

# Protecting Passive Satellite Science Users using Equivalent Power Flux Density (EPFD)

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August 2021

## Abstract

Article 22 of the International Telecommunications Union (ITU)'s Radio Regulations, Equivalent Power Flux Density (EPFD) is defined to ensure protection from harmful interference from non-geostationary (NGSO) systems into geostationary (GSO) satellites or earth stations. EPFD depends on the power flux density amplified or attenuated by the antenna gains of the NGSO and victim GSO systems. This occurs when an NGSO satellite transmits towards their system's ES, and some of the NGSO's transmitted power and causes interference to the GSO ES. EPFD calculations are performed in three directions: down, up, and intersatellite. The paper focuses on the EPFDdown algorithm and its applications in interference regulations and radio astronomy services (RAS), which tend to be more susceptible to unwanted emissions from other systems. In order to protect RAS, a new set of EPFD limits was established. To ensure that RAS is protected, the ITU Radiocommunication Sector restricts harmful interference.

EPFDdown is defined as the EPFD from the NGSO satellite into the victim GSO earth station (ES), and accounts for the gain pattern of both NGSO satellite and the GSO victim ES in a particular orbital geometry and frequency band. In terms of RAS, RAS telescope sites on Earth are victim ES. To help prevent Article 22 limit exceedances, the ITU's Radiocommunication Sector (ITU-R) defined Recommendation S.1503 to provide guidance for satellite operators developing software to evaluate EPFD limits. This study focuses on implementing the EPFDdown algorithm in ITU-R S.1503 to analyze EPFDdown. With the EPFD validation process, NGSO systems can ensure that incumbent and planned GSO networks can operate without harmful interference, reducing data loss caused by interference from NGSO satellites. By going through each step of the EPFD validation process to validate Mangata's EPFDdown showing, this paper aims to make the complex EPFDdown algorithm more accessible to companies who are operating satellite systems.

## 1 Introduction

Equivalent power flux density (EPFD) is a metric to ensure protection from harmful interference from non-geostationary (NGSO) systems into geostationary (GSO) satellites or systems. The International Telecommunications Union (ITU) Radio Regulations (RR) defines the limits of NGSO systems. There are three different types of EPFD: down, up, and intersatellite. This paper will focus on the application of EPFDdown.

EPFDdown is the interference from the NGSO's satellite transmitter into the GSO Earth Station (ES). Radio Astronomy (RAS) systems are similar to a GSO ES as the RAS telescope sites are on Earth. As NGSO satellites transmit towards their NGSO ES, some of the transmitted power will hit the telescope sites and cause interference. EPFDdown validation limits are statistical in

nature; certain power levels can be exceeded up to a certain percentage of time. Most EPFDdown operational limits are absolute, never to be exceeded.

This paper will delve into the research team’s interpretation of the official ITU documentation of EPFD in hopes to make this material more accessible and easier to understand. This paper will also compare the research team’s EPFDdown validation results with a pre-existing software’s results – AGENIUM – which has its own interpretation of the official ITU documentation [6].

## 2 Methodology

### 2.1 High Level Overview of EPFDdown Algorithm

The EPFDdown algorithm takes in the Space Radiocommunications Service (SRS) Database, a power flux density (PFD) mask, and the Article 22 EPFDdown limits. The SRS database consists of the system parameters information of all current NGSO satellites in space. A PFD mask is a database of the calculated PFD values for the NGSO system, simplifying calculations for the EPFD validation as it contains the information needed to run the validation software.

The EPFDdown algorithm takes information from the PFD mask, including the NGSO system parameters and GSO system parameters, and finds the highest PFD value for a specific geometry: the location of the NGSO satellite in relation to the GSO satellite and GSO ES. This PFD value along with the gain value of the satellite is then used to calculate the EPFD. This EPFD value is counted over the time step, creating a statistic of how often the EPFD value occurs. This statistic is then plotted against the Article 22 limits, checking to see if the EPFD statistic is over the Article 22 limits.

RAS systems usually occur in the 10.7-11.7 GHz frequency range [7]. By ensuring the EPFDdown values do not exceed the Article 22 limits in this specific frequency range, RAS systems can be protected.

### 2.2 The EPFDdown Algorithm Methodology

The following steps are the research team’s interpretation of the ITU-R S.1503-2 [4] and ITU-R S.1503-3 [5] documentation to calculate the interference from a system of NGSO satellite transmitters into the GSO’s earth station. These steps were implemented in MATLAB to ensure that the research team’s interpretation of the documentation was acceptable. The research team aims to present their interpretation of the EPFDdown algorithm methodology in a more accessible way to help satellite operators with their understanding of the EPFDdown algorithm.

#### 2.2.1 Initializing Parameters

The first step is to input the NGSO System Parameters. Table 1 shows what NGSO parameters are needed and their locations in the Mask or SRS files.

Table 1: NGSO System Parameters

NGSO Parameter	File Location	Table Name in File	Parameter Name in File	Extra Info
Satellite pfd mask	Mask.mdb	Masks	F_mask (where $f_{\text{mask}} = P$ for PFD masks)	See part C in 1503-2 for more info
Transmit centre frequency: F_DOWN_sat (GHz)	SRS.mdb	mask_info	Freq_min, freq_max	$(\text{freq\_min} + \text{freq\_max}) / 2$ for the frequency in the middle
Exclusion zone parameter: Alpha or X	SRS.mdb	non-geo	f_x_zone	if $f_{\text{x\_zone}} = Y$ , then $x_{\text{zone}} = \text{Alpha}$ , else $x_{\text{zone}} = X$
Exclusion zone angle: MIN_EXCLUDE (deg)	SRS.mdb	non-geo	x_zone	see exclusion zone parameter for what the $x_{\text{zone}}$ value represents
Max number of satellites operating at $f_{\text{sat}}$ by latitude: $N_{\text{co}}[\text{lat}]$	SRS.mdb	sat_oper	nbr_op_sat	
Number of NGSO satellites: $N_{\text{sat}}$	SRS.mdb	orbit	Nbr_sat_pl	Sum all the $\text{nbr\_sat\_pl}$ in the column for all $N$ number of satellites
Orbit has repeating ground track maintained by station keeping: Yes or No	SRS.mdb	orbit	f_stn_keep	
Administration is supplying specific node precession rate: Yes or No	SRS.mdb	orbit	f_precess	
Station keeping range for ascending node as half total range: $W_{\text{delta}}$ (deg)	SRS.mdb	orbit	keep_rnge	
Phase angle: phase_ang (deg)	SRS.mdb	phase	phase_ang	
Minimum operating height: $H_{\text{MIN}}$ (km)	SRS.mdb	grp	elev_min	

The next step is to input the GSO System Parameters. GSO parameters pertain to the GSO conditions the system will look at. Table 2 lists the required GSO parameters and what their method of input into the algorithm is.

Table 2: GSO System Parameters

GSO Parameter	Method of Input
GSO ES gain pattern: GSO_ES_PATTERN	User
Frequency: F_DOWN (MHz)	User
GSO ES dish size: GSO_ES_D_ANT (m)	User
Reference bandwidth: REFBW (kHz)	User
Array of EPFDdown values: epfd_down (dB(W/(m <sup>2</sup> * BW_ref))	Corresponding Article 22 Limits
Array of EPFDdown percentages: perc_time_epfd_down (%)	Corresponding Article 22 Limits
GSO satellite longitude: GSO_LONG (deg)	Calculated
GSO ES latitude: GSO_ES_LAT (deg)	Calculated
GSO ES longitude: GSO_ES_LONG (deg)	Calculated

GSO parameters that are selected by the user via a guided user interface are intended to select which runs the user wants to validate. These include

- GSO ES gain pattern: GSO ES PATTERN
- Frequency: F DOWN (MHz)
- GSO ES dish size: GSO ES D ANT (m)
- Reference bandwidth: REFBW (kHz)

Select runs for ARISTARCHUS

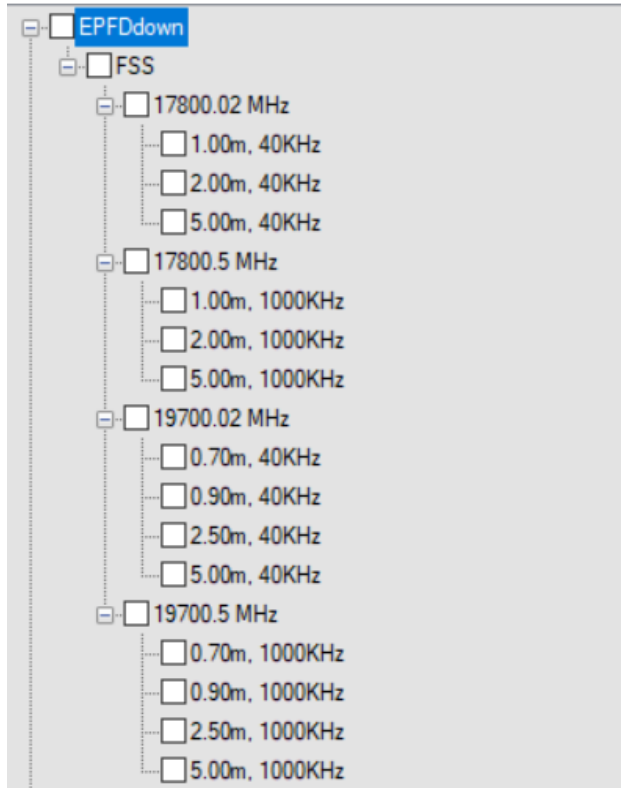


Figure 1: Example AGENIUM User Interface for the user to select validation runs

From the example shown in figure 1, the user can select the EPFDdown runs they want the algorithm to calculate based off of the parameters they choose. The GSO ES PATTERN will always be either fixed-satellite service (FSS) or broadcasting-satellite service (BSS). An example for F DOWN (MHz) is 17800.02 MHz. A GSO ES D ANT (m) example is 1.00m and a REFBW (kHz) example is 1000kHz.

Depending on which runs the user selects, the corresponding Article 22 limits will be used [1]. These include

- Array of EPFDdown values:  $epfd\ down\ (dB\frac{W}{m^2(BW_{ref})})$
- Array of EPFDdown percentages:  $perc\ time\ epfd\ down\ (\%)$

The user will select the frequency, radiation pattern, antenna diameter, and reference bandwidth for the runs they choose. These inputs will correspond to Article 22's “EPFD” and “Percentage of time during which EPFD may not exceed the limits” columns in the table which define the limits for the calculated EPFD Cumulative Density Function (CDF). For example, if the user were to pick a GSO ES PATTERN of ITU-R S.1428-1, which is FSS, an F DOWN of 10.7 GHz, a GSO ES D ANT of 60 cm, and a REFBW of 40 kHz, then according to Article 22 [1], the corresponding EPFDdown values and EPFDdown Percentages chosen would be the first row of the two corresponding columns in Table 22-1A.

There are also GSO parameters that are calculated to get the worst possible location of the GSO and ES for the systems.

- GSO satellite longitude: GSO LONG (deg)
- GSO ES latitude: GSO ES LAT (deg)
- GSO ES longitude: GSO ES LONG (deg)

The next step is to calculate the GSO longitude and ES latitude & longitude where the max EPFD occurs. This paper is working off the assumption that the user did not choose to run a “Full Worst Case Geometry (WCG) Check”. This means that the GSO longitude and ES latitude & longitude are provided by an external program.

Next, create a data structure to store EPFD values to be used to calculate the PDF (Probability Density Function) which will be used to calculate the CDF (Cumulative Density Function).

The number of time steps needed to complete a run ( $T_{run}$ ) and the step size ( $T_{fine}$ ) are calculated (which is defined in section D.4 in ITU-R S.1503-2 [4]). If the user selects “dual-time step”, then calculate  $N_{coarse}$  step size for  $T_{coarse} = T_{fine}N_{coarse}$ . If “dual-time step” is not selected,  $N_{coarse}$  is set to 1, and  $T_{coarse} = T_{fine}$ .

The amount  $t$  of the current time in the simulation is incremented by  $T_{step}$ . If the user selects “dual-time step”,  $T_{step}$  needs to be calculated for all time steps until the current time  $t$  equals the end of the simulation  $T_{run}$ . If the user selects “dual-time-step”, if it’s not the first time step, and if the  $G_{RX}(\phi)$  (any of the gain with respect to off-axis angle  $\phi$ ) for the previous time step are not within 30 dB of the max peak gain ( $G_{max}$ ) [5], then  $T_{step} = T_{coarse}$ . Otherwise,  $T_{step} = T_{fine}$ .

### 2.2.2 Simulating GSO, ES, and NGSO Satellites

Next is to simulate the position of the ES relative to the center of the Earth, the position of the GSO satellite, and the positions of the NGSO satellites at time  $t$ . Based off of the input parameters from the NGSO system parameters and GSO system parameters, the positions and orbit patterns of both the GSO and NGSO satellites as well as the ES can be calculated. This involves orbital mechanics principles which this paper will not delve into.

Then, identify which NGSO satellites are visible to the ES at the current time step. To check if an NGSO satellite is visible to the ES, the distance between the ES and the NGSO satellite is calculated. If that distance is less than the distance between the NGSO satellite and the radius of the Earth, then the NGSO satellite is visible.

For  $i$  NGSO satellites that are visible by the GSO ES, calculate and store the EPFDdown values for the current time step. To calculate the EPFDdown values for each NGSO satellite, the following steps are outlined:

From the “type” of PFD mask, calculate the input parameters needed to calculate PFD.

The PFD mask “type” of a PFD mask can be found in the Mask.mdb file located in the masks table under “f mask type”. The type of mask is either “alpha deltaLongitude” or “azimuth elevation”. Regardless of the type of PFD mask, the latitude of the NGSO must be calculated.

If the type of PFD mask is “azimuth elevation”, calculate the azimuth and elevation of NGSO  $i$ .

If the type of PFD mask is “alpha deltaLongitude”:

- Calculate the minimum  $\alpha$  (or  $X$  depending on variable NGSO system params.f x zone) angle in which there is a point P on the GSO arc that minimizes the angle between the NGSO and GSO relative to the ES.
- Calculate the delta longitude of the NGSO where delta longitude is equal to the longitude of the found minimum alpha angle minus the longitude of the NGSO.

### 2.2.3 Finding Minimum Alpha & the Corresponding Delta Longitude

To calculate the minimum  $\alpha$ , check if the ES is in the southern or northern hemisphere to determine the sign (+/-) of minimum alpha. This involves calculating the distance between the NGSO and ES:

$$R_{en} = NGSO - ES \quad (1)$$

Then getting the ratio of ES z-coordinate to the distance between the NGSO and ES in the z-axis

$$\lambda_z = -\frac{ES_z}{R_{enz}} \quad (2)$$

$$r_z = ES + \lambda_z R_{en} \quad (3)$$

This equation is used to find the Euclidean distance ( $R_z$ ) between the ES and distance between NGSO and ES.  $R_z$  will be used to determine the sign of  $\alpha$  based on the conditionals below.

If the ES is in the northern hemisphere:

If  $R_z < R_{geo}$ , sign of  $\alpha = +$

If  $R_z = R_{geo}$ , sign of  $\alpha = 0$

If  $R_z > R_{geo}$  or  $\lambda_z \leq 0$ , sign of  $\alpha = -$

If the ES is in the southern hemisphere:

If  $R_z > R_{geo}$ , sign of  $\alpha = -$

If  $R_z = R_{geo}$ , sign of  $\alpha = 0$

If  $R_z > R_{geo}$  or  $\lambda_z \geq 0$ , sign of  $\alpha = +$

To find the minimum  $\alpha$ , the following mathematical equations are implemented to approximate a range of  $\theta$  angles in which minimum  $\alpha$  can be found.  $\theta$  is a range of longitude angles on the GSO arc. The mathematical steps outlined below will walk through how it will use the NGSO and ES positions as well as the radius of the GSO to calculate a function to approximate the range of  $\theta$ . This approximation will be in the form of a quartic function.

$$A = -(NGSO_x - ES_x) * ES_x + ((NGSO_y - ES_y) * ES_y) + (NGSO_z - ES_z) * ES_z$$

$$B = (NGSO_x - ES_x) * R_{geo}$$

$$C = (NGSO_y - ES_y) * R_{geo}$$

$$E = R_{geo}^2 + R_e^2$$

$$F = -2 * (ES_x * R_{geo})$$

$$G = -2 * ES_y * R_{geo}$$

These variables can then be used for these intermediate variables.

$$a = A * G - 2 * C * E$$

$$b = B * F - C * G$$

$$c = 2 * C * F - B * G$$

$$d = A * F - 2 * B * E$$

$$e = -B * G - C * F$$

These intermediate variables will then be used as the coefficients in the approximation equation.

$$a_0 = c^2 - a^2$$

$$a_1 = 2 * c * d - 2 * a * b$$

$$a_2 = d^2 + 2 * c * e + a^2 - b^2$$

$$a_3 = 2 * d * e + 2 * a * b$$

$$a_4 = e^2 + b^2$$

From these variables, the following approximation equation can be set up

$$a_4 * x^4 + a_3 * x^3 + a_2 * x^2 + a_1 * x + a_0 = 0 \quad (4)$$

Where  $x$  can be solved, and

$$\theta = \text{asin } x \quad (5)$$

Arcsin returns angles from -90 to 90 degrees, but the values outside this domain from 90 to 270 degrees must also be considered. The solution must also be better than points on the GSO arc that are just barely visible to the ES. Different  $\alpha$  values can then be calculated by using all possible  $\theta$  values to calculate the possible GSO positions. By taking the angles between the NGSO and all possible GSO positions relative to the ES, the minimum angle can be found. This minimum angle is the minimum  $\alpha$  angle.

To get the corresponding delta longitude, find the corresponding  $\theta$  to the minimum  $\alpha$  and subtract the longitude of the NGSO satellite  $i$  from the  $\theta$ .



### 2.2.4 Calculating PFD and Gain to Calculate EPFD for NGSO Satellite $i$

From the input parameter “PFD mask”, calculate the PFD at the GSO ES. A function can be extrapolated from the PFD mask. This function is to be evaluated with the inputs from the calculated “alpha deltaLong” or “azimuth elevation” (depending on the type of PFD mask) to calculate the PFD. One such method to extrapolate a function is to use MATLAB’s Scattered Interpolant function with the “nearest” extrapolation method. This should return a single PFD value which will be used to calculate EPFD.

The off-axis angle  $\phi$  between the GSO and NGSO satellite  $i$  relative to the GSO ES should be calculated to identify the corresponding gain from the gain function. The receive gain  $G_{RX}(\phi)$  and the maximum gain  $G_{max}$  can be calculated depending on the gain pattern.

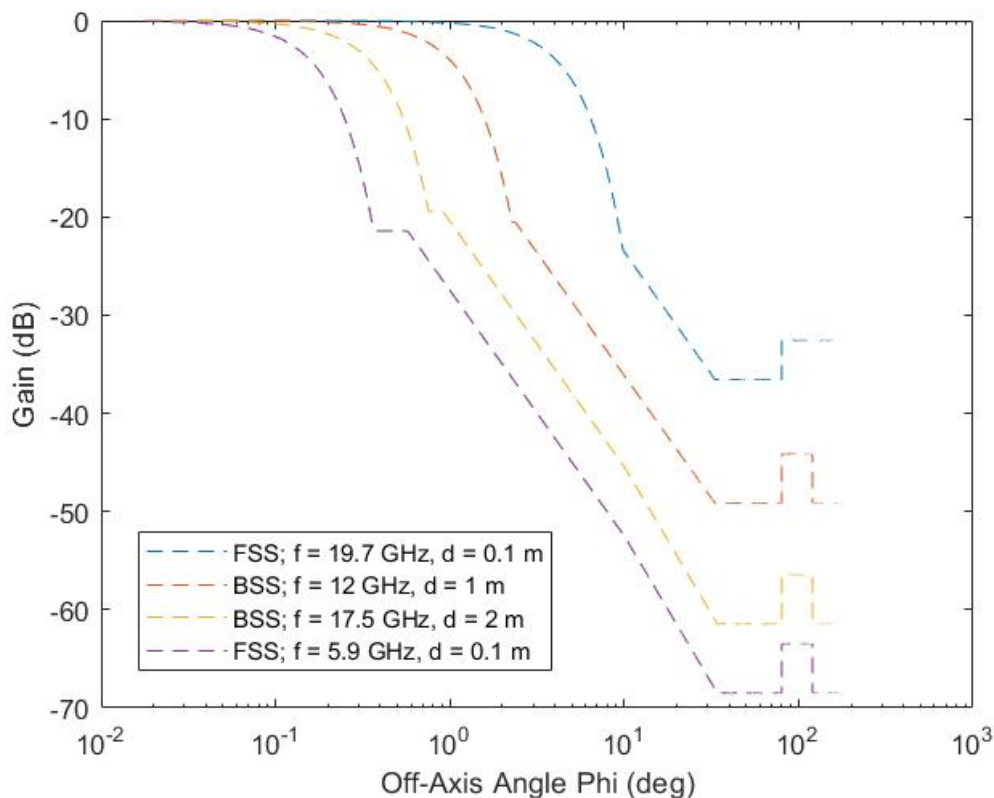


Figure 2: Example of Gain Patterns of varying frequencies, GSO ES Antenna Diameters, and if it is fixed-satellite service (FSS) or broadcasting-satellite service (BSS)

$G_{RX}(\phi)$  is a piece-wise function dependent on the gain/radiation pattern. If the ES’s gain pattern is fixed-satellite service (FSS), use the different case statements presented in Rec. ITU-R S. 1428 [3]. If the gain pattern is broadcasting-satellite service (BSS), use Rec. ITU-R BO.1443 [2]. Figure 2 shows that the gain pattern function chosen is also dependent on the frequency used and the diameter of the GSO ES Antenna. With a specific  $\phi$  value, the corresponding Gain value can be obtained from the chosen gain pattern function.

$G_{max}$ , which is the maximum gain, is defined in the ITU Recommendation documents and differs

between specific cases.  $G_{max}$  is also used to calculate EPFD.

The EPFD for the current NGSO satellite  $i$  can be calculated from the PFD, the Gain value from the calculated  $\phi$ , and  $G_{max}$

$$EPFD_i = PFD + G_{RX}(\phi) - G_{max} \quad (6)$$

The EPFD value for the  $i$ th NGSO satellite can be stored in one of two arrays depending on the following conditions:

- If the calculated absolute value of the minimum  $\alpha$  angle is outside the exclusion zone (NGSO system params.MIN EXCLUDE) and if the elevation angle of the NGSO relative to the center of the Earth is greater than the input parameter minimum elevation angle (NGSO system params.elev min), then store the  $EPFD_i$  value in the first array ( $EPFD_{i1}$ ).
- If the calculated absolute value of the minimum  $\alpha$  angle is inside the exclusion zone, store the  $EPFD_i$  value in the second array ( $EPFD_{i2}$ ).

### 2.2.5 Calculating the EPFDdown Value for Time Step $t$

Once all EPFD values are calculated for all visible NGSO satellites for that time step, sort the EPFD values of the first array. Then, calculate the total EPFD for that time step. First, sum  $n$  highest  $EPFD_{i1}$  contributions from the sorted first array where  $n$  is the number of satellites operating at the same frequency (NGSO system params. $N_{co}$ )

$$EPFD_1 = \sum_{i_1=0}^n 10^{\frac{EPFD_{i_1}}{10}} \quad (7)$$

Then, separately sum all  $EPFD_{i2}$  contributions from the second array

$$EPFD_2 = \sum_{i_2=0}^s 10^{\frac{EPFD_{i_2}}{10}} \quad (8)$$

where  $s$  is the length of the second array.

The total EPFD for that time step is the sum of the two EPFD arrays

$$EPFD = EPFD_1 + EPFD_2 \quad (9)$$

The EPFD calculated is not in decibels, so convert the EPFD value back to decibels using

$$EPFD = 10 \log(EPFD) \quad (10)$$

The statistics of the PDF are then updated by keeping track of the number of times the calculated EPFD value occurs. All EPFD values must be rounded down by the nearest 0.1 dB. For every new EPFD value, the EPFD value is added to the table with a count of "1". Each time the EPFD value calculated is the same as a previous one, the count for that EPFD value will increment by one.

This whole process is repeated until all time steps are finished (i.e. when  $t = T_{run}$ ).

When all time steps are finished, return:

- Overall “Pass” if the maximum EPFD value does not exceed the maximum Article 22 limit
- Individual Pass/Fail for each EPFD value
- The PDF
- The CDF (which is calculated from the PDF)

If the run receives an overall “Pass” and the individual EPFD values “Pass”, then the satellite services are protected.

### 3 Validation of Different Satellite Systems

Different satellite systems were run to ensure that these systems do not interfere with RAS systems. The Mangata and 3ECOM-1 satellite systems were validated by the EPFDdown algorithm mentioned in this paper and a pre-existing EPFDdown program: AGENIUM. AGENIUM uses an interpretation of the methodology outlined in ITU-R S.1503-2 to produce its results. It takes in the same inputs and the user follows the EPFD software guide to validate a system [6]. In comparison to AGENIUM, the Olin Satellite + Spectrum Technology Project (OSSTP) Group’s methodology is an interpretation of both the ITU-R S.1503-2 and ITU-R S.1503-3 documentation.

[Mangata](#) is a satellite enabled telecommunication services company. 3ECOM-1 is a data set of an anonymous satellite system. Both of these data sets contain an SRS.mdb and a Mask.mdb which is essential for running the EPFDdown algorithm. To ensure that the algorithm described in the paper is correct, the EPFDdown results were compared to AGENIUM’s EPFDdown results. Both of these satellite systems were already validated as “Pass” by the ITU, so the EPFDdown results from the paper’s algorithm and the pre-existing program’s algorithm must also return “Pass”.

### 4 System Validation Results

Figures 3 and 4 show the output of Mangata and 3ECOM-1’s EPFDdown values. The black line is from the OSSTP Group’s EPFDdown algorithm mentioned in the paper. The cyan line is constructed using the same inputs as the OSSTP algorithm, but running them through a pre-existing program’s (AGENIUM) EPFDdown algorithm. The red dashed line is the Article 22 limits.

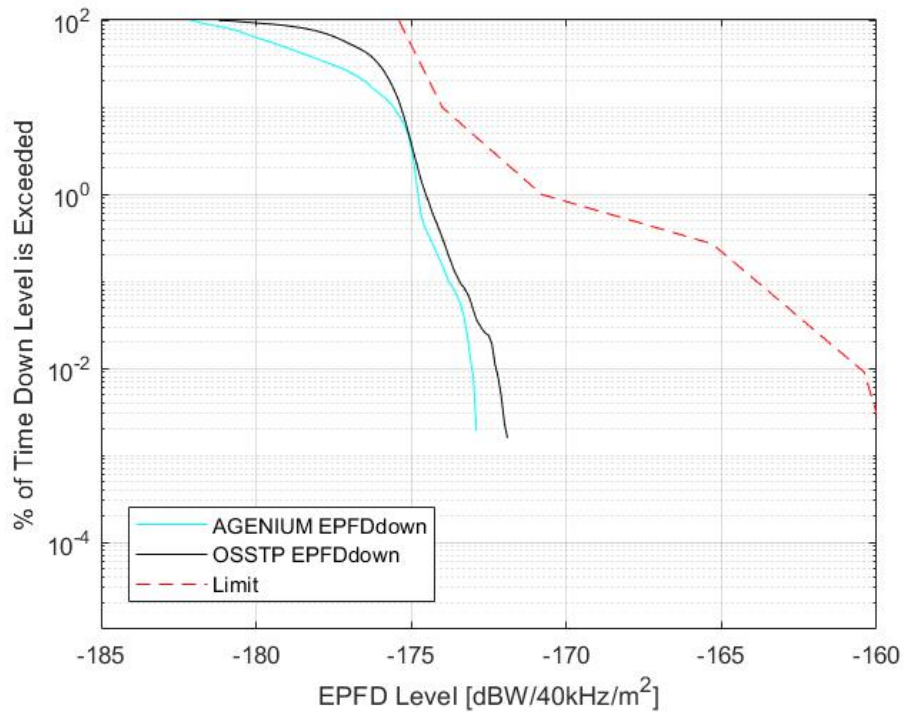


Figure 3: Mangata's EPFDdown validation plot showing both AGENIUM's and OSSTP's EPFDdown runs as well as the Article 22 limits

In Figure 3, both OSSTP's and AGENIUM's EPFDdown validation results pass the Article 22 limits, and the system is validated and does not interfere with other satellites and especially RAS systems. There is a slight difference of at most 20dB between the OSSTP and the AGENIUM percentage of time EPFD level was exceeded results. However, despite this difference, the OSSTP result follows the same trend as the AGENIUM one, and they both pass.

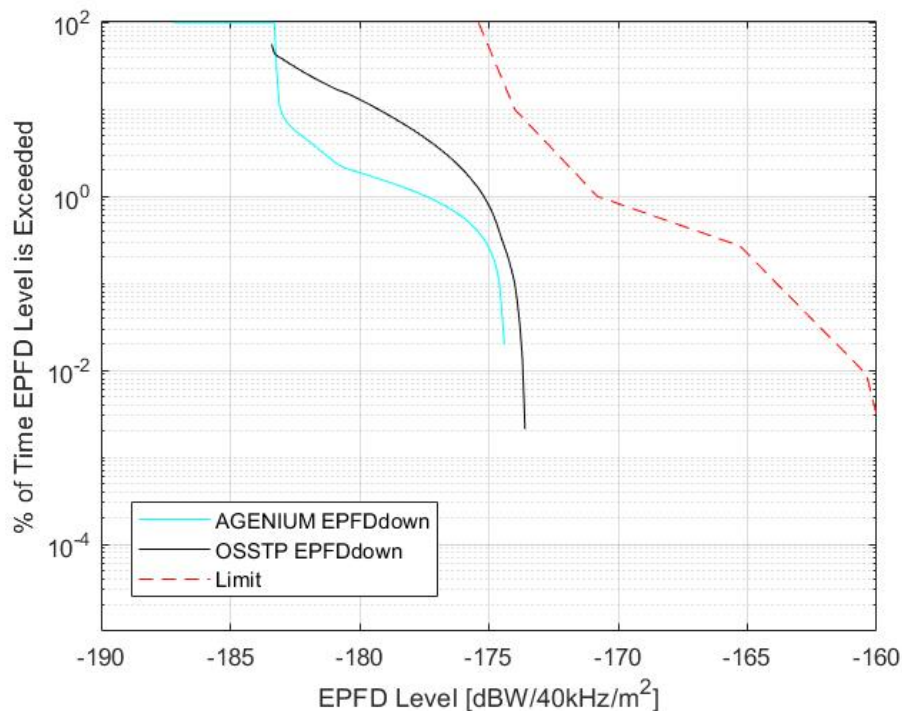


Figure 4: 3ECOM-1's EPFDdown validation plot showing both AGENIUM's and OSSTP's EPFDdown runs as well as the Article 22 limits

3ECOM-1's OSSTP and AGENIUM results both pass the Article 22 limits as shown in figure 4. In figure 4, however, the difference between the OSSTP and the AGENIUM results is more noticeable than figure 3's. However, the maximum difference in percentage level exceeded is approximately 25 dB for 3ECOM-1 compared to Mangata's maximum difference of approximately 20dB. This maximum difference is approximately the same between the two systems. However, this difference persists for EPFD levels of approximately -183 to -178 (dBW/40kHz/m<sup>2</sup>) in 3ECOM-1's results compared to Mangata's which persists for EPFD levels of approximately -180 to -176 (dBW/40kHz/m<sup>2</sup>).

Possible sources for this discrepancy could be how  $\alpha$  angle is calculated and chosen or how EPFD-down values are chosen and how they are summed. Currently, experts in this field are being consulted to identify causes in error.

Despite these discrepancies, the satellite systems are able to be validated by the OSSTP EPFDdown algorithm. Validating these systems ensures that they don't interfere with other systems.

## 5 Conclusion

With many already existing and new satellite systems being deployed into space, ensuring that these systems can transfer data safely and not harm those who passively receive data (RAS systems) will protect these systems. EPFD is important since it allows satellites to co-exist and transmit data without harming other systems. By quantifying interference and explaining the process in calculating EPFD, more information about protecting such services will be accessible to the public

and satellite operators which will promote the need for following the EPFD Article 22 limits.

## Acknowledgements

This work was completed with the guidance of Dr. Whitney Q. Lohmeyer who leads the Olin Satellite + Spectrum Technology & Policy (OSSTP) Group.

This work was funded by the Clare Boothe Luce Foundation through the Olin College of Engineering's Clare Boothe Luce Fellowship: an initiative to provide women-identifying researchers funding and support.

This work was also funded by the National Science Foundation (NSF) Center Grant (Federal Grant Number 2037732).

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