Nomograms to Determine Safe Distances For Human Exposure to EM Fields from Antennas

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INTRODUCTION

A previous article[1] emphasized that the distances determined from two described nomograms are based on the far-field, plane-wave power density equation, and that distances obtained which are less than approximately 1/6 wavelength (for linear-type antennas) may not necessarily assure a safe distance. The purpose of this article is to show how other nomograms can be developed to introduce near-field considerations to determine safe distances within the near-field of certain antennas.

Nomograms can be developed to introduce near-field considerations in the determination of safe distances within the near-field of certain antennas.

DISCUSSION

Figure 1 has been extracted from Reference 2 (in which it was identified as Figure B-5). It shows a comparison of the peak electric field strength in dB V/m between the values determined from the Numerical Electromagnetic Code (NEC) model and the POWDEN model as a function of distance from the antenna. The antenna, in this case, is a stub antenna whose length at the selected frequency of 100 megahertz is 0.05λ. The light dotted lines have been added to indicate the relative slopes of the NEC model curve for the two principal segments of that curve. The slope of dotted line (1) is about 16 dB/decade and represents the basic slope of the NEC model curve at distances greater than about 0.6 meter from the antenna. The slope of dotted line (2) is about 50 dB/decade and represents the basic slope of the NEC model curve at distances less than about 0.6 meter from the antenna. For the POWDEN model curve, the slope is that of the basic far-field equation -- 20 dB/decade. It should be noted that the NEC model makes use of the geometry of the antenna in determining the magnitude of the field strengths that exist from the radiating element(s).

Those portions of the dotted lines (1) and (2) that pertain to the two significant segments of the NEC model curve have been re-drawn as the solid lines on Figure 2. For this figure, the distance in meters has been changed to reflect a relative distance in wavelengths shown at the bottom of the figure and a relative correction factor, $D_{FF}f_{MHz}$, shown at the top of the figure. This correction factor consists of the product of a far-

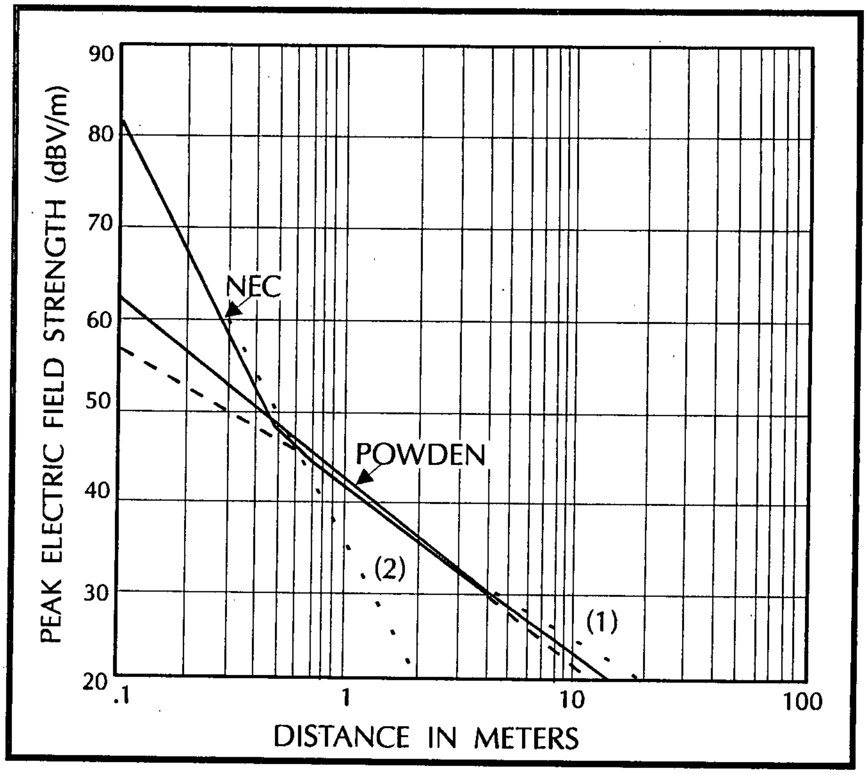

FIGURE 1. Electric Field Strength for Stub Antenna at 100 MHz, NEC vs POWDEN Models.[2] (Originally identified as Figure B-5 in Reference 2.)

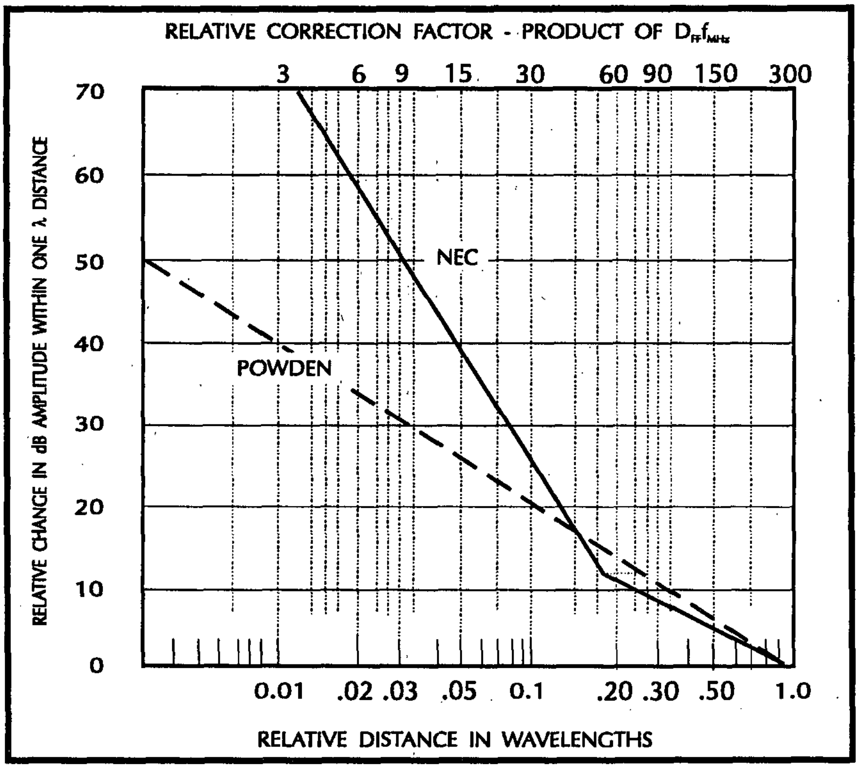

FIGURE 2. *Comparison of Relative Amplitude of Stub Antenna at 100 MHz - NEC vs POWDEN Models.*

field distance and a frequency in megahertz, and, as such, has the dimension of velocity, since frequency is considered a reciprocal of time. The far-field distance, D_{FF}, is that safe distance determined from one of the two far-field nomograms and, of course, f_{MHz} is the frequency of concern. The ordinate has been re-named to show the relative values in dB of the amplitude between the NEC and POWDEN model curves within a one (1) wavelength distance.

As evident, the amplitude of the NEC curve is less than that of the POWDEN curve for relative distances greater than that of about 0.16 wavelength. This is approximately the 1/6 wavelength, or, more precisely $\lambda/2\pi$ wavelength, mentioned earlier and in reference [1]. Since the amplitude of the NEC curve is less than that of the POWDEN curve for relative distances greater than about 0.16 wavelength, the distance in this range of the near field of this stub antenna can be decreased and still be within a safe distance based on the standard specified. For distances less than this wavelength, the amplitude of the NEC curve is greater than that of the POWDEN curve for the same distance. To correct for a given exposure limit criterion, the distance must be increased to adjust for that greater amplitude. Two nomograms, Figures 3 and 4, have been developed to determine that adjusted distance -- the near-field distance within one (1) wavelength of the antenna at which the exposure limit criterion is equalled and/or approximated. That adjusted distance in the near field can be greater, equal to, or less than the far field distance, D_{FF}.

The appendix to this paper details the mathematics used to develop the two nomograms which are based on the *modified* NEC curve of Figure 2, reflecting the slopes of those two segments of the NEC curve labeled (1) and (2), respectively, on Figure 1. In using these nomograms, the adjusted distance for the near-field is termed D_{NF}. Its value is determined from either of the two nomograms by using the outer two scales and noting where a connecting line intersects the D_{NF} scale for particular values of D_{FF} and $D_{FF}f_{MHz}$. Included on the nomograms are two other scales showing the maximum and minimum values of the range of D_{FF} vs frequency for which a near-field correction is applicable. This range is related to the relative correction factor, $D_{FF}f_{MHz}$. For the less steep slope of the NEC curve, the applicable range of $D_{FF}f_{MHz}$ is 82 to 300 (0.273λ to 1.0λ). This range corresponds to that portion of the POWDEN curve extending from one (1) wavelength down to slightly less than 0.2 (0.198) wavelength on the NEC curve where the slope undergoes the abrupt change. For the steeper slope of the NEC curve, the applicable range of $D_{FF}f_{MHz}$ is 0.96 to 82. This range corresponds to that portion of the POWDEN curve extending from 0.198 wavelength down to 0.0333 wavelength. The latter wavelength corresponds to the 0.1 meter distance shown on Figure 1, which is the least distance on the figure showing the amplitudes of the peak electric field strength resulting from the two models, NEC and POWDEN.

PROCEDURE FOR USING NOMOGRAMS

The following parameters are used to illustrate the use of the nomogram given in Figure 3.

Far-field Distance (D_{FF}): 30 meters
Frequency (f_{MHz}): 4 MHz
$D_{FF}f_{MHz}$: 120

(1) Check for applicability: For a far-field distance of 30 meters and an operating frequency of four (4) megahertz, the maximum and minimum range in meters of D_{FF} are about 76 meters and 20.5 meters, respectively. Since the 30-meter dis-

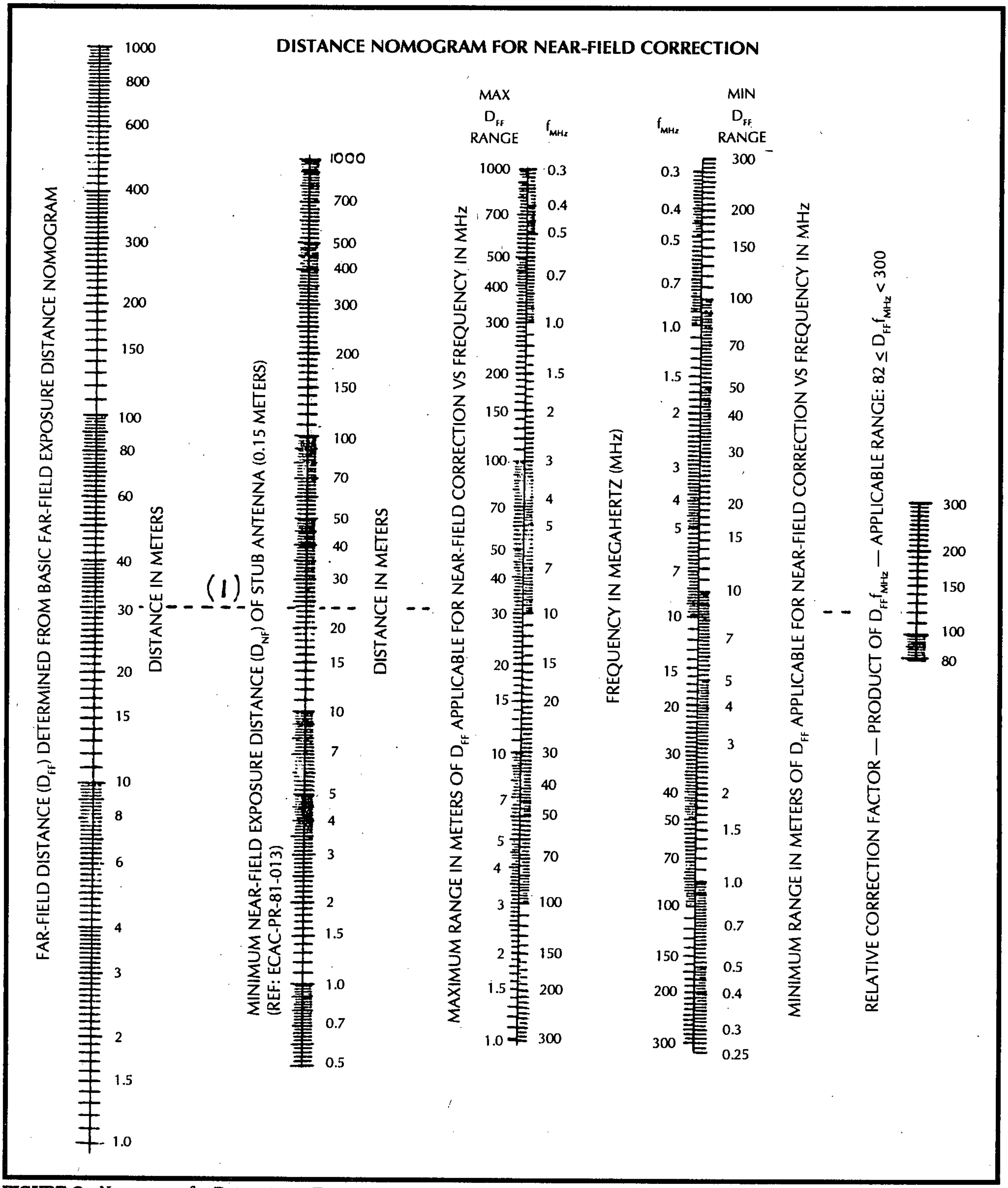

FIGURE 3. *Nomogram for Determining Exposure Distance in Near-field (0.198λ - 1.0λ) of Stub Antenna. NEC Model Curve in ECAC-PR-81-013, "RADHAZ Near-field Analysis of Linear Antennas," May 1981.*

tance for D_{FF} falls within that range for four (4) megahertz, the nomogram is applicable for near-field correction use. Accordingly,

(2) place a straightedge [line (1)] between 120 on the relative correction factor scale -- product of D_{FF} and f_{MHz} -- and 30 meters on the far-field distance (D_{FF}) scale.

(3) The near-field distance, D_{NF}, (in meters) is determined where that line (1) crosses the near-field distance scale. For this example, a near-field distance, D_{NF}, of approximately 23.7 meters is determined. For this example, applying a near-field correction resulted in a distance less than that of the far-field distance. This comes about since, for the same amplitude on the ordinate scale, and for

Continued on page 276

NOMOGRAMS...*Continued from page 276*

(1) Check for applicability: For a far-field distance of 30 meters and an operating frequency of 0.7 megahertz, the maximum and minimum range in meters of D_{FF} are about 116 meters and 1.36 meters, respectively. Since the 30-meter distance for D_{FF} falls within that range for 0.7 megahertz, the nomogram is applicable for near-field correction use. Accordingly,

The technique presented in this article can be applied to other standards and/ or criteria that have been established or are being considered.

(2) place a straightedge [line (2)] between 21 on the relative correction factor scale -- product of $D_{FF}f_{MHz}$ -- and 30 meters on the far-field distance (D_{FF}) scale.

(3) The near-field distance, D_{NF}, in meters, is determined where that line (2) crosses the near-field distance scale. For this example, a near-field distance, D_{NF}, of approximately 49 meters is determined. For this example, applying a near-field correction resulted in a distance greater than that of the far-field distance. This comes about since, for the same amplitude on the ordinate scale, and for distances on the abscissa less than $\lambda/2\pi$ wavelength, the NEC model curve lies above the POWDEN curve.

SUMMARY

The examples given in this paper use two nomograms developed from the two principal segments of the numerical electromagnetic code (NEC) model curve shown on Figure 1 (B-5 of Reference [2]). In this case, the curve shows the amplitude of the peak electric field strength in dB V/m vs distance of a stub antenna of 0.15-meter length at a frequency of 100 megahertz. This amplitude is compared to that from the basic far-field, plane-wave power density equation and a relationship is developed whereby the far-field distance can be used with the frequency of concern to determine the distance when near-field considerations should be applied. As other such curves become available, a family of nomograms can be developed to cover a wide range of antenna types for which near-field distances can be determined.

Although the examples used in this paper make use of the ANSI C95.1-1982 standard for determining safe distances for human exposure to certain near-field considerations of radio frequency electromagnetic fields, the technique presented can be applied to other standards and/or criteria that have been established or are being considered. For example, particular electronic equipment must withstand certain electric field strengths (a susceptibility requirement). If those field strengths, or equivalent plane-wave power density levels, are determined to occur within the near-field of particular antennas, a similar procedure can be followed: Determine the distance for the applicable criterion, standard, or requirement using the familiar Friis free space, far-field equation. Then determine the product of that far-field distance, D_{FF}, and the frequency(ies) of use, $D_{FF}f_{MHz}$, and apply the appropriate equation and/or nomogram that has been developed or could be developed for the particular conditions that apply.

The author is currently developing a similar technique to apply to the near-field correction curves of circular aperture type antennas for taper illuminations of ρ=0 (uniform illumination), ρ=1, 2, 3, and 4 as currently represented in the existing literature.

REFERENCES

1. Watkins, Cleveland F., "Determination of Safe Distances for Human Exposure to Radio Frequency Electromagnetic Fields Based on ANSI C95.1-1982 Standard -- A Graphical Method," 1984 IEEE National Electromagnetic Compatibility Symposium Record, San Antonio, TX, April 1984.

2. Katz, Howard B., "RADHAZ Near-Field Analysis of Linear Antennas," ECAC-PR-81-013, Electromagnetic Compatibility Analysis Center, Annapolis, MD 21402, May 1981.

APPENDIX

MATHEMATICAL DEVELOPMENT OF NEAR-FIELD EXAMPLE

Figure 1 (originally identified as Figure B-5 in Reference 2) compares the amplitude of the peak electric field strength between the NEC and POWDEN models. The slopes of the significant segments of the NEC model curve are:

Light dotted line (1): 16 dB per decade
Light dotted line (2): 50 dB per decade
Slope of the POWDEN model curve:
20 dB per decade

Consider that light dotted line (1) segment of the NEC model curve, where the field strength has the less steep slope than that of the POWDEN curve -- essentially for distances greater than about 0.6 meter from the antenna. The equivalent plane wave power density (P_D) in the near-field can be expressed in terms of the power density determined by the far-field equation and the relative slopes of the NEC curves and POWDEN curve from their respective points of intersection. For NEC curve (1), that intersection is chosen to be one (1) wavelength, as indicated in Figure 2. Accordingly, and using log notation:

$$10 \log P_{D(NF)} = 10 \log P_{D(FF)} + 4 \log (R/1.0\lambda) \quad (1)$$

where R is the distance to be determined.

But

$$P_{D(FF)} = \text{EIRP}/4\pi R^2 \quad (2)$$

where EIRP is the equivalent isotropically radiated power.

Thus:

$$10 \log P_{D(NF)} = 10 \log \text{EIRP} - 10 \log 4\pi - 20 \log R + 4 \log R - 4 \log (1.0\lambda) \quad (3)$$

Rearranging terms, and considering that the power density of concern is that of the exposure limit criterion, which is generally the same whether in the near field or far field, the subscript (NF) can be deleted for simplicity. Accordingly:

$$16 \log R = 10 \log \text{EIRP} - 10 \log 4\pi - 10 \log P_D - 4 \log (1.0\lambda) \quad (4)$$

but

$$10 \log \text{EIRP} - 10 \log 4\pi - 10 \log P_D = 20 \log D_{FF} \quad (5)$$

where D_{FF} is the distance determined using the far-field equation or one of the nomograms discussed in reference [1].

Making this substitution, Equation 4 becomes:

$$16 \log R = 20 \log D_{FF} - 4 \log (1.0\lambda) \quad (6)$$

This value of R is that distance along the "NEC-1" curve in the normalized range between 0.198λ and 1.0λ. And, since it is assumed that it exists in the near field, it is called D_{NF}. Further, making the substitution, $\lambda = 300/f_{MHz}$, Equation 6 becomes:

$$16 \log D_{NF} = 20 \log D_{FF} + 4 \log f_{MHz} - 4 \log (300) \quad (7)$$

Dividing Equation 7 through by 1.6, the following is obtained:

$$10 \log D_{NF} = 12.5 \log D_{FF} + 2.5 \log f_{MHz} - 2.5 \log (300) \quad (8)$$

But $12.5 \log D_{FF}$ can be written $10 \log D_{FF} + 2.5 \log D_{FF}$. Making this substitution and combining the $2.5 \log D_{FF}$ with the $2.5 \log f_{MHz}$, Equation 8 becomes:

$$10 \log D_{NF} = 10 \log D_{FF} + 2.5 \log D_{FF} f_{MHz} - 2.5 \log (300) \quad (9)$$

or

$$10 \log D_{NF} = 10 \log D_{FF} + 2.5 \log D_{FF} f_{MHz} - 6.1928 \text{ dB meters} \quad (10)$$

Equation 10 is the basis on which Figure 3 was developed. For Equation 10, the relative correction factor ($D_{FF} f_{MHz}$) lies in the range 82 to 300 for the bounds specified.

Taking the antilog, Equation 10 can be expressed in conventional form as follows:

$$D_{NF} = 0.2403 (D_{FF})^{1.25} (f_{MHz})^{0.25} \text{ meters} \quad (11)$$

The distance, D_{NF}, can be determined also from the initial parameters used to determine the far-field distance, D_{FF}. Equation 4 is shown below.

$$16 \log R = 10 \log \text{EIRP} - 10 \log 4\pi - 10 \log P_D - 4 \log (1.0\lambda) \quad (4)$$

Dividing through by 16 and taking antilog, Equation 12 results. Remember, in this case, R is a distance in the near-field region between 0.198λ and 1.0λ. Accordingly:

$$R \text{ or } D_{NF} = (\text{EIRP}/4\pi P_D)^{0.625} (f_{MHz}/300)^{0.25} \text{ meters} \quad (12)$$

or

$$D_{NF} = 0.0494 (\text{EIRP}/P_D)^{0.625} (f_{MHz})^{0.25} \text{ meters} \quad (13)$$

where P_D is the equivalent plane wave power density criterion against which the distance is to be determined. A similar procedure can be followed for NEC curve (2). For this segment of the NEC model curve, the intersection with the POWDEN curve occurs at an "R" distance of $\lambda/2\pi$. Accordingly, the equivalent plane wave power density (P_D) in the near-field can be written in terms of the far-field power density and the relative slope of the NEC-2 curve as follows, using log notation:

$$10 \log P_{D(NF)} = 10 \log P_{D(FF)} - 30 \log (R/\lambda/2\pi) \quad (14)$$

where again R is the distance to be determined.

But

$$P_{D(FF)} = EIRP/4\pi R^2 \quad (2)$$

thus:

$$10 \log P_{D(NF)} = 10 \log EIRP - 10 \log 4\pi - 20 \log R - 30 \log R + 30 \log (\lambda/2\pi) \quad (15)$$

Rearranging terms, and again considering that the power density of concern is that of the exposure limit criterion, which is generally the same whether in the near field or far field, the subscript (NF) can be deleted for simplicity. Accordingly:

$$50 \log R = 10 \log EIRP - 10 \log 4\pi - 10 \log P_D + 30 \log (\lambda/2\pi) \quad (16)$$

But

$$10 \log EIRP - 10 \log 4\pi - 10 \log P_D = 20 \log D_{FF} \quad (5)$$

Making this substitution, Equation 16 becomes:

$$50 \log R = 20 \log D_{FF} + 30 \log (\lambda/2\pi) \quad (17)$$

R in this case is that distance along the NEC-2 curve in the normalized range between 0.0333λ and 0.198λ. And, again making the assumption that it exists in the near field, it is called D_{NF}. With the substitution, $\lambda = 300/f_{MHZ}$, Equation 17 becomes:

$$50 \log D_{NF} = 20 \log D_{FF} - 30 \log f_{MHz} + 30 \log(300/2\pi) \quad (18)$$

But 20 log D_{FF} can be written 50 log D_{FF} - 30 log D_{FF}. Making this substitution and combining the -30 log D_{FF} with the -30 log f_{MHz}, Equation 18 becomes:

$$50 \log D_{NF} = 50 \log D_{FF} - 30 \log D_{FF}f_{MHz} + 30 \log (300/2\pi) \quad (19)$$

or:

$$10 \log D_{NF} = 10 \log D_{FF} - 6 \log D_{FF}f_{MHz} + 10.073648 \text{ dB meters} \quad (20)$$

Equation 20 is the basis on which Figure 4 was developed. For Equation 20, the relative correction factor ($D_{FF}f_{MHz}$) lies in the range 0.96 to 82 for the bounds specified.

Taking the antilog, Equation 20 can be expressed in conventional form as follows:

$$D_{NF} = 10.171\, (D_{FF})/(D_{FF}f_{MHz})^{0.6} \text{ meters} \quad (21)$$

Equation 21 can be expressed in two other ways:

$$D_{NF} = 10.171\, (D_{FF})^{0.4}/(f_{MHz})^{0.6} \text{ meters} \quad (22)$$

or

$$D_{NF} = 10.171\, (D_{FF}f_{MHz})^{0.4}/(f_{MHz}) \text{ meters} \quad (23)$$

The distance, D_{NF}, can be determined also from the initial parameters used to determine the far-field distance, D_{FF}. Equation 16 is shown below.

$$50 \log R = 10 \log EIRP - 10 \log 4\pi - 10 \log P_D + 30 \log (\lambda/2\pi) \quad (16)$$

Dividing through by 50 and taking the antilog, Equation 24 results. Remember, in this case, R is a distance in the near-field region for this stub antenna between 0.0333λ and 0.198λ. Accordingly,

$$R \text{ or } D_{NF} = (EIRP/4\pi P_D)^{0.2}\, (\lambda/2\pi)^{0.6} \text{ meters} \quad (24)$$

or:

$$R \text{ or } D_{NF} = 6.131\, (EIRP/P_D)^{0.2}\, (f_{MHz})^{-0.6} \text{ meters} \quad (25)$$

where, again, P_D is the equivalent plane wave power density criterion against which the distance is to be determined.

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