Dynamic Simulation Methodology for EESS (passive) Interference from NGSO Earth-to-Space Links

1. Introduction

Some of the Earth Exploration Satellites operate in frequency bands adjacent to the Starlink Gateway Earth Stations (ES) used for backhaul communication to and from Starlink NGSO satellites. In particular, the Starlink gateways transmitting in E-band (81-86 GHz) in Earth-to-Space direction are adjacent to the frequency band 86-92 GHz used by EESS passive sensors. The protection criteria for these sensors are specified in the Recommendation ITU-R RS.2017 in form of power spectral density (PSD) at the input of satellite receiver (output of antenna) as -169 dBW/100 MHz with allowed exceedance of 0.01% of time when calculated over a measurement Area of Interest (MAI) equal to 2 million km^2 [1]. An important aspect of the above protection criteria is the allowed probability of exceedance of the power spectral density level for 0.01% of time.

Since Earth station antennas constantly change the pointing of their beams during tracking of NGSO satellites, a constant static calculation of emission levels from Earth station will not be able to determine statistical value of interference and will lead to an unrealistic estimation of interference level that could fail the protection criteria for EESS sensors. For fixed terrestrial services (FS) where antennas have fixed direction, it has been possible to back-calculate a worst-case emission mask as defined in Table 2 of Resolution 750 in E-band [2]. However, for NGSO Earth stations in Fixed Satellite Services (FSS), it is not possible to back-calculate the emission mask for the protection of EESS satellites using static calculation as explained above. Instead, a dynamic simulation is needed to correctly compute the probability distribution of interference observed at the input of ESS passive sensor during the operation of FSS Earth station.

2. EESS (passive) Dynamic Simulation Methodology

The dynamic simulation specified in this section describes the methodology for computing the statistical behavior of aggregate RF interference into EESS passive sensors from multiple Earth stations simultaneously transmitting to multiple satellites in a constellation of NGSO system. The dynamic simulation is very similar to the methodology that is currently under development in the ITU-R Study Group 7C in response to the WRC-27 AI 1.18 [3].

The dynamic simulation constructs the NGSO constellation through the known orbital parameters of NGSO system and defines the locations of gateway sites and the number of ES antennas per site. The algorithm randomly selects satellites above the target minimum elevation angles of ES and assigns uplink beam accordingly. The orbital parameters and antenna characteristics of the EESS (passive) satellite operating in E-band are extracted from Recommendation ITU-R RS.1861 [4]. Sensors might have nadir, cross-track nadir, or conical scan pointing, which is implemented in the dynamic simulation per specifications of each sensor described in RS.1861-1.

At each time step, the directional vector between ES and EESS satellite is computed and the antenna gain for ES and EESS satellite antennas are computed along this vector. For most of the time this vector passes through the side lobes of the two antennas, but depending on the orbital alignment, there might be sporadic alignment of the boresight of one of the antenna toward the other antenna. Boresight to boresight alignment will be extremely rare.

The interference power level received by the EESS sensor at the nth step from the ith ES is calculated from the following equation

$$I(i,n) = \frac{P_{ES}.\,G_{ES}(i,n).\,G_{EESS}(i,n)}{L_a(i,n).\,L_{pol}}.\left(\frac{\lambda}{4\pi r(i,n)}\right)^2 \quad (1)$$

where

- P_{ES} : ES transmitter out of band emission in the EESS (passive) band at the input of ES antenna defined at 100 MHz bandwidth averaged over the full operational bandwidth of EESS radiometer
- $G_{ES}(i,n)$: ES antenna gain towards EESS satellite
- $G_{EESS}(i,n)$: EESS receive antenna gain towards ES
- $L_{\mathrm{a}}(i,n)$: atmospheric losses (gaseous losses) per Rec. ITU-R P. 676

L_{pol} : losses due to polarization mismatch

λ : Wavelength

$r(i,n)$: distance between ES and EESS satellite

The aggregate interference at the n[th] step will be the sum of the interference from all ES within the line of sight of EESS satellite:

$$I_{agg}(n) = \left[\sum_i \frac{G_{ES}(i,n).G_{EESS}(i,n)}{L_a(i,n).r^2(i,n)}\right].\frac{P_{ES}}{L_{pol}}\left(\frac{\lambda}{4\pi}\right)^2 \qquad (2)$$

Using this aggregate interference data samples, the CCDF of data is plotted and the probability of exceedance is compared with the limits of RS.2017.

3. Results

Dynamic simulation results for two example cases are reported in this Section[1].

3.1. Case 1

The first case is a dynamic simulation of a mega constellation with 30,000 NGSO satellites and the gateway density of 76 sites with 32 ES per site (total 2432 ES) per 2 million km^2. Custom software was developed to simulate this case. The conditions of NGSO system including emission masks, number of sites, number of antennas, and the minimum elevation angles follow the conditions of SpaceX's STA license (SES-STA-20240128-00231) developed by NASA and NOAA for protection of EESS (passive) sensors in E-band. These parameters and additional information about the Case 1 simulation are listed in the following Table.

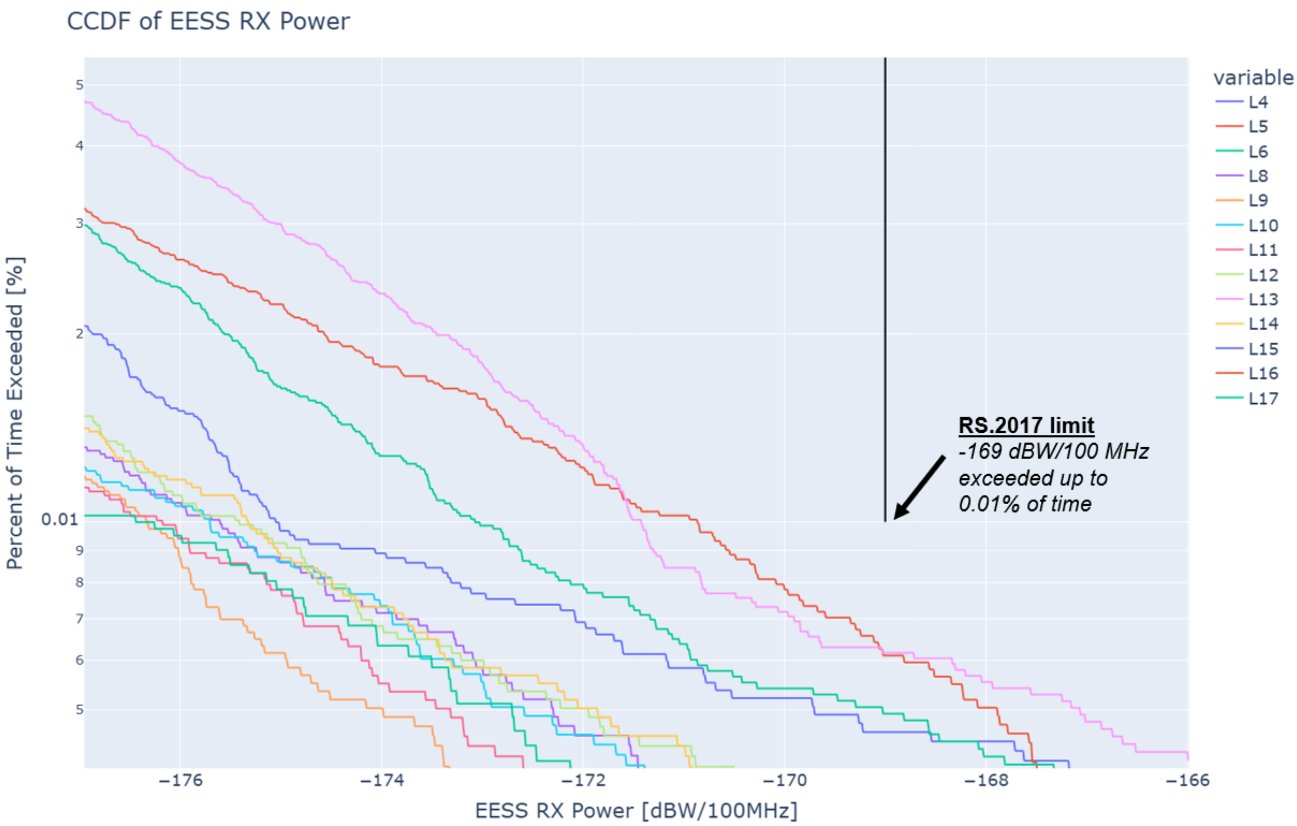
Description	Assumption
Number of Gateway Sites in 2 million km^2	76
Number of Uplink Beams per Gateway Site	32

[1] The simulations presented in this Section are for example only and the results are a function of many variables including the emission level mask, antenna pattern sidelobe envelope, and the EESS protection criteria (RF interference level and the exceedance probability) in RS. 2017. The results presented in these examples should not be interpreted as absolute maximum number of Earth station (uplink) that can coexist in the E-band adjacent to the 86-92 GHz used by EESS (passive).

Minimum Elevation Angle per Uplink Beam	25°
FSS ES Pointing Strategy per Uplink Beam	Select random satellites above minimum elevation angle.
ES Gain Pattern	ITU-R S.580[2]
Polarization Mismatch Loss	0 dB
ES emission mask	−41.2 – 16.3(f − 86) dBW/100 MHz for 86.05 ≤ f ≤ 87 GHz −57.5 dBW/100 MHz for 87 < f ≤ 91.95 GHz
EESS sensors characteristics	ITU-R RS.1861-1 L4-L6, L8-L17 (L7 is not simulated since it is not operational anymore)
EESS satellite antenna pattern	ITU-R RS.1813 [6]
Simulation Iterations	approx. 600,000 iterations per sensor

The CCDF results show that this scenario easily complies with the -169 dBW/100 MHz limit with probability of exceedance up to 0.01% of time for all operational EESS (passive) sensors. CCDF plots of individual sensors are shown in Annex 1.

[2] Refer to Annex 2 for detail of antenna pattern envelope.


CCDF of EESS RX Power
Percent of Time Exceeded [%]
EESS RX Power [dBW/100MHz]
variable
L4
L5
L6
L8
L9
L10
L11
L12
L13
L14
L15
L16
L17
RS.2017 limit
-169 dBW/100 MHz
exceeded up to
0.01% of time
0.01
−176
−174
−172
−170
−168
−166

3.2. Case 2

The second case is dynamic simulation of three gateway sites in the UK using a commercial simulation software. The software tool used for this simulation is from Transfinite System called Visualyse Pro 7.1 [5]. This tool is an industry standard for dynamic simulation of various links and mutual interferences including NGSO systems with the ability to define parameters of the systems according to the ITU-R recommendations.

The locations of the three gateway sites used for this simulation are shown in the Table below.

Country	Name	Latitude	Longitude
UK	Morn Hill, UK	51.06012	-1.26382
UK	Wherstead, UK	52.01912	1.143117
UK	Woodwalton, UK	52.40523	-0.21902

Other parameters used for dynamic simulations are listed in the following Table.

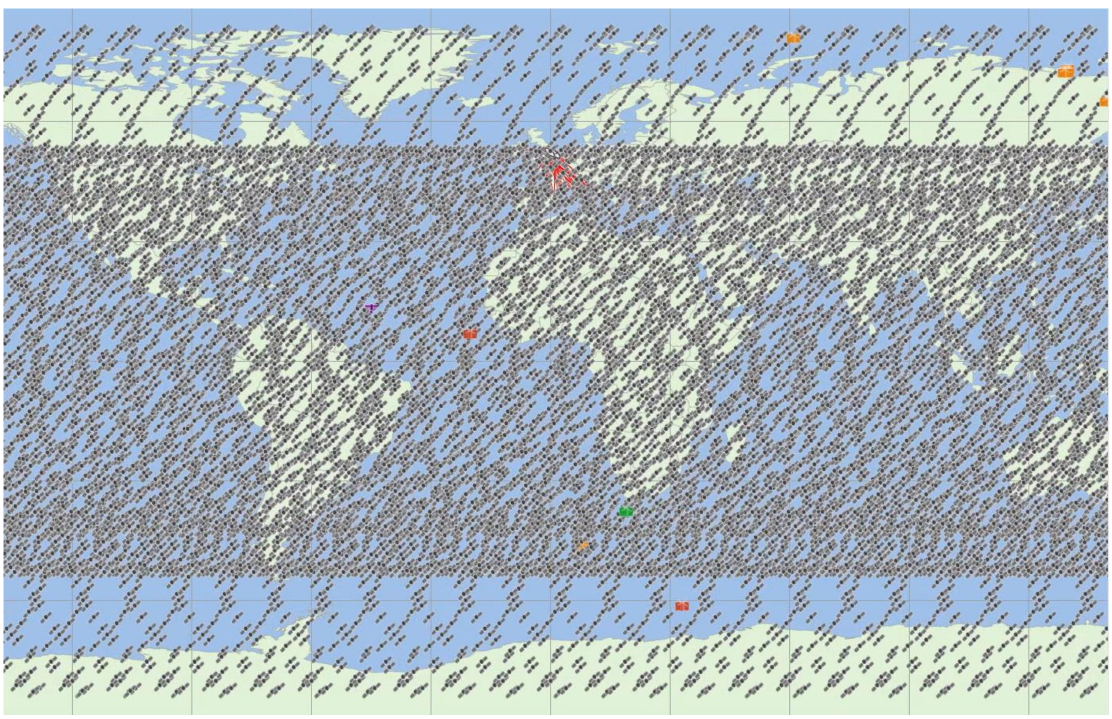
<table>
<tr><th>Description</th><th>Assumption</th></tr>
<tr><td>Number of Uplink Beams per Gateway Site</td><td>40[3]</td></tr>
<tr><td>Minimum Elevation Angle per Uplink Beam</td><td>20°</td></tr>
<tr><td>FSS ES Pointing Strategy per Uplink Beam</td><td>Select random satellites above minimum elevation angle.</td></tr>
<tr><td>Satellite Constellation for Antenna Pointing</td><td><table>
<tr><th>Total Satellites:</th><th>Altitude (km):</th><th>Inclination Angle (°):</th><th>Planes:</th></tr>
<tr><td>5280</td><td>340</td><td>53</td><td>48</td></tr>
<tr><td>3600</td><td>360</td><td>96.9</td><td>30</td></tr>
<tr><td>3360</td><td>530</td><td>43</td><td>28</td></tr>
</table>(Total satellites: 12,240)</td></tr>
<tr><td>ES Gain Pattern</td><td>ITU-R S.580[4]</td></tr>
<tr><td>Polarization Mismatch Loss</td><td>0 dB</td></tr>
</table>

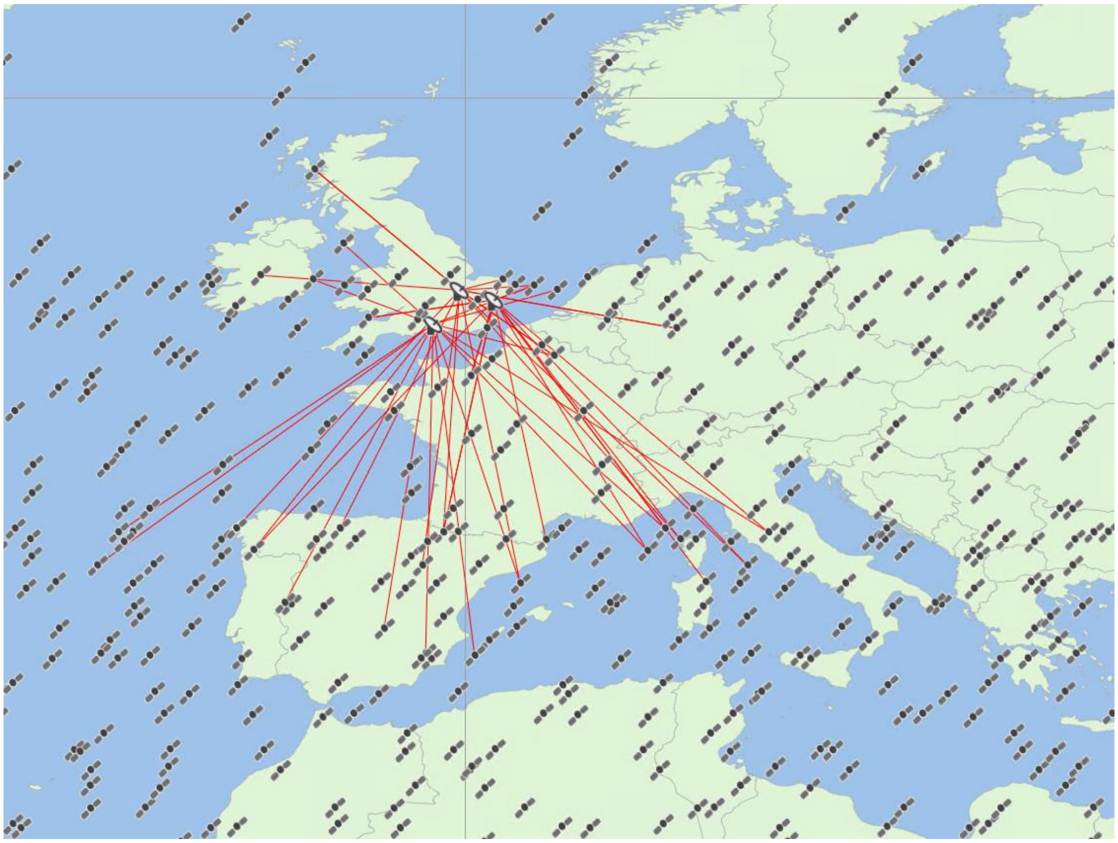
[3] In order to improve the computational efficiency of simulation for 40 stations per sites, simulation was performed for 16 stations per site and the result was scaled up using a scaling factor of $10\log\left(\frac{40}{16}\right)$=4 dB.

[4] Refer to Annex 2 for detail of antenna pattern envelope.

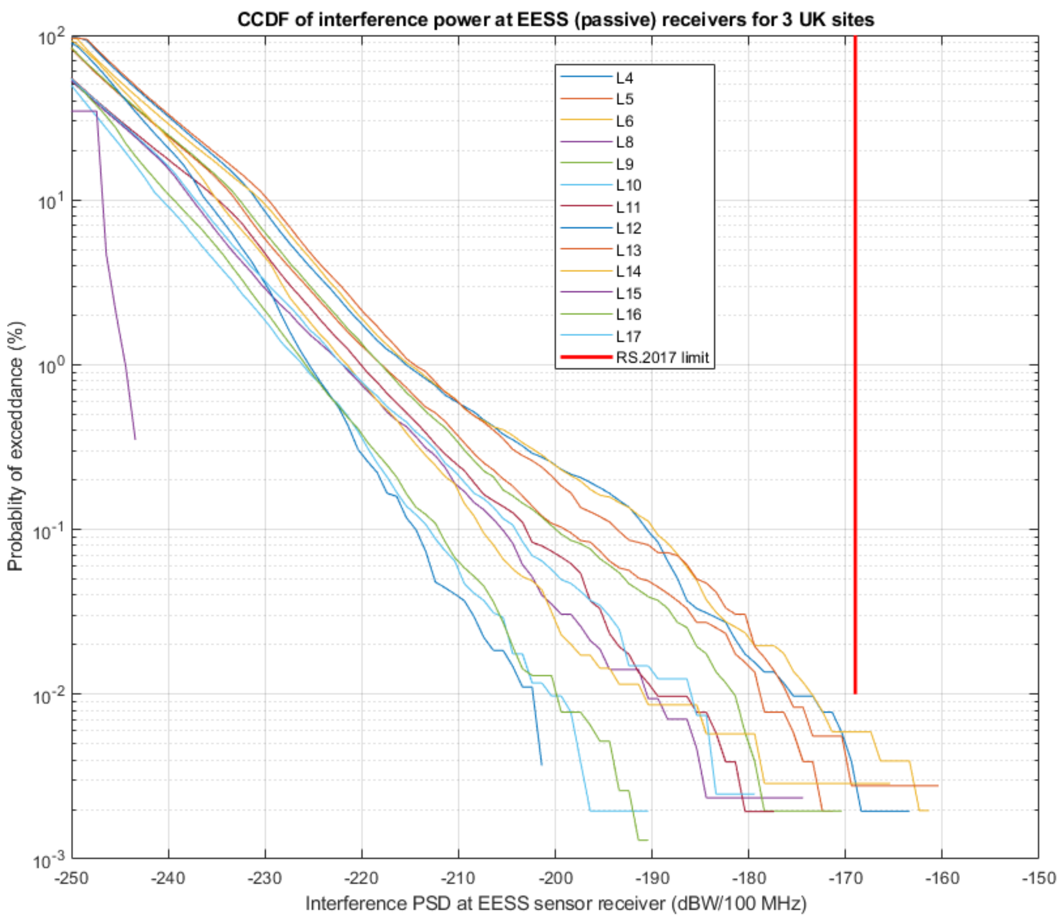
ES emission mask	−41.2 – 16.3(f − 86) dBW/100 MHz for 86.05 ≤ f ≤ 87 GHz −57.5 dBW/100 MHz for 87 < f ≤ 91.95 GHz
EESS sensors characteristics	ITU-R RS.1861-1 L4-L6, L8-L17 (L7 is not simulated since it is not operational anymore)
EESS satellite antenna pattern	ITU-R RS.1813 [6]
Simulation Steps	15 sec.
Simulation Span	120 days

Figures below show snapshots of satellite constellation globally at a single time step and a zoomed in plot over UK showing some of the uplink beams from each site to different satellites. The EESS satellites are shown with different colors and NGSO satellites are show with black color.

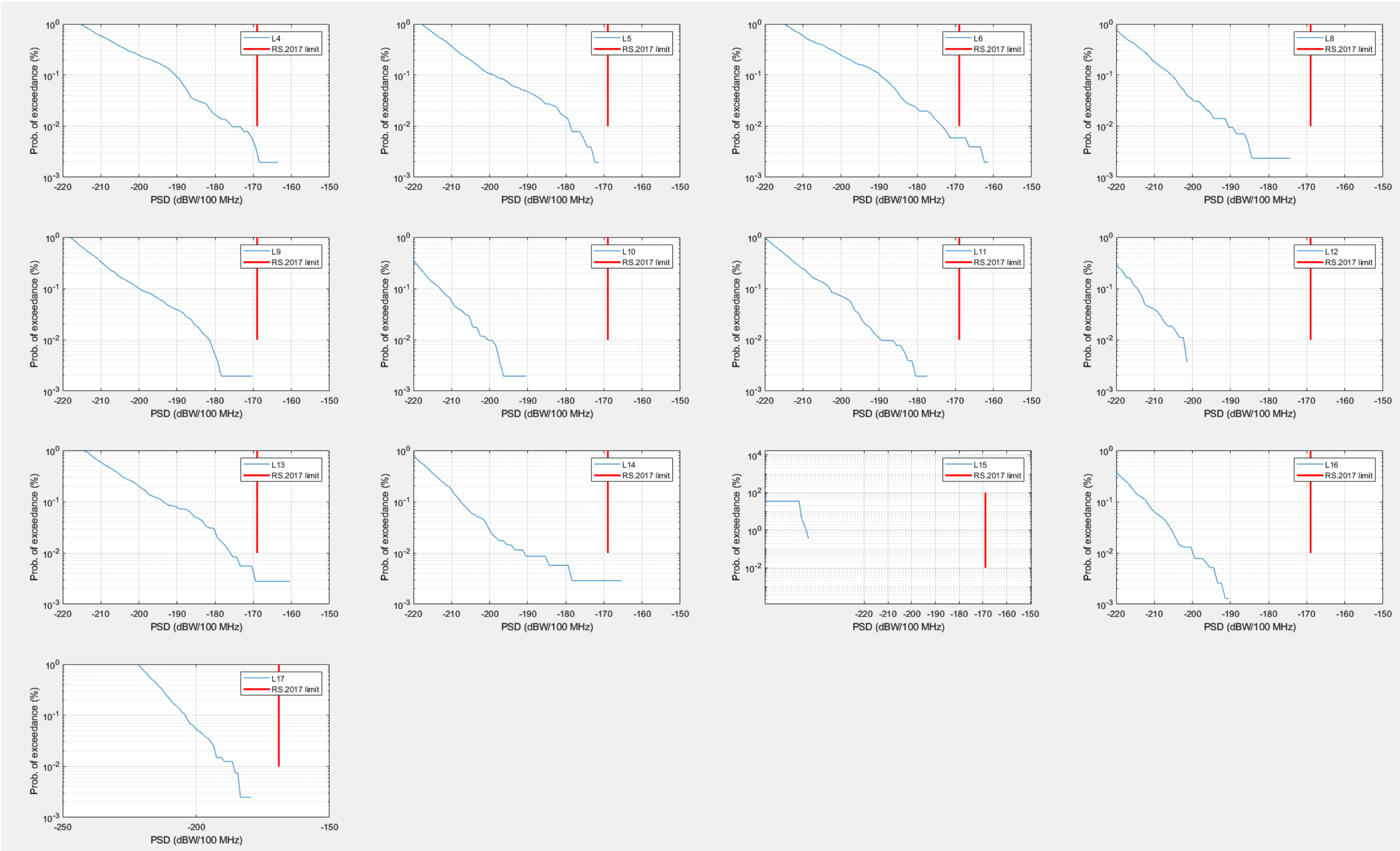




The following plot shows the CCDF of all simulated sensors compared to the EESS protection limit of -169 dBW/100 MHz for the three UK sites.



The CCDFs of individual sensors are shown in below plots.



4. References

[1] ITU-R RS.2017-0, “Performance and interference criteria for satellite passive remote sensing”.

[2] ITU-R Res. 750 (Rev. WRC-19), “Compatibility between the Earth exploration-satellite service (passive) and relevant active services” .

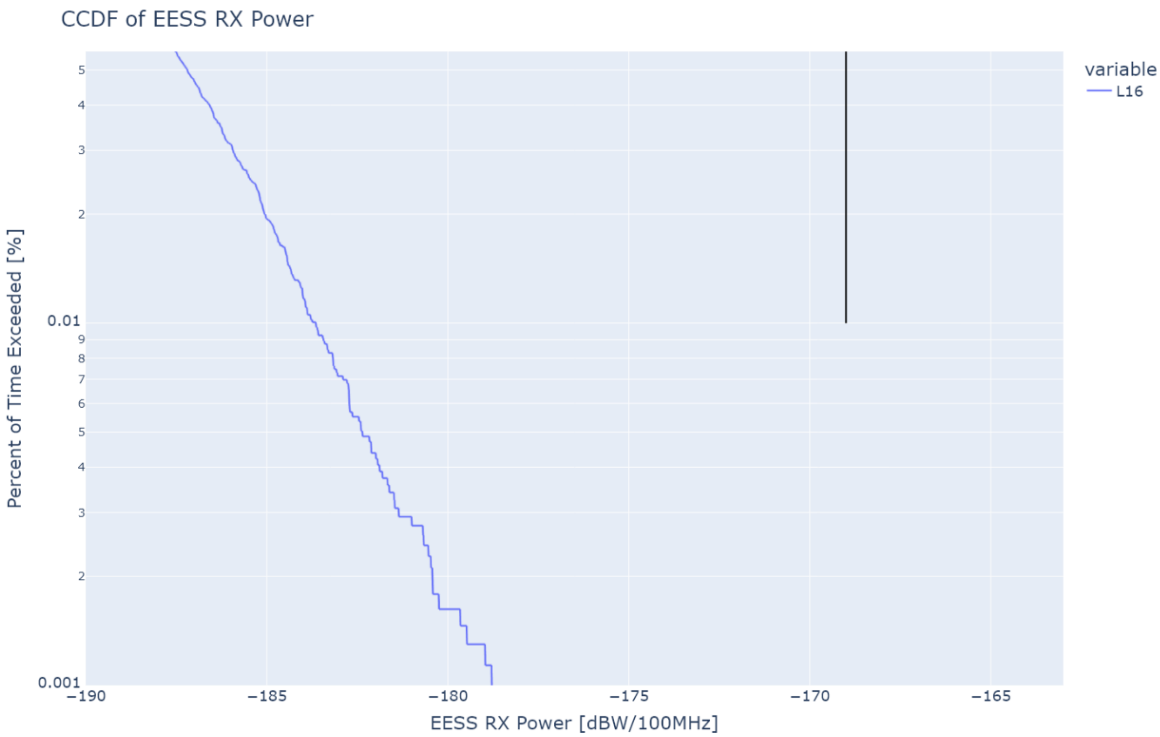
[3] ITU-R Annex 17 to Document 7C/142-E Chair’s Report, “Working Document Toward Preliminary Draft New Report ITU-R [1.18 – EESS]”.

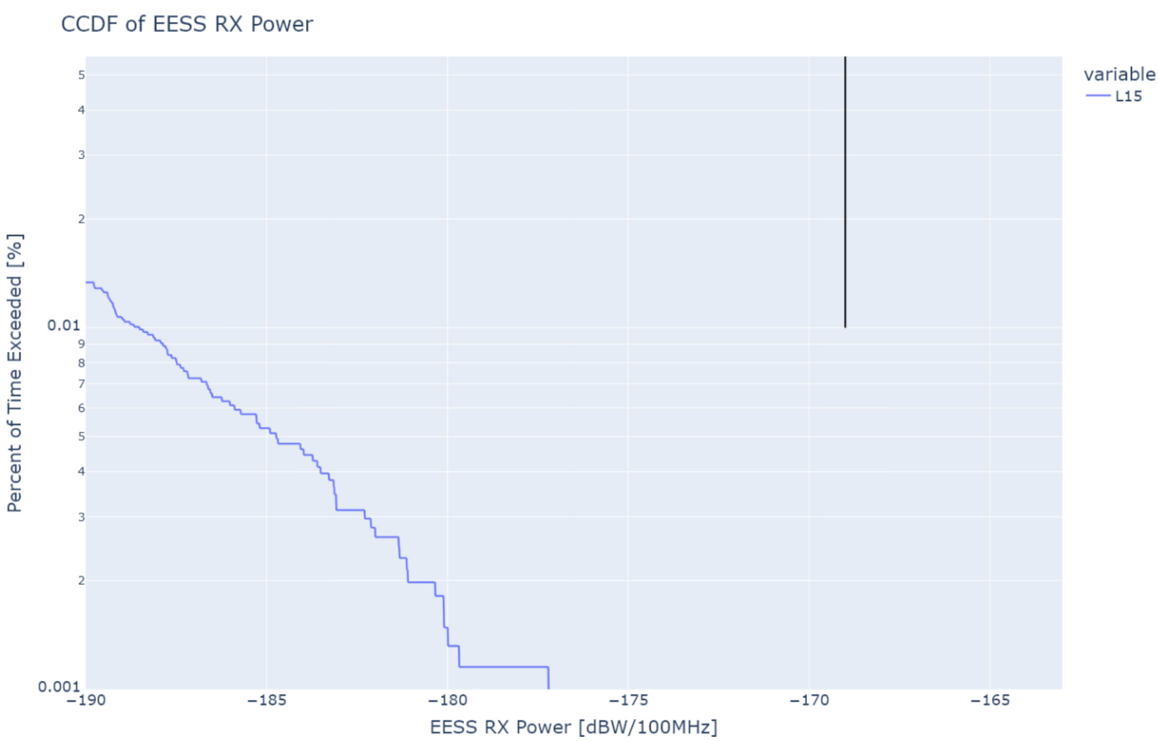
[4] ITU-R RS.1861-1, “Typical technical and operational characteristics of Earth exploration-satellite service (passive) systems using allocations between 1.4 and 275 GHz”.

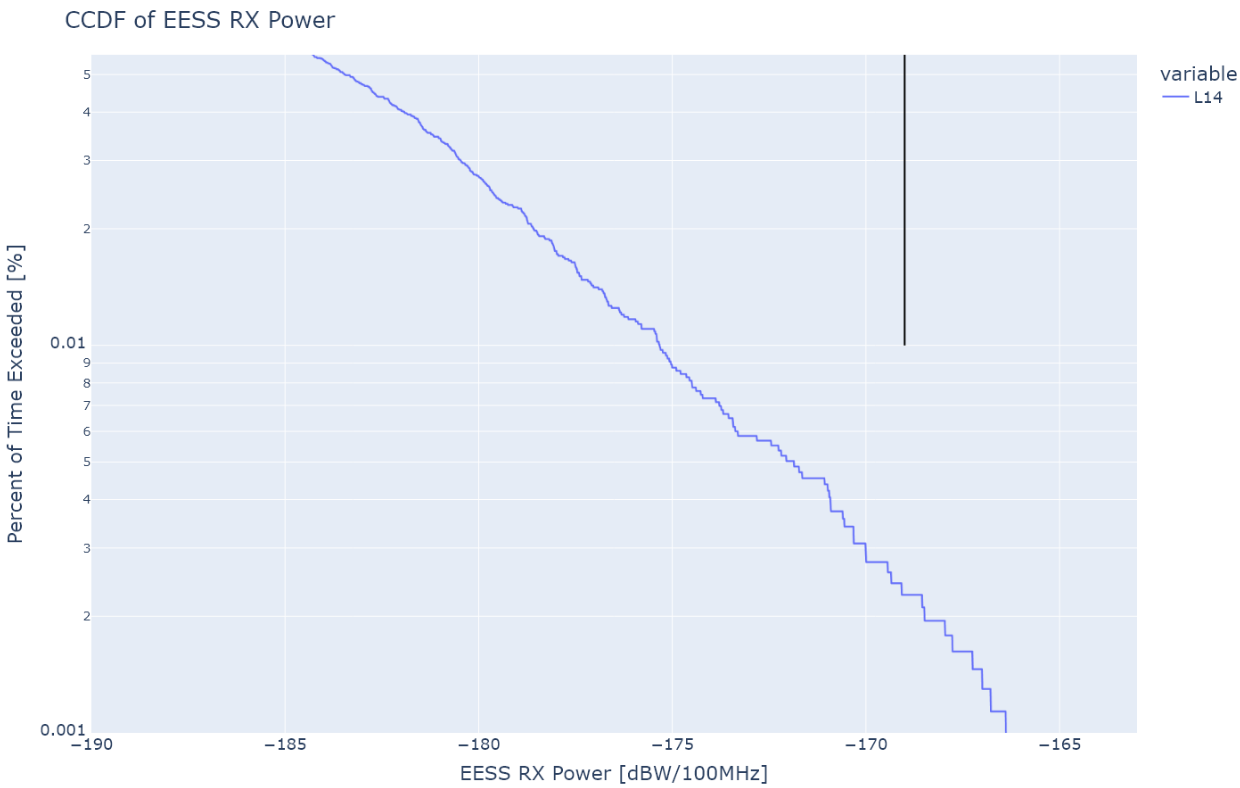
[5] Visualyse Professional, Transfinite System https://transfinite.com/content/professional.

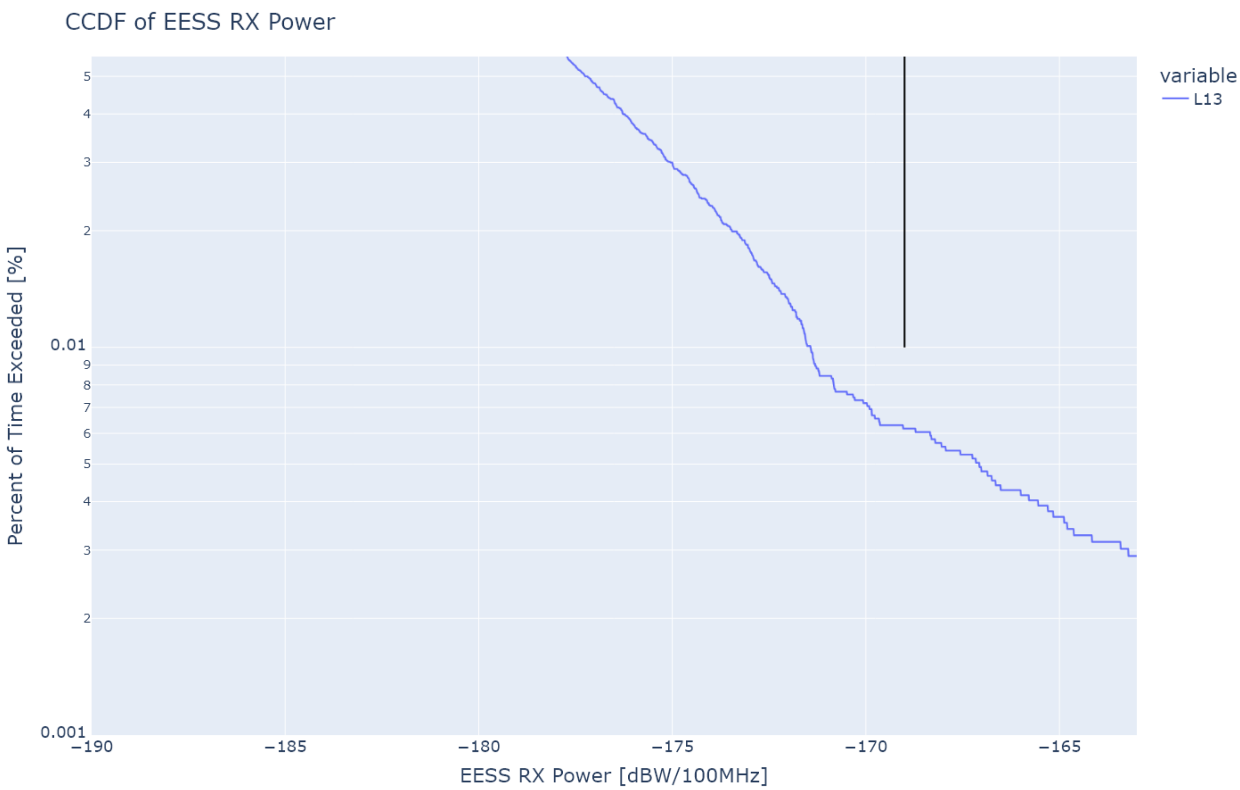
[6] ITU-R RS.1813, “Reference antenna pattern for passive sensors operating in the Earth exploration-satellite service (passive) to be used in compatibility analyses in the frequency range 1.4-450 GHz”.

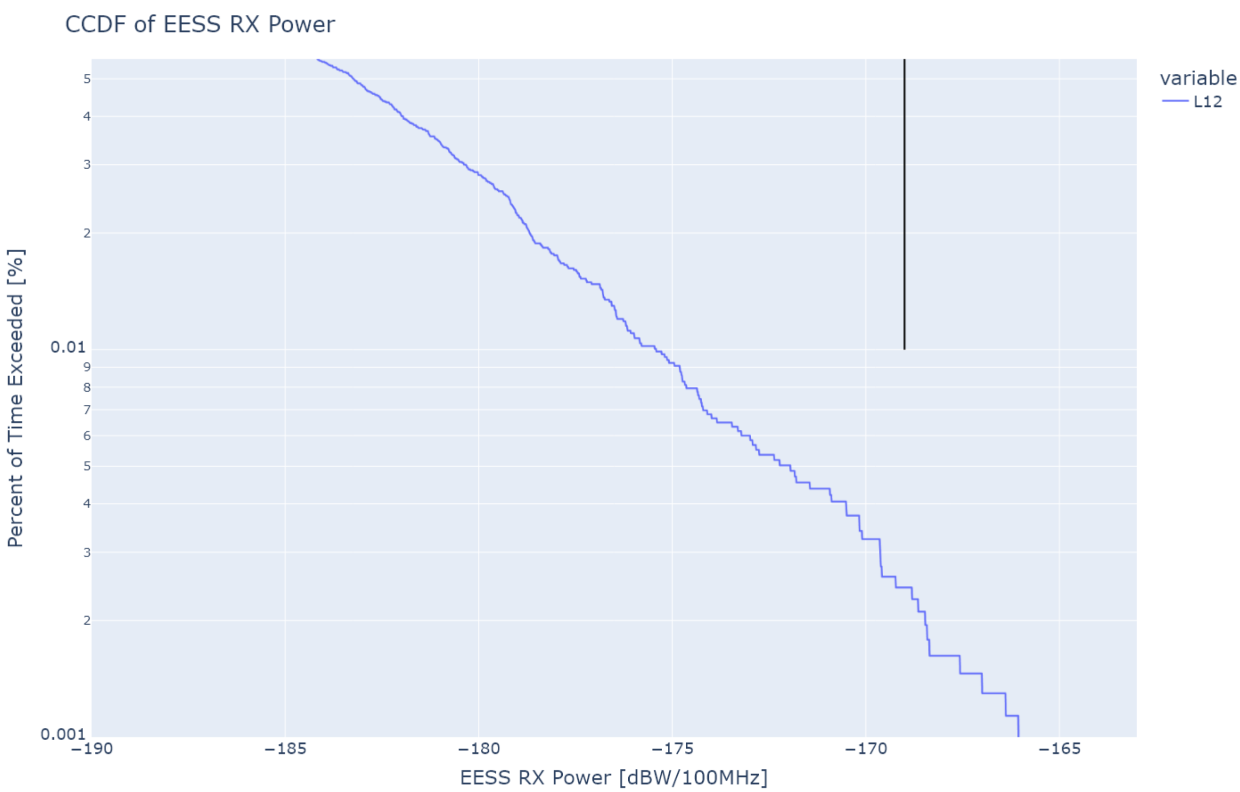
Annex 1. Individual CCDF plots for Case 1 Simulation

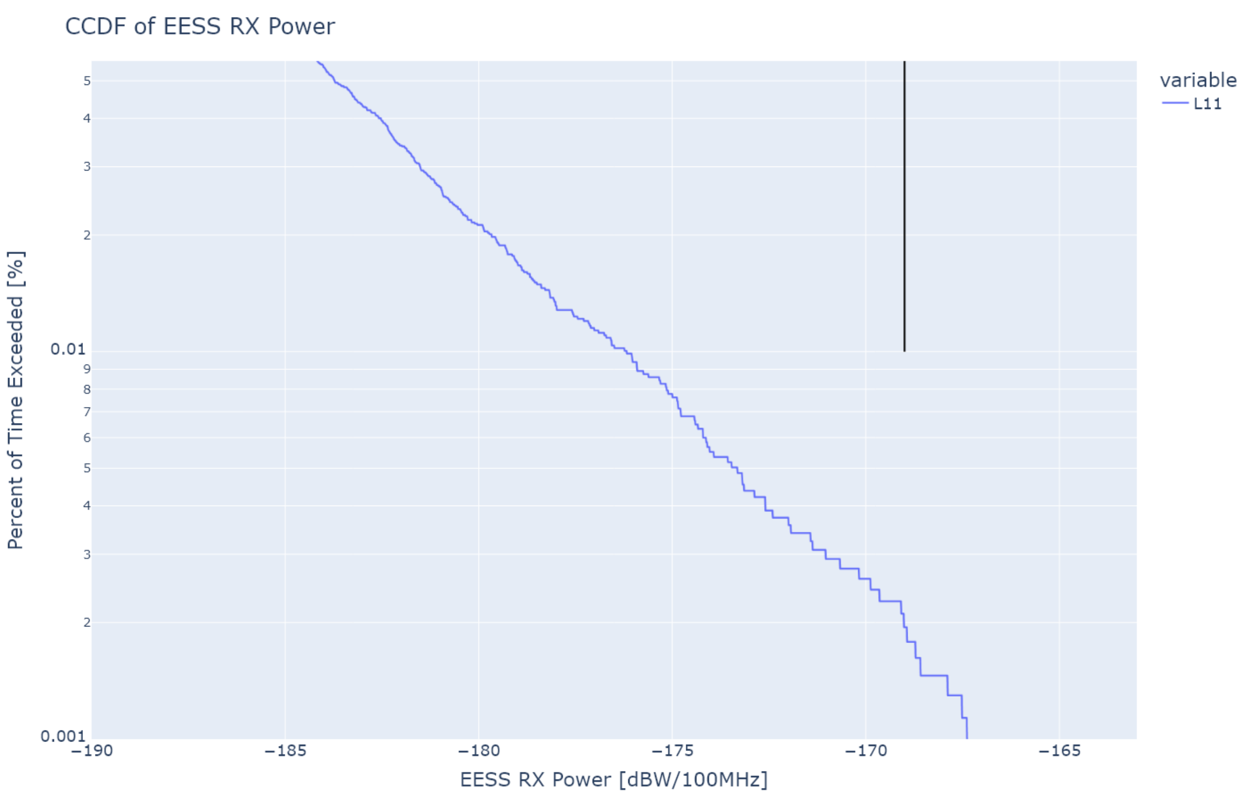


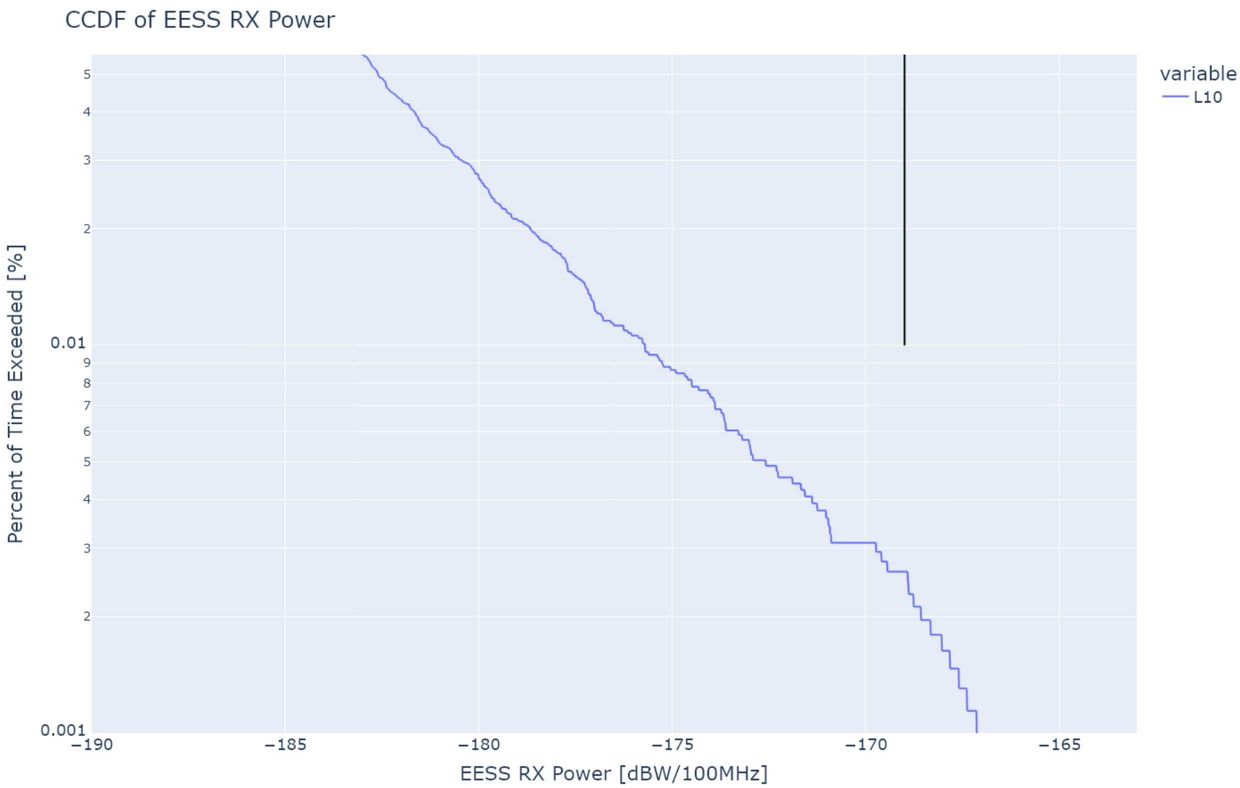


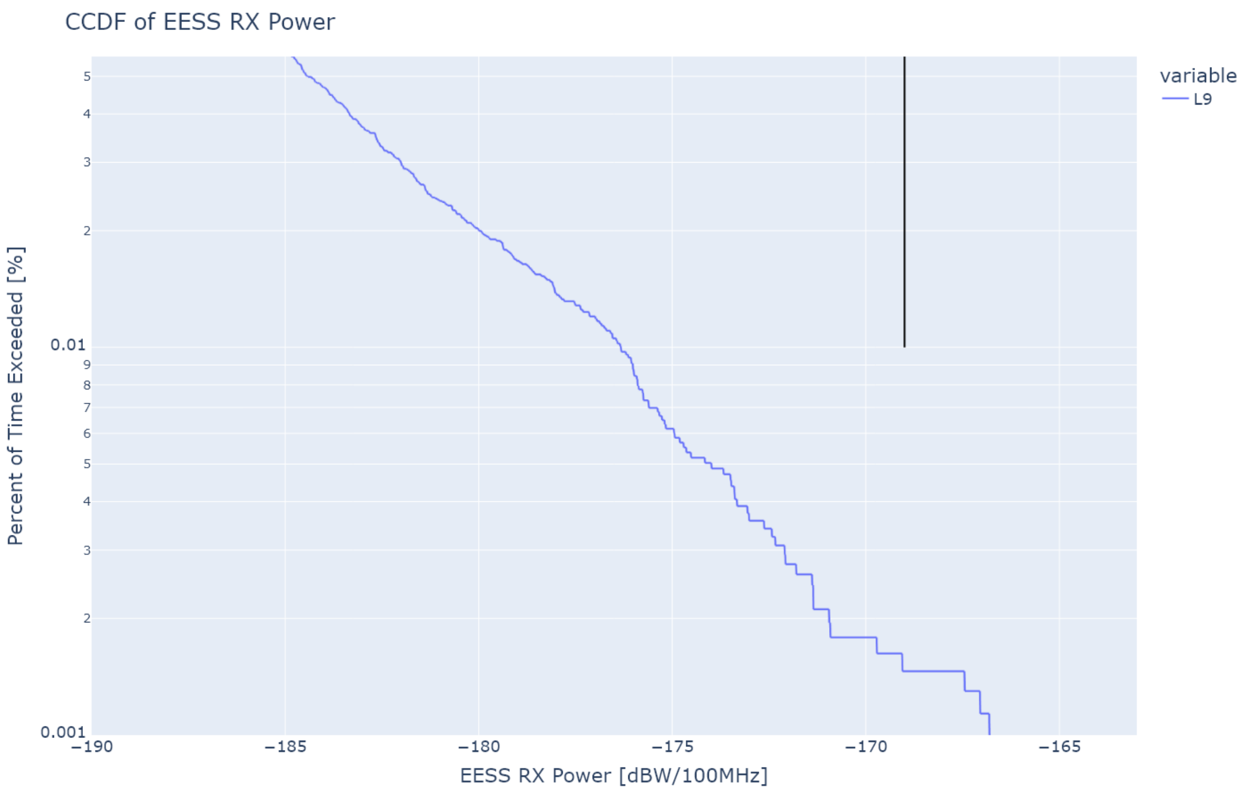

CCDF of EESS RX Power
Percent of Time Exceeded [%]
EESS RX Power [dBW/100MHz]
variable
L14
0.01
0.001
−190
−185
−180
−175
−170
−165

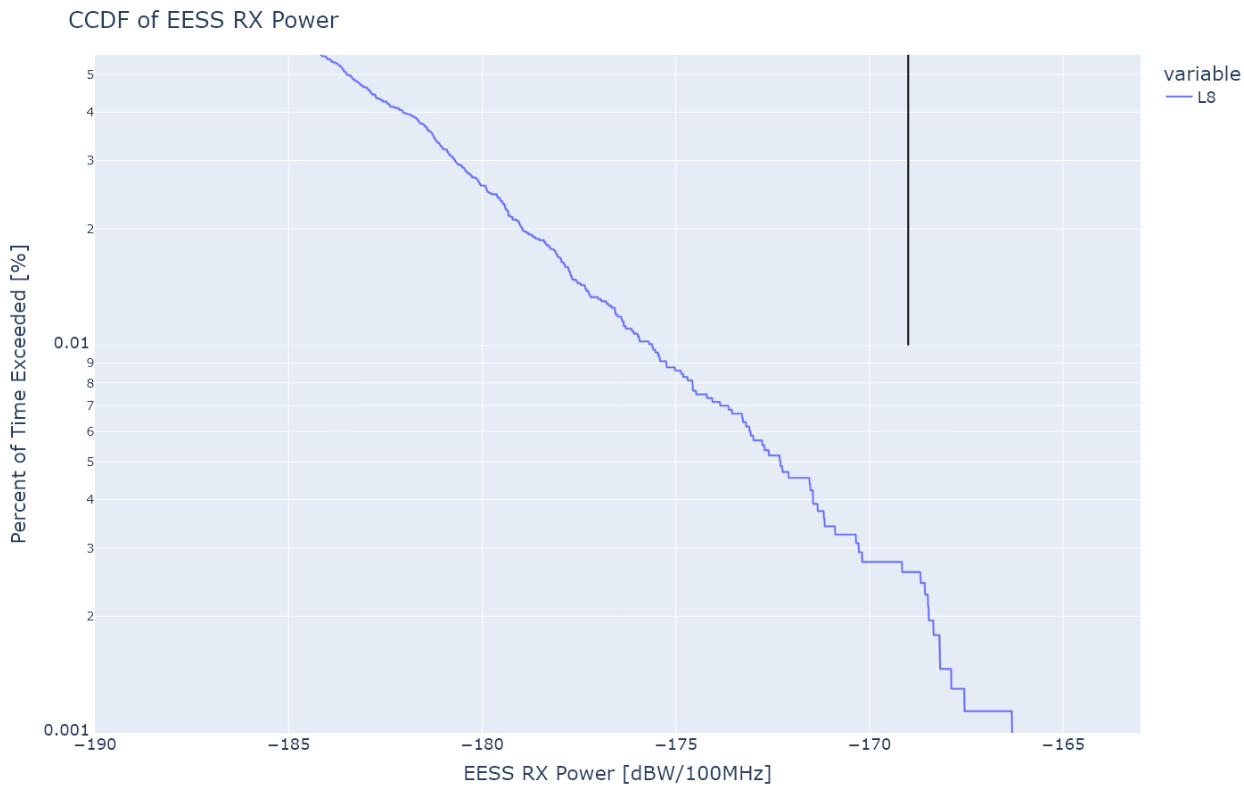

CCDF of EESS RX Power
Percent of Time Exceeded [%]
EESS RX Power [dBW/100MHz]
variable
L13
0.01
0.001
−190
−185
−180
−175
−170
−165

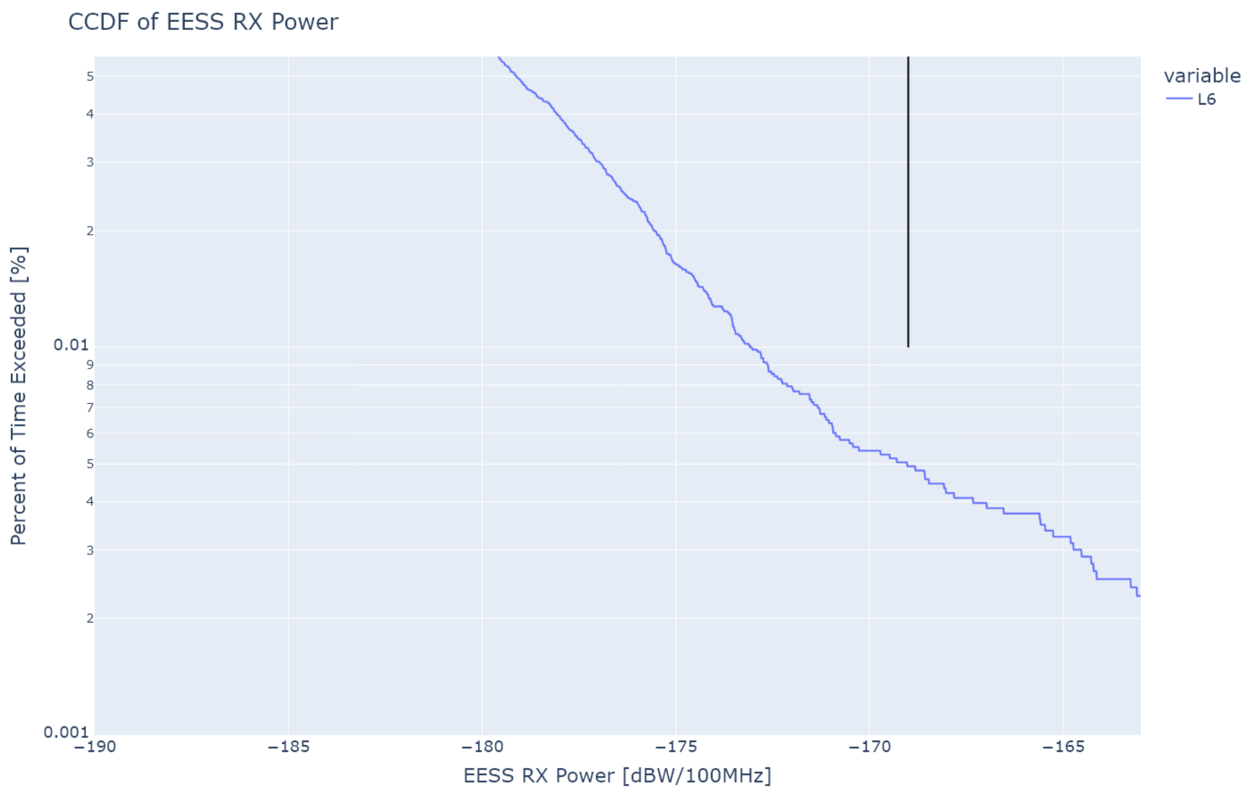

CCDF of EESS RX Power
variable
L12
Percent of Time Exceeded [%]
0.01
0.001
EESS RX Power [dBW/100MHz]
−190
−185
−180
−175
−170
−165

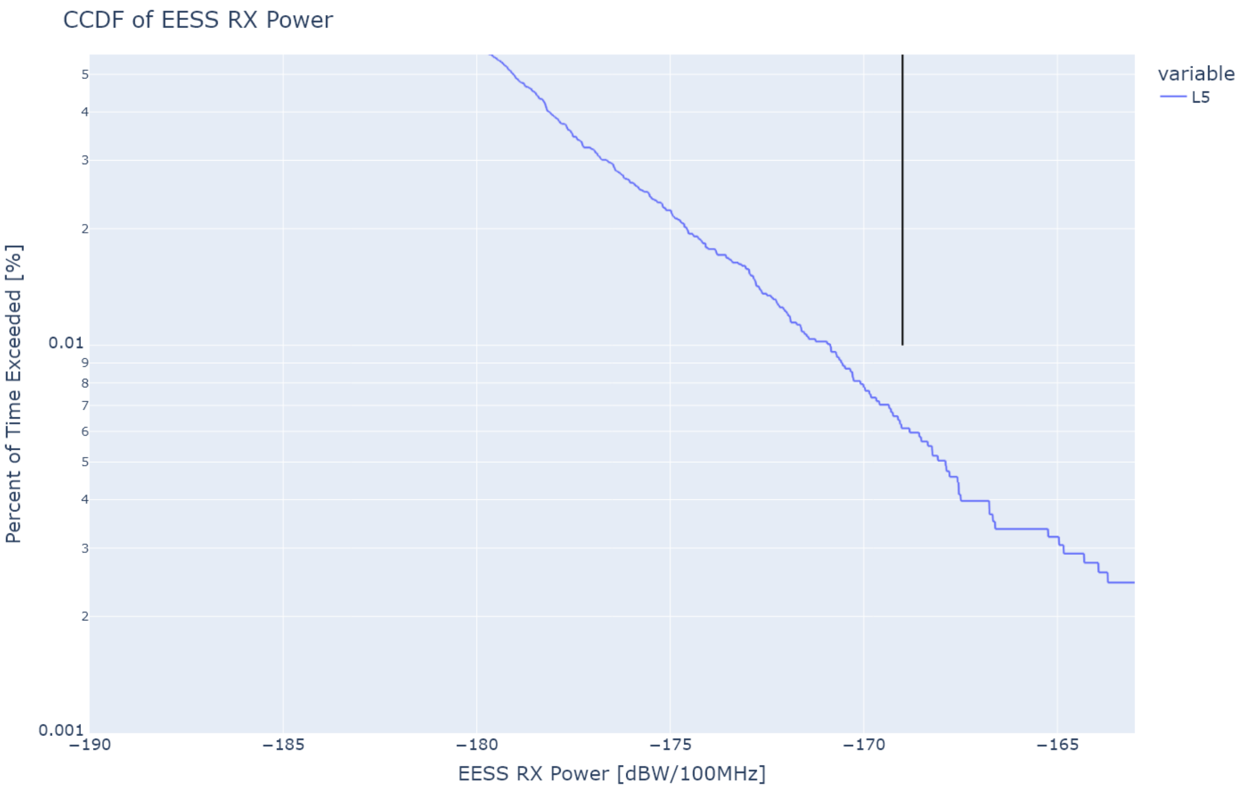

CCDF of EESS RX Power
variable
L11
Percent of Time Exceeded [%]
0.01
0.001
EESS RX Power [dBW/100MHz]
−190
−185
−180
−175
−170
−165

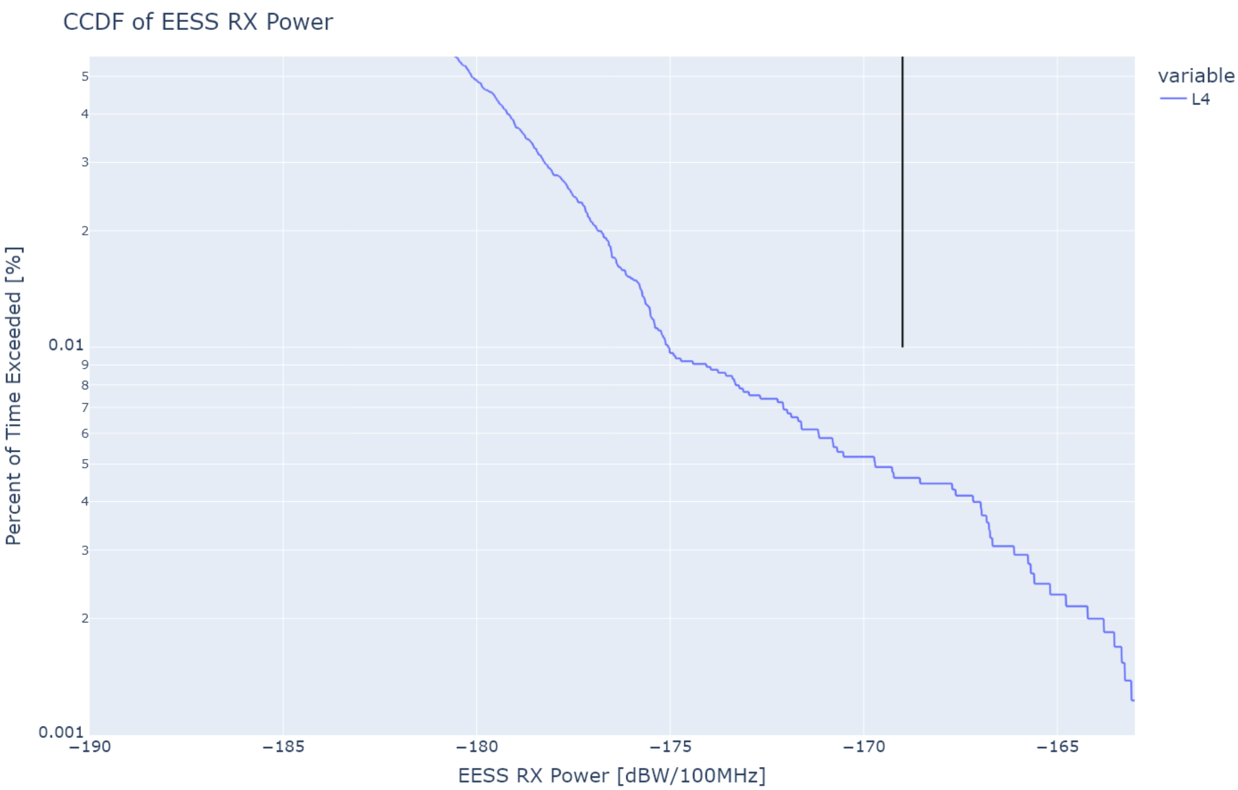

CCDF of EESS RX Power
Percent of Time Exceeded [%]
EESS RX Power [dBW/100MHz]
variable
L10
0.01
0.001
−190
−185
−180
−175
−170
−165

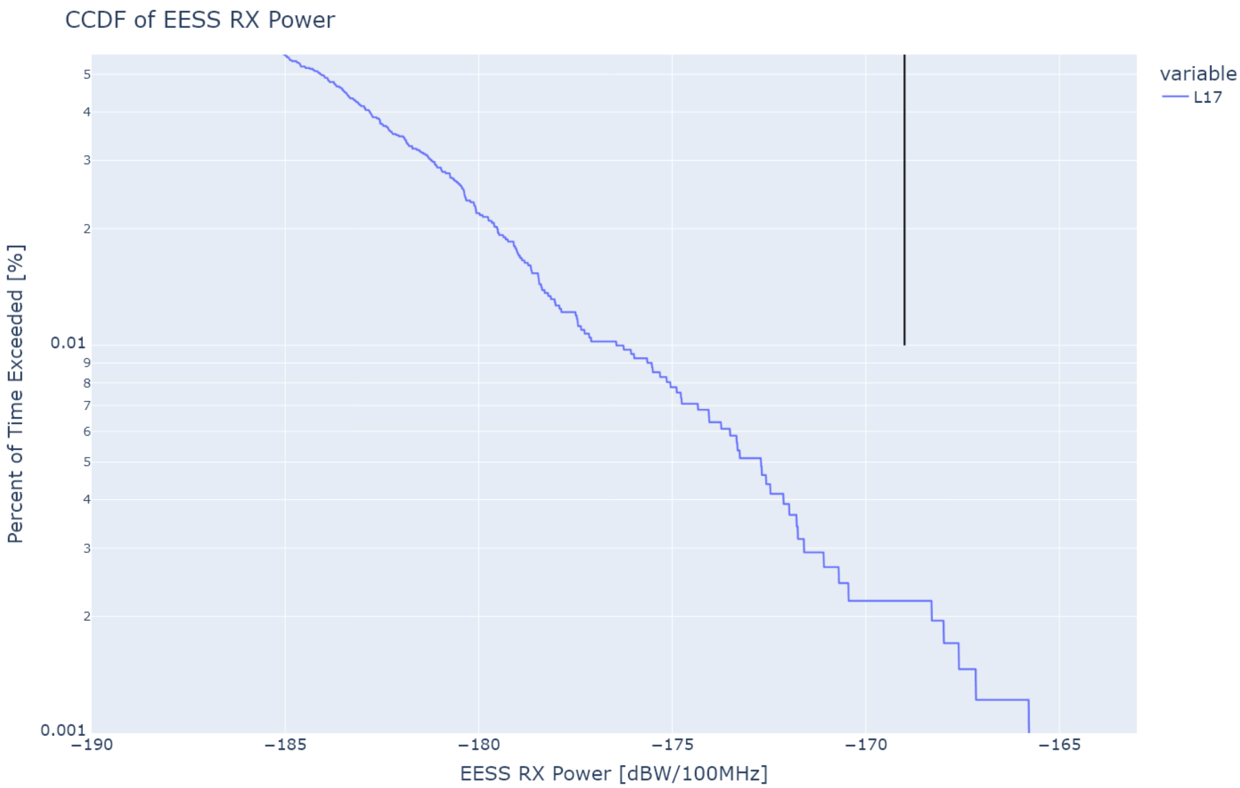

CCDF of EESS RX Power
Percent of Time Exceeded [%]
EESS RX Power [dBW/100MHz]
variable
L9
0.01
0.001
−190
−185
−180
−175
−170
−165


CCDF of EESS RX Power
variable
L8
Percent of Time Exceeded [%]
0.01
0.001
EESS RX Power [dBW/100MHz]
−190
−185
−180
−175
−170
−165


CCDF of EESS RX Power
variable
L6
Percent of Time Exceeded [%]
0.01
0.001
EESS RX Power [dBW/100MHz]
−190
−185
−180
−175
−170
−165


CCDF of EESS RX Power
Percent of Time Exceeded [%]
0.01
0.001
EESS RX Power [dBW/100MHz]
−190
−185
−180
−175
−170
−165
variable
L5

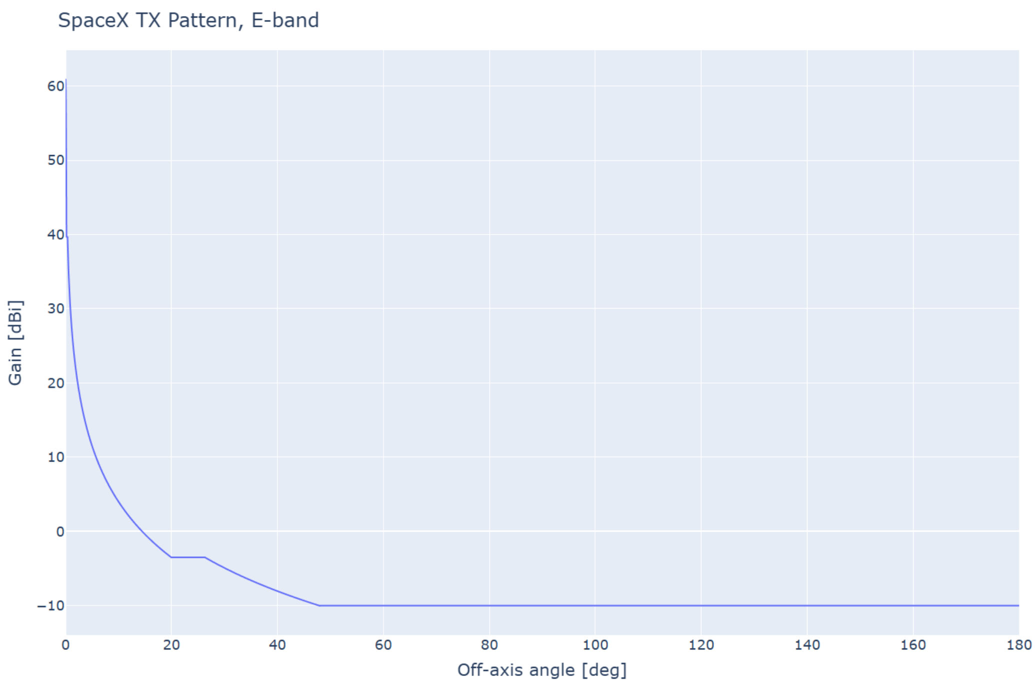

CCDF of EESS RX Power
Percent of Time Exceeded [%]
0.01
0.001
EESS RX Power [dBW/100MHz]
−190
−185
−180
−175
−170
−165
variable
L4


CCDF of EESS RX Power
variable
L17
Percent of Time Exceeded [%]
0.01
0.001
5
4
3
2
9
8
7
6
5
4
3
2
−190
−185
−180
−175
−170
−165
EESS RX Power [dBW/100MHz]

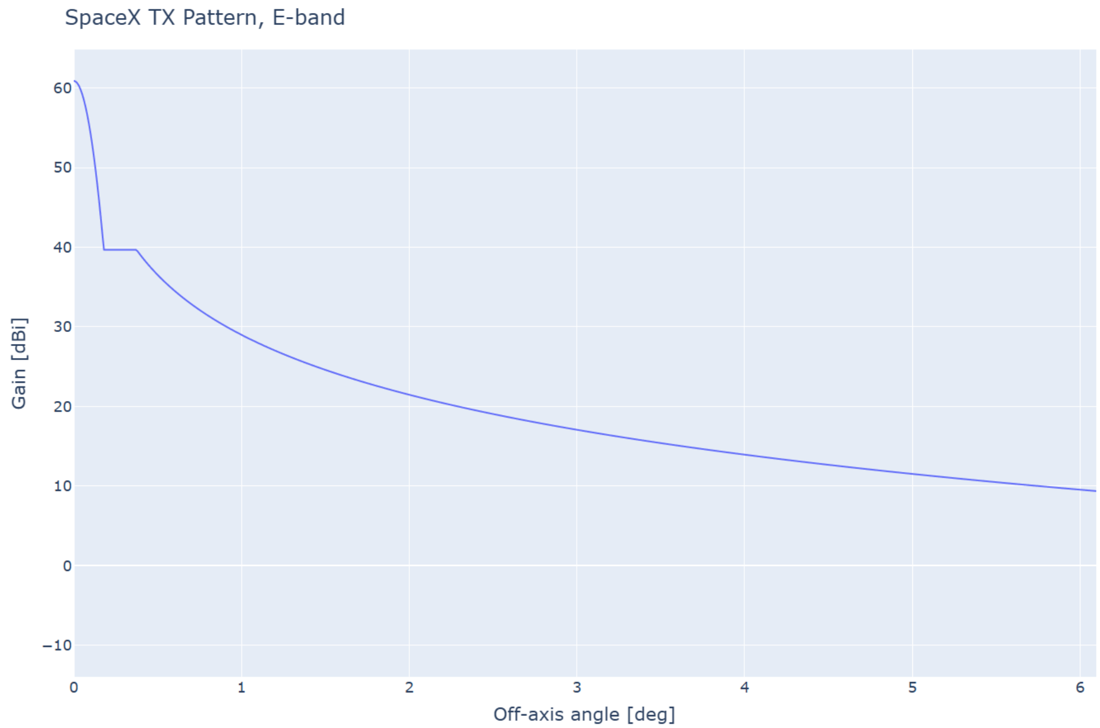
Annex 2. Antenna Pattern Envelopes

1. S.580 Antenna Pattern Envelope for Gateway Earth Stations

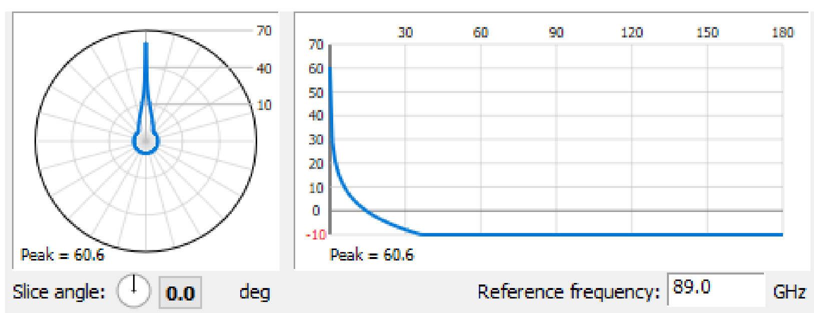
1.1 Antenna pattern envelope used in internally developed simulation tool (Case 1) for Gateway Earth Station



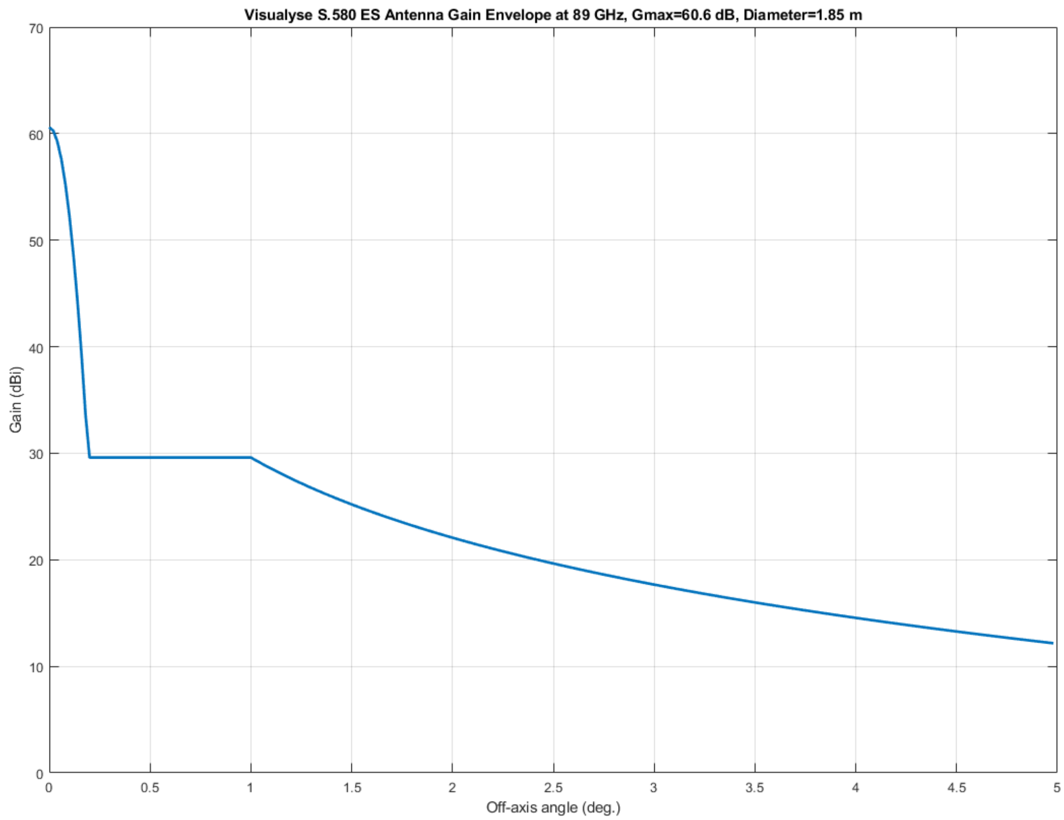
Zoomed-in pattern envelope at small off-axis angles are shown below.



1.2 Visualyse definition of antenna pattern based on S.580 used in Case 2 simulation

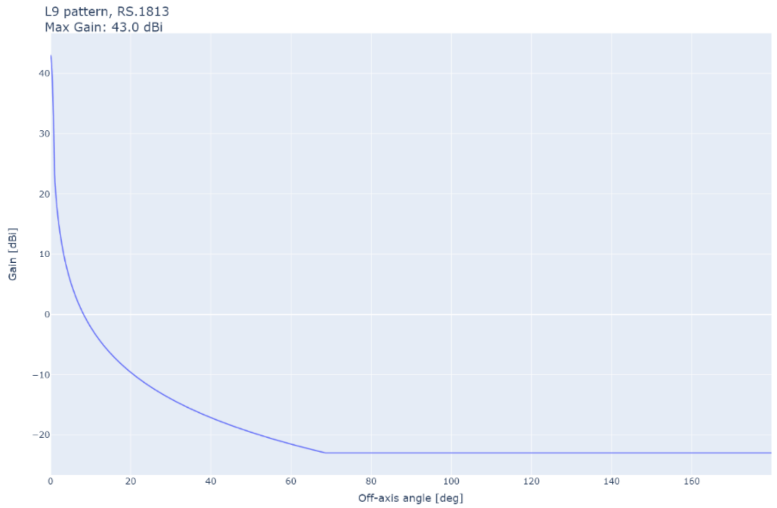
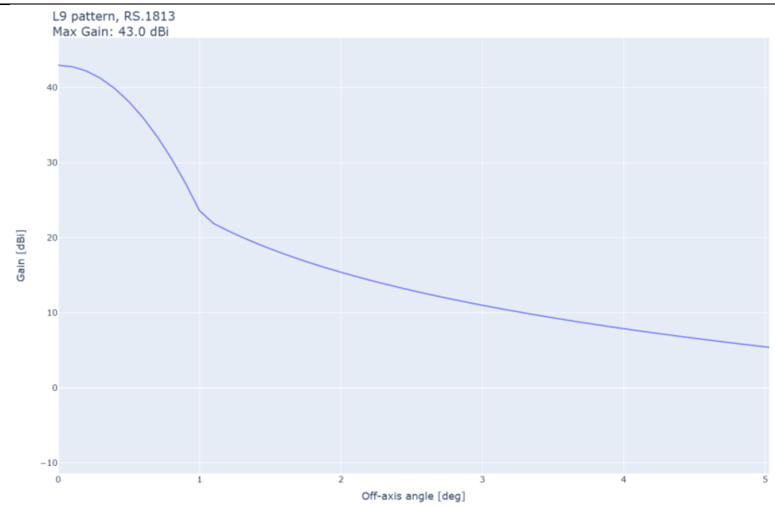


The antenna pattern envelope of the above figure for small off-axis angles is shown below. Implementation of S.580 antenna pattern envelope in Visualyse is slightly more conservative than the pattern envelope described in Section 1.1, which is based on combination of S.580 and Radio Regulation Appendix 7.

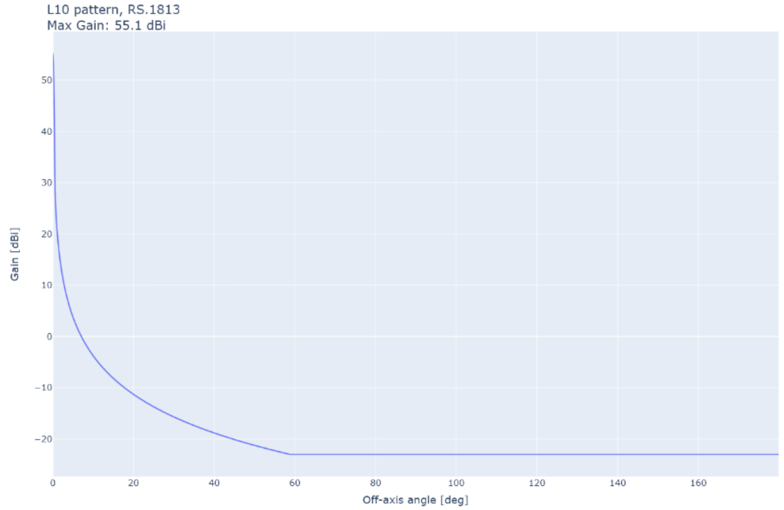

Visualyse S.580 ES Antenna Gain Envelope at 89 GHz, Gmax=60.6 dB, Diameter=1.85 m
Gain (dBi)
Off-axis angle (deg.)
0
10
20
30
40
50
60
70
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

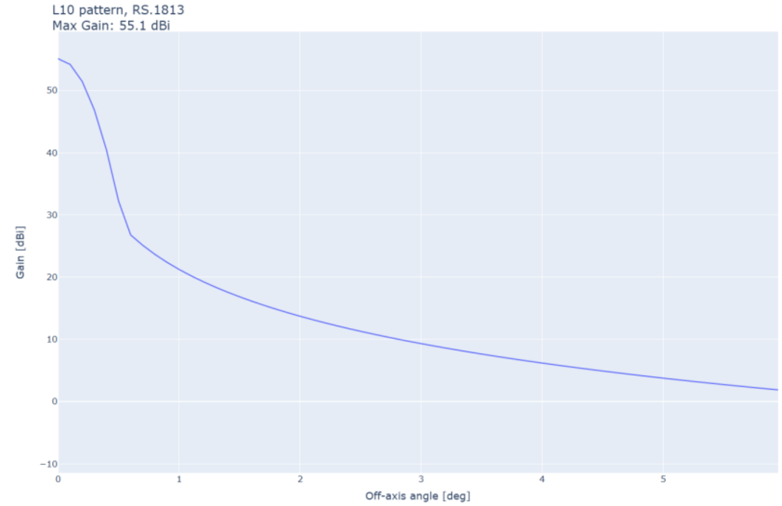
2. RS.1813 Antenna Pattern Envelopes for EESS (passive) Sensors

Example of antenna pattern envelope for some of the sensors based on RS.1813 used in the dynamic simulation are shown below.

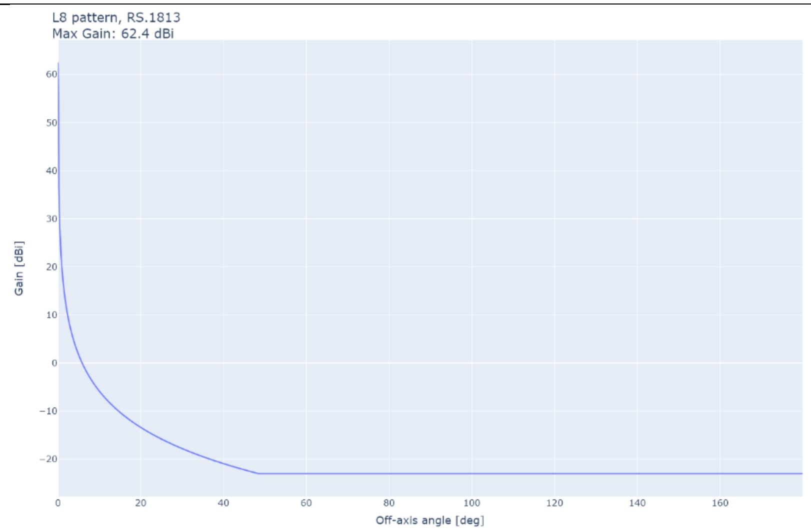
Sensor	Pattern envelope	Zoomed-in pattern
L9		

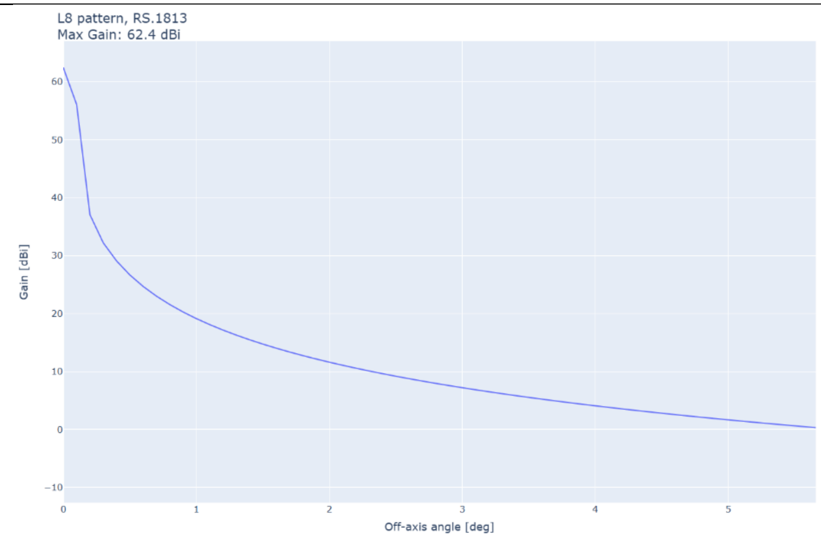
L10

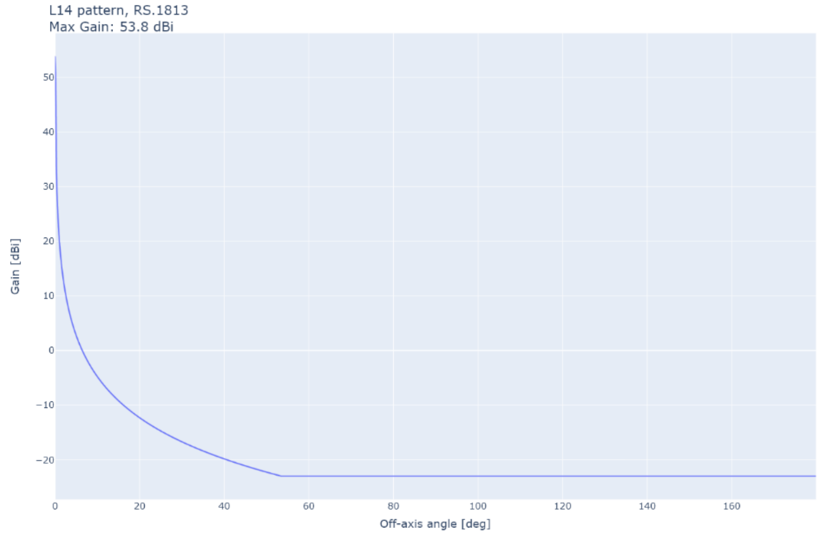
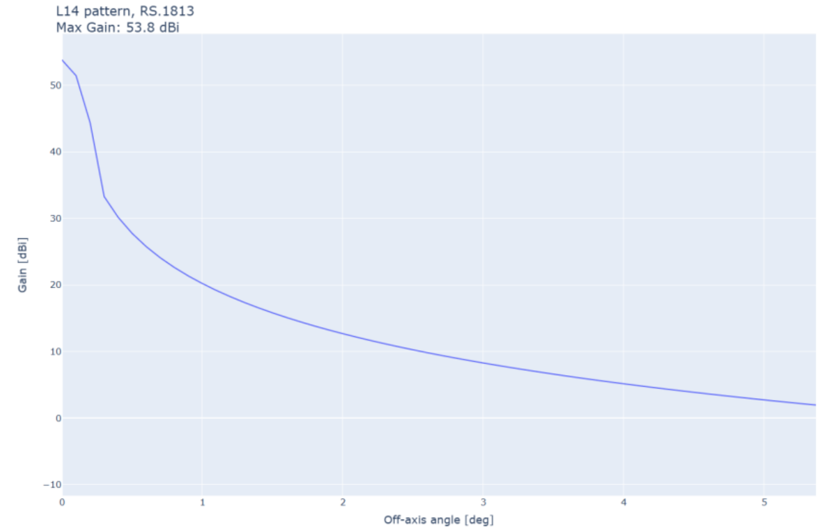

L10 pattern, RS.1813
Max Gain: 55.1 dBi
Gain [dBi]
Off-axis angle [deg]


L10 pattern, RS.1813
Max Gain: 55.1 dBi
Gain [dBi]
Off-axis angle [deg]

L8


L8 pattern, RS.1813
Max Gain: 62.4 dBi
Gain [dBi]
Off-axis angle [deg]


L8 pattern, RS.1813
Max Gain: 62.4 dBi
Gain [dBi]
Off-axis angle [deg]

L14		

L14 pattern, RS.1813
Max Gain: 53.8 dBi
Gain [dBi]
Off-axis angle [deg]