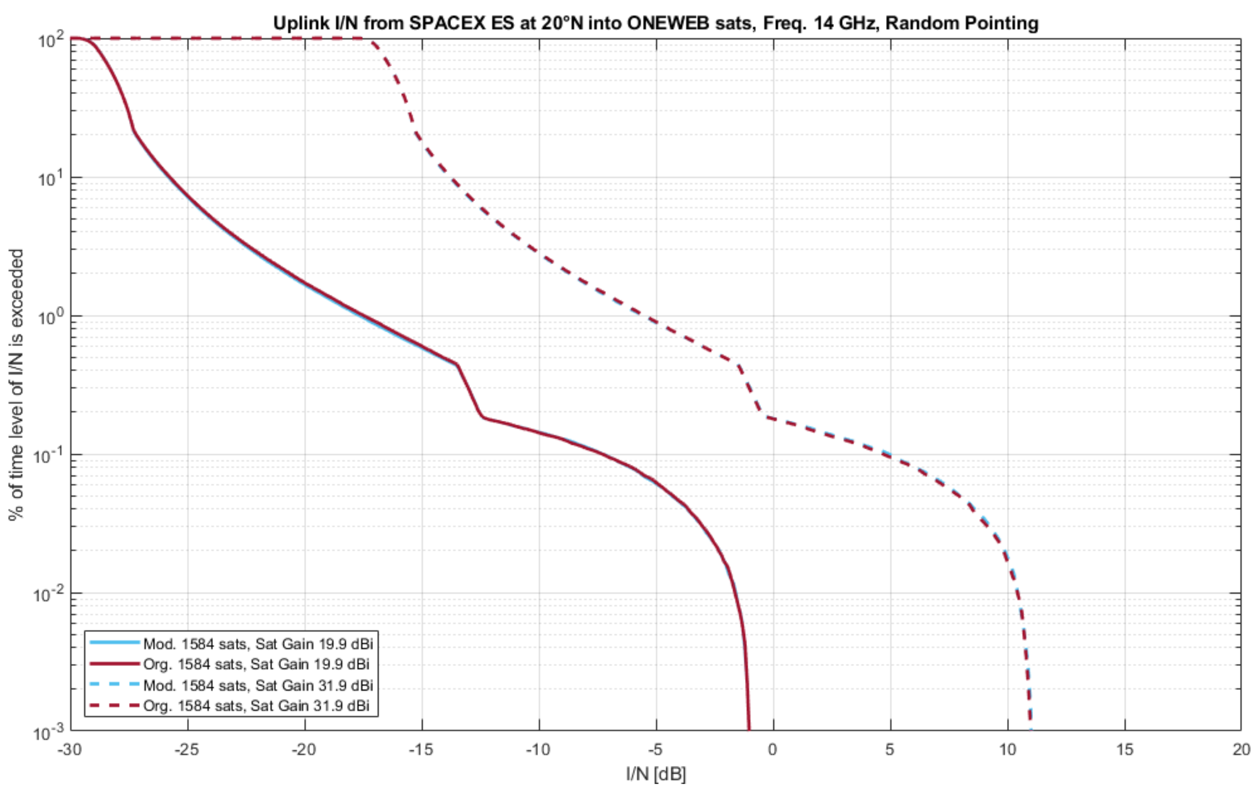


Figure A1-14. Uplink Comparison for Various OneWeb Antennas at 20ºN for Modified 550 km Shell — Random Pointing

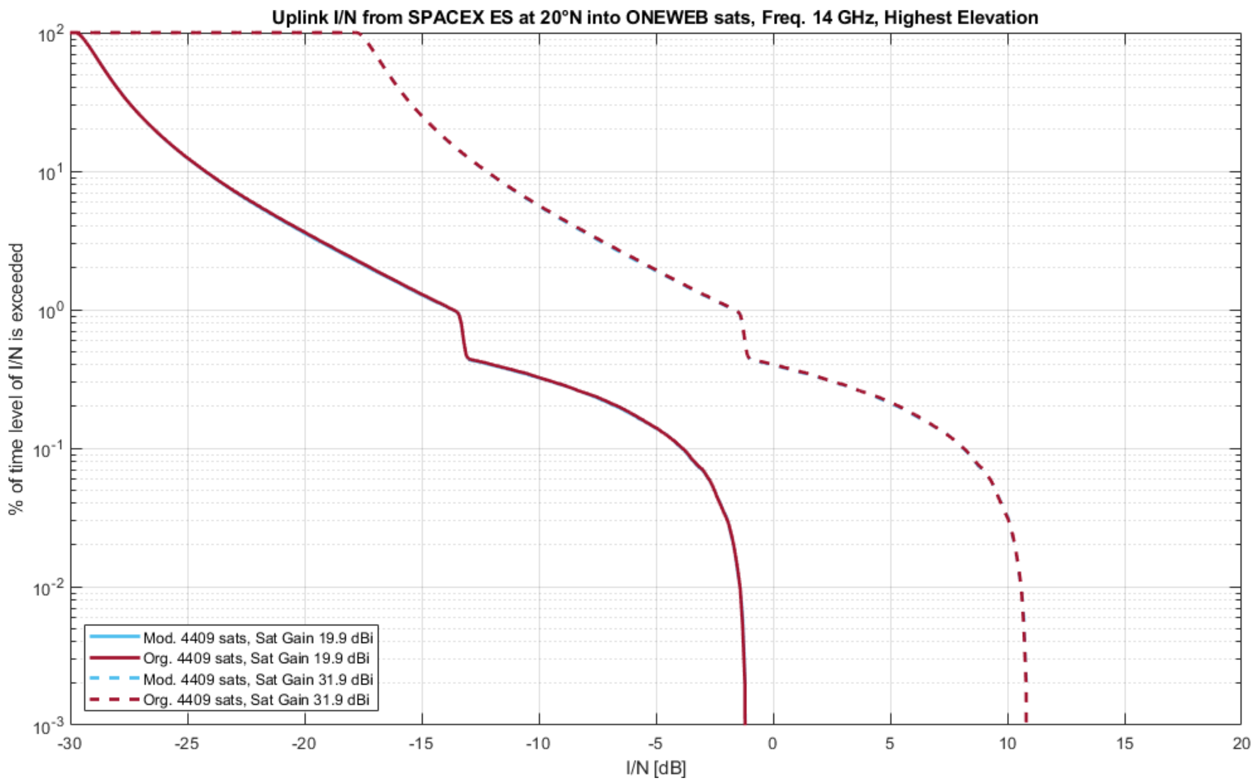


Figure A1-15. Uplink Comparison for Various OneWeb Antennas at 20ºN for Full SpaceX Constellation — Highest Elevation

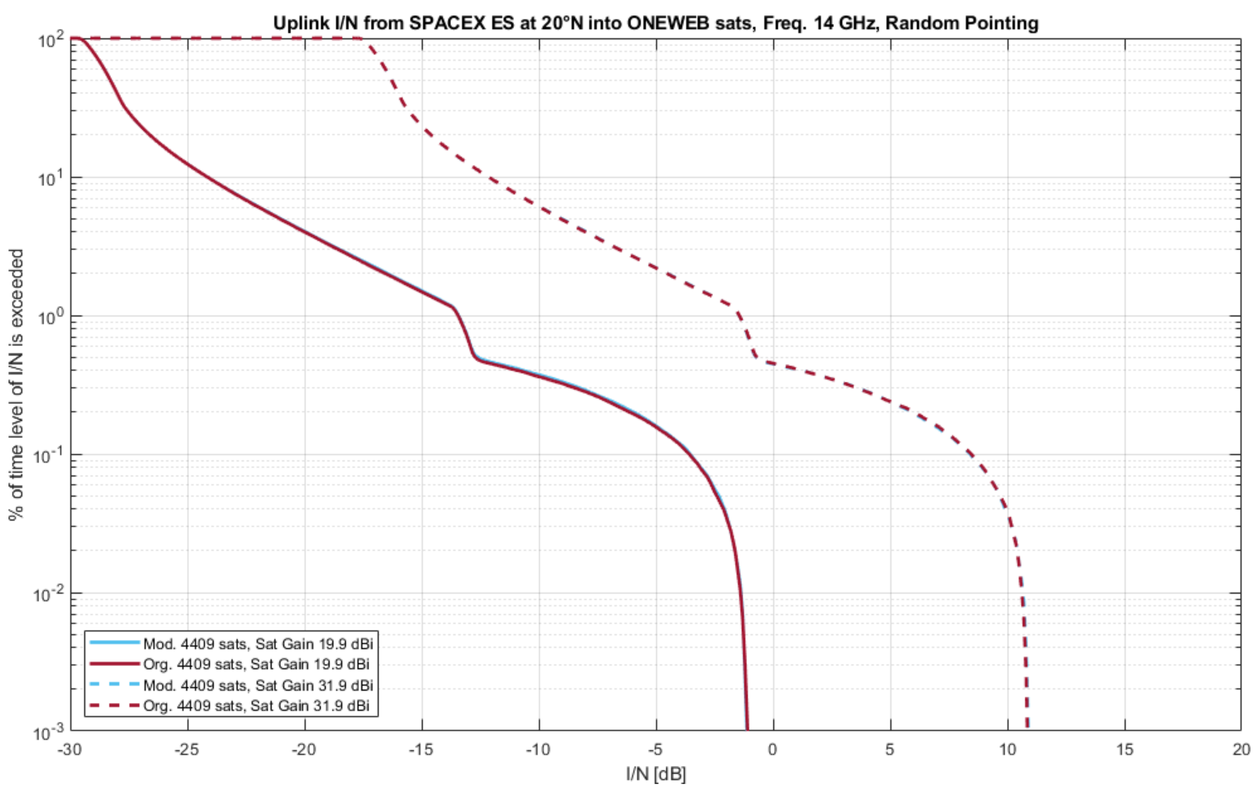


Figure A1-16. Uplink Comparison for Various OneWeb Antennas at 20ºN for Full SpaceX Constellation — Random Pointing

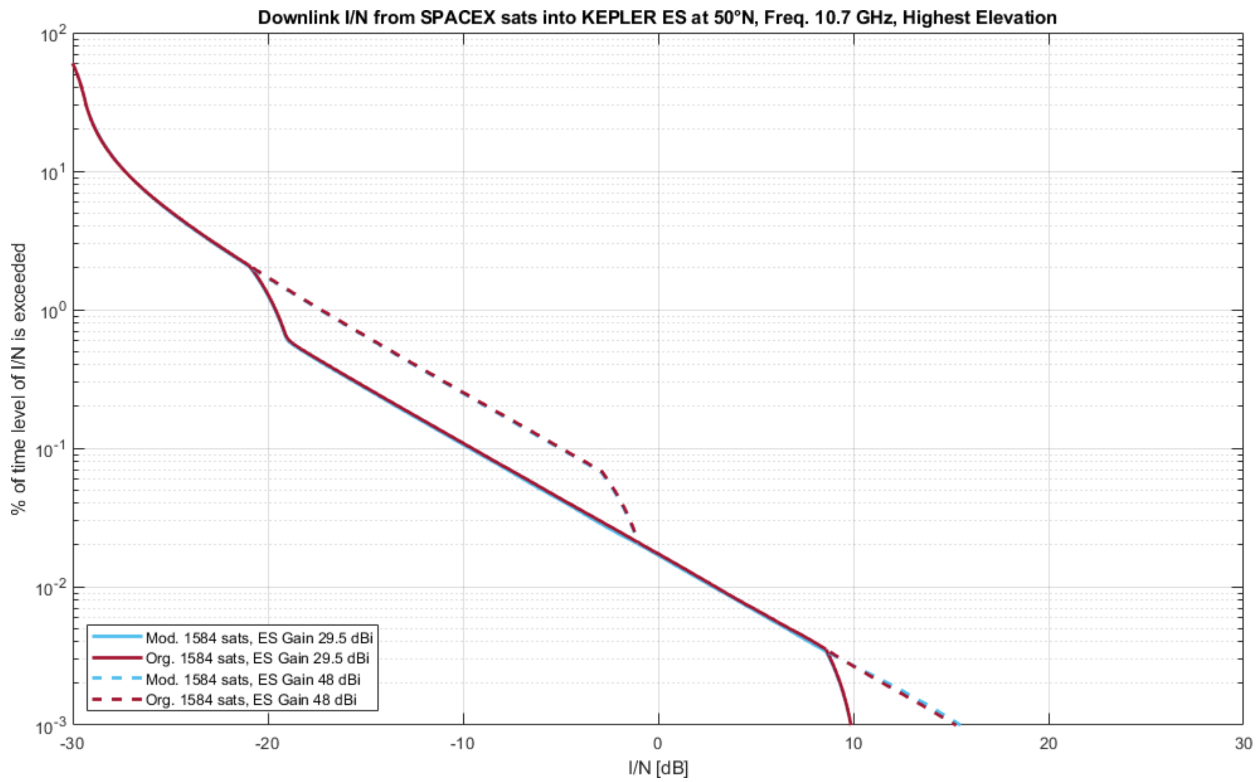


Figure A1-17. Downlink Comparison for Various Kepler Antennas at 50ºN for Modified 550 km Shell — Highest Elevation

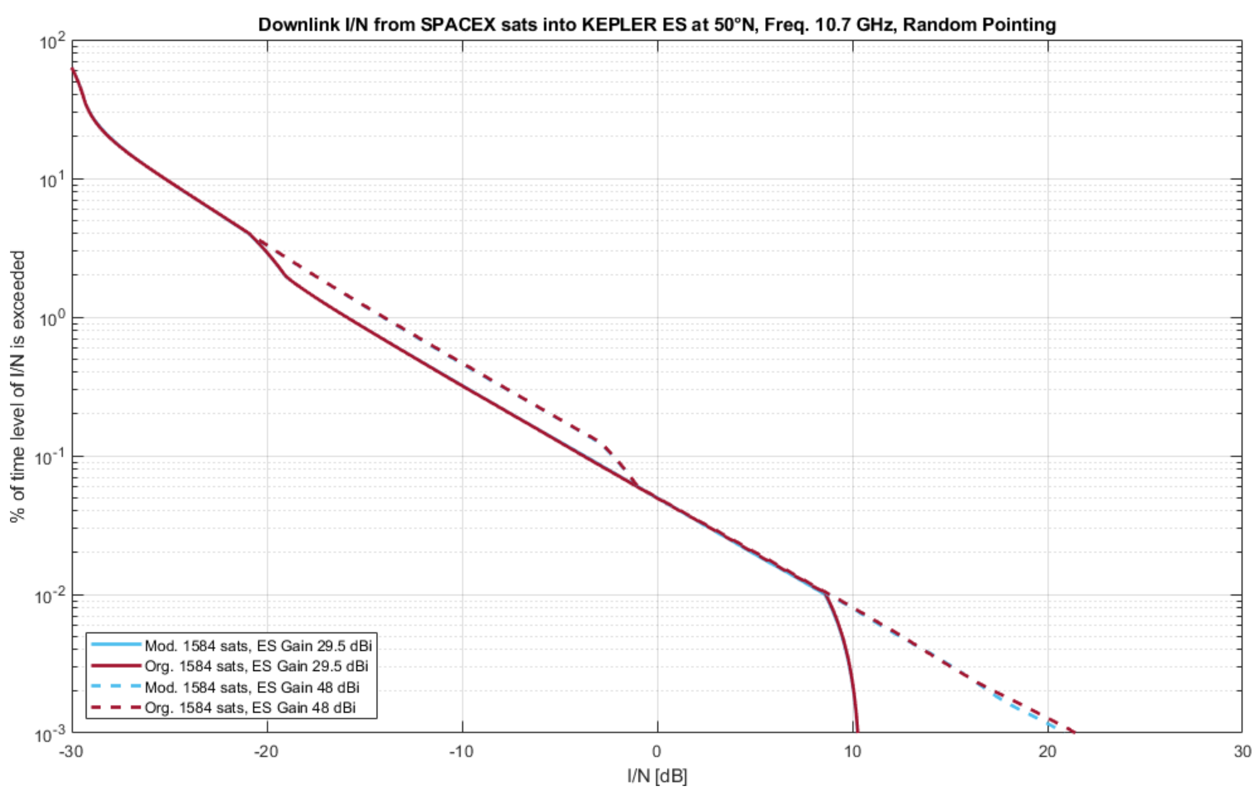


Figure A1-18. Downlink Comparison for Various Kepler Antennas at 50ºN for Modified 550 km Shell — Random Pointing

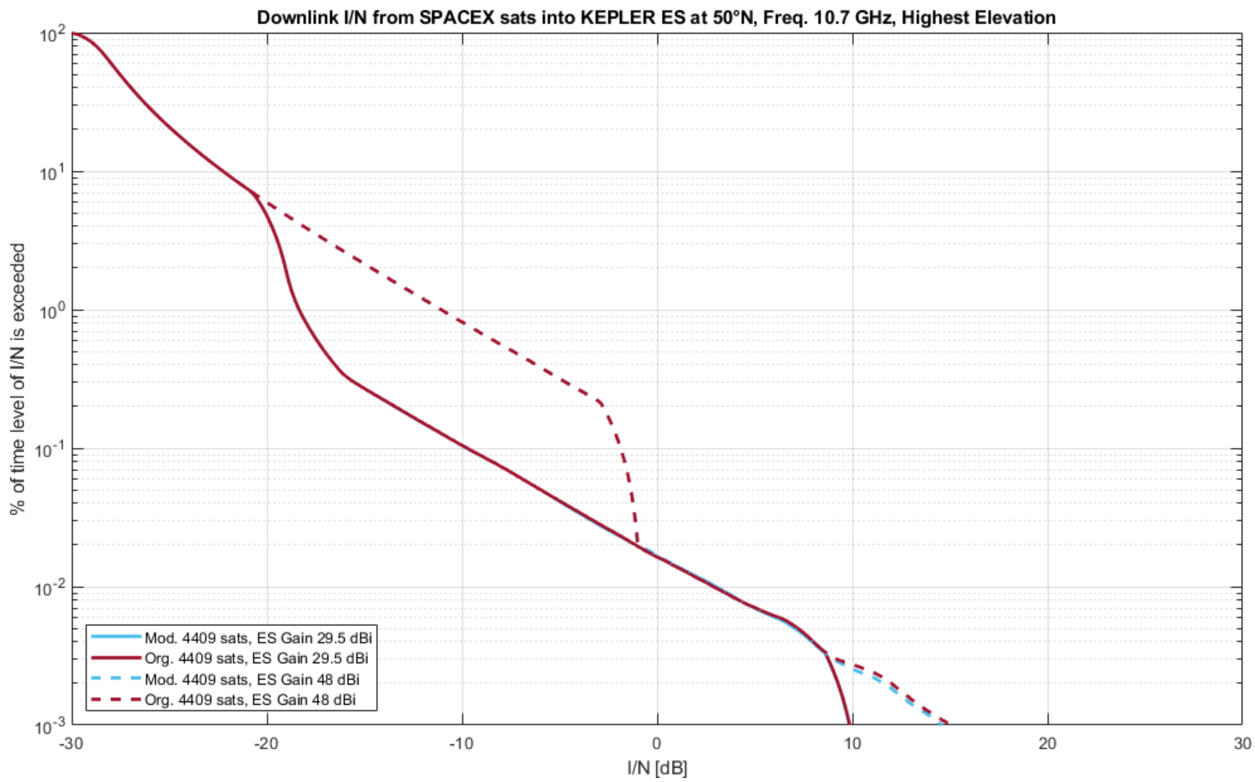


Figure A1-19. Downlink Comparison for Various Kepler Antennas at 50ºN for Full Space Constellation — Highest Elevation

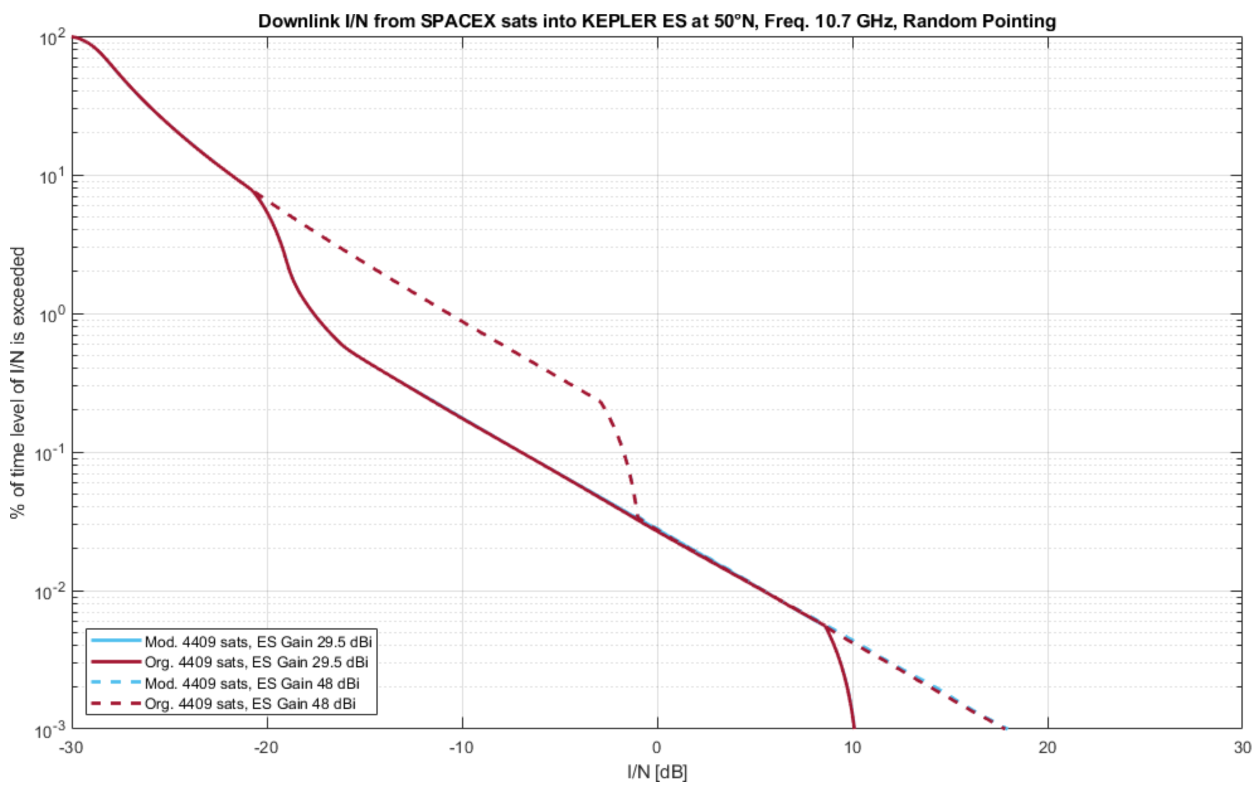


Figure A1-20. Downlink Comparison for Various Kepler Antennas at 50ºN for Full SpaceX Constellation — Random Pointing

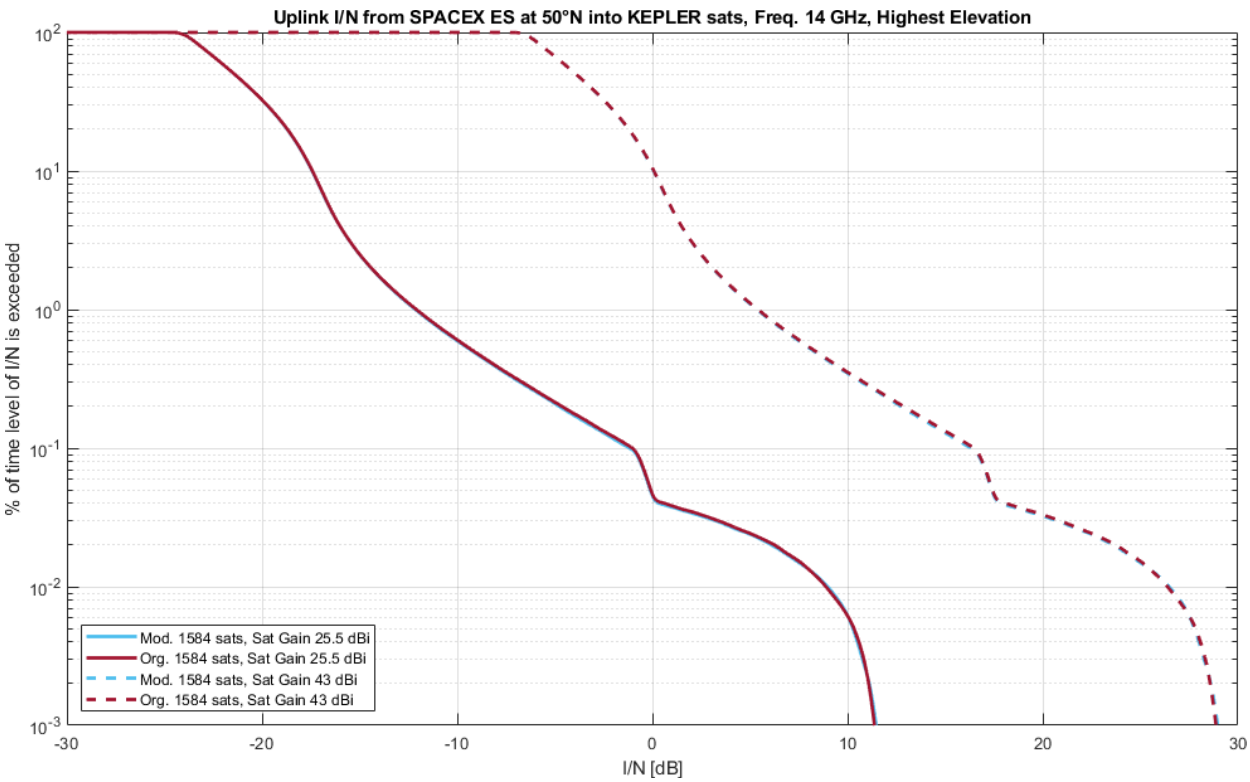


Figure A1-21. Uplink Comparison for Various Kepler Antennas at 50ºN for Modified 550 km Shell — Highest Elevation

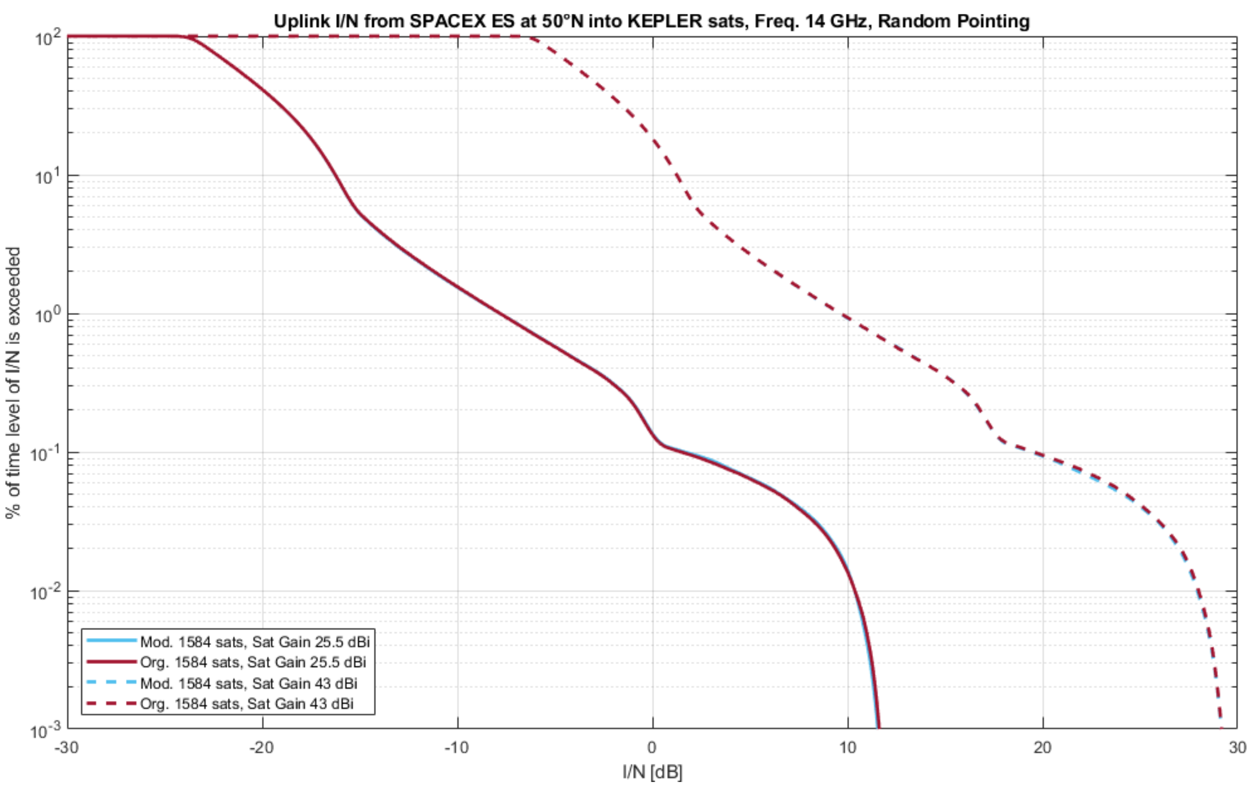


Figure A1-22. Uplink Comparison for Various Kepler Antennas at 50ºN for Modified 550 km Shell — Random Pointing

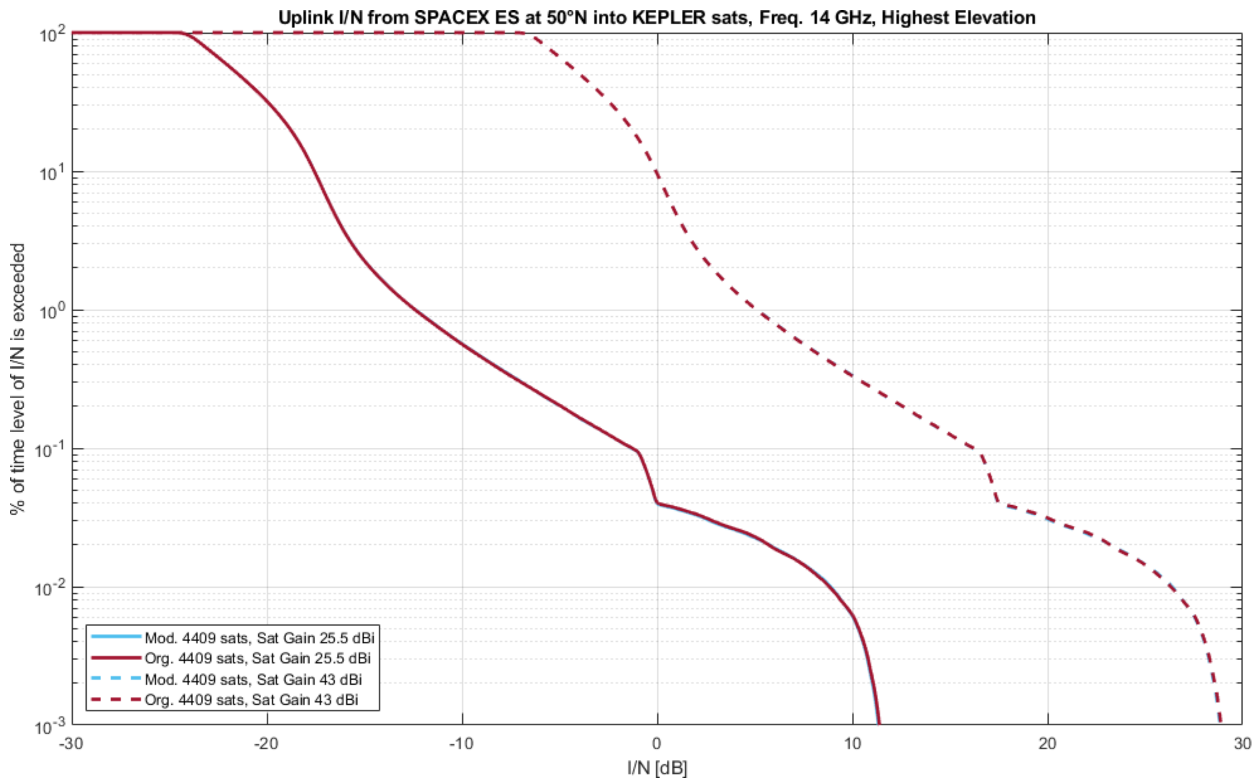


Figure A1-23. Uplink Comparison for Various Kepler Antennas at 50ºN for Full SpaceX Constellation — Highest Elevation

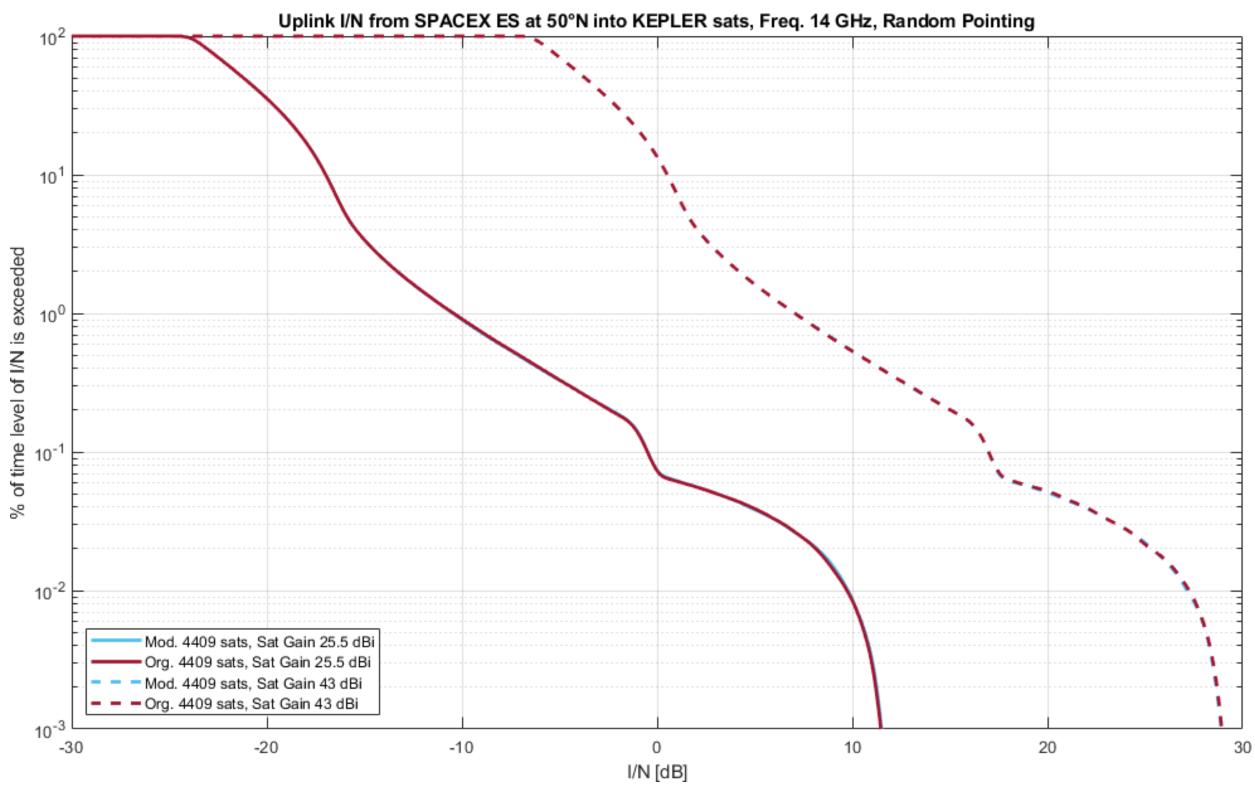


Figure A1-24. Uplink Comparison for Various Kepler Antennas at 50ºN for Full SpaceX Constellation — Random Pointing

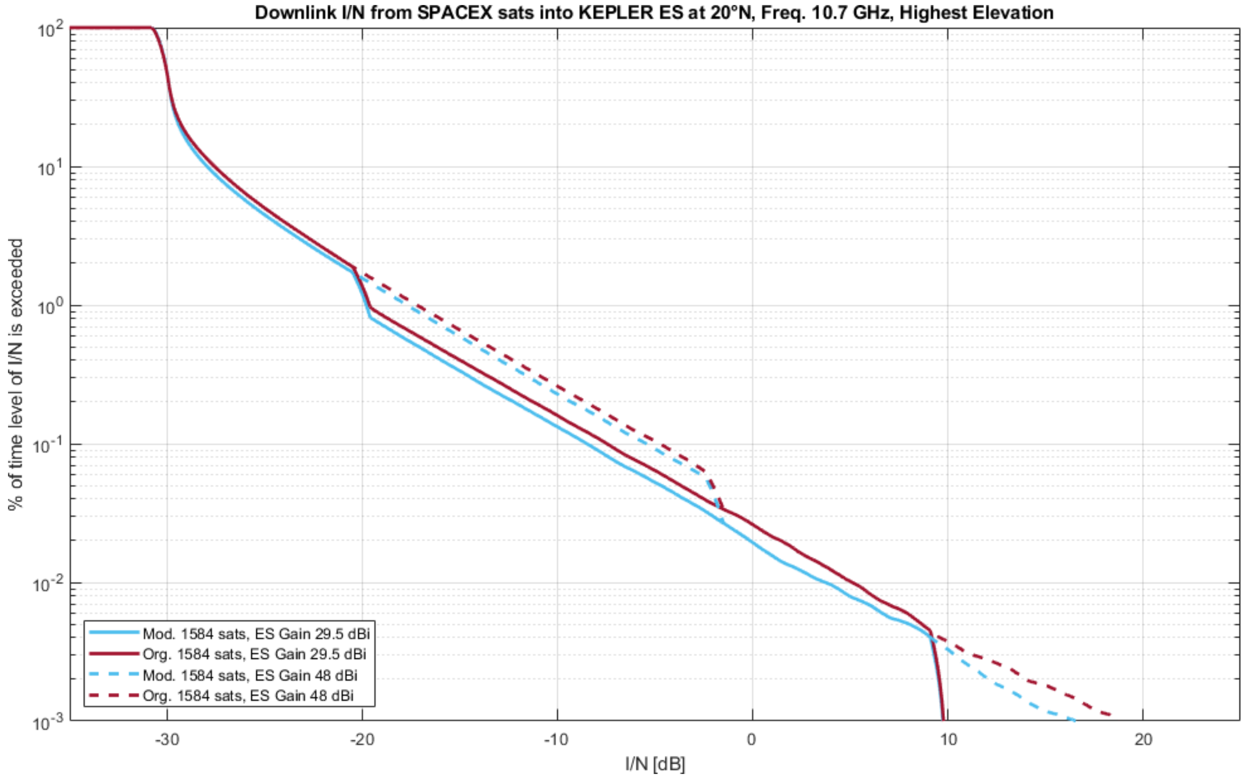


Figure A1-25. Downlink Comparison for Various Kepler Antennas at 20ºN for Modified 550 km Shell — Highest Elevation

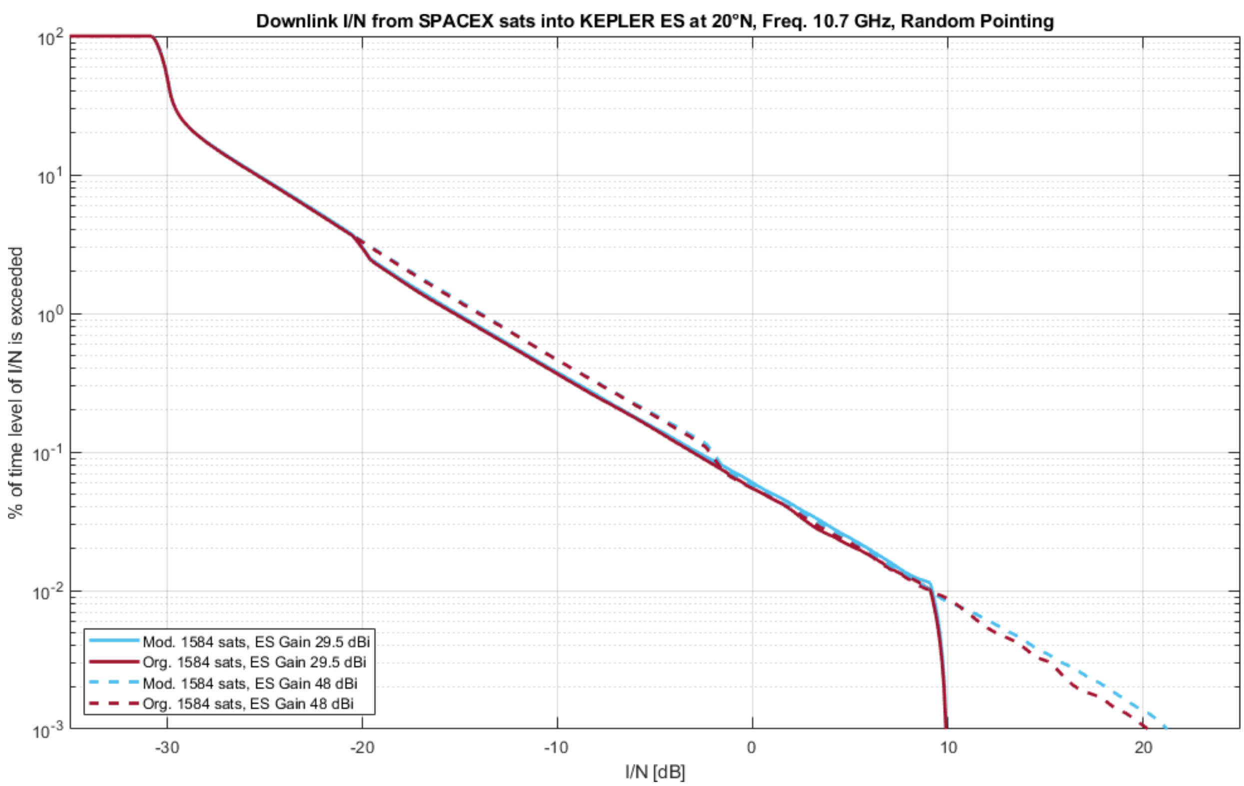


Figure A1-26. Downlink Comparison for Various Kepler Antennas at 20ºN for Modified 550 km Shell — Random Pointing

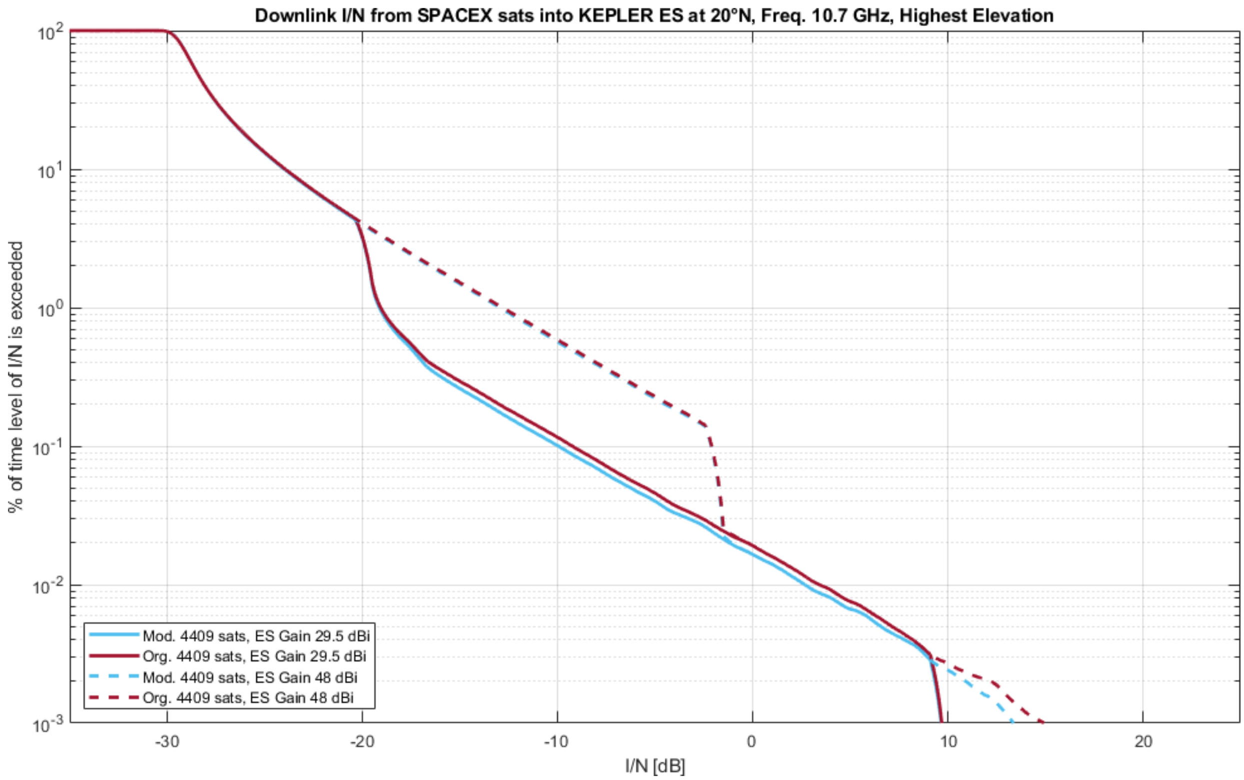


Figure A1-27. Downlink Comparison for Various Kepler Antennas at 20ºN for Full Space Constellation — Highest Elevation

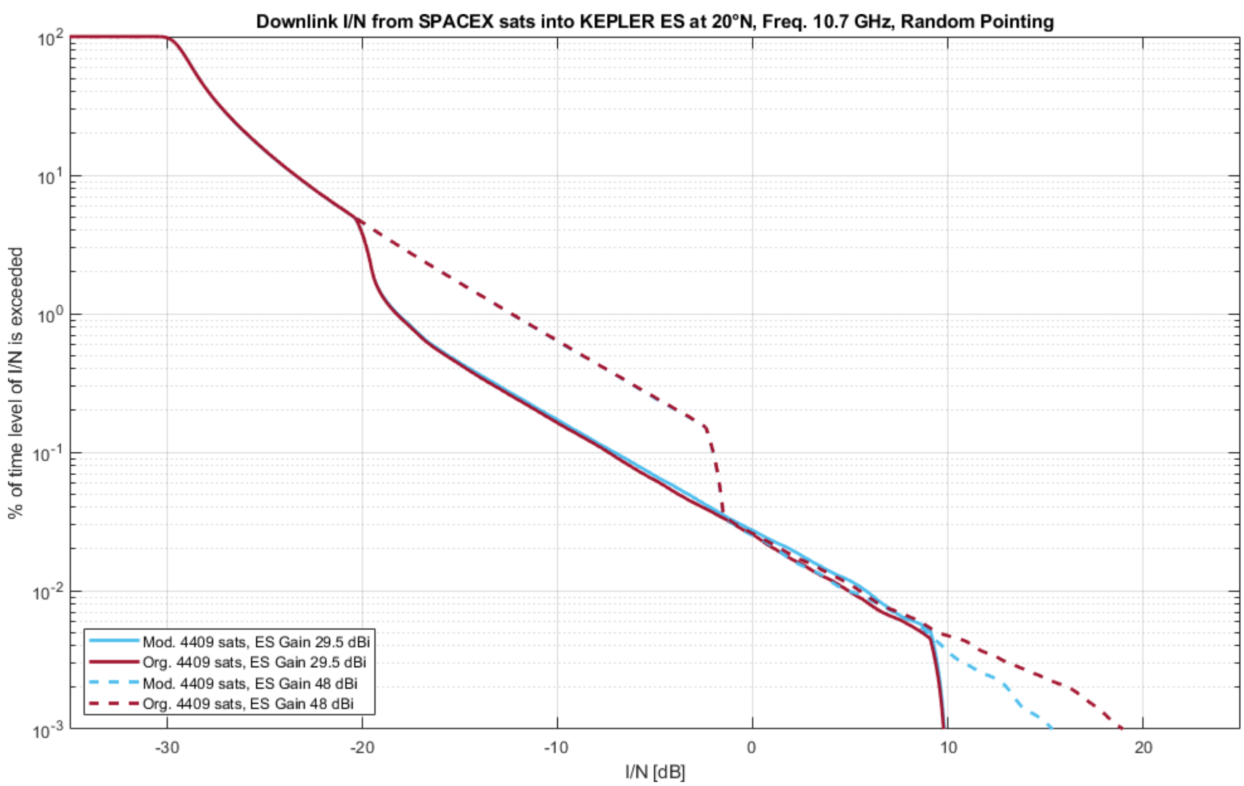


Figure A1-28. Downlink Comparison for Various Kepler Antennas at 20ºN for Full SpaceX Constellation — Random Pointing

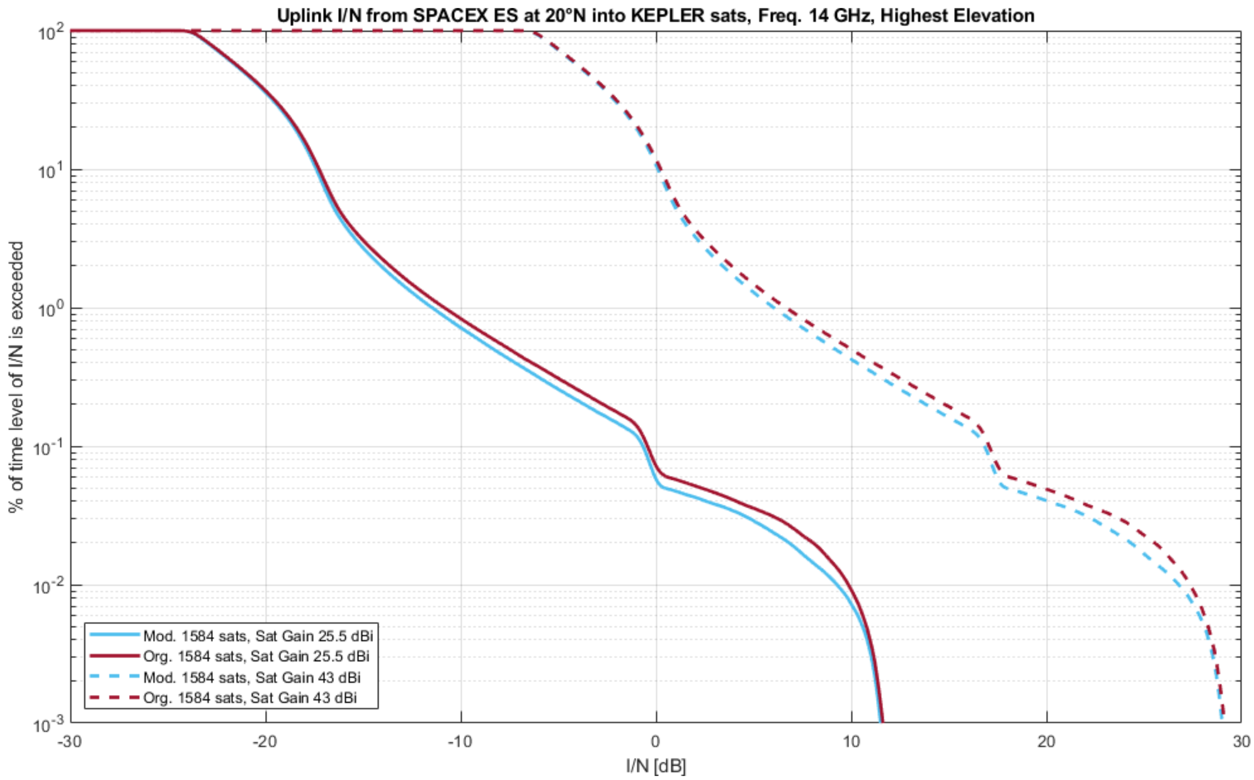


Figure A1-29. Uplink Comparison for Various Kepler Antennas at 20ºN for Modified 550 km Shell — Highest Elevation

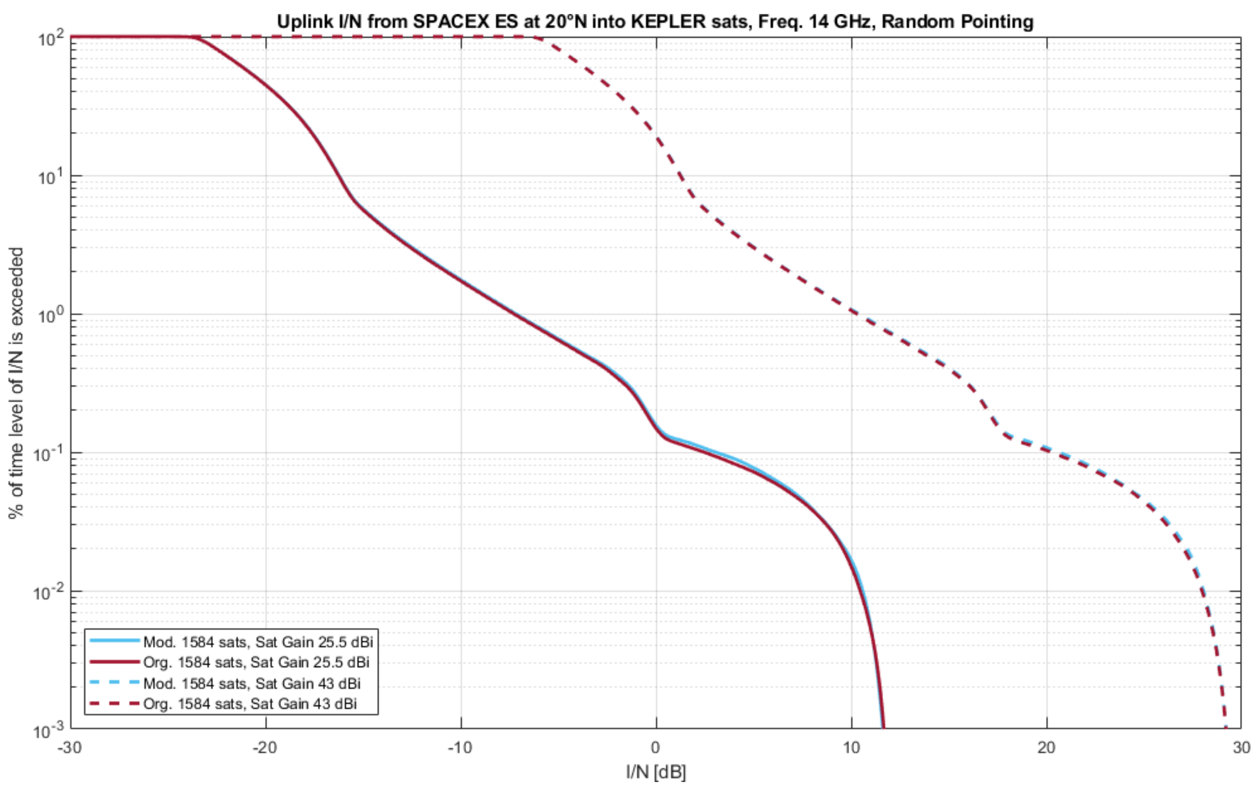


Figure A1-30. Uplink Comparison for Various Kepler Antennas at 20ºN for Modified 550 km Shell — Random Pointing

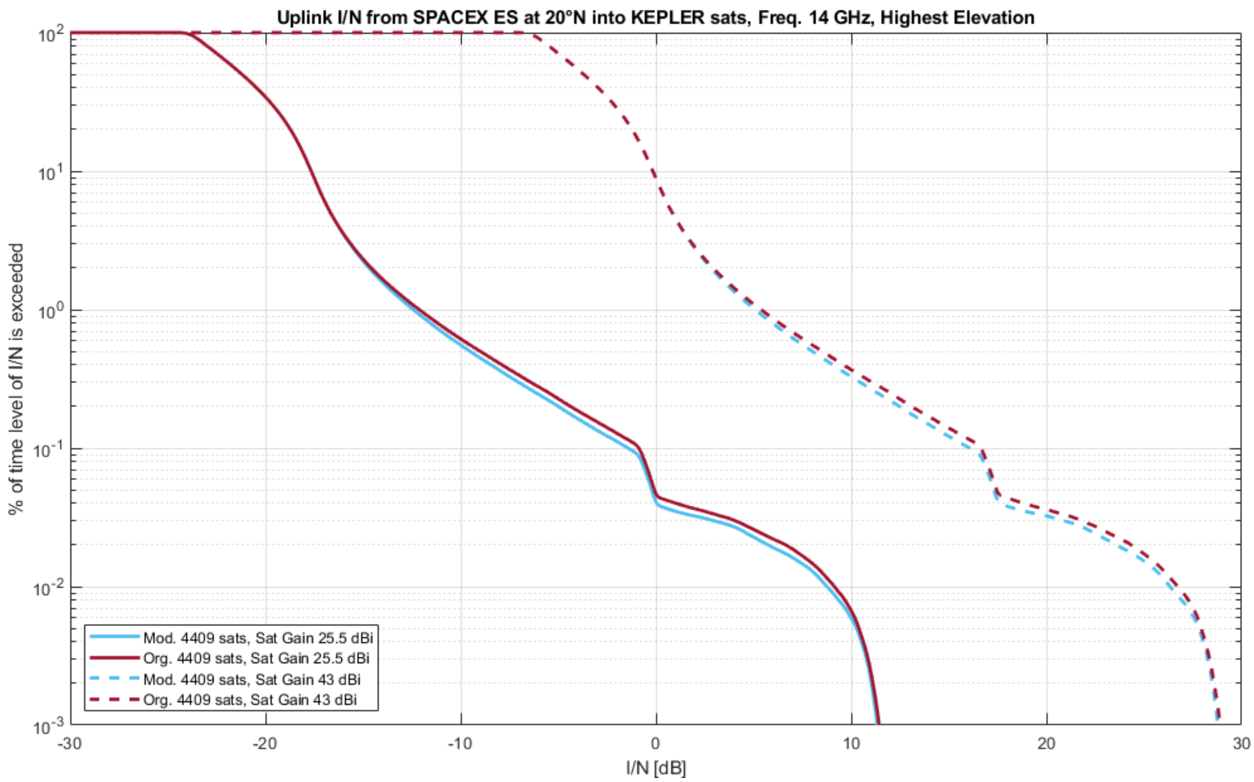


Figure A1-31. Uplink Comparison for Various Kepler Antennas at 20ºN for Full SpaceX Constellation — Highest Elevation

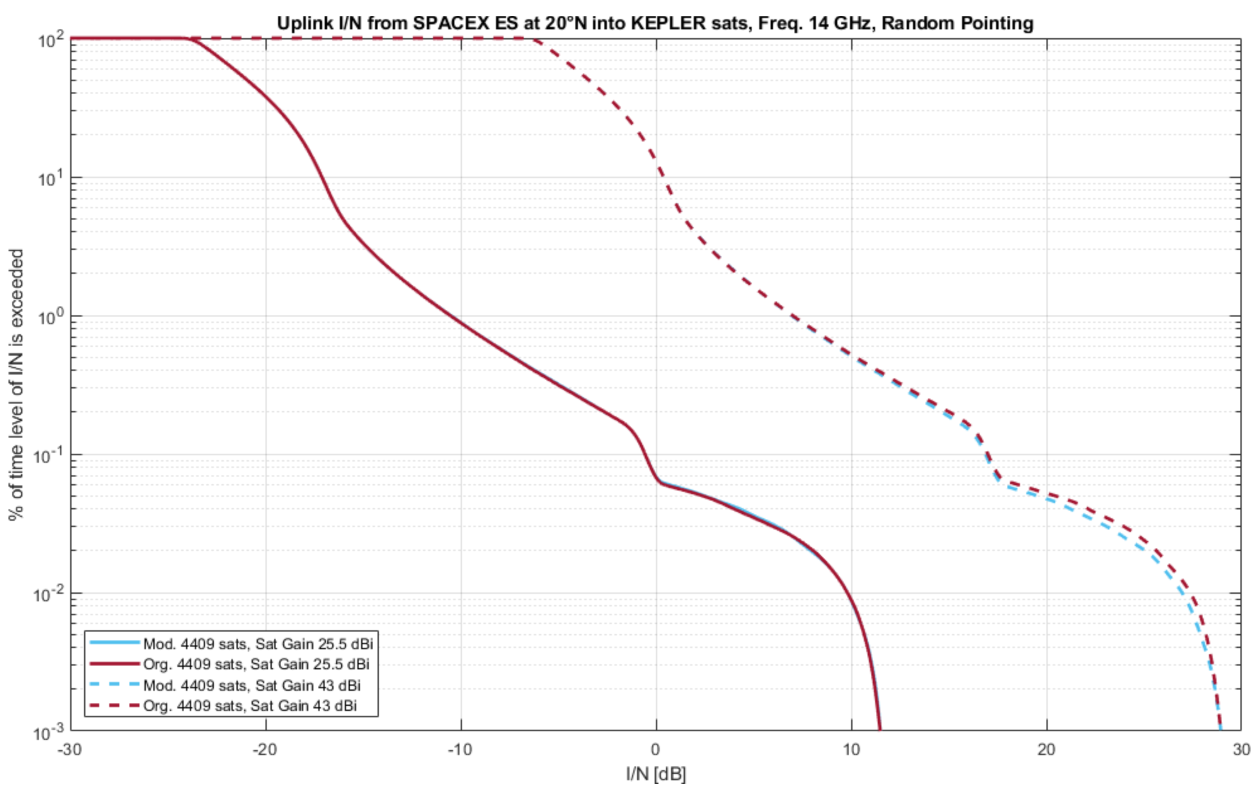


Figure A1-32. Uplink Comparison for Various Kepler Antennas at 20ºN for Full SpaceX Constellation — Random Pointing

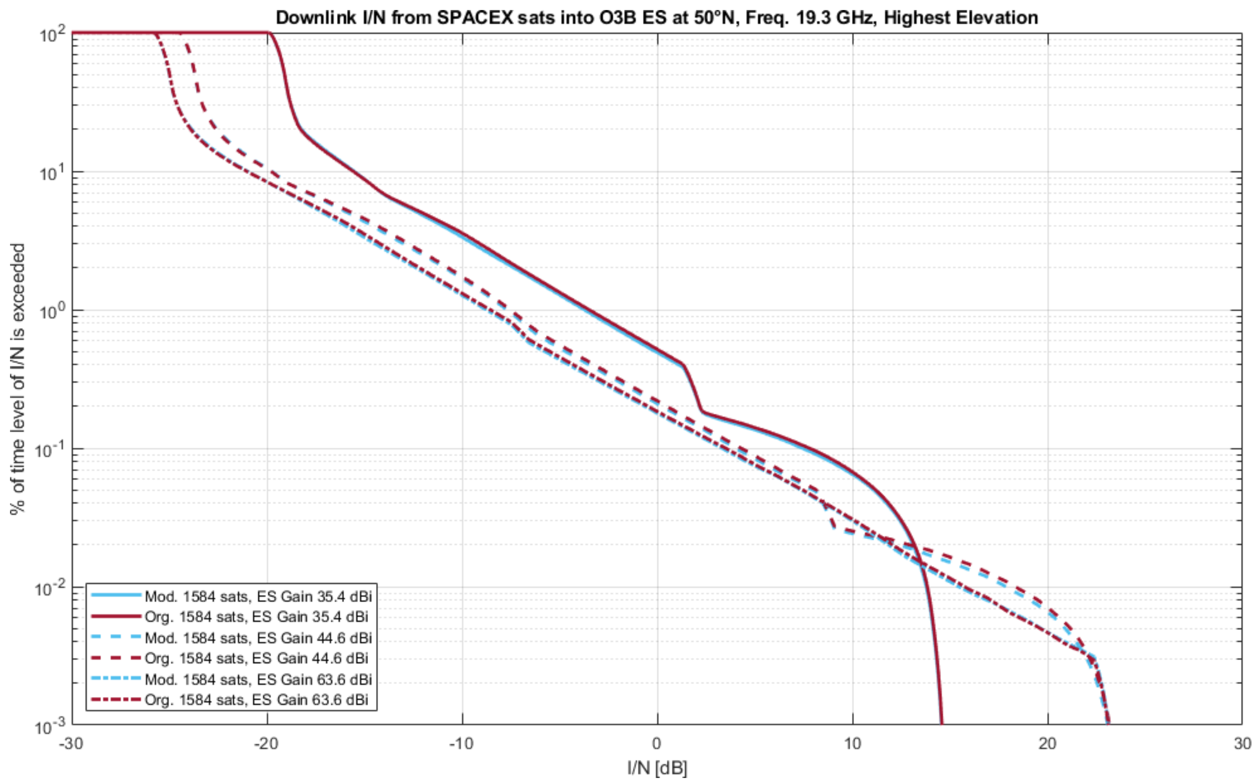


Figure A1-33. Downlink Comparison for Various O3B Antennas at 50ºN for Modified 550 km Shell — Highest Elevation

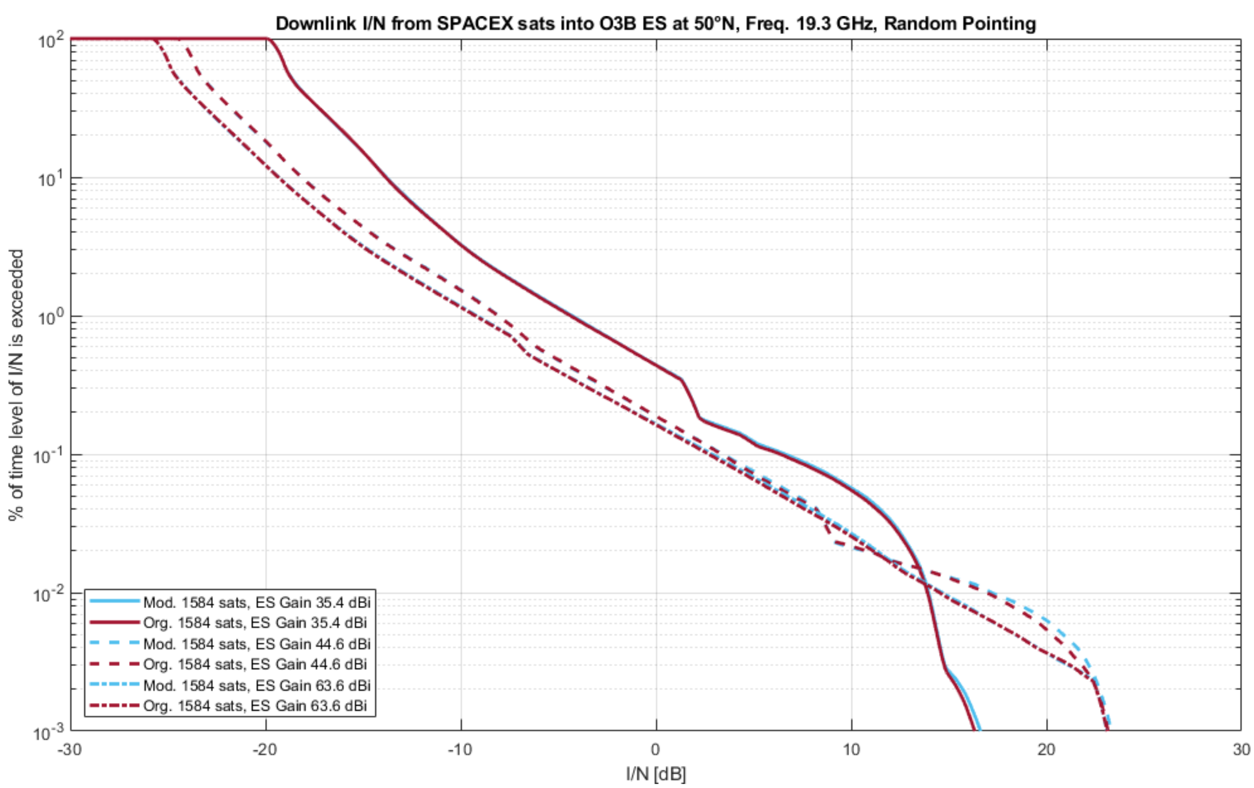


Figure A1-34. Downlink Comparison for Various O3B Antennas at 50ºN for Modified 550 km Shell — Random Pointing

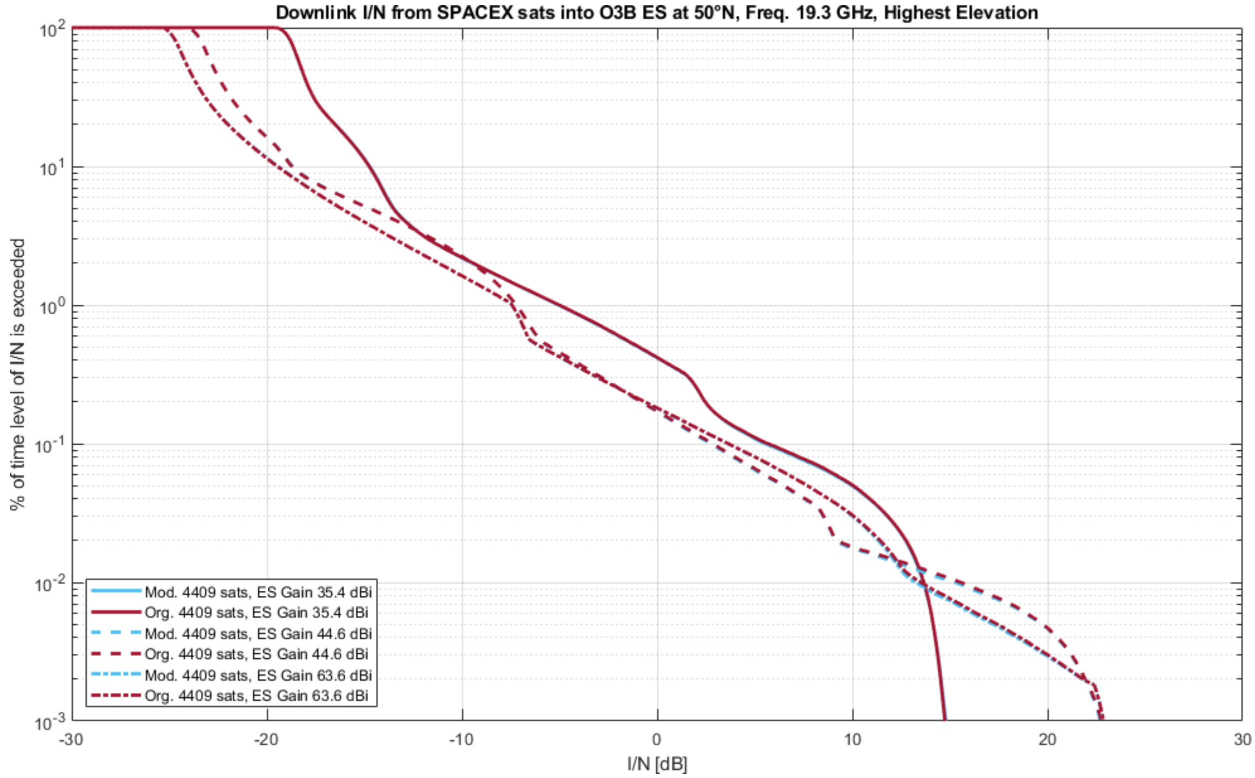


Figure A1-35. Downlink Comparison for Various O3B Antennas at 50ºN for Full Space Constellation — Highest Elevation

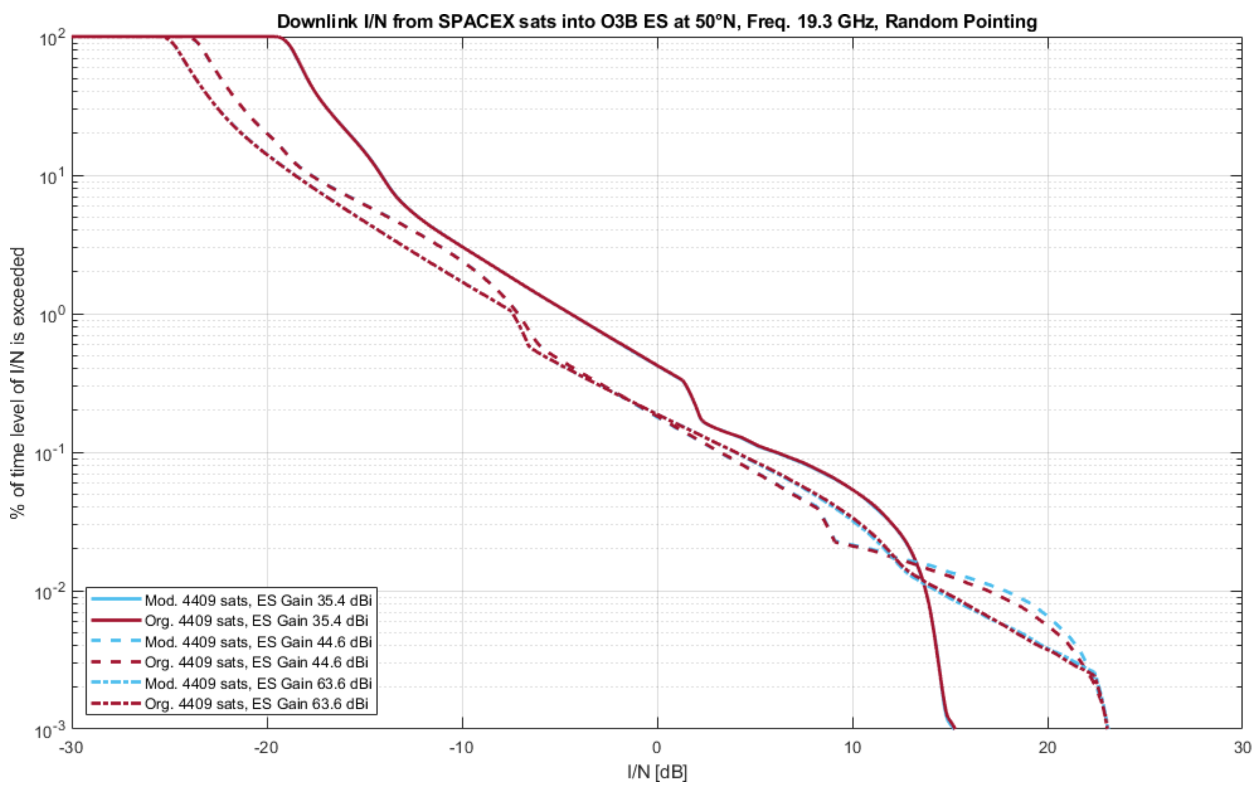


Figure A1-36. Downlink Comparison for Various O3B Antennas at 50ºN for Full SpaceX Constellation — Random Pointing

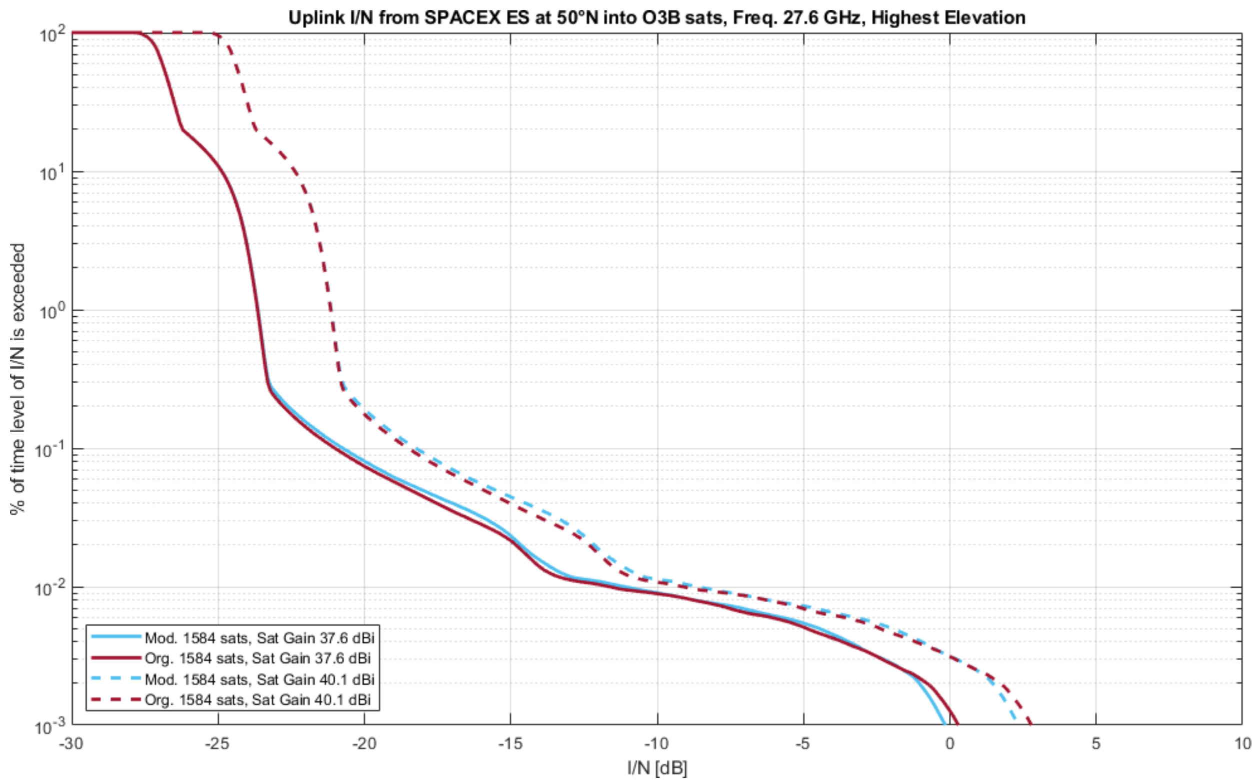


Figure A1-37. Uplink Comparison for Various O3B Antennas at 50ºN for Modified 550 km Shell — Highest Elevation

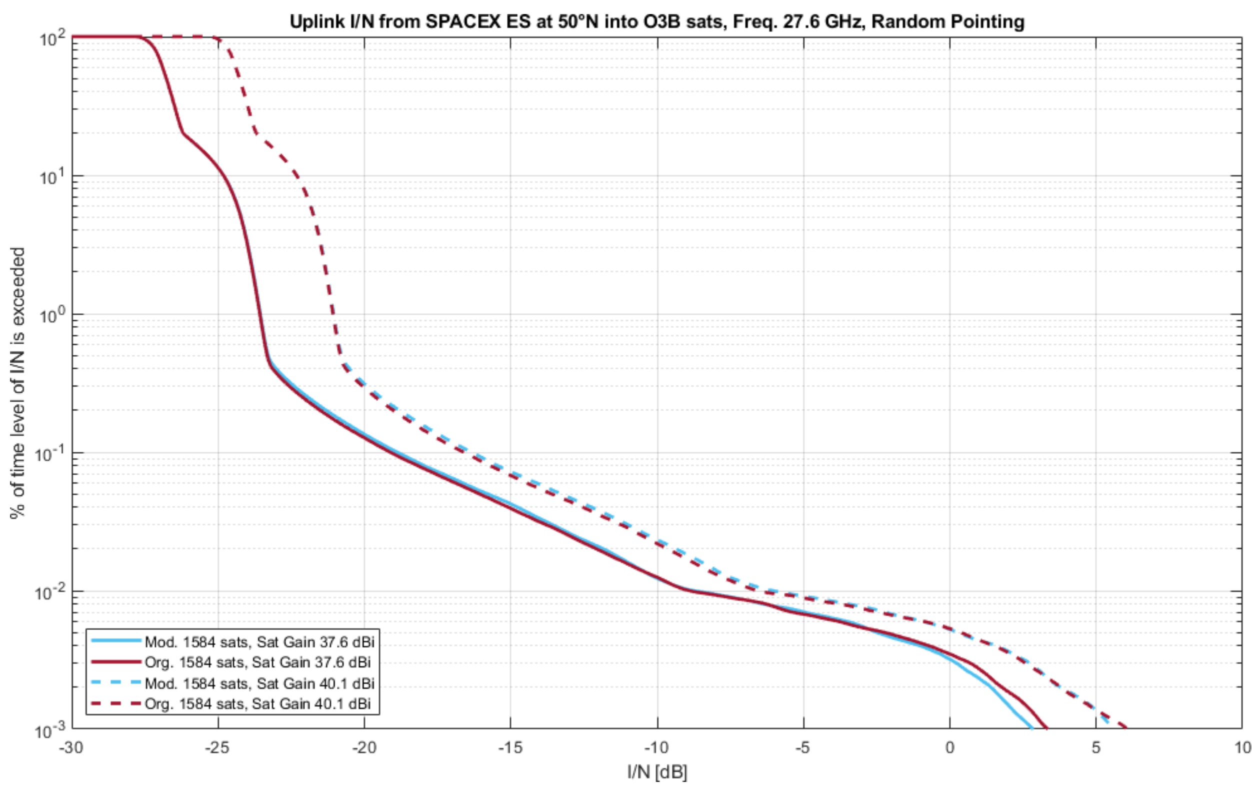


Figure A1-38. Uplink Comparison for Various O3B Antennas at 50ºN for Modified 550 km Shell — Random Pointing

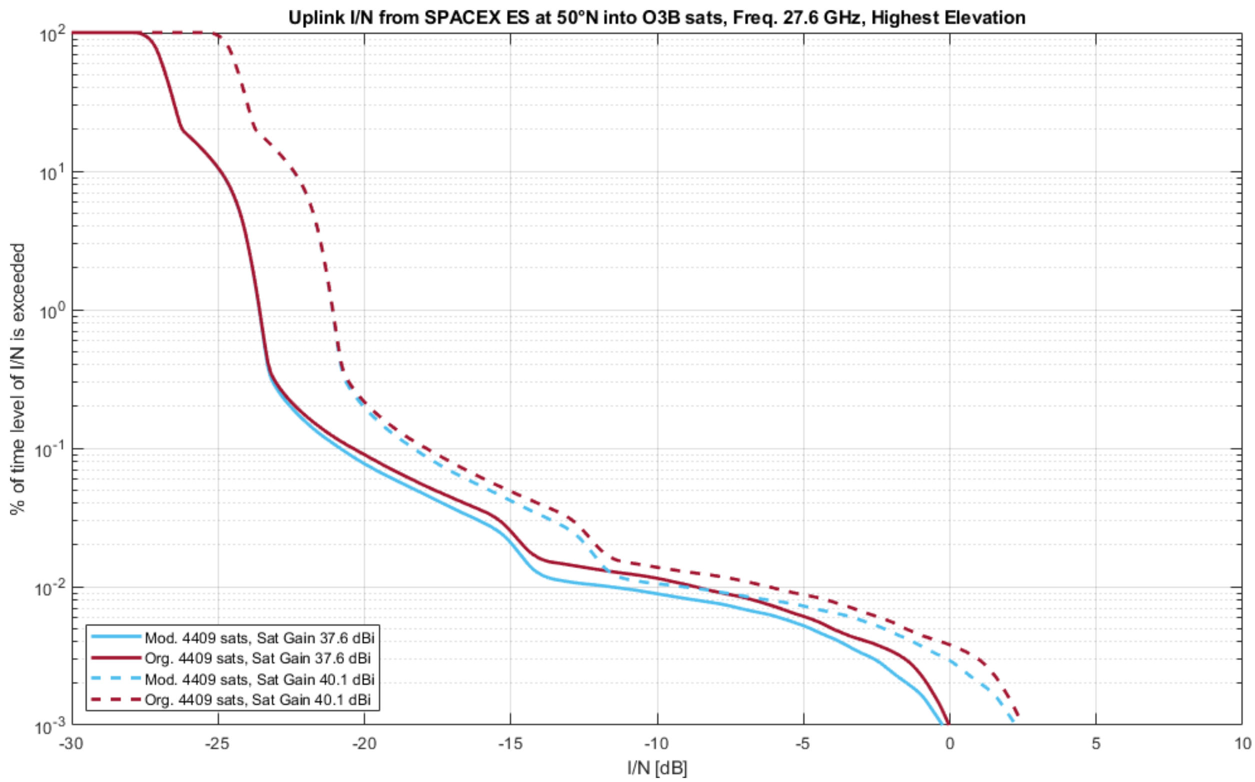


Figure A1-39. Uplink Comparison for Various O3B Antennas at 50ºN for Full SpaceX Constellation — Highest Elevation

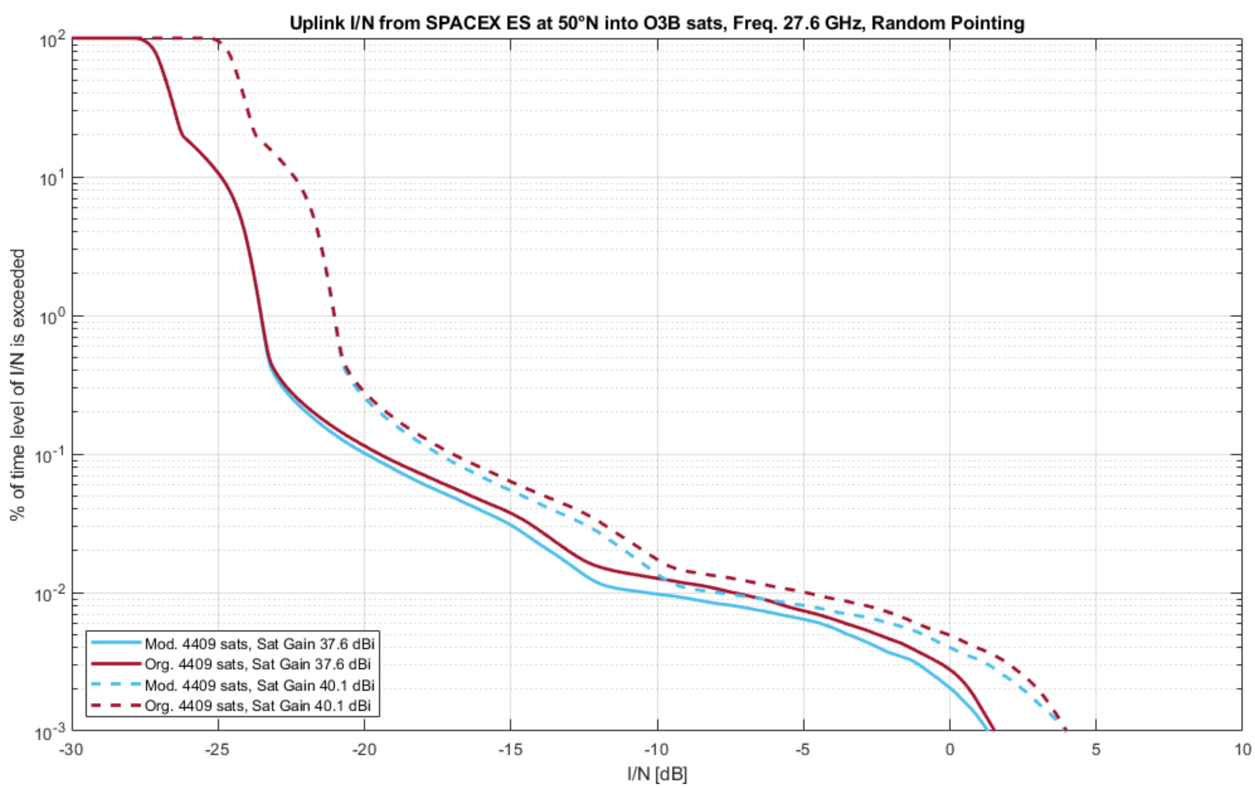


Figure A1-40. Uplink Comparison for Various O3B Antennas at 50ºN for Full SpaceX Constellation — Random Pointing

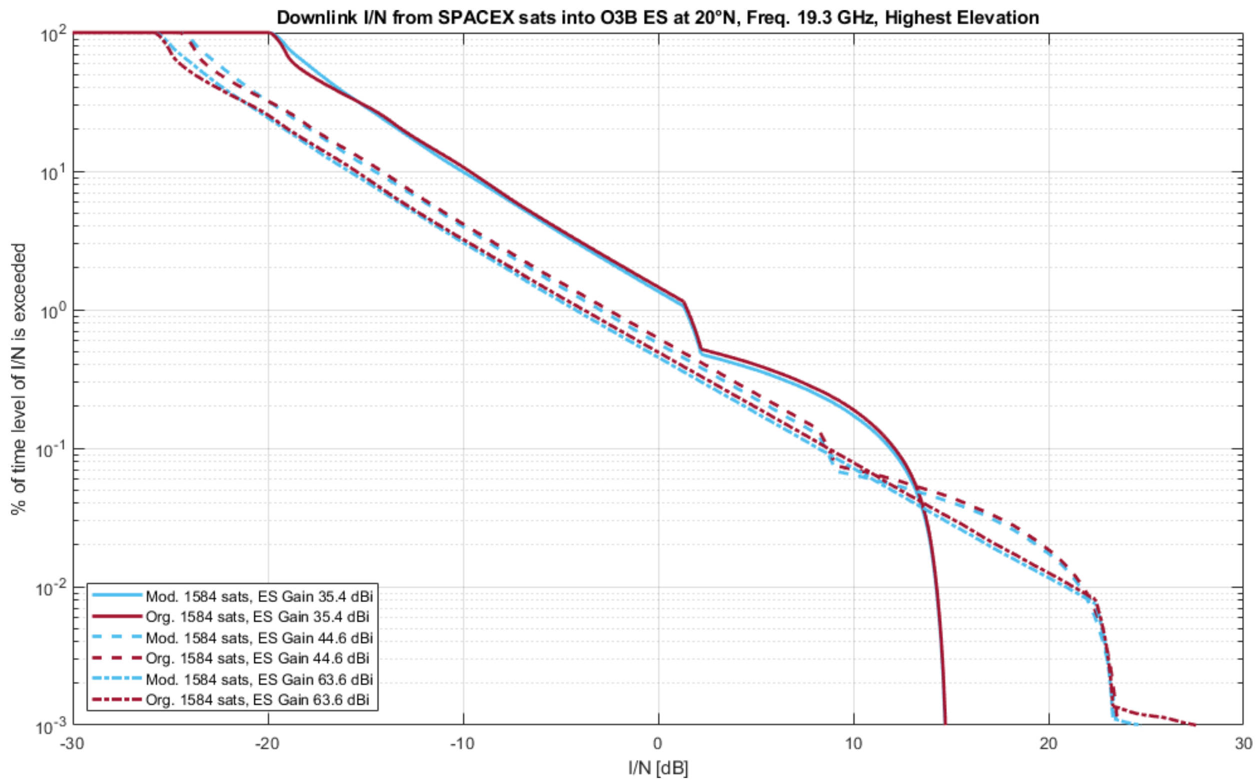


Figure A1-41. Downlink Comparison for Various O3B Antennas at 20ºN for Modified 550 km Shell — Highest Elevation

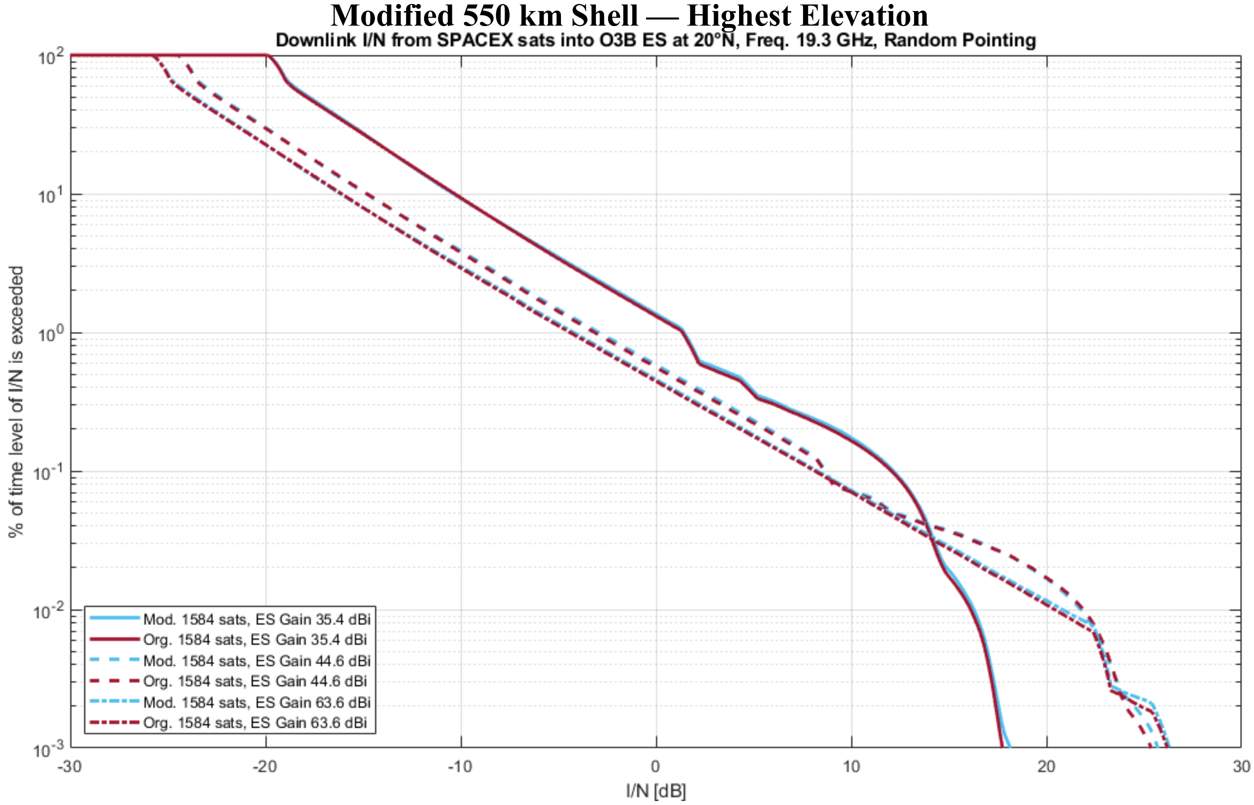


Figure A1-42. Downlink Comparison for Various O3B Antennas at 20ºN for Modified 550 km Shell — Random Pointing

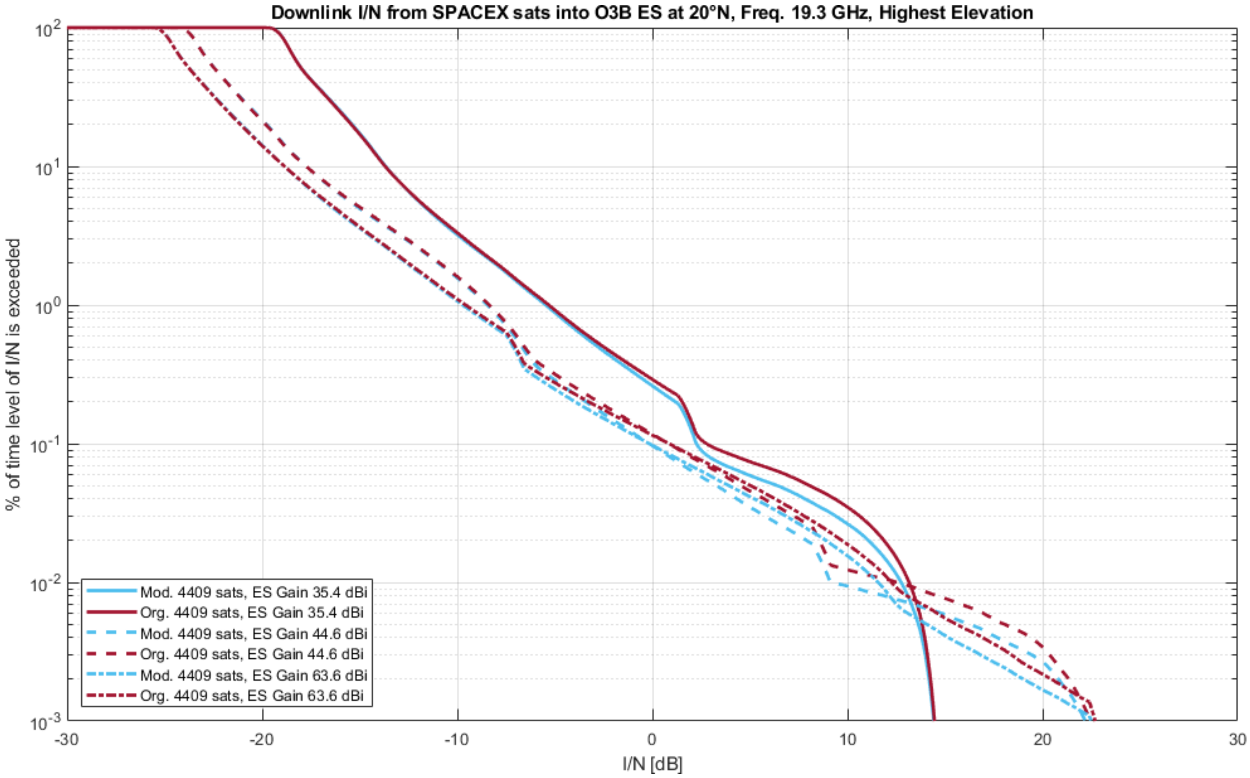


Figure A1-43. Downlink Comparison for Various O3B Antennas at 20ºN for Full Space Constellation — Highest Elevation

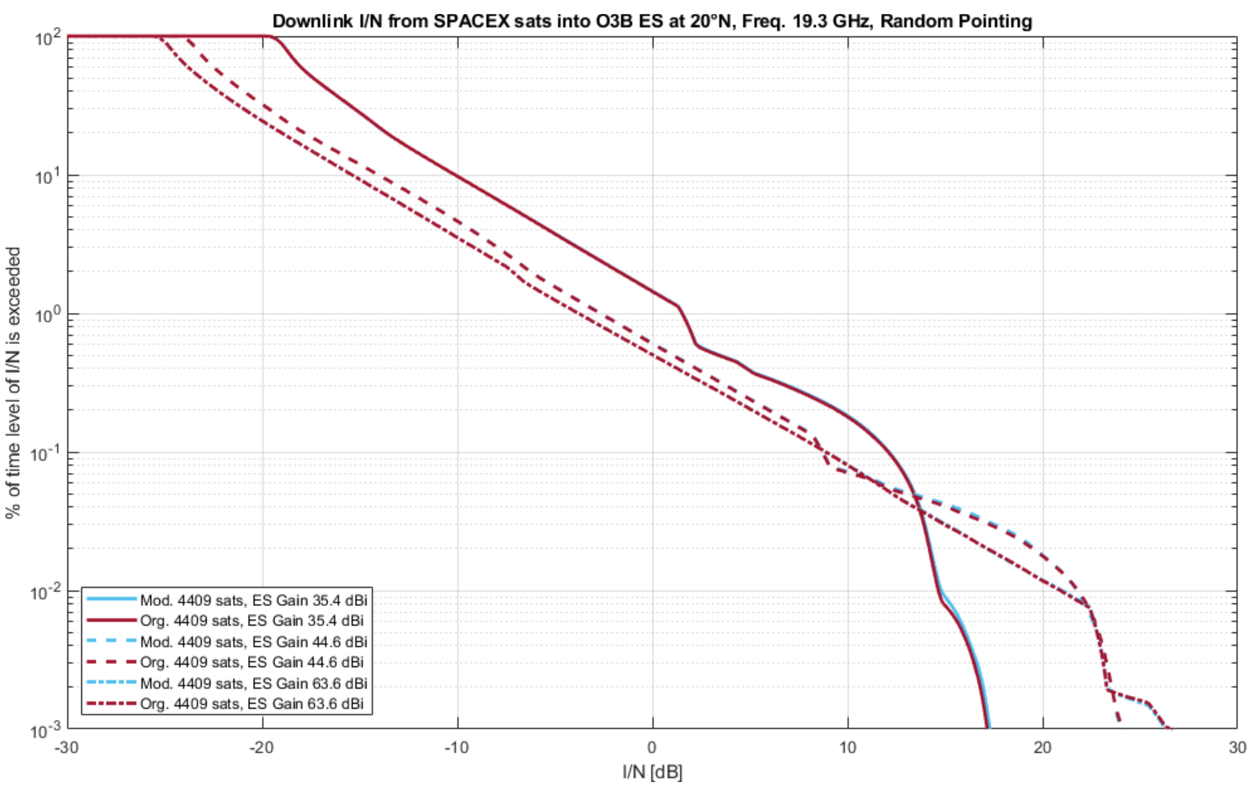


Figure A1-44. Downlink Comparison for Various O3B Antennas at 20ºN for Full SpaceX Constellation — Random Pointing

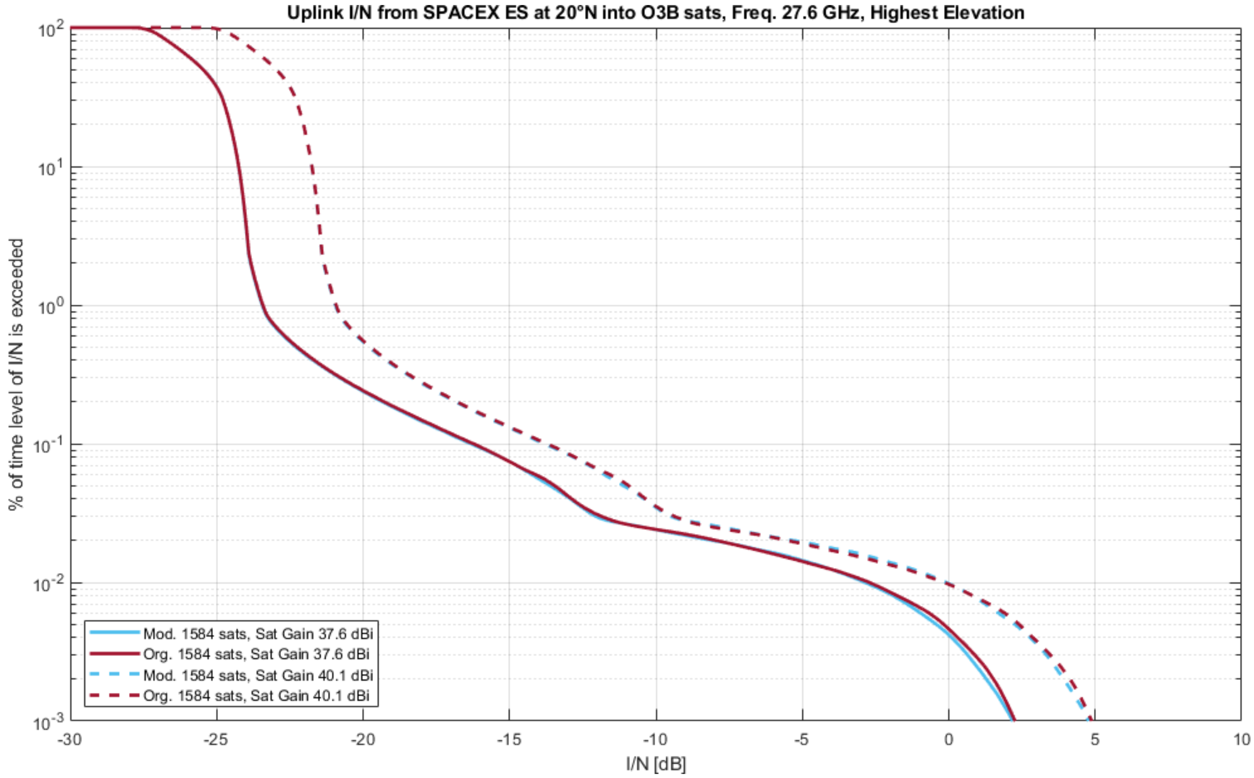


Figure A1-45. Uplink Comparison for Various O3B Antennas at 20ºN for Modified 550 km Shell — Highest Elevation

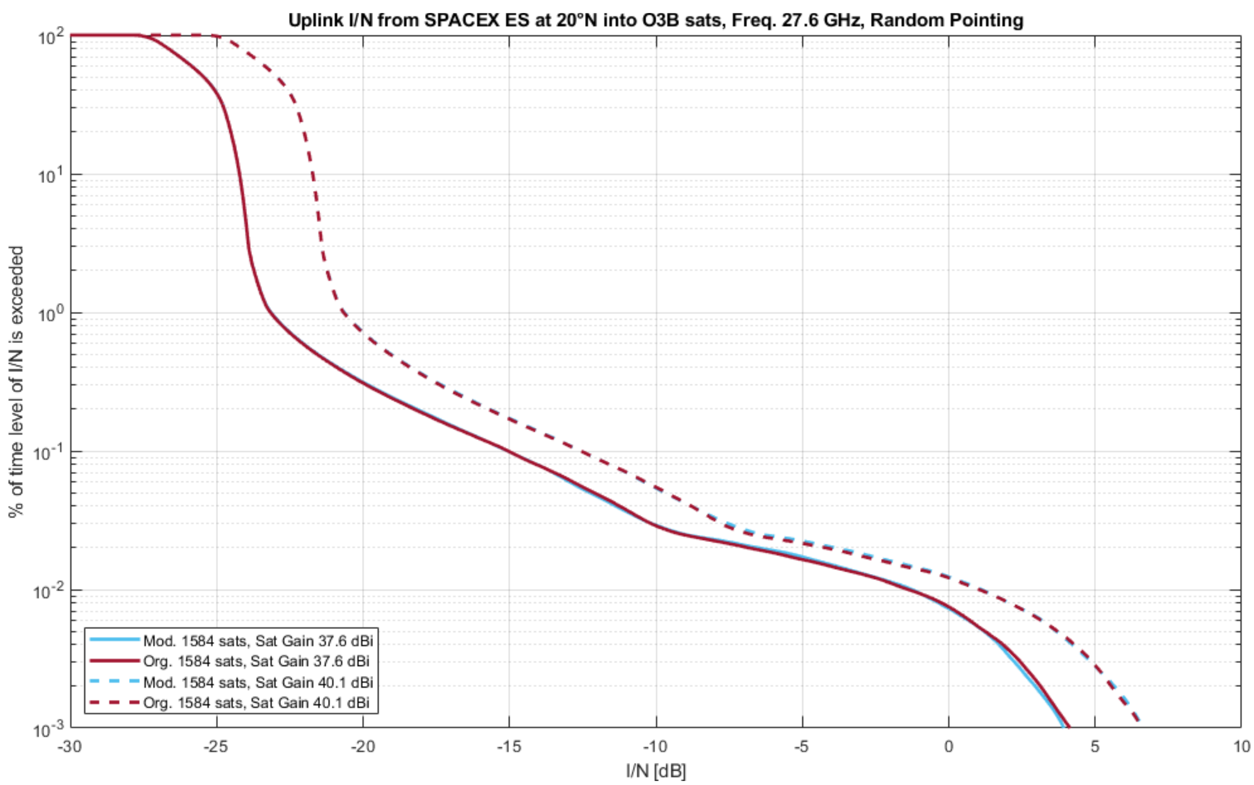


Figure A1-46. Uplink Comparison for Various O3B Antennas at 20ºN for Modified 550 km Shell — Random Pointing

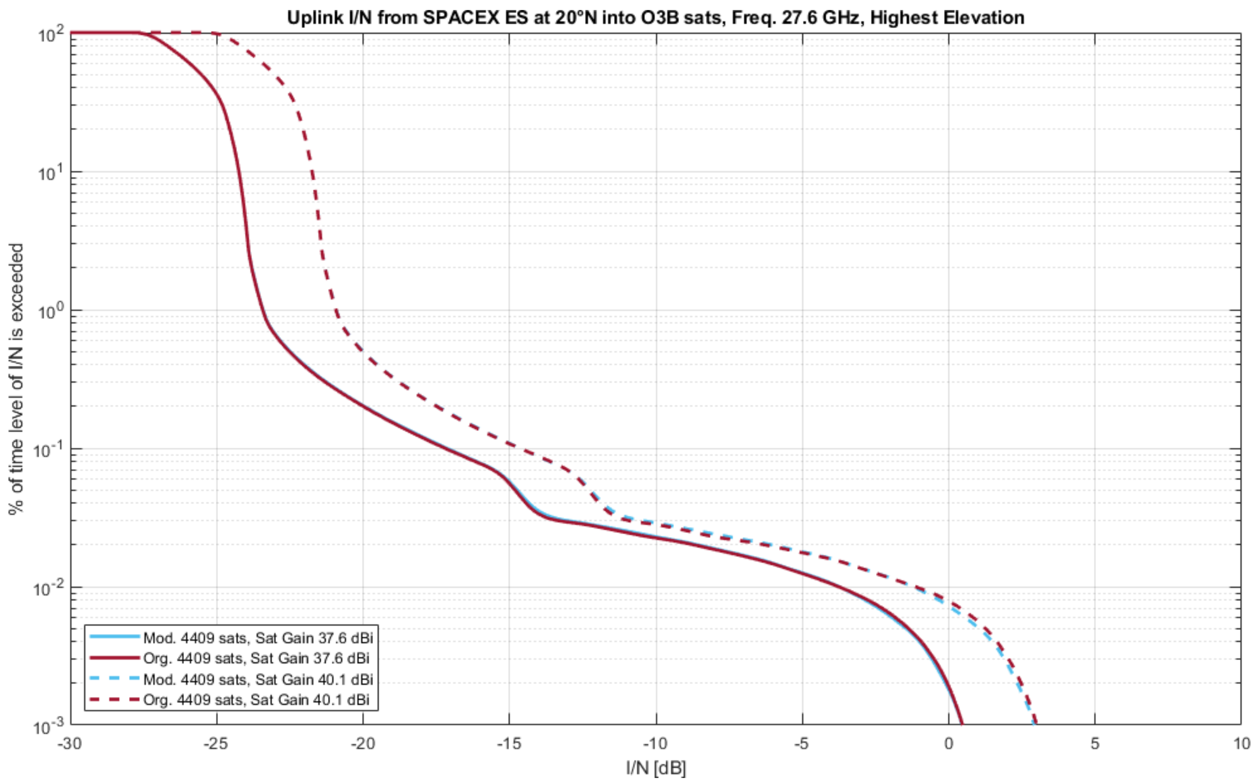


Figure A1-47. Uplink Comparison for Various O3B Antennas at 20ºN for Full SpaceX Constellation — Highest Elevation

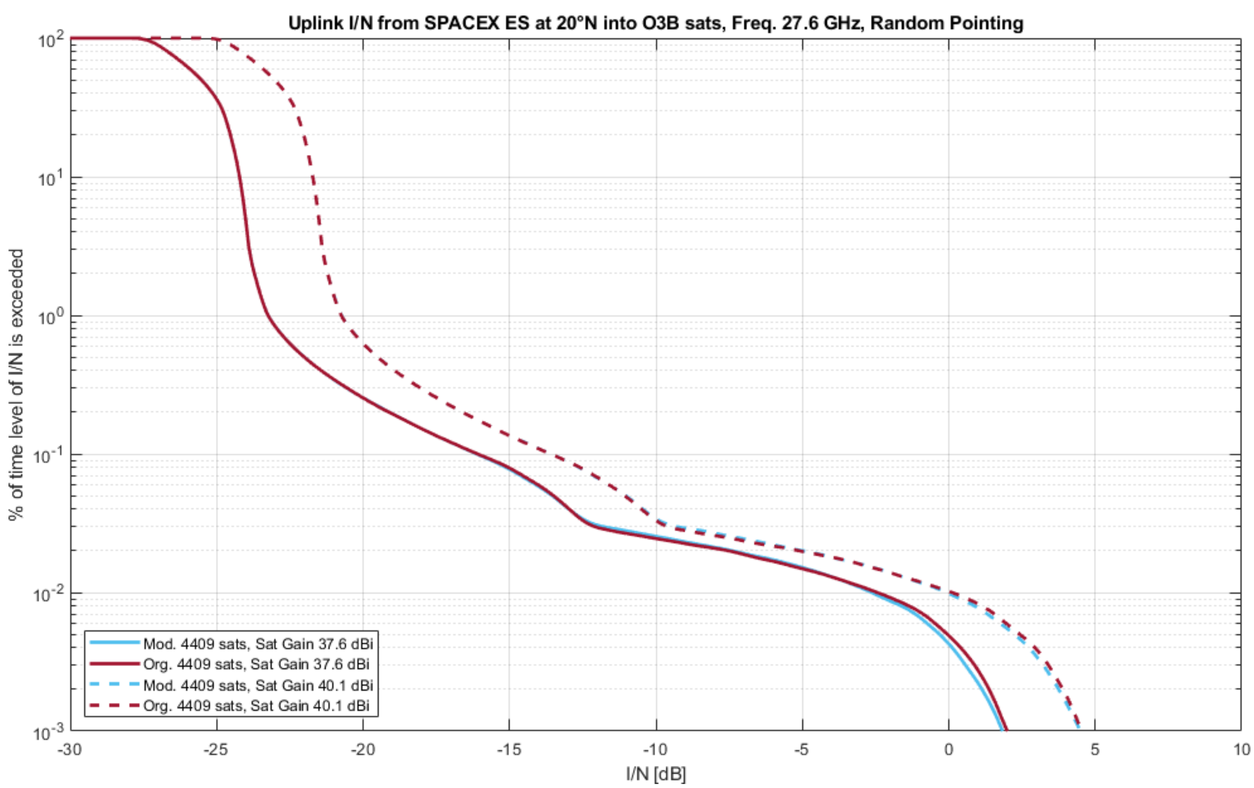


Figure A1-48. Uplink Comparison for Various O3B Antennas at 20ºN for Full SpaceX Constellation — Random Pointing

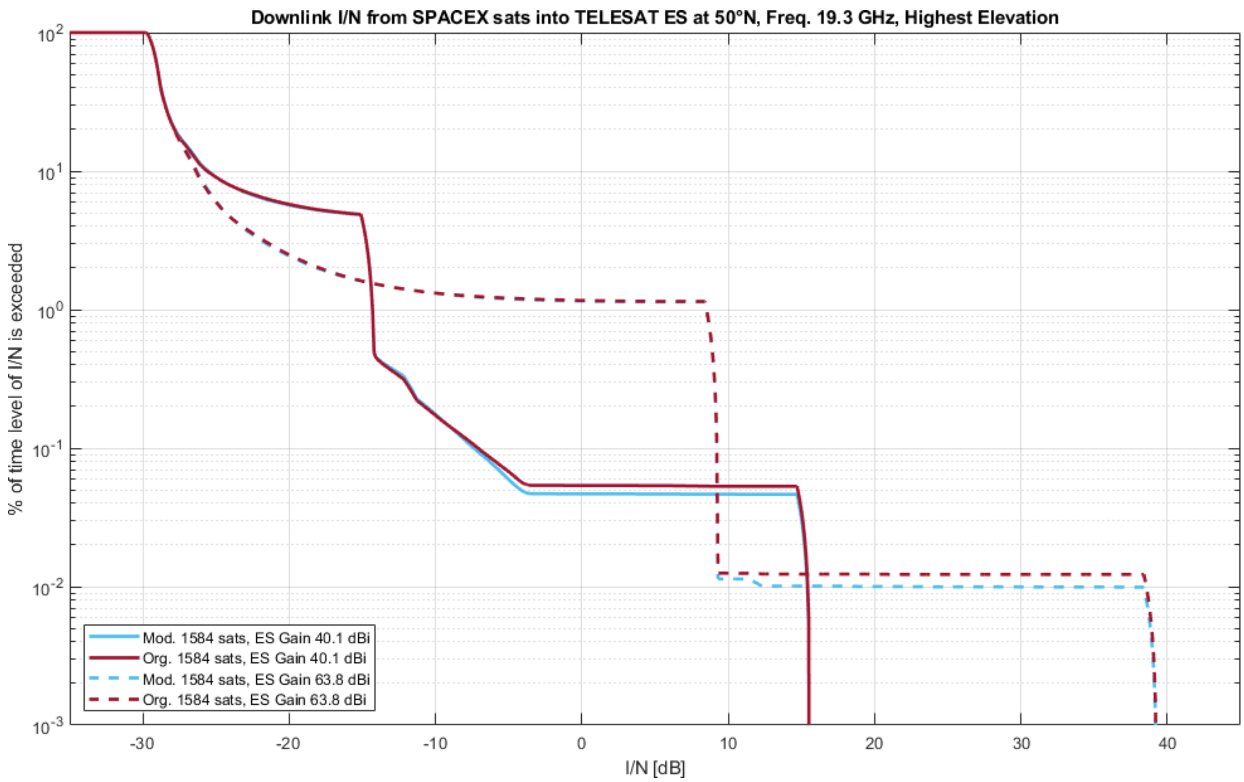


Figure A1-49. Downlink Comparison for Various Telesat Antennas at 50ºN for Modified 550 km Shell — Highest Elevation

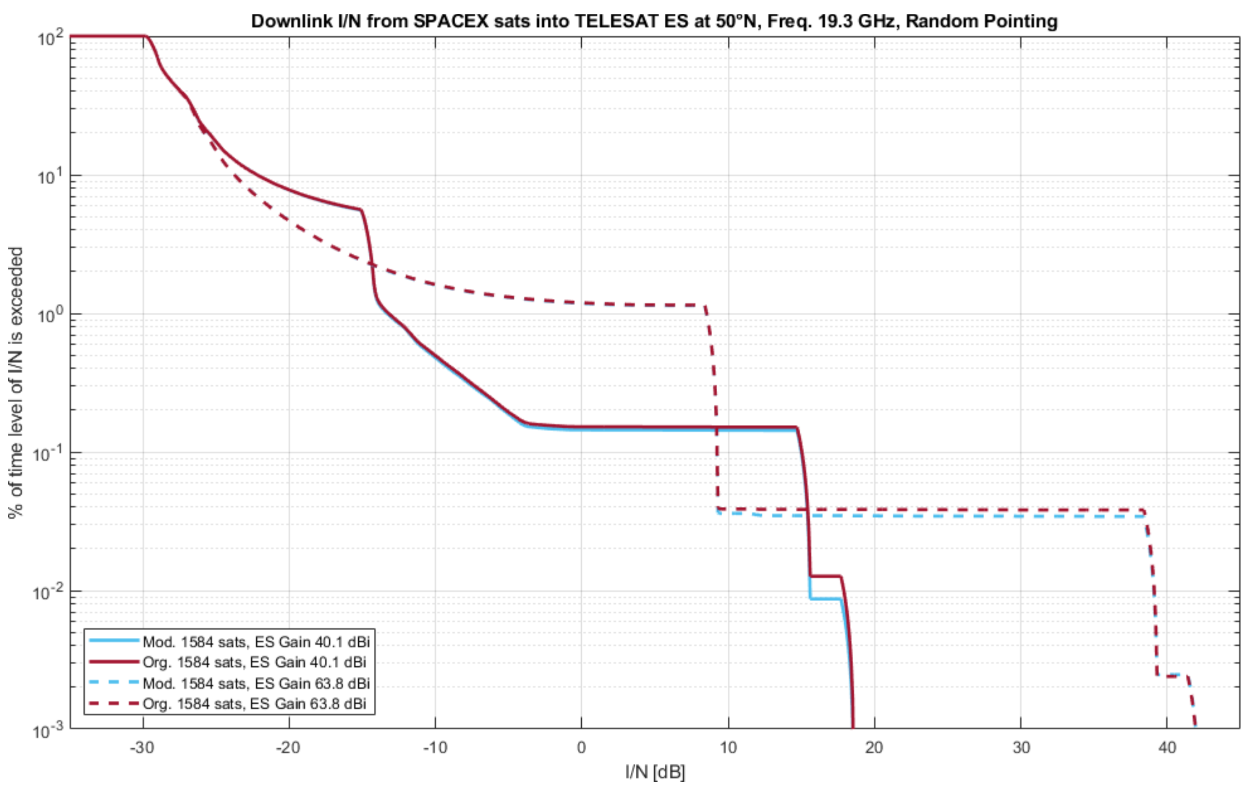


Figure A1-50. Downlink Comparison for Various Telesat Antennas at 50ºN for Modified 550 km Shell — Random Pointing

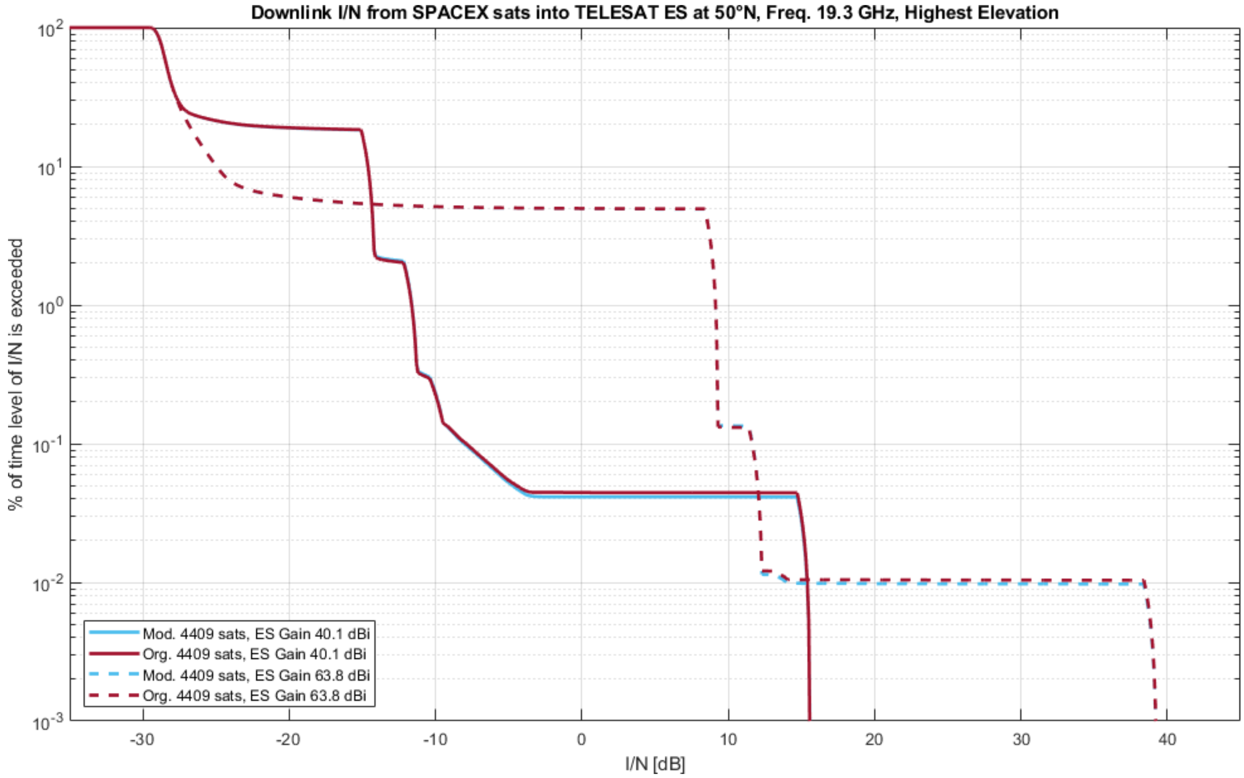


Figure A1-51. Downlink Comparison for Various Telesat Antennas at 50ºN for Full Space Constellation — Highest Elevation

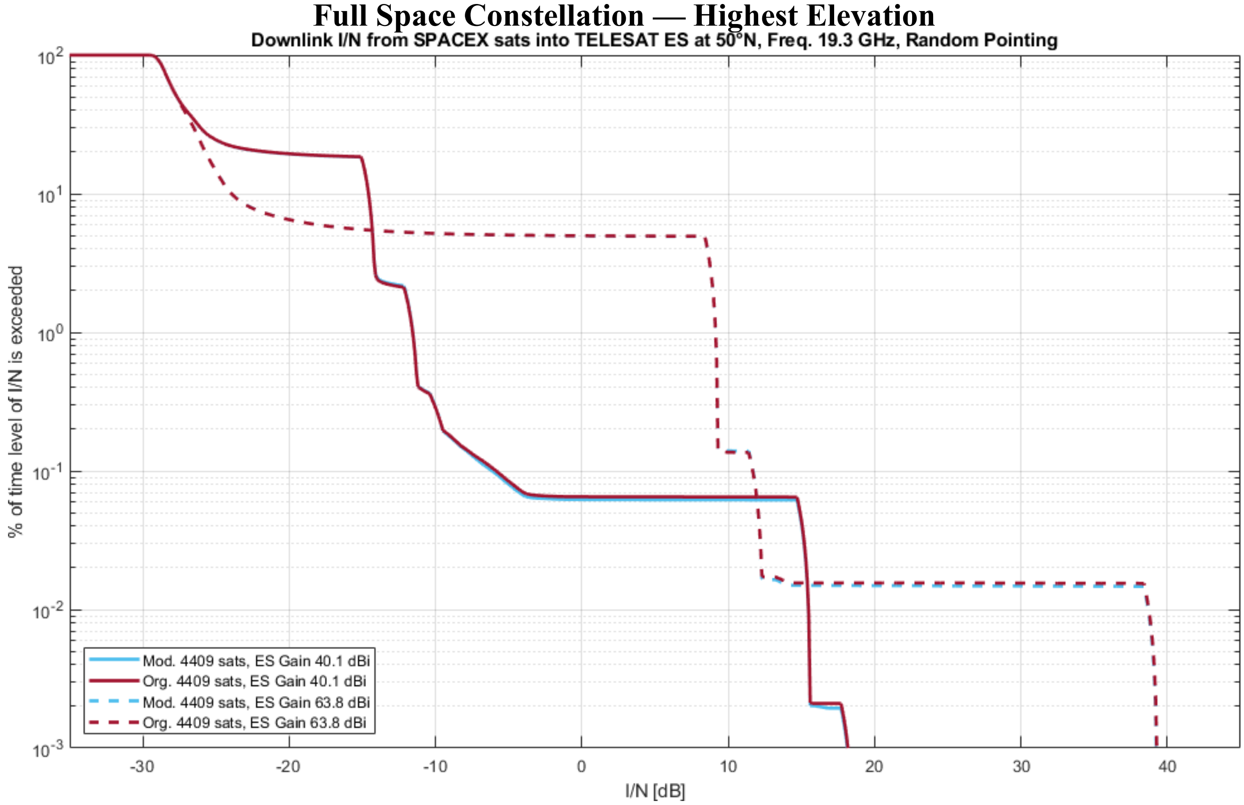


Figure A1-52. Downlink Comparison for Various Telesat Antennas at 50ºN for Full SpaceX Constellation — Random Pointing

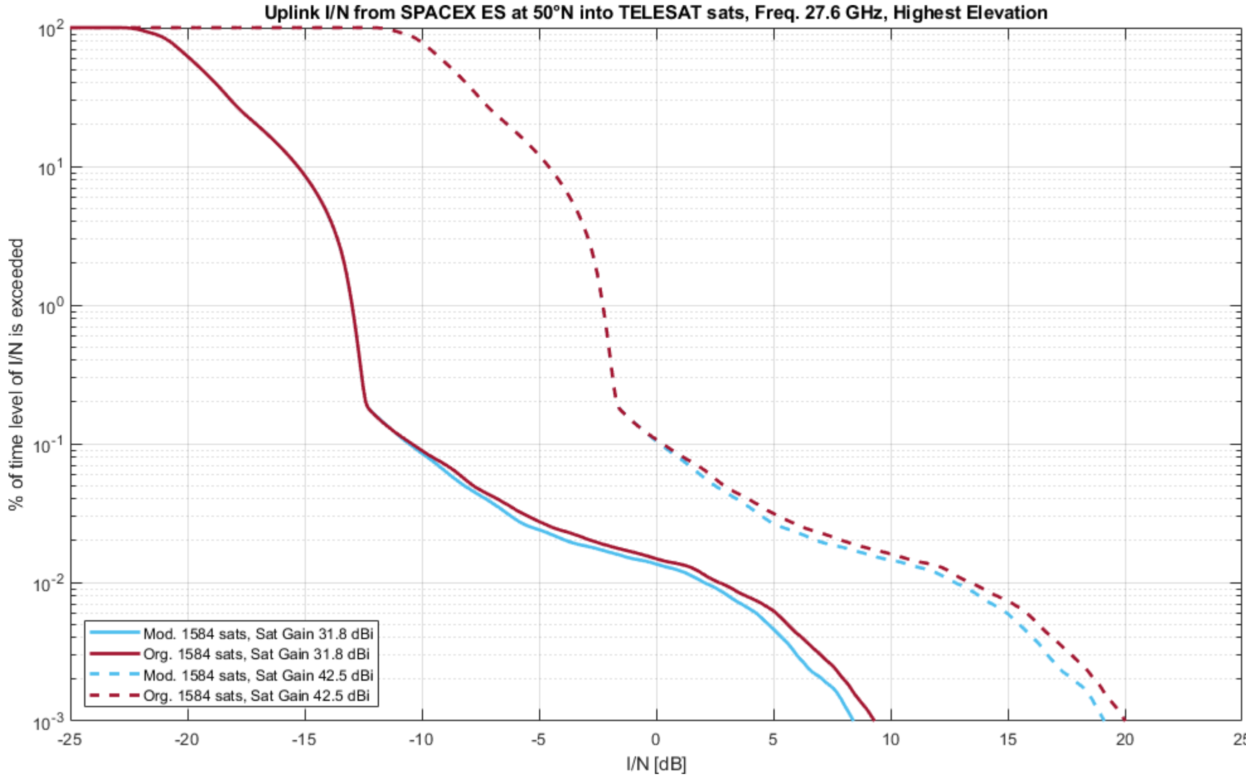


Figure A1-53. Uplink Comparison for Various Telesat Antennas at 50ºN for Modified 550 km Shell — Highest Elevation

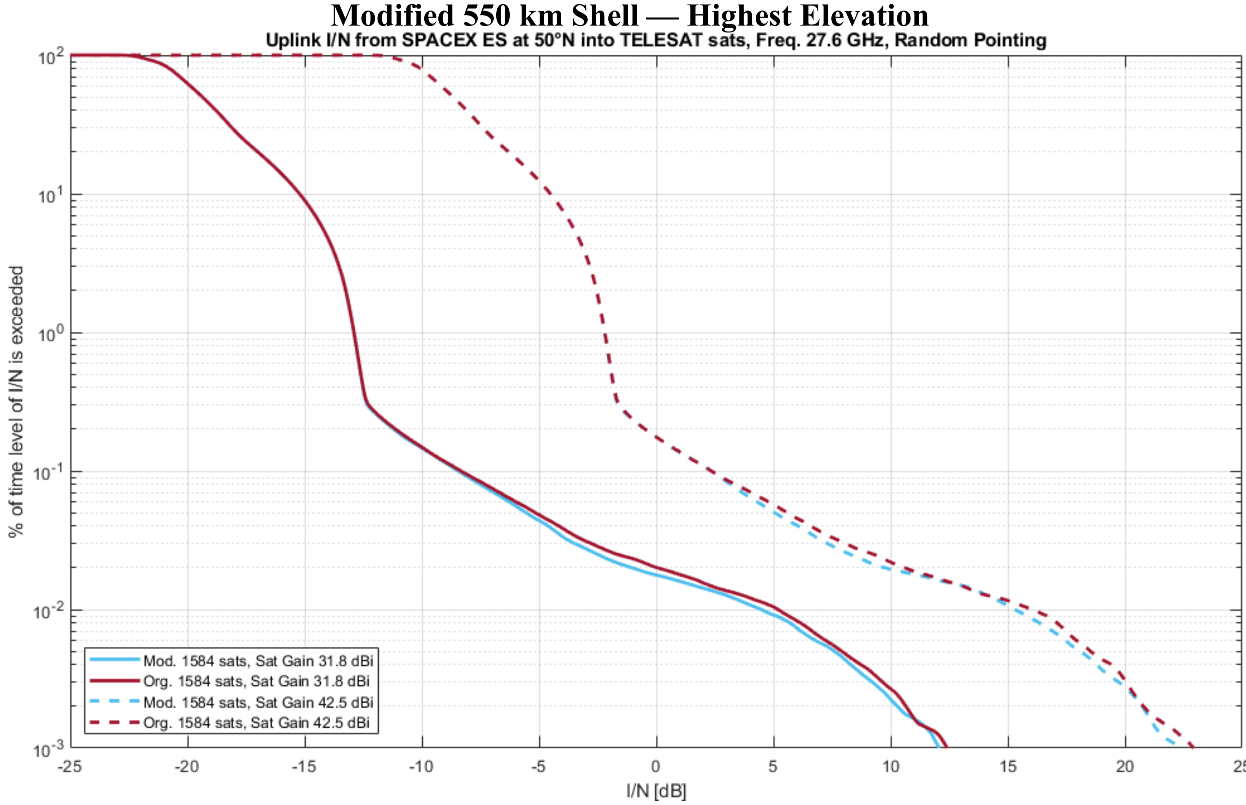


Figure A1-54. Uplink Comparison for Various Telesat Antennas at 50ºN for Modified 550 km Shell — Random Pointing

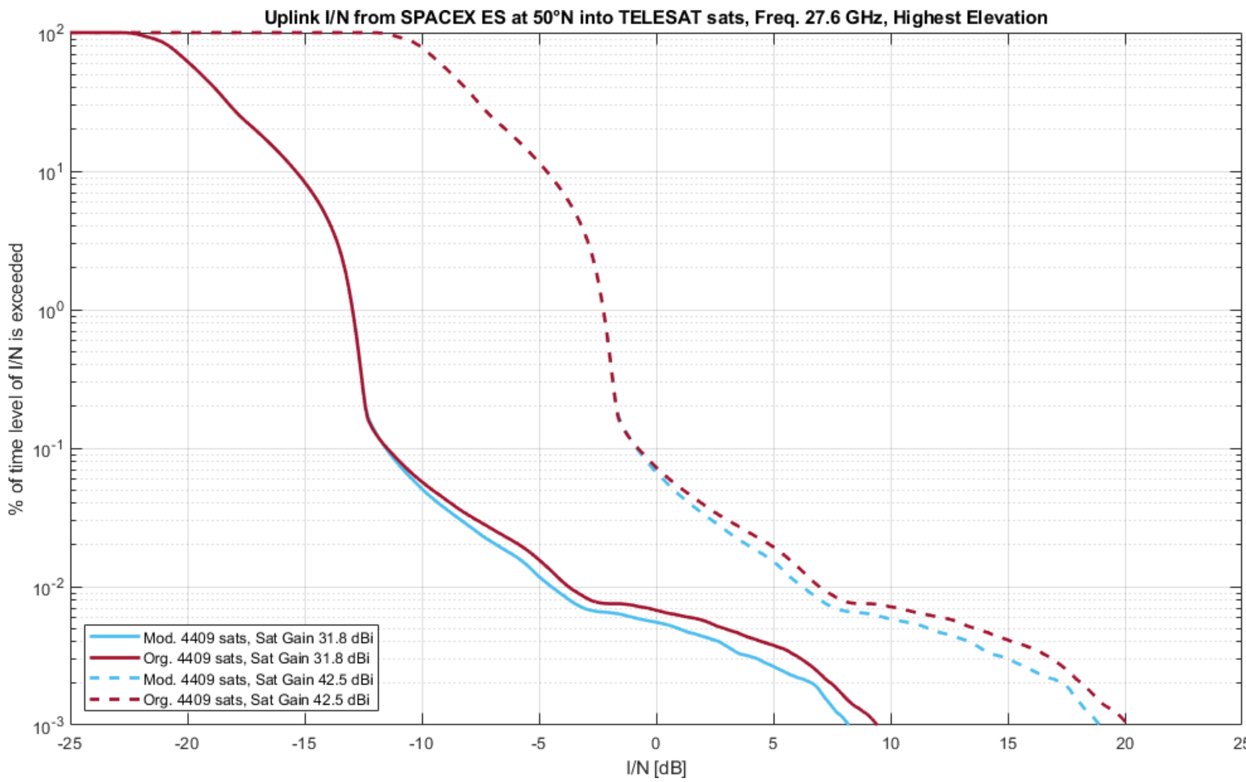


Figure A1-55. Uplink Comparison for Various Telesat Antennas at 50ºN for Full SpaceX Constellation — Highest Elevation

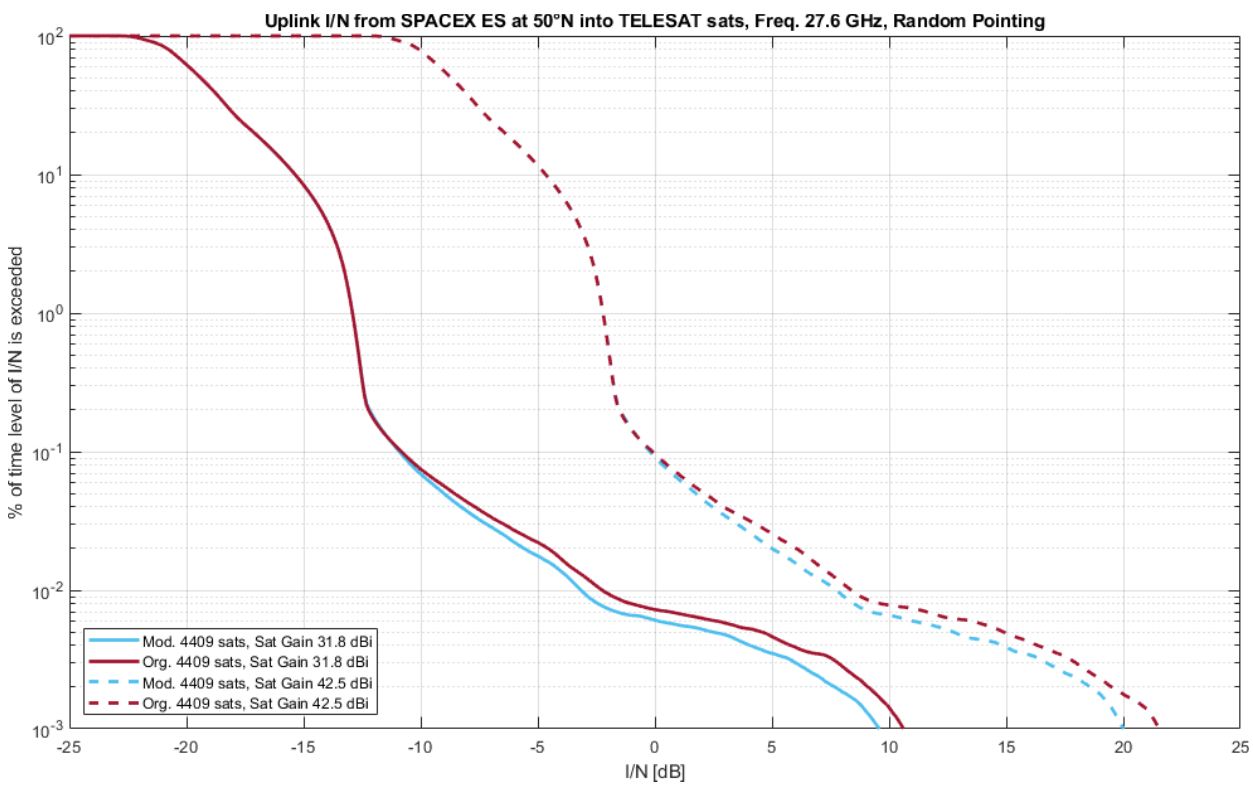


Figure A1-56. Uplink Comparison for Various Telesat Antennas at 50ºN for Full SpaceX Constellation — Random Pointing

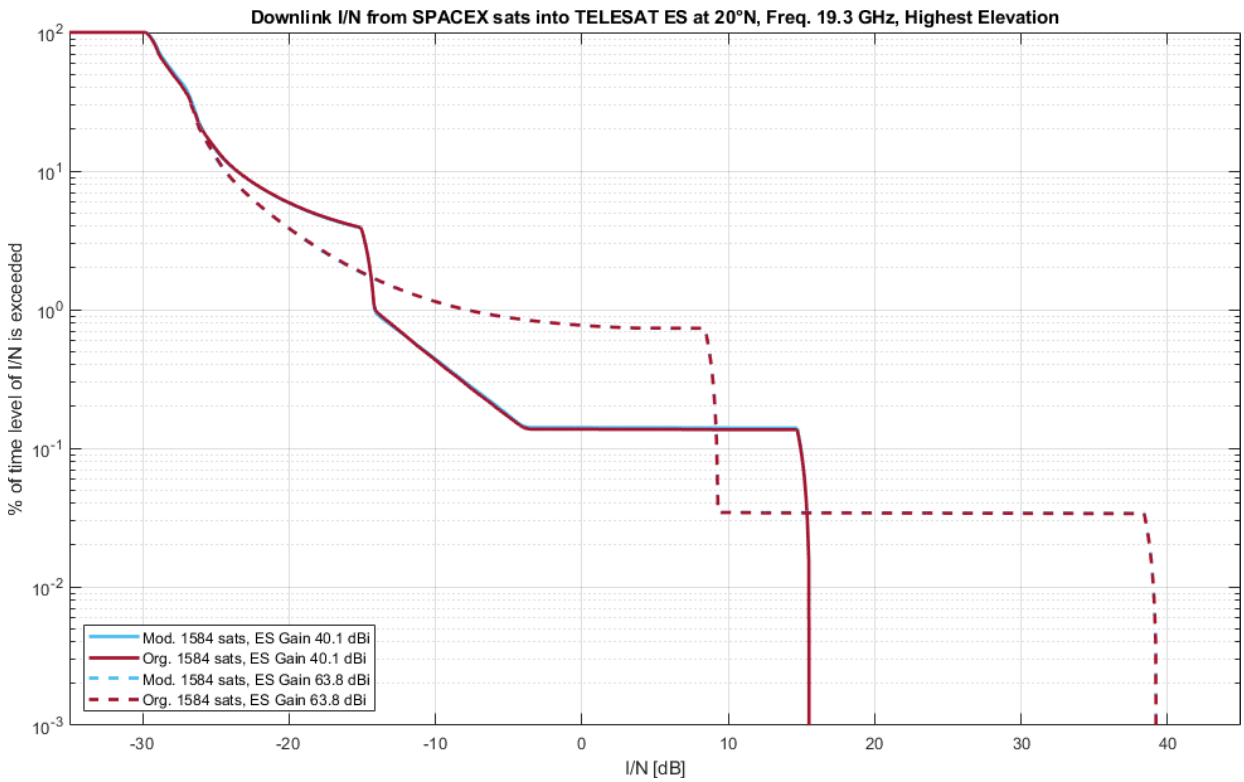


Figure A1-57. Downlink Comparison for Various Telesat Antennas at 20ºN for Modified 550 km Shell — Highest Elevation

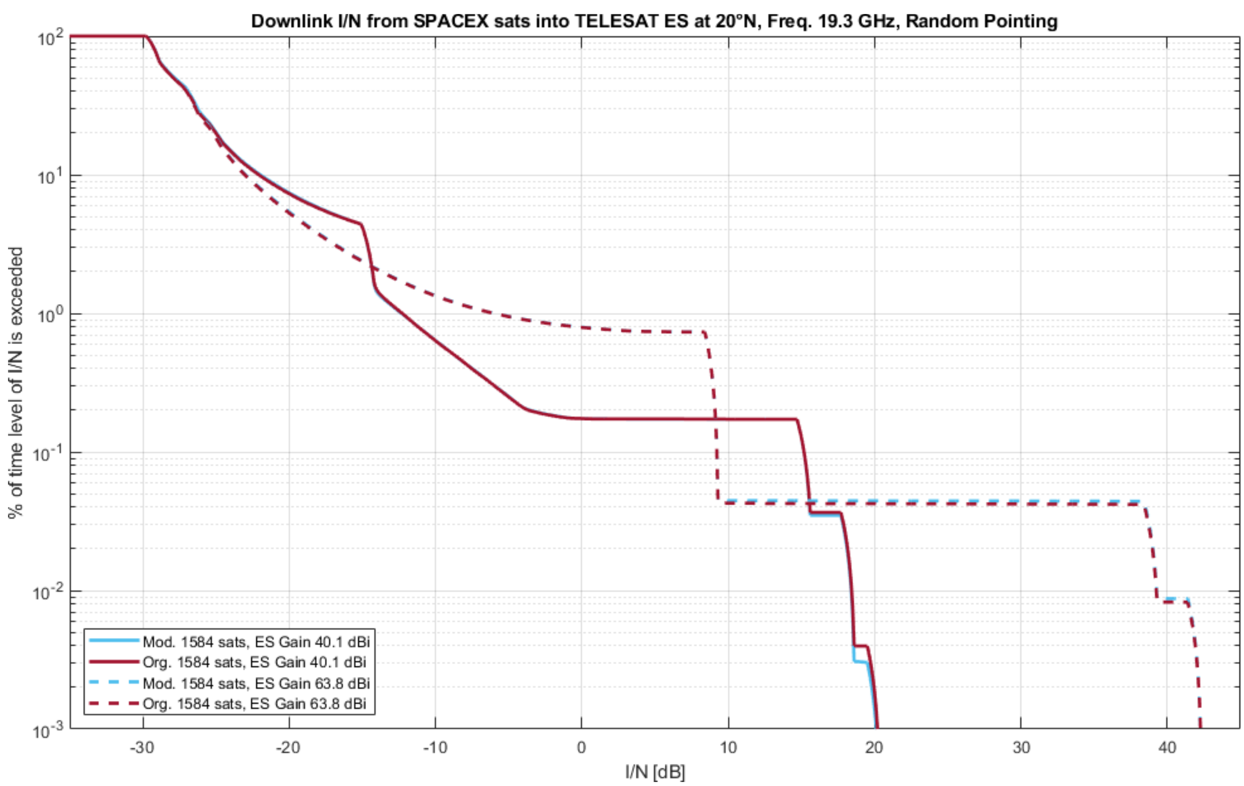


Figure A1-58. Downlink Comparison for Various Telesat Antennas at 20ºN for Modified 550 km Shell — Random Pointing

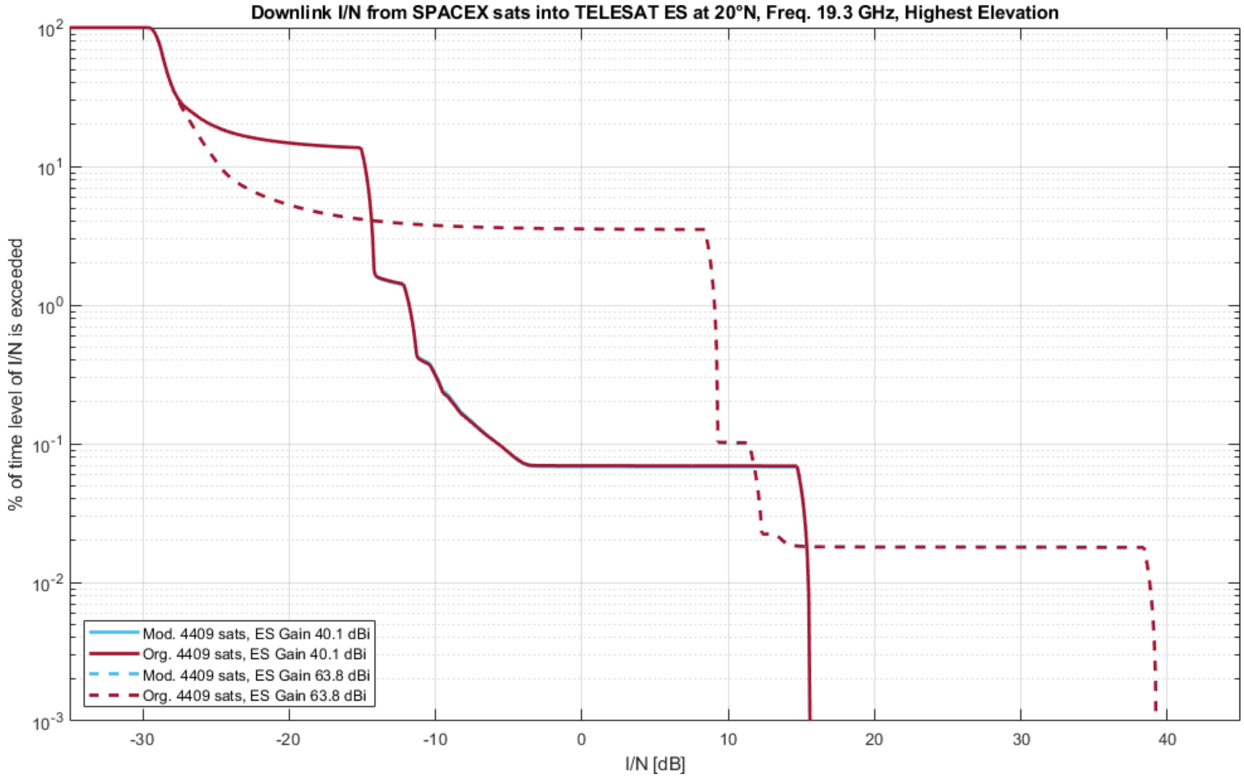


Figure A1-59. Downlink Comparison for Various Telesat Antennas at 20ºN for Full Space Constellation — Highest Elevation

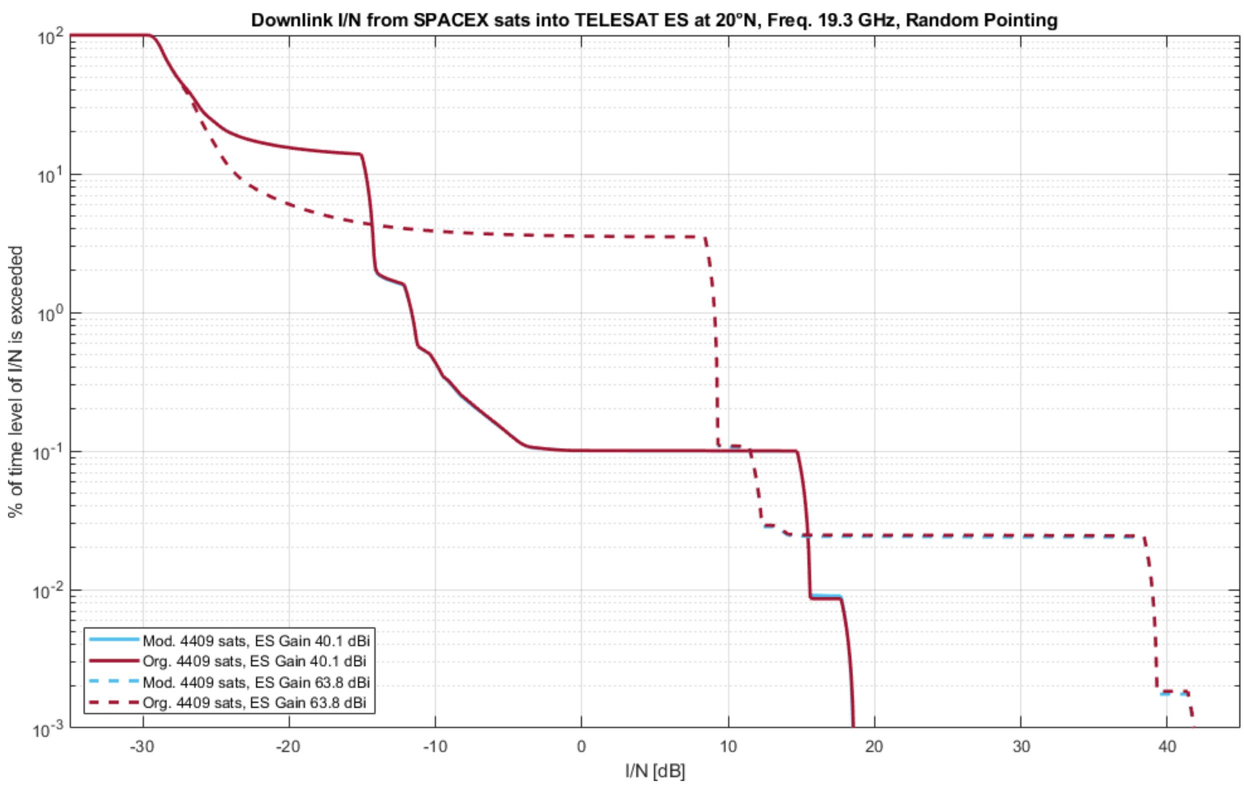


Figure A1-60. Downlink Comparison for Various Telesat Antennas at 20ºN for Full SpaceX Constellation — Random Pointing

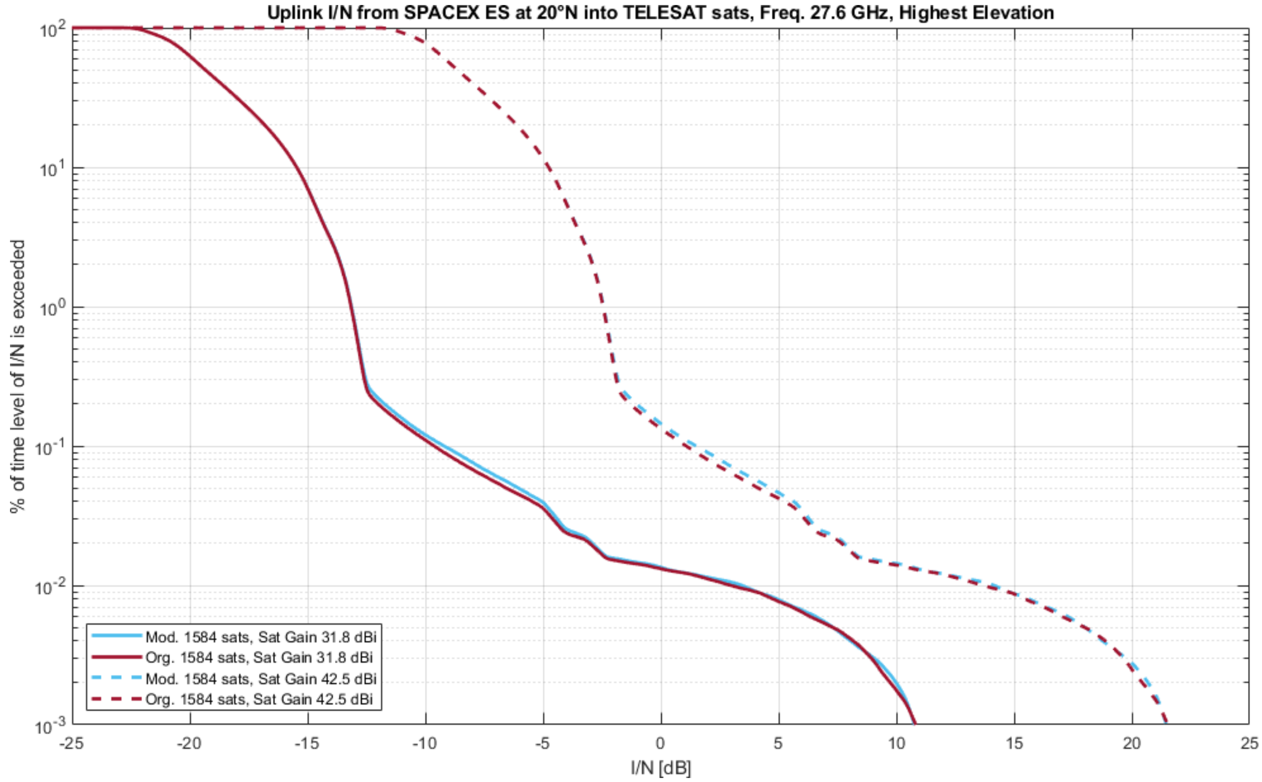


Figure A1-61. Uplink Comparison for Various Telesat Antennas at 20ºN for Modified 550 km Shell — Highest Elevation

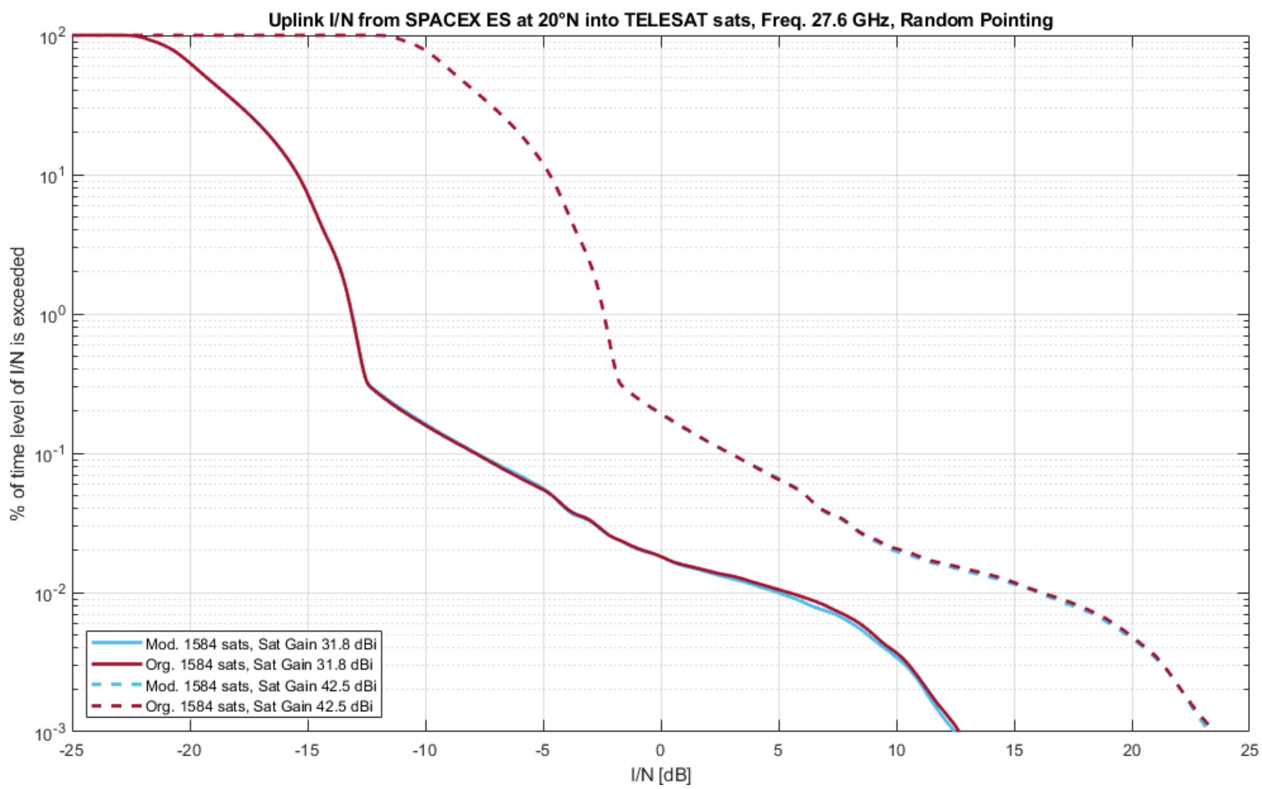


Figure A1-62. Uplink Comparison for Various Telesat Antennas at 20ºN for Modified 550 km Shell — Random Pointing

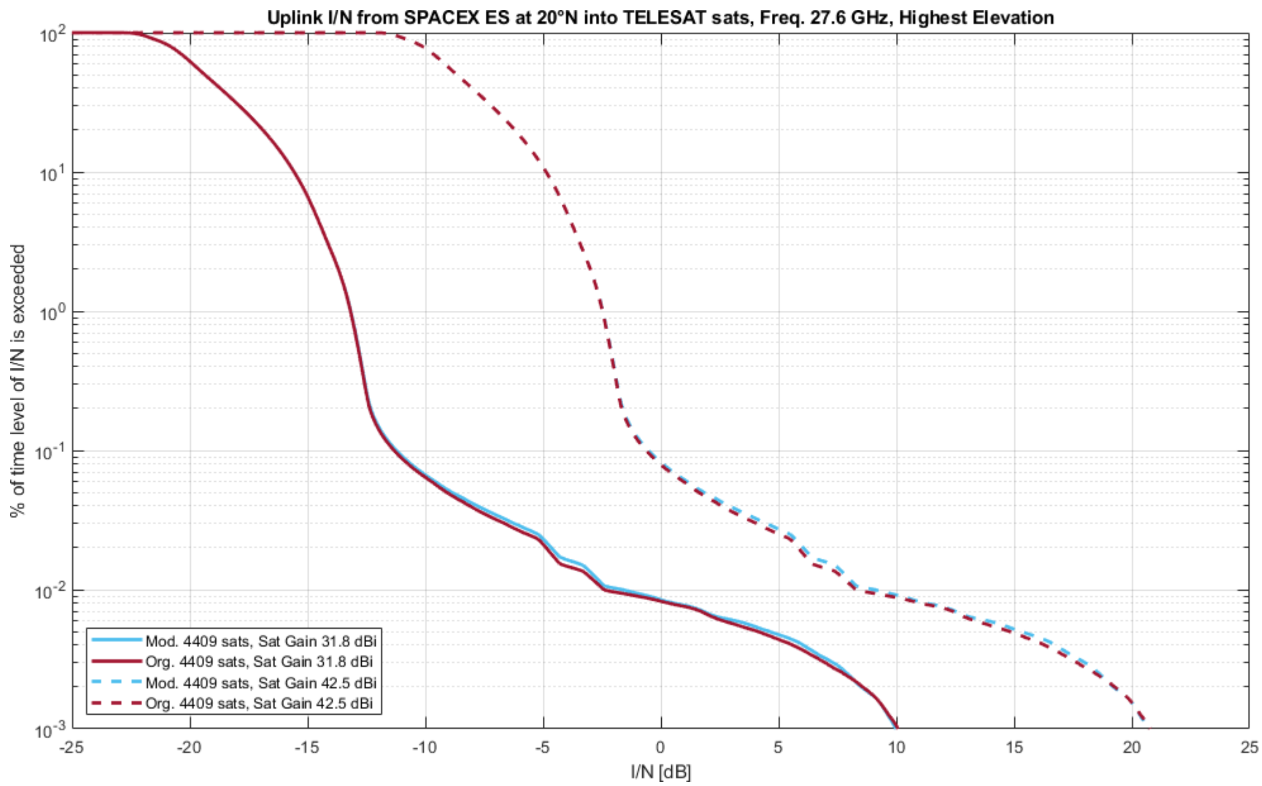


Figure A1-63. Uplink Comparison for Various Telesat Antennas at 20ºN for Full SpaceX Constellation — Highest Elevation

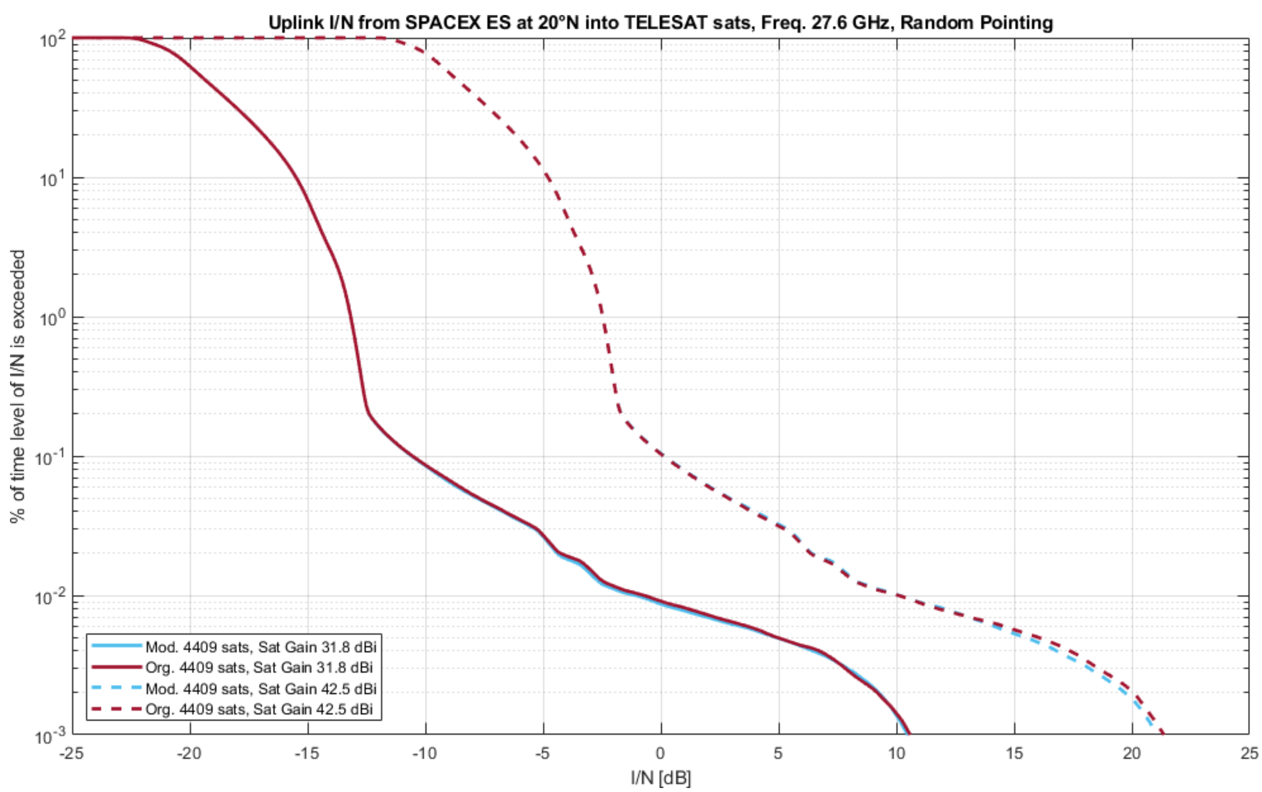


Figure A1-64. Uplink Comparison for Various Telesat Antennas at 20ºN for Full SpaceX Constellation — Random Pointing

ANNEX 2

POTENTIAL INTERFERENCE TO GSO SATELLITE SYSTEMS

A. Demonstration of EPFD Compliance for Ku-Band Operations

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

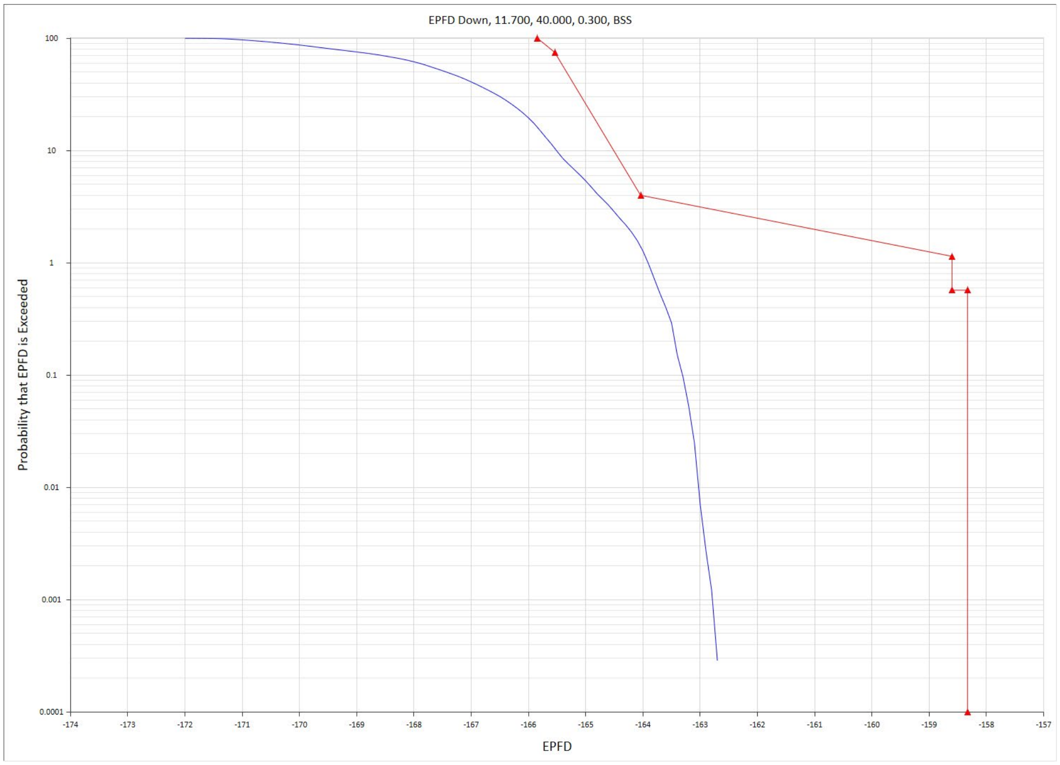
The figures below present the results of the Transfinite analysis with respect to the space-to-Earth direction ($EPFD_{down}$), the Earth-to-space direction ($EPFD_{up}$), for transmissions between satellites in orbit where spectrum is allocated bi-directionally ($EPFD_{is}$), and for gateway and TT&C 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.

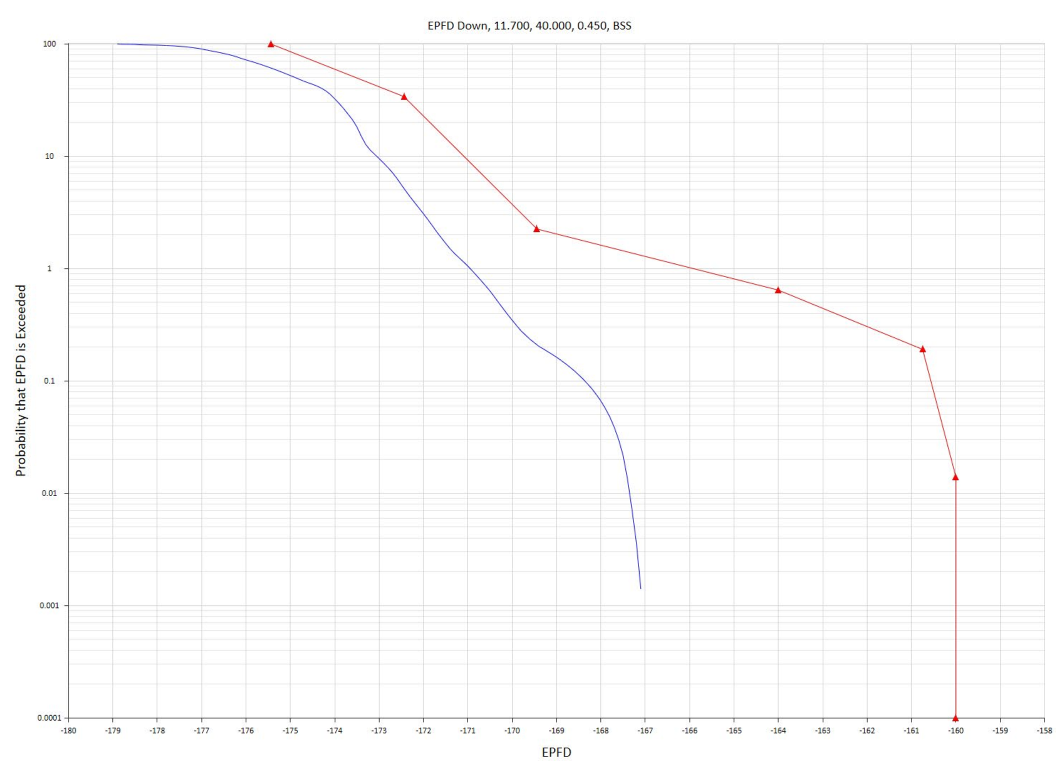
As these diagrams demonstrate, SpaceX's modified NGSO system will continue to comply with all EPFD limits applicable to its Ku-band operations.

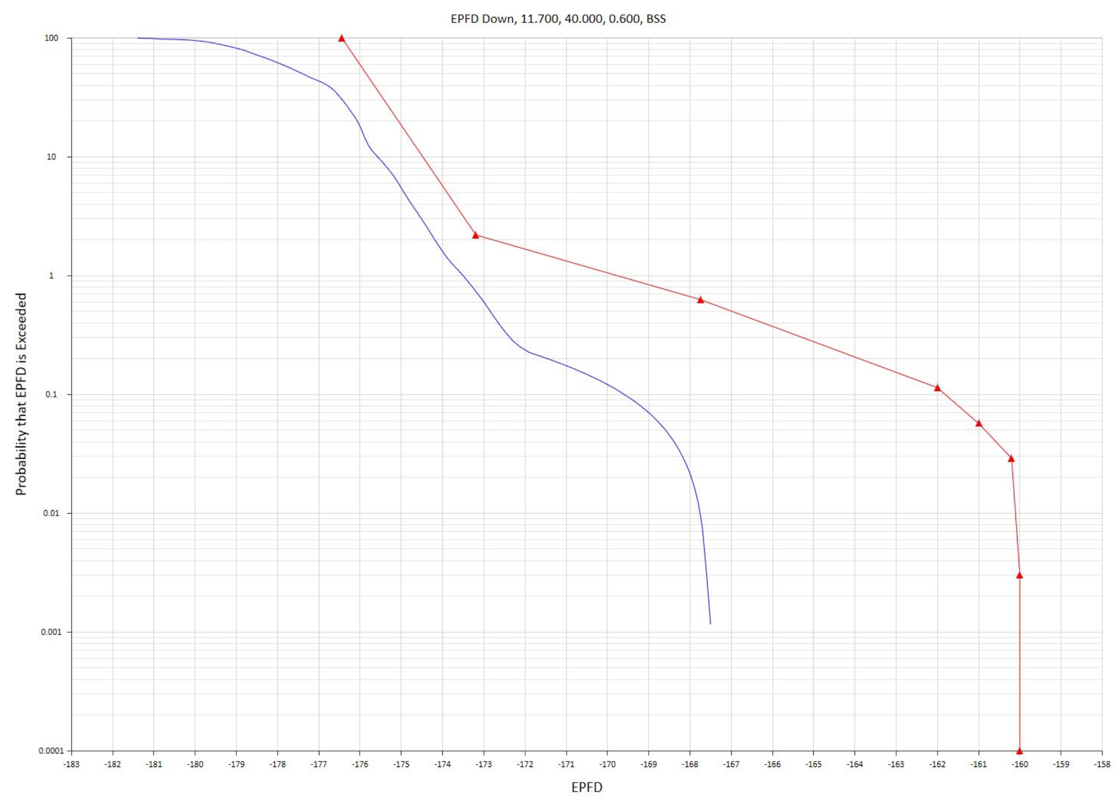
[1] *See* 47 C.F.R. § 25.146(a)(2).

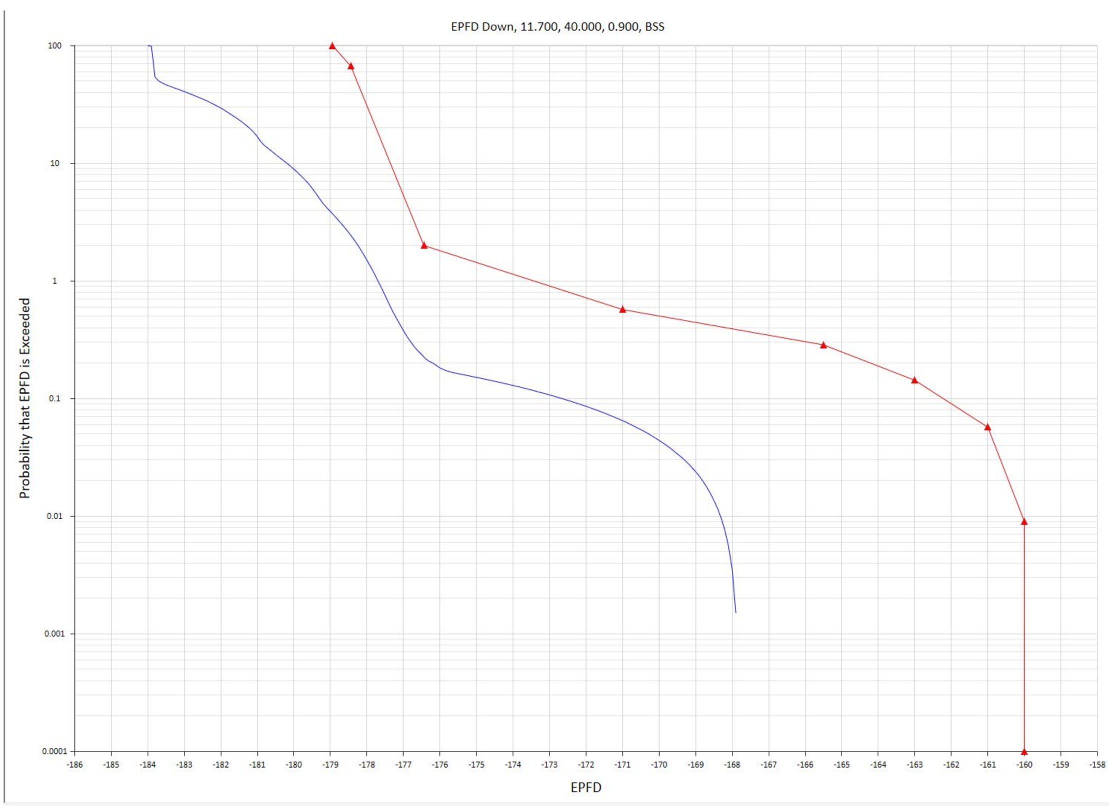
ANALYSIS OF INITIAL DEPLOYMENT

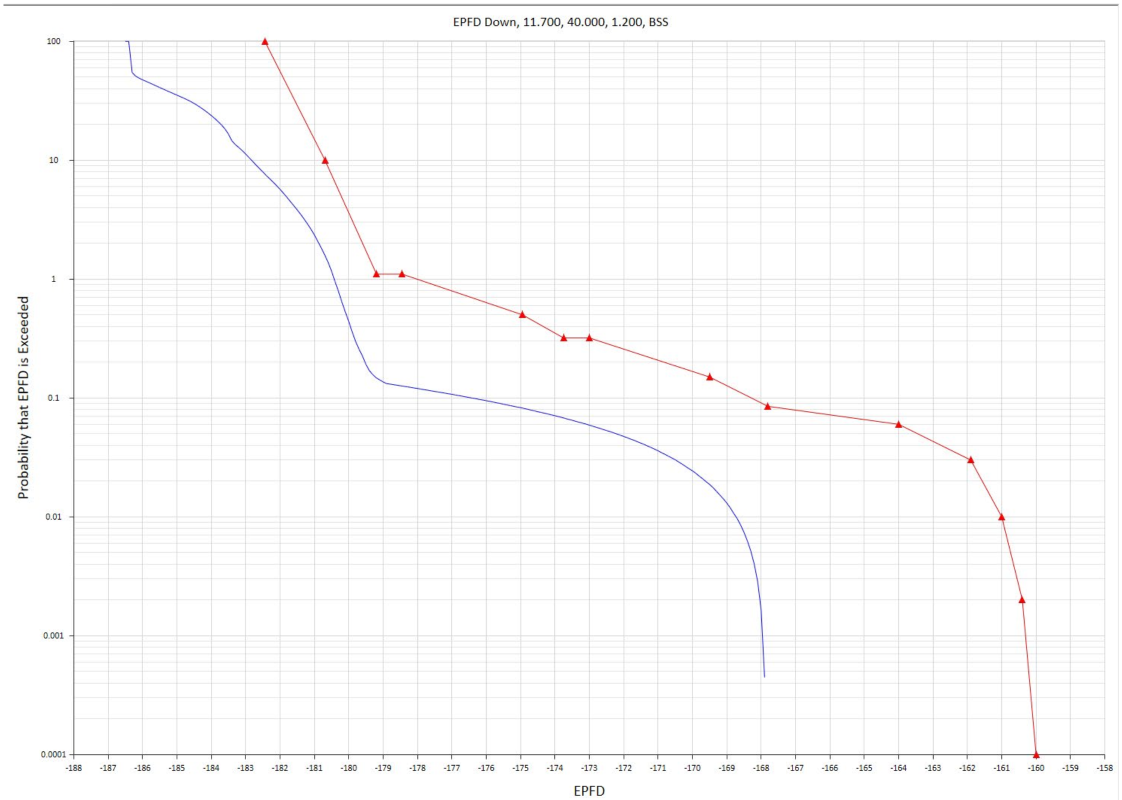
OUTPUTS FOR $EPFD_{DOWN}$ ASSESSMENT OF BSS LIMITS

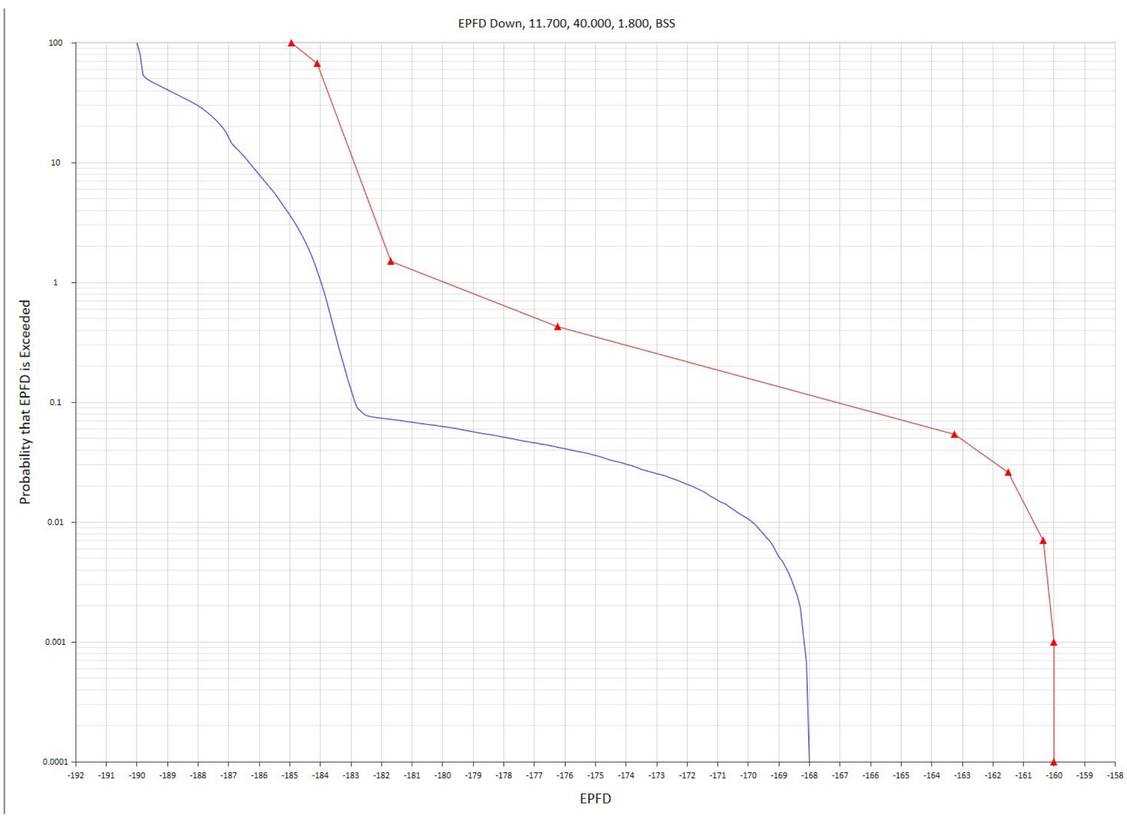


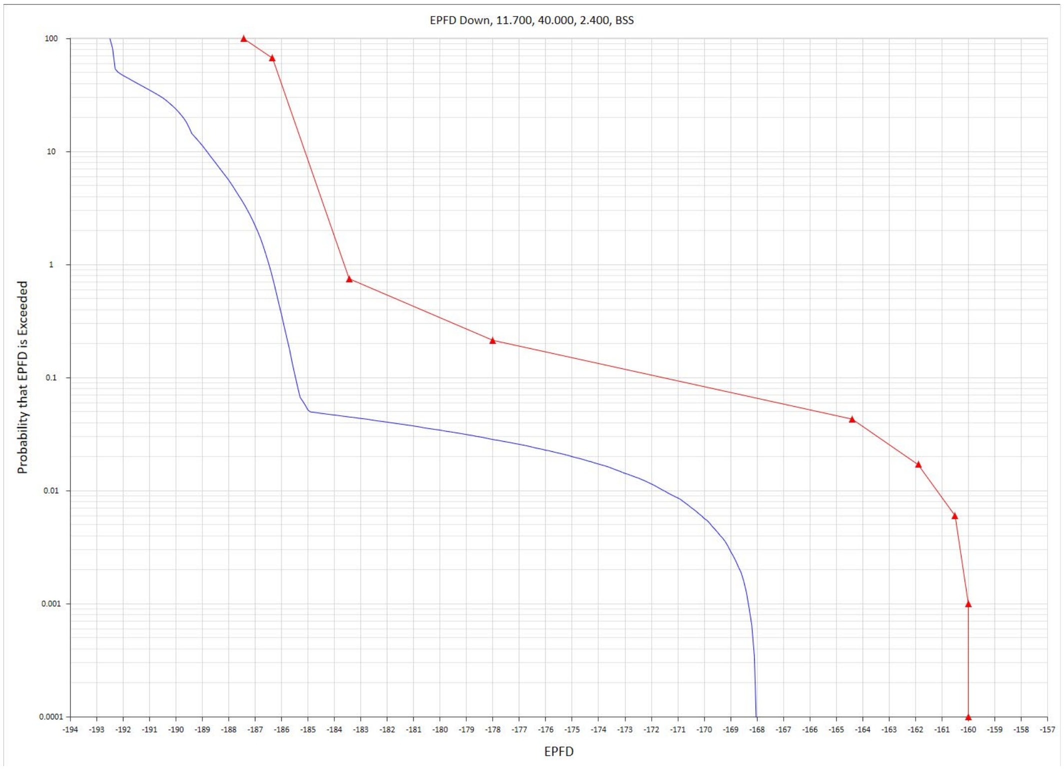



EPFD Down, 11.700, 40.000, 0.600, BSS
Probability that EPFD is Exceeded
EPFD

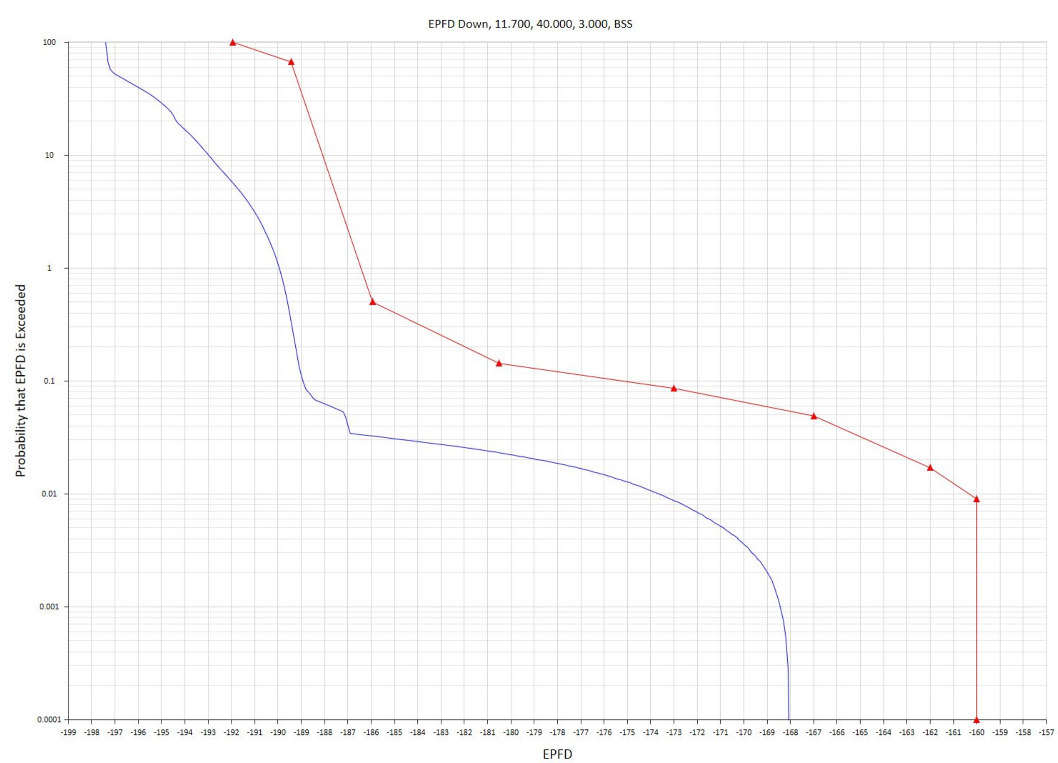

EPFD Down, 11.700, 40.000, 0.900, BSS
Probability that EPFD is Exceeded
EPFD


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


EPFD Down, 11.700, 40.000, 1.800, BSS
Probability that EPFD is Exceeded
EPFD

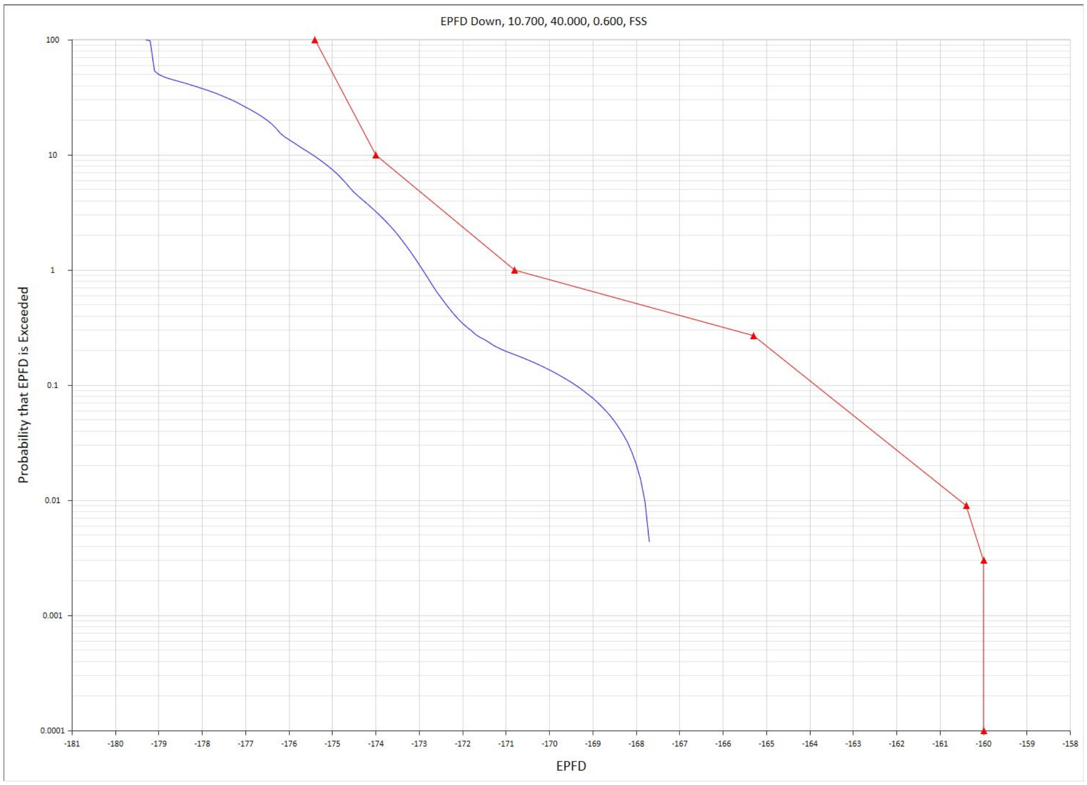


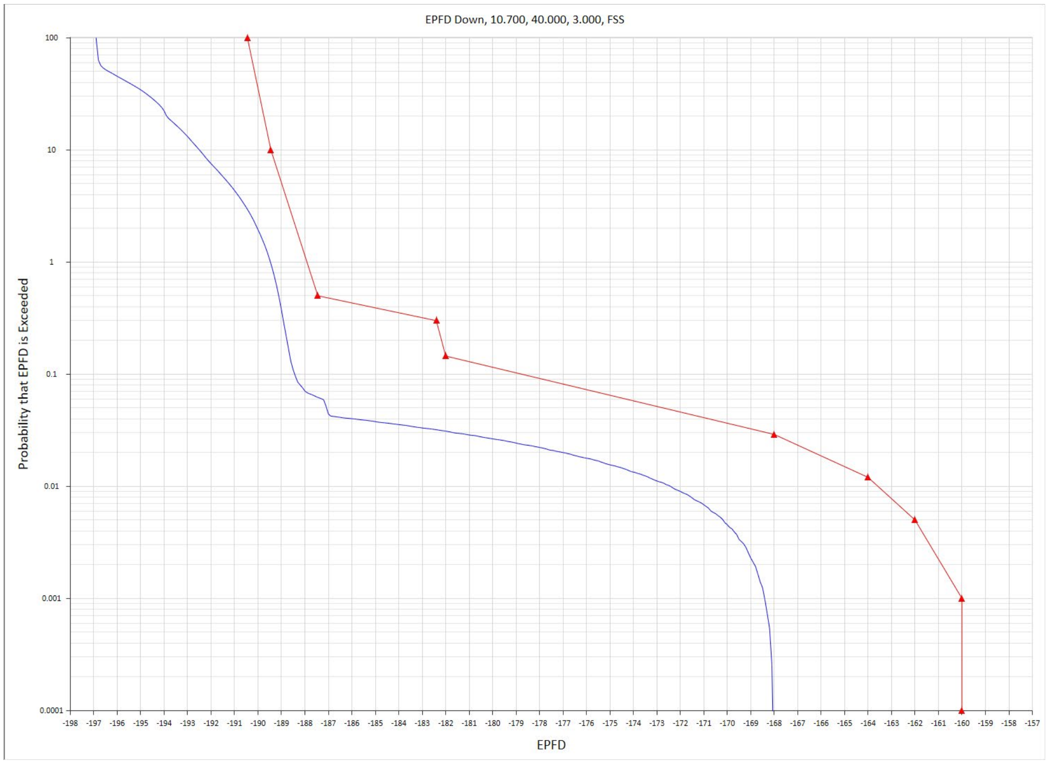
EPFD Down, 11.700, 40.000, 2.400, BSS
Probability that EPFD is Exceeded
EPFD

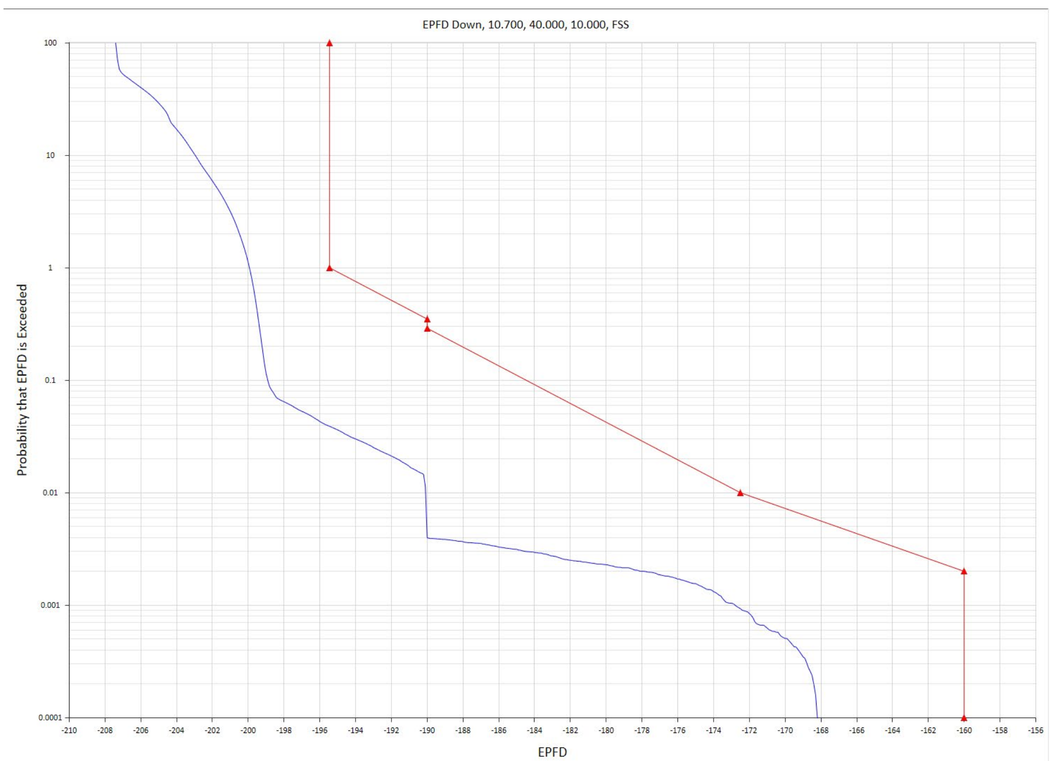


EPFD Down, 11.700, 40.000, 3.000, BSS
Probability that EPFD is Exceeded
EPFD

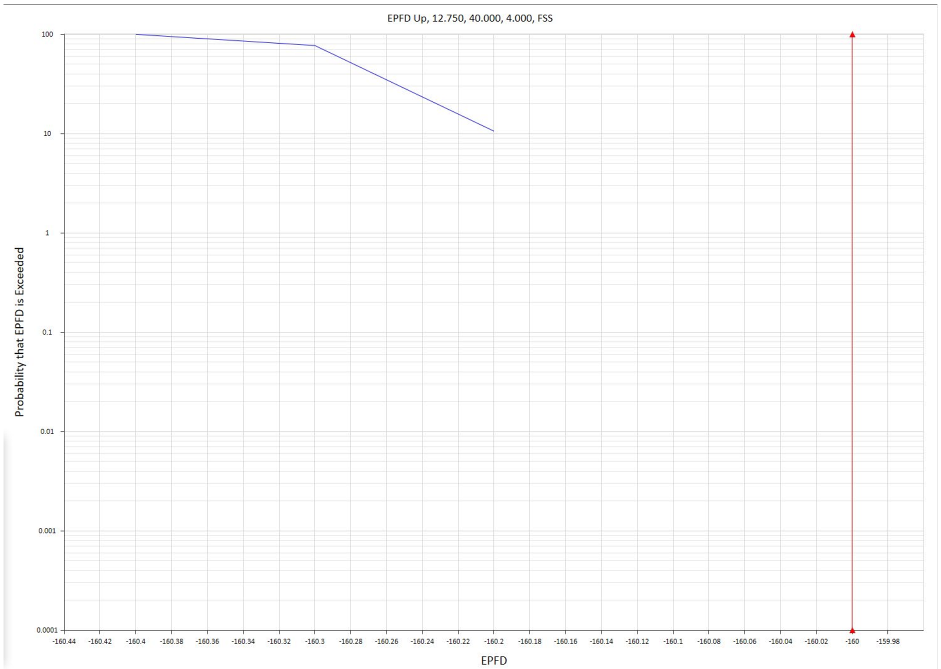
OUTPUTS FOR EPFD$_{DOWN}$ ASSESSMENT OF FSS LIMITS

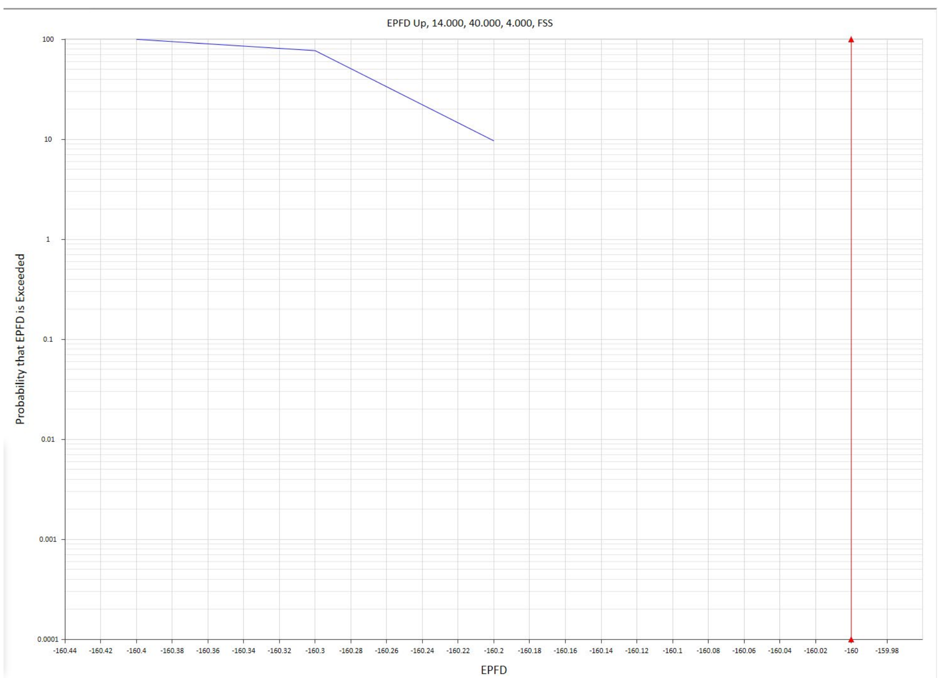



EPFD Down, 10.700, 40.000, 3.000, FSS
Probability that EPFD is Exceeded
EPFD

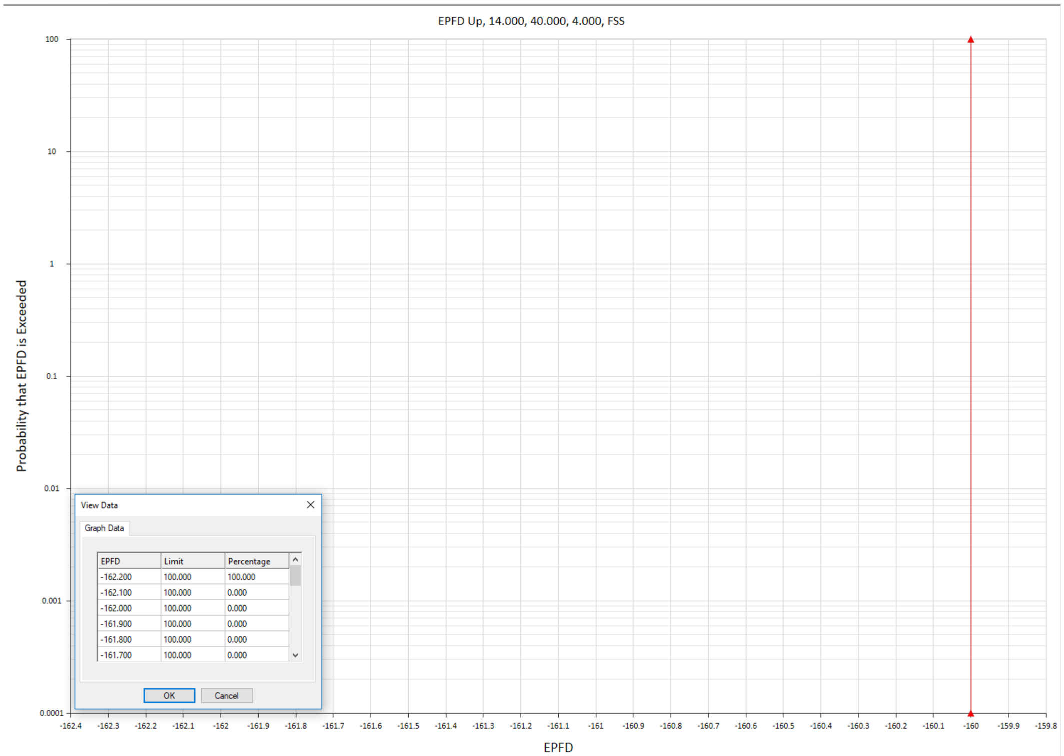

EPFD Down, 10.700, 40.000, 10.000, FSS
Probability that EPFD is Exceeded
EPFD

OUTPUTS FOR EPFD$_{UP}$ ASSESSMENT

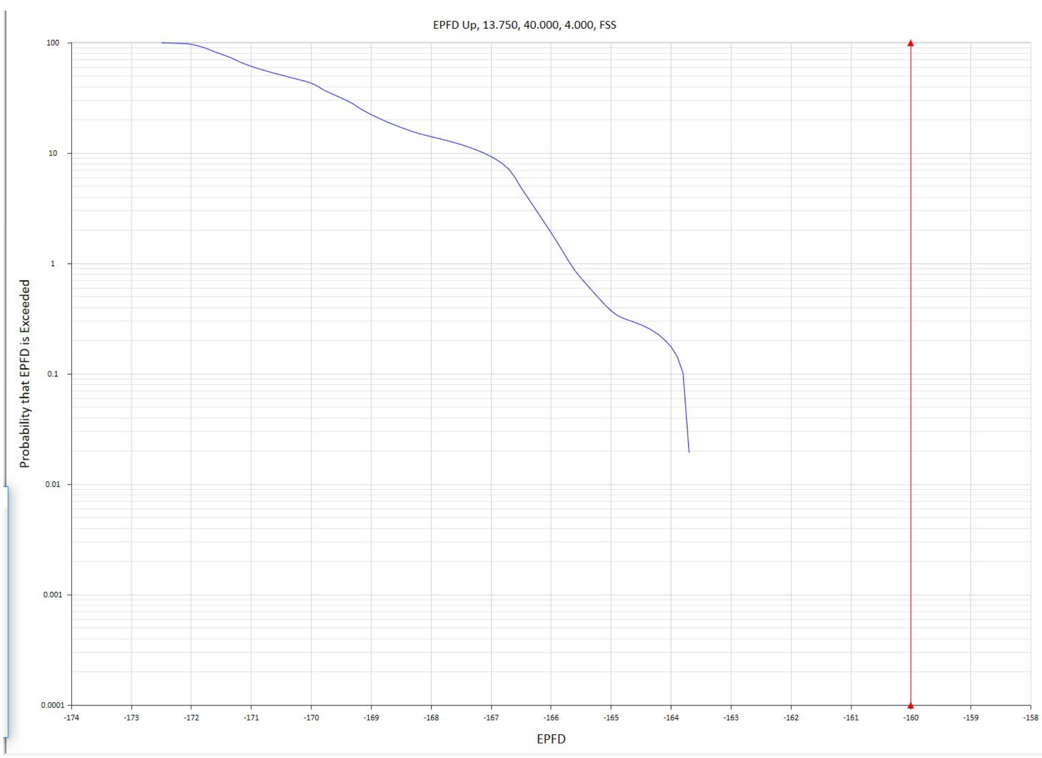




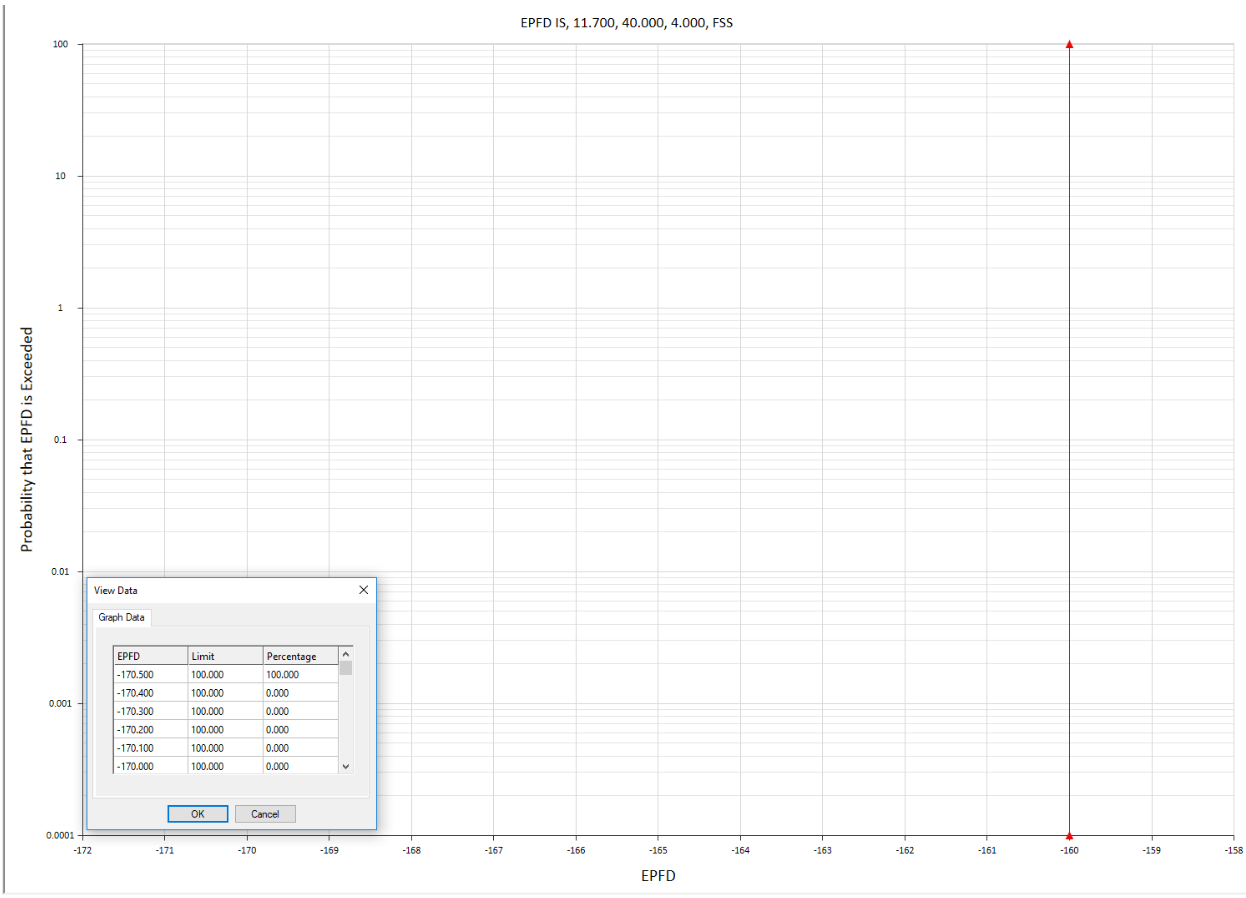
Gateway


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

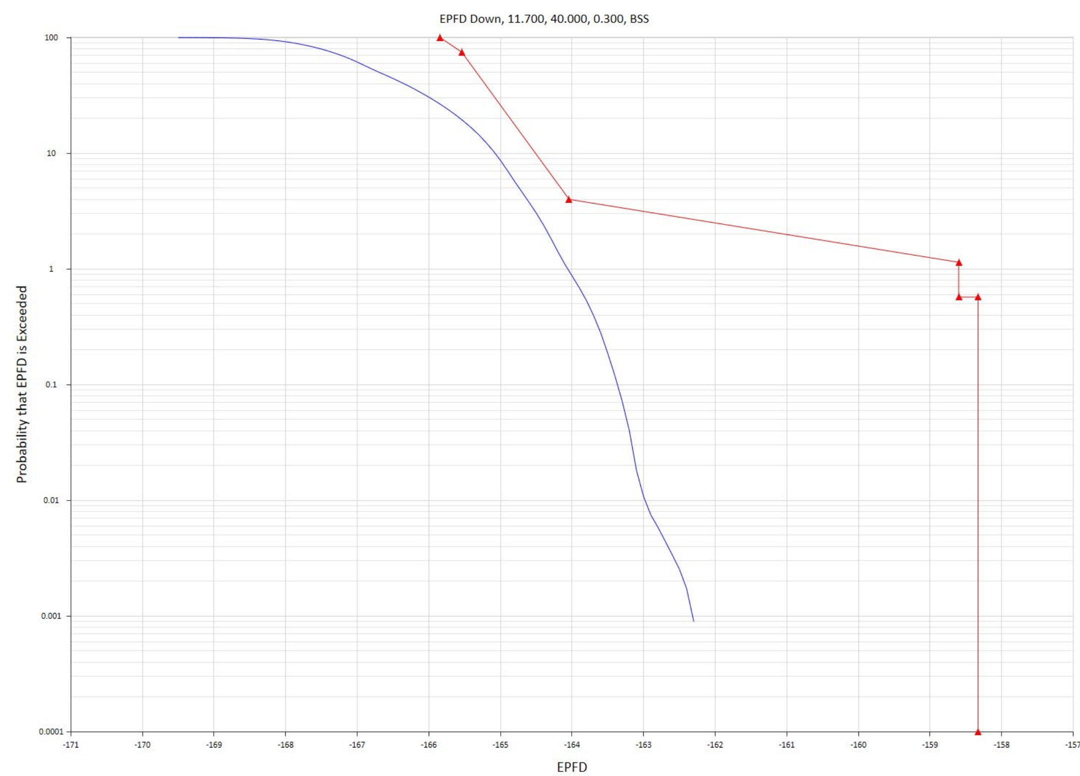
TT&C

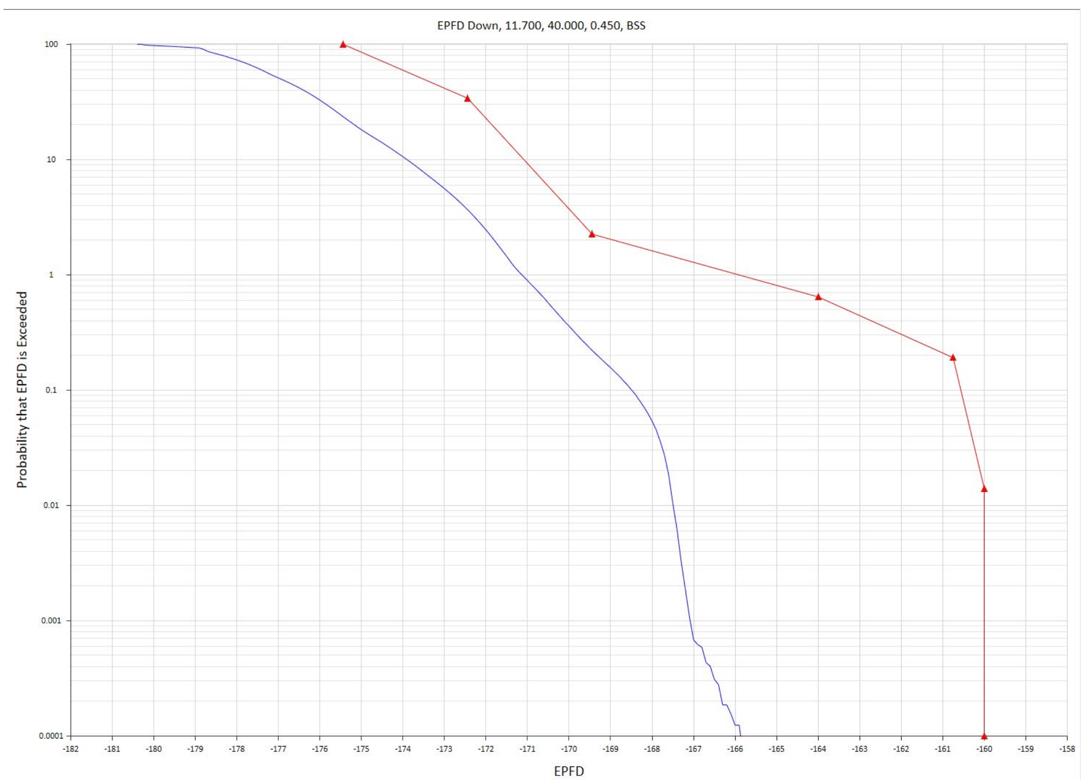

EPFD Up, 13.750, 40.000, 4.000, FSS
Probability that EPFD is Exceeded
EPFD

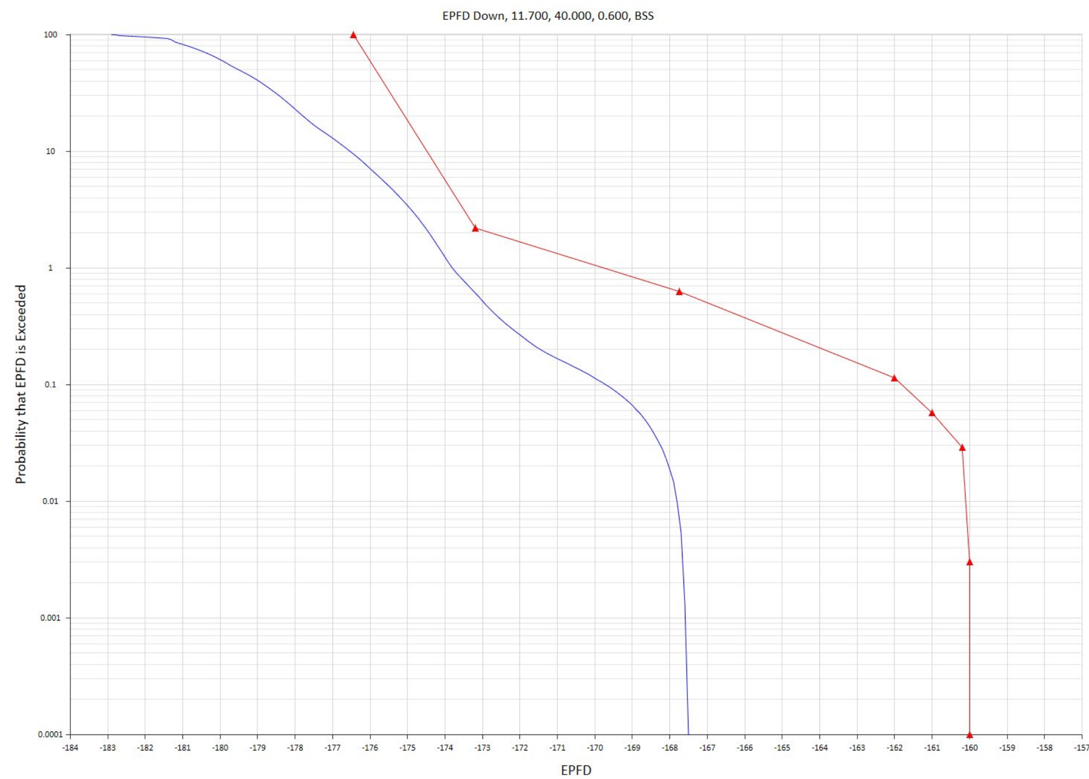
OUTPUTS FOR EPFD$_{IS}$ ASSESSMENT

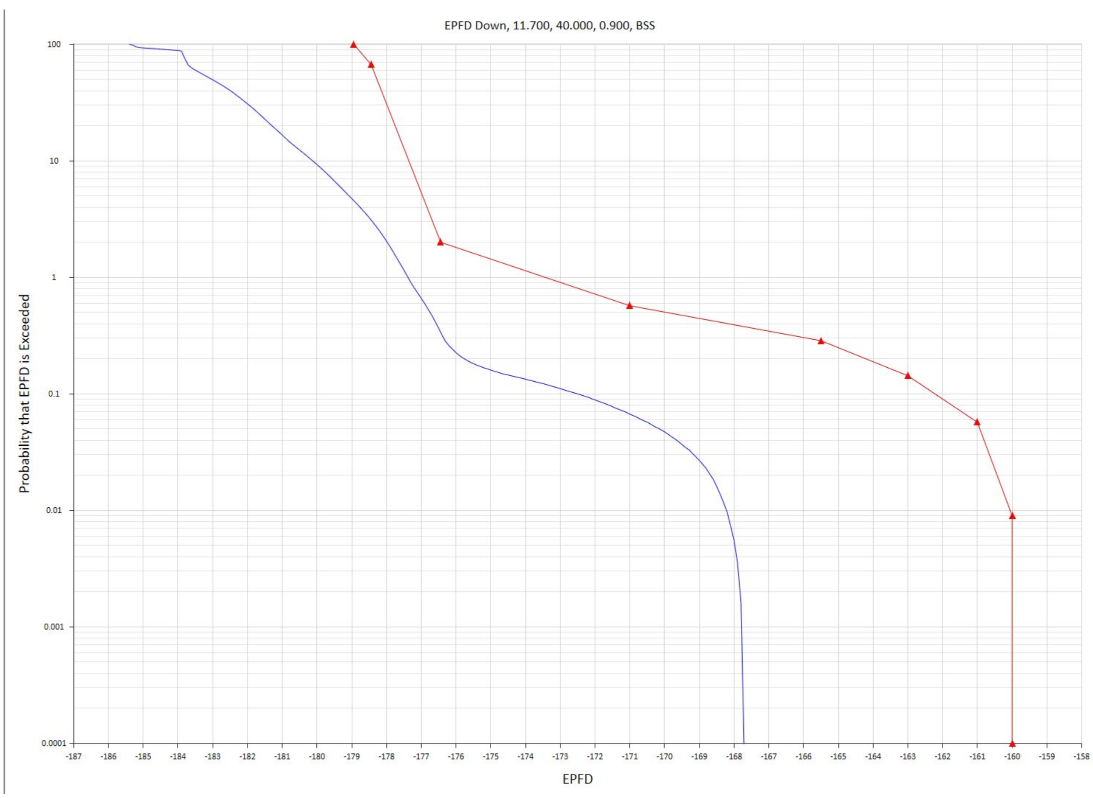


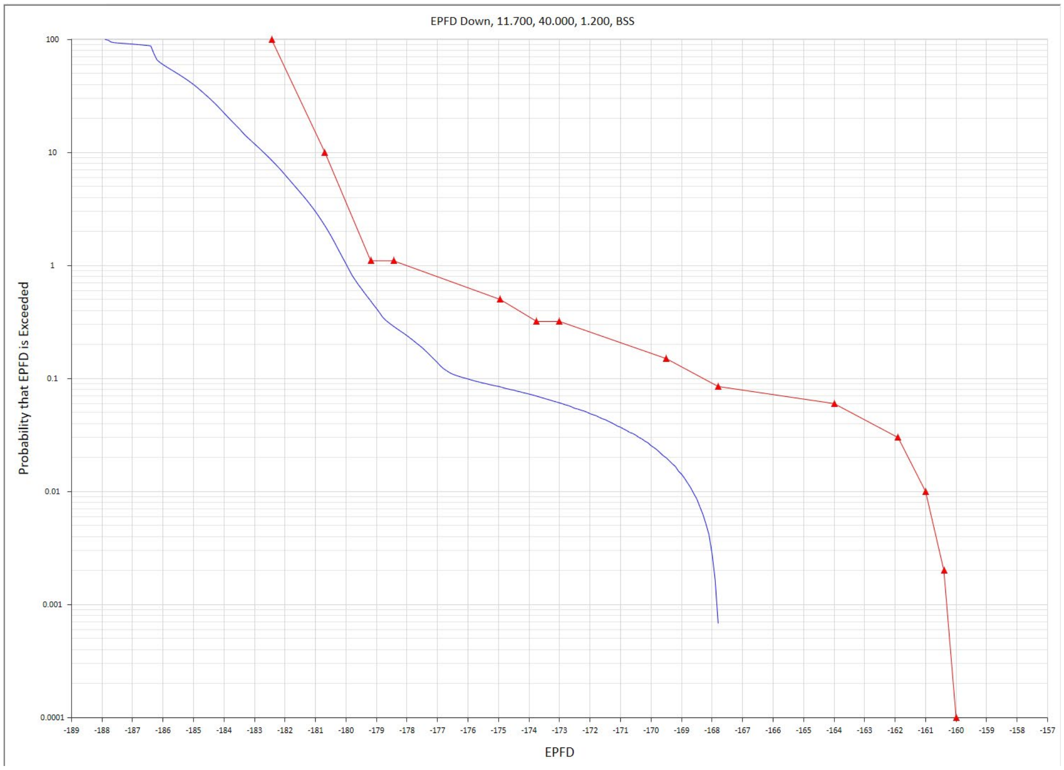
ANALYSIS OF FINAL DEPLOYMENT
OUTPUTS FOR EPFD$_{DOWN}$ ASSESSMENT OF BSS LIMITS

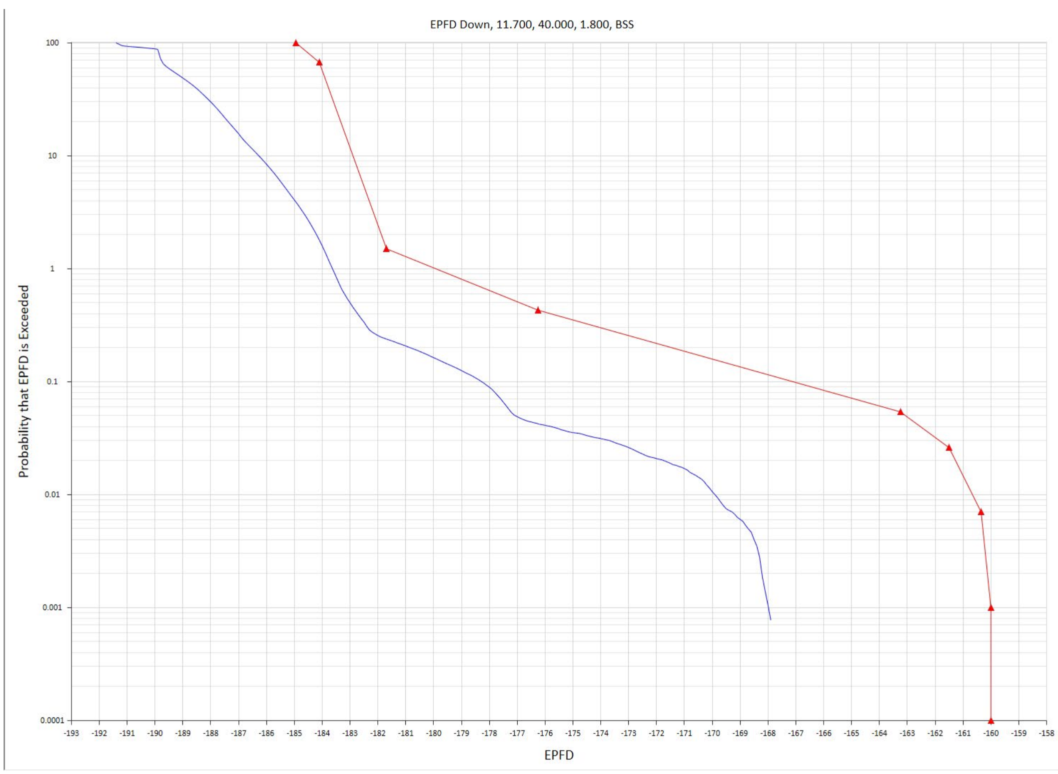


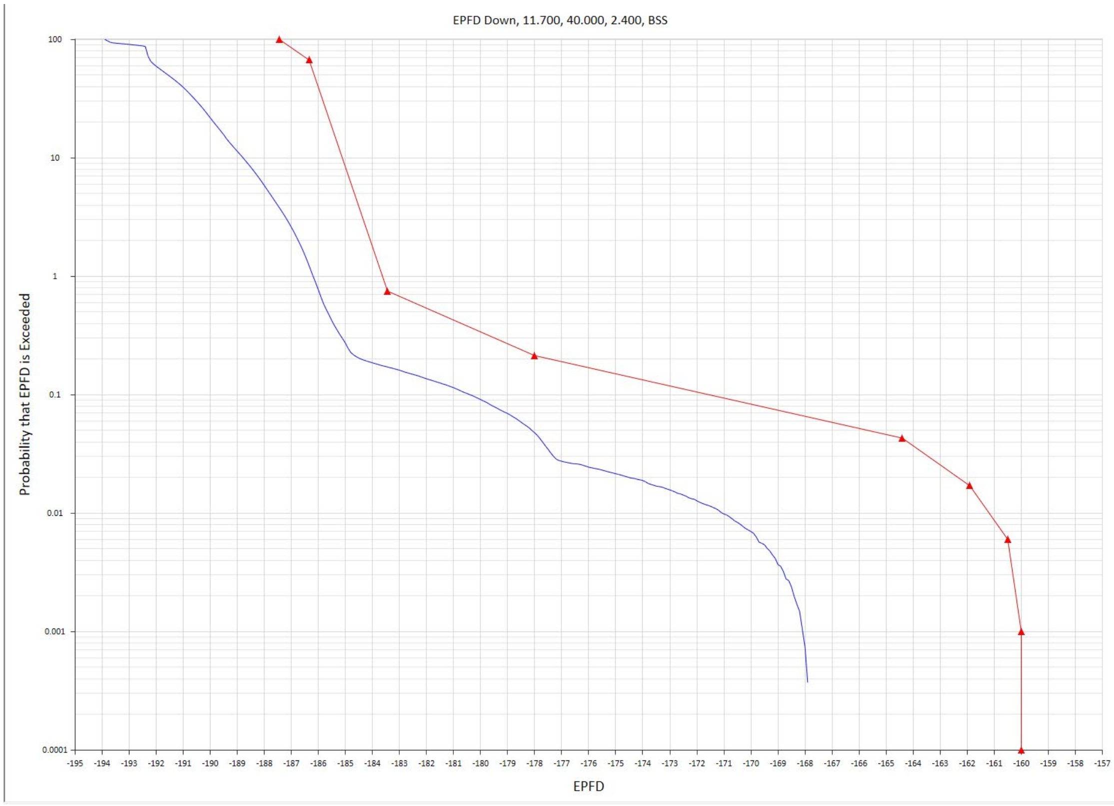


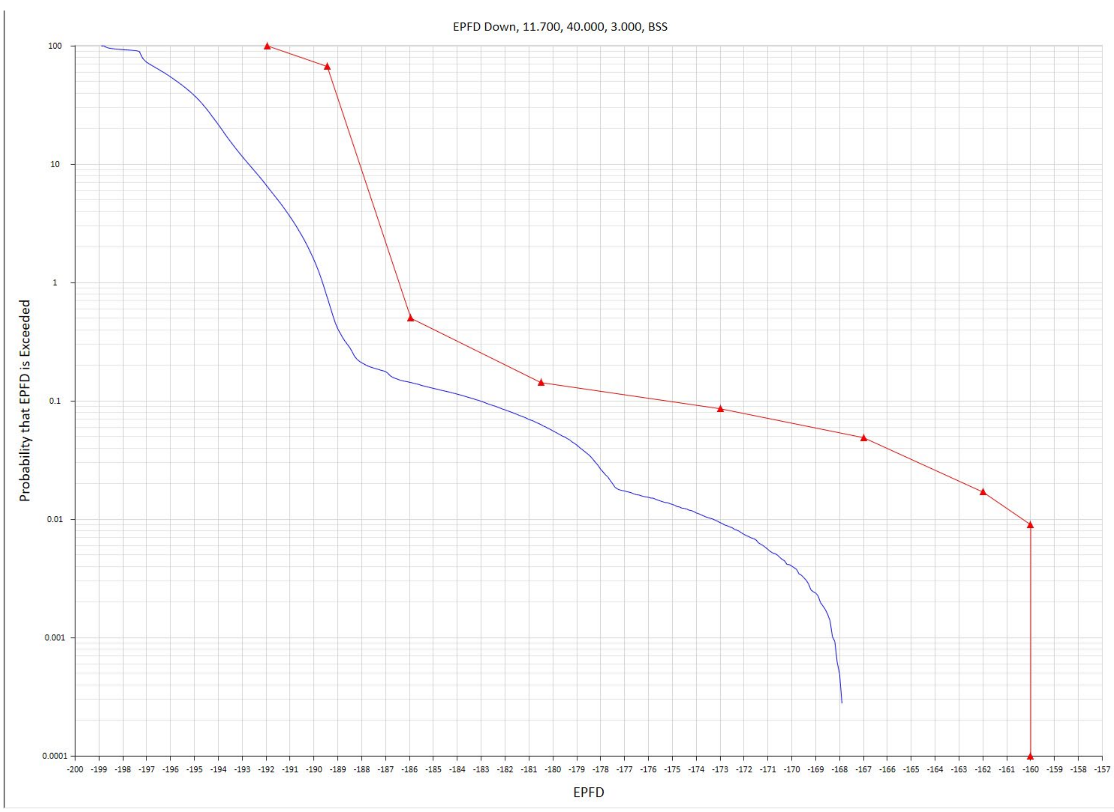

EPFD Down, 11.700, 40.000, 0.600, BSS
Probability that EPFD is Exceeded
EPFD


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

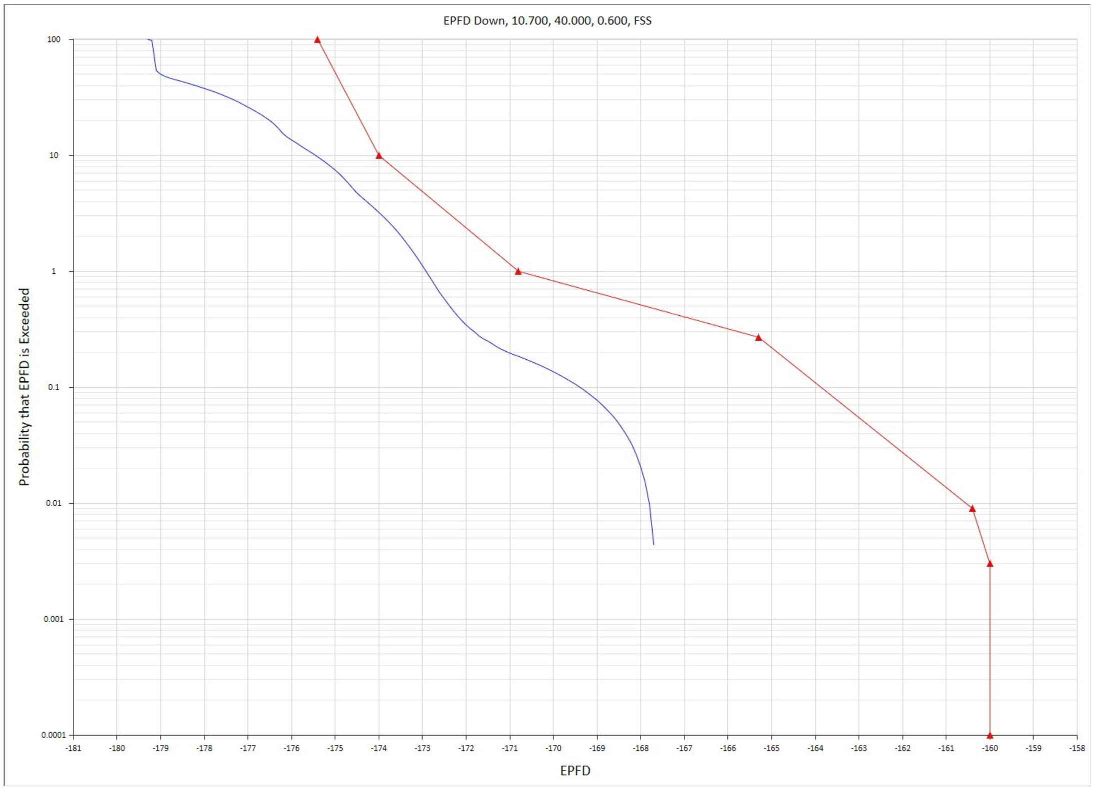

EPFD Down, 11.700, 40.000, 1.200, BSS
Probability that EPFD is Exceeded
EPFD

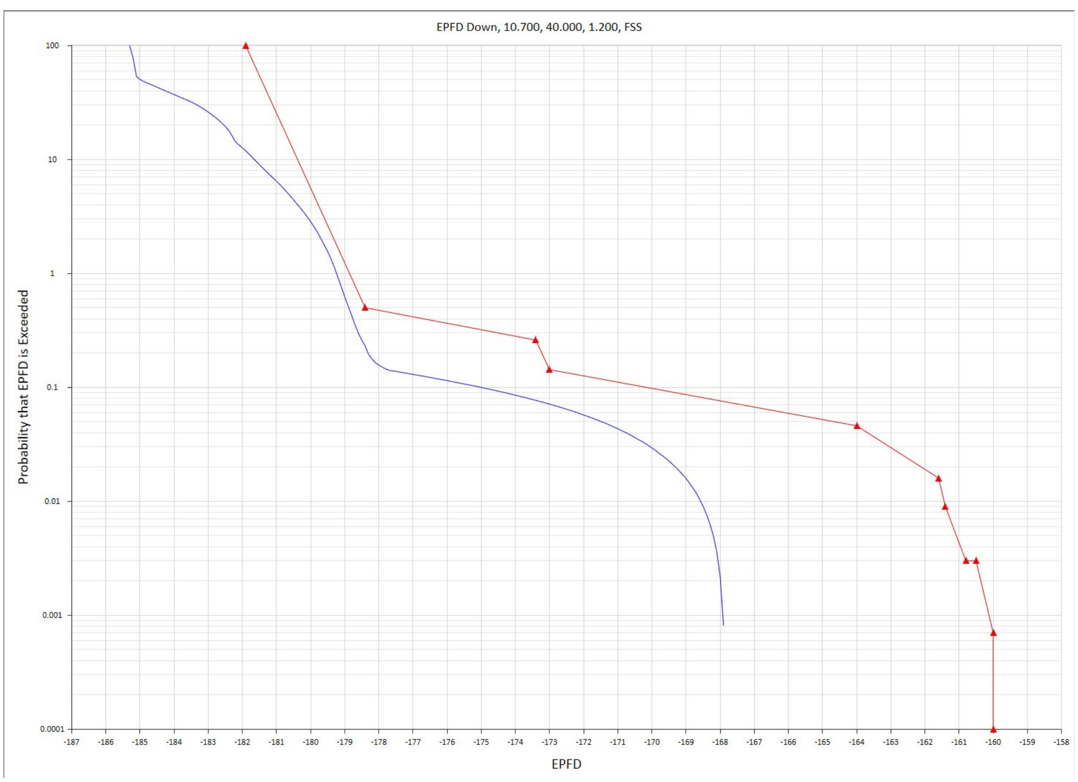

EPFD Down, 11.700, 40.000, 1.800, BSS
Probability that EPFD is Exceeded
EPFD

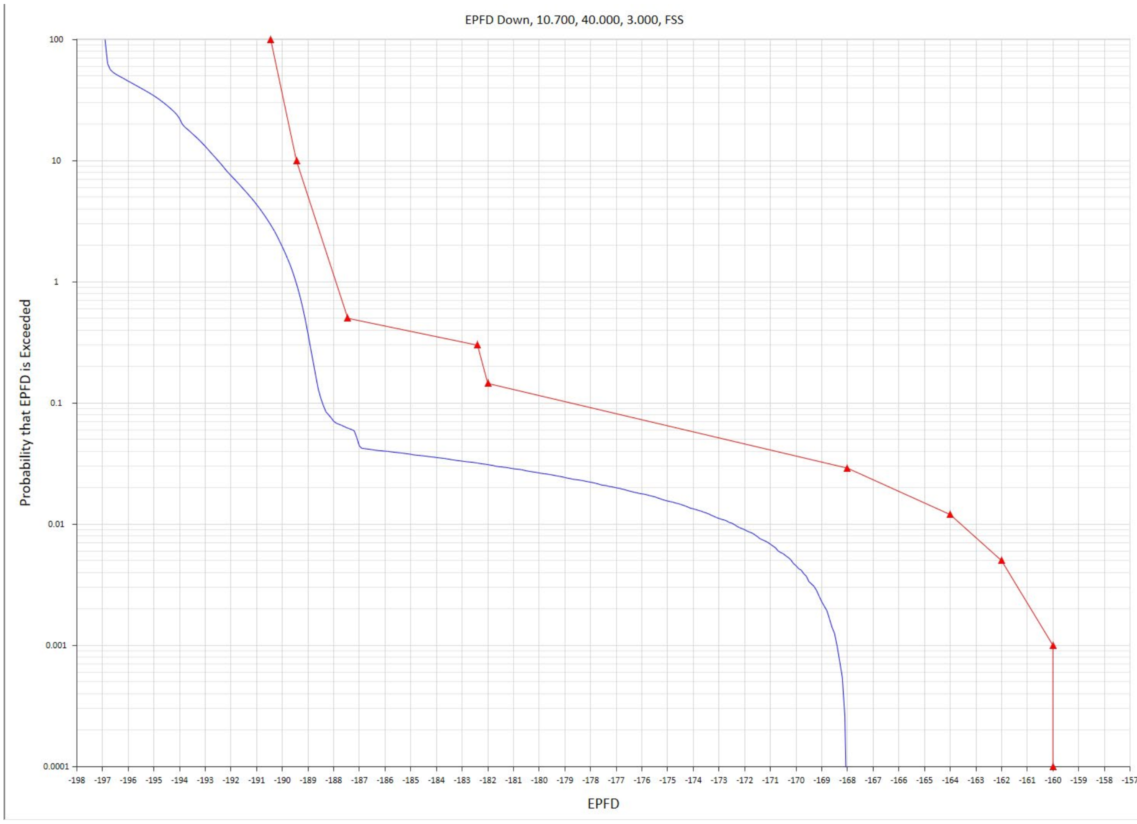

EPFD Down, 11.700, 40.000, 2.400, BSS
Probability that EPFD is Exceeded
EPFD

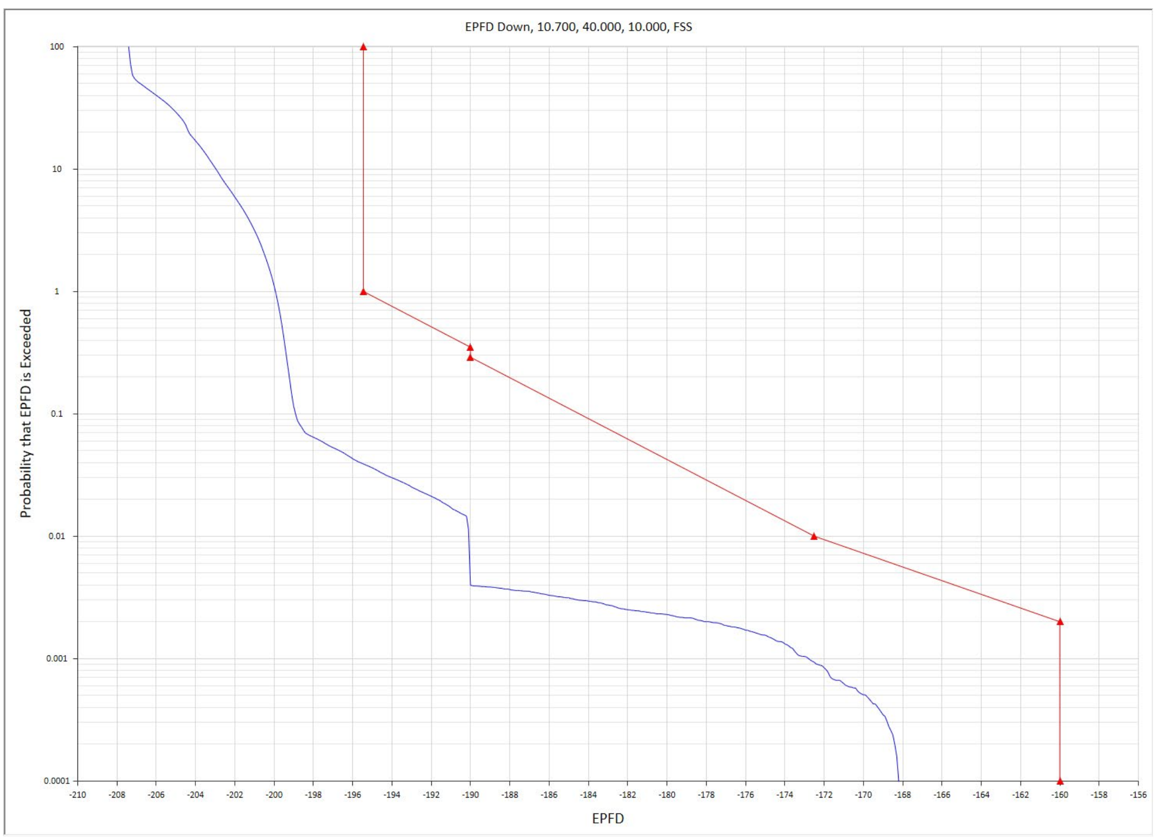

EPFD Down, 11.700, 40.000, 3.000, BSS
Probability that EPFD is Exceeded
EPFD

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

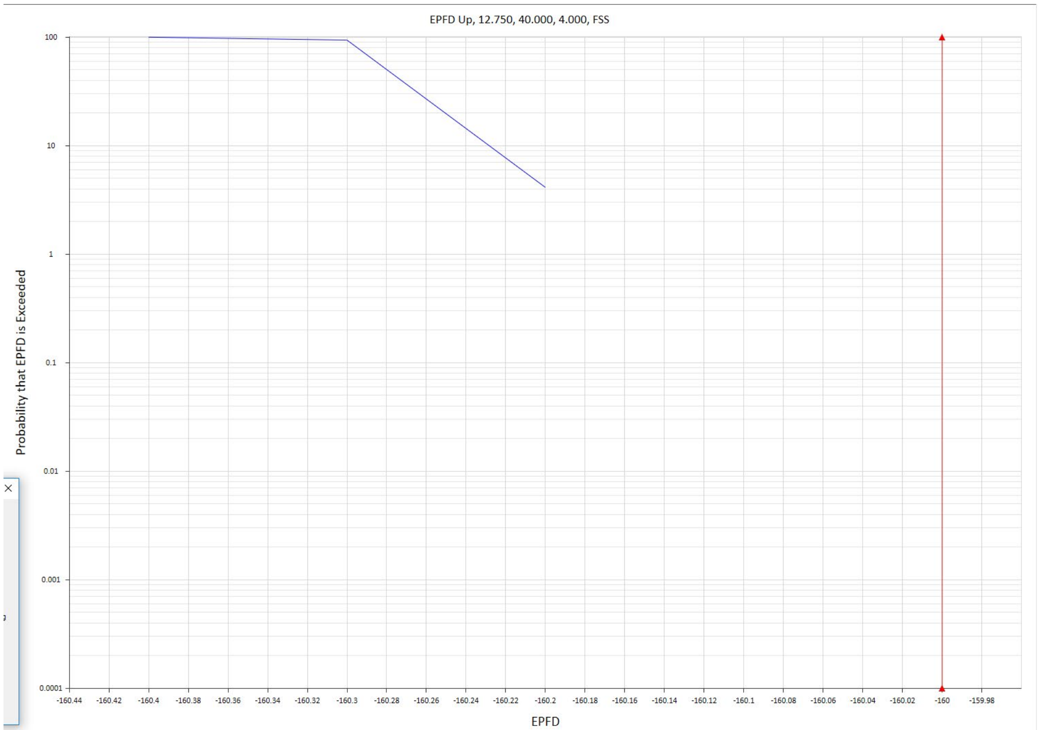


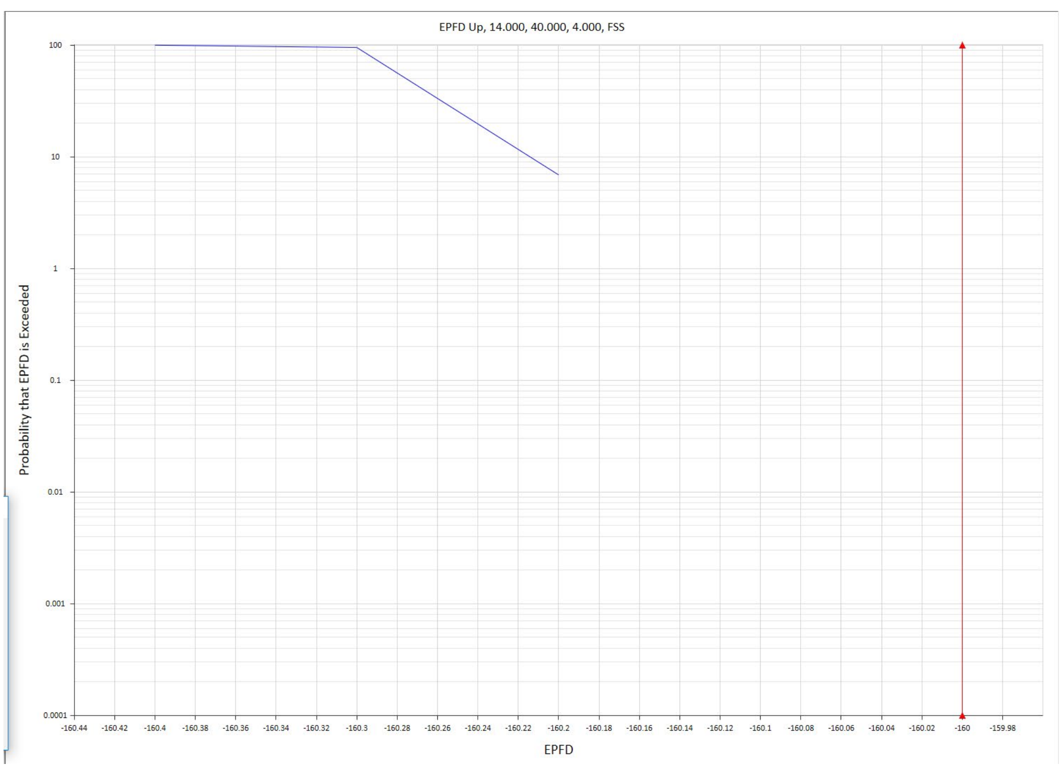



EPFD Down, 10.700, 40.000, 3.000, FSS
Probability that EPFD is Exceeded
EPFD

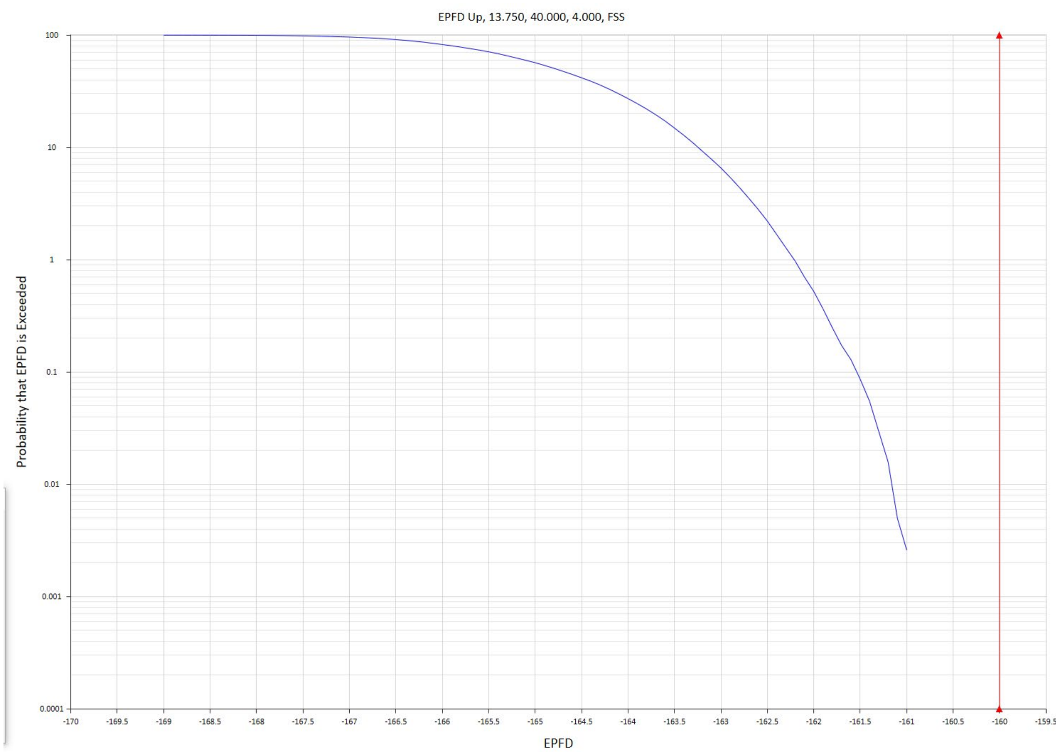

EPFD Down, 10.700, 40.000, 10.000, FSS
Probability that EPFD is Exceeded
EPFD

OUTPUTS FOR EPFD$_{UP}$ ASSESSMENT

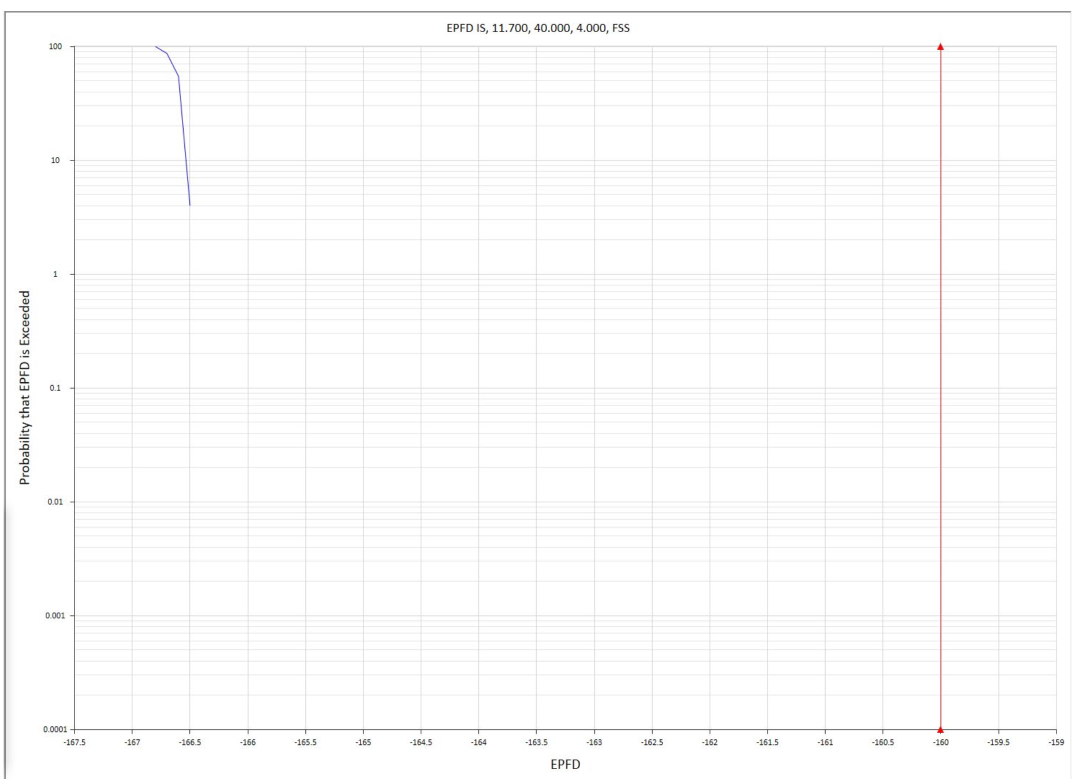




TT&C



OUTPUT FOR EPFD$_{IS}$ ASSESSMENT



B. Demonstration of EPFD Compliance for Ka-Band Operations

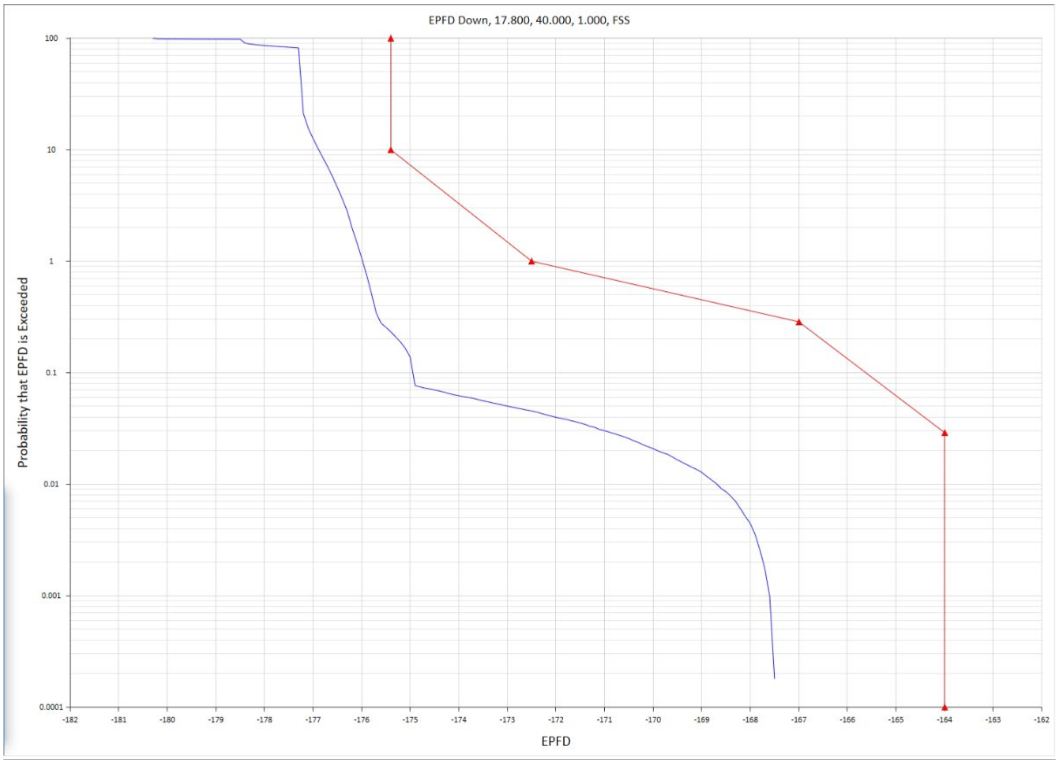
This annex demonstrates that the Ka-band operations of the SpaceX NGSO satellite system, as modified, will comply with the applicable EPFD limits. For this purpose, SpaceX has used the latest version of the ITU-approved computer program developed by Transfinite for determining compliance with the EPFD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

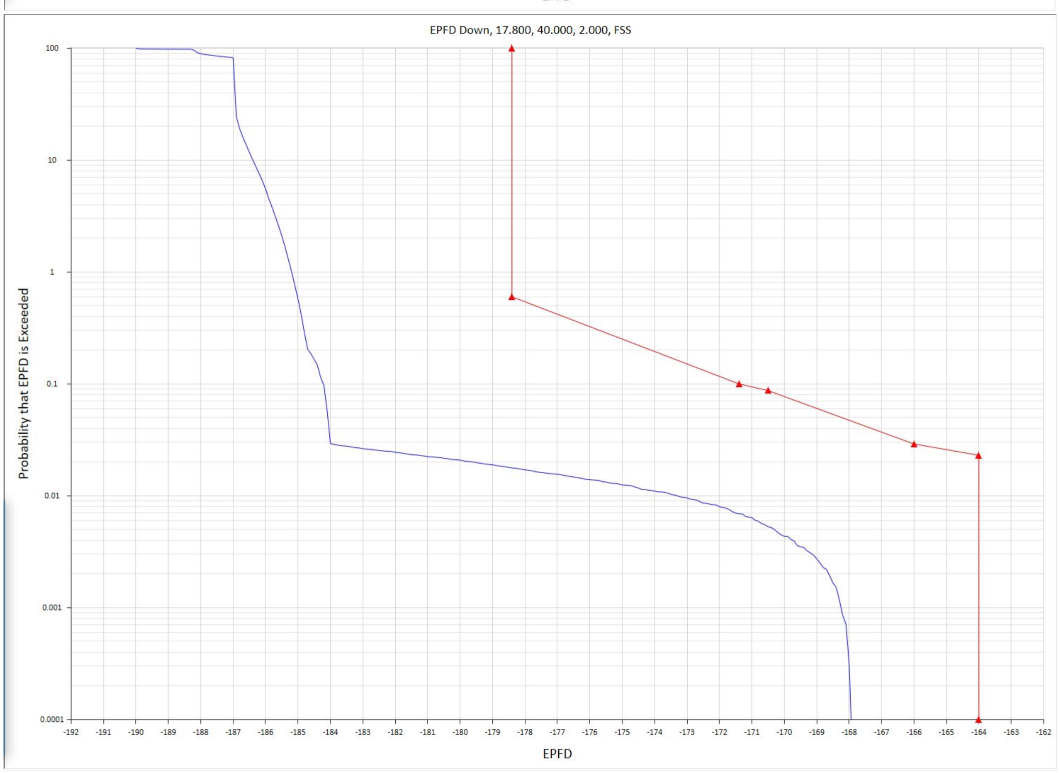
The figures below present the results of the Transfinite analysis with respect to the space-to-Earth direction ($EPFD_{down}$), the Earth-to-space direction ($EPFD_{up}$), for transmissions between satellites in orbit where spectrum is allocated bi-directionally ($EPFD_{is}$), and for TT&C transmissions, 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.

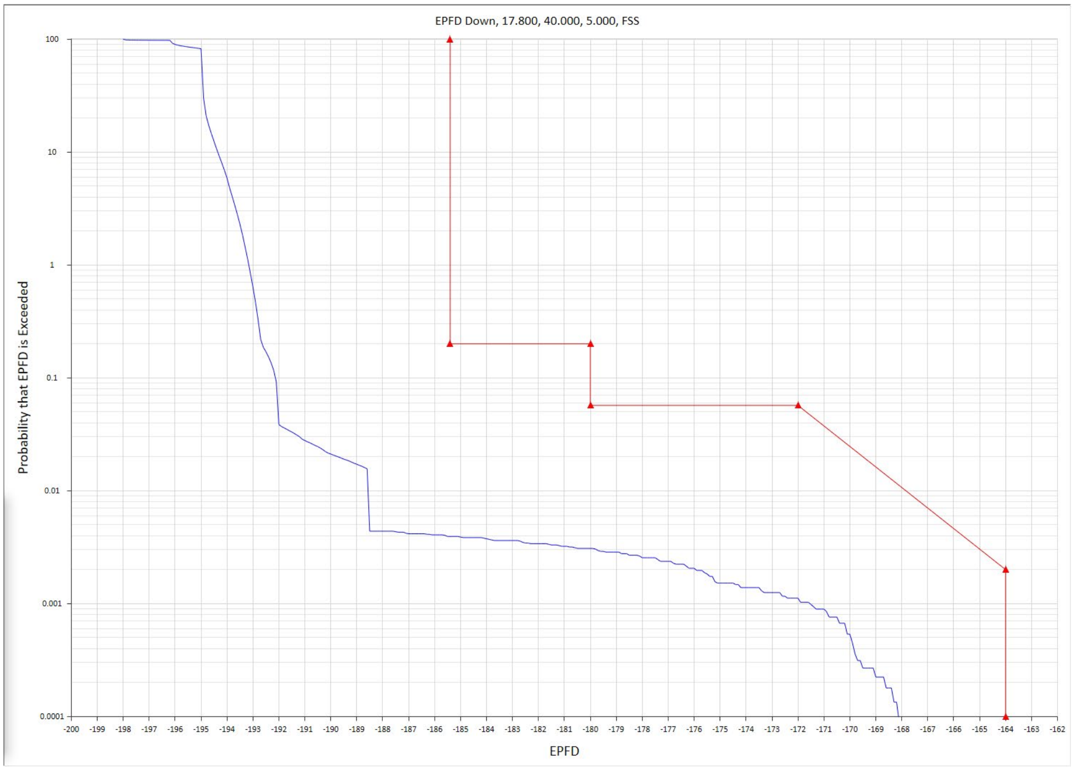
As these diagrams demonstrate, SpaceX's modified NGSO system will continue to comply with all EPFD limits applicable to its Ka-band operations.

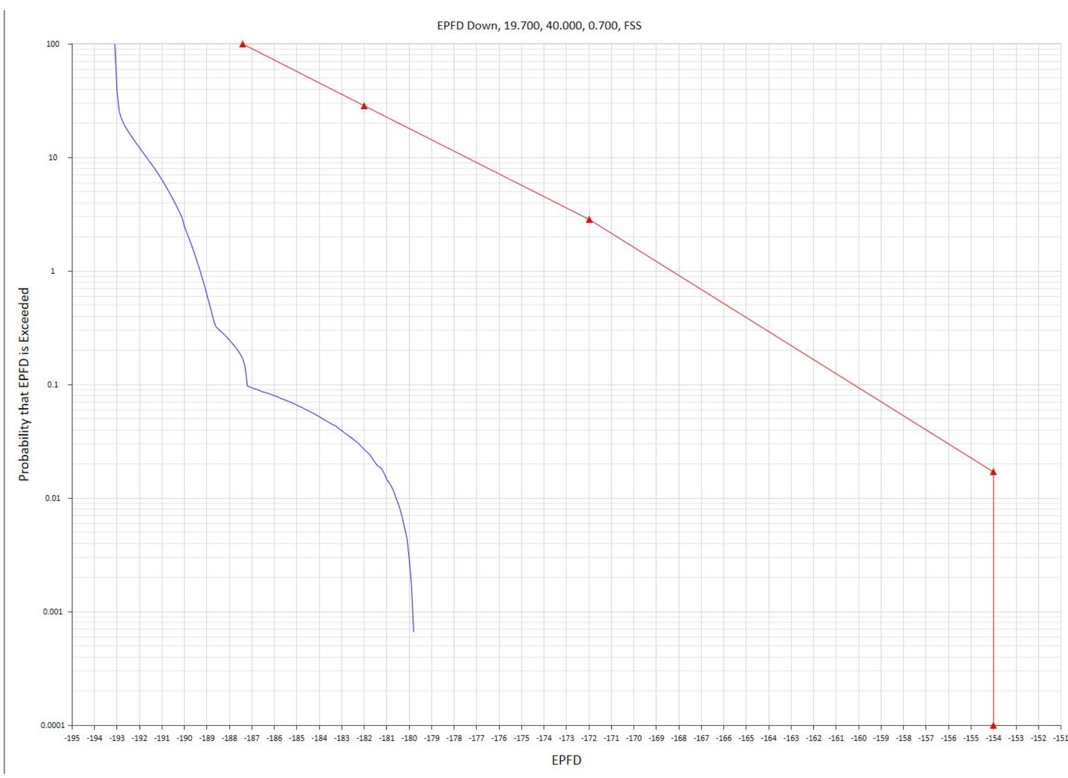
ANALYSIS OF INITIAL DEPLOYMENT

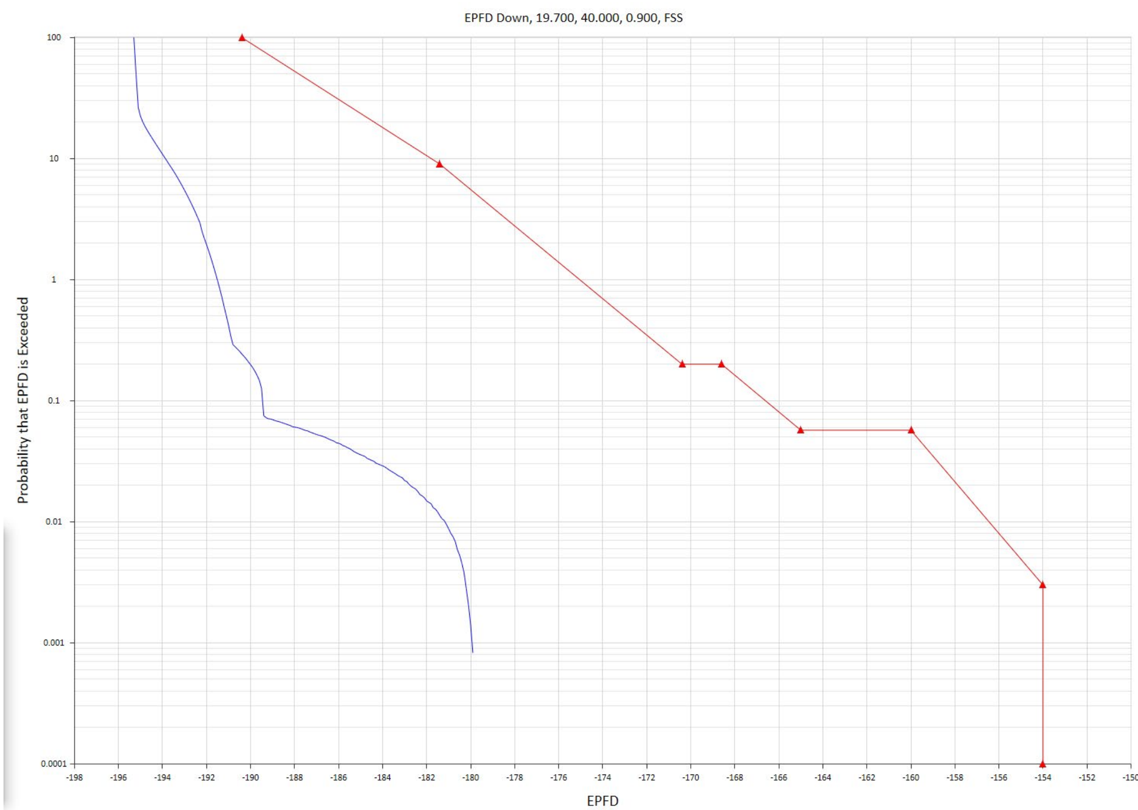
OUTPUTS FOR EPFD$_{DOWN}$ ASSESSMENT

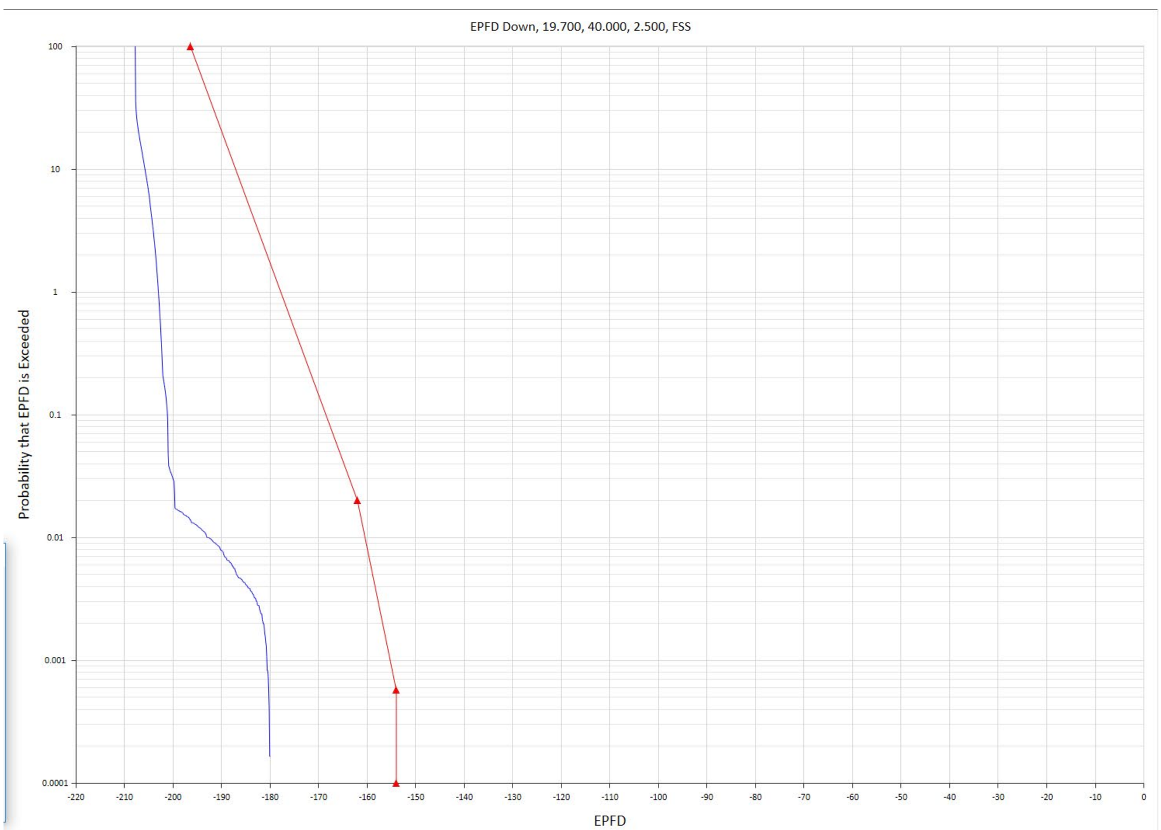


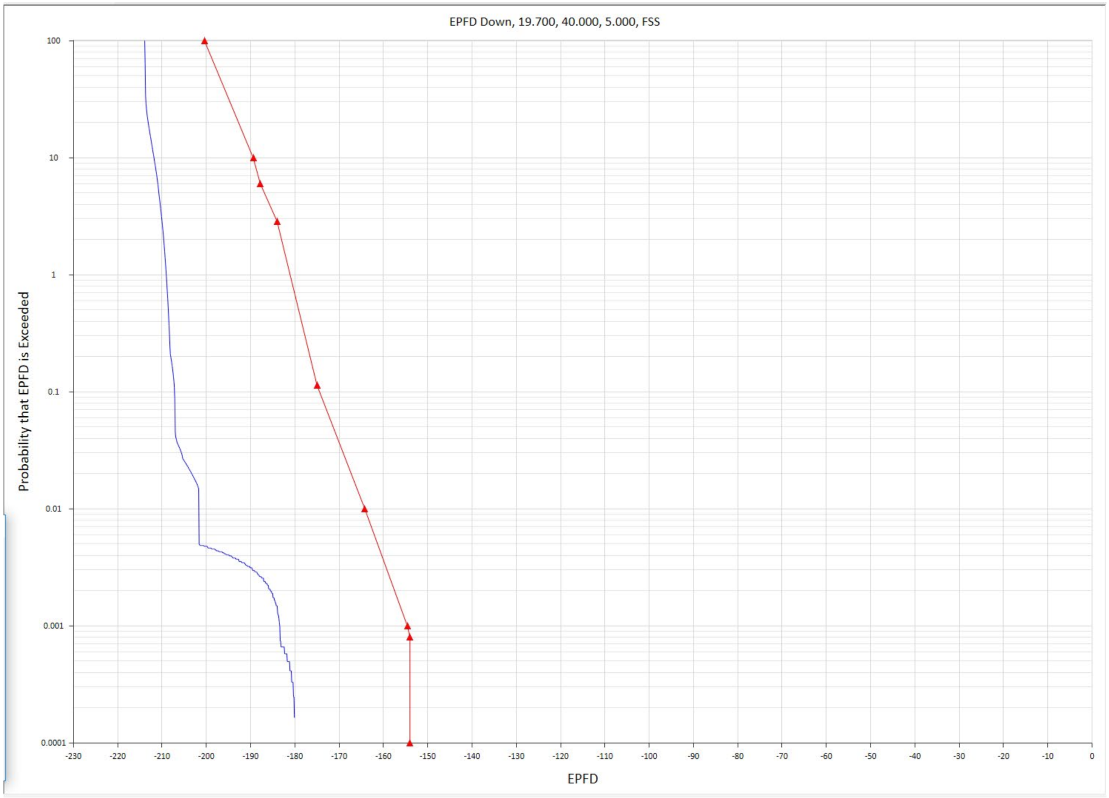



EPFD Down, 17.800, 40.000, 5.000, FSS
Probability that EPFD is Exceeded
EPFD
100
10
1
0.1
0.01
0.001
0.0001

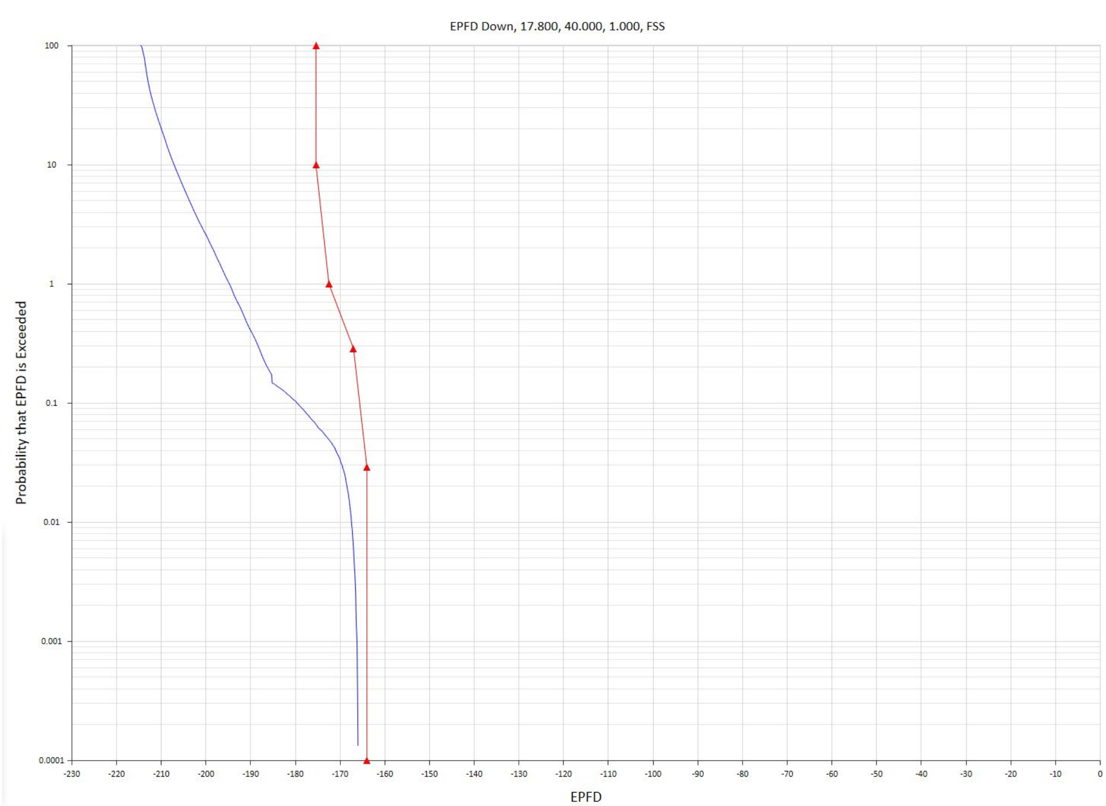

EPFD Down, 19.700, 40.000, 0.700, FSS
Probability that EPFD is Exceeded
EPFD
100
10
1
0.1
0.01
0.001
0.0001


EPFD Down, 19.700, 40.000, 0.900, FSS
Probability that EPFD is Exceeded
EPFD

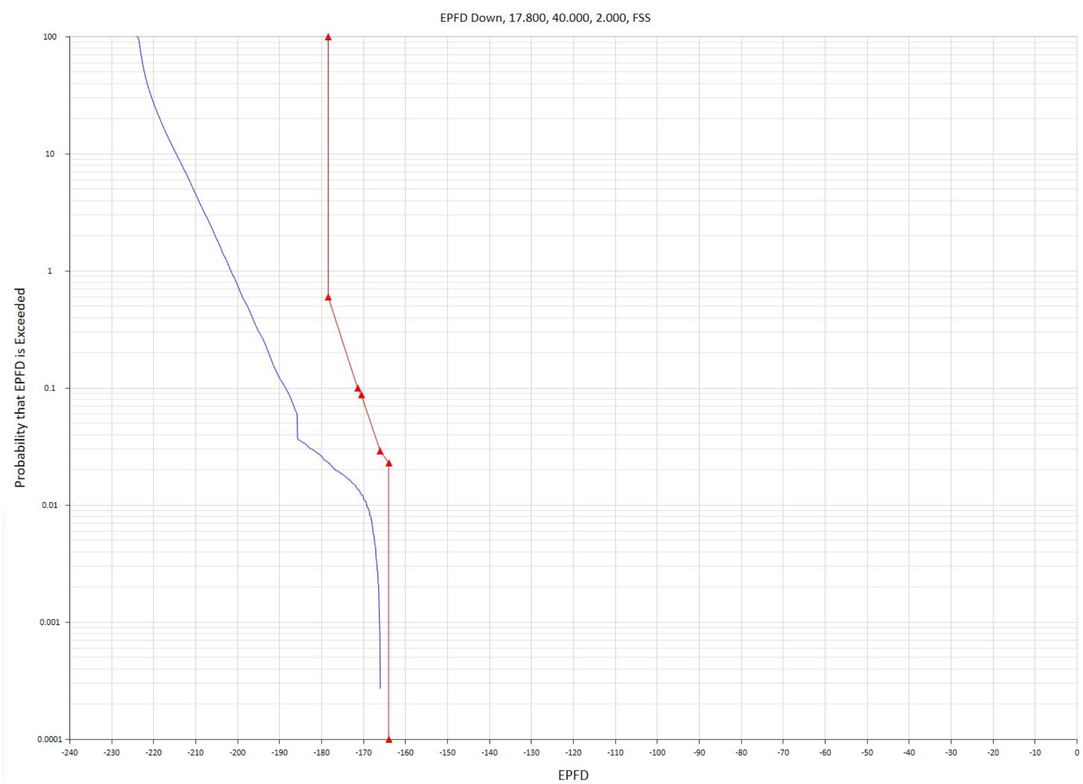

EPFD Down, 19.700, 40.000, 2.500, FSS
Probability that EPFD is Exceeded
EPFD


EPFD Down, 19.700, 40.000, 5.000, FSS
Probability that EPFD is Exceeded
EPFD

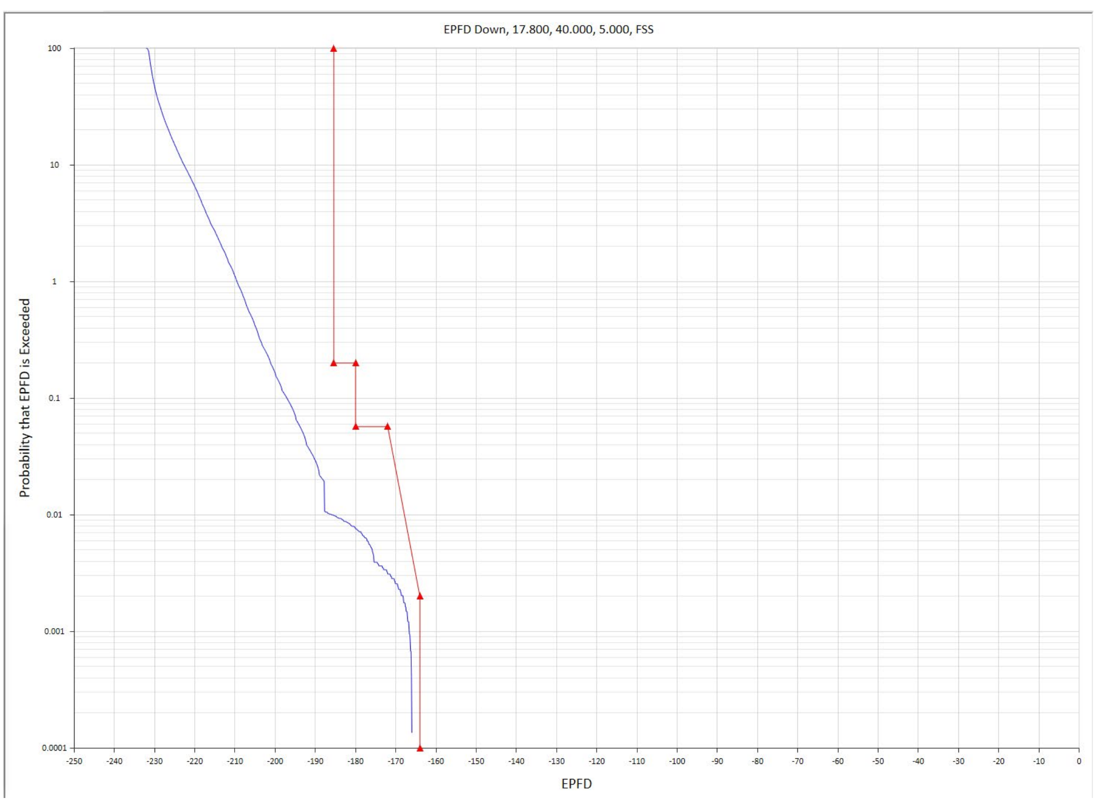
TT&C


EPFD Down, 17.800, 40.000, 1.000, FSS
Probability that EPFD is Exceeded
EPFD

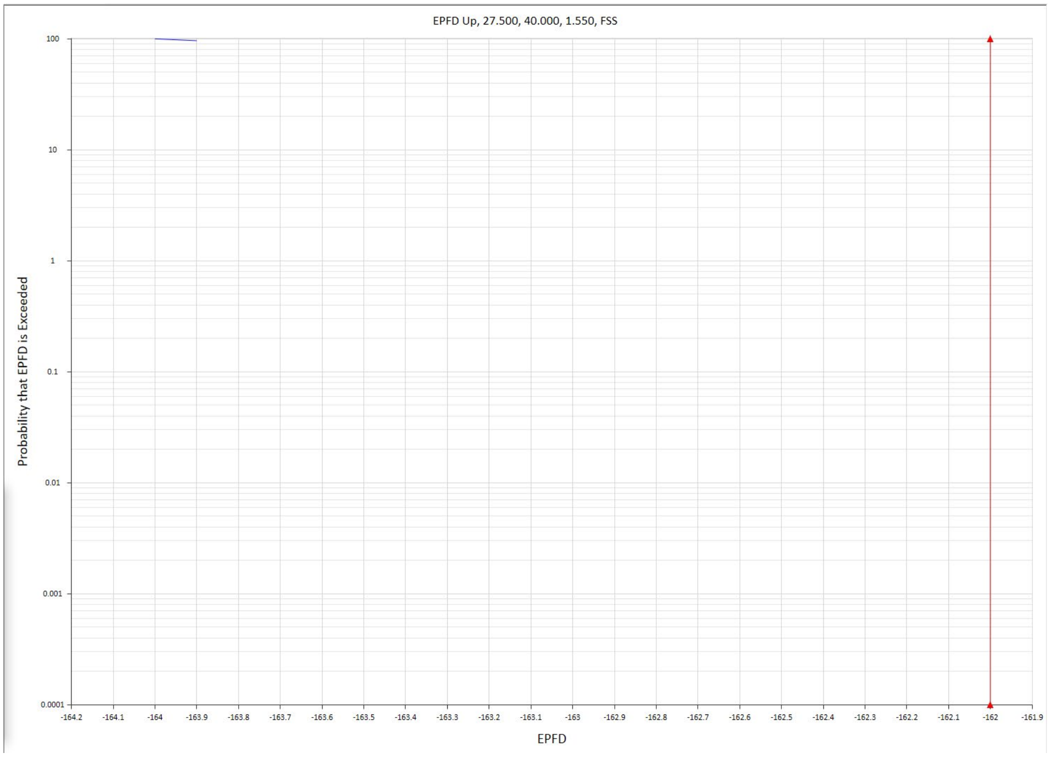
TT&C


EPFD Down, 17.800, 40.000, 2.000, FSS
Probability that EPFD is Exceeded
EPFD
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

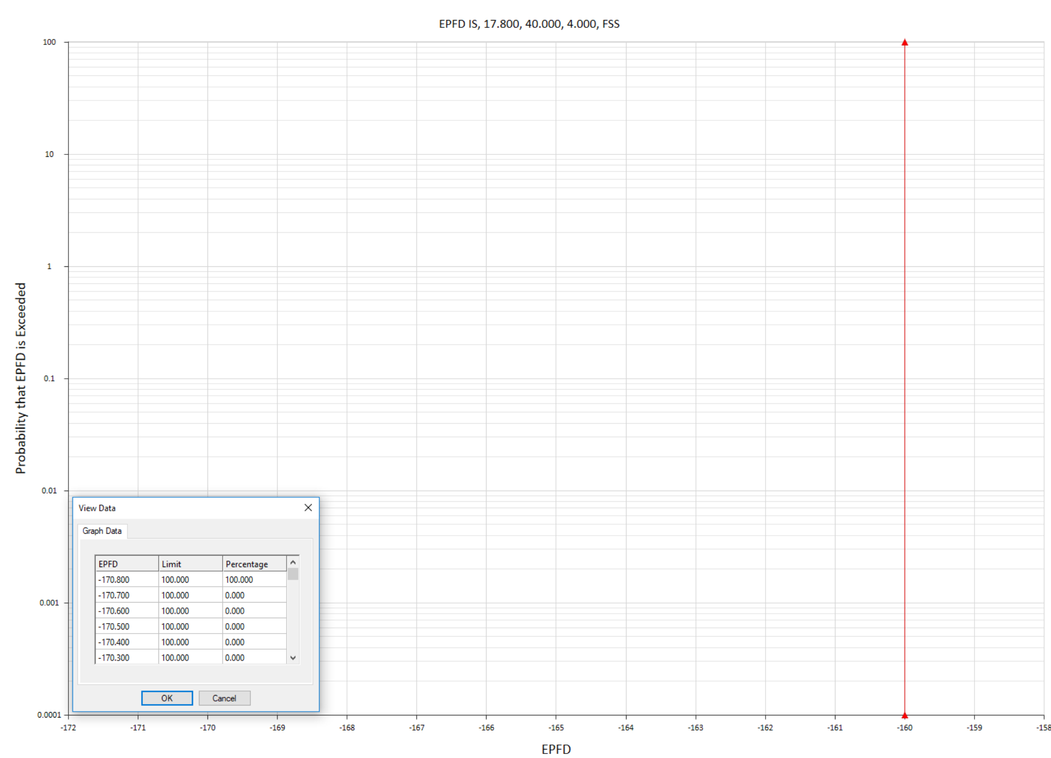
TT&C


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

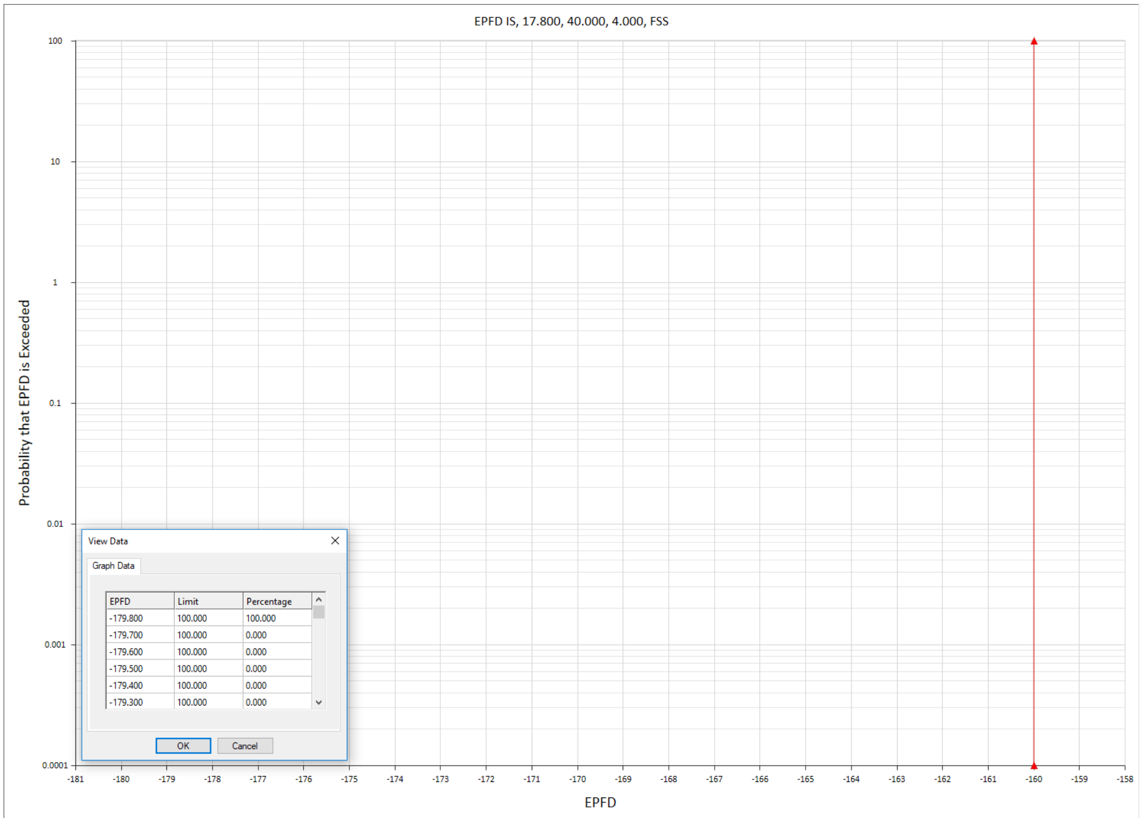
OUTPUT FOR $EPFD_{UP}$ ASSESSMENT



OUTPUTS FOR $EPFD_{IS}$ ASSESSMENT

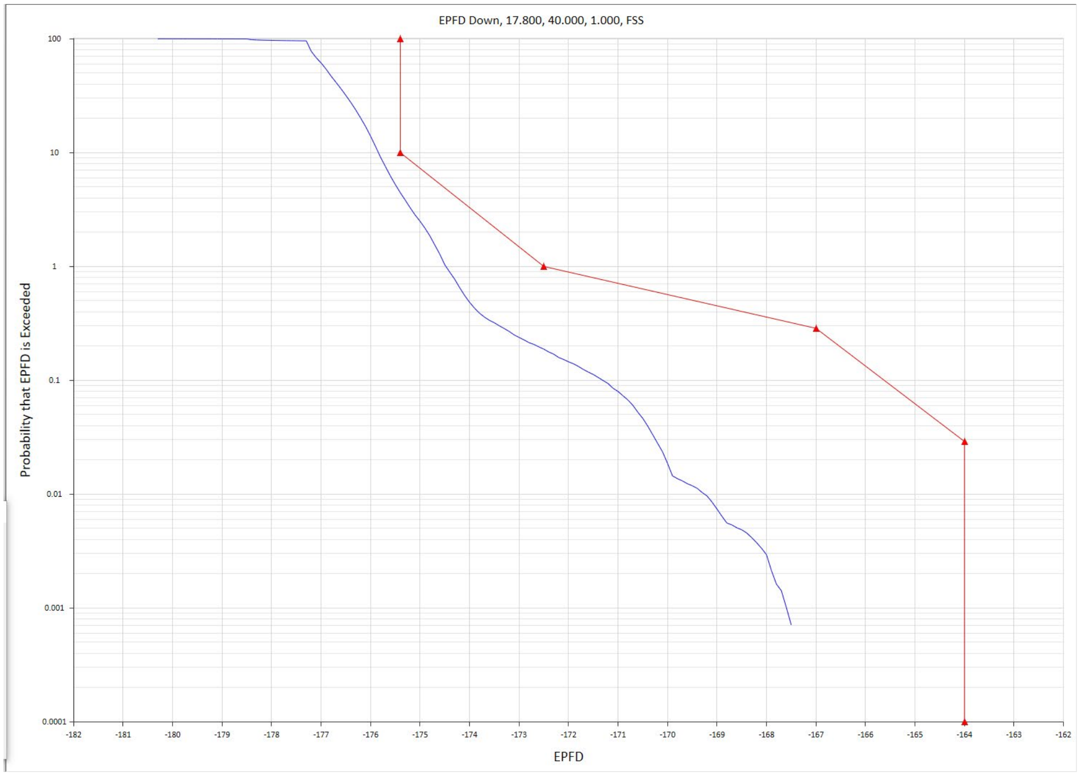


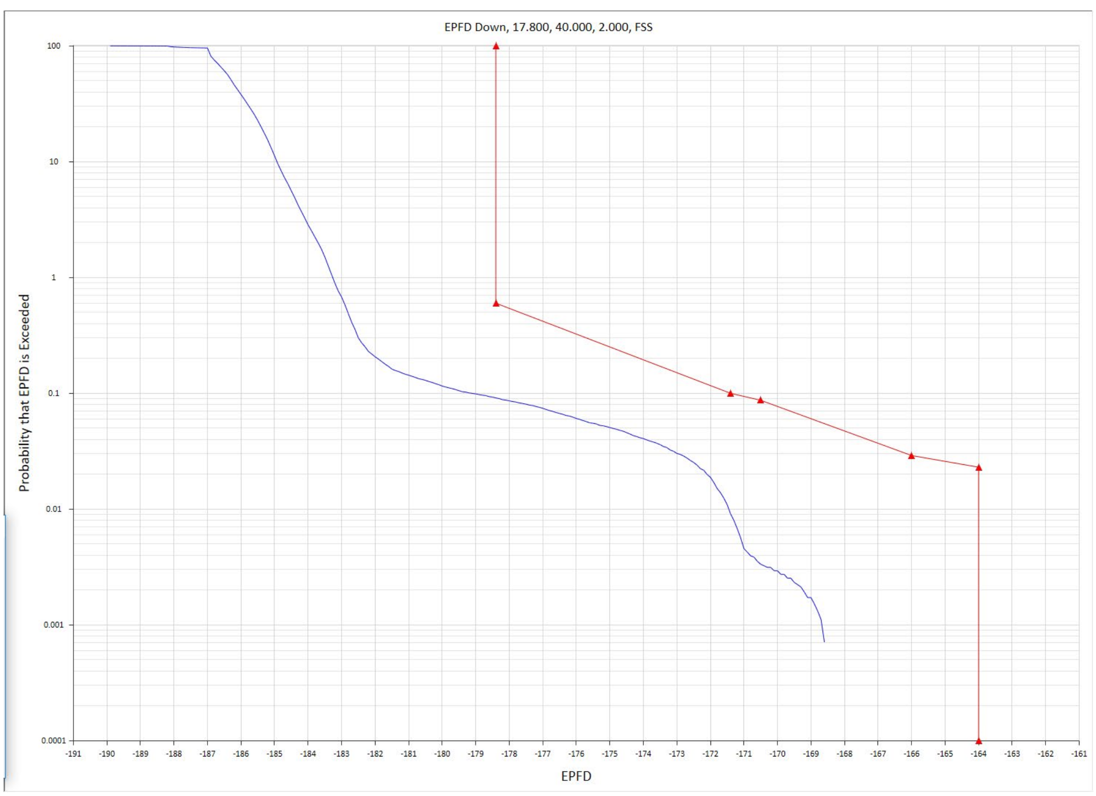
TT&C

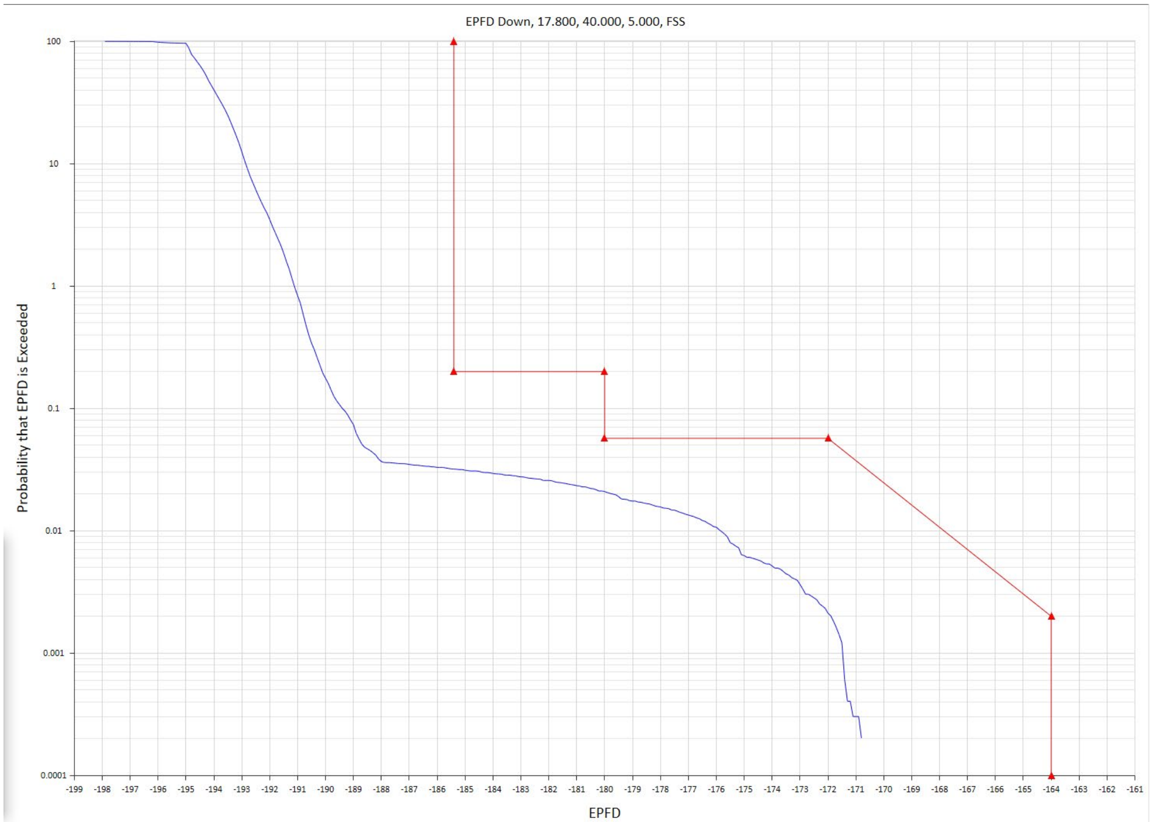

EPFD IS, 17.800, 40.000, 4.000, FSS
Probability that EPFD is Exceeded
EPFD
View Data
Graph Data
EPFD
Limit
Percentage
-179.800
100.000
100.000
-179.700
100.000
0.000
-179.600
100.000
0.000
-179.500
100.000
0.000
-179.400
100.000
0.000
-179.300
100.000
0.000
OK
Cancel

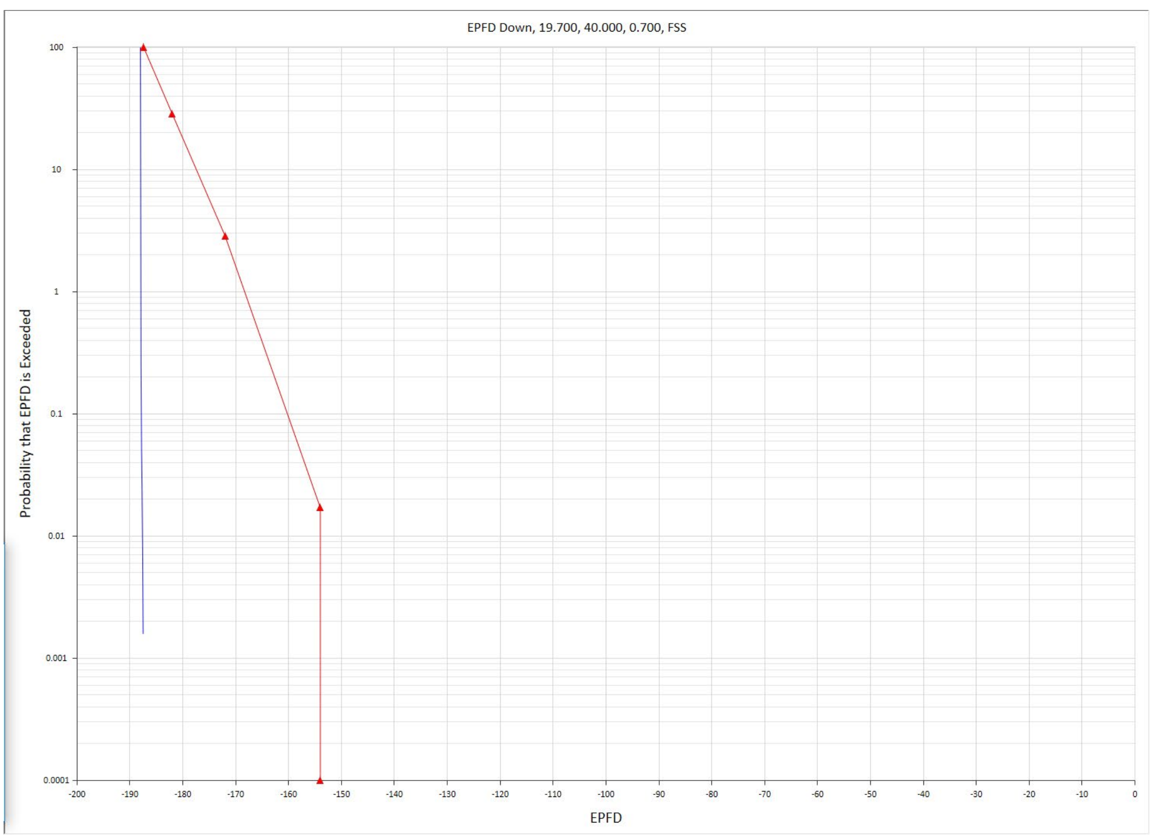
ANALYSIS OF FINAL DEPLOYMENT

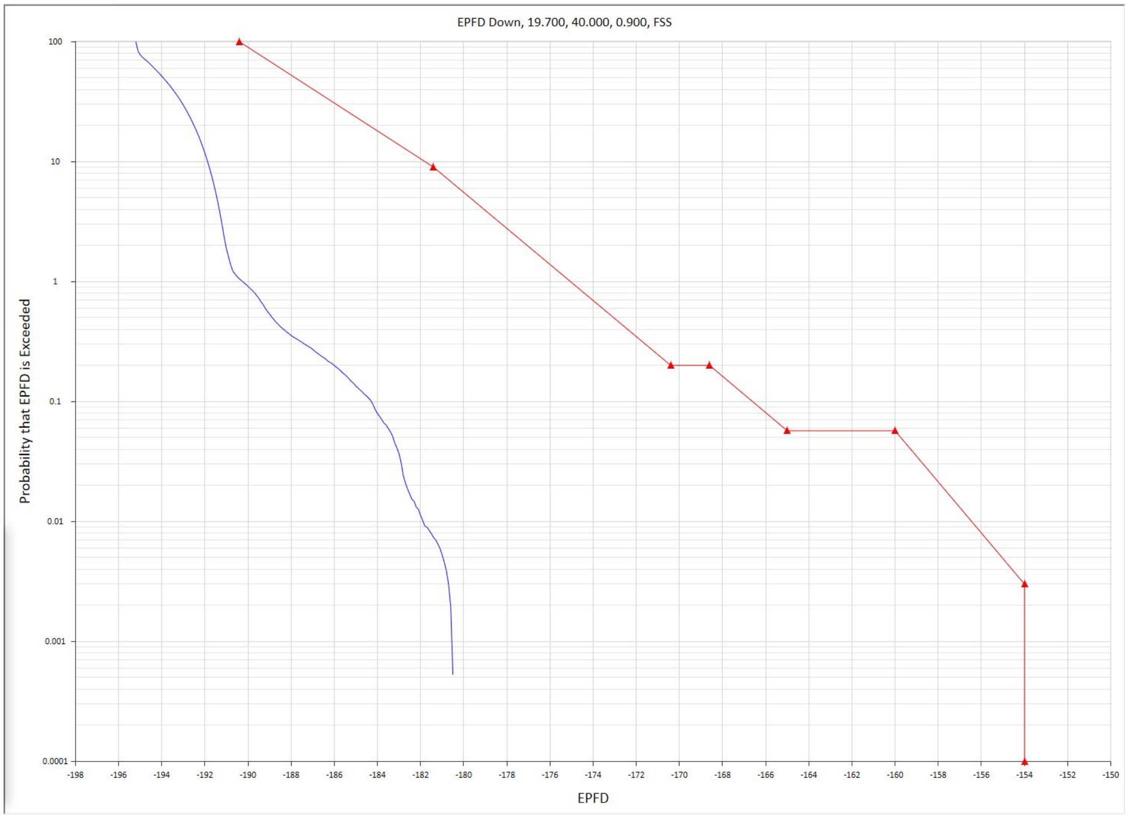
OUTPUTS FOR EPFD$_{DOWN}$ ASSESSMENT






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


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


EPFD Down, 19.700, 40.000, 0.900, FSS
Probability that EPFD is Exceeded
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
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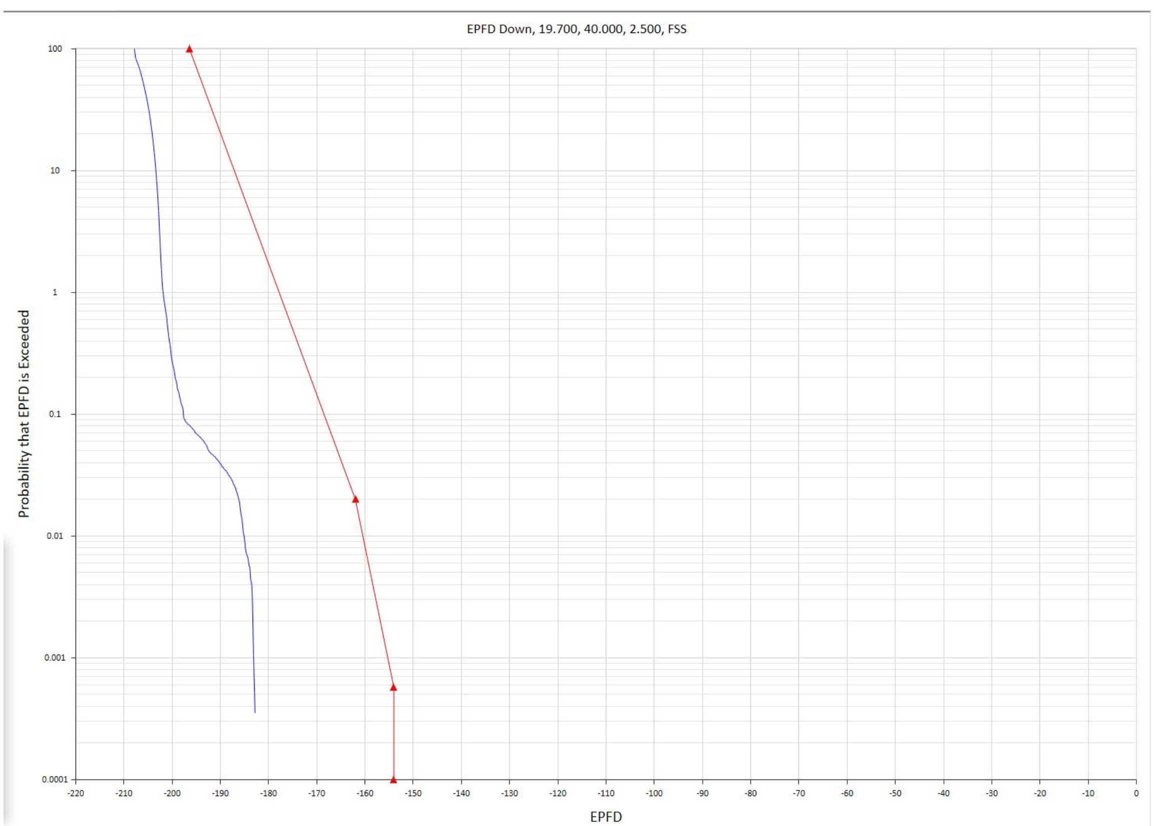
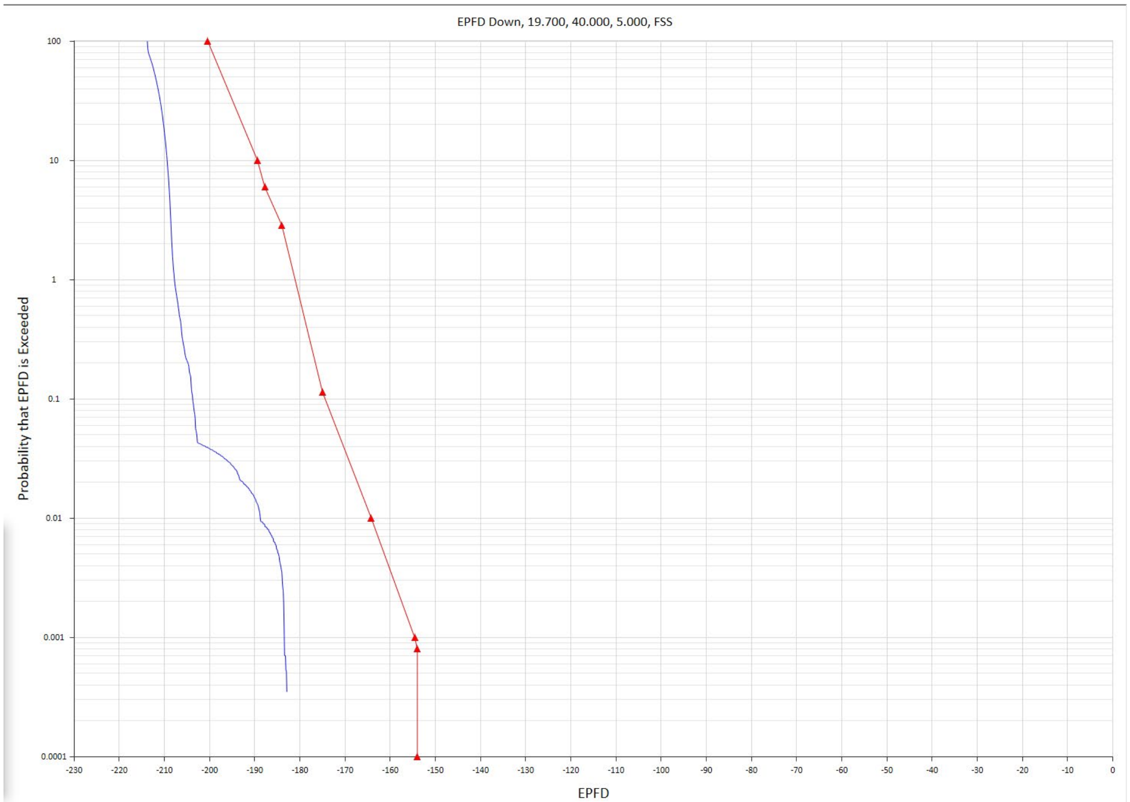
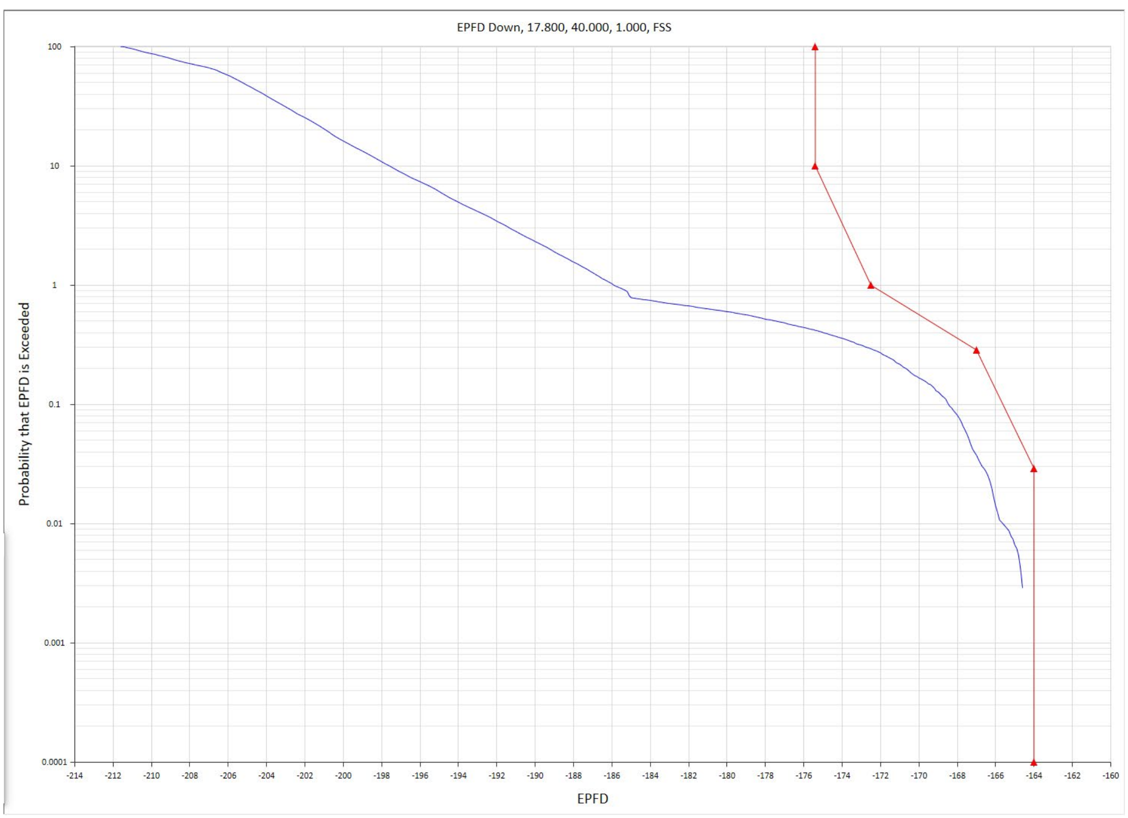
-160
-158
-156
-154
-152
-150

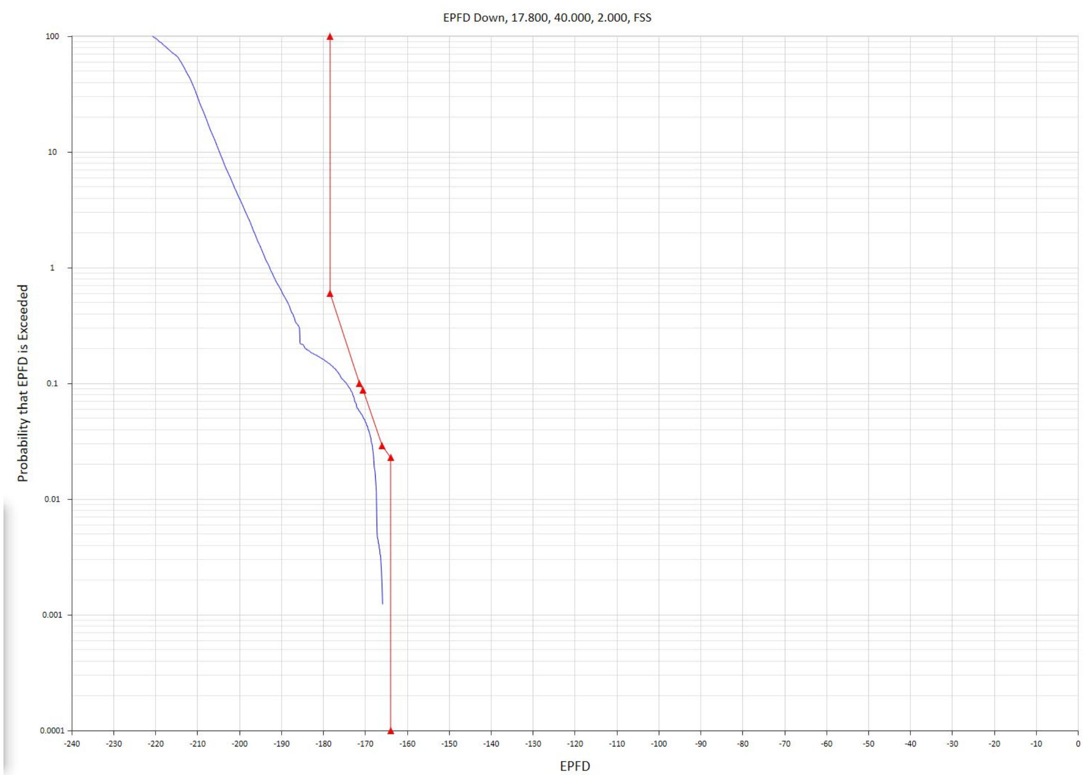

EPFD Down, 19.700, 40.000, 2.500, FSS
Probability that EPFD is Exceeded
EPFD
100
10
1
0.1
0.01
0.001
0.0001
-220
-210
-200
-190
-180
-170
-160
-150
-140
-130
-120
-110
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0


EPFD Down, 19.700, 40.000, 5.000, FSS
Probability that EPFD is Exceeded
EPFD

TT&C

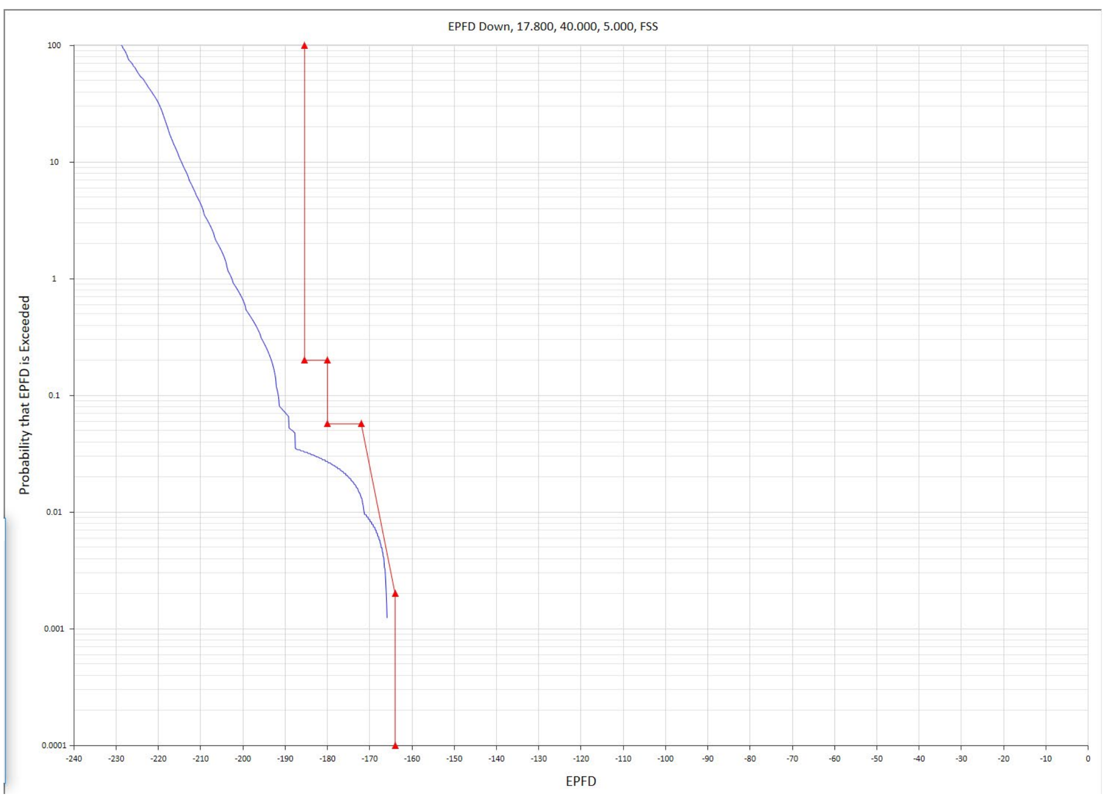

EPFD Down, 17.800, 40.000, 1.000, FSS
Probability that EPFD is Exceeded
EPFD

TT&C



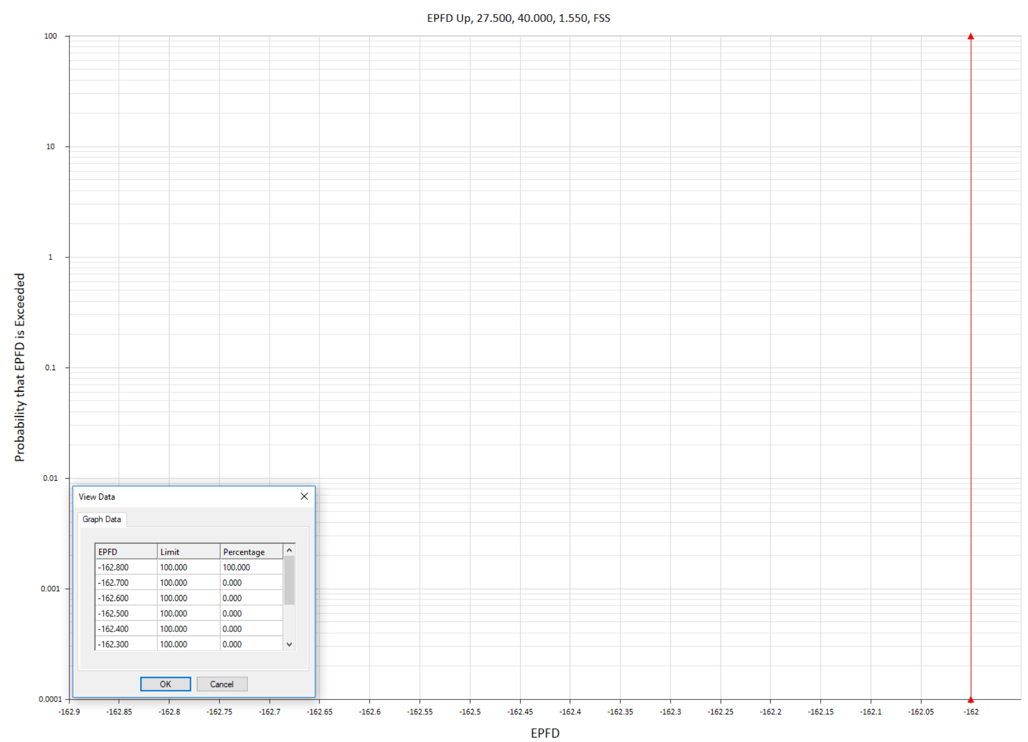
EPFD Down, 17.800, 40.000, 2.000, FSS
Probability that EPFD is Exceeded
EPFD

TT&C

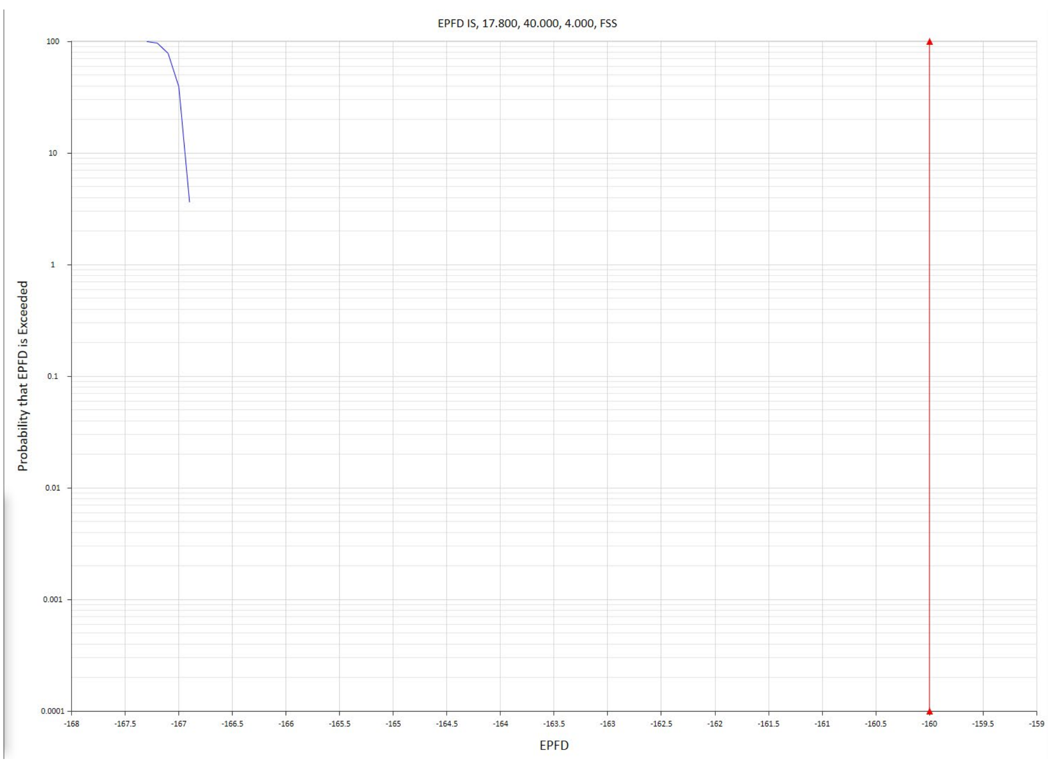


EPFD Down, 17.800, 40.000, 5.000, FSS
Probability that EPFD is Exceeded
EPFD

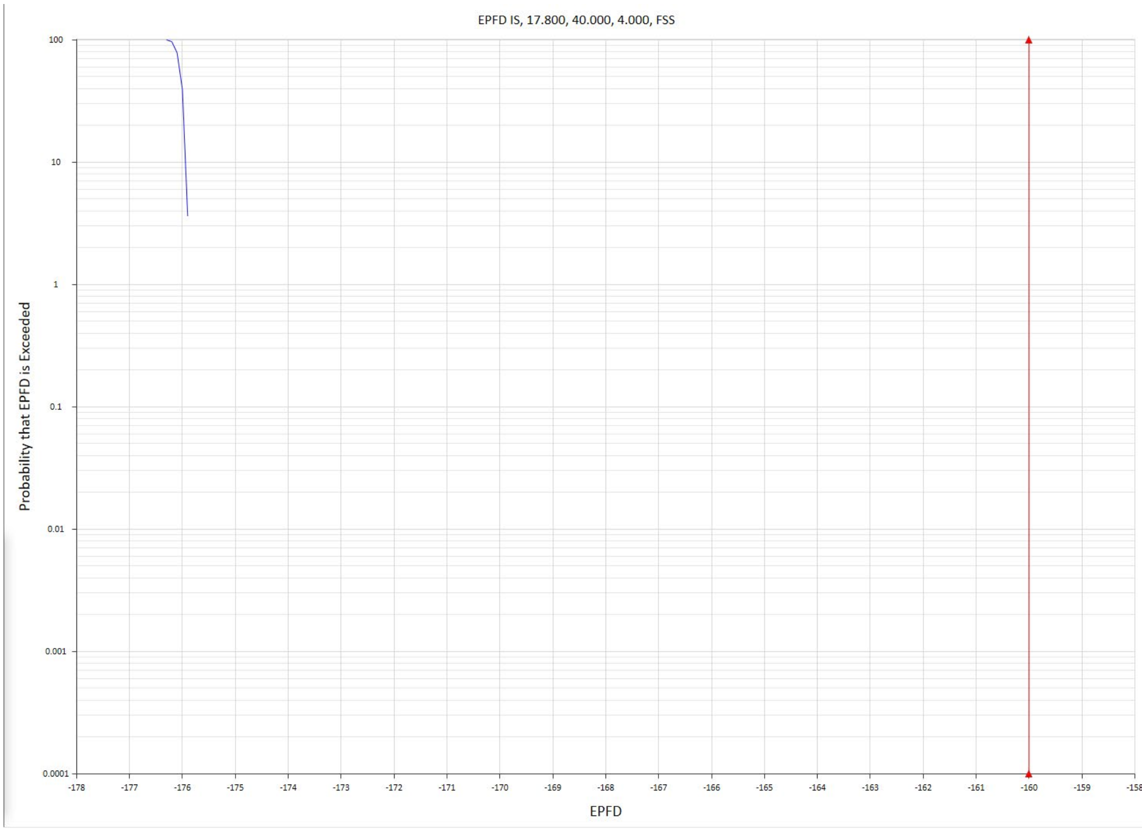
OUTPUT FOR EPFD$_{UP}$ ASSESSMENT



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

ANNEX 3

POTENTIAL INTERFERENCE TO KA-BAND FIXED SERVICE SYSTEMS

In the SpaceX Initial Authorization, the Commission imposed a condition under which SpaceX must, before starting operation, file a modification application with a technical showing demonstrating that its operation will protect a fixed-service station with the characteristics described in Recommendation ITU-R SF.1483.[1] SpaceX made such a showing in connection with its recent modification, which the Commission found to satisfy the condition.[2] Nonetheless, in an abundance of caution, we make that showing below for the SpaceX constellation as modified to reflect respacing of satellites within 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

[1] *See* SpaceX Initial Authorization, ¶ 35.

[2] *See* SpaceX Modification, ¶ 29.

2. SpaceX Constellation as modified

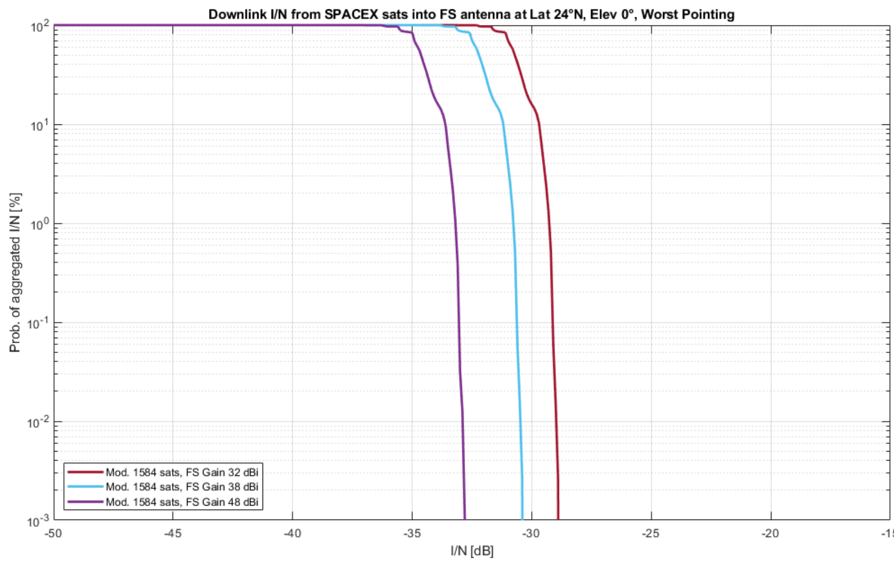
Parameters	Full Constellation					Initial Deployment
Orbit Alt. (km)	550	1110	1130	1275	1325	550
Min. Elevation	40°					25°
# Planes	72	32	8	5	6	72
# Sats/Plane	22	50	50	75	75	22
Total Sats/Shell	1584	1600	400	375	450	1584

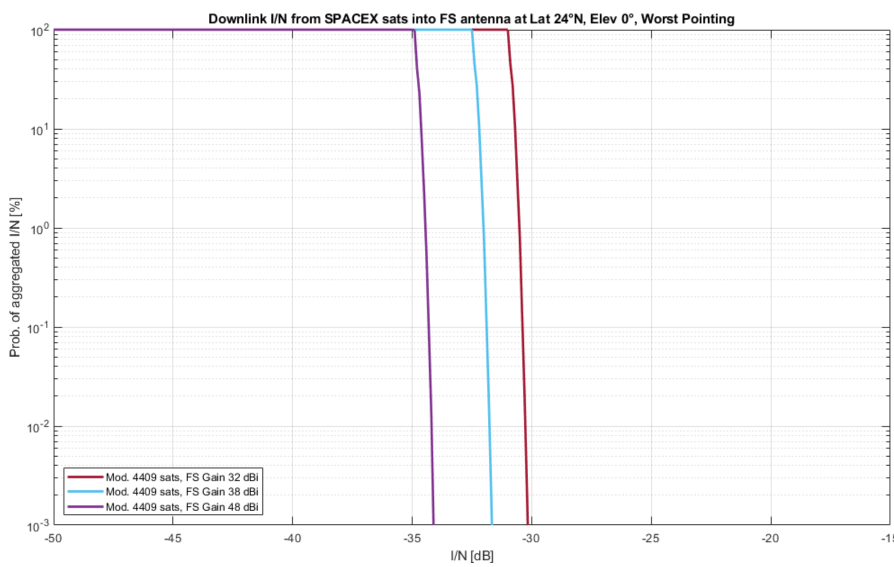
3. Protection criteria used in this analysis per Rec. ITU-R F.1495:

    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.

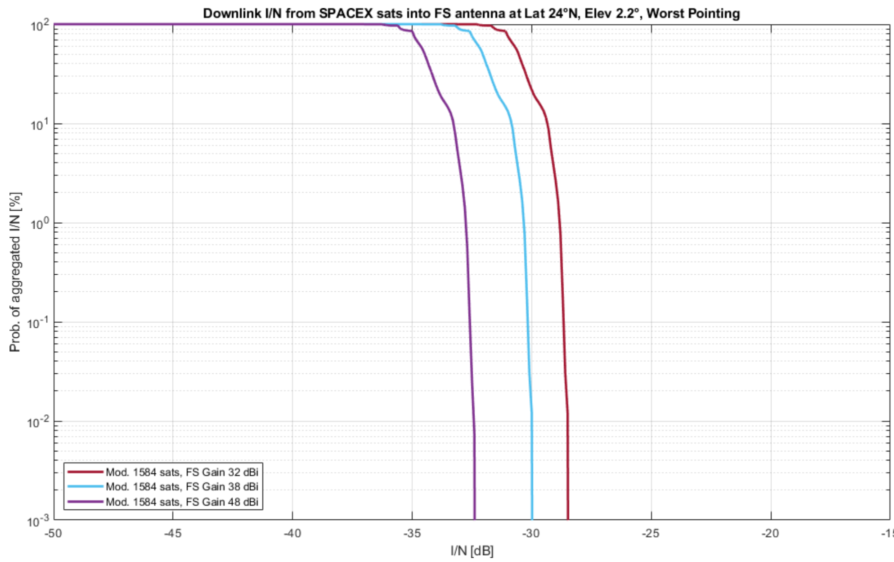
For a given FS victim antenna gain, latitude, and elevation, the analysis considers the worst-case antenna pointing. Because SpaceX operates with up to four co-frequency beams per spot in Ka-band, the analysis considers beams from the four satellites whose beams would be closest to boresight for the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

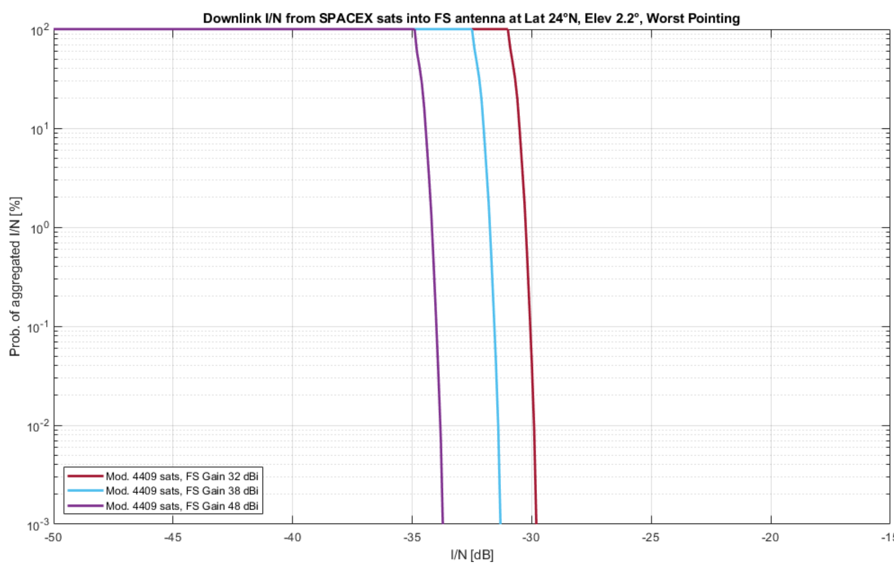
The results are shown in the figures below. In each case, the results are shown first for the modified 550 km shell only (at a minimum elevation of 25°), and then for the full constellation as modified (at a minimum elevation of 40°). Note that in all cases, the aggregate I/N complies with the long-term limit of -10 dB by a significant margin, which necessarily demonstrates compliance with the less stringent short-term limits.



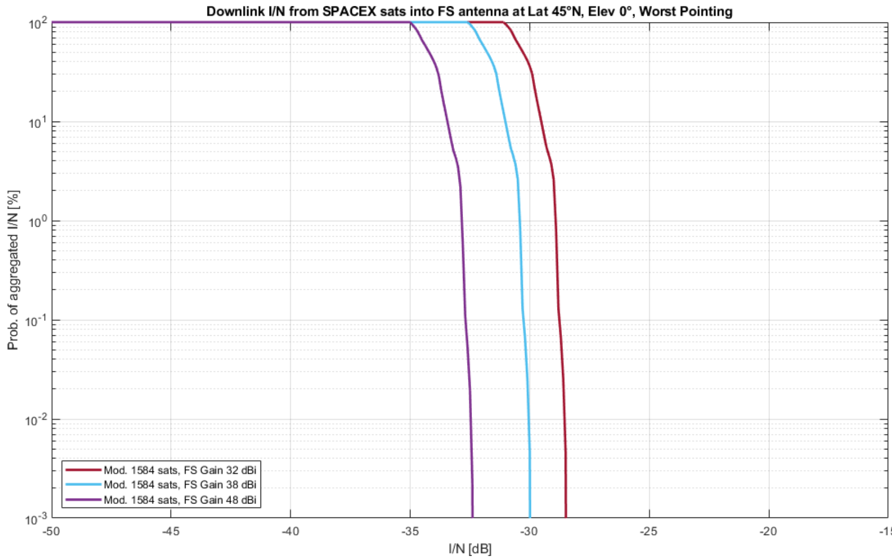


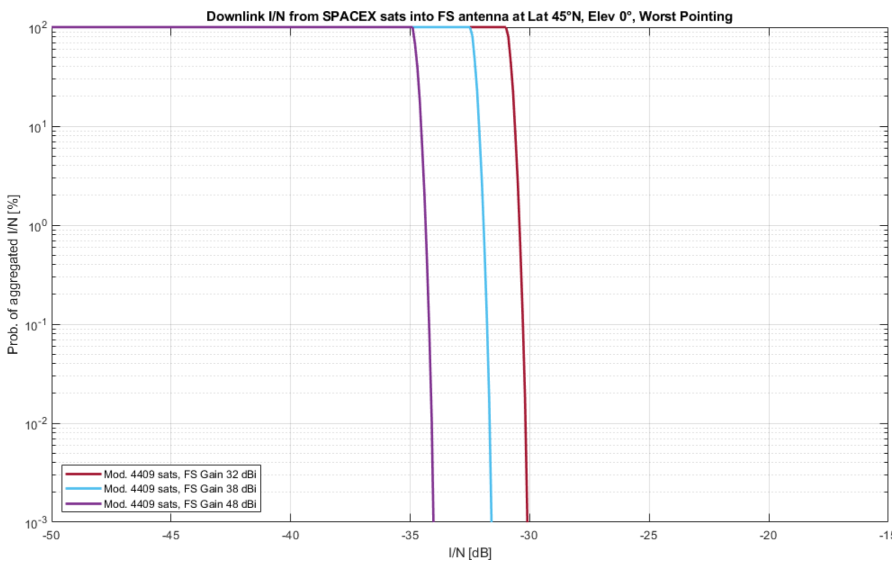
FS Station: Lat. 24°, Elevation 0°
Satellites: 550 km Shell, Min. Elevation 25° and
Full Constellation, Min. Elevation 40°



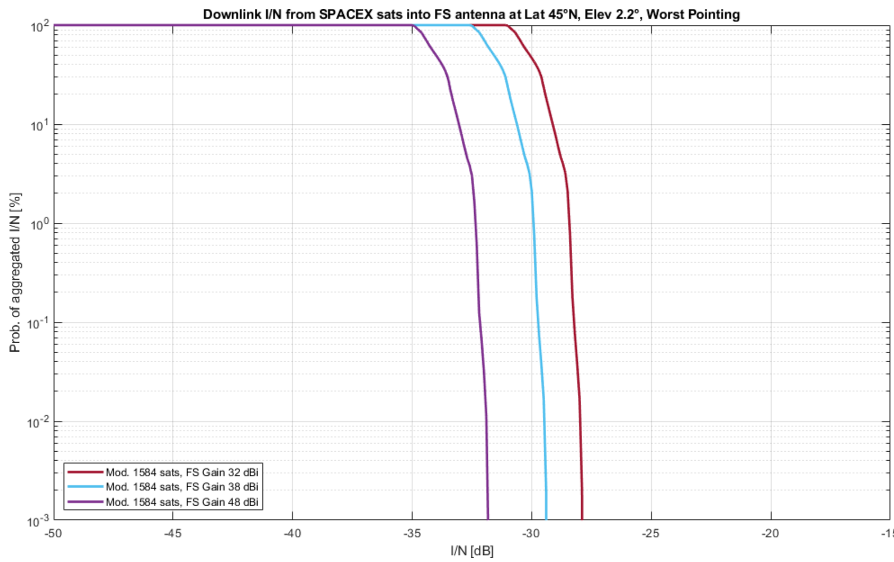


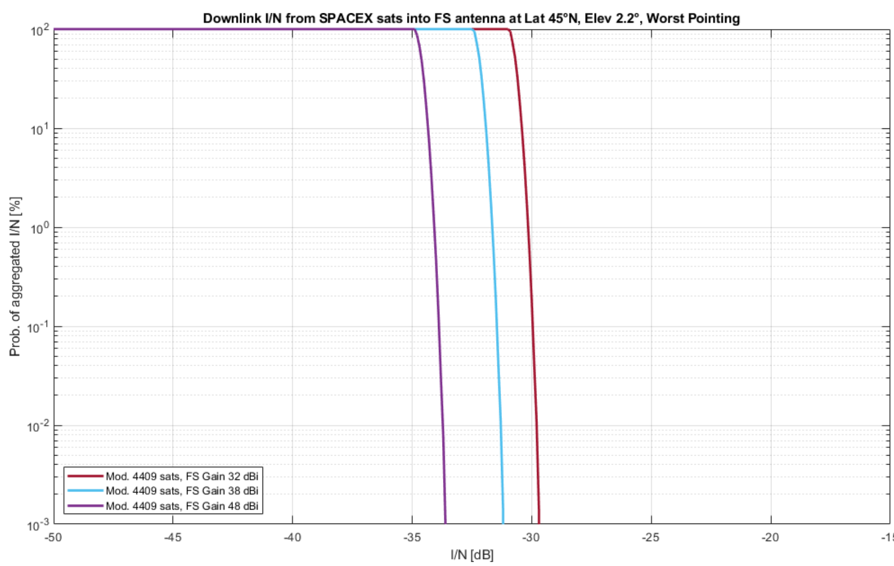
FS Station: Lat. 24°, Elevation 2.2°
Satellites: 550 km Shell, Min. Elevation 25° and
Full Constellation, Min. Elevation 40°



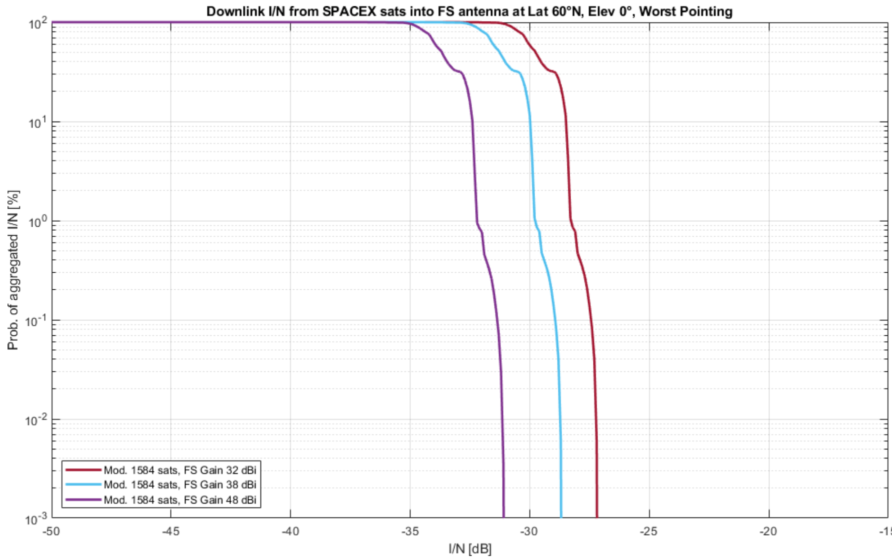


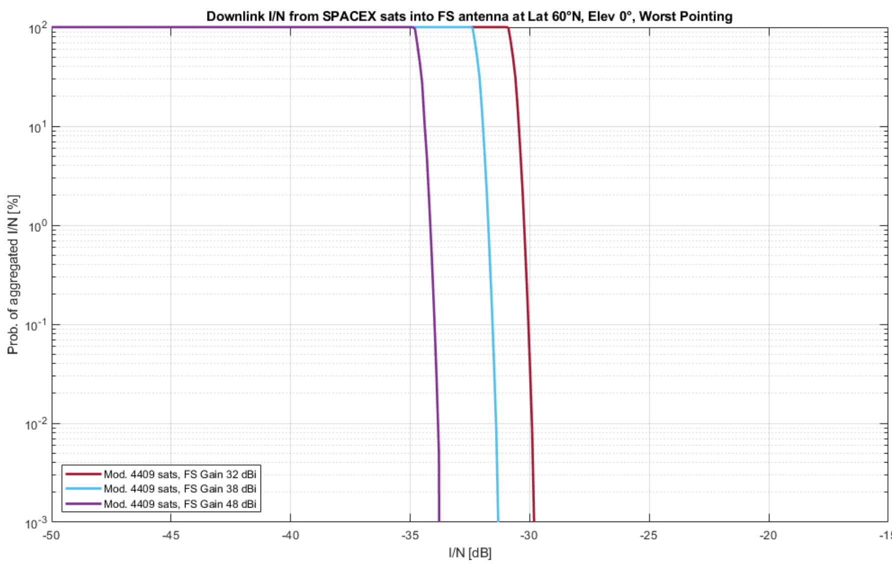
FS Station: Lat. 45°, Elevation 0°
Satellites: 550 km Shell, Min. Elevation 25° and
Full Constellation, Min. Elevation 40°



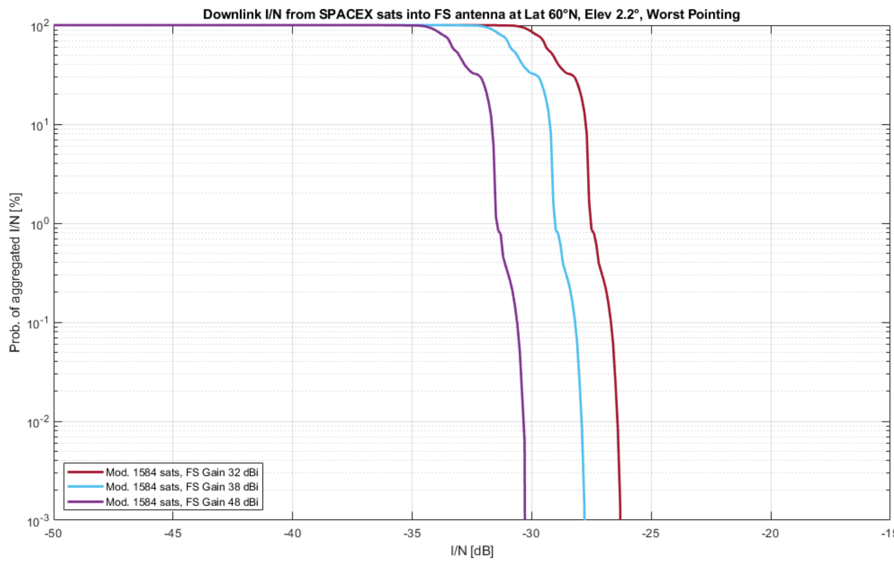


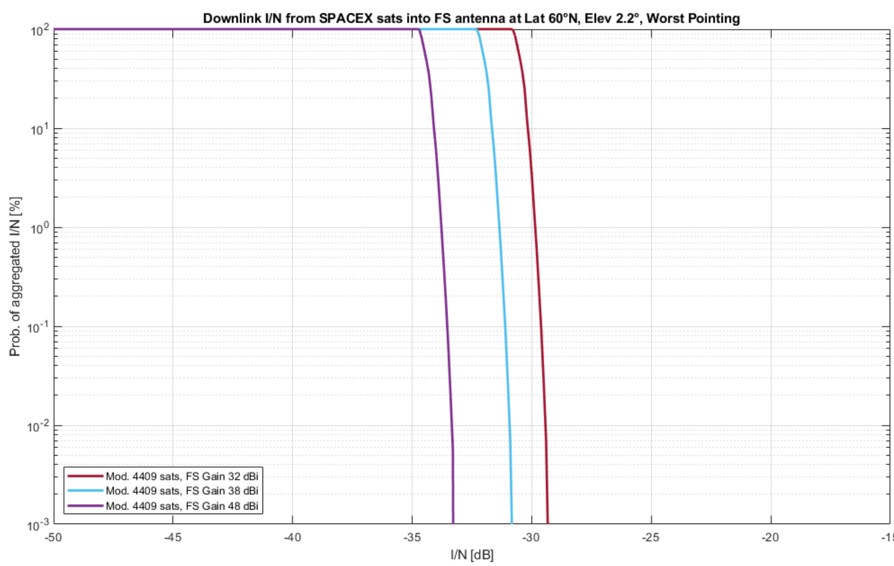
FS Station: Lat. 45°, Elevation 2.2°
Satellites: 550 km Shell, Min. Elevation 25° and
Full Constellation, Min. Elevation 40°





FS Station: Lat. 60°, Elevation 0°
Satellites: 550 km Shell, Min. Elevation 25° and
Full Constellation, Min. Elevation 40°





FS Station: Lat. 60°, Elevation 2.2°
Satellites: 550 km Shell, Min. Elevation 25° and
Full Constellation, Min. Elevation 40°