Amateur Radio RF Evaluation

Tri-County Amateur Radio Association
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Sources: FCC, ARRL

Regulatory Compliance

- **When you signed an FCC Form 610 or Form 605 to apply for your ham radio license, you attested that you would comply with FCC RF safety rules**
- **FCC November 27, 2019 Report and Order ET Docket No. 19-226 changed the rules regarding Human Exposure to Radiofrequency Electromagnetic Fields**
- **Nothing has changed or has it?**

Regulatory Compliance

- When you signed an FCC Form 610 or Form 605 to apply for your ham radio license, you attested that you would comply with FCC RF safety rules
- FCC November 27, 2019 Report and Order ET Docket No. 19-226 changed the rules regarding Human Exposure to Radiofrequency Electromagnetic Fields
- Nothing has changed or has it?
- RF emission exposure limits are unchanged from 1996
- Only implementation has changed

Regulatory Compliance

- **There are two options:**
  1. Exemption–Implementation clearly compliant with 47 C.F.R. § 1.1307(b)
  2. Evaluation–Considers unclear compliance for exemption and additional factors
- **New methods affect how licensees determine compliance and demonstrate that compliance**
- **Level of exposure is a function of power, frequency, distance, and duration for all modes**

Regulatory Compliance

- **Mobile, Portable, and Fixed RF Sources are handled the same within the regulations**
- **Mobile and handheld amateur radios are categorically exempt from routine evaluation**
- **Nevertheless, it would be reasonable to perform an evaluation to ensure the operator's safety and develop a mitigation plan. Such a plan could include reducing power, limiting transmit time, changing bands, or using a handheld microphone for an HT to increase distance between the antenna and the operator.**

Regulatory Compliance

- **Exemption–Have documentation why your station qualifies for an exemption**
- **Evaluation–Have documentation with calculations to show your station is compliant without mitigation or compliant with mitigation procedures implemented**
- **Mitigation could include power restrictions, moving the antenna, safety training, and signage for a restricted area**
- **Rules are harmonized across different FCC regulatory parts; 30, 101, 80, 90, 97, etc.**
- **Granfathered stations must comply in two years (May 23, 2023)**

Regulatory Compliance

- **Three broad classes of RF exemptions**
  1. **Extremely low-power devices no more than 1 mW**
  2. **Somewhat higher power devices with antennas within 40 cm of a body based on SAR**
  3. **Everything else based on formulas for Maximum Permissible Exposure (MPE) limits**
- **Gone is the PEP power threshold for each wavelength band (Table 1) for an exemption**

- **Example: If a transmitting antenna is near to the ground and closer to the public than the specified distance in the guidance, that station should be evaluated**

2019 FCC Change

Table 1. Power Thresholds for Routine Evaluation of Amateur Radio Stations

Wavelength Band	Evaluation Required if Power* (watts) Exceeds:
MF	
160 m	500
HF	
80 m	500
75 m	500
40 m	500
30 m	425
20 m	225
17 m	125
15 m	100
12 m	75
10 m	50
VHF (all bands)	50
UHF	
70 cm	70
33 cm	150
23 cm	200
13 cm	250
SHF (all bands)	250
EHF (all bands)	250
Repeater stations (all bands)	non-building-mounted antennas: height above ground level to lowest point of antenna < 10 m and power > 500 W ERP building-mounted antennas: power > 500 W ERP

* Transmitter power = PEP input to antenna. For repeater stations *only*, power exclusion based on ERP (effective radiated power).

- **This PEP threshold shortcut Table 1 is gone**

Regulatory Compliance - ARRL

- The ARRL argued to the FCC that routine evaluation exemption for amateur radio stations should be maintained for operations below a certain power threshold.
- The FCC disagreed because power alone does not consider distance from the antenna to people, frequency, and antenna gain
- Exemptions are a first step in determining RF compliance
- Licensees can choose between an exemption or compliance by an evaluation of RF exposure limits

RF Power Types

- **PEP: Peak Envelope Power**
  This is the set or maximum RF power measured between the upper and lower crests of a single cycle sine wave.
  It is also the output power reported in manufacturer's transceiver specifications.
- **ERP (Effective Radiated Power) is PEP referenced to a dipole antenna including all gains and losses.**
- **EIRP (Effective Isotropic Radiated Power) is PEP referenced to a theoretical isotropic radiator including all gains and losses.**

Regulatory Compliance - Exemptions - SAR

- **Amateur radio qualifies for an SAR-Based Exemption**
  SAR = Specific Absorption Rate
- **SAR is based on frequency, power, and distance from the RF source; and power per tissue mass**
- **Thresholds based on maximum time-averaged power or maximum time-averaged ERP (Effective Radiated Power), whichever is greater**
- **For antennas of length less than a half-wave dipole, maximum time-average power may be used instead of ERP if it is not known**
- **Evaluations must comply with FCC RF exposure limits in 47 C.F.R. § 1.1310**

Regulatory Compliance – SAR Limits

FCC LIMITS FOR SPECIFIC ABSORPTION RATE (SAR)

(A) Limits for Occupational/Controlled Exposure (W/kg)

Whole-Body	Partial-Body Hands	Wrists, Feet and Ankles
0.4	8.0	20.0

(B) Limits for General Population/Uncontrolled Exposure (W/kg)

Whole-Body	Partial-Body Hands	Wrists, Feet and Ankles
0.08	1.6	4.0

From FCC OET Bulletin 65 Supplement C Pg. 27
Refer to notes 1, 2, 3, 4 in document, 47 C.F.R. § 1.1310

Most restrictive limits 30 MHz – 300 MHz because RF can efficiently heat tissue in that range

Regulatory Compliance - Exemptions - MPE

- **Amateur radio also qualifies for an MPE-Based Exemption and Evaluation instead of SAR. MPE = Maximum Permitted Exposure**
- **MPE based on distance, frequency, and effective radiated power (ERP) or EIRP**
- **Thresholds based on distance, frequency, and ERP –**
- **And the new term: Power Density**
- **If maximum time-averaged ERP is ≤ calculated value from the formulas in Table 2, the source is exempt from further evaluation, providing separation distance is at least $\lambda/2\pi$ (λ/6.28). Calculate $\lambda/2\pi$ in meters = 47.7/f, where f is in MHz**

Regulatory Compliance - Exemptions - MPE

Table 2. Single RF Sources Subject to Routine Environmental Evaluation under MPE-Based Exemptions, $R \geq \lambda/2\pi$

Transmitter Frequency	Threshold ERP
0.3 – 1.34	1,920 R^2
1.34 – 30	3,450 R^2/f^2
30 – 300	3.83 R^2
300 – 1,500	0.0128 R^2f
1,500 – 100,000	19.2 R^2
Note: Transmitter Frequency is in MHz, Threshold ERP is in watts, R is in meters, f is in MHz.	

For example: Frequency 146 MHz, Distance 2.1 meters
47/146 = 0.322 meters
$3.83R^2$ = 16.9 watt threshold

ERP – Effective Radiated Power

- **Effective Radiated Power (ERP) is the product of the power supplied to the antenna and its gain relative to a half-wave dipole in a given direction.**

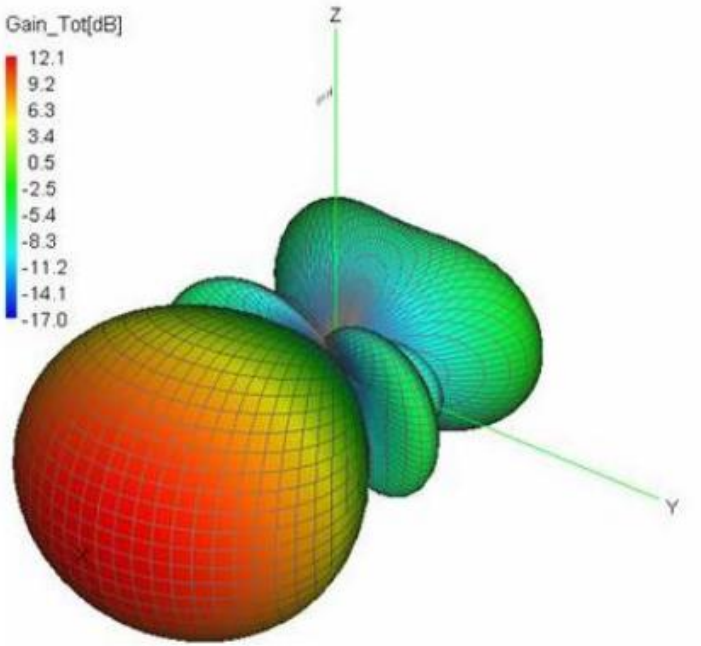
$$S = \frac{PG}{4\pi R^2} \qquad S = \frac{EIRP}{4\pi R^2} \qquad EIRP = S \times 4\pi R^2$$

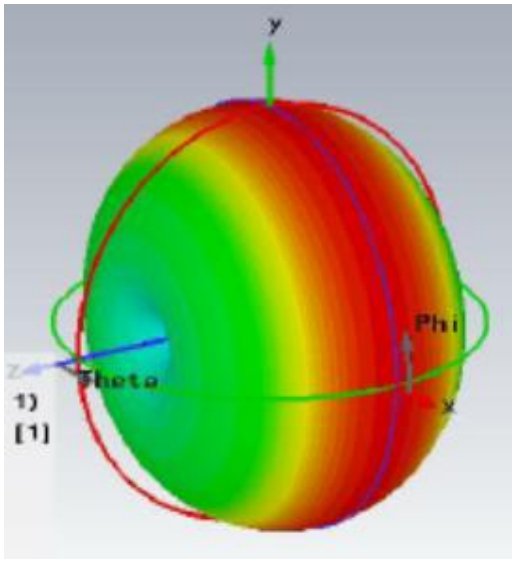
S = power density (in appropriate units, e.g. mW/cm2)
P = power input to the antenna (in appropriate units, e.g., mW)
G = power gain of the antenna in the direction of interest relative to an isotropic radiator
R = distance to the center of radiation of the antenna (appropriate units, e.g., cm)
Must convert to matching units, e.g. M to cm, W to mW
Note: $4\pi R^2$ is the surface area of a sphere

Antenna Specifications

- **Consistency in calculations is critical**
- **When calculating MPE, accurate antenna gain is necessary**
- **Use the gain and reference specified by the antenna manufacturer**
- **Diamond Antenna specifies dBi and dB**
  Per the manufacturer, dB references dBd

Antenna Type RF Pattern 3D

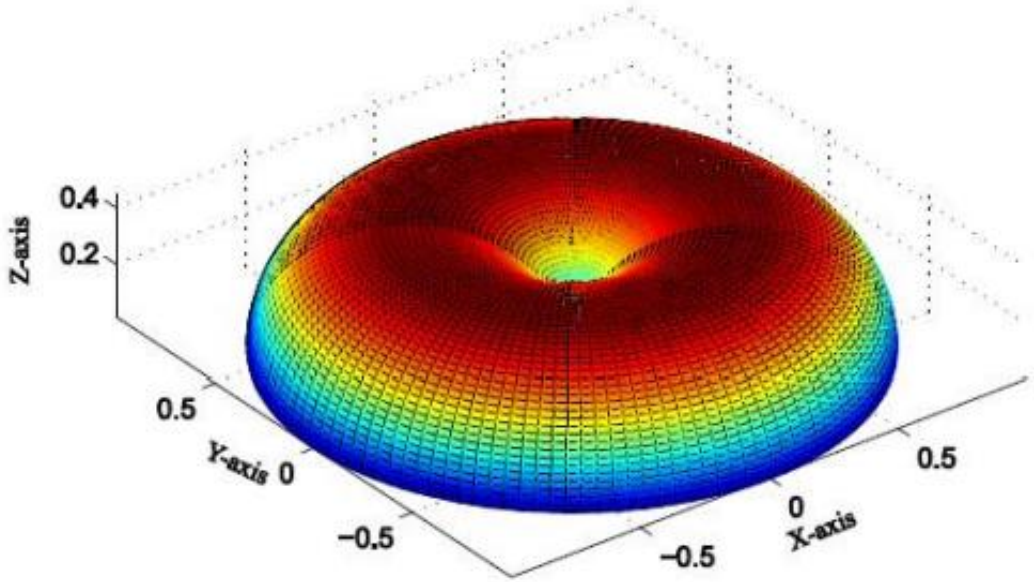




6 Element Yagi

Half-Wave Dipole

Antenna Type RF Pattern 3D



Quarter-Wave Monopole Vertical Above Ground

ERP – Effective Radiated Power

- Using $EIRP = S \times 4\pi R^2$ to calculate ERP gets you half way there. Now, you need one more calculation:

$$ERP = \frac{EIRP}{1.64}$$

- There must be an easier way. There is using decibels:
- Find the system gain by adding all gains and losses from feed line, antenna, duplexer, circulator in dB:
  System Gain = -4 dB + -2 dB + -1 dB + 6 dBd = -1 dB
  Only add what your system has
  Use maximum specified transmitter wattage (PEP) value as the reference power (P_1); let's use 100 W

ERP – Effective Radiated Power

$$dB = 10\log\left(\frac{P_2}{P_1}\right)$$

- **Rearrange to solve for P_2, plug in the numbers, and take the antilog ($\log^{-1}$) of the system gain**

$$anti\log\left(\frac{-1dB}{10}\right) = \frac{P_2}{100W}$$

P_2 = $\log^{-1}$ (-0.1) x 100 W = 0.79 x 100 W = 79 W

ERP = 79 W

ERP – Effective Radiated Power

- **Just to confuse things, dBi or dBd has to be converted to its numeric value for gain G as below**

$$G = 10^{\frac{dB}{10}}$$

- **Since ERP is referenced to a half-wave dipole instead of an isotropic radiator, it must be converted to EIRP by multiplying ERP by 1.64 to calculate S in equation**
- **Note that 2.15 dB is equivalent to 1.64 numeric**
- **Use dB/10 and then the 10^x key on your calculator**

Gain Conversion

Table 3

Gain (dBi)	Numeric Gain	Gain (dBi)	Numeric Gain
1	1.3	11	12.6
2	1.6	12	15.9
3	2.0	13	20.0
4	2.5	14	25.1
5	3.2	15	31.6
6	4.0	16	39.8
7	5.0	18	63.1
8	6.3	20	100.0
9	7.9	25	316.2
10	10.0	30	1000.0

$$G = 10^{\frac{dB}{10}}$$

G = Numeric Gain
dB = dBi

MPE-Based Exemptions - Single Source RF

Table 2. Single RF Sources Subject to Routine Environmental Evaluation under MPE-Based Exemptions, $R \geq \lambda/2\pi$

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Note: Transmitter Frequency is in MHz, Threshold ERP is in watts, R is in meters, f is in MHz.	

If ERP not easily obtained, then the maximum time-averaged power can be used instead of ERP if antenna length λ/4 or less or if the antenna gain is less than that of a half-wave dipole. If power is given in EIRP, convert to ERP for this table

MPE-Based Exemption

- **Suppose the system gain was +5 dB. This time the antilog of 0.5 = 3.16, which is multiplied by 100 W to get an ERP = 316 W**
- **If we were using 14 MHz and distance was 3 meters to the antenna, plugging the numbers into Table 2, we get 3450 x 3^2 / 14^2 = 158 W threshold, except Table 2 is usable if $R \geq \lambda / 2\pi$, which is 3.41 meters. 3 meters < 3.41 meters. Can't use Table 2 in this situation. Have to use Table 1 MPE limits.**
- **We have to convert ERP to EIRP for Table 1:**

  EIRP = 316 W x 1.64 = 518 W !

MPE LIMITS

Table 1—Limits for Maximum Permissible Exposure (MPE)

(A) Limits for Occupational/Controlled Exposure

Frequency Range (MHz)	Electric Field Strength (V/m)	Magnetic Field Strength (A/m)	Power Density (mW/cm^2)	Averaging Time (Minutes)
0.3-3.0	614	1.63	(100)*	≤6
3.0-30	1842/f	4.89/f	($900/f^2$)*	<6
30-300	61.4	0.163	1.0	<6
300-1500	--	--	f/300	<6
1500-100,000	--	--	5	<6

(B) Limits for General Population/Uncontrolled Exposure

Frequency Range (MHz)	Electric Field Strength (V/m)	Magnetic Field Strength (A/m)	Power Density (mW/cm^2)	Averaging Time (Minutes)
0.3-1.34	614	1.63	(100)*	<30
1.34-30	824/f	2.19/f	($180/f^2$)*	<30
30-300	27.5	0.073	0.2	<30
300-1500	--	--	f/1500	<30
1500-100,000	--	--	1.0	<30

f = frequency in MHz *Plane-wave equivalent power density

Calculation Time

$$S = \frac{P_{mw} \times G_n \times 1.64}{4\pi R^2}$$

EIRP (isotropic)

Where *n* = numeric
P is ERP in mW
R in cm

$$S = \frac{0.41 \times P_{mw} \times G_n}{\pi R^2}$$

ERP (dipole)

Where *n* = numeric
P is ERP in mW
R in cm

Multiply P by duty% x time-average of 6 or 30 min

Calculation Time – RF Reflections

- **RF reflections can double the power density and should be considered at or near a surface.**
- **The EPA recommended a more realistic 1.6 fold increase in field strength, which when squared equals a 2.56 increase in power density.**

$$S = \frac{0.64\,EIRP}{\pi R^2} \qquad S = \frac{1.05\,ERP}{\pi R^2}$$

- **Be conservative! Use the EPA guidance and multiply power density by 2.56 for reflections**

MPE-Based Exemptions
Single Source RF

- **BUT MY ANTENNA IS AN ELECTRICAL LENGTH HALF-WAVE DIPOLE**
- **Sorry, but your station is not exempt using MPE**
- **You must prepare an evaluation**
- **Refer to FCC OET Bulletin 65, Supplement B (1997), and Ed Hare, *RF Exposure and You*, ARRL 1998**

  Lots of tables to spare the heavy calculations
- **Lots of math and several online calculators to do it for you if you enter correct power and gain**

MPE LIMITS

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30–300	61.4	0.163	1.0	< 6
300–1500			f/300	< 6
1500–100,000			5	< 6
(B) Limits for General Population/Uncontrolled Exposure				
0.3–1.34	614	1.63	*(100)	< 30
1.34–30	824/f	2.19/f	$*(180/f^2)$	< 30
30–300	27.5	0.073	0.2	< 30
300–1500			f/1500	< 30
1500–100,000			1.0	< 30

f = frequency in MHz * = Plane-wave equivalent power density

What about Field Day

- **Field Day is MULTI-SOURCE RF**
- **Don’t panic. Well, maybe just a little.**
- **The MPE of RF generated by each antenna is ADDITIVE and dependent on MODE and simultaneous transmission then normalized to each threshold power–must be less than 100%**
- **Just sum the percentage compliance for each transmitter and band. Total must not exceed 100%**
- **Mode determines duty cycle of transmitter**
- **Duty cycle is used to calculate MPE**

Mode and Duty Cycle

- **FCC OET Bulletin 65 Supplement B**
- **Table 2 summarizes this with a modification to include digital modes like FT8, PSK-31, etc.**
- **Note that FT8 is a 100% duty cycle and can easily overheat a transmitter running at full power**
- **Use reduced power in digital modes**
- **For those of us with 100 W transmitters, just assume a 100% duty cycle for worst case for compliance**
- **Duty cycle is important when using a linear amp to maintain compliance and safety**

Mode and Duty Cycle

Table 2
Operating Duty Factors by Mode (modified)

Mode	*Duty Factor*	*Notes*
Conversational SSB	20%	Note 1
Conversational SSB	40%	Note 2
Voice FM	100%	
FSK/RTTY, Digital (FT8, PSK-31, etc.)	100%	
AFSK	100%	
Conversational CW	40%	
Carrier / AM	100%	Note 3

Note 1: Includes voice characteristics and syllabic duty factor. No speech processing.
Note 2: Moderate speech processing employed. Duty Factor 50% if heavy speech processor.
Note 3: A full carrier is commonly used for tune-up purposes.

- **Next slide shows duty factor and time-averaging calculation**

Average Power – Average Exposure

- Average power is calculated by multiplying PEP (Peak Envelope Power of an RF cycle) by the duty factor for the mode. Then multiply that value by the percentage of time the transmitter is in use during the averaging period, e.g., 2 min / 6 min = 0.33
- Averaging period: 6 minutes; controlled or 30 minutes; uncontrolled
- Most amateurs will use the tables in Supplement B or an online calculator to estimate their station's compliance with MPE
- Table 3 in Supplement B lists typical antenna gain for consideration in evaluating a station

Antenna Gain dBi and dBd

Table 3
Typical Antenna Gains in Free Space

Antenna	*Gain*	
	dBi	*dBd*
Quarter-wave ground plane or vertical	1.0	-1.1
Half-wavelength dipole	2.15	0.0
2-element Yagi array	6.0	3.9
3-element Yagi array	7.2	5.1
5-element Yagi array	9.4	7.3
8-element Yagi array	13.2	11.1
10-element Yagi array	14.8	12.7
17-element Yagi array	16.8	14.7

Note the 2.15 dB difference between dBi and dBd

- **Antenna gain explains why there is a limitation on antenna type for exemptions or evaluations**

Meeting Power-Density Limits Reflections

Table 4 (Excerpt)
Estimated distances from transmitting antennas necessary to meet FCC power-density limits for MPE for occupational/ controlled (Con) exposures and uncontrolled exposures (Unc) assuming a 100% duty cycle and typical surface reflection. Worst case scenario.

Distance from antenna (feet)					
Frequency (MHz)	Gain (dBi)	100 W		500 W	
		Con	Unc	Con	Unc
4	0 3	0.6 0.9	1.4 2.0	1.4 2.0	3.1 4.4
7.3	0 3 6	1.1 1.6 2.3	2.5 3.6 5.1	2.5 3.6 5.1	5.7 8.0 11.4
14.35	0 3 6 9	2.2 3.2 4.5 6.3	5.0 7.1 10.0 14.1	5.0 7.1 10.0 14.1	11.2 15.8 22.3 31.6

This ARRL Table 4 is converted to FEET. FCC Table 4a is in METERS. There is no FCC Table 4. Don't confuse the two. https://www.arrl.org/files/file/Technology/tis/info/pdf/Table4567.pdf

Compliance Using Tables

TABLE 6. Omnidirectional HF quarter-wave vertical or ground plane antenna (estimated gain 1 dBi) assumes surface (ground) reflection

Distance (meters) from any part of the antenna for compliance with either occupational/controlled or general population/uncontrolled exposure limits										
	3.5 MHz		**7 MHz**		**14 MHz**		**21 MHz**		**28 MHz**	
Transmitter power (watts)	con.	unc.	con.	unc.	con.	unc.	con.	unc.	con.	unc.
100	0.2	0.4	0.4	0.8	0.8	1.7	1.1	2.5	1.5	3.3
500	0.4	0.9	0.8	1.9	1.7	3.7	2.5	5.6	3.3	7.5
1000	0.6	1.3	1.2	2.7	2.4	5.3	3.5	7.9	4.7	10.6
1500	0.7	1.6	1.4	3.2	2.9	6.5	4.3	9.7	5.8	12.9

- **Rather than doing calculations, you can find your antenna type in published tables and find the safe distance for controlled and uncontrolled limits**

Compliance Using Tables

TABLE 16. Quarter-wave half-sloper antenna (estimated average gain 6.7 dBi); main beam exposure, assumes surface (ground) reflection

Distance (meters) from any part of the antenna for compliance with either occupational/controlled or general population/uncontrolled exposure limits								
	7 MHz		**14 MHz**		**21 MHz**		**28 MHz**	
Transmitter power (watts)	con.	unc.	con.	unc.	con.	unc.	con.	unc.
100	0.7	1.6	1.4	3.2	2.2	4.8	2.9	6.4
500	1.6	3.6	3.2	7.2	4.9	10.7	6.4	14.3
1000	2.3	5	4.5	10.2	6.9	15.2	9.1	20.2
1500	2.8	6.2	5.6	12.5	8.4	18.6	11.1	24.8

- **Interpolation can be used for power levels between two adjacent rows in a table, e.g., 125 Watts**

Compliance Using Tables

TABLE 10. Seventeen (17) element Yagi on five-wavelength boom designed for weak-signal communications on 144 MHz (estimated gain 16.8 dBi); main beam exposure assuming surface (ground) reflection

Transmitter power (watts)	Distance (m) to comply with occupational/ controlled exposure limit	Distance (m) to comply with gen. population/ uncontrolled exposure limit
10	3.1	7
100	9.9	22.1
500	22.1	49
1500	38.2	85.5

- **Notice that tables include the estimated antenna gain. It is helpful to know the specs or model of any antenna purchased without documentation at a swap meet.**

Online Calculator – hintlink.com

Calculate Radio Frequency Exposure

The average power at the antenna:
In watts — 100

The antenna gain in dBi:
Enter 2.2 for dipoles; add 2.2 for antennas rated in dBd — 3

The distance to the area of interest:
From the centre of the antenna, in metres — 7

The frequency of operation:
In MHz — 7.2

Ground Reflection Effects

In most cases, the ground reflection factor is needed to provide a truly worst-case estimate of the compliance distance in the main beam of the antenna. Including the ground reflection effects may yield more accurate results especially with very low antennas, non-directional antennas, and calculations below the main lobe of directional antennas.

Do you wish to include effects of ground reflections? (•) Yes ( ) No

[Calculate RF Power Density] [Reset Values]

Online Calculator – hintlink.com

Calculation Results

Performed on: _____ By: _____

Average Power at the Antenna	100 watts
Antenna Gain in dBi	3 dBi
Distance to the Area of Interest	7 metres 22.97 feet
Frequency of Operation	7.2 MHz
Are Ground Reflections Calculated?	Yes
Estimated RF Power Density	0.083 mW/cm^2

	Controlled Environment	**Uncontrolled Environment**
Maximum Permissible Exposure (MPE)	17.37 mW/cm^2	3.48 mW/cm^2
Distance to Compliance From Centre of Antenna	0.5 metres 1.64 feet	1.1 metres 3.6 feet
Does the Area of Interest Appear to be in Compliance?	Yes	Yes

References

FCC Docket 19-126 Resolution of Notice of Inquiry, Second Report and Order, Notice of Proposed Rulemaking, and Memorandum Opinion and Order; Adopted November 27, 2019

FCC OET Bulletin 65: Evaluating Compliance with FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields; August 1987

FCC OET Bulletin 65 Supplement B Amateur Radio: Evaluating Compliance with FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields; January 1987

FCC OET Bulletin 65 Supplement C: Additional Information for Evaluating Compliance of Mobile and Portable Devices with FCC Limits for Human Exposure to Radiofrequency Emissions; January 2001

References

FCC OET Bulletin 56 Fourth Edition: Questions and Answers about Biological Effects and Potential Hazards of Radiofrequency Electromagnetic Fields; August 1999

FCC Docket 13-39 First Report and Order Further Notice of Proposed Rule Making and Notice of Inquiry; Adopted March 27, 2013

RF Exposure and You, Ed Hare, W1RFI; ARRL, 1998-2003, ISBN: 0-87259-662-1, 316 pp.

Personal Communication with Kevin Graff FCC OET July 27, 2021

Online Calculators

http://hintlink.com/power_density.htm

http://www.lakewashingtonhamclub.org/resources/rf-exposure-calculator/