The Far-Field: How Far is Far Enough?

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This tutorial paper reviews the basic criteria used in establishing the far-field region for electromagnetic fields from microwave/RF sources, including antennas for cellular telephone, microwave radar and many other uses.

When calculating microwave/RF communication link power budgets using the well-known Friis power transmission equation [1-4], or when planning antenna radiation-pattern measurements, a necessary underlying assumption is that the transmitting and receiving antennas are sufficiently far enough away from each other to be considered in the far-field. Where exactly does this far-field start from? Lets look at a concrete example:

A satellite reflector antenna has a diameter of 1 meter and transmits at 6 GHz. How far from the antenna should a test receiver be located to ensure it is in the far field?

The answer [1, 2] is that the receiver should be located at least at a distance (r), where

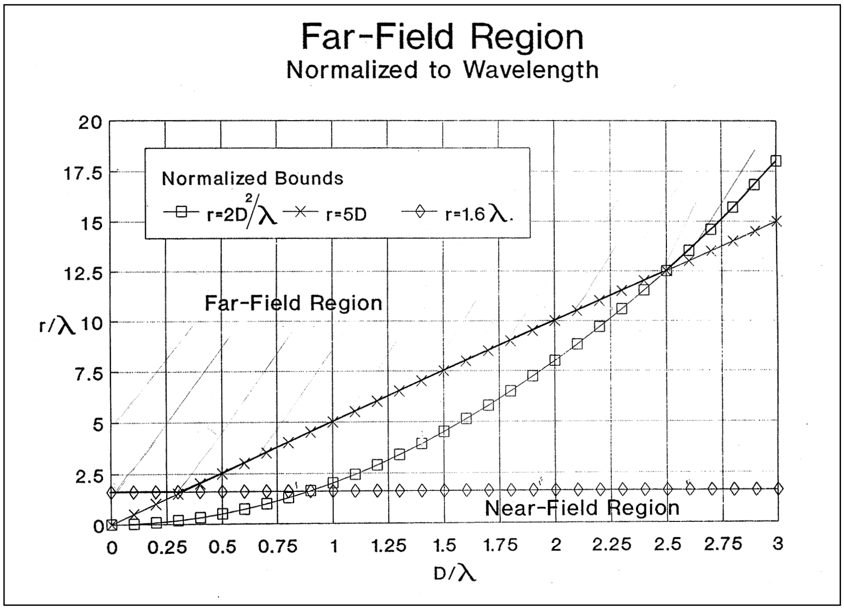
$$r = \frac{2D^2}{\lambda} \tag{1}$$

In this equation, D is the maximum linear dimension of the antenna and λ is the operating wavelength. For the example above, D = 1 m and λ = 5 cm, and so a simple "back-of-the-envelope" calculation tells us that r should be at least 40 m, which seems reasonable.

But does the above criterion always hold? Let us consider another example: If a $\lambda/2$-dipole is operating at 900 MHz, where does the far-field region begin?

The blind application of the $r = 2\,D^2/\lambda$ formula yields r = 17 cm, which seems incorrect. Reference [3] inserts the caveat that, for the above formula to be valid, D must also be large compared to the wavelength (λ), which explains why the second example failed.

We next turn to reference [4] (page 30), which summarizes the far-field conditions as follows:



▲ **Figure 1. The three criteria in as a function of the electrical size (*D*/λ) of the antenna.**

$$r > \frac{2D^2}{\lambda} \tag{2}$$

$$r >> D \tag{3}$$

$$r >> \lambda \tag{4}$$

Only when all the above conditions are met are we safely in the far field. One small problem remains though; the inequalities listed above still leave a lot of room to maneuver, while we would prefer more specific (although admittedly somewhat arbitrary like most rules of thumb) constraints in practice. The answer we are seeking is actually buried within the text of a problem on page 53 of [4] and can be rephrased as follows:

$$r > \frac{2D^2}{\lambda} \tag{5}$$

$$r > 5D \quad (6)$$

$$r > 1.6\lambda \quad (7)$$

Figure 1 shows these three far-field criteria in a graphical form as a function of the electrical size (D/λ) of the antenna. From the graph, we see that the widely cited formula $r = 2\,D^2/\lambda$ is acceptable once the antenna size (D) exceeds about 2.5 λ. At the other extreme, when the antenna is very small ($D < 1/3\lambda$), the operative criterion is that $r > 1.6\,\lambda$. In the intermediate range ($1/3\,\lambda < D < 2.5\,\lambda$), the criterion $r > 5D$ sets the far-field behavior. ■

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References

1. D. M. Pozar, *Microwave Engineering*, 2nd ed., Wiley, 1998.
2. M. Sadiku, *Elements of Electromagnetics*, 2nd ed., OUP, 1994.
3. C. Balanis, *Antenna Theory: Analysis and Design*, 2nd ed., Wiley, 1997.
4. W. Stutzman and G. Thiele, *Antenna Theory and Design*, 2nd ed., Wiley, 1998.
5. *IEEE Standard Dictionary of Electrical and Electronics Terms*, IEEE standard 100-1984, 1984.
6. C. Paul, K. Whites, and S. Nasar, *Introduction to Electromagnetic Fields*, 3rd ed., McGraw-Hill, 1998.
7. *Reference Data for Radio Engineers*, 6th ed., SAMS, 1981.
8. G. Smith, *An Introduction to Classical Electromagnetic Radiation*, Cambridge, 1997.

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Appendix

How does one arrive at the various criteria for the far-field zone? Basically, the criteria are guidelines to the boundaries where the fields start to approximate the "ideal" assumed characteristics. First of all, only the radiation ($1/r$) terms remain significant; higher order terms fade away. Second, in the far-field zone, the angular field distribution becomes independent of the distance [5]. Third, only transverse field components remain, and the ratio of the electric and magnetic field components approaches the free-space impedance, 377 ohms [6 ,7]. Finally, for a receiving antenna, the incoming wave-front is nearly planar across the aperture. In fact, the $r = 2\,D^2/l$ formula corresponds to a phase error (due to the curvature of the actual spherical wave-front) of no more than ±22.5 degrees across the aperture, as compared with the ideal plane wave-front [6, 8].