29 October 2022

Technical Analysis:
Starlink Violations of EPFD↓ Limits (Fuchsstadt, Germany)

This analysis calculates exceedances of ITU interference limits for the first and second generation Starlink configurations, based on the guidance provided in ITU-R Recommendation S.1503-3. It assesses the expected levels of interference generated by the Starlink system with respect to an earth station location at Fuchsstadt, Germany (50.118°N. 9.924°E) communicating with geostationary orbit (GSO) satellites serving Germany, located at 17.6°E longitude (H2M-17.6E) operating in both Ku and Ka-bands.

I. BACKGROUND

The ITU has established permissible levels of interference into GSO networks from non-GSO systems, like Starlink, in Article 22 of the ITU Radio Regulations. Exceeding these levels would violate the Radio Regulation 22.2 requirement that:

> *"Non-geostationary-satellite systems shall not cause unacceptable interference to [] geostationary-satellite networks in the fixed-satellite service and the broadcasting-satellite service operating in accordance with these Regulations."*

These interference limits are specified as single-entry equivalent power flux density downlink (EPFD↓) limits for individual non-GSO systems (in Tables 22-1A and 22-1B for the FSS and in Table 22-1D for the BSS), and EPFD↓ limits for all non-GSO systems of all operators considered together (in ITU Resolution 76).

The limits are specified as cumulative distribution function (cdf) curves. Each limit curve is defined, for a reference bandwidth and a reference antenna diameter, by a series of points, EPFD↓ (dBW/m^2) values and associated values for percentages of time during which EPFD↓ may not be exceeded. The complete limit curves are obtained by interpolating between those points.[1] Thus for any EPFD↓ value, there is a percentage of time that value

[1] RR 22.5C.5 For each reference antenna diameter, the limit consists of the complete curve on a plot which is linear (dB) for the epfd↓ levels and logarithmic for the time percentages, with straight lines joining the data points.

may not be exceeded. Similarly, for each percentage of time from 0% to 100%, there is an EPFD↓ value that may not be exceeded.

Any exceedance of those EPFD↓ levels—whether for the 100% of time value, the 10% value, the 1% value, or for any other percentage of time value—is a violation of the ITU Radio Regulations and has the potential to result in interference into GSO networks that degrades service and causes capacity losses. This includes GSO direct-to-home television and BSS networks as well as broadband GSO FSS networks with which Starlink seeks to compete.

Based on the data provided in a given ITU EPFD input filing (consisting of SRS and Mask databases), the ITU's Radiocommunication Bureau (BR) does a limited assessment of the EPFD levels that may be generated by a non-GSO system *with respect to one particular combination of earth station location and GSO satellite location*. This "examination" uses a software package developed in collaboration with Transfinite to calculate expected EPFD levels that would be produced with respect to that particular non-GSO satellite filing in those limited circumstances. As explained below, ***those limited circumstances have little bearing on the interference that Starlink can be expected to produce in Germany.***

The BR's examination is actually a limited spot check, based on the "worst-case geometry" (WCG), one particular GSO earth station (ES) location and one particular GSO satellite location, which is identified as the geometry maximizing the instantaneous non-GSO EPFD↓ level for a specific case of the Table 22 limits (service, frequency, antenna diameter, and radiation pattern).[2] That maximum EPFD↓ value is typically produced for a very short period of time, and thus lies at the bottom-right corner of the relevant EPFD↓ cdf curve (*i.e.,* the alignment of the non-GSO system with the GSO orbital location that produces the highest instantaneous interference level—for a very small percentage of the time, typically on the order of 0.001%, or less). This examination does not consider the ability of a non-GSO system to satisfy EPFD↓ limits at any other GSO ES location or with respect to any other GSO orbital location.

Further, the ITU does not evaluate the ability of a non-GSO operator to actually operate in a manner consistent with the operator supplied EPFD input data, and concerns have been raised that some inputs in the data files provided to the ITU are inconsistent with the laws of physics. Critically, it ultimately falls on the non-GSO system operator to actually conduct its operations in full compliance with all EPFD↓ limits, regardless of any limited evaluation initially conducted by the ITU. Moreover, it is difficult to attribute interference to a particular non-GSO system once it is in operation, particularly when more than one non-GSO system operates in the same or overlapping frequencies. Some of these factors are why the French space agency, CNES, has recommended that frequency regulators require applicants to provide more detailed information that allows an analysis of foreseeable interference with other systems, existing or future.[3]

Critically, EPFD↓ levels calculated for geometries other than the one identified by the WGC algorithm in ITU-R Recommendation S.1503 that is implemented in the Transfinite

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[2] *See generally* ITU-R Rec. S.1503.

[3] *See* Letter from CNES to ARCEP regarding Starlink's request for a radio frequency use authorization, Ref. DS/DAI/D-2022-0006202 (May 9, 2022).

software can exceed the relevant EPFD↓ limit cdf curve at any point. Specifically, this can occur at different GSO ES locations on Earth, and with different GSO satellite locations, than those identified by the S.1503 WCG algorithm. An analysis at those other geometries can be conducted with Transfinite's commercially available Visualyse EPFD software, which uses the same algorithm and EPFD calculation engine as in the software it developed for the ITU, with an added feature that allows the geometry (GSO ES location and GSO satellite location) to be set manually, so that compliance with *all EPFD limits, at all GSO ES locations* and *for all GSO satellite locations* can be evaluated. This is particularly valuable when an examination is desired of the expected interference into GSO services in a given country, or into one of its GSO satellite networks.

ITU-R Recommendation. S.1503-3 explains the necessity of complying with all EPFD limits at all locations and for all geometries. Specifically:

> *The epfd limits in Article 22 are applicable for all GSO ESs and all pointing angles towards that part of the GSO arc visible from that ES. [] It remains necessary for the non-GSO operator to meet the epfd limits in Article 22 for all [] geometries including the testing of specific GSO networks as noted in § A1.3.*[4]

The Transfinite Visualyse EPFD software used in this analysis allows precisely that type of evaluation called for by S.1503-3. It assesses the expected impact of the Starlink system for a GSO ES located at Fuchsstadt, Germany (50.118°N. 9.924°E) with a GSO satellite located at 17.6°E longitude serving Germany.

This analysis uses (i) the constellations defined by SpaceX's EPFD input files for the particular ITU filings that it has specified as relevant (which data vary in some respects from the data initially provided in ITU notifications), and (ii) the particular orbital deployment configuration that SpaceX specified, all during the licensing process at the United States Federal Communications Commission (FCC).

Notably, this analysis does not suggest that Starlink *could not be* operated in a manner compliant with the ITU Radio Regulations.

This analysis shows that SpaceX *does not plan* to operate Starlink in a manner compliant with the EPFD↓ limits in the ITU Radio Regulations.

To comply with those EPFD↓ limits, Starlink could employ various combinations of its own choosing of (i) numbers of satellites, (ii) specific orbit parameters, (iii) power flux density (PFD) emissions masks, (iv) effective isotropic radiated power (EIRP) emissions masks, (v) GSO network avoidance angles, and (vi) frequency reuse parameters.

II. ANALYSIS OF EPFD↓ VIOLATIONS BY 4,408 SATELLITES IN STARLINK'S FIRST GENERATION CONFIGURATION

The following are examples of EPFD↓ exceedances for the first generation Starlink configuration of 4,408 satellites, which, when tested only with the WCG combination of GSO ES location and GSO satellite longitude, has received a favorable finding under the

[4] ITU-R Rec. S.1503-3, § D3.

ITU's "spot check" process[5] described above. By way of example, the WCG for the 10.7 GHz, 1.2 m, FSS limit is a GSO ES in the ocean approximately 200 km off the coast of West Africa with a GSO satellite at about 1.5°E longitude.

This analysis is for a GSO ES located in Fuchsstadt, Germany (50.118°N. 9.924°E) with a Ku-band GSO satellite located at 17.6°E longitude. The instances depicted below in which EPFD↓ limits are violated 1%, 10%, and even 100% of the time are most concerning and violate ITU Radio Regulations. Interference generated at those levels could well degrade service levels and cause capacity losses to GSO networks.

The following figures show that the Starlink STEAM-1 and STEAM-2 filings exceed the Article 22 EPFD↓ limits in Tables 22-1A, 22-1B, and 22-1D in the Ku and Ka bands for a GSO ES located in Fuchsstadt, Germany (50.118°N. 9.924°E) with a GSO satellite located at 17.6°E longitude, even though it does not exceed the limits at the so-called WCG[6]. The peak exceedances are shown in Table 1. Combinations of other earth stations and satellite locations serving Germany could result in larger violations of ITU limits than these examples.

Table 1 – Example Peak STEAM-1 and STEAM-2 Exceedances in Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

System	Service	Freq	Antenna Diameter	Radiation Pattern	Peak Exceedance	Percent of Time	Figure
STEAM-1	FSS	10.7 GHz	1.2	S.1428	6.3 dB	0.50%	1
STEAM-1	FSS	11.7 GHz	1.2	S.1428	5.5 dB	0.50%	2
STEAM-1	BSS	11.7 GHz	0.45	BO.1443	5.3 dB	93.58%	3
STEAM-1	BSS	11.7 GHz	0.6	BO.1443	4.1 dB	59.58%	4
STEAM-1	FSS	12.2 GHz	1.2	S.1428	5.1 dB	0.50%	5
STEAM-1	BSS	12.2 GHz	0.45	BO.1443	4.9 dB	91.48%	6
STEAM-1	BSS	12.2 GHz	0.6	BO.1443	3.7 dB	59.58%	7
STEAM-1	FSS	12.5 GHz	1.2	S.1428	4.8 dB	0.50%	8
STEAM-1	BSS	12.5 GHz	0.45	BO.1443	4.7 dB	90.89%	9
STEAM-1	BSS	12.5 GHz	0.6	BO.1443	3.5 dB	60.10%	10
STEAM-2B	FSS	17.8 GHz	1	S.1428	3.3 dB	10.00%	11

[5] 319520108_STEAM-1_ResultsSummary.pdf (itu.int) and 319520109_STEAM-2B_ResultsSummary.pdf (itu.int)

[6] The EPFD data underlying the WCG plots was generated with the ITU's EPFD software using the STEAM EPFD input databases available from the ITU at EPFD data and EPFD examination results (itu.int).

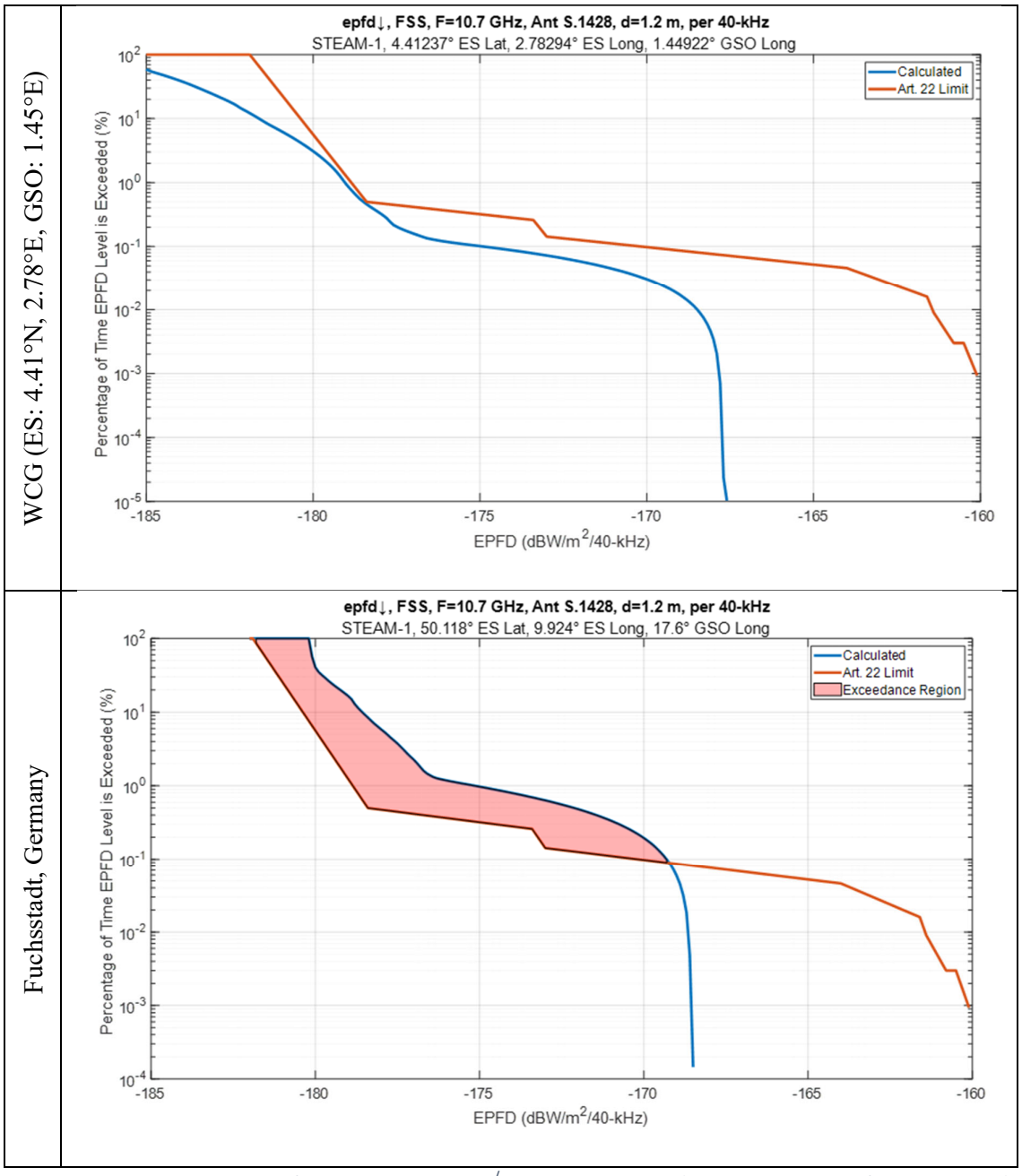


Figure 1 - Comparison of STEAM-1 EPFD↓ at 10.7 GHz with 1.2 m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

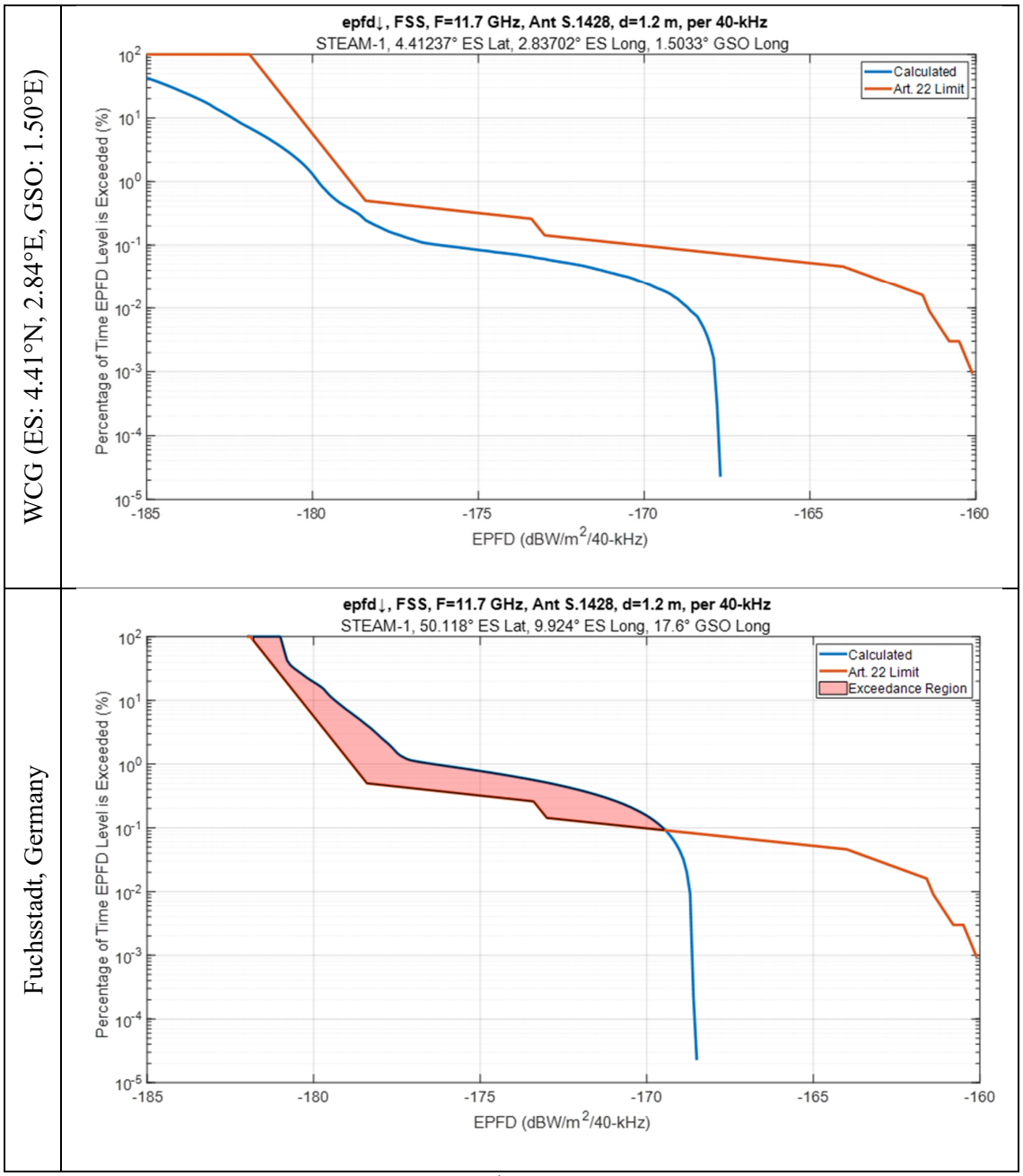


Figure 2 - Comparison of STEAM-1 EPFD↓ at 11.7 GHz with 1.2 m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

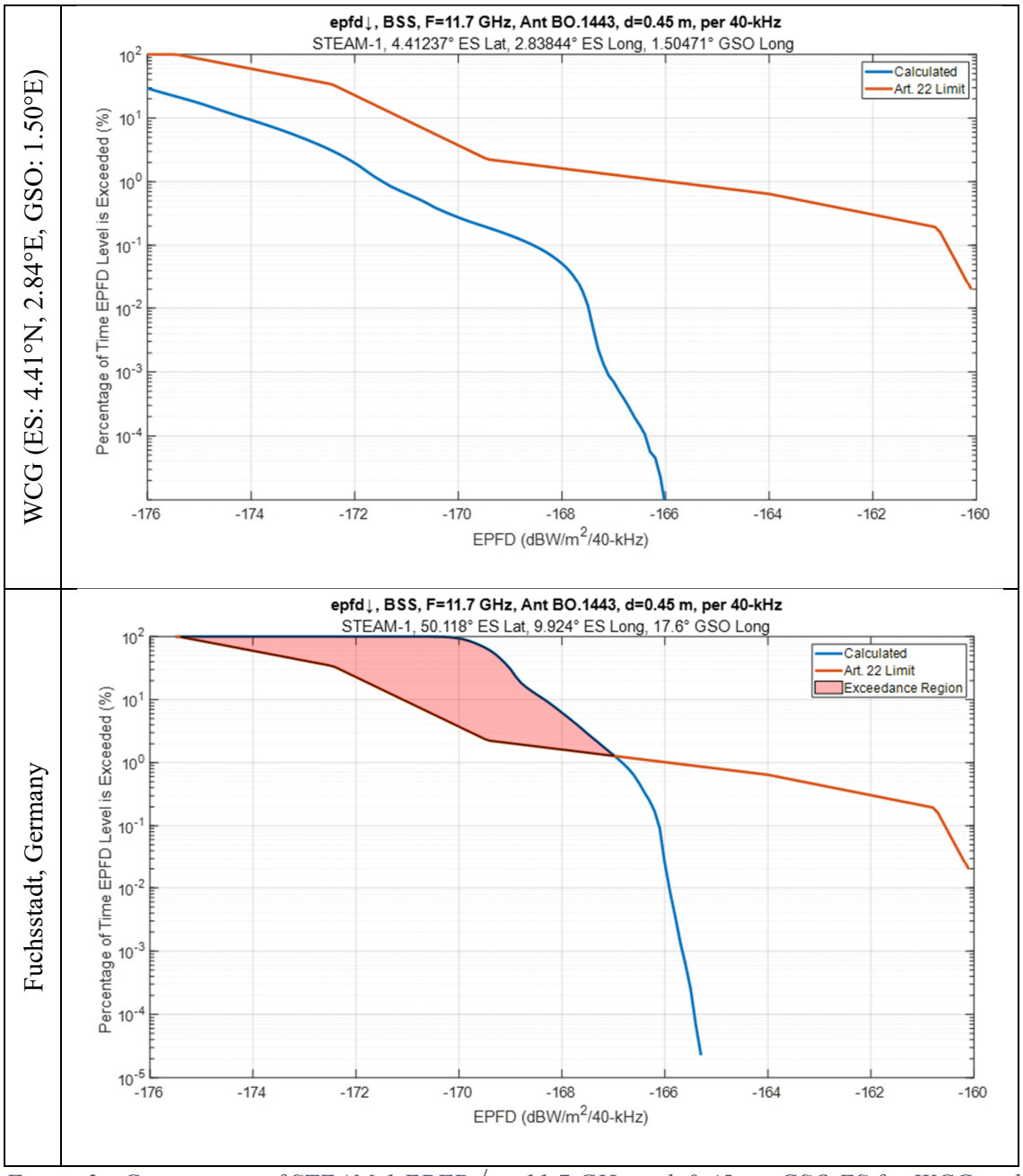


Figure 3 - Comparison of STEAM-1 EPFD↓ at 11.7 GHz with 0.45 cm GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

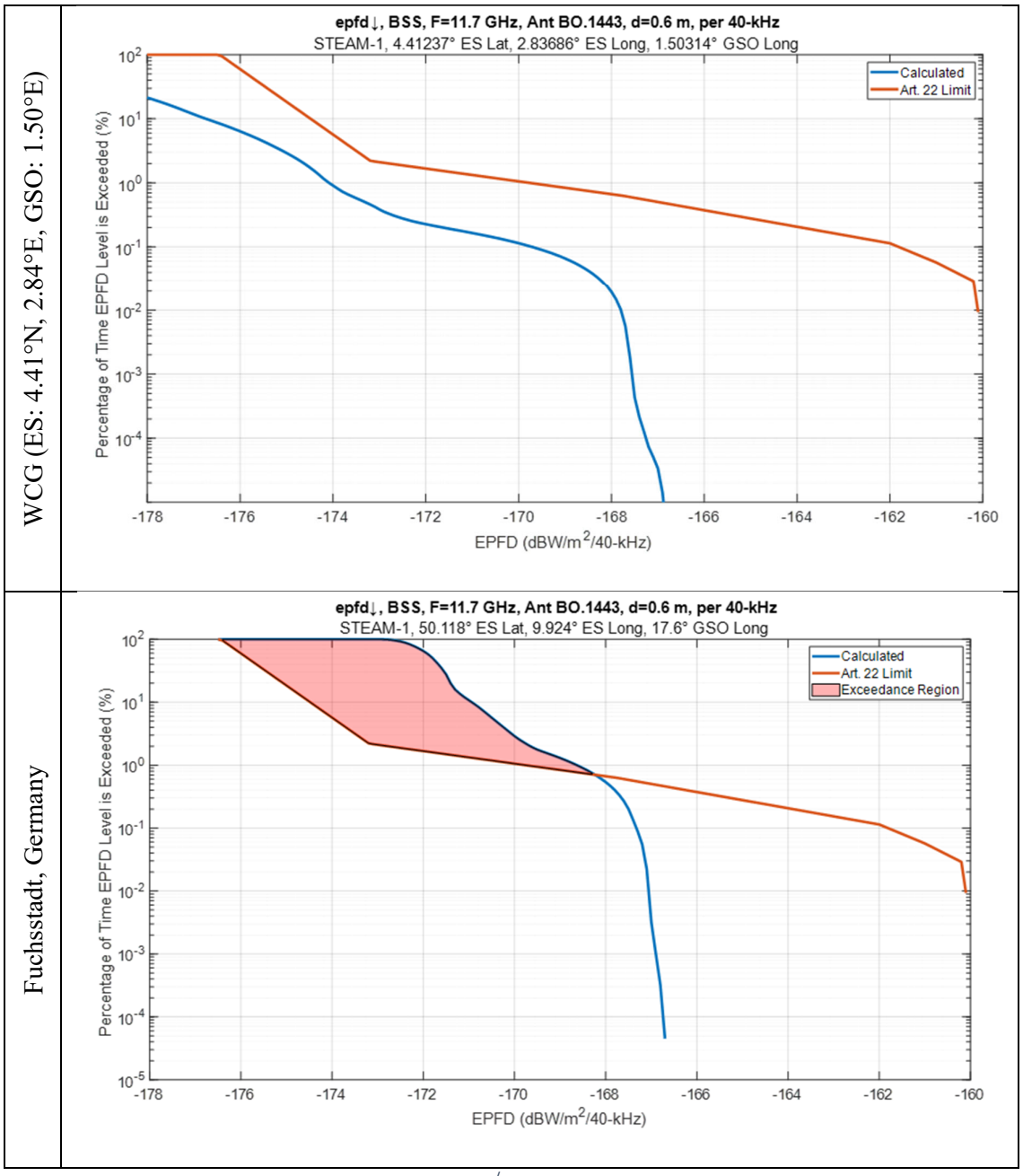


Figure 4 - Comparison of STEAM-1 EPFD↓ at 11.7 GHz with 0.6 m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

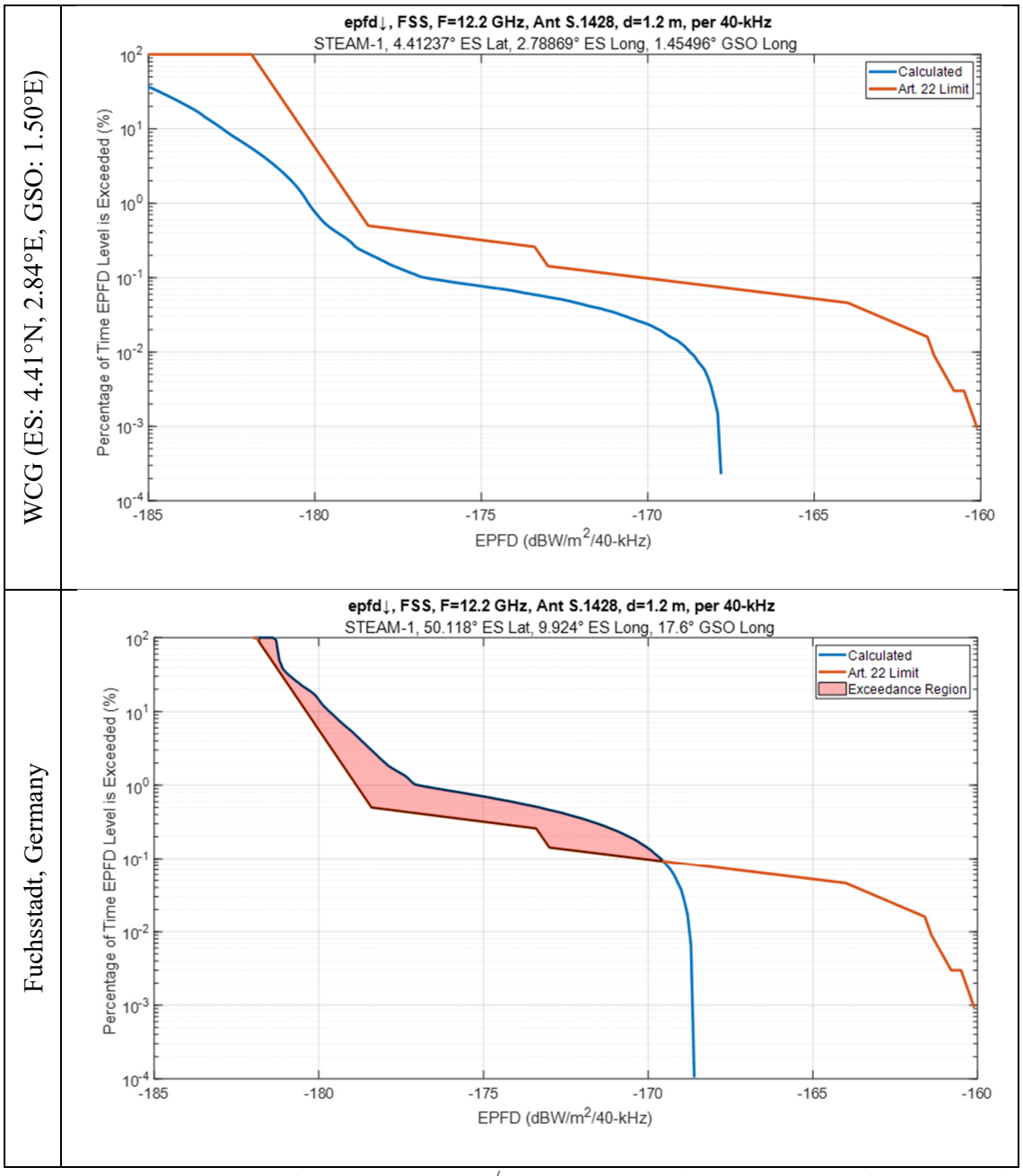


Figure 5 - Comparison of STEAM-1 EPFD↓ at 12.2 GHz with 1.2 m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

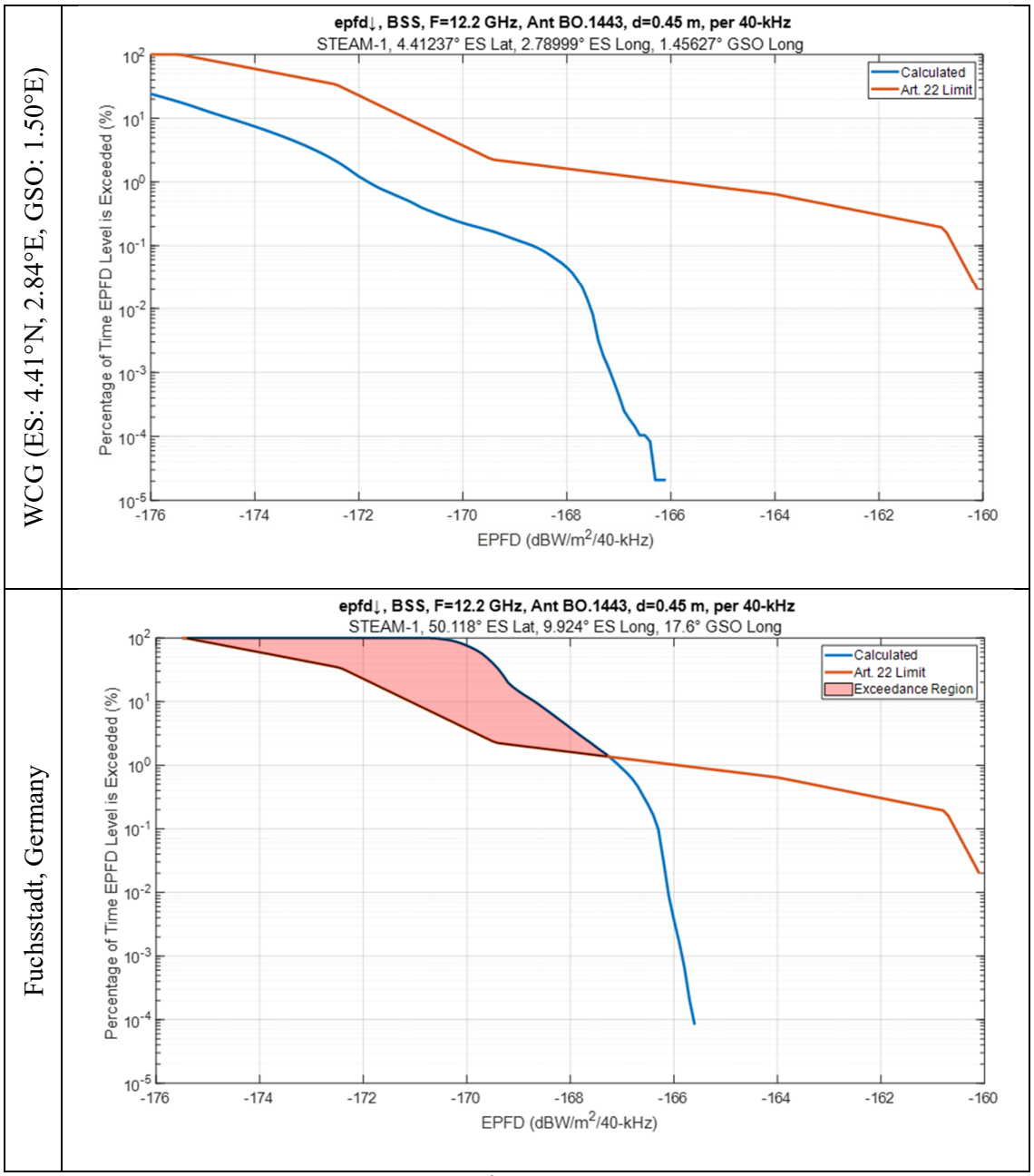


Figure 6 - Comparison of STEAM-1 EPFD↓ at 12.2 GHz with 0.45 cm GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

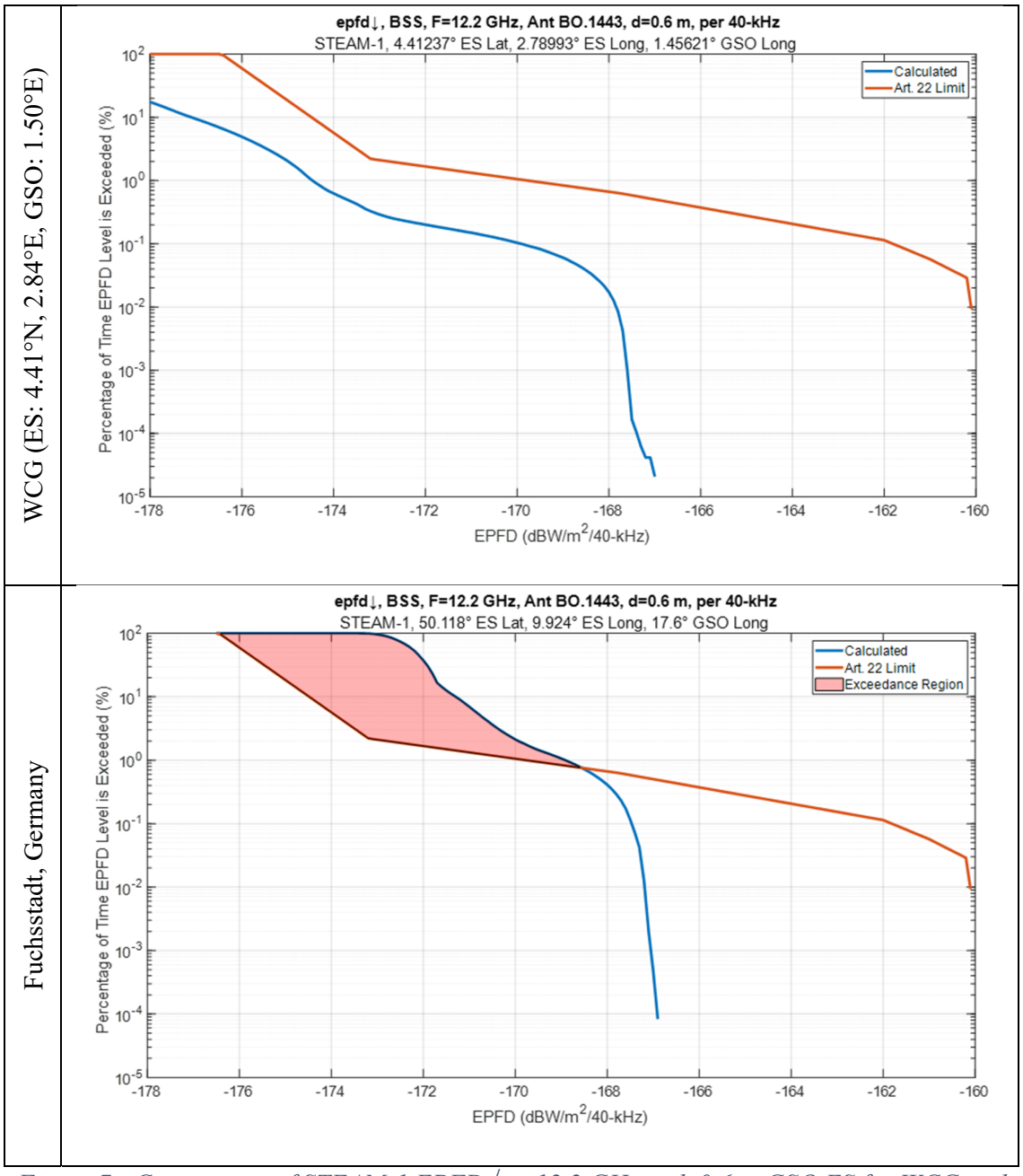


Figure 7 - Comparison of STEAM-1 EPFD↓ at 12.2 GHz with 0.6 m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

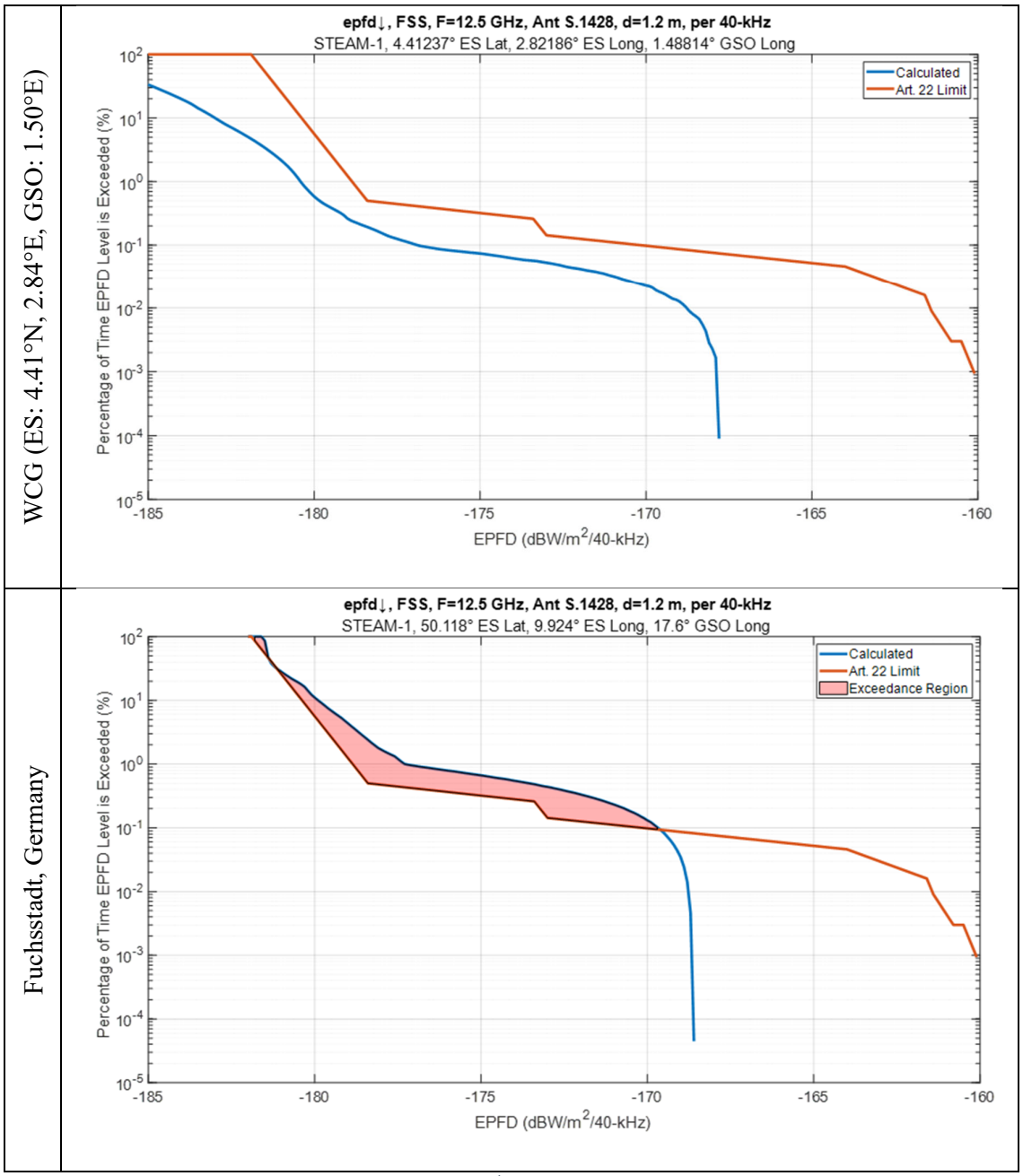


Figure 8 - Comparison of STEAM-1 EPFD↓ at 12.5 GHz with 1.2 m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

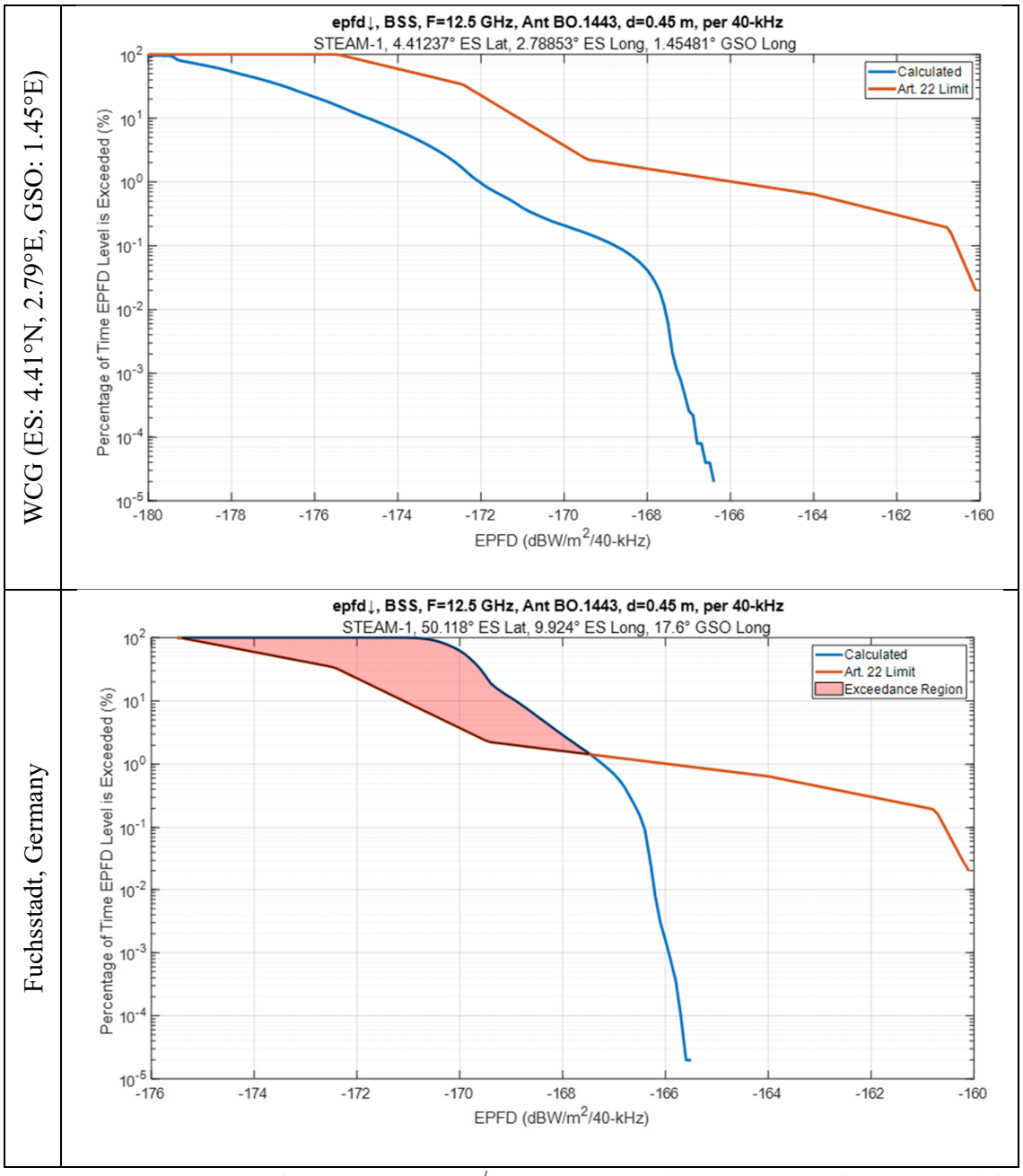


Figure 9 - Comparison of STEAM-1 EPFD↓ at 12.5 GHz with 0.45 GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

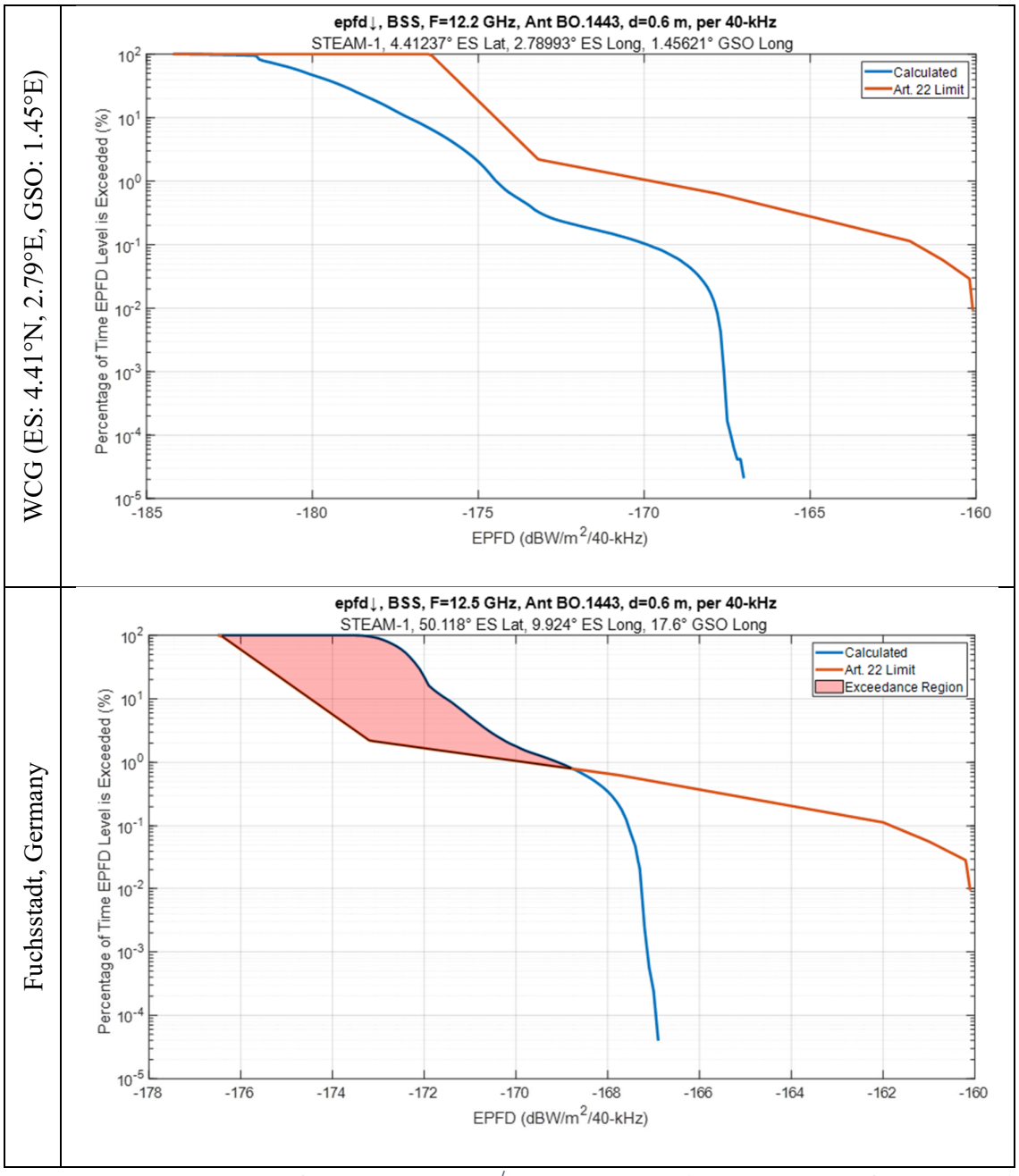


Figure 10 - Comparison of STEAM-1 EPFD↓ at 12.5 GHz with 0.6 m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

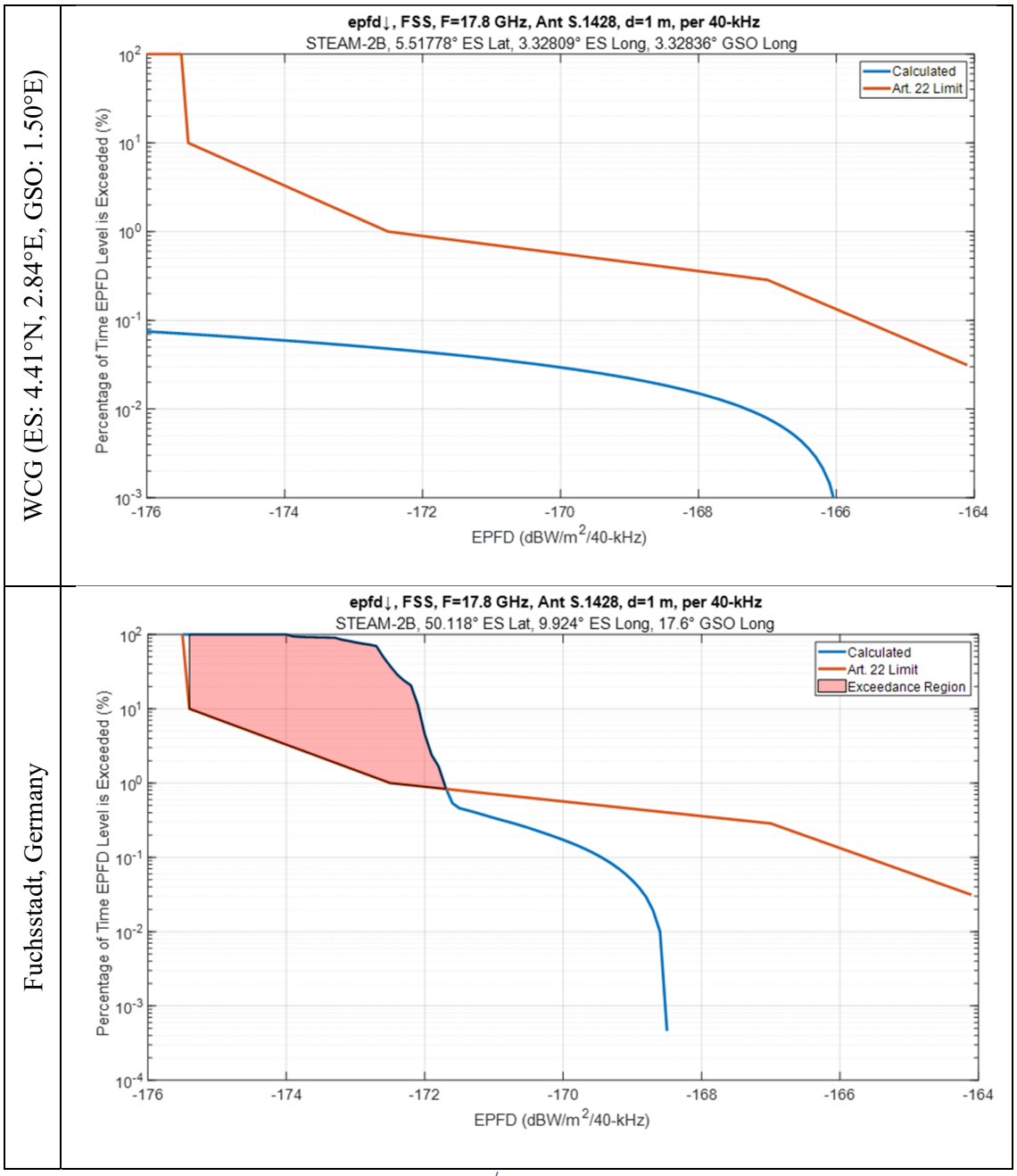


Figure 11 - Comparison of STEAM-2 EPFD↓ at 17.8 GHz with1 m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

III. ANALYSIS OF EPFD↓ VIOLATIONS BY ADDITIONAL 29,988 SATELLITES IN STARLINK'S SECOND GENERATION CONFIGURATION

The following are examples of EPFD↓ exceedances for the additional 29,988 satellites in the second generation Starlink configuration, which has not yet been evaluated by the ITU. SpaceX proposes to operate those additional satellites under 18 different ITU filings.[7] As shown below, Starlink exceeds the Article 22 EPFD↓ limits in Table 22-1B for the 17.8 – 18.6 GHz band with several of these filings even when they are evaluated individually. Moreover, when all 18 ITU filings are considered together, the EPFD↓ exceedances are substantially greater.

This analysis is for a GSO ES located in Fuchsstadt, Germany (50.118°N. 9.924°E) with a Ka-band GSO satellite located at 17.6°E longitude. The instances depicted below in which EPFD↓ limits are expected to be violated 1%, 10%, and even 100% of the time are most concerning and violate the ITU Radio Regulations. Interference generated at those levels could well degrade service levels and cause capacity losses to GSO networks.

Notably, this analysis does not factor in the aggregate effect of the Starlink satellites operated under ITU filings other than those listed in the footnote below, such as the 4,408 first generation satellites discussed above.

A. Starlink Second Generation EPFD↓ Exceedances under Individual ITU Filings

Table 2 shows examples of EPFD↓ exceedances that exist for the second generation Starlink configuration when the various 18 underlying ITU filings are examined in isolation. Combinations of other earth stations and satellite locations serving Germany could result in larger violations of ITU limits than these examples.

Table 2– Example Peak SpaceX Gen2 Exceedances in Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E for the 17.8 – 18.6 GHz Band with 1-m GSO ES Antenna Diameter

System	Peak Exceedance	Percent of Time	Figure
USASAT-NGSO-3V-2	3.2 dB	10%	12
USASAT-NGSO-3W-1	3.2 dB	10%	13
USASAT-NGSO-3W-2	3.2 dB	10%	14

[7] The relevant ITU system filings are: USASAT-NGSO-3N, USASATNGSO-3O, USASAT-NGSO-3P, USASAT-NGSO-3Q, USASAT-NGSO-3R1, USASATNGSO-3R2, USASAT-NGSO-3S1, USASAT-NGSO-3S2, USASAT-NGSO-3S3, USASAT-NGSO-3T1, USASAT-NGSO-3T2, USASAT-NGSO-3T3, USASAT-NGSO-3U1, USASAT-NGSO-U2, USASAT-NGSO-3V1, USASAT-NGSO-3V2, USASAT-NGSO-3W1, and USASAT-NGSO-3W2.

The following figures contrast these EPFD↓ violations in Germany with the WCG results. By way of example, the WCG[8] for the 17.8 GHz, 1.0 m, FSS limit, calculated for the USASAT-NGSO-3V-2 system, is a GSO ES in Tathlith Saudi Arabia with a GSO satellite located near 5°E longitude.

As can be seen, the second generation Starlink configuration is clearly non-compliant with the ITU Radio Regulations.

[8] The EPFD data underlying the WCG plots was generated with the ITU's EPFD software using the STEAM EPFD input databases provided by SpaceX for each of the 18 Gen2 ITU filings.

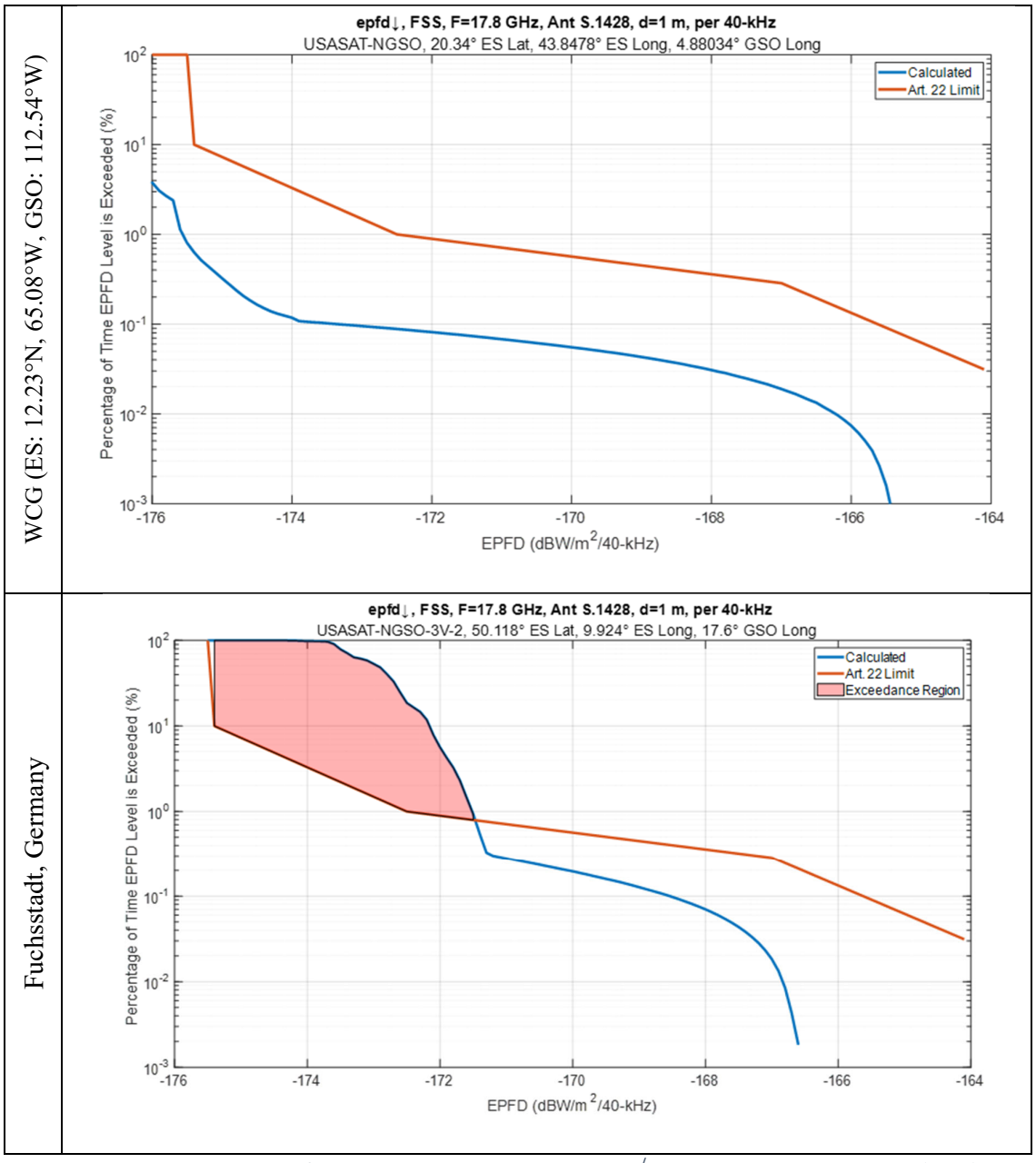


Figure 12 – Comparison of USASAT-NGSO-3V-2 EPFD↓ in 17.8 – 18.6 GHz Band with 1-m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

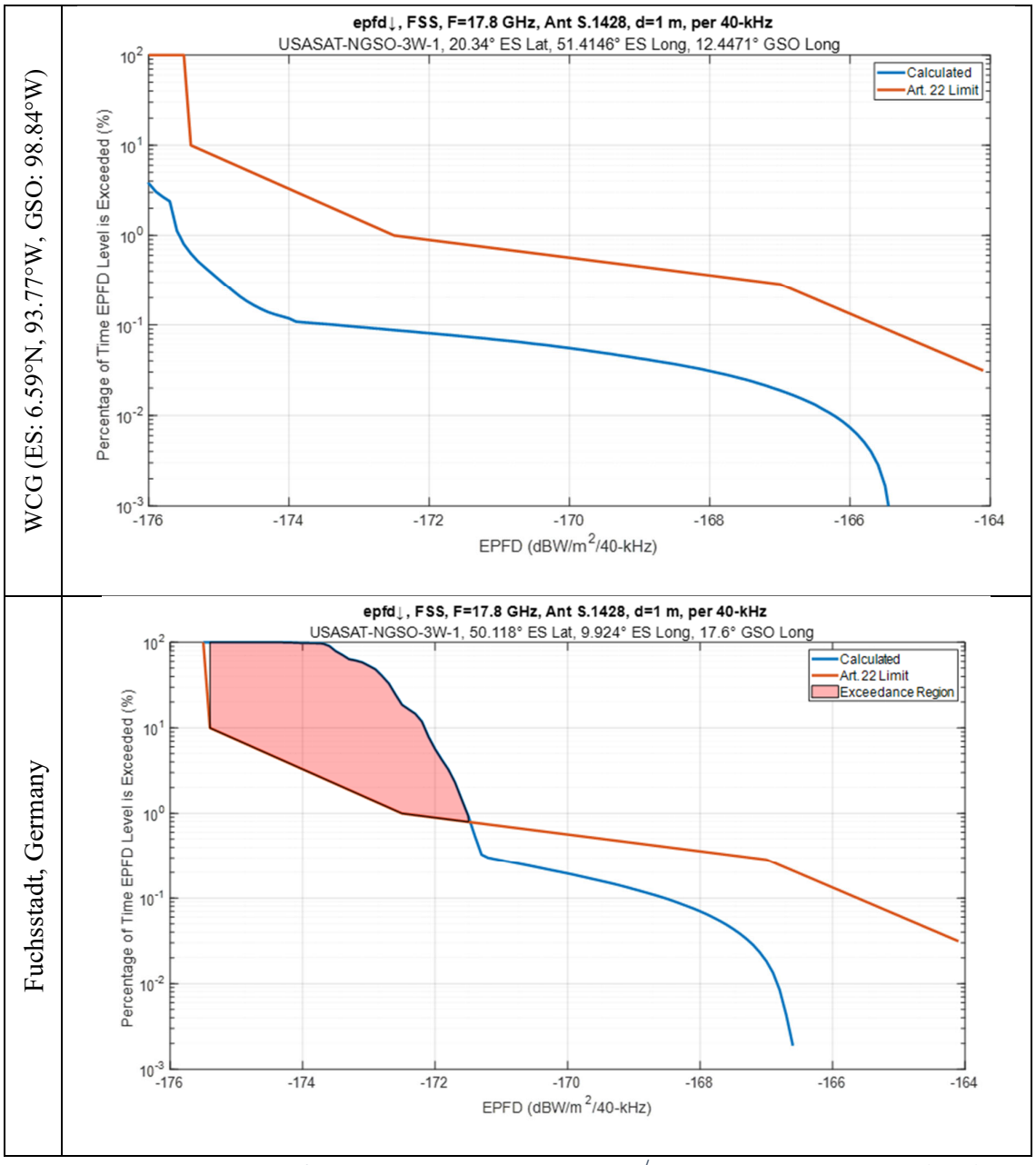
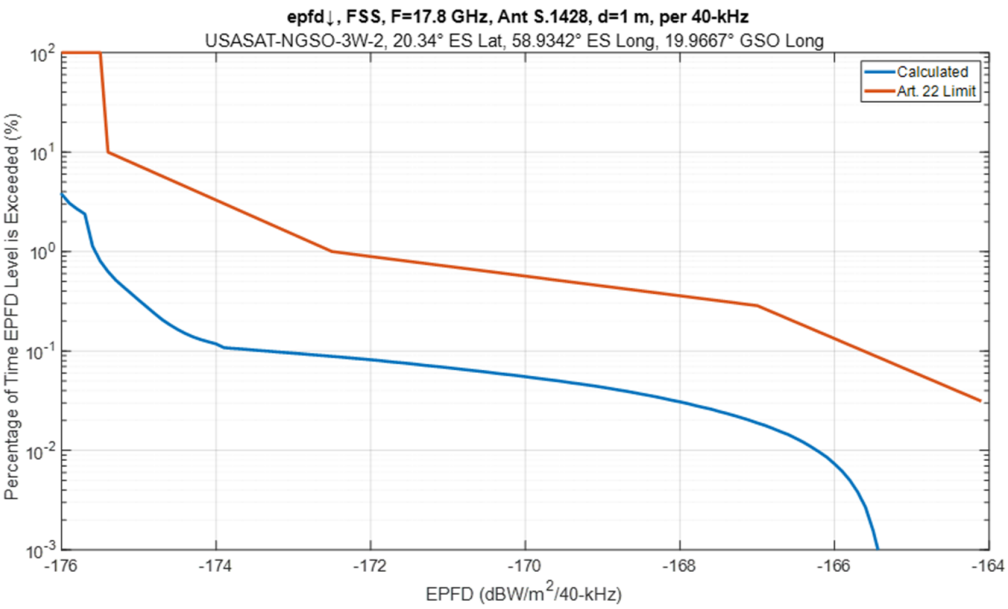


Figure 13 – Comparison of USASAT-NGSO-3W-1 EPFD↓ in 17.8 – 18.6 GHz Band with 1-m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

WCG (ES: 6.59°N, 80.89°W, GSO: 85.95°W)



Fuchsstadt, Germany

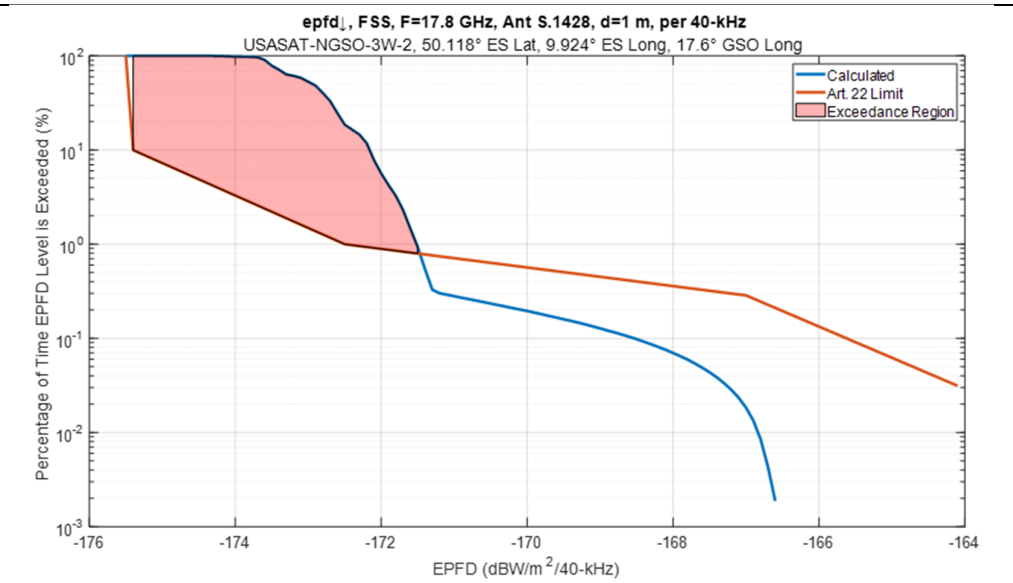


Figure 14 – Comparison of USASAT-NGSO-3W-2 EPFD↓ in 17.8 – 18.6 GHz Band with 1-m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

B. Starlink Second Generation EPFD↓ Exceedances under Combined ITU Filings

This section evaluates the interference levels that would be generated by the additional 29,988 second generation Starlink satellites operating under SpaceX's 18 new ITU filings—and compares those interference levels to applicable ITU Article 22 single-entry EPFD↓ limits and ITU Resolution 76 aggregate EPFD↓ limits. Notably, SpaceX *has* made clear that its 29,988 additional satellites would operate as a single non-GSO system.[9]

Combined EPFD↓ curves were generated for all 29,988 satellites operating under these 18 filings with a 1-m GSO ES in the 17.8 – 18.6 GHz band, using the EPFD input files provided by SpaceX for each of those 18 ITU filings. The GSO ES is located in Fuchsstadt, Germany (50.118°N. 9.924°E) with the GSO satellite at 17.6°E longitude. The resulting 18 EPFD↓ probability density functions (pdf's) for each of the cases identified in the Article 22 and Resolution 76 EPFD↓ limits were combined, using standard techniques for the sum of independent random variables,[10] to generate the combined EPFD↓ cdf curves.

Figure 15 shows the results of this analysis and depicts: (i) the Article 22 single-entry limit cdf curve; (ii) the Resolution 76 aggregate limit cdf curve; and (iii) the combined EPFD cdf curve for 29,988 Starlink satellites generated using the methodology described above. **The analysis shows that Starlink would exceed both the Article 22 single-entry limits and the Resolution 76 aggregate limits for all percentages of time and all EPFD levels. The peak exceedances are 9.4 dB above the Article 22 limit and 4.0 dB above the Resolution 76 limit, each at 10% of the time.[11]**

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[9] *See, e.g.,* Consolidated Opposition, at 3, (confirming that SpaceX intends to operate a single "Gen2 system").

[10] The relevant techniques used are discussed in most textbooks on probability theory. *See, e.g.,* Marco Taboga, *Sums of independent random variables*, STATLECT, available at https://www.statlect.com/fundamentals-of-probability/sums-of-independent-random-variables (last visited Aug. 24, 2022); Alex Tsun, *Convolution*, available at https://courses.cs.washington.edu/courses/cse312/20su/files/student_drive/5.5.pdf (last visited Aug. 24, 2022).

[11] Does not factor in the aggregate effect of the 4,408 first generation satellites discussed above.

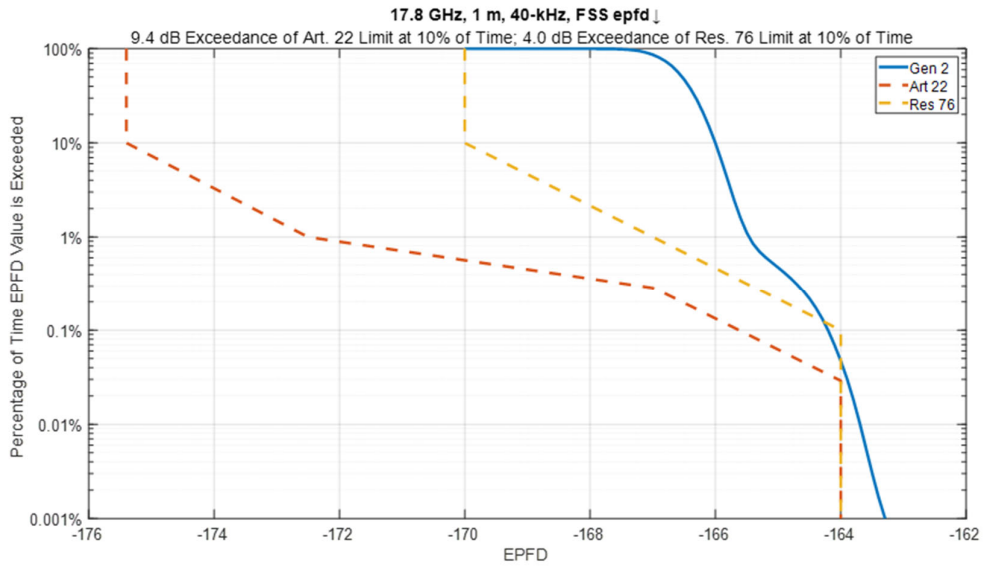

Figure 15 – Combined EPFD↓ for 29.988 Second Gen2 Starlink Satellites in 17.8 – 18.6 GHz Band with 1-m GSO ES for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

Again, ITU-R Recommendation S.1503 is instructive. It is based on the premise that the parameters specified in relevant EPFD input files reflect the way that a non-GSO system would actually operate once implemented. Among other things, the methodology is based on *all satellites that could contribute to the EPFD levels generated by the entire system being considered together*. Thus, for example, that Recommendation explicitly anticipates that where a large constellation is divisible into separate "sub-constellations," *EPFD compliance will still be evaluated across the constellation as a whole*.[12]

[12] *See, e.g.,* ITU-R Rec. S.1503-3, § A2.4 (specifying constellation types that can be evaluated using specified procedures and explicitly noting that "[c]onstellations can contain sub-constellations with different orbit parameters and shape . . .").

Appendix 1 – STEAM-1 ID Number 121520025 Exceedance

BR International Frequency Information Circular (Space Services) (BR IFIC) Number 2981 (4 October 2022) promulgated a "favorable" finding for STEAM-1 ID 121520025. This modified version of the STEAM-1 notice corresponds to the current 4,408 satellite configuration in four shells (540 km, 550 km, 560 km, and 570 km).

As with the prior STEAM-1 favorable finding (ID 114520273), reported upon above, even though this new filing received a favorable finding from the BR it exceeds the Art. 22 EPFD↓ limits in Tables 22-1A and 22-1D for a GSO ES located in Fuchsstadt, Germany (50.118°N. 9.924°E) with a GSO satellite located at 17.6°E longitude[13]. Exemplary peak exceedances are shown in Table 3. Combinations of other earth stations and satellite locations serving Germany could result in larger violations of ITU limits than these examples.

Table 3 – Example Peak STEAM-1 (ID 121520025) Exceedances in Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

System	Service	Freq	Antenna Diameter	Radiation Pattern	Peak Exceedance	Percent of Time	Figure
STEAM-1	FSS	10.7 GHz	1.2 m	S.1428	0.6 dB	0.79%	16
STEAM-1	BSS	12.7 GHz	0.45 m	BO.1443	4.2 dB	89.75%	17
STEAM-1	BSS	12.7 GHz	0.6 m	BO.1443	3.1 dB	71.6%	18

[13] The EPFD data underlying the WCG plots was generated with the ITU's EPFD software using the STEAM EPFD input databases available from the ITU at EPFD data and EPFD examination results (itu.int).

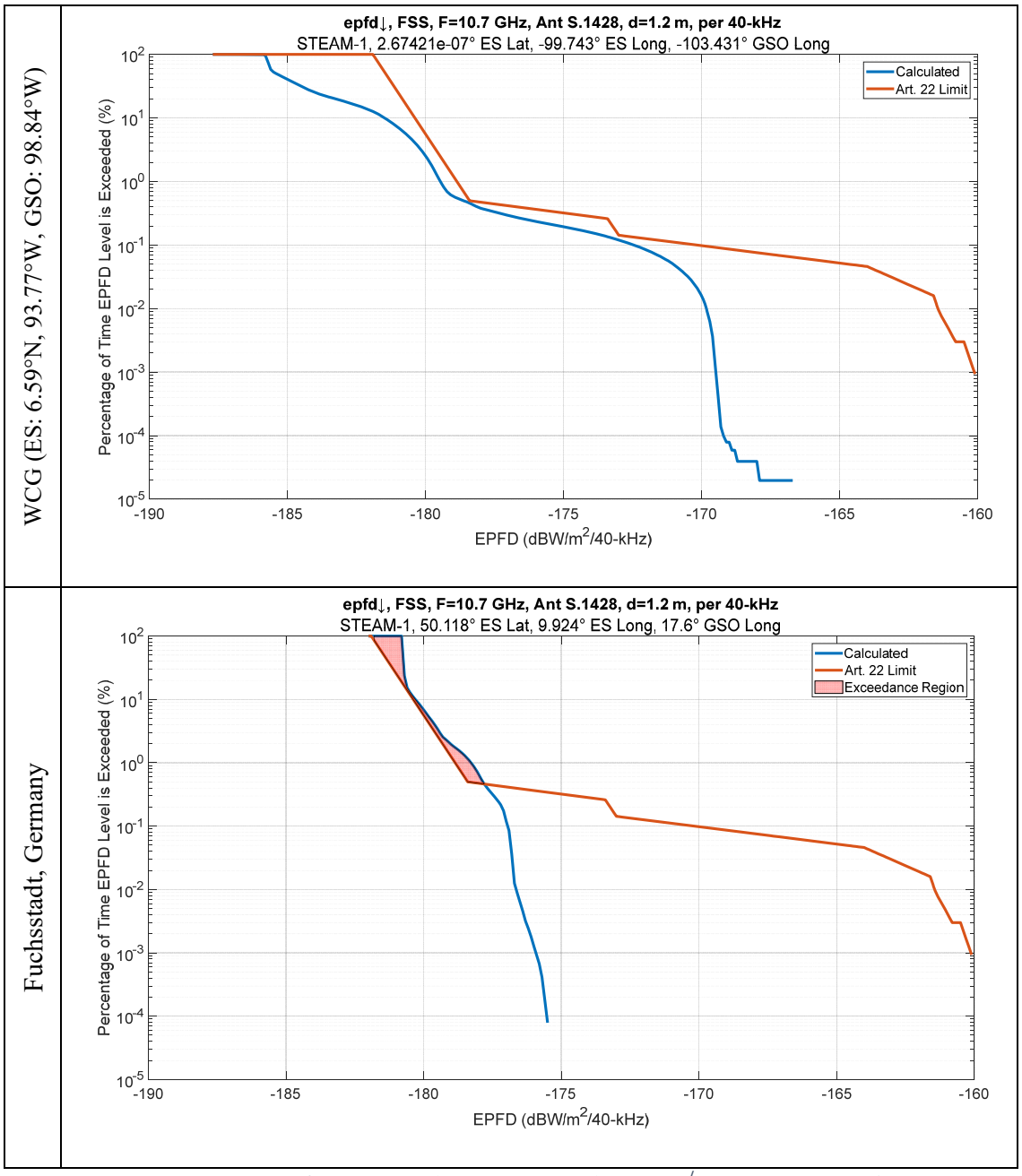

Figure 16 – Comparison of STEAM-1 (ID 121520025) EPFD↓ at 10.7 GHz with 1.2 m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

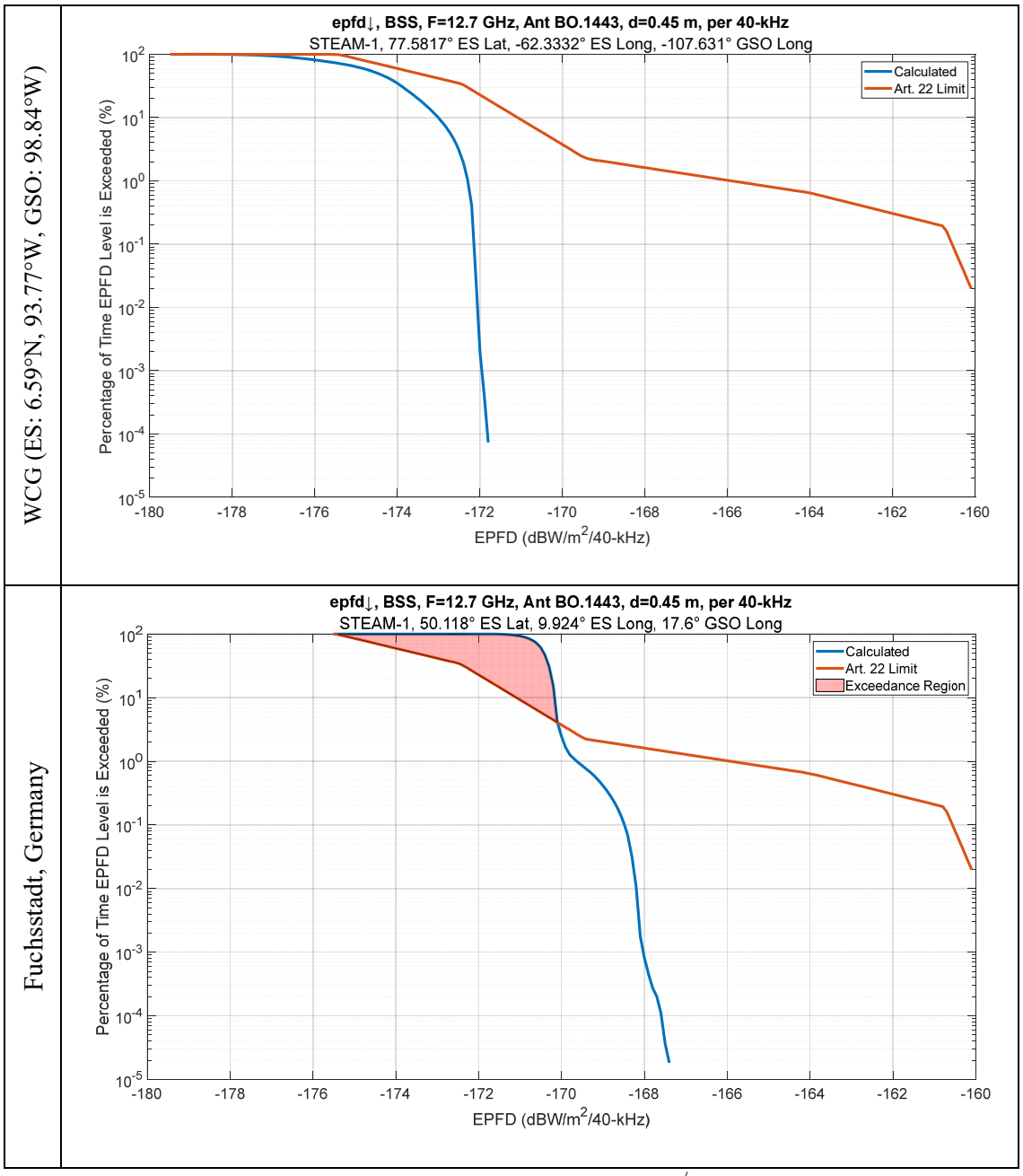

Figure 17 – Comparison of STEAM-1 (ID 121520025) EPFD↓ at 12.7 GHz with 0.45 m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E

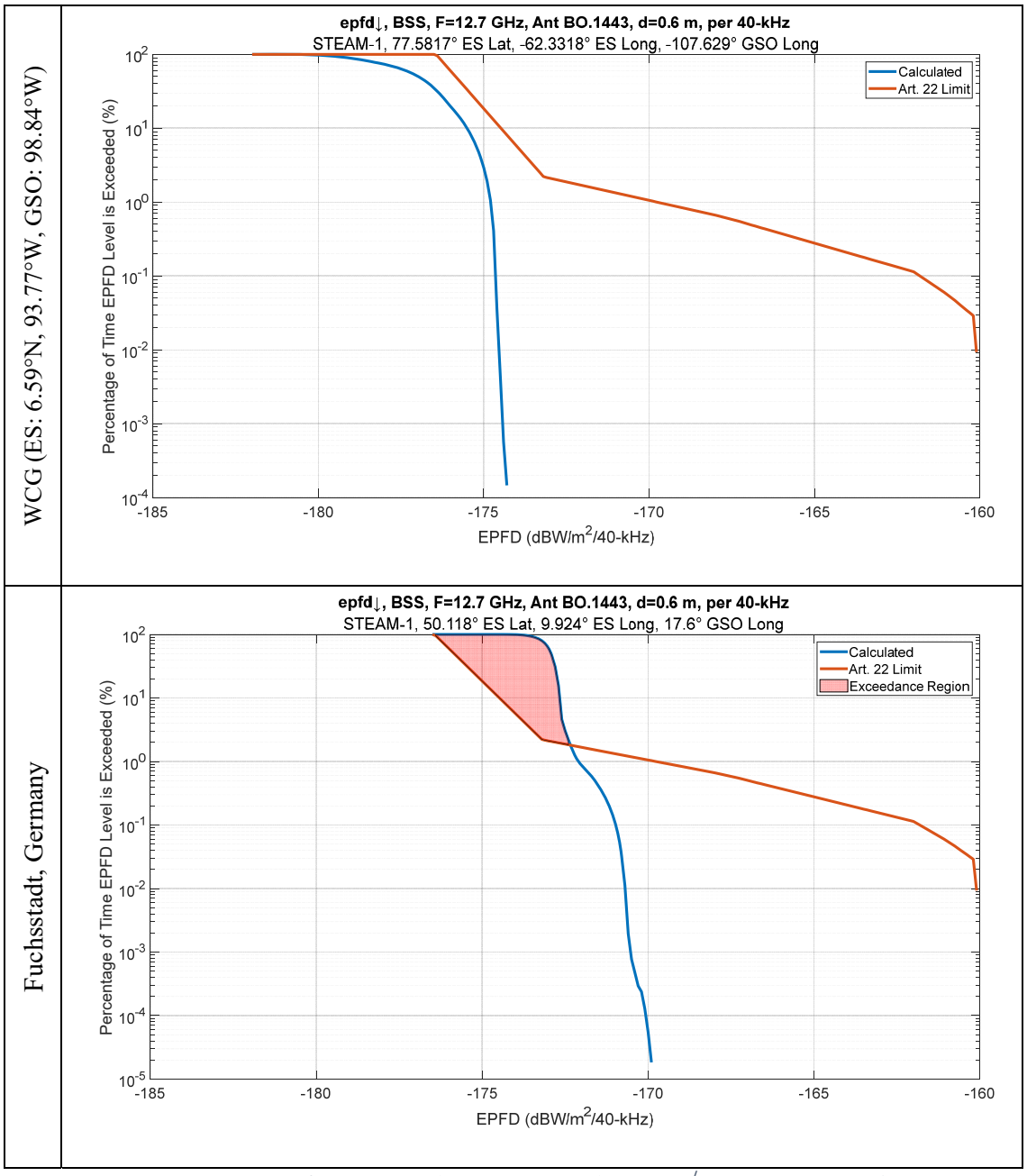

Figure 18 – Comparison of STEAM-1 (ID 121520025) EPFD↓ at 12.7 GHz with 0.6 m GSO ES for WCG and for Fuchsstadt, Germany (50.118°N. 9.924°E) with GSO Satellite at 17.6°E